agriculture

Article

Fertigation Strategies to Improve Water and Nitrogen Use Efficiency in Surface Irrigation System in the North China Plain

Xiulu Sun [1,2,*], Yizan Li [3], Marius Heinen [4], Henk Ritzema [2], Petra Hellegers [2] and Jos van Dam [5]

1 Institute of Farmland Irrigation, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China
2 Water Resources Management Group, Wageningen University & Research, 6708 PB Wageningen, The Netherlands
3 Soil Biology Group, Wageningen University & Research, 6708 PB Wageningen, The Netherlands
4 Soil, Water and Land Use, Wageningen Environmental Research, 6708 PB Wageningen, The Netherlands
5 Soil Physics and Land Management Group, Wageningen University & Research, 6708 PB Wageningen, The Netherlands
* Correspondence: sunxiulu@caas.cn

Abstract: Irrigation and fertilisation are often over-applied, which exceeds crop requirements. Surface fertigation, a technique of applying pre-dissolved fertilisers together with irrigation water, seems to be a viable way to improve the on-farm performance in the North China Plain (NCP). Thus, we conducted a field experiment based on farmers' practices from 2017 to 2019. Moreover, we calibrated and validated SWAP-WOFOST-N, a seasonal integrated agro-hydrology and crop growth model, to assess the effects of different practices on yield, water and nitrogen use efficiency (WUE and NUE) and resource loss. Lastly, we developed various scenarios using the model to determine improved strategies. The results showed that the SWAP-WOFOST and extended Soil-N model offered satisfactory accuracy when compared with field measured data for the tested domain of the hydrological and nitrogen cycle; farmers' current irrigation and fertilisation practices resulted in low WUE and NUE, but the practice of split top-dressing nitrogen did not show significant improvement in the surface irrigation system; WUE, NUE and nitrogen loss were closely related to irrigation practices. We further concluded that an optimised irrigation practice combined with an optimal fertigation scenario is the feasible strategy to achieve sustainable crop yield, high WUE and NUE and reduced nitrogen loss.

Keywords: surface fertigation; topdressing; field experiment; SWAP-WOFOST-N

Citation: Sun, X.; Li, Y.; Heinen, M.; Ritzema, H.; Hellegers, P.; van Dam, J. Fertigation Strategies to Improve Water and Nitrogen Use Efficiency in Surface Irrigation System in the North China Plain. *Agriculture* **2023**, *13*, 17. https://doi.org/10.3390/agriculture13010017

Academic Editor: Dominika Lewicka-Szczebak

Received: 11 November 2022
Revised: 16 December 2022
Accepted: 18 December 2022
Published: 21 December 2022

1. Introduction

Irrigation and fertilisation are vital agricultural practices to ensure food security [1,2]. To achieve high yields, farmers usually increase the application of water and fertiliser [3]. In the North China Plain (NCP), which is one of the most densely populated areas in the world and has an intensive wheat–maize cropping system [4], agriculture is responsible for more than 60% of the total water use [5,6]. The efficiency with which this water is used is also much lower than the world average [7]. The convenience of access to groundwater in the NCP has led to a lack of awareness among local farmers of water conservation [8]. In addition, to achieve high crop yields, excessive fertilisation is widespread, resulting in low fertiliser use efficiency and severe nitrogen (N) losses [9,10]. The pollution of soil and groundwater from N leaching caused by the excessive application of chemical fertilisers has now become a major environmental problem in the NCP [11,12]. The sustainability of the winter wheat–summer maize rotation in the NCP is now in doubt due to the inefficient use of irrigation water and N fertiliser [13]. Improving irrigation and fertilisation practices in the NCP is therefore of paramount importance.

Surface irrigation and broadcast fertilisation are widely used but poorly managed by smallholder farmers in the NCP [14]. Numerous experimental and modelling studies have been conducted to improve current water and N management practices [5,15–17]. Fertigation is one improved technique for achieving better water and N management practices, and involves applying pre-dissolved chemical fertilisers together with the irrigation water [18]. Compared with the broadcast fertilisation method, fertigation achieves a higher fertiliser efficiency, lower fertiliser loss and lower labour input requirements, and therefore shows great potential for the sustainable development of agriculture in the NCP [19]. Due to the significance of the NCP in agricultural development in China, the government has shown considerable interest in promoting fertigation techniques in the region [20]. Although pressurised fertigation methods, such as advanced drip fertigation, are more effective, these technologies are difficult to adopt for smallholder farmers because of their conservative attitudes and insufficient budgets to pay for the systems [21]. It is therefore easier and more feasible for farmers to convert to a fertigation system by modifying their existing surface irrigation system. Thus, surface fertigation seems to be the most viable method to improve on-farm irrigation and fertilisation performance [22].

Most of the studies on surface fertigation in the NCP concentrate on field performance assessment and event-based model development. For example, the spatial and temporal distribution of N in soil and surface water was analysed based on field experiments with different fertilisation methods and inflow rates during the greening period of winter wheat [23]. The distribution of NO3-N in soil water was also investigated with varying fertigation methods to explore optimal border fertigation regimes for summer maize [24]. Researchers have also established event-based hydraulic models of surface water flow and solute transport for the surface fertigation process. For instance, a one-dimensional model for surface water flow and solute transport for border fertigation was established based on the implicit–explicit time scheme, the finite difference method, the finite volume method and the finite element method [25]. A two-dimensional coupled model for surface water flow and solute transport in basin fertigation has also been developed [26], which successfully simulated the surface water flow and solute transport in basin fertigation for further application in basin fertigation systems design. A new model approach based on field experiments was also proposed to improve the accuracy of the simulation of water and N transport in basin fertigation [27]. However, while these models performed well in the simulation of a single fertigation event, they cannot be used for seasonal analysis. Furthermore, these event-based models do not consider mineralisation, nitrification, and denitrification processes. Therefore, research on seasonal surface fertigation in the NCP is still required.

Various seasonal models have been developed for water and N management at the field scale to understand the dynamics of water and nutrients in agricultural production [28]. Commonly used models include the vadose zone model HYDRUS, the agro-hydrology model SWAP-WOFOST-N, the nutrient model ANIMO, the root zone water quality model RZWQM [3]. Although these models can be used to assess the influence of water and nutrient management on crop yield and resource use efficiency, they also have their disadvantages. For example, HYDRUS does not have a detailed crop growth module [29], which means that it cannot be used to explain the complex exchange of the seasonal N between crop and soil [30]. The nutrient model ANIMO and RZWQM, on the other hand, can simulate the effect of N loss but require many parameters that are difficult to measure in the field [31,32]. The choice of model therefore depends on the research objectives, ease of use and balance between fewer parameter requirements and accuracy. The seasonal integrated agro-hydrology and crop growth model SWAP-WOFOST-N, extended by the Soil-N module, makes it possible to unravel interactions between water stress and limited N availability and facilitates the analysis of yield gaps [33,34]. Moreover, the integrated Soil-N module is substantially less complex and requires the specification of fewer input parameters than many other mechanical N simulation models. Thus, the newly updated model is suitable for evaluating the impacts of water and fertiliser management scenarios on crop growth and the environment [35]. In addition, SWAP-WOFOST-N has been tested and validated for a wide range of climate and agricultural systems in the NCP [36–38].

