MSc
Thesis

Simulation Surface Fertigation Practices of Winter Wheat–Summer Maize Rotation in the North China Plain with WinSRFR/SWAP

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Abstract

The North China Plain (NCP), as the major food producer of China, has seen significant increases of grain yields in recent years. The NCP is experiencing problems of water shortage and chemical pollution from fertilizers. With the imperfect or backward irrigation and fertilization technology and poor management, the problems are intensified. Therefore, it is of great importance to develop the irrigation and fertilization practices in the NCP. Surface fertigation, as an acceptable way to alleviate problems in this region, can both reduce chemical pollution and improve fertilizer efficiency. In this study, surface fertigation practices in one representative experiment site, Xinxiang was simulated through application of WinSRFR and SWAP model. After calibration, the models were applied to five scenarios with same fertilizers applied and different irrigation amount for three years. From simulation we found that both crop yields and N leaching are closely related to irrigation volume. By comparing the simulation results for three years, considerable yields can be achieved when the sum of rainfall and irrigation reached 490mm in winter wheat season and 450mm in summer maize season; or irrigation amount both reached 200mm. It is recommended for farmers to reduce the irrigation volume by increasing inflow rates and pump head; and strengthen the observation of precipitation and soil conditions to adjust the irrigation/fertigation plan. Furthermore, through the experience of this model testing, recommendations are given to other model users and further studies.

Key words: Surface Fertigation; Winter Wheat; Summer Maize; Simulation model; WinSRFR; SWAP; The North China Plain

Acknowledgement

Table of Contents

1 Introduction

The North China Plain (NCP) is one of the most important food production regions in China. Covering only 3.3 % of the national area, the NCP provides 40 % and 25 % of wheat and maize production in China (Meng et al., 2018). Surface irrigation and broadcast fertilisation are widely used but poorly managed by smallholder farmers. The precipitation in this area varies greatly from year to year and the water demand for crops cannot be guaranteed. With the lack of surface water, intensive groundwater exploration becomes a significant way to access irrigation water in this area. In current agricultural production, farmers are unilaterally pursuing high yields and tend to over irrigate the field (Zhang et al., 2002). The convenience of access to groundwater has led to a lack of awareness among local farmers on water conservation. Water shortage is in contradiction with the behaviour of farmers using excessive water. To achieve high crop yields, excessive fertilization is widespread, resulting in low fertilizer efficiency and severe nitrogen loss. The accumulation of nitrate in farmland soil and pollution of groundwater from N leaching caused by excessive application of chemical fertilizers have become the second major environmental problem in the NCP after continuous over-exploitation of groundwater (Pei et al., 2015). Therefore, it is of great importance to develop the irrigation and fertilization practices in the NCP.

Fertigation is an irrigation and fertilization method in which pre-dissolved chemical fertilizers are applied together with the irrigation process. Compared with traditional fertilization method, it has the characteristics of high fertilizer efficiency, low fertilizer loss and low labour input requirement (Zhang et al., 2011). Compared with more advanced fertilization method like the drip fertilization, it is easier and more feasible to improve the current situation by modifying the existing system. Thus surface fertigation seems to be the most practicable method to improve the on-farm irrigation and fertilisation performance.

There are not many studies on surface fertigation in the NCP, while most of them concentrated on field experiments (Liang et al., 2009; Zai, 2010; Li et al., 2012; Chen et al., 2016; Bai et al., 2011). Researchers from China Institute of Water Resources and Hydropower Research established event-based coupled models of surface water flow and solute transport in surface fertigation process (Zhang et al., 2011; Li et al., 2009; Li et al., 2015). These models performed well in the simulation of a single fertigation event, while the seasonal analysis is still missing. Besides, mineralisation, nitrification and denitrification process were not considered in these event-based models. Therefore, research of long-term simulation surface fertigation in the NCP is still required.

This MSc thesis takes place in cooperation with the PhD research “Surface Fertigation Practices for Smallholder Farmers in the North China Plain” of Xiulu Sun. Information and data needed for the modelling were collected through field experiments and interaction with farmers before this research. The research processes of this MSc thesis can be mainly divided to these five steps: (i) Literature review; (ii) Data collection; (iii) Model testing; (iv) Model calibration; (v) Data analysis. On basis of a literature review and consultancy from supervisors, the indicators to assess the performances of fertigation practices are listed in Table 1.

Table 1. Indicators for fertigation performance analysis.

Irrigation Event Analysis	Application efficiency (AE)
	Distribution uniformity (DU)
Seasonal Analysis	Water use efficiency (WUE)
	Water productivity (WP)
	Nitrogen use efficiency (NUE)
	Nitrogen uptake efficiency (N capture)
	Crop yields
	N uptake
	N leaching

In order to obtain these indicators in Table 1, the model WinSRFR and SWAP were applied in this research. The WinSRFR can deal with assessment of one surface irrigation event (Bautista et al., 2012). With the Soil-N module, SWAP can work on evaluation of soil water, crop growth and nitrogen movement to assess the potential chemical pollution in a long time period (Kroes et al., 2017; Groenendijk et al., 2016). SWAP model is a one-dimensional model (vertical direction), without considering the differences along the direction of field length. However, in our experiments, the length of the field was 200 m, where big differences may exist. Therefore, WinSRFR model can help to cut the field into two parts to take the direction of field length into account.

The main objective of this research is:
to simulate surface fertigation practices in the North China Plain through application of WinSRFR and SWAP model and give recommendations on field monitoring.

The specific objectives are:
(1) To combine the event analysis and seasonal analysis of fertigation practices by model coupling of WinSRFR and SWAP model;
(2) To calibrate the model WinSRFR and SWAP based on data collected in field survey stage;
(3) To access the performance of fertigation practices in field experiments and find the potential influencing factors on crop growth and N pollution;
(4) To apply the WinSRFR and SWAP models to more scenarios and explore the impact of

changes in potential influencing factors;

(6) To give recommendations of field management based on simulated results;

(7) To give recommendations about model simulation and field experiments based on my research process.

The main research question of this research is:

What measures can be taken to optimize the performance of surface fertigation practices in the NCP through WinSRFR/SWAP modelling?

The specific research questions are:

(1) Can WinSRFR and SWAP models be coupled to simulate surface fertigation practices in the NCP?

(2) What is the performance of current fertigation practices in field experiments in the NCP?

(3) What can be potential influencing factors on crop growth and N pollution?

(4) What is the response of crop growth and N pollution to changes of the potential influencing factors?

(5) What can be improved to optimize fertigation practices of small holder famers in the NCP?

2 Research Background

2.1 Regional background

The North China Plain is the second largest plain in China (Figure 1). The terrain of the NCP is low-lying and flat, mostly below 50 meters above the sea level. The NCP is a typical alluvial plain, with the zonal soil of brown soil or cinnamon soil. The arable lands in the NCP account for around one-fifth of the total in China (Liu, 1989). As a major producer of food in China, the NCP is the most important production base of grain, cotton and oil (Li et al., 2005).

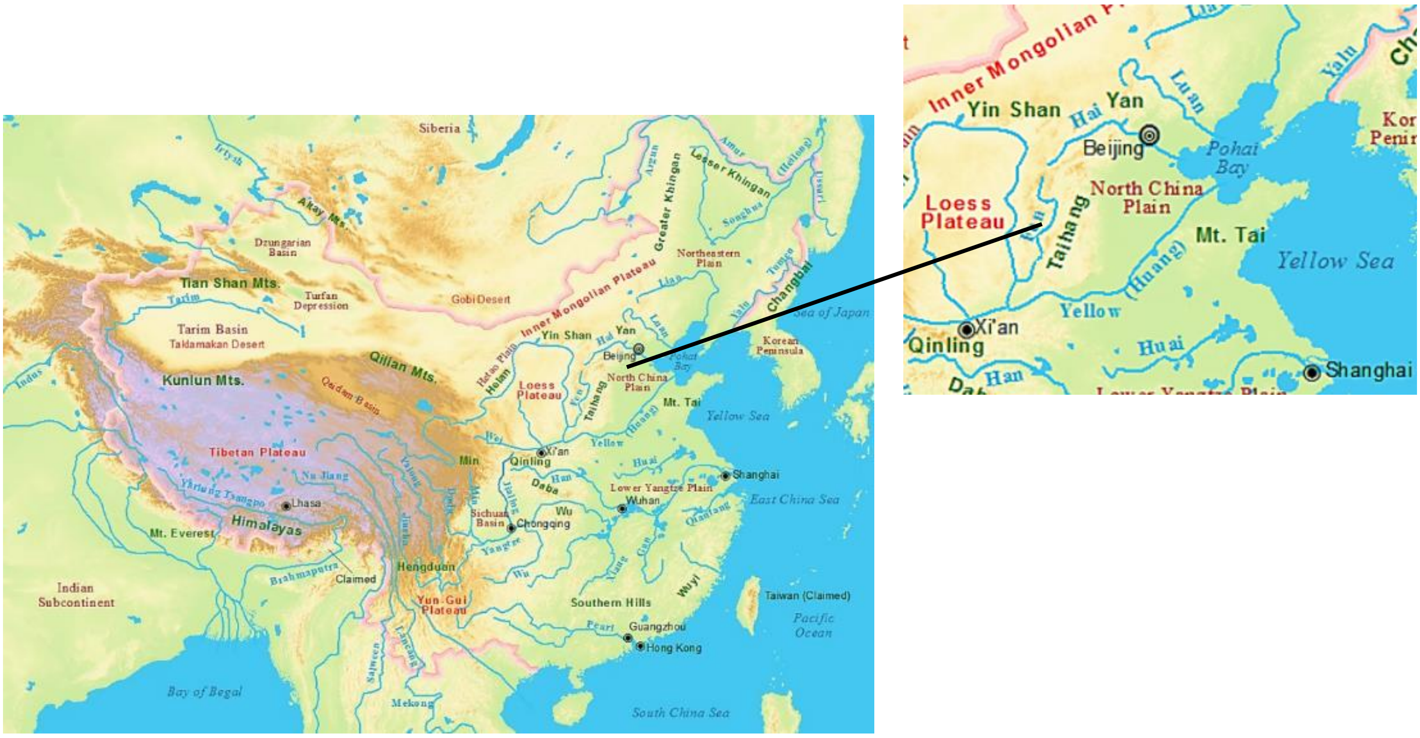


Figure 1. Location of The North China Plain.

The NCP is now experiencing problems of irrigation and fertilizers use. In this region, 70% of the total water use is for agriculture (Wang et al., 2002). However, precipitation is not sufficient in the NCP, while it is concentrated in summer, with large differences between regions, seasons, and years (Mo et al., 2005). Surface irrigation is widely used in the NCP. However, the systems are poorly managed with low efficiency by smallholder farmers. From Sun's interviews and questionnaire survey, the farmers believe that irrigation is completed when water flow reaches end of the field (2019). With no estimation of water requirement and assessment of irrigation amount, their irrigation practices can easily result in over-irrigation and losses of water due to deep percolation. The low irrigation efficiency has intensified water shortage problem.

The consumption of fertilizers in the NCP is about 330 kg/ha for one year, mainly by broadcast fertilization (Ministry of Agriculture, 2015). With inappropriate operation with very low fertilizer efficiency, the wasted fertilizers are infiltrated into soil or flow away through irrigation water, resulting in serious nitrogen pollution to surface water and groundwater (Zhen et al., 2006).

Furthermore, with no assess to organic fertilizers (manure, slurry etc.) and the high costs, farmers in this region gave up the traditional fertilizers during these past thirty years, while the chemical fertilizers became widely adopted (Sun, 2019). Consequently, the organic matters entering into the soil were reduced, resulting in unbalance of soil organic matters (Wang et al., 2016).

Fertigation, as an emerging agronomic technology to supply irrigation water and fertilizers together, can both reduce chemical pollution and improve fertilizer efficiency (Hagin and Lowengart, 1996). Although the most advanced fertigation technology like the drip fertigation can be the most effective way in this region, such kind of technologies are difficult to be adopted by farmers with conservative attitudes and insufficient budgets to pay for the systems. Therefore, surface fertigation can be the most acceptable way to alleviate irrigation and fertilization problems in this region.

2.2 Scientific background

2.2.1 Fertigation

Fertigation is a technology of dissolving fertilizers in water, using irrigation and pressure system to apply irrigation and fertilization at the same time. Fertigation can meet the needs of crops for water and nutrients in a timely and appropriate amount, and realize integrated management and efficient utilization of water and fertilizer (Li & Lu, 2000). Compared with traditional fertilization methods, fertigation has the advantages of improving water and fertilizer efficiency, saving labors, ensuring uniform supply of nutrients and reducing environmental pollution (Gao et al., 2015). However, according to Gao's colloquium in the 4th China International Water-soluble Fertilizer High-Level Forum (2013), the application area of fertigation in China only accounts for 3.2% of the total irrigated area (Figure 2). Therefore, the application of fertigation has broad prospects for development in China.

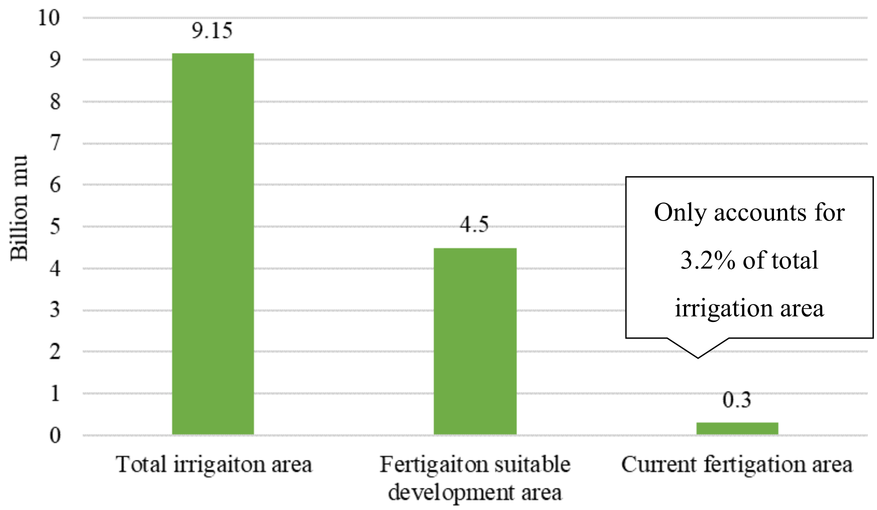


Figure 2. Total irrigation area, fertigation suitable development area and current fertigation area (mu is a unit of area, 1 billion mu equals 6.67 million ha) (Gao, 2013).

In order to improve the efficiency and distribution uniformity of irrigaiton and fertilization to achieve high crop yields, agricultural experts have carried out extensive research on fertigation application. With the development of science and technology, new irrigation methods such as drip irrigation and sprinkler irrigation have been used, which promoted great progress of drip fertigation and sprinkler fertigation technology in field experimental research, e.g. Wang et al. (2008) conducted drip fertigation experiments to analyze the distribution of soil moisture and NO_3-N under different drip flow rates, water and fertilizers application; Feng et al. (2017) conducted a 2-year field experiment of potato to establish appropriate drip fertigation scheduling with loss control fertilizer as a basal fertilizer in sandy soil; Yan et al. (2018) conducted research of evaluation of the cumulative effect of drip irrigation and fertigation on productivity in a poplar plantation through field experiments. In addition to experimental research, relevant model simulations also made great progress, mainly through the HYDRUS model, e.g. Li et al. (2005) simulated water and Nitrate transport in soil from a surface point source of NH_4NO_3 by application of HYDRUS-2D software; Wang et al. (2014) used the water and solute transport model HYDRUS-2D to evaluate effects of drip system uniformity and precipitation on deep percolation and Nitrate leaching under maize in a subhumid region; Zhang et al. (2015) analyzed the critical factors that affect the nutrient distribution under different drip fertigaiton strategies through HYDRUS2D/3D simulations.

In China, current fertigation technology is mainly used for micro-irrigation, but little involved in surface (border) irrigaiton which accounts for more than 95% of China's total irrigated area (Li, 2004; Li et al., 2004). Existed research on surface fertigation mainly focused on experimental research: Bai et al. (2011) analyzed the spatial and temporal distribution of Nitrogen in soil and surface water based on the field experiments with different fertilization methods and inflow rates in the greening period of winter wheat. Chen et al. (2016) investigated the distribution of NO_3-N in soil water with different fertigation methods to explore the optimal border fertigation parttern of summer maize. Zai (2010) conducted field trials and laboratory experiments to establish a resonable fertigation system. Researchers from China Institute of Water Resources and Hydropower Research established event-based coupled models of surface water flow and solute transport in surface fertigation process: Li et al. (2009) introduced the integrated model consisting solute transport model of border strip fertigation based on one-dimensional convection dispersion equation and the HYDRUS-2D model to simulate the two-dimensional solute transport; Zhang et al. (2011) established a one-dimensional model for surface water flow and solute transport for border fertigation based on the implicit-explicit time scheme, the finite-difference method, the finite-volume method and the finite-element method; Li et al. (2015) developed an overland flow and solute transport model based on characteristic curve method, which introduced more reasonable results compared with models based on finite methods. These models performed well in the simulation of a single fertigation event, while the seasonal analysis is still missing. Besides, mineralisation, nitrification and denitrification processes were not considered in these event-based models.

2.2.2 SWAP model application in China

The earlier versions of SWAP model have been tested and validated for a wide range of climate and agricultural systems in semi-arid areas including the NCP: Li et al. (2005) simulated the water regimes of aerobic rice to evaluate the effect of groundwater depth on water saving irrigation; Ma et al. (2010) evaluated the field water cycle for a winter wheat-summer maize double cropping system under deficit irrigation in Beijing with application of SWAP model; Feng et al. (2012) simulated the process of crop water requirements and water conversion under deficit irrigation to analyse the field water transformation process under effects of deficit irrigation; Huo et al. (2012) quantified the vertical water fluxes through simulation the soil water content and fluxes at the water table and in the subsoil under different irrigation and groundwater conditions using SWAP model; Ma et al. (2015) evaluated the optimal irrigation scheduling and groundwater recharge of winter wheat-summer maize rotation at three representative sites in the NCP with SWAP model and field experiments; Liu et al. (2010) developed an integrated model of SWAP and 3D transient groundwater model MODFLOW to simulate the irrigation schedules in different groundwater depth to propose the appropriate irrigation control standard and optimum range of groundwater depth. In previous research of SWAP application in the NCP, although the model simulation involved crop growth, the research used simple crop module rather than the detailed WOFOST crop module. Besides, previous studies using earlier versions SWAP model mainly focused on soil water transport, without solute transport. The Soil-N module added in the latest version of SWAP has not been applied in the NCP.

To be concluded: (1) Current research on fertigation mainly focused on drip fertigation or sprinkler fertigation, but little involved in surface fertigation; (2) Models used to simulate surface fertigation in the NCP were mostly event based. Seasonal analysis considering mineralization, nitrification and denitrification is still missing; (3) SWAP model have been tested and validated in the NCP, but most of them used the simple crop module, and the new version with Soil-N module has not been used in current literatures. Therefore, fertigation simulation in the NCP requires more research; using SWAP to simulate fertigation for seasonal analysis is a new study.

2.3 Social background

Due to the significance of the NCP in agricultural development in China, the Chinese government has attached great importance to optimization and development of farmland irrigation and drainage systems in the NCP. With the support of relevant policies in China, there have been many farmland improvement projects in the NCP in recent years. For instance, since the 18th National Congress of the Communist Party of China in 2012, Henan Province (the major part of the NCP) vigorously promoted the construction of agricultural water-saving projects, adding 6.1 million mu (407 thousands ha) of water-saving irrigation area with drip or sprinkler irrigation (Wang, 2017). While these projects have brought benefits to the NCP and alleviated problems to a certain degree, there are still remaining problems and negative effects developing, especially with smallholder farmers.

3 Experiment Set-up

3.1 Study area

Since the data and information as the inputs of the model simulation came from field survey conducted in the previous sections of Xiulu Sun's PhD research, the study area for this thesis is the same as the PhD research.

One-year field experiment of winter wheat and summer maize rotation was conducted in an agricultural water and soil environment observation experimental station of Farmland Irrigation Research Institute (FIRI). The experiment site is located in the People's Victory Canal Irrigation District (PVCID) (113° 30' ~ 114° 5' E, 35° ~ 35°20' N), which is situated in the southern part of the North China Plain. Figure 3 shows the locations of PVDID and experiment site.

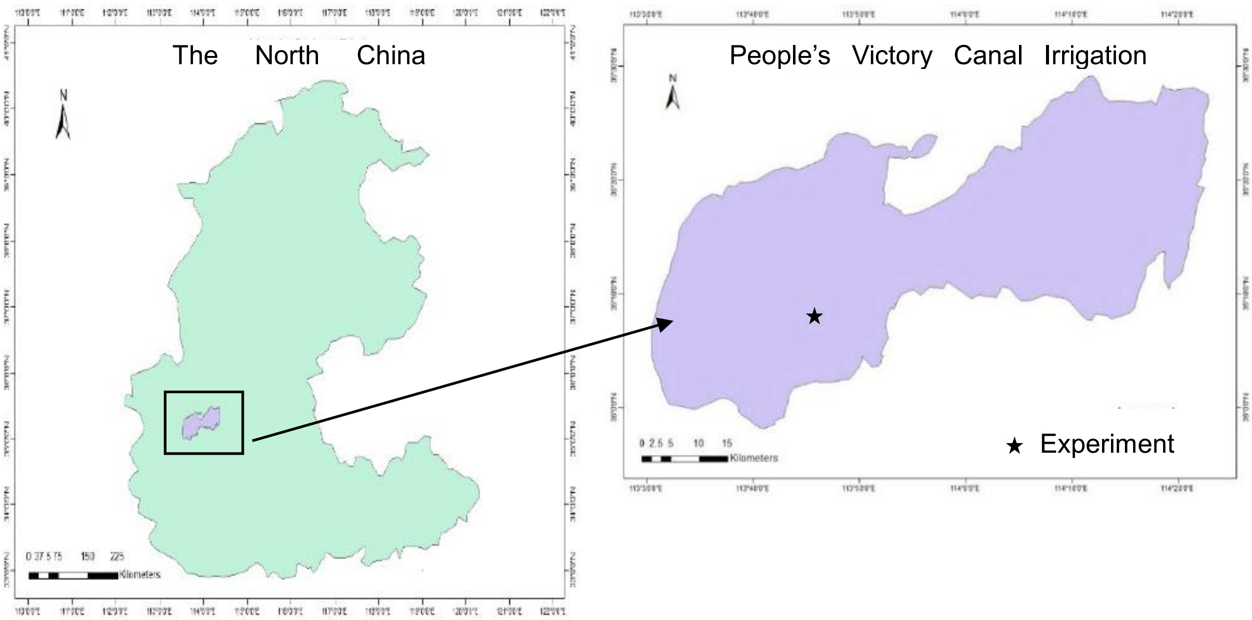


Figure 3. Location of the People's Victory Canal Irrigation District and experiment site.

This area has a typical temperate monsoon climate, with a mean annual precipitation of 617mm, which concentrated in the period from June to September (Administration Bureau of PVCID, 2002). Figure 4 and 5 show the average monthly rainfall amount and evaporation of 1981 to 2010 in this region, which was derived from Chinese National Meteorological Information Centre (CMA, 2019). Furthermore, there is a meteorological station in the area that can provide reliable weather data.

The main cropping pattern of the area is winter wheat - summer maize rotation. The irrigation water of this scheme mostly comes from the Yellow River and groundwater (ground water level: 17 m deep), and the average irrigation water efficiency is around 44% (Zhu et al., 2012). The soil texture of this area is loamy soil, with an average bulk density of 1.464 g/cm^3. It is representative of irrigated practices in this intensive agricultural area in the NCP.

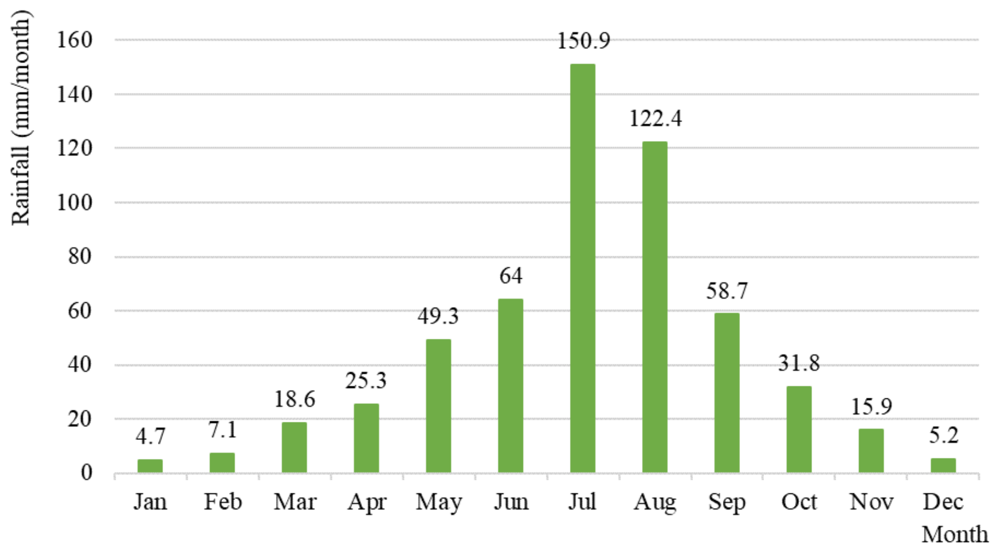


Figure 4. Monthly average rainfall in study area.