Despite the large amount of research conducted on surface fertigation system performance in the last few decades [39], optimum seasonal fertigation strategies differ according to crop, soil and climate. Hence, the overall research objective of this paper is to develop seasonal fertigation strategies for surface irrigation to improve the water and nitrogen use efficiencies (WUE and NUE) in the NCP. Specifically, its objectives are to (1) analyse the WUE and NUE under current farmer practices in the experimental field, and (2) explore alternative surface fertigation strategies to improve the WUE and NUE by modelling with SWAP-WOFOST-N.

2. Materials and Methods

2.1. Research Design

This study combined field experiments with simulation using SWAP-WOFOST-N, a seasonal integrated agro-hydrology and crop growth model (Figure 1). The field experiments and observations were used to evaluate farmers' fertigation practices and calibrate and validate the SWAP-WOFOST-N model. The calibrated model was then used to develop alternative strategies.

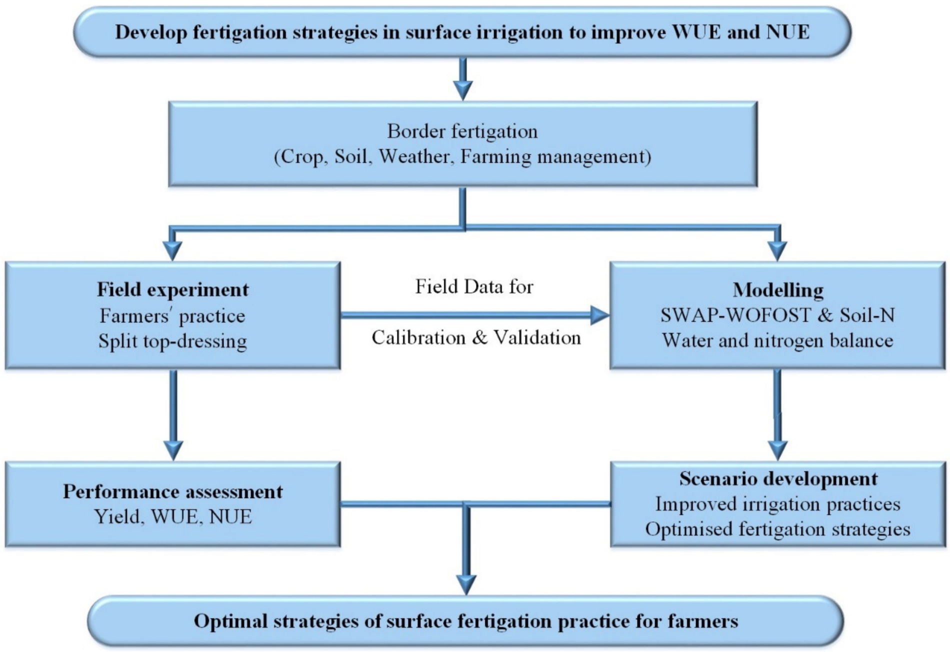


Figure 1. Flowchart of the research design.

2.2. Field Experiment

The field trials were conducted at an agricultural water and soil environment observation experiment station of the Institute of Farmland Irrigation, which is located in the southern part of the NCP (113°54′ E, 35°18′ N, Figure 2). The main cropping pattern in this area is a winter wheat–summer maize rotation, which is representative of farming practices in this intensive agricultural area. The irrigation water mostly comes from groundwater [40] and the soil type at the experiment site was classified as loam, with an average bulk density of 1.49 g/cm^3 to one metre depth. The volumetric field capacity and saturated water content were 33% and 44%, respectively [41]. The area has a typical temperate monsoon climate, and the mean annual precipitation was 554 mm over the past 30 years, with rainfall concentrated in the period from June to September (Figure 2). Figure 2 also shows the monthly precipitation during the experimental period from October 2017 to October 2019. As this shows, 2018 was a relatively wet year, while 2019 was more or less a normal year.

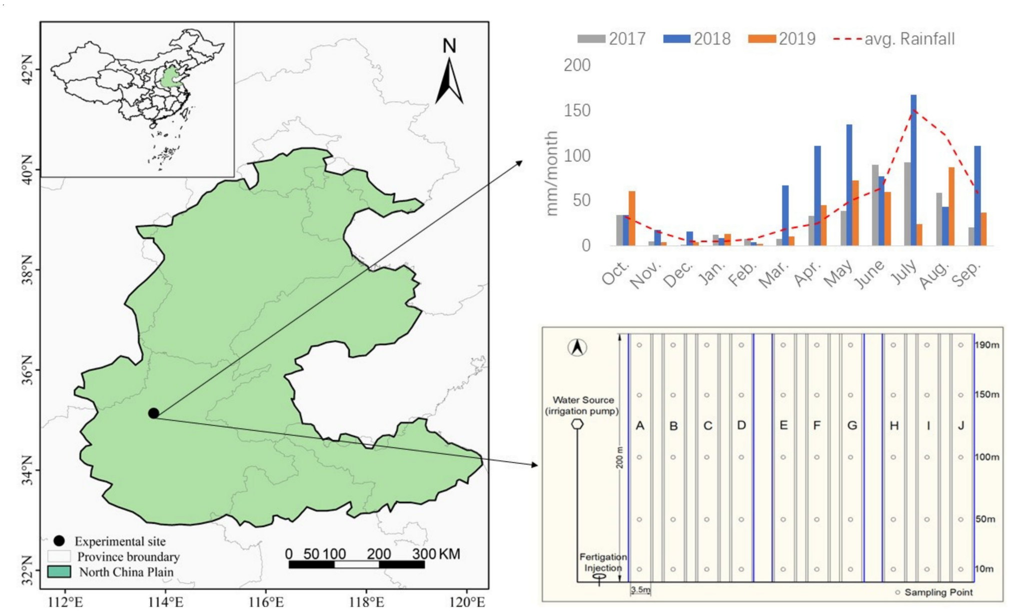


Figure 2. Location of the study area, rainfall pattern and experimental field layout.

The two-year field experiment of winter wheat–summer maize rotation was conducted from October 2017 to October 2019. The set-up was based on existing farming, irrigation and fertilisation practices of farmers in the region [42]. Ten closed-end border strips were set, measuring 200 m × 3.5 m and named plots A to J. Plots H to J were set up following actual farmers' practice, while the improved practice of the split top-dressing application of urea was applied in plots A to G, as reported in another report [43]. The crop pattern was the same as current farmers' practice: wheat was planted in mid-October and harvested the following June, followed by maize from June to early October. The irrigation water was pumped from a nearby well with a groundwater depth of 10 m. The applied irrigation water depth varied between plots and dates because it was based on the existing farmers' practice to stop irrigation when the water covers the whole field rather than at a fixed irrigation depth. We thereby noted the average water amount for each treatment set per irrigation event. We applied fertiliser as farmers do in their fields, one basal fertilisation using a compound synthetic fertiliser before sowing, plus a single top-dressing application of urea during crop growth. In the improved practice, we split the top-dressing application of urea into two applications rather than one. We also reduced the basal fertiliser rate in the second year. Furthermore, instead of broadcasting the fertilisers as farmers do, the top-dressing urea was applied with irrigation water, known as fertigation (the dissolved urea is applied in the irrigation water). The crop calendar and an overview of the management data (sowing, harvest, irrigation, fertilisation) for each event are provided in Table 1.