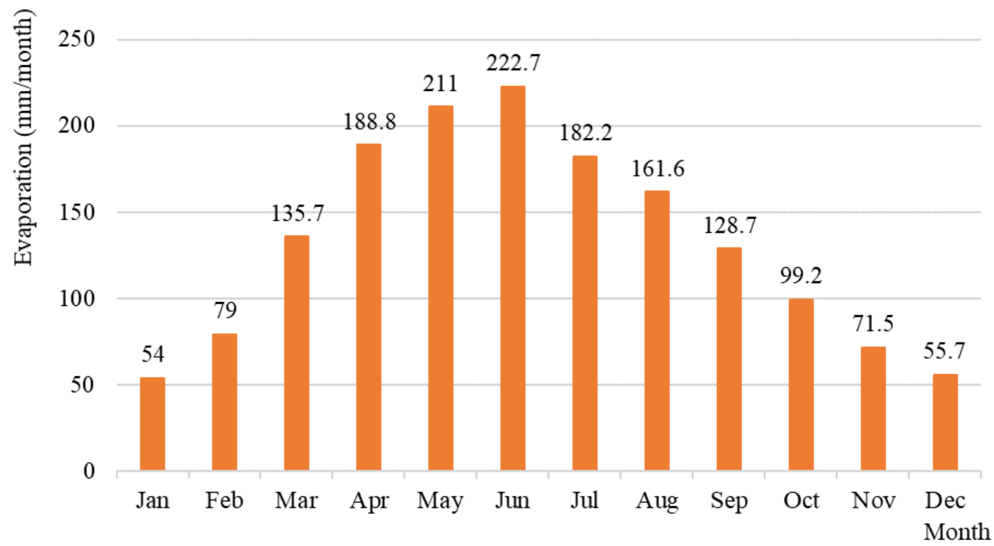


Figure 5. Monthly average evaporation in study area.

3.2 Experiment design

3.2.1 Experiment layout and treatments

As a part of Xiulu Sun's PhD research, field experiments of winter wheat – summer maize rotation were conducted by Xiulu Sun and other researchers from FIRI, in the period of October 15, 2017 to October 1, 2018 (one winter wheat season and one summer maize season). Table 2 shows the general information of experiment crops adopted, while the detailed crop calendar is illustrated in Figure 6.

Table 2. General information of crops grown for field experiments.

Crop	Crop variety	Row spacing	Plant spacing	Border size
Winter wheat	Aibai 207	22cm	1.6cm	200m * 3.5m
Summer maize	Xianyu 335	60cm	20cm	

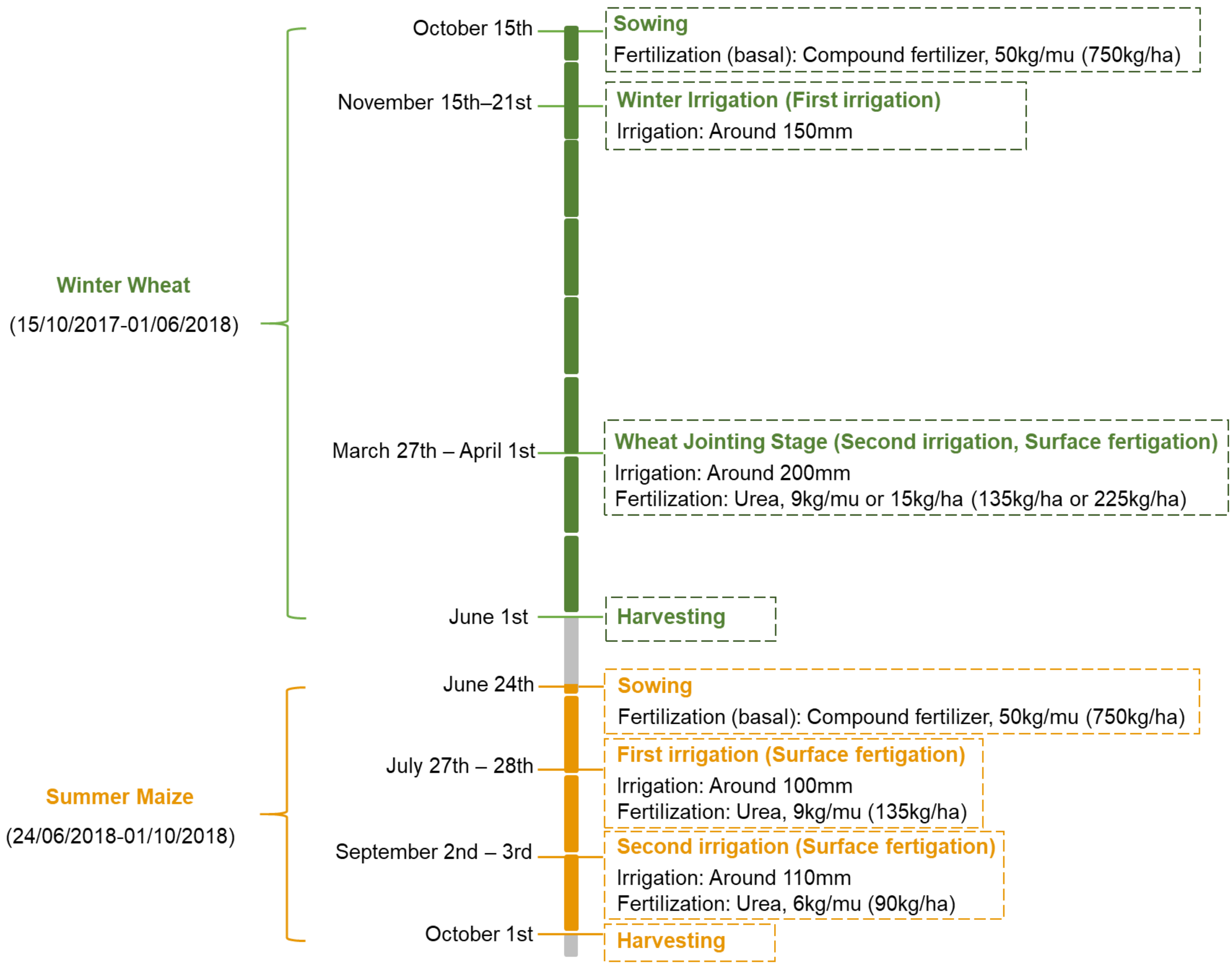


Figure 6. Crop calendar of Winter wheat – summer maize rotation in field experiments.

The experiment site consisted 10 borders, with an area of 200m * 3.5m for each border. The 10 borders were divided into three different treatment groups, marked from east to west by Plot A to Plot J. In experiment period, four irrigation/fertigation experiments were conducted (two of winter wheat and two of summer maize). Border irrigation and surge border irrigation were adopted, with groundwater from variable pump as water resource. Table 3 summarizes different treatments for each border. The detailed layout of experiment site is shown in Figure 7.

Table 3. Treatments of experiment fields.

Crop season	Treatment	Time	Plot A-C	Plot D-F	Plot G-J
Winter wheat	Basal fertilization	Oct 15	750kg/ha, compound fertilizer		
	Winter irrigation	Nov 11 – Nov 21	Surge border irrigation	Border irrigation	
	Fertigation	Mar 27 – Apr 1	Surge border irrigation 135kg/ha, Urea	Border irrigation 135 kg/ha, Urea	Border irrigation 225 kg/ha, Urea

Summer maize	Basal fertilization	June 24	750kg/ha, compound fertilizer	
	Fertigation 1	Jul 27 – Jul 28	Surge border irrigation 135kg/ha, Urea	Border irrigation 135kg/ha, Urea
	Fertigation 2	Sep 2 – Sep 3	Surge border irrigation 90kg/ha, Urea	Border irrigation 90 kg/ha, Urea

* The amounts of water applied in each irrigation/fertigation event are different. In field experiments, irrigation/fertigation stopped when water flow reached 180/190m (advance). All plots were blocked at the end of the field (200m).

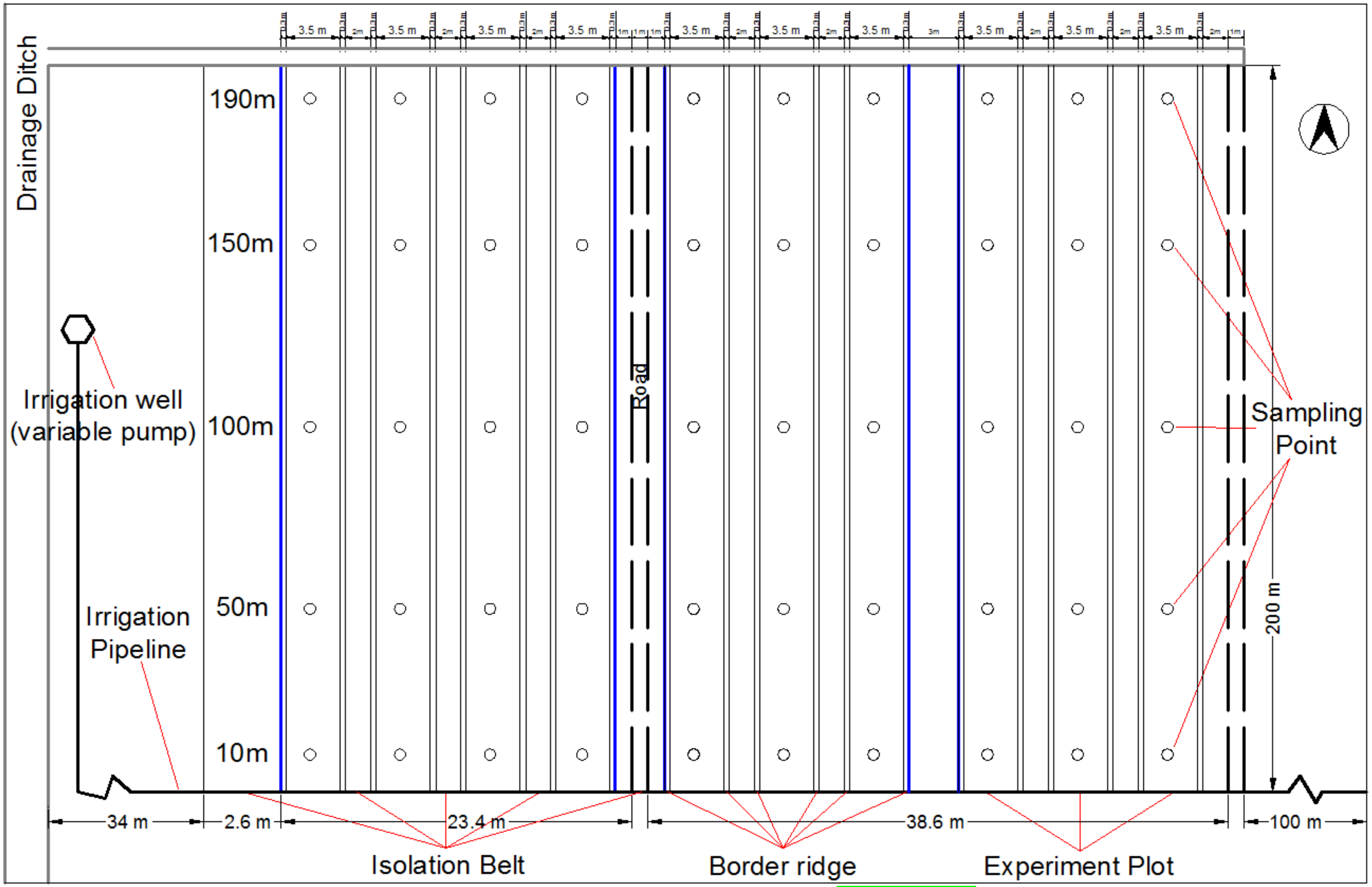


Figure 7. Layout of experiment fields in Xinxiang (Liu et al., 2019).

3.2.2 Field measurement

Table 4 to Table 6 give a detailed introduction of the field measurements and methods related to soil, irrigation experiments and crop respectively.

Table 4. Soil related field measurements and methods.

Measured item	Detailed information	Measuring time	Measuring method / tool
Bulk density Field capacity Saturated water content	200cm deep in one optional border, 10cm deeper each time; 3 samples per layer	August 13 2018	Cutting ring; Oven drying; Weighing
Soil particle size distribution → Soil texture	3 points in one optional border: 10m, 100m, 190m along the field; 170cm deep in one piont, 10cm deeper each time	January 2018	BT-9300HT laser particle size analyzer
Field slope	3 optional borders; Elevation of field head and field end in each border	July 2018	Level
Soil water content	All borders (before & after fertigation) / 3 optional borders at ordinary time (one for each treatment group); 5 points in each border: 10m, 50m, 100m, 150m, 190m along the field; 170cm deep in one piont, 10cm deeper each time	Routine monitoring: each 2 weeks; Before & after fertigation; 3 & 7 days after rainfall	TDR / Oven drying; Weighing
Soil NO_3-N concentration	All borders (before & after fertigation) / One optional border at ordinary time; 3 points in each border: 10m, 100m, 190m along the field; 200cm deep in one piont, 20cm deeper each time	Before & after fertigation; before sowing; after harvest	Continous Flow Analyzer

* The measuring time of soil water content changed in the ordinary time. The actual number of measurements was less than planned.

Table 5. Field measurements and methods during irrigation & fertigation experiments.

Measured item	Detailed information	Measuring time	Measuring method / tool
Advance and recession	Distance: 0, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200m	Each irrigation/ fertigation event	Stopwatch
Irrigation amount	Read the watermeter in pump station before & after irrigaiton		Watermeter
Flow rate	When water flow reached 0, 20, 40, 60, 80, 100, 120, 140, 160, 180m		Turbine flowmeter

Table 6. Crop related field measurements and methods.

Measured item	Detailed information	Measuring time	Measuring method / tool
Leaf area	3 optional borders (one for each treatment group) 3 points in each border: 10m, 100m, 190m along the field; 1 plant each point	Each development stage	Ruler Leaf Area = length × width × 0.86
Crop height			
Predicted yield	All borders; 3 points in each border: 10m, 100m, 190m along the field; $1m^2$ of each point was harvested and measured	2 days Before harvesing	Weighing
Crop yields	All borders were harvested together by combine harvester; So the measured yields was an average of all borders	After harvesting	Oven drying; Weighing

4 Model Set-up

4.1 WinSRFR

The WinSRFR 4.1.3 is a one-dimensional model for hydraulic analysis of surface irrigation, developed by the Arid Land Agricultural Research Center of United States Department of Agriculture. It is a comprehensive analysis software that integrates surface irrigation evaluation, design and simulation. The WinSRFR software consists of four analytical functions: (1) Event analysis: An irrigation event analysis and evaluation module using measured field experiments data (water flow advance, regression, etc.) and field roughness coefficient to derive the soil infiltration parameters and comprehensively evaluate the irrigation performance; (2) Simulation: A hydraulic simulation module using soil water infiltration parameters and irrigation elements to solve the unsteady flow equation of open channel; (3) Physical design: An irrigation system design module changing physical layout of the field to optimize irrigation performance; (4) Operations analysis: An irrigation monitoring module changing inflow and cut-off time for a given field size to optimize irrigation performance (Bautista et al., 2012).

This research is based on the model's Event Analysis module, which includes three methods: (1) Probe penetration analysis, relying on post-irrigation water penetration depth; (2) Merriam-Keller post-irrigation volume balance analysis, relying on water advance and recession data; (3) Elliot-Walker two-point method analysis, relying on two points of water advance data. The Elliot-Walker two-point method was adopted in this research, of which the soil water infiltration model introduced the Kostiakov infiltration equation:

$$Z = k\tau^{\alpha} \qquad \text{(Equation 1)}$$

where Z is the cumulative depth of infiltration (m);

τ is the intake opportunity time (min);

α is an empirical fitting parameter (-);

k is an empirical fitting parameter (m/min^α).

The input data of WinSRFR modelling are illustrated in Table 7.

Table 7. Required input data of WinSRFR model.

Input element	Unit
Required depth	mm
Border size (length, width, maximum depth)	mm
Slope	m/m
Manning n	-
Inflow rate	l/s
Cut-off time	hour
Advance and recession time in field measurements	m, hour

Kostiakov α	-
Kostiakov k (calculated by WinSRFR model)	m/hour^α

4.2 SWAP

The SWAP model is a professional software developed by Wageningen University. It is mainly used for the simulation of soil water movement, solute transport, heat transfer and crop growth on field scale. The upper boundary of the SWAP model is above the canopy of the plant, and the lower boundary is located above the unsaturated zone and groundwater. The model employs the Richards equation including root water extraction to simulate soil moisture movement in variably saturated soils. Between the upper and lower boundaries, the water flow is mainly considered in the vertical direction, the soil is divided into several layers, and the finite difference method is used to solve the equations of moisture, solute and heat motion (Kroes et al., 2017). Figure 8 illustrates the model domain and transport processes from SWAP version 4 user manual.

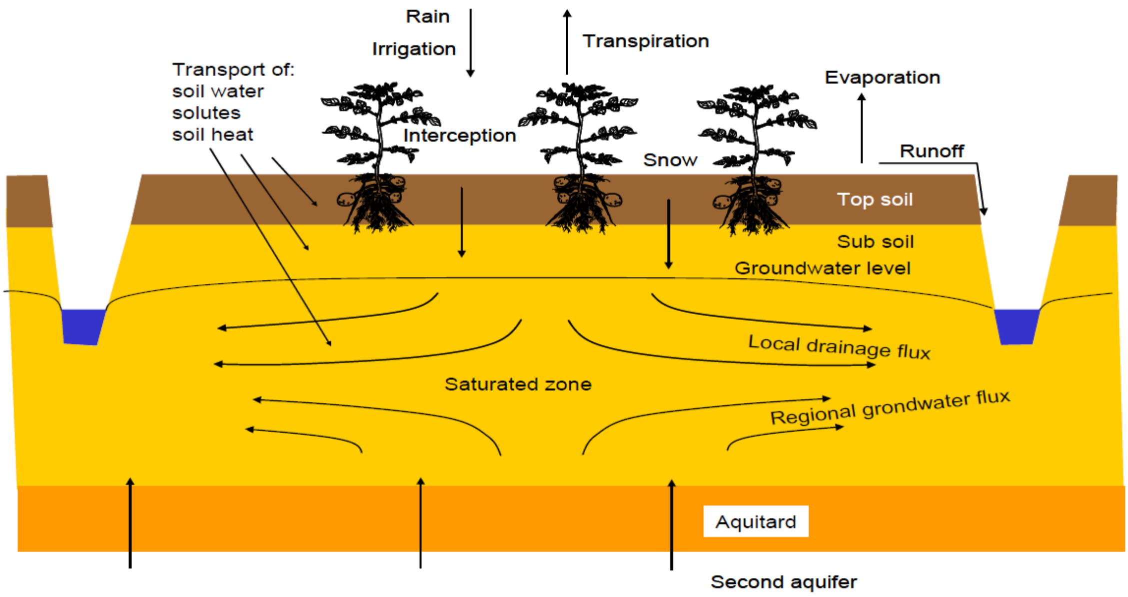


Figure 8. SWAP model domain and transport processes (Kroes et al., 2017, p. 11)

The generic crop growth module WOFOST is incorporated to simulate leaf photosynthesis and plant growth. In combination with specialized module Soil-N, the SWAP model can take mineralization, nitrification and denitrification into account to simulate transport of nitrogen. The soil moisture, heat and solute modules exchange information on each time step to account for their interactions. On a daily basis crop growth is affected by actual conditions of weather, soil moisture and nitrogen availability (Groenendijk et al., 2016). Figure 9 shows the interdependencies between the SWAP, WOFOST and Soil-N modules within the SWAP modelling.

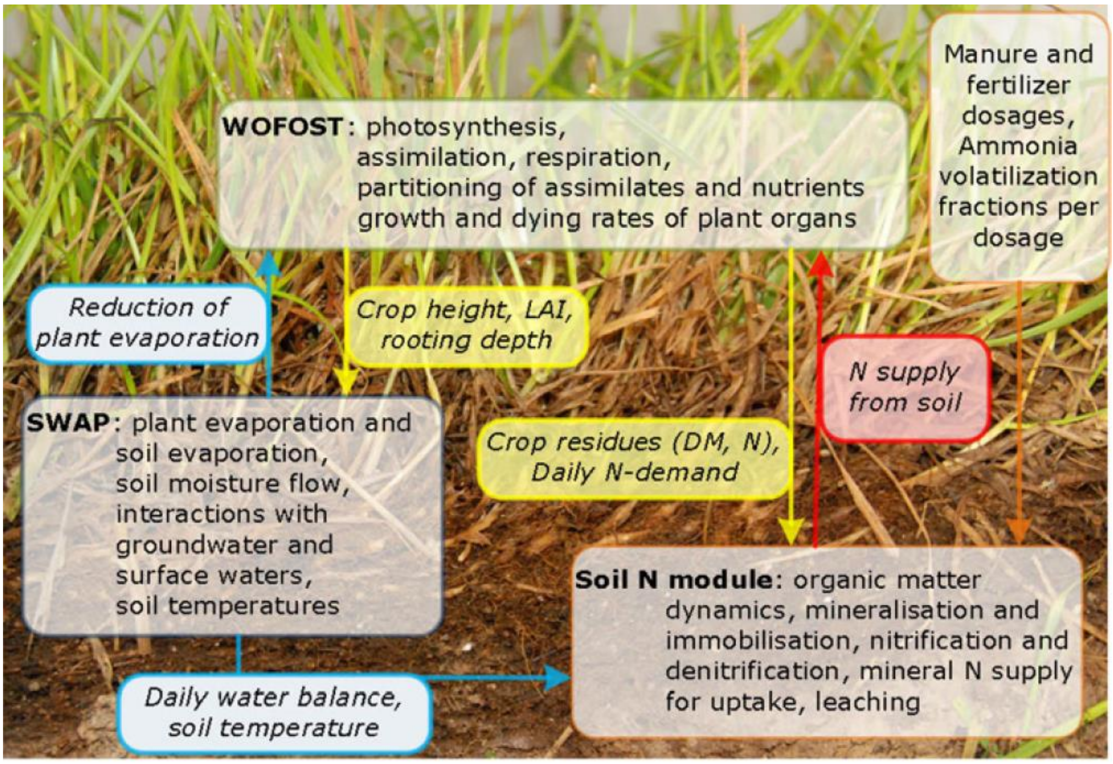


Figure 9. Interdependencies between the SWAP, WOFOST and Soil-N modules in the SWAP/WOFOST model (Groenendijk et al., 2016, p. 10).

The input data required for SWAP modelling are summarized in Table 8 to Table 12 (the optional data not used in this research are not listed in the tables).

Table 8. General information in SWAP input.

Input element	Unit
Simulation period	KJ/m^2
Crop rotation scheme (Date of emergence and harvesting)	-
Initial soil moisture condition (pressure head)	cm
Irrigaiton parameters (date, amount, method)	Amount: mm

Table 9. Required soil related data in SWAP input.

Input element		Unit
Vertical discretization of soil profile		cm
ORES (θr)	Residual water content	cm^3/cm^3
OSAT (θs)	Saturated water content	cm^3/cm^3
ALFA (α)	Parameter α on main drying curve (The inverse of the air-entry value)	cm
NPAR (n)	Parameter n (The shape parameter)	-
KSATFIT (Ks)	Saturate hydraulic conductivity	cm/d

LEXP (L)	The pore-connectivity parameter in dydraulic conductivity function	-
BDENS (BD)	Soil bulk density	mg/cm^3

Table 10. Required climate data in SWAP input.

Input element	Unit
Solar radiation	KJ/m^2
Daily maximum temperature	°C
Daily minimum temperature	°C
Air humidity[1]	KPa
Wind speed	m/s
Daily rainfall	mm

[1]The air humidity here means vapour pressure, with a unit of kPa.

Table 11. Required crop data in SWAP input.

Input element		
Crop height / Crop factor		Maintenance respiration
Crop development (temperature sum)		Dry matter partitioning
Initial crop dry weight & LAI		Death rates
Green surface area		Crop water use
CO_2 assimilation		Interception
Assimilates conversion into biomass		Root growth and density distribution

Table 12. Required soil-N data in SWAP input.

Input element	Unit
Relations between C02 and Amax, Radiation use efficiency and Tranpiration	-
CO2 concentration in atmosohere	ppm
Fertilization parameters (date, amount, fertilizer type)	Amount: kg/ha
Initial soil organic matter and N	kg/m^3 soil volume
Response function parameters	-
Soil N supply uptake parameters	-
Effective depth of soil layer	m

4.3 Model coupling

SWAP model is a one-dimensional model (vertical direction), without considering the differences along the direction of field length. However, in our experiments, the length of the field was 200m, where big differences may exist. Therefore, we introduced the model WinSRFR and cut the field into two parts to take the direction of field length into account.

The interdependencies between WinSRFR and each module in SWAP model are illustrated in framework below (Figure 10).

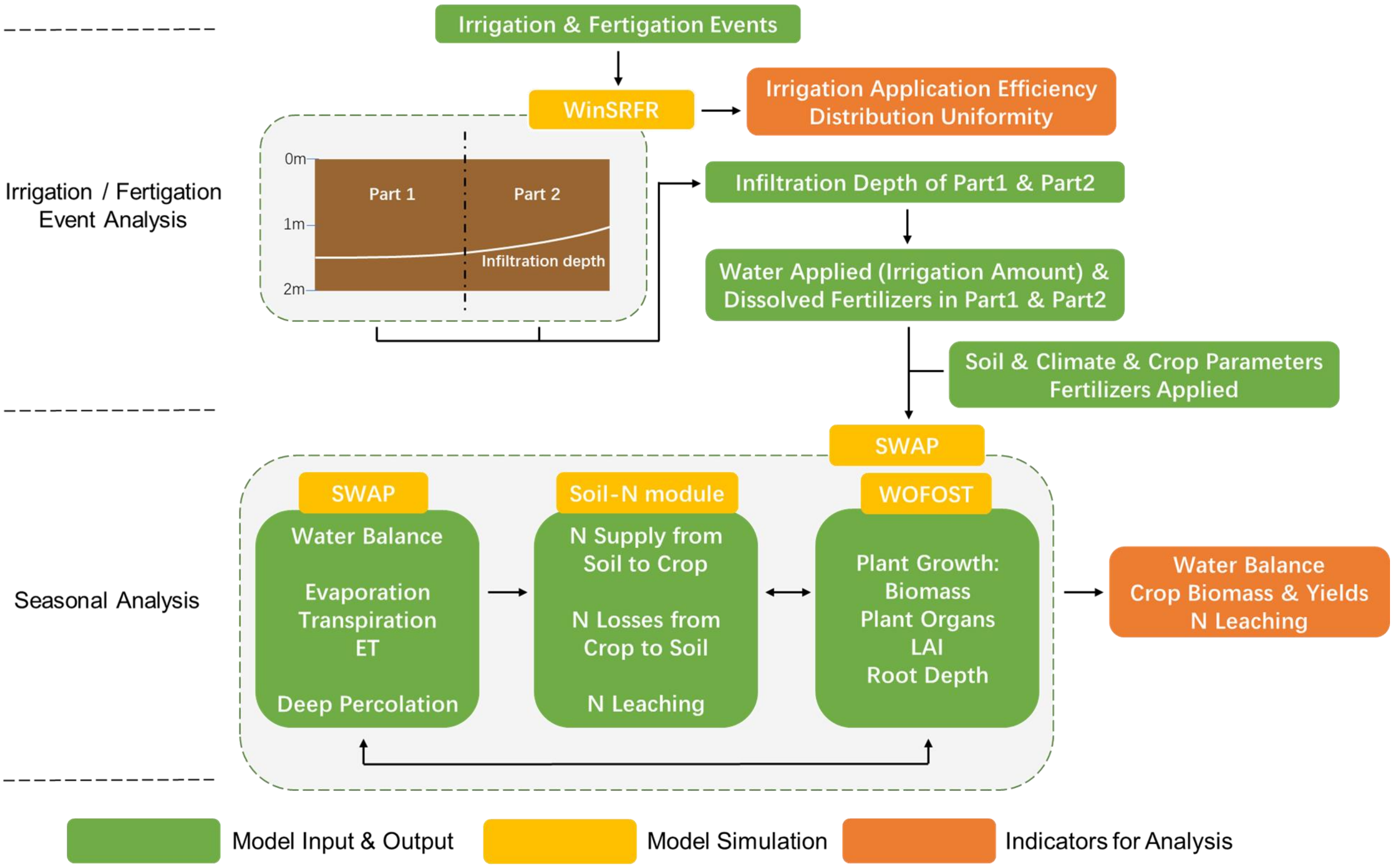


Figure 10. Framework of Interdependencies in WinSRFR-SWAP model coupling.

The process of running each model and the mutual transfer of information between each compartment are described as follows:

Step 1: Calculations by WinSRFR model

Each irrigation and fertigation event are simulated by WinSRFR model. Measured advance and recession time can be used for model calibration (Manning-n and α in Kostiakov equation). Infiltration depths are shown as figures in model output, while the data is available to calculate the average infiltration depth of first and second half of the field respectively, which is taken as irrigation amount for next calculation. With same fertilizer concentration in fertigation water, amount of dissolved fertilizers is calculated based on different irrigation amount of two parts of the field. The application efficiency and distribution uniformity in model output are used to evaluate irrigation performance.

Step 2: Calculations by SWAP model (soil water)

Soil water balance is calculated by SWAP model according to initial soil water content of the day, including precipitation, irrigation, transpiration and soil evaporation of the day. Root water absorption is calculated based on the pressure head of the root zone, where wet or drought stress may exist. The ratio between actual and potential transpiration is calculated based on existence of wet or drought stress, which will be passed to WOFOST model. Soil temperatures and daily water balance are transferred to Soil-N module.

Step3: Calculations by WOFOST model (nested in SWAP model)
Photosynthesis, assimilation, respiration, growth and maintenance respiration, partitioning of assimilates and nutrients growth of plant organs are calculated by WOFOST model on basis of temperature accumulation. According to soil moisture and nitrogen conditions, crop growth rates are changed to the actual condition. The N demand of crop from soil is transferred to Soil-N module.

Step4: Calculations by Soil-N module
Soil-N module calculates the N balance through NO_3-N pool and NH_4-N pool, including Ammonia volatilisation, mineralization, nitrification and denitrification. Balancing N demand of crops and mineral N availability for crop uptake in soil, N uptake is calculated and passed to WOFOST model.

Step5: Calculations by WOFOST model (nested in SWAP model)
With available N amount passed from Soil-N module, growth rates of plants will be adjusted. New actual LAI, crop height, rooting depth, dry matter of leaves, stems and roots, and the partitioning of N in crop residues are calculated by WOFOST on basis of the adjusted growth rates. These crop parameters become the initial conditions for next day simulation.

5 Model Calibration

With more complete data records compared with other borders, Plot I was selected for model calibration. Four quantitative performance criteria: RE (Relative error); R^2 (Coefficient of determination); RMSE (Root mean square error) and NSE (Nash–Sutcliffe model efficiency coefficient) were adopted to evaluate the deviation between simulated and measured data, which are expressed in Table 13.

Table 13. Criteria to evaluate the model performance and their equations.

Coefficient		Equation[1]
RE	Relative error	$RE = \frac{S_i - O_i}{O_i} \times 100\%$
R^2	Coefficient of determination	$R^2 = \frac{[\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})]^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \times \sum_{i=1}^{n}(S_i - \bar{S})^2}$
RMSE	Root mean square error	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{n}}$
NSE	Nash–Sutcliffe model efficiency coefficient	$NSE = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$

[1] where n is the total number of observations; O is observed value; S is simulated value.

5.1 WinSRFR

The Merriam-Keller post-irrigation volume balance analysis was chosen in simulation. Downstream condition was set to blocked-end. In most of related research of WinSRFR modelling for event analysis, the Manning's roughness coefficients were calculated by Manning formula (Cai et al., 2016; Wang et al., 2005; Li et al., 2013):

$$n = \frac{J^{0.5} \times h^{1.67}}{q} \quad \text{(Equation 2)}$$

where n is the Manning roughness coefficient;

J is the slope of the field (m/m);

h is the water depth at the head of the border (m);

q is the average inflow rate L/s/m.

However, in our field experiments the water depths at head of the border were not measured. Thus the initial values for Manning roughness were according to relevant research in the NCP (Nie et al., 2017; Chen et al., 2012; Xu et al., 2019; Jin et al., 2014; Cai, et al., 2016), while the k was calculated by WinSRFR model. We put advance and recession times into the WinSRFR model, and then compared simulated advance and recession curves with observed one. The n and α were calibrated to rerun the model until good fits between the two curves were achieved. Table 14 shows the final n, α and k values as input of the model after calibration. The advance and recession curves in model output of four irrigation/fertigation events are illustrated in Figure

11. Due to high crop height of summer maize during second fertigation in maize season, the field was hard to enter, thus recession times were not recorded in I-M-2.

Table 14. Calibrated input parameters in WinSRFR modelling.

Irrigation / fertigation event[1]	Date	n	α	k (m/hour^α)
I-W-1	20-11-2017	0.15	0.4	85.116
I-W-2	28-03-2018	0.19	0.6	95.603
I-M-1	27-07-2018	0.14	0.62	77.793
I-M-2	02-09-2018	0.15	0.8	67.949

[1] The number of irrigation/fertigation event is “Plot number - Crop – irrigation/fertigation number”. For example, “I-W-1” means “PlotI - Wheat - Irrigaiton1”.

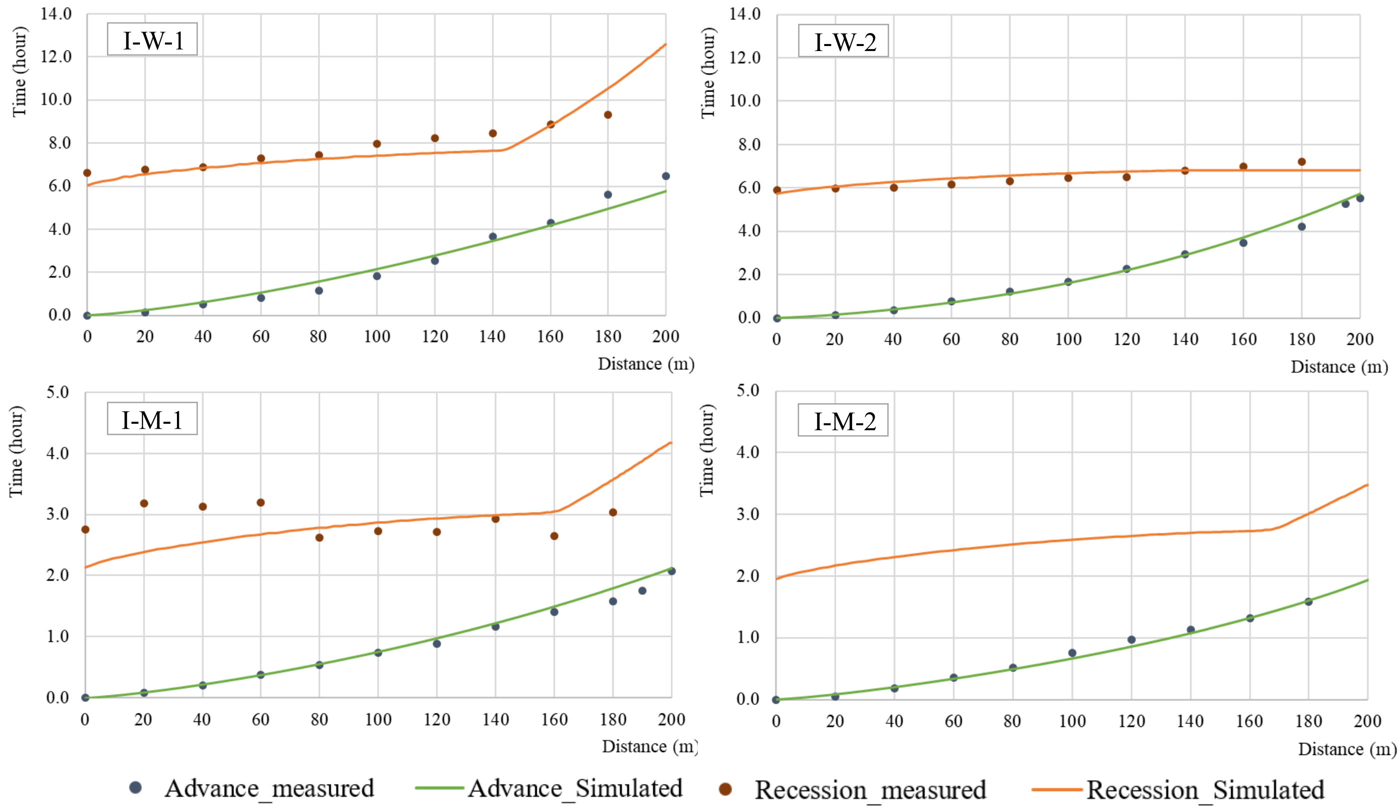


Figure 11. Comparison of measured and simulated advance and recession of Plot I.

Due to large fluctuations of field surface, the observed recession curve of I-M-1 is not smooth as others. In I-M-1, the shortest recession time happened at distance of 160 m, where elevation was the highest. Similar situation was found at 80 m distance. Surface roughness changed in the fields as crops grew. Although the irrigation methods were similar in four irrigation/fertigation events, different pumps used (inflow rates) and Manning roughness resulted in differences of advance and recession curves. The R^2, RMSE and NSE to evaluate each simulation are listed in Table 15.

Table 15. R^2, RMSE and NSE values for advance and recession simulations (Plot I).

	Irrigation / fertigation event	R^2 (-)	RMSE (hour)	NSE (-)
Advance	I-W-1	0.988	0.354	0.964
	I-W-2	0.996	0.166	0.992
	I-M-1	0.995	0.082	0.986
	I-M-2	0.994	0.064	0.989
Recession	I-W-1	0.837	0.576	0.956
	I-W-2	0.718	0.235	0.987
	I-M-1	0.015	1.400	0.309

In Table 15, except the large errors of the first irrigation/fertigation in maize season caused by surface fluctuations, the simulation results of the four irrigations are satisfactory. Therefore, the WinSRFR model is reliable to be applied for irrigaiton/fertigation event analysis.

Infiltration depths of each irrigation/fertigation event are presented in Figure 12. As is shown in Figure 12, each field was divided into two parts from the middle to calculate the average infiltration depths of both two parts, the values of which are presented in Table 16.

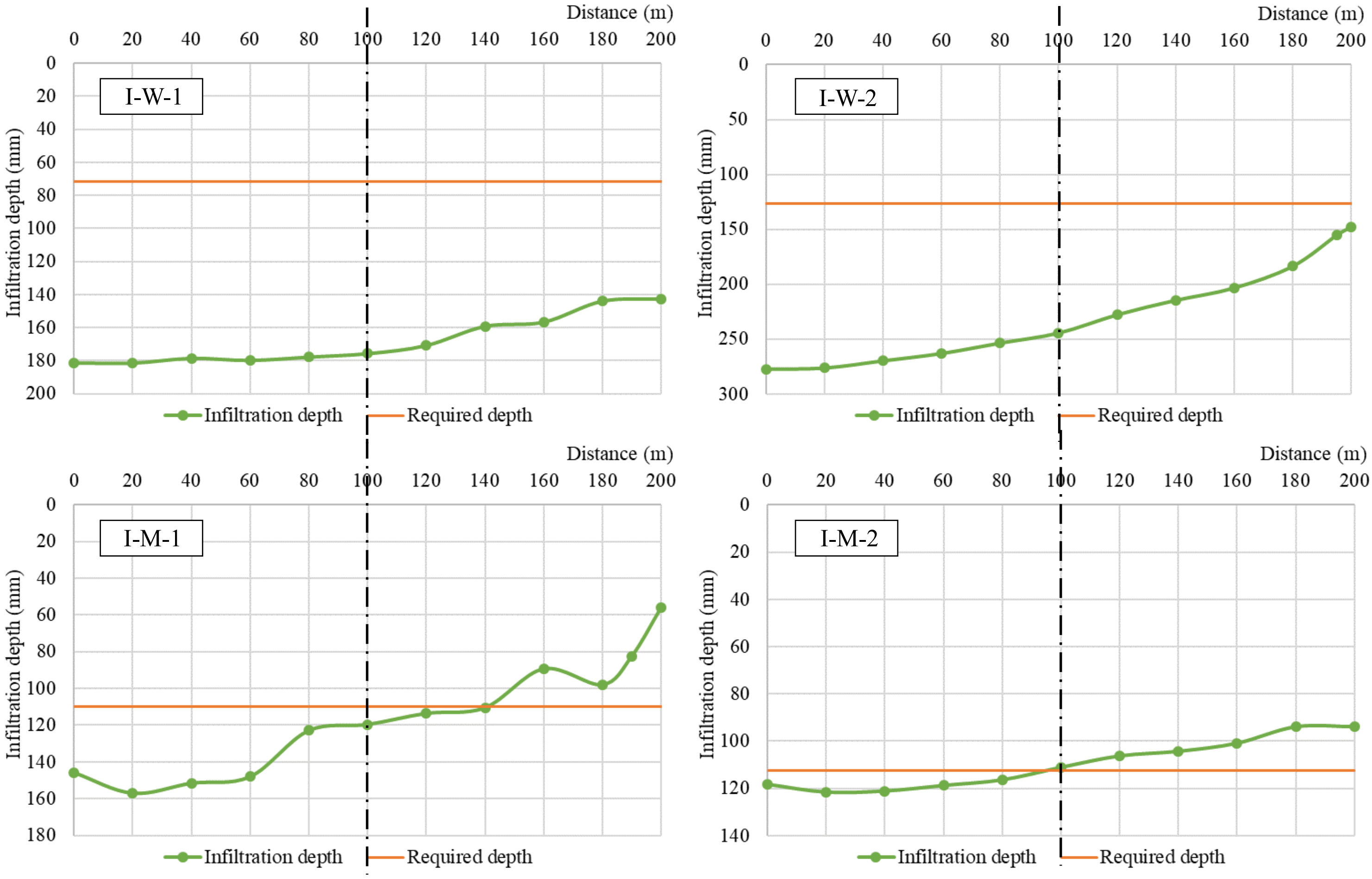


Figure 12. Infiltration depth in each irrigation/fertigation event.

Table 16. Output of WinSRFR modelling (Plot I).

Irrigation / fertigation event	Infiltration depth (mm)			Dissolved fertilizers (kg/ha)			AE[1]	DU[2]
	Part 1	Part 2	Average	Part 1	Part 2	Average		
I-W-1	179.354	156.502	167.928	-	-	-	43%	0.88
I-W-2	265.789	228.222	247.006	242.110	207.890	225	54%	0.79
I-M-1	142.658	110.847	126.753	151.940	118.060	135	86%	0.74
I-M-2	118.512	100.941	109.727	97.206	82.794	90	97%	0.88

[1] AE, Application efficiency = Infiltrated depth contributing to the irrigation target / Average depth of applied water;

[2] DU, Low-Quarter Distribution Uniformity = Low quarter average infiltration depth for quarter of the field receiving the least amount of water / Average depth of infiltrated water (Bautista et al., 2012).

As is shown in Figure 12 and Table 16, in most cases of winter wheat season, the field was over-irrigated with low AE. Even with same irrigation methods, irrigation in maize season with high inflow rates showed higher AE. It can be found in the infiltration curves of all irrigation/fertigation events that the head of the field had the largest amount of infiltration. The field was blocked-end, but the imaginary large amount of infiltration at the end of the field did not occur, which means that the cut-off time corresponding to the 180 m advance distance was relatively early. The lowest DU occurred in the first irrigation of maize season. In addition to the factors of inflow rates and irrigation time, the DU was also affected by uneven land surface. Evaluated from the two indicators of AE and DU, the second irrigation in maize season performed best, while the other irrigation/fertigation events all had problems of ununiform or excessive irrigation.

5.2 SWAP

5.2.1 Simulation of whole Plot I

To simplify the calibration process of SWAP model, we selected the whole field (Plot I) as the simulation object. Using average values of the entire field (Plot I) for model input and output comparison, other input parameters were calibrated.

Model input: Climate data

Climate data was derived from the meteorological station in the experimental station belong to FIRI. The database was recorded every half hour and was organized into a daily based data to input the SWAP model.

Model input: Soil texture and soil hydraulic functions

The soil particle size distribution of sand, silt and clay were measured by BT-9300HT laser particle size analyser. The soil texture was classified for each measured layer (10cm) according to the International system, proposed by Albert Atterberg (1905) (Table 17). Parameters of soil hydraulic functions were calculated by Rosetta module in RETC model as the starting point (van Genuchten et al., 1991). Through comparison of simulated and measured soil profile (water content), considering data in relevant research in nearby regions (He & Yang, 2017; Ma, Feng & Song, 2015; Li et al., 2017), the soil hydraulic function parameters were calibrated and listed in Table 18.

Table 17. Soil texture of 170cm depth (10cm each layer).

Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil texture
0-10	4.98	49.57	45.45	Silt loam
10-20	5.17	46.31	48.53	Silt loam
20-30	5.40	40.96	53.65	Loam
30-40	6.67	44.67	48.66	Loam
40-50	6.50	42.97	50.53	Loam
50-60	6.02	40.56	53.42	Loam
60-70	4.93	36.35	58.71	Sandy loam
70-80	3.10	26.75	70.15	Sandy loam
80-90	3.16	22.67	74.17	Sandy loam
90-100	2.73	21.50	75.77	Sandy loam
100-110	2.86	30.26	66.87	Sandy loam
110-120	3.95	32.80	63.25	Sandy loam
120-130	2.91	19.71	77.39	Sandy loam
130-140	2.51	18.52	78.98	Sandy loam
140-150	2.57	18.83	78.60	Sandy loam
150-160	2.46	17.33	80.21	Sandy loam
160-170	2.26	15.25	82.49	Sandy loam

Table 18. Calibrated soil hydraulic parameters in the SWAP model.

Soil depth (cm)	ORES (cm3/cm3)	OSAT (cm3/cm3)	ALFA (cm)	NPAR (-)	KSATFIT (cm/d)	LEXP (-)
0-10	0.1	0.280	0.0135	1.52	5.00	0.5
10-20	0.1	0.290	0.0185	1.42	4.80	0.5
20-30	0.1	0.310	0.0230	1.42	4.50	0.5
30-40	0.1	0.360	0.0185	1.45	3.70	0.5
40-50	0.1	0.380	0.0195	1.41	3.90	0.5
50-60	0.1	0.380	0.0170	1.45	3.90	0.5
60-70	0.1	0.340	0.0170	1.40	3.54	0.5

70-80	0.1	0.340	0.0185	1.40	4.20	0.5
80-90	0.1	0.310	0.0185	1.40	4.20	0.5
90-100	0.1	0.295	0.0185	1.40	3.40	0.5
100-110	0.1	0.295	0.0185	1.40	3.40	0.5
110-120	0.1	0.340	0.01851.40	3.56	0.5	
120-130	0.1	0.380	0.0190	1.40	3.30	0.5
130-140	0.1	0.380	0.0190	1.40	3.30	0.5
140-150	0.1	0.380	0.0190	1.40	3.30	0.5
150-160	0.1	0.380	0.0190	1.40	3.30	0.5
160-170	0.1	0.380	0.0190	1.40	1.20	0.5

Model input: Crop data

The starting point of WOFOST (detailed crop module in SWAP) crop parameter were on basis of “WWH105.CAB” for winter wheat in Germany and Luxemburg and “MAG201.CAB” for summer maize in France, northern and central Italy, northern Spain and northern Portugal, with changes made of crop height according to our measured data.

The calibration followed the procedure described by Wolf and De Wit about WOFOST calibration within CGMS (2003); by Akkermans et al. about platform CALPLAT for calibrating CGMS (2008); and by Boogaard et al. about WOFOST simulation in China in SIGMA project (2017).

The starting point of calibration was the phenological development of the crop. Since crop development stages were not recorded, the date of emergence, anthesis and maturity were determined by phenology stage of crops from literature (Gao et al., 2018; Tian et al., 2019; Zhang et al., 2004; Iqbal et al., 2014; Lin et al., 2017). Considering that the date of summer maize sowing was half a month later than the farmer's fields, but the harvest date was the same, the maize in our experiments may be immature at harvest. Therefore the DVS (development stage) of maize didn’t reach 2.0 (maturity) at harvest (October 1, 2018). The TSUMEA (Temperature sum from emergence to anthesis) and TSUMAM (Temperature sum from anthesis to maturity) were calculated based on our measured temperature and calibrated development stages.

Calibration of leaf area related parameters, partitioning factors of different plant organs, and photosynthesis parameters were followed. The final parameters were determined until a good fit between measured and simulated LAI and crop yields were achieved. Table 19 illustrates calibrated crop data in *.crp file, their description and the data sources.

Table 19. Calibrated crop data, description and data sources.

Parameters	Description	Unit	Calibrated values		Data sources
			Winter wheat	Summer maize	
CH	Crop height as function of development stage	cm	0.00 3.00 0.27 17.93 0.48 14.64 1.00 51.59 1.43 62.05	0.00 3.00 0.45 97.15 0.78 268.11 1.83 256.89	Field observation
TSUMEA	Temperature sum from emergence to anthesis	℃·d	1193.47	1148.00	Huang et al. (2017) Wu et al. (2003) Wang et al. (2009) Zhang et al. (2014) Field observation; Calibration
TSUMAM	Temperature sum from anthesis to maturity	℃·d	944.30	1034.00	
TWDI	Initial total crop dry weight	kg/ha	60.0	100.0	
SPAN	Life span under leaves under optimal conditions	Day	31.3	40.00	
SLATB	Specific leaf area as a function of development stage	ha/kg	0.00 0.0024 0.50 0.00252 1.00 0.0025 1.50 0.0023	0.00 0.0026 0.70 0.0020 2.00 0.0020	
AMAXTB	Max co2 assimilation rate as function of development stage	kg/ha/hour	0.00 42.0 1.00 42.0 1.30 42.0 2.00 42.0	0.00 70.0 1.25 70.0 1.50 65.0 1.75 55.0 2.00 30.0	
CVO	Efficiency of conversion into storage organs	kg/kg	0.720	0.695	

FLTB	Fraction of total above ground dry matter increase partitioned to the leaves as function of development stage	kg/kg	-[1]	0.00 0.50 0.88 0.50 0.95 0.50 1.10 0.00 1.20 0.00 2.00 0.00	Calibration
FSTB	Fraction of total above ground dry matter increase partitioned to the stems as function of development stage	kg/kg	-	0.00 0.50 0.88 0.50 0.95 0.50 1.10 0.00 1.20 0.00 2.00 0.00	
FOTB	Fraction of total above ground dry matter increase partitioned to the storage organics as function of development stage	kg/kg	-	0.95 0.00 1.10 1.00 1.20 1.00 2.00 1.00	
RDI	Initial rooting depth	cm	10.0	10.0	Huang et al. (2017) Wu et al. (2003) Wang et al. (2009) Zhang et al. (2014)
RDC	Maximum rooting depth crop/cultivar	cm	125.0	100.0	
DVSNLT	Development stage above which no crop nitrogen uptake does occur	1	1.7	1.9	Xia et al. (2011) Wang et al. (2009)

[1] “ – ” means no changes were made in model calibration.

Model input: Soil N

Table 20 expresses the fertilizers applied and their N content as input in *.smm file. The N related crop data were derived from LINTUL model (Wolf, 2012). The parameters in *.snp file were calibrated according to comparison between measured and simulated soil NO_3-N content, N uptake values in literature and N effect on crop yields (N stress), which are listed in Table 21.

Table 20. Fertilizers applied and their N concentrations.

Fertilizer	N concentration	NH_4-N concentration	NO_3-N concentration
Basal fertilizer[1]	26%	13%	13%
Urea	46%	46%	0

[1] Xinlianxin high tower compound controlled release fertilizer, N-P2O5-K2O 26-14-5.

Table 21. Calibrated parameters in *.snp file in Soil-N module.

Parameters	Description	Unit	Calibrated values
TCSF_N	Transpiration concentration stream factor	-	2.0
LaiCritNupt	Critical LAI value to calculate uptake rate based on the ammonium availability	-	0.3
dz_WSN	Thickness of the soil layer considered for the simulation of the soil organic matter and nitrogen dynamics.	m	1.0

Model output: Water balance

Table 22 illustrates the water balance in SWAP output for two crop seasons separately. The water use efficiency (WUE) and water productivity (WP) were calculated and listed in Table 23.

Table 22. Water balance in SWAP model output for two crop seasons.

Crop season	In (mm)		Out (mm)	
Winter wheat	Precipitation	340.3	Evaporation	147.9
	Irrigation	407.8	Transpiration	214.1
			Interception	1.42
			Deep percolation	375.4
Summer maize	Precipitation	270.4	Evaporation	82.6
	Irrigation	229.7	Transpiration	252.3
			Interception	14.3
			Deep percolation	196.6

Table 23. Calculated water use efficiency and water productivity in simulation.

Crop season	WUE (kg/m^3)[1]	WP (kg/m^3)[2]
Winter wheat	0.744	1.539
Summer maize	1.373	2.050

[1] WUE, water use efficiency (kg/m^3) = kg product / water applied, water applied means sum of irrigation and rainfall amount;

[2] WP, water productivity (kg/m^3) = kg product / Actual ET (Van Halsema & Vincent, 2012).