Five sampling points were established in each test border, at 10, 50, 100, 150 and 190 m from the border head. The gravimetric soil water content was measured before and after irrigation and during the growing season using the oven drying method. The volumetric soil water content was then calculated by multiplying with the bulk density for each soil layer. Soil nitrate concentrations were monitored at every sampling point by carrying out soil sample analysis in the laboratory using a flow analyser. A detailed description of the field measurements and methods used to determine the soil hydraulic parameters, soil moisture, N content, crop leaf area indices (LAIs) and yields are listed in Appendix A.

Table 1. Crop calendar and field treatments.

Crop	Date	Farming Practice	Irrigation and Fertiliser Amount	
			FP *	SP *
2018 wheat	25 October 2017	Sowing with basal fertilisation	750 kg/ha, compound fertiliser (26% N)	
	November 2017	Irrigation	249 mm	210 mm 90 kg/ha, Urea
	March 2018	Top-dressing N with irrigation	212 mm 225 kg/ha, Urea	194 mm 135 kg/ha, Urea
	3 June 2018	Harvest		
2018 maize	24 June 2018	Sowing with basal fertilisation	600 kg/ha, compound fertiliser (28% N)	
	July 2018	Top-dressing N with irrigation	119 mm 225 kg/ha, Urea	95 mm 135 kg/ha, Urea
	August 2018	Top-dressing N with irrigation	108 mm	116 mm 90 kg/ha, Urea
	12 October 2018	Harvest		
2019 wheat	23 October 2018	Sowing with basal fertilisation	375 kg/ha, compound fertiliser (15% N)	
	December 2018	Top-dressing N with irrigation	247 mm	237 mm 90 kg/ha, Urea
	March 2019	Top-dressing N with irrigation	228 mm 225 kg/ha, Urea	208 mm 135 kg/ha, Urea
	May 2019	Irrigation	154 mm	169 mm
	10 June 2019	Harvest		
2019 maize	21 June 2019	Sowing with basal fertilisation	450 kg/ha, compound fertiliser (27% N)	
	June 2019	Irrigation	103 mm	103 mm
	July 2019	Top-dressing N with irrigation	110 mm 225 kg/ha, Urea	123 mm 135 kg/ha, Urea
	August 2019	Top-dressing N with irrigation	134 mm	135 mm 90 kg/ha, Urea
	20 October 2019	Harvest		

* FP: Farmers' practice; SP: Split top-dressing urea application.

2.3. Model Set-Up and Testing

The modelling study was performed using SWAP 4.0, which is completely integrated with WOFOST and embeds a N module called Soil-N [33,34]. Information about the SWAP model can be found at https://swap.wur.nl/ (accessed on 17 December 2022). A brief description of the key calculating flows that are performed by SWAP-WOFOST-N is provided below. The use of a soil–plant interaction engine in SWAP ensures that important biophysical crop–water relations are represented. It can also consider a variety of irrigation management strategies, making the model ideally suited for analysing crop–water production relationships. Furthermore, the newly developed Soil-N module, incorporated in the SWAP-WOFOST-N model, can help illustrate the interdependencies between crop growth, water and N processes.

2.3.1. Description of the Model SWAP-WOFOST-N

SWAP is used to simulate soil water movement, solute transport, heat transfer and crop growth at the field scale [34,44]. SWAP applies the one-dimensional vertical Richards equation integrally for the unsaturated/saturated zone [45]:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_a(h) - S_d(h) - S_m(h), \quad (1)$$

where θ is the volumetric water content (cm^3/cm^3), t is time (d), $K(h)$ is the hydraulic conductivity (cm/d), h is the soil water pressure head (cm), z is the vertical coordinate (cm) taken positively upwards, $S_a(h)$ is the soil water extraction rate by plant roots (d^{-1}), $S_d(h)$ is the extraction rate by drain discharge in the saturated zone (d^{-1}) and $S_m(h)$ is the exchange rate with macropores (d^{-1}).

In this study, root water extraction was accounted for, but we did not use the options to account for exchange water flow with macropores and lateral exchange with surface water. The Richards equation is solved numerically using specified boundary conditions and the Mualem-Van Genuchten functions [46,47] for relations between θ, h and K:

$$\theta = \theta_{res} + (\theta_{sat} - \theta_{res})\left(1 + |\alpha h|^{n}\right)^{-m}, \quad (2)$$

$$K = K_{sat} S_e^{\lambda}\left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^{m}\right]^{2}, \quad (3)$$

where θ and h are the soil moisture and pressure head, θ_{res} is the residual water content in the very dry range (cm^3/cm^3), θ_{sat} is the saturated water content (cm^3/cm^3), α (cm^{-1}), n ($-$) and m ($-$) are empirical shape factors and m = $1 - 1/n$. K_{sat} is the saturated conductivity (cm/d), λ ($-$) is an empirical coefficient, S_e is the relative degree of saturation defined as $S_e = (\theta - \theta_{res})/(\theta_{sat} - \theta_{res})$.

WOFOST (World Food Studies) [48], a generic crop growth model, has been integrated into SWAP. It simulates in detail photosynthesis and crop development, taking light interception and CO_2 assimilation as the main growth driving processes. CO_2 assimilation is calculated as a function of solar radiation and crop leaf area and is reduced when water and/or salinity and/or nutrient stress occur. As a result of such stresses, the maintenance respiration decreases and the remaining assimilates are partitioned between the plant organs (i.e., leaves, stems, roots and storage organs).

The N balance of the soil (Soil-N) is implemented parallel to the organic matter balance [33]. N supplied to the soil through fertiliser applications and organic matter decay is stored in the soil, while mineralisation rates of ammonia (NH_4) and nitrous oxide (N_2O) control N mineralisation and immobilisation in relation to the processes in the organic matter cycle. Ammonium and nitrate balances are calculated as a result of mineralisation, nitrification, denitrification, plant uptake and nitrate leaching rates. Other than in detailed N models, here the N balance is considered for a single soil compartment often equal to the root zone.

Figure 3 shows the exchange of information between the Soil-N module, the SWAP model for soil hydrology and the WOFOST model for crop growth [33]. On a daily basis, the Soil-N module interacts by exchanging information with SWAP and WOFOST. Both the amounts of organic matter and the associated N contents of crop residues are calculated by the WOFOST model and passed to the Soil-N module. The SWAP model provides information on daily water balances of the single compartment Soil-N module. The Soil-N module provides information on the resulting daily plant uptake rates, which are the minimum of the uptake demand and the mineral N availability in the soil.

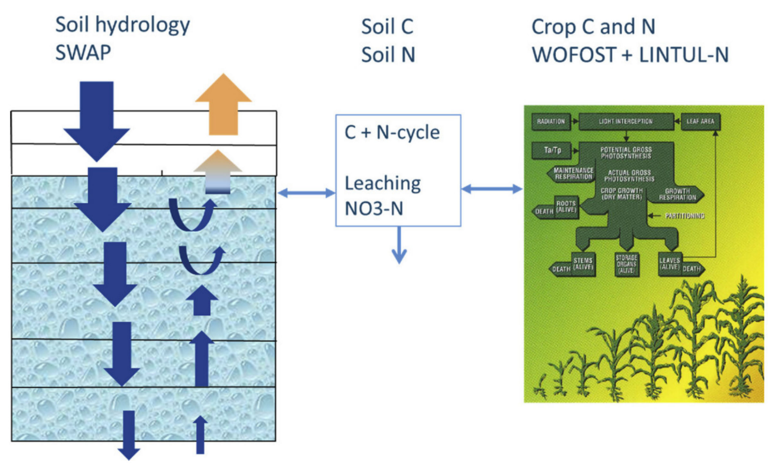


Figure 3. Schematic representation of the three modules in the innovated SWAP-WOFOST-N model [33].

2.3.2. Model Initialization and Calibration

The hydrological simulations used meteorological data as the top boundary and a free-draining bottom boundary at a depth of 10 m. Initial conditions were defined based on the measured soil water content, which was converted into a soil matric potential using the Retention Curve (RETC) computer program [49], with no hysteresis in water retention considered. The soil profile was 100 cm in depth and a spatial discretisation of 1 cm was used for the topsoil layer to 10 cm, followed by 10 cm intervals for the deeper layers.

The nutrient simulations used dry and wet deposition as the top boundary, in addition to management events. Deposition values were derived from long-term experiments and estimated to be 23 kg/ha N annually for rain and 12 kg/ha N annually for irrigation [50]. Deposition was then evenly distributed over NO_3-N and NH_4-N. All nutrient simulations were initialised with organic matter distributions in the soil profile that were derived from the measured data sets. A pre-processing simulation period of 15 years (2002–2017) was carried out to enable a proper approach of initial conditions in the carbon and N cycle and to achieve initial mineral N contents. Volatilisation was estimated at 20% of the top-dressing N, but 0% of the basal fertilisation, as the fertiliser was then applied using the deep placement method in tandem with sowing [51].

The calibrated parameters were categorised as soil hydraulic parameters, crop parameters and Soil-N parameters (detailed in Appendix B). The input data required for modelling is summarised in Appendix A (optional data not used in this research is not listed). The parameter sensitivity for SWAP-WOFOST-N for the NCP region was analysed by Li and Ren [52,53], and we therefore calibrated and validated the model based on their research.

The observed soil moisture (average value over 1 m depth), soil residual nitrate content (total amount over 1 m depth), LAI and yield for the wheat–maize rotation in the year 2018/19 in the field trials were used for parameter calibration, while the data collected in 2017/18 were used for model validation as detailed data were only available in the second year. In addition, only the measured values from the farmers' practice strips (plots H–J) were used for model parametrisation. Three modelling performance evaluation criteria—the Pearson's correlation coefficient (r), the root mean square error (RMSE) and the mean absolute error (MAE)—were adopted to show the deviation between the simulated and measured data. The simulation performance criteria were calculated as follows [54,55]:

$$r = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(S_i - \overline{S})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(S_i - \overline{S})^2}}, \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2}, \quad (5)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|S_i - O_i|, \quad (6)$$

where O_i is the ith observation for the constituent being evaluated, S_i is the ith simulated value for the constituent being evaluated, $\overline{O}$ is the average of the observed data for the constituent being evaluated, $\overline{S}$ is the average of the simulated data for the constituent being assessed and n is the total number of observations.

2.3.3. Scenario Development

Alternative strategies were developed on the basis of optimized irrigation and fertigation scenarios. Optimal irrigation is applying the right amount of water at the right time in response to the crop's water requirement [56]. In other words, water stress, which affects the plant's growth, should be avoided, but water should not be wasted. Plant growth is directly related to the crop's water status and indirectly related to soil moisture and atmospheric conditions. Therefore, accurate criteria for the time and depth of irrigation application are needed to determine the rational irrigation schedule. In a surface irrigation system, however, it is difficult to achieve a high irrigation frequency and a low irrigation depth. Thus, the irrigation depth is not variable in the simulation and is set as a fixed depth criterion in this study. The optimal fertigation scenarios were established based on the recommended fertiliser amount and practical N split application between basal fertilisation and top-dressing fertigation. For the scenario development, we used the climatological data of 2018/19, a year with an average rainfall pattern (Figure 2). We developed the following scenarios to assess the effect of irrigation and fertilisation practices on yield, WUE and NUE (Table 2):

- S0: the farmers' conventional irrigation and fertilisation practices. For all scenarios, fertigation instead of broadcast fertiliser application was used for topdressing urea.
- S1: reduced irrigation depth with farmers' fertilisation practice. For each irrigation event, fixed irrigation depths were applied: 95 mm for wheat and 80 mm for maize, as recommended by Sun et al. [43].
- S2: optimal irrigation schedule based on the irrigation depth in S1 and the optimal depletion of readily available water.
- S3: farmers' irrigation practice with application of the recommended N rate, which is 151 kg/ha N for wheat and 168 kg/ha N for maize [57]. The top-dressing urea amount was the same as S0 while the basal fertiliser amount was calculated by subtracting the top-dressing rate from the recommend rate.
- S4: farmers' irrigation practice with the recommended fertiliser application rate plus an optimal N split ratio between basal fertilisation and top-dressing fertigation.
- S5: a combination of the optimal irrigation scenario S2 and fertilisation scenario S4.

Table 2. Overview of developed scenarios.

Scenario	Irrigation	Fertilisation
S0	Farmers' practice	Farmers' practice
S1	Reduced water amounts for each irrigation by improving irrigation method	Farmers' practice
S2	Optimal irrigation schedule based on crop water requirement and soil moisture	Farmers' practice
S3	Farmers' practice	Reduced basal fertiliser amount based on recommended N rate
S4	Farmers' practice	Optimal split ratio for basal and top-dressing with recommended N rate
S5	Optimal irrigation schedule based on crop water requirement and soil moisture	Optimal split ratio for basal and top-dressing with recommended N rate

2.4. Evaluation Indicators and Statistical Analysis

Various indicators are used in the literature to assess water efficiency, such as water use efficiency (WUE), water productivity (WP) and irrigation water use efficiency (IWUE) [58]. Our research focused on the impact of a change in irrigation and fertilisation practice on the water and N balance, as well as water percolation and N leaching. Therefore, we define WUE as the ratio of crop yield to water applied, including irrigation and rainfall.

Nitrogen efficiency indicators used in the literature include recovery efficiency, physiological efficiency, internal utilisation efficiency, agronomic efficiency, partial factor productivity and partial nutrient balance [59]. All of these indicators have an optimal range and application for specific problems. In this paper, nitrogen use efficiency (NUE) is defined as the ratio between crop yield and total N inputs (also known as partial factor productivity (PFP)) [60]. Note that the estimates of NUE only consider the N input via fertilisers and neglect the inputs via atmospheric N deposition and biological N fixation. The reason for this is that the latter processes are incorporated into the model simulation, and that this study's primary interest is in the efficiency of synthetic fertiliser utilisation [61].

$$WUE = \frac{Y}{10\,(I + R)}, \tag{7}$$

$$NUE = \frac{Y}{N}, \tag{8}$$

where WUE is expressed as kg/m^3, Y is the harvested crop yield (kg/ha), I and R are irrigation and rainfall water amount (mm), respectively, NUE is expressed as kg/kg and N is the sum of the N input via fertiliser (kg/ha).