From calculation, the total ET for winter wheat and summer maize were 361.91 mm and 335.04 mm respectively. In relevant literature, the total ET for winter wheat ranges from 279 mm to 479 mm, with a concentration around 400mm; for summer maize season ranges from 325 mm to 448 mm, with a concentration around 380mm (under full irrigation conditions, in the North China plain) (Iqbal et al., 2014; Zhang et al., 2004; Chu et al., 2016; Liu et al., 2012; Umair et al., 2017; Xiao et al., 2017). Therefore, the simulated ET are within the range of relevant literature. As Table 22 shows, both in two crop seasons the deep percolation almost equals to irrigation amount, which means the field was extremely over irrigated and the irrigation practice requires improvement. Considering annual and interannual changes of precipitation, the irrigation could be reduced according to climate conditions of the year.

According to ranges of WP of wheat and maize summarized by Zwart and Bastiaanssen (2014) based on a review of 84 literature sources, the globally measured ranges of WP values were 0.6–1.7 kg/m3 and 1.1-2.7 kg/m3 for wheat and maize respectively. Therefore, our simulated WP of both two crops reached a relatively high level worldwide. Through literature review, we found that WUE was often defined as the ratio between crop yields and ET in relevant research in China, which is the same as definition of WP in this study. Therefore, the WUE in this study could not be compared with data from literature.

Model output: Soil water content (SWC)

SWC was measured by TDR (Volumetric SWC) and oven drying method (Gravimetric SWC, Volumetric SWC = Gravimetric SWC × BD). Due to high differences between measured data of two ways, the TDR measured data were calibrated (Appendix 3). SWC was the main indicator for soil hydraulic functions calibration. Figure 13 shows SWC of four soil profiles after calibration (the examples used for calibration). Figure 14 shows the annual curve of SWC (average of 20-60cm; 60-100cm; 100-160cm). Since there were large errors between SWC of top 20 cm layer measured by TDR and the actual situation, the upper 20 cm was removed in comparison. The R^2, RMSE and NSE to access simulation performance are listed in Table 24.

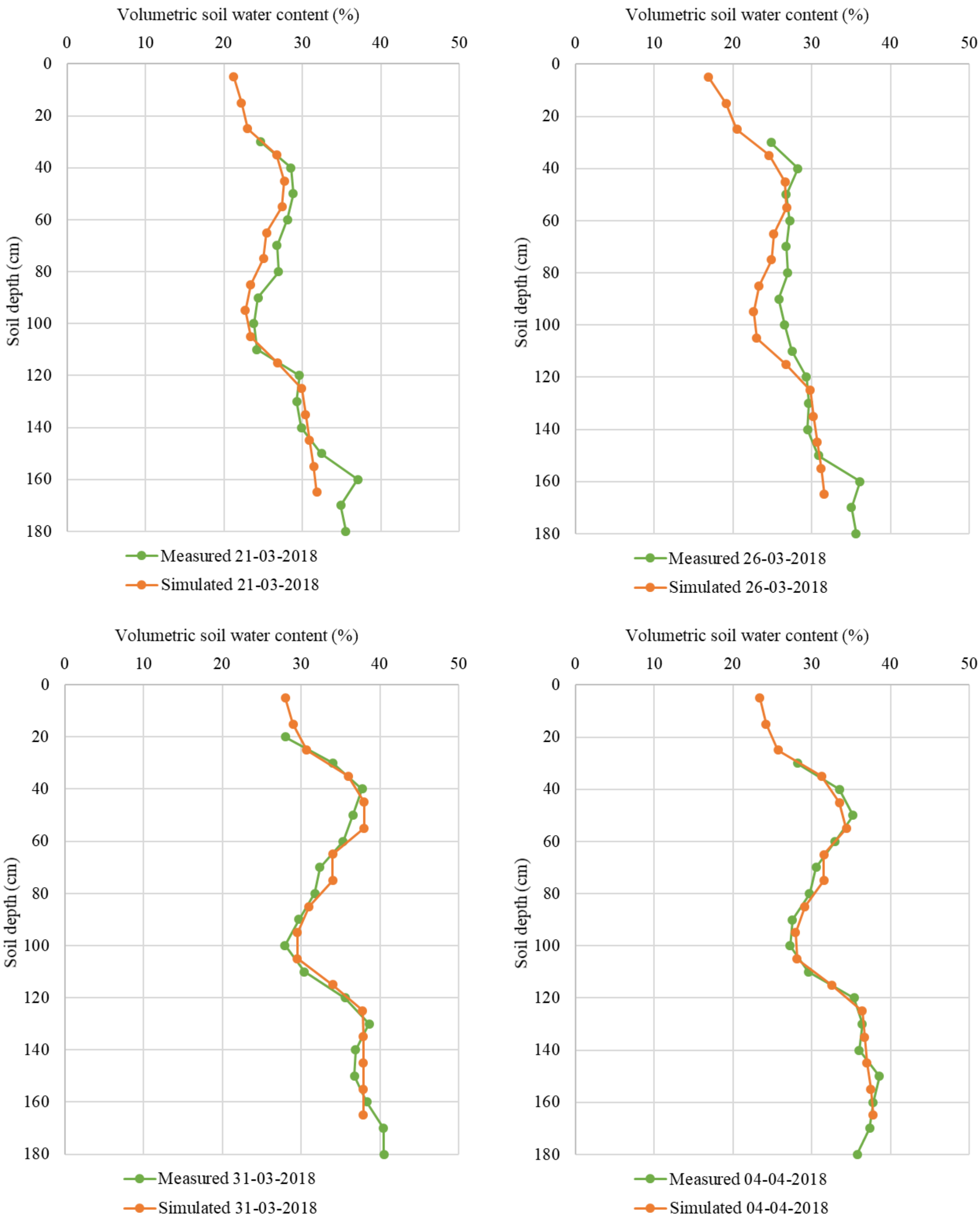


Figure 13. Comparison of simulated and measured volumetric soil water content (Four examples: 7 days before irrigation 21-02-2018, 2 days before irrigation 26-03-2018, 3 days after irrigation 31-03-2018, 7 days after irrigation 04-04-2018).

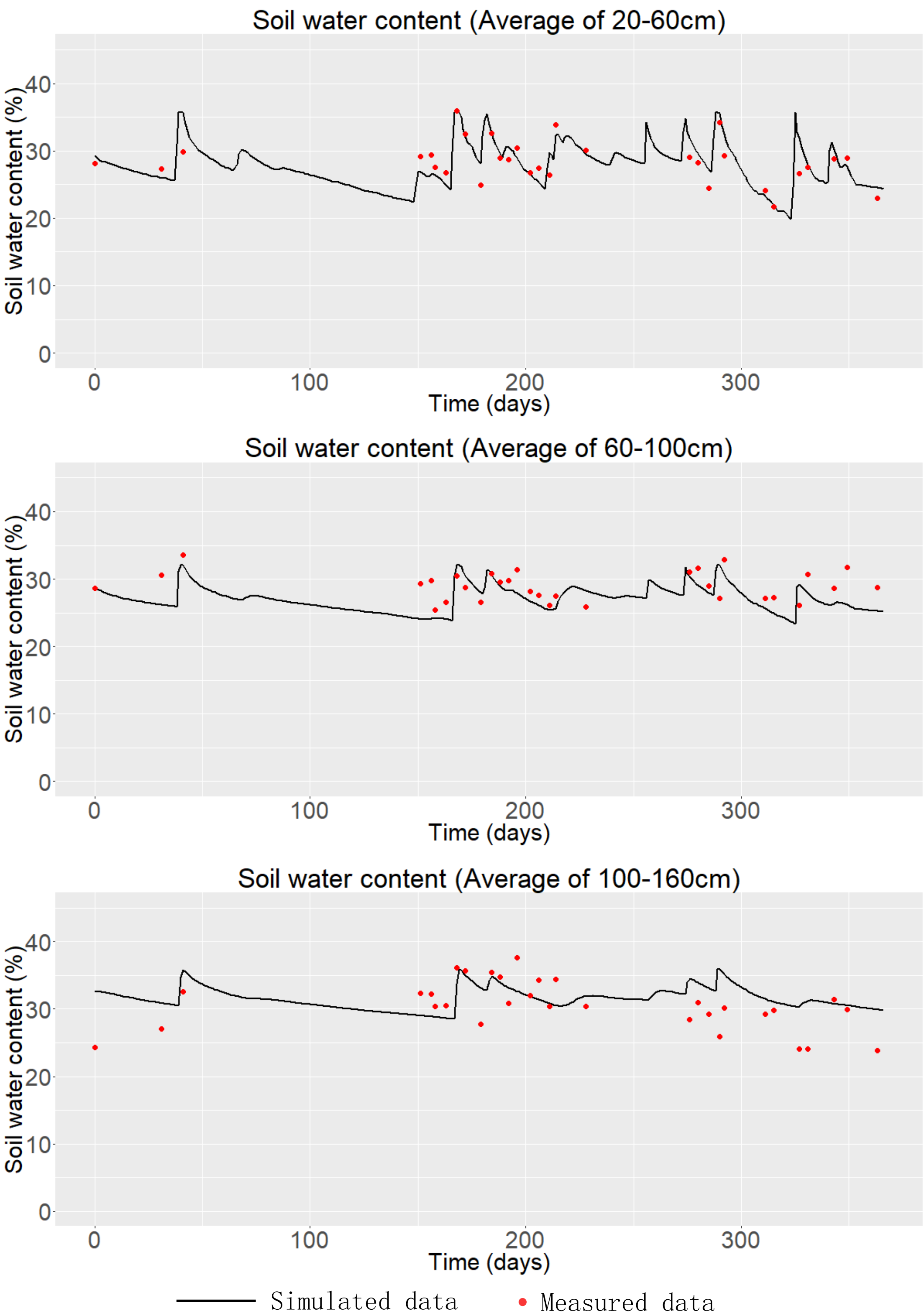


Figure 14. Simulated and measured volumetric soil water content (average of 20-60cm; average of 60-100cm; average of 100-160cm).

Table 24. R^2, RMSE and NSE values for SWC simulations (Plot I).

Soil depth	R^2 (-)	RMSE (%)	NSE (-)
20-60 cm	0.632	2.420	0.967
60-100 cm	0.152	3.236	0.941
100-160 cm	0.052	5.162	0.878

As is shown in Figure 14 and Table 24, the simulation of top layers with higher R^2 is better than sub layers, which requires more calibration of soil hydraulic function parameters. In field experiments, not all fields were measured in ordinary time, thus some of the data in Figure 14 were not from the field we simulated, resulting in some errors. Because the range of SWC changes was small in whole crop seasons (around 24% to 36%), the errors are more obvious in the figure. Among the criteria of simulation, the values of the NSE show good simulation performance, which is because the overall range of the simulated SWC is in line with the measured values.

Model output: crop

The model output of LAI, crop yields and above ground biomass are presented in Figure 15, 16 and Table 25. According to GYGA protocol and literature about dry weight or water content of wheat grains (Pepler, Gooding, & Ellis, 2006; Mou et al., 2016; Cai and Wu, 1993), the water content of wheat grains after maturity is around 10 to 20%. Here we assumed 86.5% of measured crop yields (fresh weight, 6.683ton/ha) is dry weight of living storage organs, that is, 5.781 ton/ha (Marked as red point in Figure 15). The RE, R^2, RMSE and NSE values for crop yields and LAI simulations are listed in Table 26.

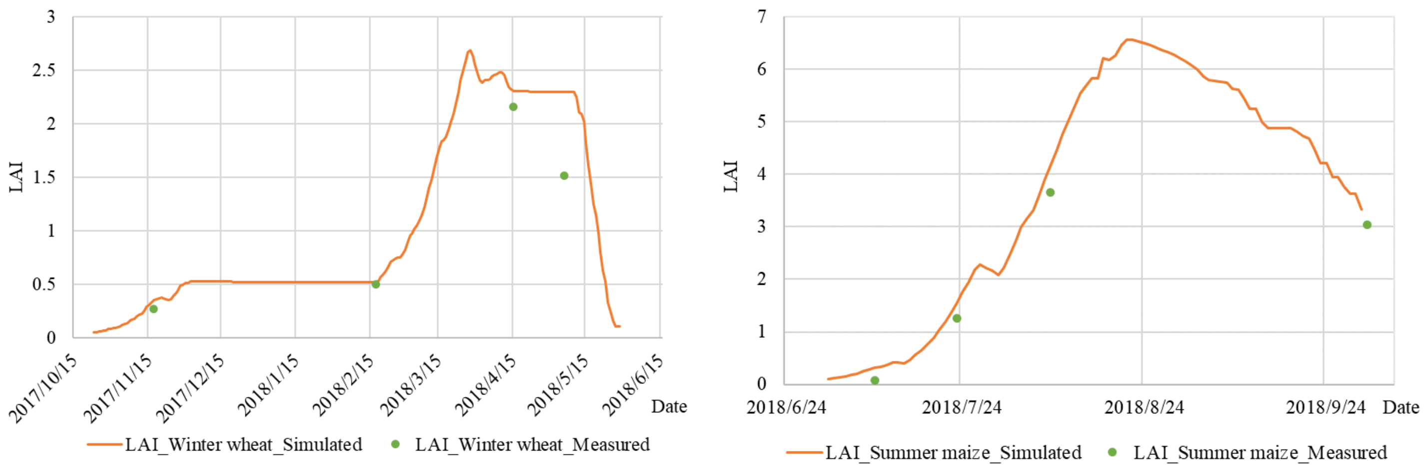


Figure 15. Measured and simulated LAI in Plot I.

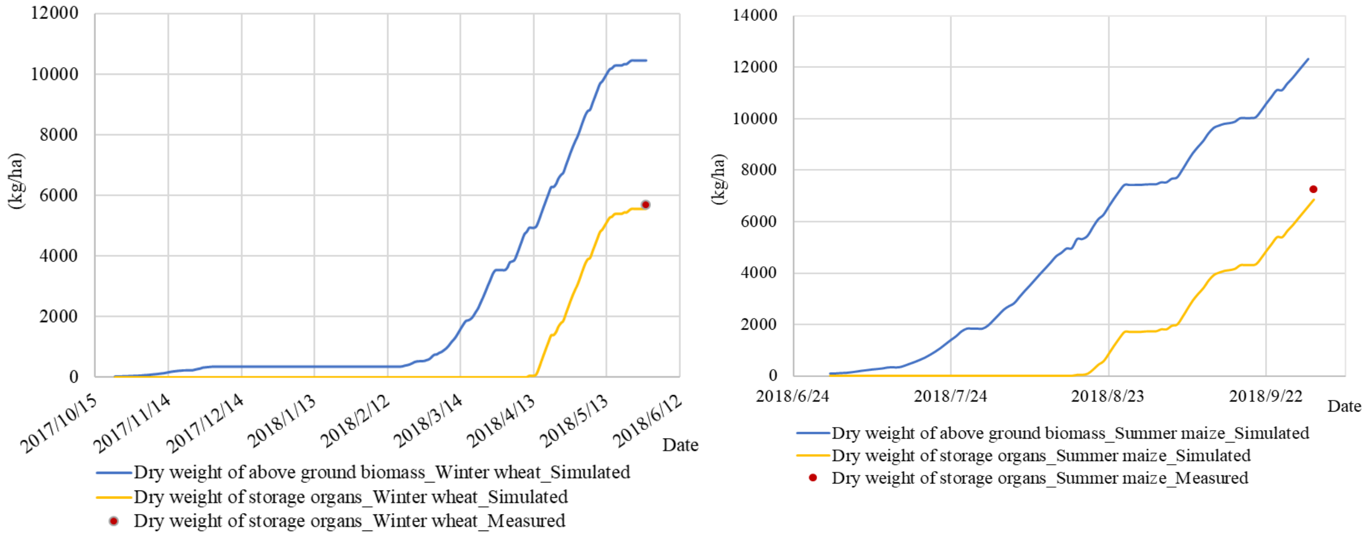


Figure 16. Measured and simulated dry weight of above ground biomass and dry weight of storage organs in Plot I.

Table 25. Measured and simulated dry weight of above ground biomass and storage organs.

Item	Winter wheat		Summer maize	
	Measured	Simulated	Measured	Simulated
Dry weight of above ground biomass (kg/ha)	-	10454	-	12591
Dry weight of storage organs (kg/ha)	5781	5569	7257	6867

Table 26. RE, R^2, RMSE and NSE values for crop yields and LAI simulations (Plot I).

Crop season	Item	RE	R^2 (-)	RMSE (-)	NSE (-)
Winter wheat	Crop yields	3.67%	-	-	-
	LAI	-	0.910	0.404	0.990
Summer maize	Crop yields	5.37%	-	-	-
	LAI	-	0.983	0.337	0.997

As is shown in Figure 15, 16 and Table 26, simulations of LAI and crop yields are acceptable. In relevant literatures, crop yields and biomass vary greatly due to differences in crop varieties and climate (crop yields: 5.4 to 9.5 ton/ha for winter wheat, and 4.61 to 9.8 ton/ha for summer maize; biomass: 10.0 to 13.66 ton/ha for winter wheat, and 8.01 to 12.43 for summer maize) (Iqbal et al., 2014; Chu et al., 2016; Umair et al., 2017; Xiao et al., 2017). Therefore, our simulated values match the approximate range in literature. Due to the immaturity of summer maize at harvest, the curves of dry weight of above ground biomass and storage organs in maize season still show a significant upward trend at the end of simulation period.

Model output: N balance

Table 27 illustrates the N balance of two crop seasons. The Nitrogen use efficiency (NUE) and Nitrogen uptake efficiency (N capture) were calculated and listed in Table 28. The soil N content and the fertilization/fertigation time are shown in Figure 17.

Table 27. N balance in two crop seasons of Plot I.

Crop season	In (kg/ha)		Out (kg/ha)	
Winter wheat	NH_4-N	201.0	NH_4-N Volatilisation	50.25
	NO_3-N	97.5	N uptake	112.62
			N leaching	267.51
			Nitrification and Denitrification	0.50
Summer maize	NH_4-N	201.0	NH_4-N Volatilisation	50.25
	NO_3-N	97.5	N uptake	164.64
			N leaching	111.86
			Nitrification and Denitrification	0.25
Total	NH_4-N	402.0	NH_4-N Volatilisation	100.5
	NO_3-N	195.0	N uptake	277.27
			N leaching	381.98
			Nitrification and Denitrification	0.77

Table 28. Calculated Nitrogen use efficiency in two crop seasons of Plot I.

Crop season	NUE (kg/kg)[1]	N capture (%)[2]
Winter wheat	18.657	37.73%
Summer maize	22.673	55.16%
Total	20.665	46.44%

[1] NUE (Nitrogen use efficiency) = the yield of grain (or harvested product) achieved per unit of nitrogen available to the crop (Moll et al., 1982);

[2] N capture (N uptake efficiency) = N uptake / N available (Sylvester-Bradley & Kindred, 2009).

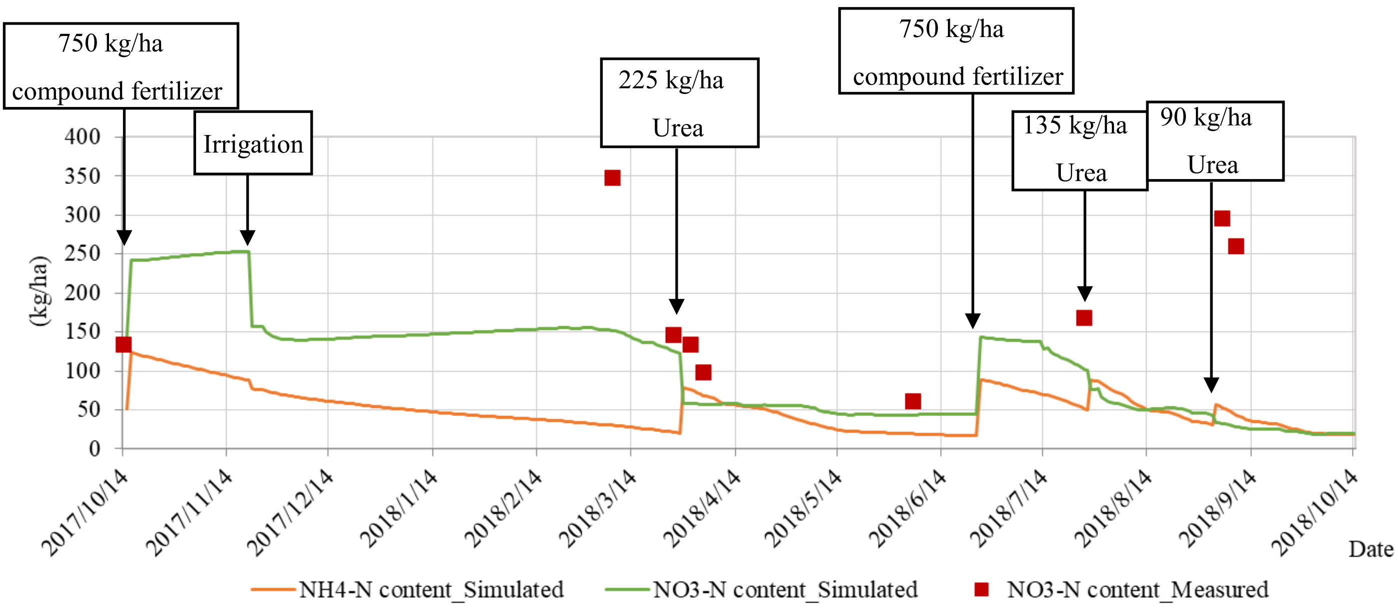


Figure 17. NH_4-N and NO_3-N concentration in Plot I in the simulated period.

As is shown in Figure 17, some of the measured NO_3-N concentration are extremely high and impossible to exist in reality, which may due to errors in field measurements (The calculation process is demonstrated in Appendix 3).

Pei et al. summarized the nitrogen cycling in winter wheat and summer maize rotation system in in typical cropland of the North China Plain (2015). Based on their summary of data from literature review since 1900 with more than 3,000 samples included, the annual total nitrogen input as commercial fertilizer was around 523 kg/ha, with an average N uptake of 289 kg/ha (121kg/ha for winter wheat and 152 kg/ha for summer maize), which is very similar to our simulation results. At the same time, the literature shows that in the general fertilization practices in the NCP, the application rate is about double of N uptake, which is also consistent with our calculated N capture. In the experimental study of NUE in this region, the NUE values vary greatly: under sufficient nitrogen application, the range of variation is around 4.9 to 45 kg/kg and 25 to 90 kg/kg in wheat and maize season respectively (Liu et al., 2018; Jin et al., 2012; Gao et al., 2017). Therefore, the NUE in the field experiments is relatively low.

According to Table 27 and Figure 17, with high irrigation amount, N leaching occupies the largest proportion of N loss. After each irrigation/ fertigation, the concentration of NO_3-N decrease for two reasons: (1) The NO_3-N in previous soil water was leached out; (2) Urea, as fertilizer applied in fertigation, only contains NH_4-N, which requires time for nitrification to generate NO_3-N. Therefore, less irrigation amount may be a solution to reduce N leaching and increase N efficiency, which will be analysed in Chapter 6.

5.2.2 Simulation of two divided parts of Plot I

The irrigation and fertilizer amount of two parts in Plot I from WinSRFR output was passed to SWAP model for simulation separately (Table 16).

Model output: Water

Table 29 illustrates the water balance of two parts of simulated plot. The WUE and WP were calculated and listed in Table 30.

Table 29. Simulated water balance of Part 1 and Part 2 in Plot I in two crop seasons.

Crop season	In (mm)			Out (mm)		
		Part 1	Part 2		Part 1	Part 2
Winter wheat	Precipitation	340.3	340.3	Evaporation	148.6	145.0
	Irrigation	436.1	384.7	Transpiration	210.0	217.5
				Interception	13.9	14.5
				Deep percolation	406.5	351.6

Summer maize	Precipitation	270.4	270.4	Evaporation	76.0	72.2
	Irrigation	261.2	211.8	Transpiration	250.4	255.5
				Interception	14.2	14.5
				Deep percolation	224.0	186.6
Two crops in total	Precipitation	610.7	610.7	Evaporation	224.6	217.2
	Irrigation	697.3	596.5	Transpiration	460.4	473
				Interception	28.1	29
				Deep percolation	630.5	538.2

Table 30. Calculated WUE and WP of Part 1 and Part 2 in Plot I in two crop seasons.

Crop season	Part	WUE (kg/m^3)	WP (kg/m^3)
Winter wheat	Part 1	0.710	1.547
	Part 2	0.775	1.551
Summer maize	Part 1	1.280	2.084
	Part 2	1.436	2.112
Two crops in total	Part 1	0.942	1.798
	Part 2	1.039	1.817

According to simulation of WinSRFR, the irrigation amount of Part 1 was higher than Part 2, resulting in higher deep percolation and evaporation of Part 1 compared with Part 2. The transpiration of two parts in winter wheat season remains the same, while the value is higher in Part 1 in summer maize season, which depends on the growth conditions. As the Table 30 shows, Part 2 expresses higher WUE and WP in both two crop seasons.

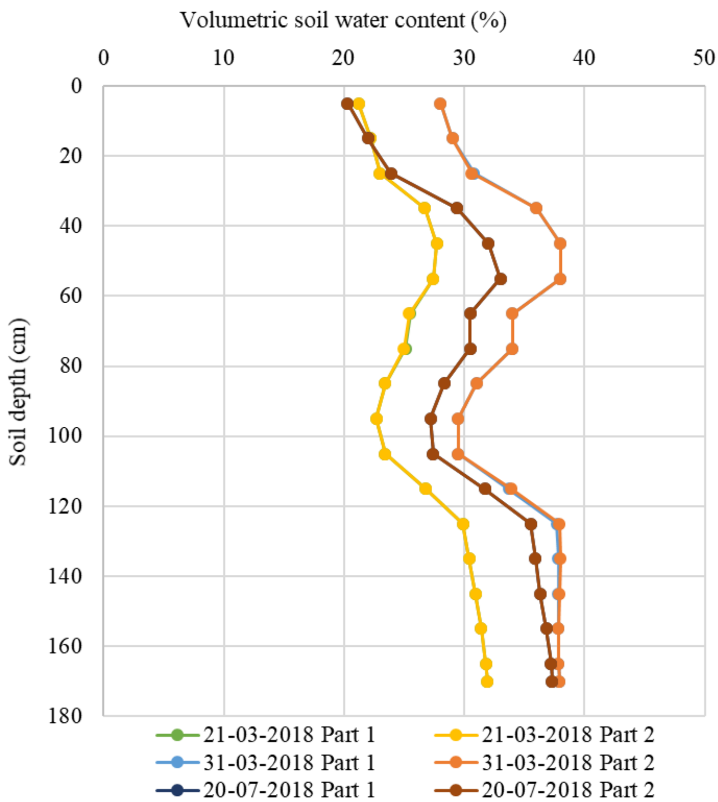


Figure 18. Simulated volumetric soil water content on 21-03-2018, 31-03-2018 and 20-07-2018 in two parts.