The water and N balance analysis and evaluation focused on total leaching of ammonium and nitrate at a depth of 1 m (root zone for wheat and maize) below the soil surface. The observed and simulated values of soil water content and N content and crop yield were compared using quantitative (statistical) and qualitative (graphical) methods.

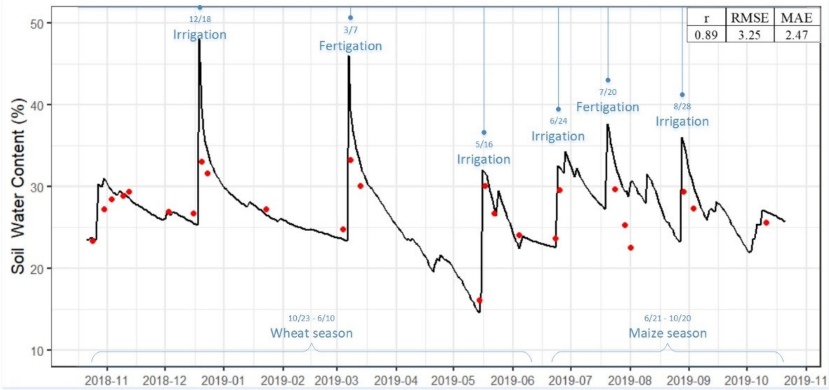
3. Results

3.1. Calibration and Validation of the SWAP-WOFOST-N Model

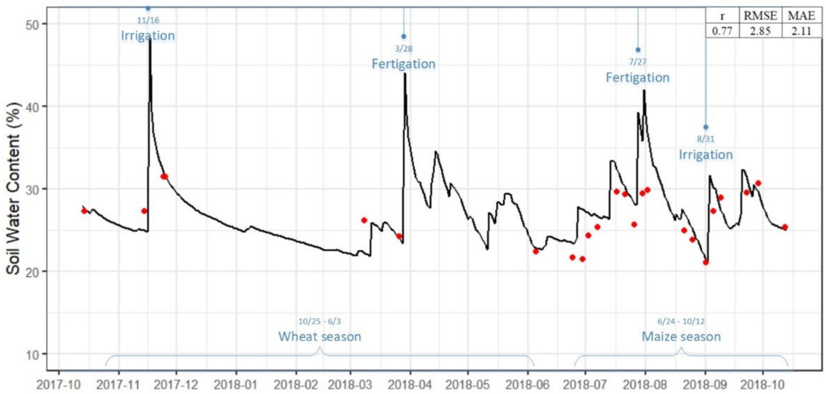
The field data collected on farmers' practice between 2017 and 2019 was used to calibrate and validate the SWAP-WOFOST-N model. A good performance of soil water content (SWC) simulations, with a high *r* (0.89 for calibration and 0.77 for validation) was determined (Figure 4(a1,a2)) in the model parametrisation. As can be seen in Figure 4(b1,b2), the simulated soil nitrate content (SNC) showed some deviation from the measured values, but with satisfactory RMSE (28.98 kg/ha for calibration and 39.21 kg/ha for validation) and MAE (22.39 kg/ha for calibration and 28.19 kg/ha for validation). Furthermore, the simulated yields and leaf area index (LAI) were close to the measured yields and LAI (represented by the red dots, Figure 4(c1,c2)). The performance of the calibrated SWAP-WOFOST-N model was evaluated based on its simulations of SWC, crop yields and SNC. The results of the error performance criteria indicate that the calibration of the SWAP-WOFOST-N model is satisfactory for further application.

Figure 4 (a1 and a2) also shows the variation in SWC in relation to irrigation in the wheat–maize rotation in the growing seasons 2017/18 and 2018/19. The figure shows a significant increase in soil moisture after irrigation, especially in the wheat season. The SWC increased to above 33% (the field capacity) following most irrigation events, indicating that high percolation occurred after these events. Water stress was seen in April, May and August, which meant that irrigation of the crops in these periods was critical to sustain the yields.

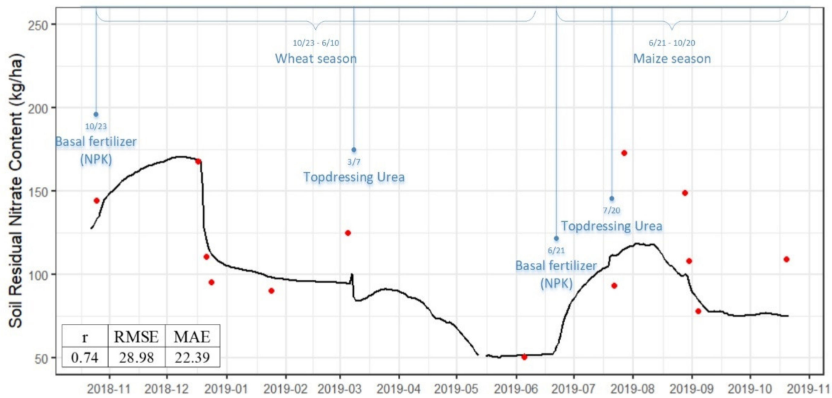
Figure 4 (b1 and b2) illustrates the soil nitrate trend in relation to fertilisation by simulation for two growing years. The nitrate content increased considerably following basal fertilisation and rose slightly following top-dressing fertigation. However, it decreased significantly following irrigation with no fertiliser added; for example, the irrigation events on 18 December 2018 and 16 November 2017. This explains why the N content only increased slightly after top-dressing fertigation, as the irrigation leached a lot of nitrates below the root zone. The simulated nitrate content was less than the measured values in the maize season, indicating an underestimation of soil residual N and an overestimation of N loss (mainly leaching) in the maize seasons.



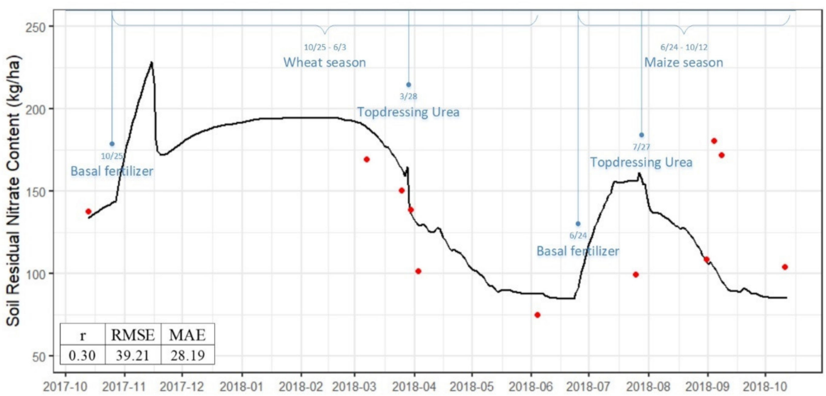
(**a1**)



(**a2**)

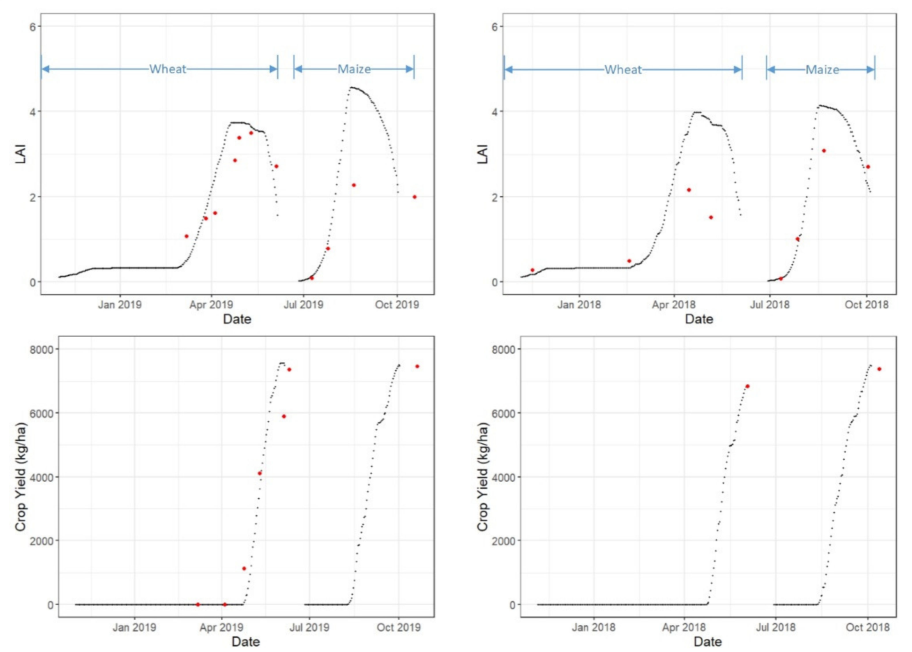


(**b1**)



(**b2**)

Figure 4. *Cont*.



(**c1**) (**c2**)

Figure 4. The model calibration and validation. (**a1**,**a2**): soil water content; (**b1**,**b2**): soil residual nitrate content; (**c1**,**c2**): leaf area index and crop yield; 1: model calibration; 2: model validation; red dots: field observed data; lines: simulated values.

3.2. Analysis of Two-Year Field Experiment

3.2.1. Overview of the Performance of the Experimental Practices

The calibrated SWAP-WOFOST-N model was used to analyse the water percolation and N leaching over two agricultural years, and the corresponding WUE and NUE (Table 3). The simulated yields were in good agreement with the measured yields, except for the 2019 maize season. The wheat yield in the first year was much lower than in the second year because of extreme weather conditions: in the 2017/18 growing season, a lower accumulated temperature and a cold spell in spring damaged wheat flowering and reduced the yield. The maize yield was much lower in the second year, mainly because of the reduced basal fertiliser amount in the second 2018/19 crop season.

Table 3. The seasonal performance for wheat and maize under farmers' practice (FP) and split top-dressing practice (SP) in the period 2017–2019.

Crop	Rainfall (mm)	Irrigation (mm)	Basal N (kg/ha)	Top-Dressing N (kg/ha)	Measured Yield (t/ha)	Simulated Yield (t/ha)	WUE (kg/m^3)	NUE (kg/kg)	Water Percolation (mm)	N Leaching (kg/ha)
FP-18W	330	461	195	104	6.85	6.84	0.87	22.92	438	323
FP-19W	290	629	56	104	7.36	7.49	0.82	46.91	478	250
Average	310	545	126	104	7.11	7.17	0.84	34.92	458	287
SP-18W	330	404	195	104	6.96	6.87	0.94	23.01	380	319
SP-19W	290	614	56	104	7.65	7.31	0.81	45.78	449	258
Average	310	509	126	104	7.30	7.09	0.87	34.39	415	288
FP-18M	371	227	168	104	7.38	7.48	1.25	27.57	242	174
FP-19M	242	347	122	104	7.47	7.47	1.27	33.22	218	128
Average	306	287	145	104	7.42	7.48	1.26	30.39	230	151
SP-18M	371	211	168	104	7.25	7.55	1.30	27.79	221	162
SP-19M	242	361	122	104	7.40	7.47	1.24	33.18	250	129
Average	306	286	145	104	7.33	7.51	1.27	30.49	236	145

Note: FP means farmers' practice, SP means split top-dressing practice. 18W means wheat season in 2018, 18M means maize season in 2018. Note that different basal fertiliser amounts were applied in 2018 and 2019, and a different top-dressing strategy was applied between FP and SP.

The results show that the calculated WUE for winter wheat ranged from 0.81 to 0.94, less than in the maize season, which ranged from 1.24 to 1.30. The WUE in 2018/19 was also less than in 2017/18, as the irrigation amount in 2018 was less than in 2019. The results reveal that there was a large amount of deep percolation in the 2018/19 growing seasons, which meant over-irrigation. Furthermore, the simulation results show high percolation in all seasons, especially in the wheat seasons. Understandably, surface irrigation under farmers' control results in low application efficiency (average of 40% and 60% for wheat and maize, as reported by Sun et al. [43]).

The total N input for the rotation in 2018 was higher than that of in 2019. However, the NUE was significantly higher in 2019 than in 2018, particularly in the wheat season. Therefore, the fertilisation scheme applied in 2018 was less efficient. As shown in Table 3, the simulated N leaching during the winter wheat–summer maize rotation in 2018 was higher than that of in 2019. Cui et al. [9] stated that excessive irrigation and N fertiliser input can result in high levels of N leaching. The water and N balance also shows that the reason for the N leaching in 2018 is not only over-irrigation but also excessive N input. Under sufficient N application, the average value of NUE in China for winter wheat and summer maize are 43 kg/kg and 51.6 kg/kg, respectively [62]. As presented in Table 3, the calculated NUE for summer maize was low, while the NUE for wheat in 2019 season was relatively good.

The analysis shows an excessive amount of deep percolation in the crop growing season, which means that the field was over-irrigated. Due to excessive irrigation, N leaching was the largest constituent of N loss. In the second year of the simulation period, when irrigation water and rainfall did not meet crop growth requirements, the WUE was low due to poor irrigation management. When crop water requirements are guaranteed, reduced irrigation can significantly increase the WUE. A similar trend was found for the NUE: the NUE was higher, and leaching was less, in the second year compared with the first year. The reason was that we reduced the basal fertiliser rate in the second crop season, leading to a reduced N input into the field. We can therefore conclude that reducing the basal fertiliser amount is a promising strategy to achieve better fertilisation management practice.

3.2.2. Insight into the Water and Nitrogen Balance of the Experimental Practices

To better understand the seasonal performance of irrigation and fertigation, the calibrated model was used to analyse the water and N balance over two years, before proposing alternative strategies. Figure 5 shows the water and N balance for two field treatments (FP, SP) of wheat and maize (W, M) in the seasons 2017/18 and 2018/19. Water inputs were rainfall and irrigation, while outputs were soil evaporation, plant transpiration and interception, and percolation. In general, wheat consumed more water than maize did, but a large portion of this was percolation across the whole season. Transpiration was more or less the same for both wheat and maize, while evaporation was higher in the wheat season. As rainfall was more intensive in 2018 than in 2019, more irrigation water was applied in the second year and slightly more percolation took place in the wheat season. The water balance also shows that rainfall was able to meet the evapo-transpiration (ET) requirement in the 2018 maize season, while the other seasons required supplementary irrigation. Percolation can be reduced by applying less water, for example, by optimising the irrigation schedule and improving the irrigation efficiency. Although irrigation was higher in the second year, the total amount of water applied (rainfall + irrigation) was more or less the same for both years and crops. Taking the irrigation schedule into consideration, we found that a high irrigation frequency in a surface irrigation system did increase water percolation, especially in wheat.