As is shown in Figure 18, both on dates before and after irrigation, the SWC in two parts almost remains the same and overlaps in the figure. Although water applied was different in two parts, SWC did not response significantly to changes of irrigation amount.

Model output: Crop growth and N

The simulated dry weight of above ground biomass, storage organs of the two parts are illustrated in Table 31. The N application and simulated N uptake, NH_4-N volatilisation and N leaching of two parts are given in Table 32. The simulated NO_3-N, NH_4-N and total N concentration in Part 1 and Part 2 are expressed in Figure 19.

Table 31. Simulated dry weight of above ground biomass, storage organs and LAI max in Part 1 and Part 2 of Plot I in two crop seasons.

Crop season	Item	Potential	Measured	Part 1		Part 2	
				Without Soil-N	With Soil-N	Without Soil-N	With Soil-N
Winter wheat	Dry weight of above ground biomass (kg/ha)	14065	-	10284	10279	10603	10599
	Dry weight of storage organs (kg/ha)	6888	5781	5515	5513	5624	5622
	LAI max	4.01	-	2.66	2.66	2.73	2.73
Summer maize	Dry weight of above ground biomass (kg/ha)	14384	-	12535	12497	12691	12715
	Dry weight of storage organs (kg/ha)	7381	7257	6839	6802	6953	6922
	LAI max	7.79	-	6.52	6.52	6.56	6.64

Table 32. N application and simulated N uptake, NH_4-N volatilisation and N leaching in Part 1 and Part 2 of Plot I in two crop seasons.

Item	Winter wheat		Summer maize		Two crops in total	
	Part 1	Part 2	Part 1	Part 2	Part 1	Part 2
N application	306.37	290.63	309.60	287.4	616.00	578.00
N uptake	110.70	114.15	163.02	164.71	273.72	278.86
NH_4-N Volatilisation	52.22	48.28	53.03	47.47	105.25	95.76
N leaching	275.46	259.77	121.30	105.65	399.33	368.07

Table 33. Calculated Nitrogen use efficiency of Part 1 and Part 2 in two crop seasons.

Crop season	Part	NUE (kg/kg)	N capture (%)
Winter wheat	Part 1	17.995	36.13%
	Part 2	19.344	39.28%
Summer maize	Part 1	21.970	52.66%
	Part 2	24.085	57.31%
Two crops in total	Part 1	19.993	44.44%
	Part 2	21.702	48.25%

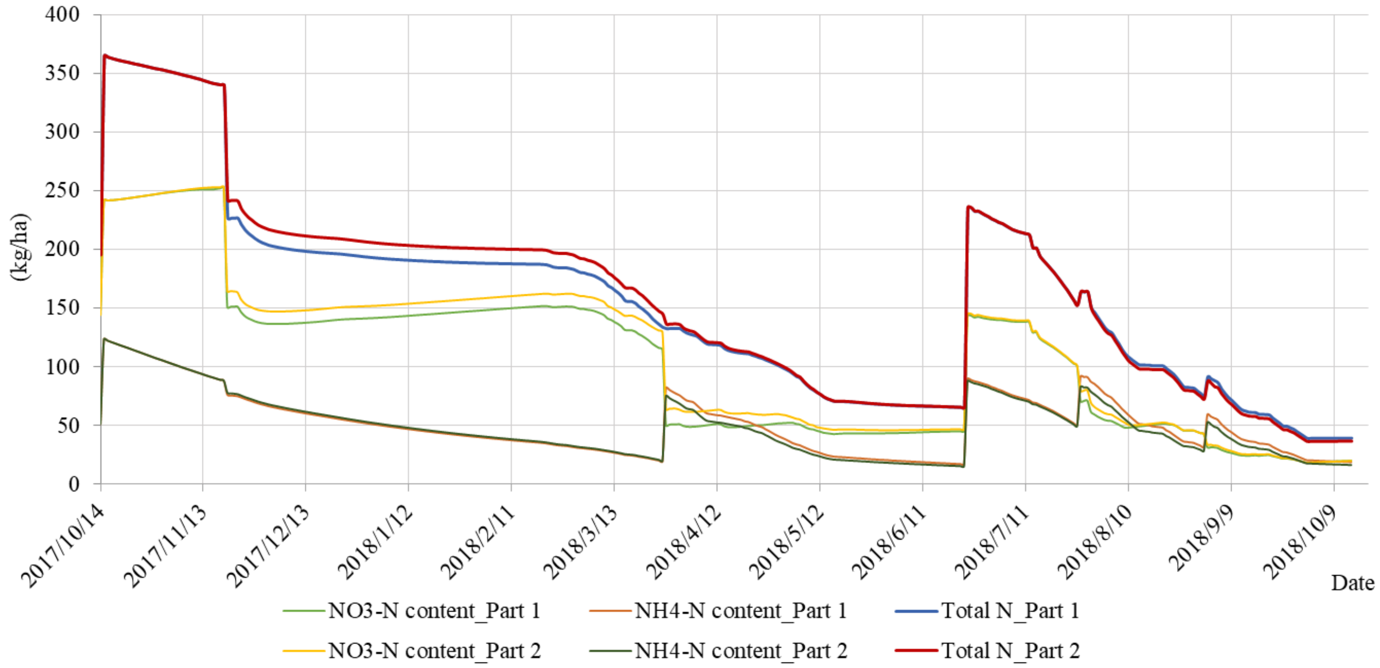
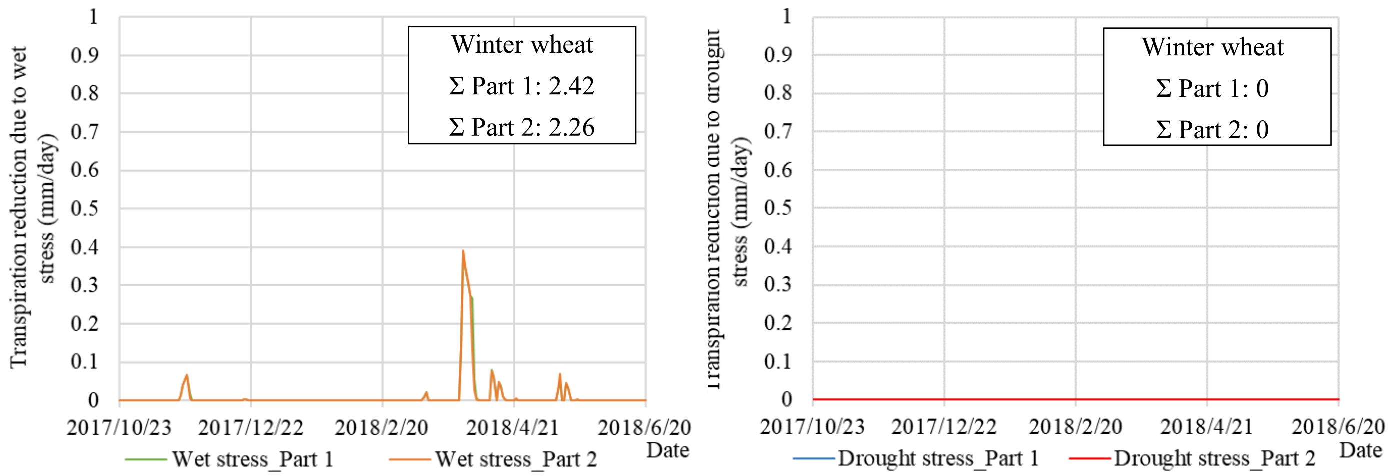


Figure 19. Simulated N concentration in Part 1 and Part 2 (NO3-N, NH4-N and total N).

Table 31 to 33 together illustrate that both two crops in Part 2 grew more vigorously than in Part 1, with higher transpiration, N uptake, crop yields and NUE. As is shown in Table 31, both two crops suffered water stress and N stress. In order to find the main factors of these differences and production reduction, we listed the following table and figure to compare the two parts (Table 34 and Figure 20).

Table 34. Above ground biomass & storage organs reduction due to water stress and N stress in summer maize season (dry weight, kg/ha).

Crop season	Water stress		N stress	
	Part 1	Part 2	Part 1	Part 2
Winter wheat	1373	1264	2	2
Summer maize	542	428	37	31



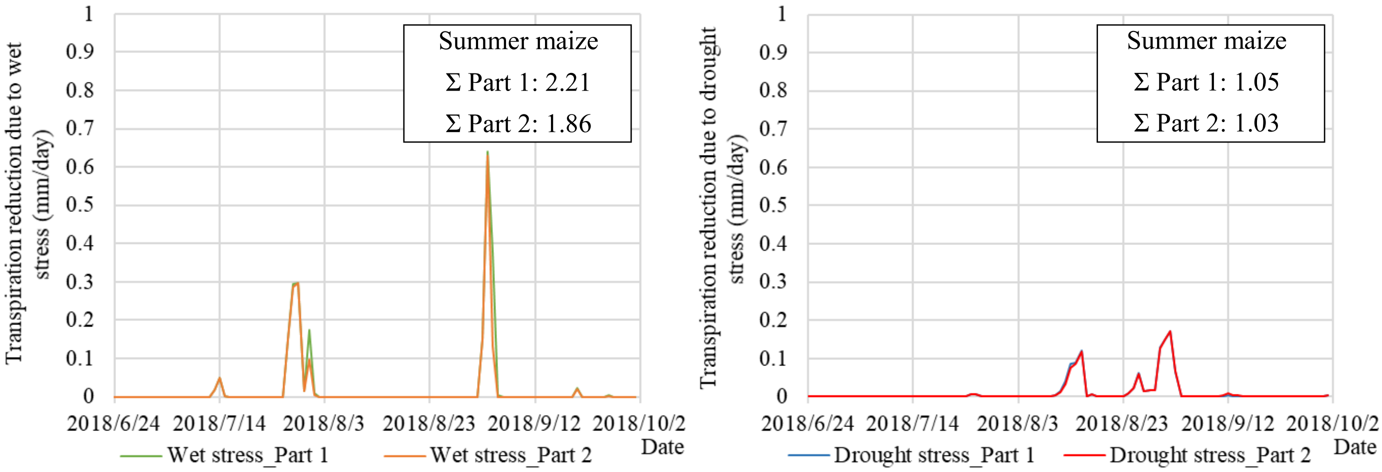


Figure 20. Simulated transpiration reduction due to water stress in Part 1 and Part 2.

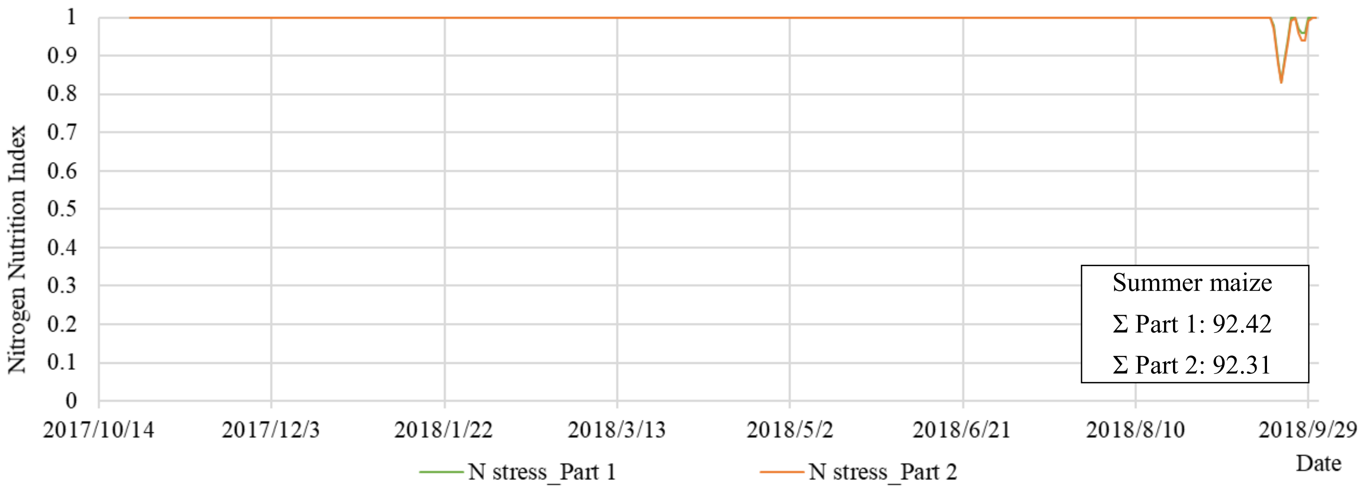


Figure 21. Simulated Nitrogen Nutrition Index in summer maize season in Part 1 and Part 2.

[1] Since the curves in graph are almost overlapped and the contrast is not obvious enough, we calculated the accumulated values for comparison (Marked in figure).

[2] Nitrogen Nutrition Index (NNI) ranges from 0 (maximum N shortage) to 1 (no shortage).

$$\mathrm{NNI} = \frac{Actual\ crop\ N - Residual\ N}{Critical\ N - Residual\ N} \quad \text{(Equation 2)}$$

Table 33, Figure 20 and 21 together reveal that wet stress after irrigation/fertigation was the main reason for crop yields reduction and differences in growth status between the two parts. Due to the higher amount of irrigation, Part 1 was under higher wet pressure than Part 2, resulting in more yields reduction. The amount of precipitation in maize season was relatively small, although wet stress occurred after irrigation, drought stress still happened between the two fertigations. Drought stress of the two parts remains basically the same.

Although the degree of growth is obviously different in the presentation of Table 33, the yield difference between two parts only accounts for less than 2% of the total crop yields (dry weight), so the distinction is not very significant in the curves of Figure 20 and 21.

Figure 19 illustrates that the N concentration in Part 2 was higher than Part 1 in most of the simulated period. Although the N application in Part 2 was less than Part 1, due to lower irrigation amount, the deep leakage of N due to irrigation was less. Figure 21 shows that the reduction due to N deficiency occurred in the final stage of the summer maize season, and the N stress suffered by the two parts was with subtle difference. This is also verified in the N concentration plot (Figure 19). Although there was significant difference in N concentration in the wheat season, the total amount of N was nearly the same at the end of the maize growing season, resulting in nearly equal NNI (similar N stress).

6 Model Application

During the model calibration we observed an excessive amount of deep percolation in the water balance, which means that the field was heavily over-irrigated. Due to excessive irrigation, N leaching became the largest part of N loss. By comparing the two parts of Plot I, we found that Part 2, with less irrigation and fertilization, achieved higher WUE, NUE, crop yields with fewer N leaching.

Therefore, in this chapter we will discuss these questions:

With same amount of N application, if the irrigation amount is decreased,

(1) Can deep leakage of N be reduced to increase NUE and decrease N stress?

(2) Considering that reducing irrigation amount will affect both wet and drought stress, what is the response of the crop yields to these changes?

(3) Where is the balance between water stress and N stress to achieve optimal crop yields under same N application conditions?

Taking into account the annual and interannual variability of rainfall in this region, however precipitation in the simulation period of model-testing chapter was relatively sufficient, in this chapter we will simulate the three-year winter wheat – summer maize rotation to include the variability of the climate.

Considering that when the irrigation amount is low, it is difficult to achieve uniform irrigation using WinSRFR simulation; Dividing field into two pieces is equivalent to add one more scenario in each field, which is of little significance for the issues discussed in this chapter. Therefore, in this chapter we will firstly obtain the optimal irrigation amount without changing the N application from the SWAP analysis results (optimization of irrigation/fertigation pattern), and then use WinSRFR model to achieve this goal by changing the inflow rates and irrigation time (optimization of irrigation/fertigation methods).

6.1 Scenarios

According to the completeness of the data from the meteorological station, we selected the simulation period from October 14, 2015 to October 14, 2018, covering 3 winter wheat growing seasons and 3 summer maize growing seasons in total. To simplify the simulation process, it was assumed that the annual crop sowing, emergence, harvesting time and the irrigation and fertilization treatment time were the same in each year, which almost remains the same with crop calendar in field experiments (Figure 6). Since the maize sowing was delayed for nearly half a month compared with farmers' fields in the experiments, it was advanced to the June 9 of each year in the simulation of this chapter. Different treatments in scenario S0, S1, S2, S3 and S4 are listed in Table 35.

Table 35. Treatments in scenario S0 to S4.

Treatment	Date	S0	S1	S2	S3	S4
Basal fertilizer	October 15	750kg/ha Compound fertilizer				
Irrigation	November 20	0mm	50mm	100mm	150mm	200mm
Fertigation	March 28	225kg/ha Urea				
		0mm	50mm	100mm	150mm	200mm
Basal fertilizer	June 9	750kg/ha Compound fertilizer				
Fertigation	July 27	135kg/ha Urea				
		0mm	50mm	100mm	150mm	200mm
Fertigation	September 2	90kg/ha Urea				
		0mm	50mm	100mm	150mm	200mm

6.2 Results & discussions

6.2.1 SWAP

<u>Water balance</u>

The simulated water balance is illustrated in Table 36, with evapotranspiration and deep percolation presented as figures separately to analyse the trends (Figure 22 and 23).

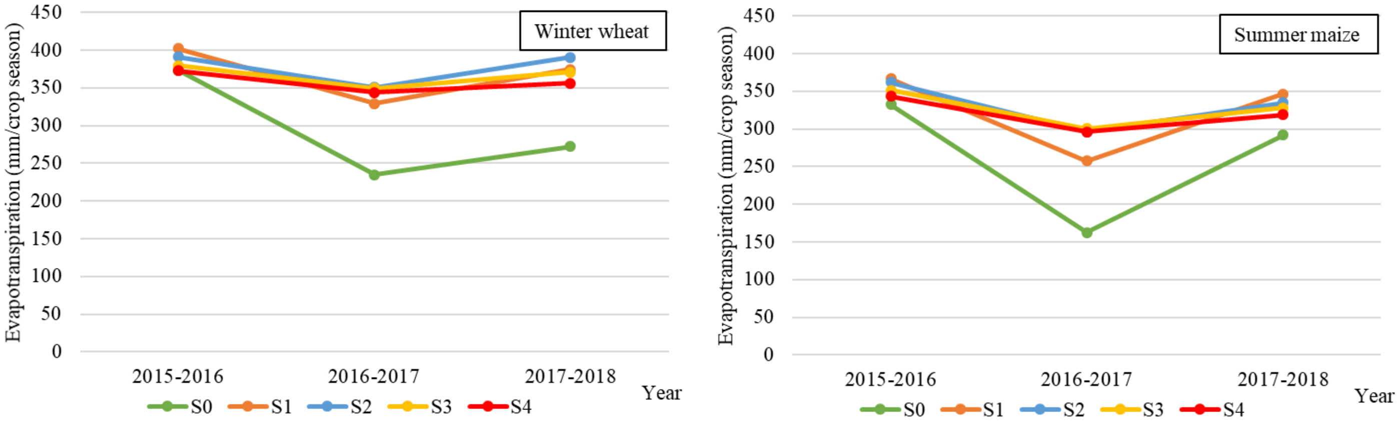


Figure 22. Simulated evapotranspiration in two crop seasons in all scenarios.

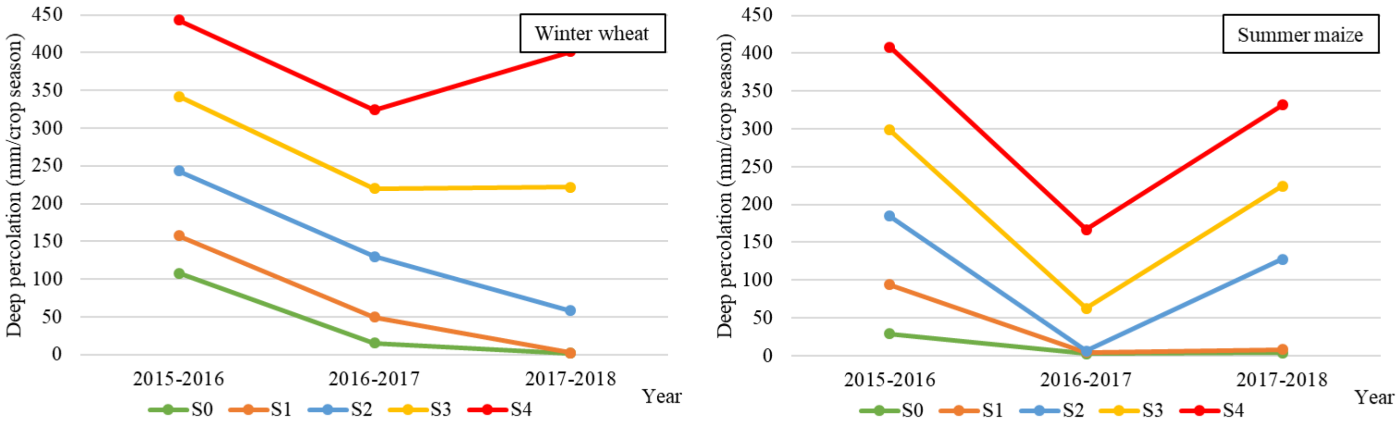


Figure 23. Simulated deep percolations in two crop seasons in all scenarios.

Table 36. Simulated water balance in all scenarios: P (precipitation); I (irrigation); E (evaporation); T (transpiration); ET (evapotranspiration); D (deep percolation). **Unit: mm.**

Crop season	Treatment	2015 - 2016					2016 - 2017					2017 - 2018				
		P+I	E	T	ET	D	P+I	E	T	ET	D	P+I	E	T	ET	D
Winter wheat	S0	313.4	109.6	263.5	373.1	107.8	190.2	83.8	151.2	235	15.5	340.3	114.3	157.6	271.9	1.5
	S1	413.4	127.9	274.4	402.3	157.2	290.2	95.7	233.2	328.9	49.6	440.3	128.9	245.5	374.4	2.5
	S2	513.4	135.1	256.1	391.2	243.1	390.2	101.1	249.7	350.8	130.1	540.3	130.1	260.1	390.2	57.9
	S3	613.4	139.7	239.9	379.6	342.1	490.2	104.9	244.7	349.6	220	640.3	138.2	232.8	371	221.6
	S4	713.4	142.8	229.6	372.4	442.7	590.2	106.5	237.5	344	324.3	740.3	144.1	212.2	356.3	401.3
Summer maize	S0	359.2	62.4	270.1	332.5	29.2	136.9	50.0	122.7	172.7	2.3	293.0	68.2	223.8	292.0	4.0
	S1	459.2	63.9	302.6	366.5	94.0	236.9	45.3	211.9	257.2	4.6	393.0	76.8	269.8	346.6	8.0
	S2	559.2	72.8	288.7	361.5	184.8	336.9	47.7	248.1	295.8	6.4	493.0	85.0	249.8	334.8	127.8
	S3	659.2	75.7	275.3	351.0	298.5	436.9	50.0	250.5	300.5	62.6	593.0	84.4	243.6	328	224.5
	S4	759.2	78.1	265.4	343.5	408.3	536.9	54.2	242	296.2	166.8	693.0	88.2	230.3	318.5	331.7

According to Table 36, the rainfall amount during crop growth period in 2016 - 2017 was very low, leading to varying degrees of soil desiccation with different treatments. As is shown in Figure 23, from 2015 to 2018, the deep percolation in wheat growing season showed a downward trend. Low rainfall amount in 2016 – 2017 resulted in low soil water storage after summer maize harvesting. Although irrigation amount in winter wheat season in 2017 – 2018 was more abundant compared with previous year, most of the water stayed in relative shallow soil layers (1.8m deep) to improve water storage, without evolving into deep percolation. Thus the deep percolation in wheat season in 2017-2018 decreased instead. For instance, the initial soil water storage in 1.8 m soil profile in S2 of wheat season in 2016-2017 was 46.70 cm, while it decreased to 36.97 cm after harvesting. However, in wheat season of 2017-2018, the soil water storage increased from 44.49 cm to 51.96 cm. Before entering the maize growing season in 2018, the soil water storage has already reached a relatively high level, so the deep leakage of the maize season has increased compared with the previous year.

Under the same climatic conditions (same year), for the same crop, as the irrigation amount increase, deep percolation shows different degrees of growth due to differences in initial soil water storage. Evaporation values show a similar trend of upward with increasing irrigation amount. Transpiration is related to crop growth and will be discussed in detail in the next section.。

Crop growth

The simulated dry weight of above ground biomass and crop yields of two crops in each crop season of simulation both with and without Soil-N module in all scenarios is given in Table 37. To make the data comparison more obvious, the dry weight of storage organs (crop yields) is expressed in Figure 20 and 21.

Table 37. Simulated dry weight of above ground biomass and crop yields of two crops in each year respectively in all scenarios.

Crop season	Treatment	Simulation	2015-2016		2016-2017		2017-2018	
			Biomass	Yields	Biomass	Yields	Biomass	Yields
Winter wheat	Potential		15618	7951	13659	7448	14065	6888
	S0	Without Soil-N	13495	6552	6432	2209	7571	4211
		Soil-N	13494	6552	6432	2209	7565	4207
	S1	Without Soil-N	14308	7380	10951	5056	11477	5857
		Soil-N	14305	7380	10951	5057	11477	5857
	S2	Without Soil-N	13527	7271	11681	6063	12327	6199
		Soil-N	13521	7268	11679	6063	12326	6199
	S3	Without Soil-N	12768	7006	11428	6115	11322	5863
		Soil-N	12763	7004	11425	6114	11310	5858
	S4	Without Soil-N	12290	6809	11124	6080	10407	5526
		Soil-N	12281	6805	11121	6079	10398	5522
Summer maize	Potential		16933	9144	16825	8574	14625	7345
	S0	Without Soil-N	13384	6768	5271	620	10277	4011
		Soil-N	13380	6769	5268	620	10276	4012
	S1	Without Soil-N	15572	9039	10377	4857	12987	6626
		Soil-N	15570	8974	10374	4857	12985	6627
	S2	Without Soil-N	15083	8929	12561	6987	12246	6433
		Soil-N	15057	8872	12557	6987	12242	6433
	S3	Without Soil-N	14608	8696	12652	7133	12052	6224
		Soil-N	14411	8498	12601	7085	11993	6167
	S4	Without Soil-N	14255	8539	12262	7010	11523	5919
		Soil-N	13700	7986	12085	6836	11433	5832

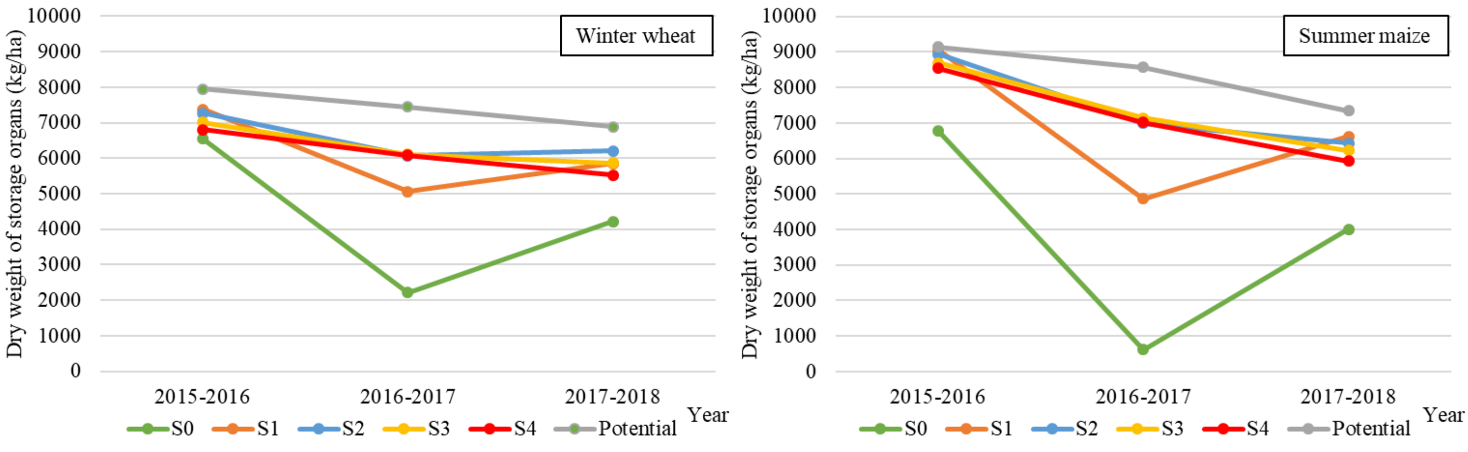


Figure 24. Simulated dry weight of storage organs of two crops in all scenarios (Without Soil-N).

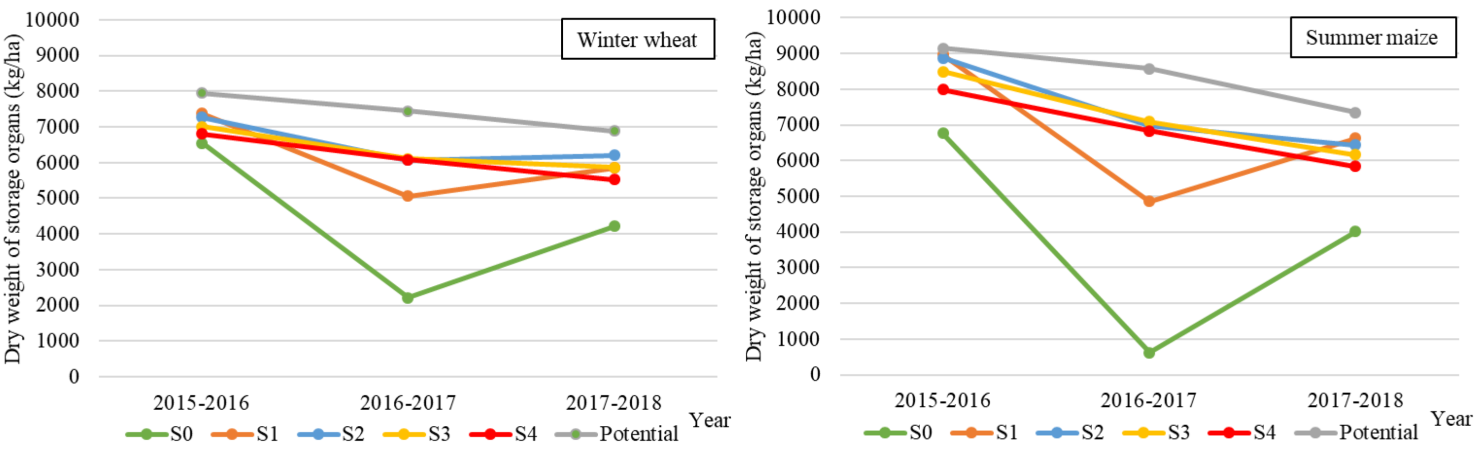


Figure 25. Simulated dry weight of storage organs of two crops in all scenarios (With Soil-N).

According to the grey lines in Figure 24 and 25 which represents the potential maximum yields can be achieved, there are significant differences in various growth seasons due to interannual climate differences. Since in the WOFOST model, the stage of crop growth and development is determined by the temperature accumulation, we can conclude that the difference in temperature fluctuations during the growth period has a significant impact on crop yields.

Throughout the crop yields in all scenarios per year, that is, under the same conditions of climate and fertilizers application, in both two crop seasons, crop yields first showed an upward trend with the increase of irrigation amount until a certain level was reached.
When the irrigation amount continued to increase to an excessive value, crop yields began to decline. This trend of first rising and then falling down with increasing irrigation amount is particularly evident in first and last year. In crop growth period of 2016-2017, due to low rainfall, higher irrigation did not result in significant reductions in production. The addition of the Soil-N module had almost no effect on winter wheat, while it caused reductions in maize crop yields mainly in scenarios with high irrigation amount.

Water and N stress

In this section we will conduct a detailed analysis of stress during the simulation period. The crop yields reduction due to water stress and N stress is given in Table 38. The curves of water stress over time are presented in Figure 26.

Table 38. Simulated crop yields reduction due to water stress and N stress. Unit: kg/ha.

Crop season	Treatment	2015 - 2016		2016 - 2017		2017 - 2018	
		Water stress	N stress	Water stress	N stress	Water stress	N stress
Winter wheat	S0	1399	0	5239	0	2677	4
	S1	571	0	2392	0	1031	0
	S2	680	3	1385	0	689	0
	S3	945	2	1333	1	1025	5
	S4	1142	4	1368	1	1362	4
Summer maize	S0	2376	0	7954	0	3334	0
	S1	105	65	3717	0	719	0
	S2	215	57	1587	0	912	0
	S3	448	198	1441	48	1121	57
	S4	605	553	1564	174	1426	87

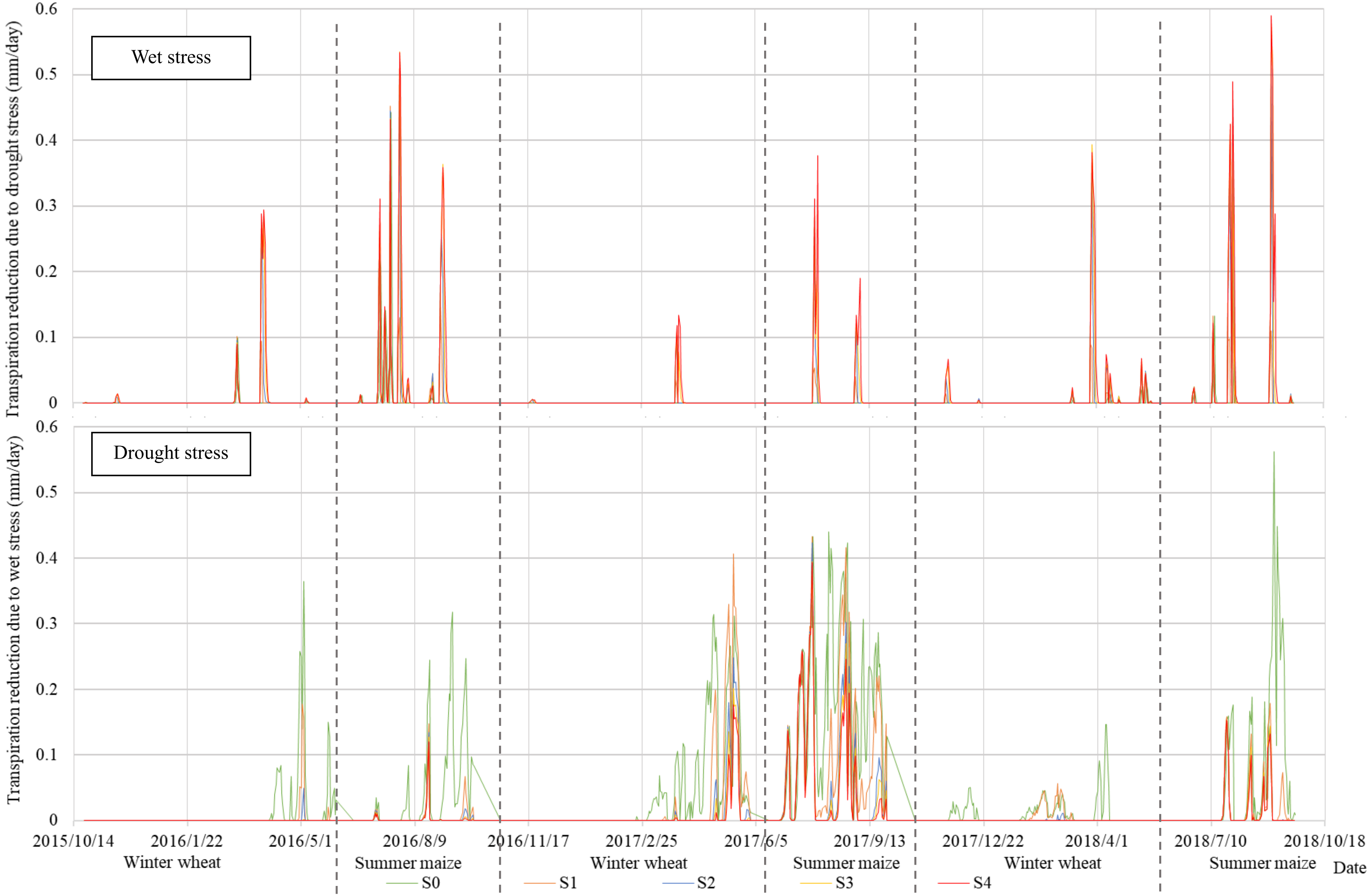


Figure 26. Simulated wet and drought stress in all scenarios.

According to Figure 26, the water stress is directly related to the amount of irrigation, declining with increasing irrigation volume. When the irrigation amount was low, drought stress dominated among the limiting factors. As the irrigation amount increased, the drought stress dropped while wet stress went up to a relative equilibrium optimal state, and then the wet stress became main factor for yields reduction.

The curves of N stress over time are presented in Figure 27. The simulated N uptake and N leaching are given in Table 39. Total N concentration in all scenarios is showed in Figure 28.

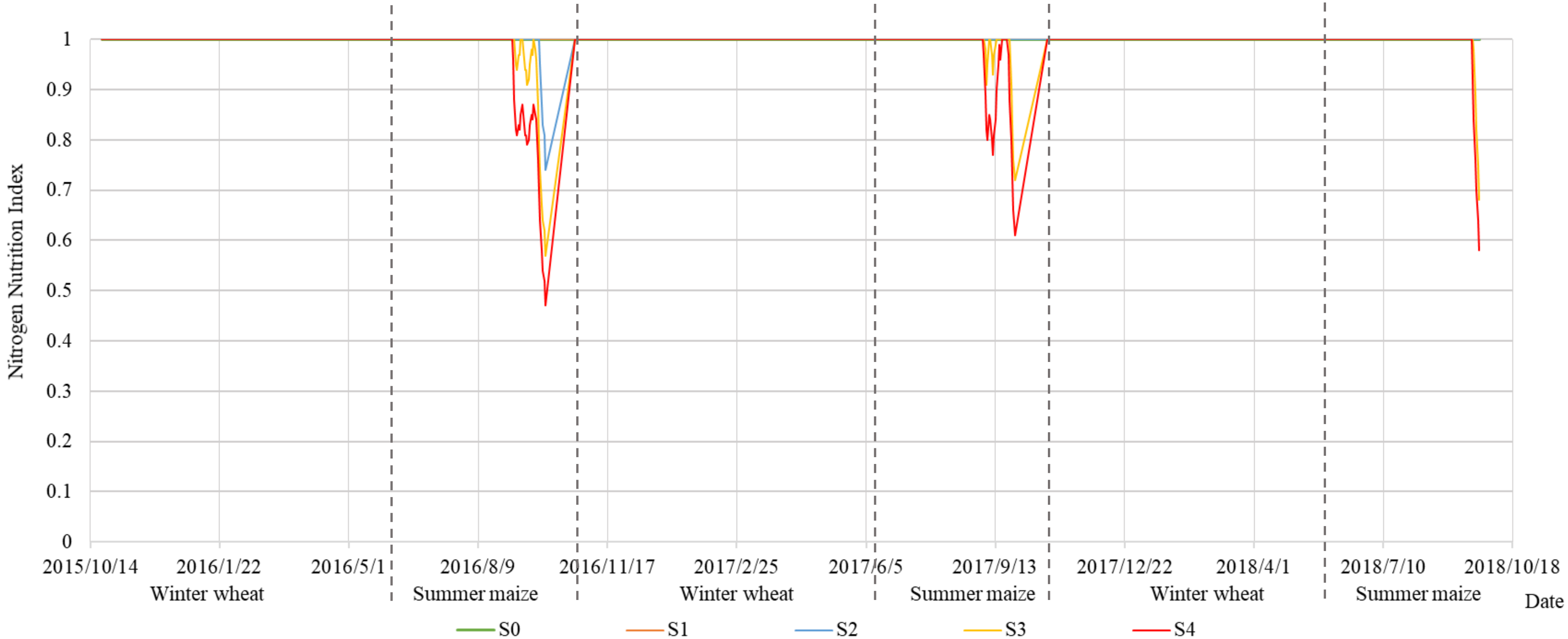


Figure 27. Simulated Nitrogen Nutrition Index in all scenarios.

Table 39. Simulated N uptake and N leaching in each crop season in all scenarios.

Crop	Treatment	2015-2016		2016-2017		2017-2018	
		N uptake	N leaching	N uptake	N leaching	N uptake	N leaching
Winter wheat	S0	135.45	103.13	70.63	0	88.28	14.97
	S1	173.46	142.63	123.57	36.58	125.16	27.78
	S2	159.95	201.09	130.13	89.57	131.56	103.65
	S3	148.93	238.99	127.12	118.28	119.47	131.31
	S4	139.85	266.63	120.65	133.41	104.46	151.04
Summer maize	S0	265.00	117.74	88.03	0	231.04	82.23
	S1	226.66	97.26	218.02	11.63	249.95	78.07
	S2	185.33	104.69	200.54	52.73	180.95	89.73
	S3	161.83	107.97	164.42	79.81	156.21	94.23
	S4	145.52	110.34	147.44	88.19	143.44	101.41

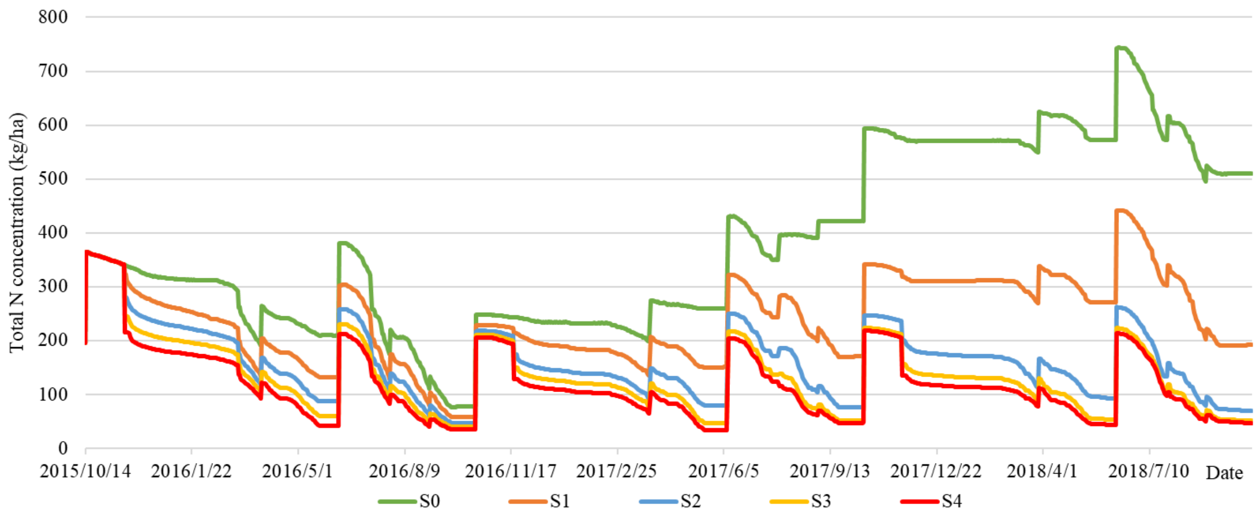


Figure 28. Simulated total N concentration in all scenarios.

As is shown in Figure 23, N stress shows subtle effects on the wheat growing season. Comparing N uptake of the two crops in Figure 24 and literature (described in Chapter 5), wheat requires less N, so the N provided by the fertilizers during the simulation period can meet the crop growth needs. However, maize has a relatively high demand for N. It can be seen from Figure 23 that N stress occurred at the end of each maize season. At this time, the soil N concentration reached the lowest point of the year and could not meet the crop demand.

In the case when water availability is low with limited rainfall and irrigation, increasing irrigation amount can reduce drought stress and promote crop growth, thereby increasing the crop's N requirement and N uptake. When the crop get a sufficient amount of water, continuing to increase irrigation amount will lead to an increase in N leaching. It is apparent in Figure 24 that N leaching due to irrigation is the main reason for declines in N concentration. When field is over-irrigated, deep N leakage is exacerbated. The soil N content at root zone become insufficient with crop growth, resulting in N stress and yields reduction.

WUE, WP, NUE and N capture

The WUE, WP, NUE and N capture were calculated and listed in Table 40. To make it obvious to compare, the WUE and WP are expressed in Figure 29 and 30. Since the amount of fertilizers applied was the same in each scenario, the trend of NUE and N capture is the same as trend of crop yields and N uptake. Therefore it will not be described as figure separately.

Table 40. WUE, WP, NUE and N capture of all scenarios in two crop seasons.

Crop season	Treatment	2015 - 2016					2016 - 2017					2017 - 2018				
		S0	S1	S2	S3	S4	S0	S1	S2	S3	S4	S0	S1	S2	S3	S4
Winter wheat	WUE (kg/m^3)	2.091	1.785	1.416	1.142	0.954	1.161	1.742	1.554	1.247	1.030	1.237	1.330	1.147	0.916	0.746
	WP (kg/m^3)	1.756	1.834	1.859	1.846	1.828	0.940	1.537	1.728	1.749	1.767	1.549	1.564	1.589	1.580	1.551
	NUE (kg/kg)	21.950	24.724	24.358	23.471	22.811	7.400	16.938	20.312	20.486	20.369	14.107	19.621	20.767	19.642	18.513
	N Capture	45.38%	58.11%	53.58%	49.89%	46.85%	23.66%	41.40%	43.59%	42.59%	40.42%	29.57%	41.93%	44.07%	40.02%	34.99%
Summer maize	WUE (kg/m^3)	1.884	1.968	1.597	1.319	1.125	0.453	2.050	2.074	1.633	1.306	1.369	1.686	1.305	1.050	0.854
	WP (kg/m^3)	2.035	2.466	2.470	2.477	2.486	0.381	1.888	2.362	2.374	2.367	1.374	1.912	1.921	1.898	1.858
	NUE (kg/kg)	22.673	30.281	29.913	29.132	28.606	2.077	16.271	23.407	23.896	23.484	13.437	22.198	21.551	20.851	19.829
	N Capture	88.78%	75.93%	62.09%	54.21%	48.75%	29.49%	73.04%	67.18%	55.08%	49.39%	77.40%	83.74%	60.62%	52.33%	48.05%

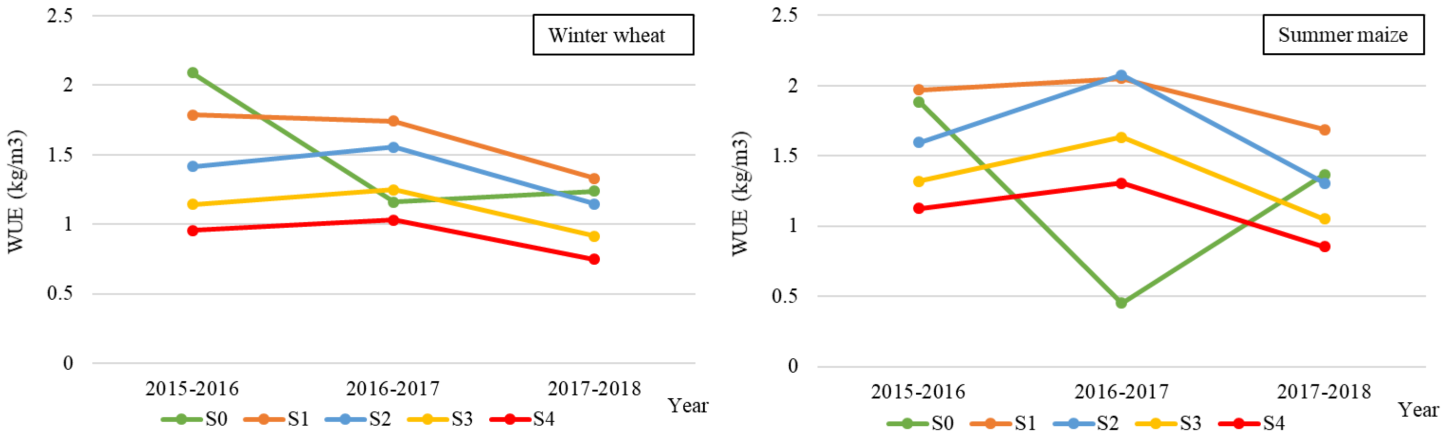


Figure 29. Water use efficiency (WUE) of all scenarios in winter wheat and summer maize season.

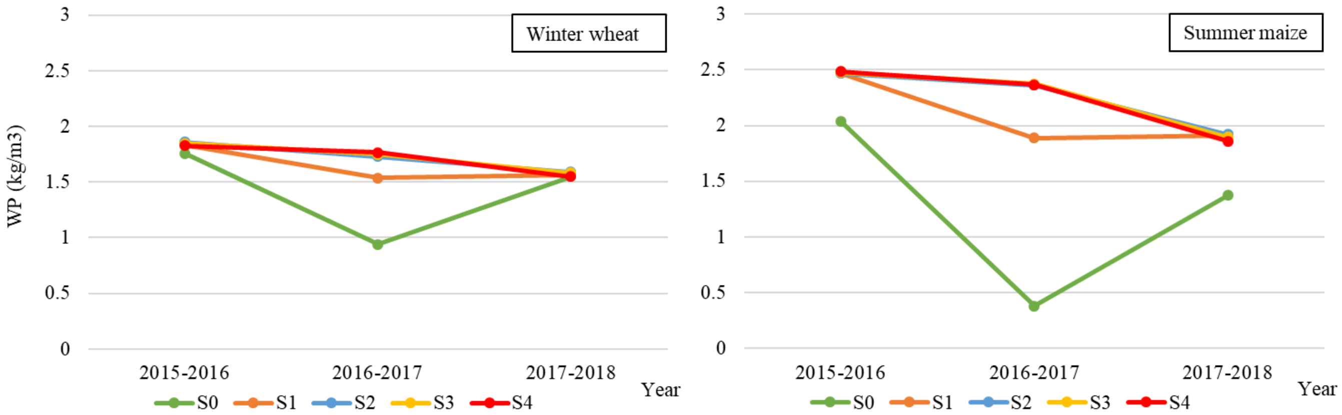


Figure 30. Water productivity (WP) of all scenarios in winter wheat and summer maize season.

As is shown in Figure 29, in the second year of simulation period, in S0 scenario, when irrigation water and rainfall cannot meet crop growth requirements, the WUE is low due to poor crop growth conditions. When crop water requirements are guaranteed, less irrigation can significantly increase the WUE. According to Figure 30, when the irrigation is insufficient, increasing the amount of irrigation can significantly increase WP, while the continued increase in irrigation volume will not bring obvious changes to WP. According to indicators of WUE and WP, the highest WUE and WP could be achieved with each single irrigation event of 100mm.

Conclusion

In order to find the irrigation amount that makes the wet stress, drought stress and N stress more balanced to achieve higher yields, we made a graph of the relationship between crop yields and sum of rainfall and irrigation amount (Figure 31); and relationship between crop yields and irrigation amount (Figure 32).

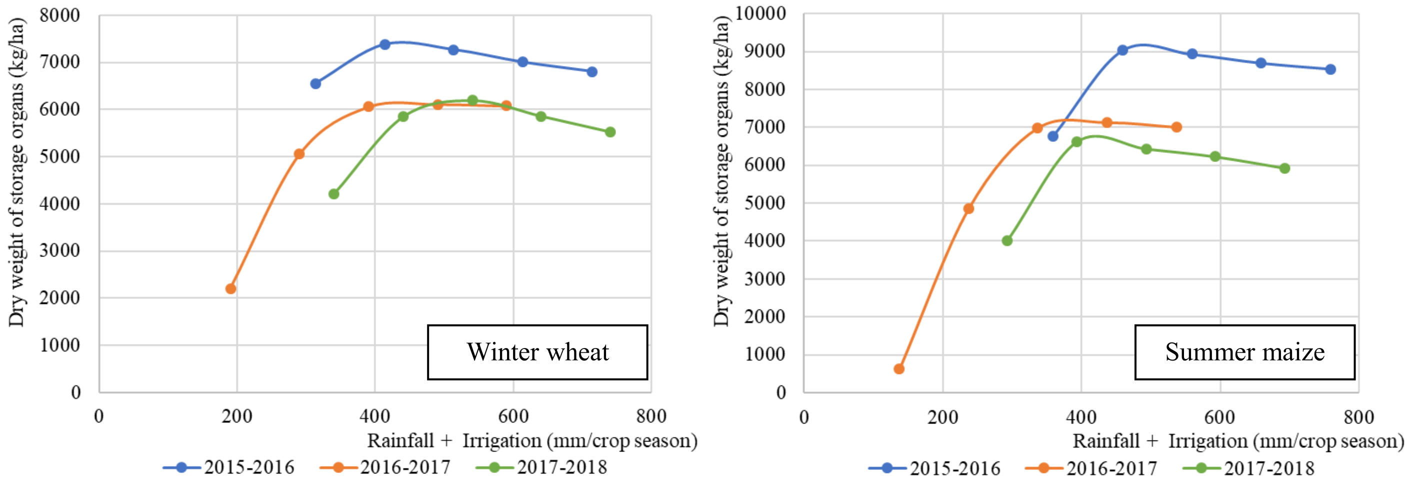


Figure 31. Relations between simulated dry weight of storage organs and total amount of irrigation and precipitation water.