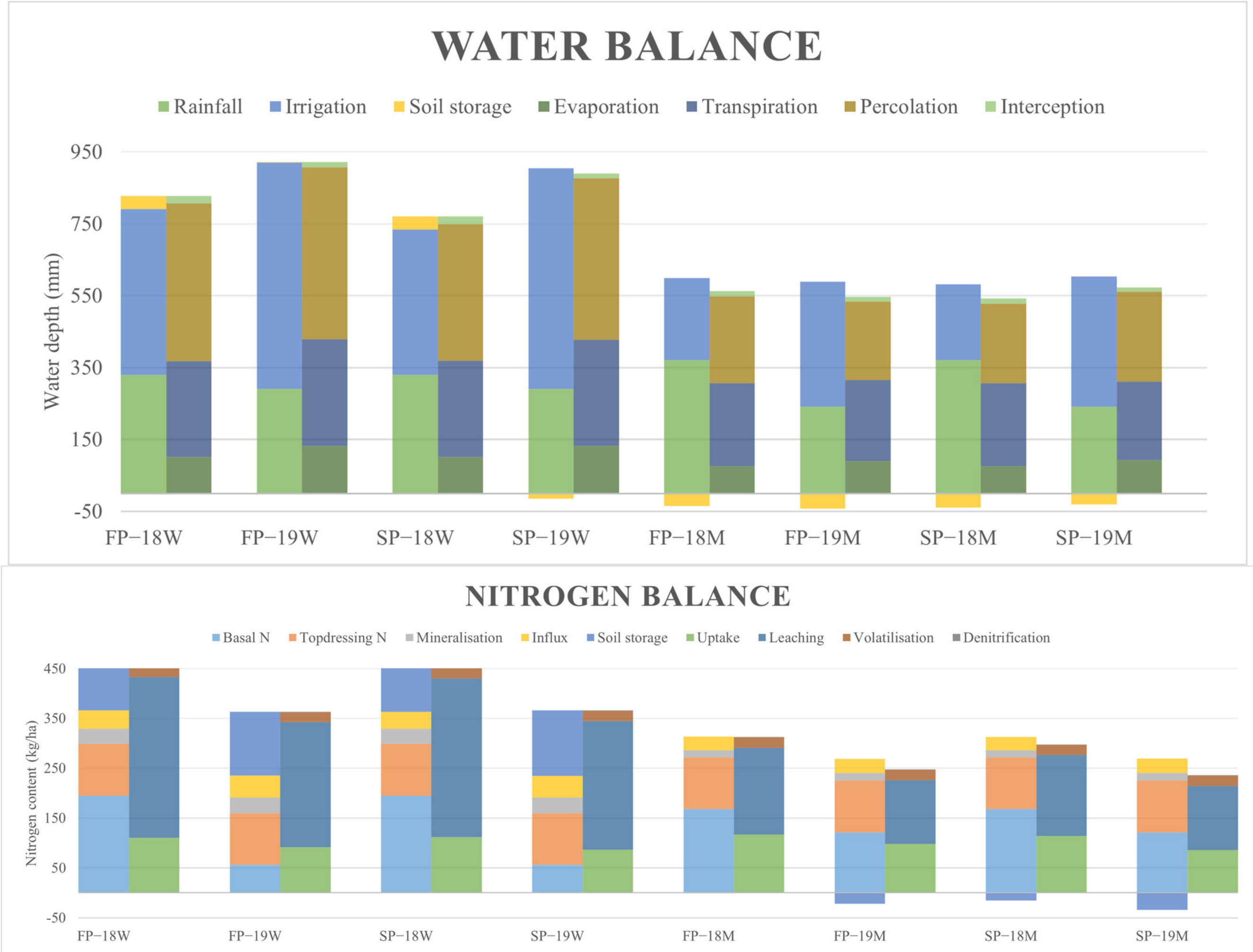


Figure 5. Water and nitrogen budgets for experimental treatments in the wheat and maize seasons in 2018 and 2019.

The N balance in terms of ammonium (NH_4) and nitrate (NO_3) is illustrated with an input (left bar, Figure 5) and output (right bar, Figure 5) demonstration for each treatment. The N added includes basal and top-dressing fertiliser amendment, mineralisation from organic matter, and nitrogen deposition flux from rainfall and irrigation water. The NH_4 and NO_3 outputs include plant uptake, volatilisation during fertilisation, denitrification and leaching. Leaching was the main route for the seasonal N loss, and more N was leached in the wheat season than in the maize season, probably due to high water percolation in the wheat season. Furthermore, more leaching took place in the first year (2017/18) than in the second year (2018/19), possibly because less basal fertiliser was applied in the wheat–maize rotation of 2018/19. However, there was no difference in terms of yield and leaching for SP treatments, i.e., splitting the top-dressing urea in two applications rather than one (as in FP). Thus, split N top-dressing with surface fertigation does not show a large improvement in terms of WUE, NUE and leaching. We can further conclude that a split top-dressing fertiliser application did not affect leaching materially, while reducing the fertiliser rate was more effective. Regarding plant uptake in N, this was slightly higher for maize than for wheat, indicating that maize was more sensitive to N application. A study that measured N uptake during a winter wheat–summer maize rotation in the NCP also indicated that N stress affected maize growth more significantly than wheat growth; in other words, maize is more N-limited [63]. Therefore, more N amendment was required in the maize season.

3.3. Scenarios to Improve Water and Nitrogen Use Efficiency

3.3.1. Optimal Irrigation Schedule for Irrigation Strategy Development

Several methods are available for determining the irrigation timing criteria, such as the plant-based method, ET-based methods and soil-based methods. However, plant and ET-based methods are not sensitive to plants that maintain a high-water status over a wide range of soil moisture contents, especially in a surface irrigation situation (with a high variation in soil moisture before and after irrigation). Therefore, we selected the allowable depletion of totally available water (field capacity minus wilting point) as the timing criteria. The depletion of water can be evaluated relative to the total amount of water available (TAW) in the root zone, and irrigation is triggered whenever the TAW exceeds a specific depletion factor. To determine a feasible depletion factor for the irrigation schedule, we carried out a number of simulations for various values without water stress and under sufficient N supply (Table 4).

Table 4. Irrigation frequency and amount for different management depletion factors.

Crop	Depletion Factor	Yield (kg/ha)	Irrigation Frequency	Irrigation Amount (mm)
Wheat	FP	8099	3	629
	0.8	7181	1	95
	0.45	8150	2	190
	0.4	8150	3	285
Maize	FP	8177	3	347
	0.7	8014	1	80
	0.45	8177	2	160
	0.4	8177	3	240

As can be seen in Table 4, the maximum yield was reached with a depletion factor of 0.45 for both wheat and maize. In this case, two irrigations for wheat and maize could meet the requirement. The total irrigation application should then be 190 mm for wheat and 160 mm for maize. The optimal irrigation schedule is based on the corresponding simulated scenarios.