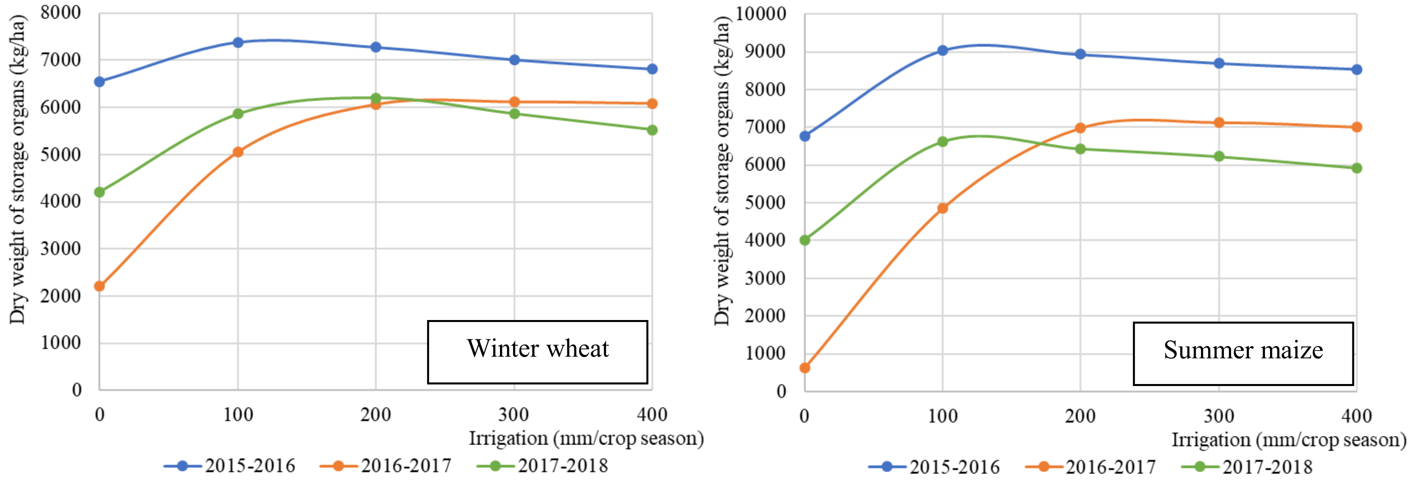


Figure 32. Relations between simulated dry weight of storage organs and irrigation amount.

Based on situations of the whole three years, according to Figure 31 and 32, when the sum of rainfall and irrigation amount reached 490mm and 450mm in wheat and maize season; irrigation amount both reached 200mm, crop yields could reach a considerable level.

6.2.2 WinSRFR

On basis of simulation results in previous section, in this section we will use the WinSRFR model to find the reasonable inflow rates and irrigation time to achieve the 200mm irrigation depth in each crop season. Since there were both two irrigation/fertigation events in each crop season, here we assume an irrigation amount of 100mm in each irrigation event. The same model parameters a, n and k as calibrated values in Model testing chapter will be used here. Considering that the irrigation method of farmers was based on the distance of inflow advance, the simulated irrigation time is also determined by the advance distance.

The simulated inflow rates, irrigation time and irrigation depth to achieve uniform irrigation around 100mm are given in Table 41. The application efficiency and distribution uniformity of each irrigation/ fertigation event are listed in Table 42. Curves of infiltration depth are presented in Figure 33.

Table 41. Simulated inflow rates, irrigation time and irrigation depth to approach 100mm uniform irrigation.

Irrigation/ fertigation event	Date	Inflow rate (l/s)	Cut-off distance (m)	Irrigation time (hour)	Irrigation depth (mm)
Wheat-1	Dec 20	14.7	148	2.55	109
Wheat-2	March 28	26.0	140	1.65	118
Maize-1	July 27	14.5	166	1.97	109
Maize-2	Sep 2	14.5	174	1.74	105

Table 42. Simulated application efficiency and distribution uniformity of each irrigation / fertigation event.

Irrigation/ fertigation event	Application efficiency	Distribution uniformity
Wheat-1	90%	0.85
Wheat-2	83%	0.82
Maize-1	89%	0.84
Maize-2	93%	0.87

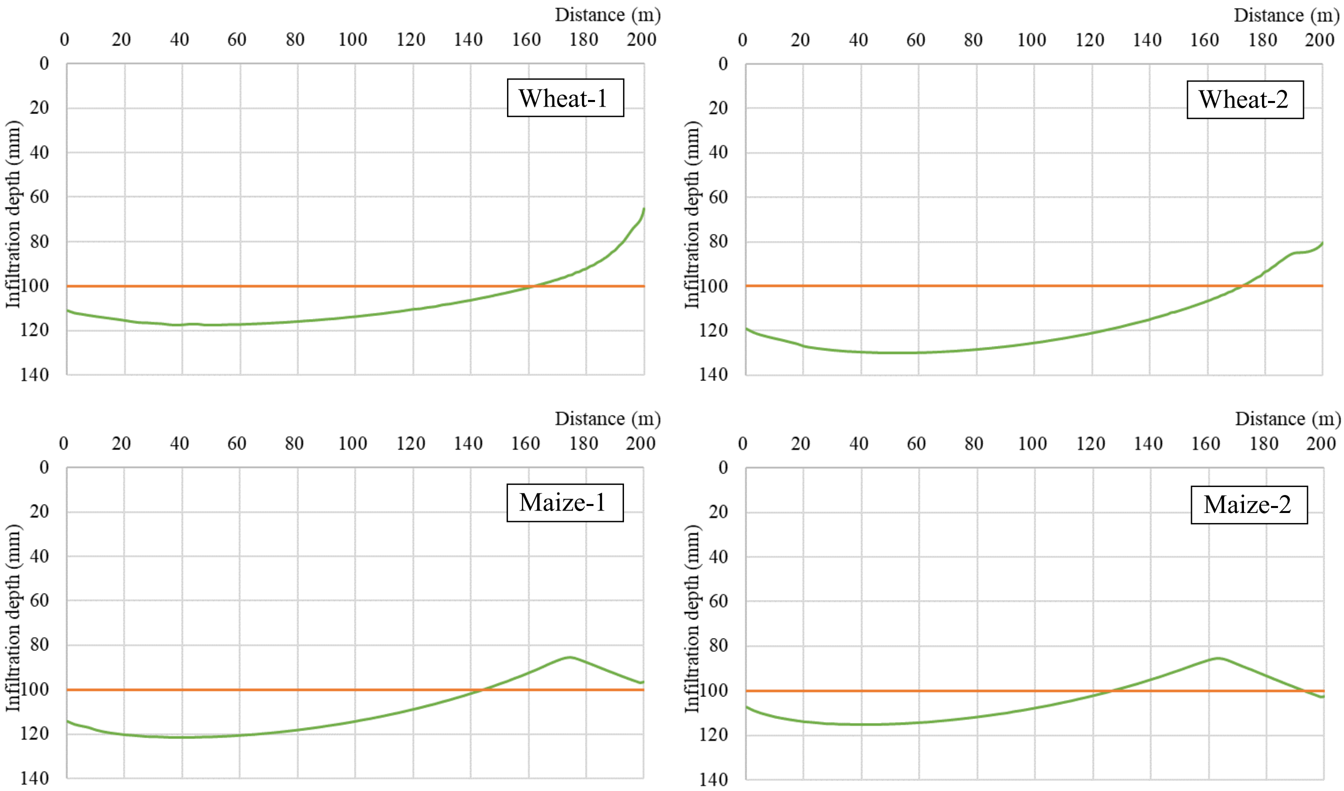


Figure 33. Simulated infiltration depth in each irrigation/fertigation event.

Reducing irrigation amount can be achieved by increasing inflow rates. According to the recorded inflow rates in field experiments, the existing pump system can reach the inflow rate of 14.7 l/s. With large inflow rates, the cut-off time becomes more sensitive to the irrigation amount. So it is necessary to observe the advance distance to control the irrigation time.

We observed that in "Wheat-2" fertigation, based on the soil conditions, the roughness was large and 100mm uniform irrigation was difficult to achieve. This was also confirmed in the field experiment data. According to the experiment records, irrigation amount of each field on the same day, using the same irrigation method, were all above 200mm. Therefore, the irrigation method can be modified in the second irrigation of the wheat season, e.g. apply two irrigation from the head and middle of the field respectively. After simulation by WinSRFR model, the required inflow rate and irrigation time are shown in Table 43.

Table 43. Simulated irrigation parameters of Wheat-2.

Irrigation/ fertigation event	Inflow rate (l/s)	Cut-off distance (m)	Irrigation time (hour)	Irrigation depth (mm)	AE	DU
Wheat-2	14.5	82; 182	0.69	103	97%	0.94

7 Weakness of this research

(1) Incompetence and inaccuracy existed in the experimental measurement data, e.g. SWC on ordinary days with no irrigation or rainfall were not measured on each field; SWC and soil N content were not measured in the few months before the first irrigation of wheat season; Some of the soil N content data was not realistic. Therefore, accuracy needs to be improved in model calibration.

From the comparison of the simulated and measured data, although the model results were acceptable, errors still exist. Some of the simulation results, such as above ground biomass, were not measured in the experiments, thus only the data from literature can be compared in model calibration and data analysis. Although the simulated values correspond to the range of variation in literature, whether it is consistent with the actual situation remains to be discussed.

(2) In addition to the input data and information in the model, the process of fertigation is subject to other influencing factors. But these factors were not considered during the simulation:

A. Cai et al. (2016) found in their experiment that due to the tillage before the wheat growing season and the compaction effect of rainfall and irrigation on the soil, the soil bulk density changed greatly during the year, ranging from 1.15 to 1.38 g/cm^3. In essence, the bulk density is an indirect reflection of the degree of soil compaction, which affects the soil water infiltration of to a certain extent. However, in our simulation, the change in soil bulk density was not considered.

B. Loss control fertilizer is a new type of high-efficiency and environmentally friendly fertilizer developed by the Chinese Academy of Sciences, which can reduce the loss of fertilizer nutrients and slows the rate of nutrient release (Zhou et al., 2015). A large number of experimental studies show that, compared with convention fertilizer, the loss control fertilizer could significantly improve crop yields and agronomic nutrient efficiency (Qiu et al., 2010; Bai et al., 2017). However, in the soil-N module, the difference between loss control fertilizer and common fertilizer was not considered.

C. Wang's experimental study in the NCP shows that the combination of nitrogen and phosphate fertilizer had a significant effect on the growth of wheat and maize. At the same time, the use of phosphate fertilizer has a significant effect on the leaching of nitrogen fertilizer. When the N and P fertilizers are combined in a certain ratio, not only the maximum yield can be achieved, but the N leaching can be controlled at a certain level (Wang et al., 2009). In our field experiments, the fertilizer used in basal fertilization was a NPK compound fertilizer, which contained a large proportion of P. Compared with urea (N fertilizer), the use of compound fertilizer should show an influence on crop yields and N leaching, but the factor of P was not considered in the simulation.

8 Conclusion

From the results of this study, the following conclusions can be derived:

(1) According to modelling results and model application, the WinSRFR and SWAP model after calibration can be combined to simulate surface fertigation practices in the NCP.

(2) Simulation of field experiments shows that there was excessive irrigation in fertigation practices. Due to the relatively sufficient amount of precipitation in simulated year, the irrigation efficiency was very low, and the amount of deep leakage was almost the same as the amount of irrigation. At the same time, N leaching caused by excessive irrigation can also bring a lot of chemical pollution. Water stress was the main reason for yields reduction. By comparing the two parts of a field, Part 2 with less irrigation and fertilization, achieved higher crop yields, water use efficiency, water productivity, Nitrogen use efficiency and N capture.

(3) When the precipitation water is not enough for crop growth, increasing irrigation amount can reduce drought stress to improve the crop yields. When the amount of irrigation continues to increase, excessive irrigation will lead to an increase in wet stress and N stress, resulting in crop yields reduction.

(4) Through data analysis of three years with significant interannual variation, climatic conditions have a large impact on crop growth. Differences in crop N uptake and precipitation amount together lead to differences in N leaching.

(5) By comparing the simulation results for three years, considerable yields can be achieved when the sum of rainfall and irrigation reached 490mm in winter wheat season and 450mm in summer maize season; or irrigation amount both reached 200mm.

(6) Two irrigation/fertigation events of 100mm irrigation amount in each crop season can achieve better crop development and high WUE and WP, which can be achieved in most cases at an inflow rate of about 14.7l/s. However, during the second irrigation of wheat season when the surface roughness is large, 100mm uniform irrigation is difficult to achieve. Therefore, increasing the pump head or changing the irrigation method may be an alternative way.

9 Recommendations

9.1 Recommendations for field management

(1) Current distance-based cut-off irrigation method can easily result in over irrigation and yield reduction. It is recommended to increase pump head and inflow rates to reduce irrigation amount. The recommended inflow rates and cut-off time are illustrated in Table 44.

Table 44. Recommended inflow rates and cut-off time.

Irrigation/ fertigation event	Date	Inflow rate (l/s)	Advance distance to stop irrigation (m)	Irrigation time (hour)
Wheat-1	Dec 20	14.7	148	2.55
Wheat-2	March 28	26.0	140	1.65
Maize-1	July 27	14.5	166	1.97
Maize-2	Sep 2	14.5	174	1.74

(2) After inflow rate is increased, cut-off time becomes more sensitive for irrigation amount. Therefore, more attention should be paid to the advance distance to adjust the cut-off time, in this way over-irrigation could be alleviated.

(3) As for the second irrigation/fertigation in winter wheat season, if the inflow rate cannot reach 26 l/s, there is one alternative way to achieve the 100 mm uniform irrigation:
Apply two irrigation in one field: Once from the start of the field, once from the middle of the field. Figure 34 expresses the irrigation process and the infiltration depth.

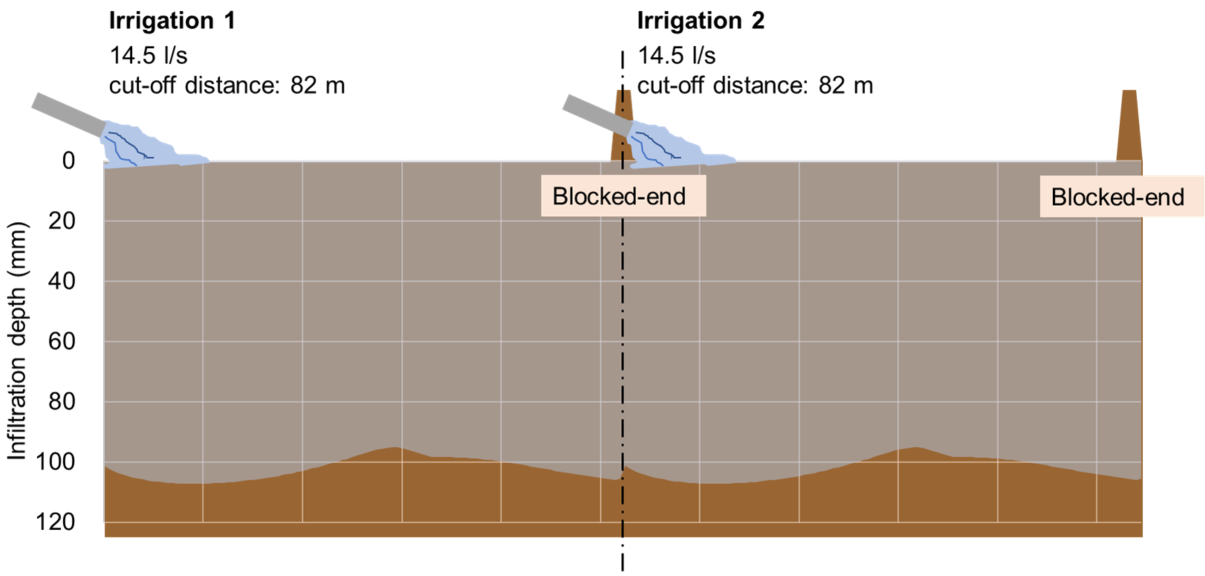


Figure 34. Recommended process of second irrigation/fertigation in winter wheat season.

(4) Pay attention to precipitation amount and soil conditions and adjust irrigation/fertigation plans based on climate condition: When the precipitation occurs frequently with large amount, and the soil become wet, the inflow rate can be increased and the irrigation time can be reduced; when rainfall amount is low and soil becomes dry, the inflow rates can be reduced, and the irrigation time can be controlled by the cut-off distance.

9.2 Recommendations for WinSRFR & SWAP modelling

9.2.1 Field experiments

Table 45. Experiments/data required in field experiments for model input/calibration.

Experiment/data to be measured	Releated procedure	Related input		Related output	
		Input paramter	Input file	Output paramter	Output file
Border width & length	WinSRFR input	Field size	WinSRFR		
Field slope	WinSRFR input	Slope			
Soil texture (soil layer)	SWAP input	Soil layers	*.swp		
Bulk density	SWAP input	BD			
Soil hydraulic functions	SWAP input/calibration	Soil hydraulic function parameters		SWC, pressure head	*.vap
Irrigaiton advance & recession	WinSRFR input	Measured advance & recession	WinSRFR		
Inflow rates	WinSRFR input	Inflow rates			
Irrigaiton amount	SWAP input	Irrigaiton depth			
Soil water content	SWAP calibration			SWC	*.vap
Fertilization parameters	Soil-N input	Fertilization amount & date	*.sme		
Type of fertilizer applied	Soil-N input	NH_4-N, NO_3-N concentration in fertilizer	*.smm		
Soil N concentration	Soil-N calibration			NH4_end, NO3_end	*_nut.csv
Crop height	WOFOST input	CH	*.crp		
Leaf area → LAI	WOFOST calibration	SLA		LAI, Biomass, Yield	Result.crp
Dry weight of total biomass at emergence	WOFOST input	TWDI		Biomass, Yield	
Date of Sowing, emergence, anthesis, matuarity, harvest	SWAP input WOFOST calibration	Crop pattern TSUMAE, TSUMEM	*.swp *.crp		
Crop yields (dry weight)	WOFOST calibration			Yield	Result.crp
Above ground biomass (dry weight)	WOFOST calibration			Above ground biomass	
N concentration in crop biomass	WOFOST calibration Soil-N calibration			NH4_upt, NO3_upt	*_nut.csv

9.2.2 Model calibration

Table 46. Parameters required to be calibrated in WinSRFR/SWAP simulation.

Input data require calibration[1]		Related output	
Input paramter	Input file	Output paramter	Output file
Manning n	WinSRFR model	WinSRFR advance and recession	WinSRFR output
Kostiakov α			
Soil hydraulic functions	*.swp	Water balance, Soil water content, Soil water pressure head	*.bal, *.blc, *.end, *.vap
Initial soil water pressure head			
TSUMEA	*.crp	Crop development stage (DVS)	*.crp
TSUMAM			
SLATB		LAI, Crop yields, Above ground biomass	
AMAXTB			
SPAN			
TWDI			
CVO			
FLTB			
FSTB			
FOTB			
RDI			
RDC			
DVSNLT			
Initial soil organic matter and NH_4-N, NO_3-N concentration	*.snp	NH_4-N, NO_3-N concentration	*_nut.csv
TCSF_N		LAI, Crop yields, Above ground biomass	*.crp
LaiCritNupt			
dz_WSN		Depth of Soil-N calculation	*_nut.csv

[1] The model input data that do not require calibration, such as the meteorological data, are not included in this table.

9.3 Recommendations for further study

(1) Due to limited time, in the model application chapter we only studied the effects of changing the irrigation amount without changing the amount of fertilizer applied, and the results show that water stress was the main factor for crop yields reduction. However, the amount and type of fertilizer applied, and the time of fertigation are all potentially important factors. Therefore, it is recommended to conduct further research on the following situations:

A. With same amount of water and different amount of fertilizer applied;
B. Adjust the fertigation time, such as making changes based on rainfall time;
C. Change the type of fertilizers, e.g. organic fertilizer (manure);
D. Obtain more years of meteorological data for longer time span simulations.

(2) Nitrogen efficiency is one of the key indicators in fertilization research, while a concept closely related to it is called nitrogen fertilizer recovery efficiency (NRE/REN) or percent fertilizer recovery (PFR). There are many definitions of NRE/REN or PFR, e.g. Difference method (Varvel and Peterson, 1990; Cassman et al., 2002):

$$REN = (UN - IN) / FN \qquad \text{(Equation 3)}$$

where UN is the measured crop-N uptake in plots with N fertilizer applied (kg/ha);
IN is the measured crop-N uptake in plots without applied N (kg/ha);
FN is the amount of applied N fertilizer (kg/ha).

Therefore, in many studies about fertilization and crop N uptake, blank controlled groups without nitrogen fertilizer application were often established. It is recommended to add blank controlled groups without fertilization practices in future experiment design to introduce the REN indicator into analysis.

(3) During the model calibration process, we found that some of the data were not complete or accurate enough, e.g. soil moisture on ordinary days with no irrigation or rainfall, and nitrogen concentration in the soil. Besides, some data, such as TWDI, were not measured in field experiments, making the calibration process more dependent on the data from literature. Although the simulation results are satisfactory, whether it is consistent with the actual situation remains to be discussed. It is therefore recommended that the data measured and recorded in future experiments more standardized to facilitate further calibration of the model. Hear we list the extra data/experiments recommended to add in future experimental design:

- Soil hydraulic functions parameters;
- Date of emergence, anthesis and maturity;
- Total crop dry weight at emergency;
- More crop height and measured date;
- More Leaf area and measured date;
- Dry weight of above ground biomass at harvesting;
- N concentration in crop biomass at harvesting;
- More soil water content;
- Calibrated soil NH_4-N and NO_3-N concentration.

References

Administration Bureau of People's Victory Canal Irrigation District (PVCID). (2002). 50 Years of Irrigation using the Yellow River water in People's Victory Canal Irrigation District (in Chinese). Zhengzhou: The Yellow River Water Conservancy Press.

Akkermans, W., Boogaard, H., Wit, A. De, & Hessel, R. (2008). CALPLAT: platform for calibrating CGMS.

Atterberg, A. (1905). Die rationalle Klassifikation der Sande und Kiese. *Chemiker Zeitung* 29, 195-198.

Bai, M., Xu, D., Li, Y., & Zhang, S. (2011). Spatial and temporal distribution of nitrogen in surface water and soil under scattering and fertigating ammonium-sulphate for border irrigation. *Transactions of the CSAE*, 27(8), 19–25. (in Chinese with English abstract). https://doi.org/10.3969/j.issn.1002-6819.2011.08.004

Bai, S., Wan, S., Kang, Y., & Liu, S. (2017). Effect of Different Loss-control Fertilizers on Winter Wheat Yield and Agronomic Nutrient Efficiency. *Acta Agriculturae Boreali-Sinica*, 32(1), 149–155. (in Chinese with English abstract).

Bautista, E., Schlegel, J. L., & Strelkoff, T. S. (2012). WinSRFR 4.1 User Manual.

Boogaard, H., Zhang, M., & Yan, N. (2017). Technical description of crop model (WOFOST) calibration and simulation activities Shandong province, China (Vol. 79).

Cai, H., Xu, J., Wan, J., Chen, X., & Zhu, D. (2016). Yearly variation of soil infiltration parameters in irrigated field based on WinSRFR4.1. *Transactions of the Chinese Society of Agricultural Engineering*., 92–98. (in Chinese with English abstract). https://doi.org/10.11975/j.issn.1002-6819.2016.02.014

Cai, Q., & Wu, Z. (1993). The relations of dry matter accumulation of grain growth stages to grain weight in wheat. *Journal of Nanjing Agricultural University*, 16(1), 27–32. (in Chinese with English abstract).

Cassman, K., Dobermann, A., Walters, D. (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio*. 31, 132–40.

Chen, B., Ouyang, Z., & Zhang, S. (2012). Evaluation of Hydraulic Process and Performance of Border Irrigation with Different Regular Bottom Configurations. *Journal of Resources and Ecology*, 3(2), 151–160. https://doi.org/10.5814/j.issn.1674-764x.2012.02.007

Chen, X., Zhang, J., Shen, X., Gao, Y., Liu, X., Wu, X., & Gong, X. (2016). Effects of Border Strip Fertilization on Soil Water and Nitrogen Distribution in Summer Maize Field. *Journal of Soil and Water Conservation*, 30(5), 140–148. (in Chinese with English abstract). https://doi.org/10.13870/j.cnki.stbcxb.2016.05.024

China National Meteorological Information Center. (2019). Accessed in 2016. Available: http://data.cma.cn/en

Chu, P., Zhang, Y., Yu, Z., Guo, Z., & Shi, Y. (2016). Winter wheat grain yield, water use, biomass accumulation and remobilisation under tillage in the North China Plain. *Field Crops Research*, 193, 43–53. https://doi.org/10.1016/j.fcr.2016.03.005

Feng, S., Ma, Y., & Huo, Z. (2012). Simulation Study of Field Water Transformation under Deficit Irrigation with SWAP model. *Transactions of the CSAE*, 28(4), 60–68. (in Chinese with English abstract).

Feng, Z., Kang, Y., Wan, S., & Liu, S. (2018). Effect of Drip Fertigation on Potato Productivity with Basal Application of Loss Control Fertilizer in Sandy Soil. *Irrigation and Drainage*, 67(2), 210–221. https://doi.org/10.1002/ird.2183

Gao, S., Zhang, F., Zhi, Y., Chen, F., & Xiao, K. (2016). The yields, agronomic, and nitrogen use efficiency traits of wheat cultivars in north China under N-sufficient and -deficient conditions. *Journal of Plant Nutrition*, *40*(7), 1053–1065. https://doi.org/10.1080/01904167.2016.1263328

Gao, X., Du, S., Zhong, Y., Wu, Y., & Zhang, G. (2015). Current Status and Prospects of Water and Fertilizer Integration Development. *China Agricultural Information*, 14–19. (in Chinese).

Gao, X. (2013). Current Status and Prospects of Water and Fertilizer Integration Development.

The 4th China International Water-soluble Fertilizer High-Level Forum. Nanning, Guangxi, China. (in Chinese).

Gao, Z., Feng, H., Liang, X., Zhang, L., Lin, S., Zhao, X., & Shen, S. (2018). Field Crops Research Limits to maize productivity in the North China Plain: A comparison analysis for spring and summer maize. *Field Crops Research*, 228, 39–47. https://doi.org/10.1016/j.fcr.2018.08.022

Global Yield Cap Atlas. (2019, March). Protocol for estimating average actual yields for yield gap determination. GYGA Protocol for estimating actual yields and yield gaps. Retrieved from http://www.yieldgap.org/methods-actual-yield

Groenendijk, P., Boogaard, H., Heinen, M., Kroes, J., Supit, I., & Wit, A. De. (2016). Simulation of nitrogen-limited crop growth with SWAP / WOFOST.

Hagin, J., & Lowengart, A. (1996). Fertigation for minimizing environmental pollution by fertilizers. *Fertilizer Research,* 43(1-3), 5-7. http://dx.doi.org/10.1007/Bf00747675.

He, K., & Yang, Y. (2017). HYDRUS Simulation of Sustainable Brackish Water Irrigation in a Winter Wheat-Summer Maize Rotation System in the North China Plain. *Water*, 9(536), 19. https://doi.org/10.3390/w9070536

Huang, J., Jia, S., Ma, H., Hou, Y., & He, L. (2017). Dynamic Simulation of Growth Process of Winter Wheat in Main Production Areas of China based on WOFOST Model. *Transactions of the Chinese Society of Agricultural Engineering*, *33*(10), 222–228. (in Chinese with English abstract).

Huo, Z., Feng, S., Dai, X., Zheng, Y., & Wang, Y. (2012). Simulation of hydrology following various volumes of irrigation to soil with different depths to the water table. *Soil Use and Management*, 28(2), 229–239. https://doi.org/10.1111/j.1475-2743.2012.00393.x

Iqbal, M., Shen, Y., Stricevic, R., Pei, H., Sun, H., Amiri, E., & Penas, A. (2014). Evaluation of the FAO AquaCrop model for winter wheat on the North China Plain under deficit irrigation from field experiment to regional yield simulation. *Agricultural Water Management*, 135, 61–72. https://doi.org/10.1016/j.agwat.2013.12.012

Jin, J., Zhang, X., Xu, B., Wang, W., & Zhang, J. (2014). Evaluation on backstepping method of infiltration parameters of soil water under furrow irrigation based on the software SRFR. *Agricultural Research in the Arid Areas*, 32(4), 59–64. (in Chinese with English abstract).

Jin, L., Cui, H., Li, B., Zhang, J., Dong, S., & Liu, P. (2012). Effects of integrated agronomic management practices on yield and nitrogen efficiency of summer maize in North China. *Field Crops Research*, *134*, 30–35. https://doi.org/10.1016/j.fcr.2012.04.008

Kroes, J. G., Van Dam, J. C., Bartholomeus, R. P., Groenendijk, P., Heinen, M., Hendriks, R. F. A., Mulder, H. M., Supit, I., & Van Walsum, P. E. V. (2017). SWAP version 4, Theory description and user manual J.G. https://doi.org/10.18174/416321

Liang, Y., Xu, D., Li, Y., & Bai, M. (2005). Field Experiment on Water and Nitrogen Distribution for Winter Wheat under Border Strip Fertigation. *Transactions of the CSAE*, *25*(3), 22–27. (in Chinese with English abstract). https://doi.org/10.3724/SP.J.1042.2011.01658

Li, F. & Lu, S. (2000). Study on the Fertigation and Its Application. *Plant Nutrition and Fertilizer Science*, 6(2), 233-240. (in Chinese with English abstract).

Li, H., Mei, X., Hao, W., Xia, X., Liu, Q., & Li, Y. (2012). Effects of Different Irrigaiton and Fertilizer Regimes on Soil Moisture and Grain Yield of Summer Maize. *Journal of Irrigation and Drainage*, *31*(4), 72–74. (in Chinese with English abstract). https://doi.org/10.13522/j.cnki.ggps.2012.04.010

Li, J., Inanaga, S., Li, Z., & Eneji, A. (2005). Optimizing irrigation scheduling for winter wheat in the North China Plain. *Agricultural Water Management,* 76 (1), 8-23. (in Chinese with English abstract). http://dx.doi.org/10.1016/j.agwat.2005.01.006.

Li, J., Li, B., & Rao, M. (2004). Influence of Surface Irrigation Technical Parameter on Nitrogen Transport and Distribution A Review. *Transactions of the CSAE*, 20(6), 51–55. (in Chinese with English abstract).

Li, J., Zhang, J, & Rao, M. (2013). Modelling of Water Flow and Nitrate Transport Under Surface

Drip Fertigation. *Transactions of the ASAE*, 48(2), 627–637. (in Chinese with English abstract). https://doi.org/10.13031/2013.18336
Li, S., Cai, H. & Chen, X. (2013). Evaluation of border irrigation performance based on principal component and correlation analyses. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 29(24), 86-93. (in Chinese with English abstract).
Li, X., Cui, Y., & Xie, X. (2005). Study on Water Regimes of Aerobic Rice and Effect of Groundwater Depth on Water Saving Irrigation on the basis of SWAP. (in Chinese with English abstract).
Li, Y., Chen, D., White, R. E., Zhu, A., & Zhang, J. (2007). Estimating soil hydraulic properties of Fengqiu County soils in the North China Plain using pedo-transfer functions. *Geoderma*, 138, 261–271. https://doi.org/10.1016/j.geoderma.2006.11.018
Li, Y. (2004). Evaluation of Surface Irrigation Technology and Development Trend in China. In Proceedings of the First Youth Science and Technology Forum of Chinese Hydraulic Engineering Society (pp. 201–207). (in Chinese).
Li, Z., Xu, D., & Li, Y. (2015). Research Review of Integrated Simulation of Surface-subsurface Flow and Solute Transport. *Shanxi Shuili*, 119–120. (in Chinese). https://doi.org/10.13989/j.cnki.0517-6611.2015.05.032
Li, Z., Xu, D., Li, Y., & Zhang, S. (2009). Integrated Simulation of Surface-subsurface Flow and Solute Transport for Border Strip Fertigation I. Model. *Shuili Xuebao*, 40(6), 673–687. (in Chinese with English abstract).
Liu, C. (1989). Water saving, regulation and control for agriculture in the North China Plain. *Geographical Research,* 8(3), 1-9.
Lin, C., TongXiao, L., & RongHua, L. (2017). Effect of climate change on growth and yield of winter wheat in Henan Province. *Chinese Journal of Eco-Agriculture*, 25(6), 931–940. (in Chinese with English abstract). http://doi.org/10.13930/j.cnki.cjea.161054
Liu, C., Zhang, X., & Zhang, Y. (2002). Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. *Agricultural and Forest Meteorology*, 111, 109–120.
Liu, L., Cui, Y., & Feng, Y. (2010). Water management strategies of Yellow River Irrigation District based on SWAP and MODFLOW models. *Transactions of the CSAE*, 26(4), 9–17. (in Chinese with English abstract).
Liu, W., Ma, G., Kang, G., Wei, Q., Lu, H., Xie, Y., … Wang, J. (2018). Root Growth, Water and Nitrogen Use Efficiencies in Winter Wheat Under Different Irrigation and Nitrogen Regimes in North China Plain. *Frontiers in Plant Science*, *9*(December), 1–14. https://doi.org/10.3389/fpls.2018.01798
Liu, Y., Li, J., & Sun, X. (2019). Effects of Different Irrigation and Fertilization Ways on Growth Index and Yield of Summer Maize. Manuscript submitted for publication. (in Chinese with English abstract).
Ma, Y., Feng, S., Huo, Z., & Song, X. (2011). Application of the SWAP model to simulate the field water cycle under deficit irrigation in Beijing, China. *Mathematical and Computer Modelling*, 54(3–4), 1044–1052. https://doi.org/10.1016/j.mcm.2010.11.034
Ma, Y., Feng, S., & Song, X. (2015). Evaluation of optimal irrigation scheduling and groundwater recharge at representative sites in the North China Plain with SWAP model and field experiments. *Computers and Electronics in Agriculture*, 116, 125–136. https://doi.org/10.1016/j.compag.2015.06.015
Meng, Z., Xu, X., Lin, W., Ge, B., Xie, Y., Song, B., Jia, S., Zhang, R., Peng, W., Wang, Y., Cheng, H., Yang, W., & Zhao, H., 2018. Role of ambient ammonia in particulate ammonium formation at a rural site in the North China Plain. *Atmos. Chem. Phys.* 18, 167–184. https://doi.org/10.5194/acp-18-167-2018
Ministry of Agriculture, People's Republic of China. (2015). Zero growth in synthetic fertilizer use from 2020 onwards (in Chinese) [online]. Available: http://www.moa.gov.cn/zwllm/tzgg/tz/201503/t20150318_4444765.htm

Moll, R. H., Kamprath, E. J., & Jackson, W. A. (1982). Analysis and Interpretation of Factors Which Contribute to Efficiency of Nitrogen Utilization. *Agron*, 74, 562-564. https://doi.org/10.2134/agronj1982.00021962007400030037x

Mou, H., He, J., Xing, J., Yao, S., Tang, Y., & Wang, Z. (2016). Water changes in wheat spike during grain filling stage investigated by nuclear magnetic resonance. *Transactions of the Chinese Society of Agricultural Engineering*, 32, 98–104. (in Chinese with English abstract). https://doi.org/10.11975/j.issn.1002-6819.2016.08.014

Mo, X., Xue, L., & Lin, Z. (2005). Spatio-temporal distribution of crop evapotranspiration from 1981-2001 over the North China Plain. *Journal of Natural Resources,* 20(2), 181-188.

Nie, W., Zhang, F., Ma, Xi., & Huang, H. (2017). Optimization of discharge per unit width of border irrigation based on soil infiltration variability. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 33(16), 119-126. (in Chinese with English abstract). https://doi.org/10.11975/j.issn.1002-6819.2017.16.016

Pei, H., Shen, Y., & Liu, C. (2015). Nitrogen and water cycling if typical cropland in the North China Plain. *Chinese Journal of Applied Ecology*, 26(1), 283–296.

Pepler, S., Gooding, M. J., & Ellis, R. H. (2006). Modelling simultaneously water content and dry matter dynamics of wheat grains. *Field Crops Research*, 95, 49–63. https://doi.org/10.1016/j.fcr.2005.02.001

Qiu, G., Wu, Y., Wang, Y., Chen, T., Zhao, J., Yu, L., & Yu, Z. (2010). Impact of An New and High Efficient Loss- Control Fertilizer on Wheat Yield in Huang –Huai-Hai Area. *Chinese Agricultural Science Bulletin*, 26(18), 186-191. (in Chinese with English abstract).

Sun, X. (2019). Collaborative research to assess the current performance of irrigation and fertilisation practices at farmers' field in the North China Plain. Unpublished manuscript.

Sylvester-Bradley, R., & Kindred, D. R. (2009). Analysing nitrogen responses of cereals to prioritize routes to the improvement of nitrogen use efficiency. *Journal of Experimental Botany*, 60(7), 1939–1951. https://doi.org/10.1093/jxb/erp116

Tian, B., Zhu, J., Nie, Y., Xu, C., Wang, P., & Meng, Q. (2019). Mitigating heat and chilling stress by adjusting the sowing date of maize in the North China Plain. *Journal of Agronomy and Crop Science*, 205, 77–87. https://doi.org/10.1111/jac.12299

Umair, M., Shen, Y., Qi, Y., Zhang, Y., & Ahmad, A. (2017). Evaluation of the CropSyst Model during Wheat-Maize Rotations on the North China Plain for Identifying Soil Evaporation Losses. *Frontiers in Plant Science*, 8, 1–14. https://doi.org/10.3389/fpls.2017.01667

Van Genuchten, M. Th., Leij, F. J., & Yates, S. R. (1991). The RETC code for quantifying the hydraulic functions of unsaturated soils, USEPA Rep. IAG-DW12933934, R.S. Kerr Environ. Res. Lab., US Environmental Protection Agency, Ada, OK, USA.

Van Halsema, G. E., & Vincent, L. (2012). Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. *Agricultural Water Management*, *108*, 9–15. https://doi.org/10.1016/j.agwat.2011.05.016

Varvel, G.E., Peterson, T.A. (1990). Nitrogen fertilizer recovery by corn in monoculture and rotation systems. *Agron*. 82, 935–938.

Wang, F., Wang, Z., Kou, C., Ma, Z., & Zhao, D. (2016). Responses of Wheat Yield, Macro- and Micro-Nutrients, and Heavy Metals in Soil and Wheat following the Application of Manure Compost on the North China Plain. *PLOS ONE*, 11 (1).

Wang, H., Wang, X., & Zhao, S. (2008). Distribution of Soil Water and Nitrate in Lou Soil under Drip Fertigation. *Acta Agriculturae Boreali-Occidentalis Sinica*, 17(6), 309-314. (in Chinese with English abstract).

Wang, Q., Wang, W., & Zhang, J. (2005). Determination of Philip infiltration parameter and Manning roughness according to hydraulic factors in the advance of irrigation water. *Journal of Hydraulic Engineering*, 36(1), 125-128. (in Chinese with English abstract).

Wang, T., Lv, C., & Yu, B. (2009). Assessing the Potential Productivity of Winter Wheat Using WOFOST in the Beijing-Tianjin-Hebei Region. *Journal of Natural Resources*, *25*(3), 475–487. (in Chinese with English abstract). https://doi.org/10.1080/19390450903040454

Wang, X. (2017). Henan promoted agricultural water "revolution". Water-saving irrigation area reaches 27 million mu (in Chinese) [online]. Available: http://www.ha.xinhuanet.com/news/2017-10/12/c_1121788976.htm
Wang, Y., HAN, Y., ZHANG, X., & TAN, J. (2009). Effects of Different Fertilizers on Yield and Plant Nutrient Accumulation of High-yield Summer Maize. *Journal of Maize Sciences*, 17(6), 88–92. (in Chinese with English abstract).
Wang, Z., Li, J., & Li, Y. (2014). Simulation of nitrate leaching under varying drip system uniformities and precipitation patterns during the growing season of maize in the North China Plain. *Agricultural Water Management*, 142, 19–28. https://doi.org/10.1016/j.agwat.2014.04.013
Wolf, J., & De Wit, A. (2010). Calibration of WOFOST crop growth simulation model for use within CGMS.
Wolf, J. (2012). LINTUL4 and LINTUL4V: Simple generic model for simulation of crop growth under potential, water limited and nitrogen limited conditions (Vol. 4).
Wu, D., Ouyang, Z., Zhao, X., Yu, Q., & Luo, Y. (2003). The Applicability Research of WOFOST Model in North China Plain. *Acta Phytoecologica Sinica*, 27(5), 594–602. (in Chinese with English abstract).
Xia, L., Tao, H., Wang, P., Xu, X., Lu, L., & Wang, R. (2011). Effects of Nitrogen Application Period on Nitrogen Accumulation, Translocation and Nitrogen Use Efficiency of Summer Maize. *Journal of Maize Sciences*, *19*(1), 112–116. (in Chinese with English abstract).
Xiao, D., Shen, Y., Qi, Y., Moiwo, J. P., Min, L., & Zhang, Y. (2017). Impact of alternative cropping systems on groundwater use and grain yields in the North China Plain Region. *Agricultural Systems*, 153, 109–117. https://doi.org/10.1016/j.agsy.2017.01.018
Xu, J., Cai, H., Saddique, Q., Wang, X., & Li, L. (2019). Evaluation and optimization of border irrigation in di ff erent irrigation seasons based on temporal variation of in fi ltration and roughness. *Agricultural Water Management*, 214(23), 64–77. https://doi.org/10.1016/j.agwat.2019.01.003
Yan, X., Dai, T., & Jia, L. (2018). Evaluation of the cumulative effect of drip irrigation and fertigation on productivity in a poplar plantation. *Annals of Forest Science*, 75(1). https://doi.org/10.1007/s13595-017-0682-6
Zai, S. (2010). Soil Water and Nutrient Transport under the Interaction of Irrigation and Fertilization. Northwest A&F University.
Zhang, J., Li, J., Zhao, B., & Li, Y. (2015). Simulation of water and nitrogen dynamics as affected by drip fertigation strategies. *Journal of Integrative Agriculture*, 14(12), 2434–2445. https://doi.org/10.1016/S2095-3119(15)61231-X
Zhang, S., Xu, D., Li, Y., & Bai, M. (2011). One-dimensional Model for Coupling Surface Water Flow with Solute Transport for Border Fertigation: I. Model solution. *Advances in Water Science*, 22(2), 189–195. (in Chinese with English abstract). https://doi.org/10.14042/j.cnki.32.1309.2011.02.023
Zhang, S., Xu, D., Li, Y., & Wei, Z. (2011). Review on Simulation Study of Surface Flow and Solute Transport for Basin Fertigation. *Journal of Irrigation and Drainage*, 30(3), 124–128. (in Chinese with English abstract). https://doi.org/10.13522/j.cnki.ggps.2011.03.003
Zhang, S., Zhang, J., Li, J., Cheng, Y., & Li, G. (2014). Calibration and Validation of WOFOST in Main Maize-Producing Regions in Henan. *Journal of Henan Agricultural Sciences*, *43*(8), 152–156. (in Chinese with English abstract).
Zhang, Y., Kendy, E., & Qiang, Y. (2004). Effect of soil water deficit on evapotranspiration, crop yield, and water use efficiency in the North China Plain. *Agricultural Water Management*, 64, 107–122. https://doi.org/10.1016/S0378-3774(03)00201-4
Zhang, Y., Liu, C., Shen, Y., Kondoh, A., Tang, C., Tanaka, T., & Shimada, J. (2002). Measurement of evapotranspiration in a winter wheat field. *Hydrological Processes*, 16, 2805–2817. https://doi.org/10.1002/hyp.1072
Zhen, L., Zoebisch, M., Chen, G., & Feng, Z. (2006). Sustainability of farmers' soil fertility

management practices: a case study in the North China Plain. *J Environ Manage*, 79 (4), 409-19. http://dx.doi.org/10.1016/j.jenvman.2005.08.009.

Zhou, L., Cai, D., He, L., Zhong, N., Yu, M., Zhang, X., & Wu, Z. (2015). Fabrication of a high-performance fertilizer to control the loss of water and nutrient using micro/nano networks. *ACS Sustainable Chemistry and Engineering*, 3(4), 645–653. https://doi.org/10.1021/acssuschemeng.5b00072

Zwart, S.J. & Bastiaanssen, W.G.M. (2004) Review of Measured Crop Water Productivity Values for Irrigated Wheat, Rice, Cotton and Maize. *Agricultural Water Management, 69*, 115-133. http://dx.doi.org/10.1016/j.agwat.2004.04.007

Appendix 1 – Acronyms and Abbreviations

Definitions of abbreviations

NCP	The North China Plain
PVCID	People's Victory Canal Irrigation District
FIRI	Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences
CMA	China National Meteorological Information Center
AE	Application efficiency (%)
WUE	Water use efficiency (kg/m^3)
DU	Distribution uniformity
WP	Water productivity (kg/m^3)
NUE	Nitrogen use efficiency (kg/kg)
SWC	Soil water content (%)
E	Evaporation (mm)
T	Transpiration (mm)
ET	Evaportranspiration (mm)
R^2	Coefficient of determination
RMSE	Root mean square error
NSE	Nash–Sutcliffe model efficiency coefficient

Definitions of abbreviations used in the WinSRFR model

n	Manning roughness coefficient
α	Empirical fitting parameter in Kostiakov equation
k	Empirical fitting parameter in Kostiakov equation (mm/h^α)

Definitions of abbreviations used in the SWAP model

ORES (θr)	Residual water content (cm^3/cm^3)
OSAT (θs)	Saturated water content (cm^3/cm^3)
ALFA (α)	Parameter α on main drying curve (The inverse of the air-entry value) (cm)
NPAR (n)	Parameter n (The shape parameter)
KSATFIT (Ks)	Saturate hydraulic conductivity (cm/d)
LEXP (L)	Exponent in dydraulic conductivity function (The pore-connectivity parameter)
BDENS	Bulk density (g/cm^3)
DVS	Crop development stage
CH	Crop height (cm)
TSUMEA	Temperature sum from emergence to anthesis (℃ • day)
TSUMAM	Temperature sum from anthesis to maturity (℃ • day)
TWDI	Initial total crop dry weight (kg/ha)
SPAN	Life span under leaves under optimal conditions (Day)
SLATB	Specific leaf area as a function of development stage (ha/kg)
AMAXTB	Max co2 assimilation rate as function of development stage (kg/ha/hour)
CVO	Efficiency of conversion into storage organs (kg/kg)
FLTB	Fraction of total above ground dry matter increase partitioned to the leaves as function of development stage (kg/kg)
FSTB	Fraction of total above ground dry matter increase partitioned to the stems as function of development stage (kg/kg)
FOTB	Fraction of total above ground dry matter increase partitioned to the storage organics as function of development stage (kg/kg)
RDI	Initial rooting depth (cm)
RDC	Maximum rooting depth crop/cultivar (cm)
DVSNLT	Development stage above which no crop nitrogen uptake does occur
TCSF_N	Transpiration concentration stream factor

LaiCritNupt	Critical LAI value to calculate uptake rate based on the ammonium availability
dz_WSN	Thickness of the soil layer considered for the simulation of the soil organic matter and nitrogen dynamics (m)
NNI	Nitrogen Nutrition Index

Appendix 2 – Calibration of TDR soil water content

In our field experiments, the SWC were mostly measured by TDR, and some were measured by oven drying method. Through data analysis we found large distances existed between SWC measured by TDR and oven drying method. Considering that the gravimetric soil water content measured by oven drying method is more reliable, the SWC data from TDR requires calibration. The correction coefficient for calibration was found through comparing SWC data measured in two methods on the same day of the same plot. Figure 10 shows an example of SWC calibration. The correction coefficient was set to 12.5%. SWC (after calibration) = SWC (TDR) + 12.5%.

* Volumetric SWC (cm^3/cm^3) = Gravimetric SWC (g/g) × Bulk density of each 10cm (g/cm^3)

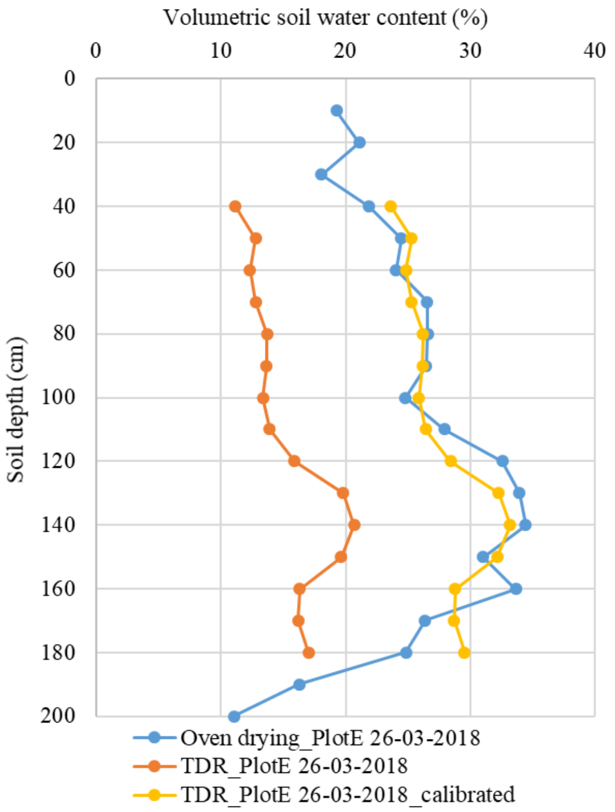


Figure 35. Calibration of volumetric soil water content measured by TDR (Example: PlotE 26-03-2018)

Appendix 3 – Calculation of soil N content

In our experiments, the soil NO_3-N content was measured by continuous flow analyser, and the unit is mg N/kg soil.

$$\text{mg N/kg soil} \xrightarrow{\div 1000 * BD(g/cm^3)} \text{mg N}/cm^3 \text{ soil} \xrightarrow{\div 100000 \times 100000} \text{kg N}/m^3 \text{ soil} \xrightarrow{\div 10 \times 10000} \text{kg N/(10cm} * \text{1ha)}$$

$$\xrightarrow{sum\ 0f\ 10\ layers\ \ (10cm\ each\ layer\ )} \text{kg N/ha}$$

Table 47 shows an example of soil NO_3-N content calculation.

Table 47. Example of soil NO_3-N content calculation.

Depth(cm)	mg N/kg soil	mg N/cm3 soil	kg N/m3 soil	kg N/(10cm*1ha)
0-10	17.74	0.0260	0.0260	25.9655
10-20	16.23	0.0238	0.0238	23.7571
20-30	10.58	0.0155	0.0155	15.4891
30-40	6.67	0.0098	0.0098	9.7693
40-50	6.05	0.0089	0.0089	8.8609
50-60	8.01	0.0117	0.0117	11.7259
60-70	7.38	0.0108	0.0108	10.8094
70-80	7.82	0.0114	0.0114	11.4419
80-90	9.00	0.0132	0.0132	13.1709
90-100	4.93	0.0072	0.0072	7.2139
100-110	5.34	0.0078	0.0078	7.8243
110-120	5.09	0.0074	0.0074	7.4481
120-130	4.40	0.0064	0.0064	6.4467
130-140	4.82	0.0071	0.0071	7.0609
140-150	6.54	0.0096	0.0096	9.5672
150-160	5.07	0.0074	0.0074	7.4232
160-170	5.06	0.0074	0.0074	7.4086

(Sum of the first 10 layers, 0-100 cm:) 138.20 kgN/ha