3.3.2. Optimal Top-Dressing Ratio for the Fertigation Strategy Development

Although split top-dressing does not show any advantage compared to a single top-dressing in the growing season, the N ratio between basal and top-dressing affects the plant uptake considerably due to the variation in crop N requirement during the season [16]. Although the top-dressing N has an impact on leaching, the basal fertiliser provides a huge N input, which has a larger influence on the N balance. We therefore need to determine the optimal ratio between basal and top-dressing application on the basis of yield and N loss (leaching).

Figure 6 illustrates the yield and N leaching in correlation to different basal/top-dressing N ratios. As can be seen, a better yield is obtained for wheat if all the N is applied through top-dressing fertigation. The reason is possibly that there was a wintering period after wheat sowing and following the re-greening stage, and wheat needs more N in the re-greening stage when top-dressing occurs and less N in the wintering period [16]. However, the ratio 2:1 was the best scenario for maize, implying that two thirds of the N be applied through basal fertilisation. The results confirm the findings of the N balance analysis (Figure 5), as considerable soil N depletion was observed by the end of the wheat season. Therefore, abundant basal fertiliser is critical for maize while top-dressing is more important for wheat growth.

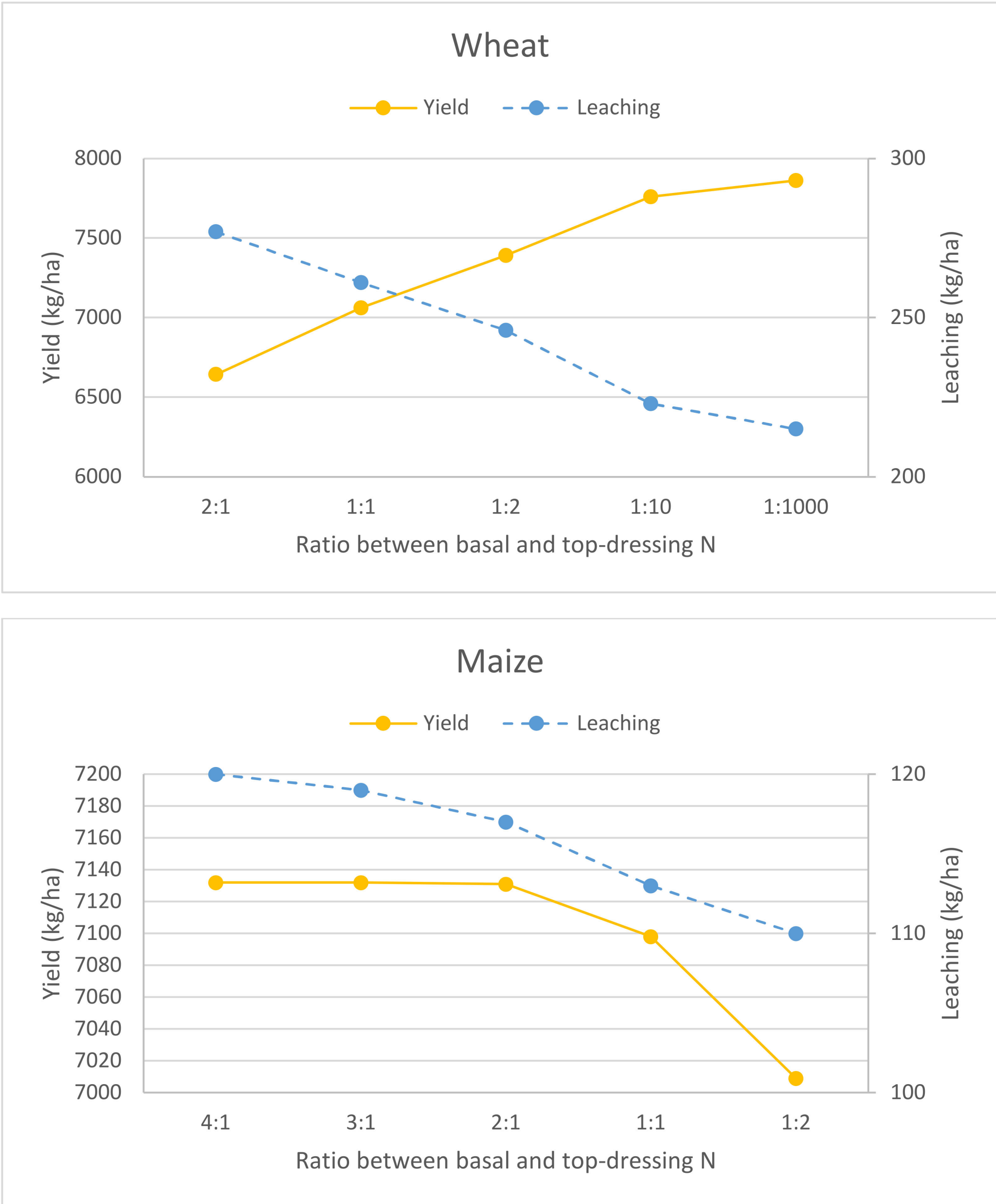


Figure 6. Yield and leaching for different basal/top-dressing N ratios for wheat and maize.

3.3.3. Comparison of Irrigation and Fertigation Scenarios

We developed scenarios based on the previous analysis for irrigation and fertilisation practice. The simulation period was 2018/19, a normal rainfall year, as shown in Figure 2. The practices considered in the scenarios are farmers' practice (S0), reduced water depth per irrigation (S1), a rational irrigation schedule with reduced water depth (S2), recommended fertiliser amount (S3), a reasonable fertilisation ratio with recommended fertiliser amount (S4) and a combination of S2 and S4 (S5). The yield, WUE, NUE, water percolation and N leaching for different irrigation and fertilisation strategies are presented in Table 5.

Table 5. Alternative scenarios for the reference year 2018/19.

Crop	Scenario	Input Data			Simulation Results				
		Irrigation (mm)	Basal N (kg/ha)	Top-Dressing N (kg/ha)	Yield (t/ha)	WUE (kg/m^3)	NUE (kg/kg)	Percolation (mm)	Leaching (kg/ha)
Wheat	S0	629	195	104	8.02	0.87	26.86	477	358
	S1	285	195	104	8.07	1.40	27.03	204	262
	S2	190	195	104	8.07	1.68	27.03	110	201
	S3	629	48	104	7.42	0.81	49.15	478	244
	S4	629	0	151	7.86	0.86	52.11	477	215
	S5	190	0	151	8.07	1.68	53.47	110	112
Maize	S0	347	168	104	7.69	1.31	28.33	206	150
	S1	240	168	104	8.01	1.66	29.50	59	130
	S2	160	168	104	8.09	2.01	29.81	25	103
	S3	347	65	104	6.93	1.18	41.25	235	110
	S4	347	112	56	7.13	1.21	42.42	216	117
	S5	160	112	56	7.96	1.98	47.32	25	66

As the table shows, reducing the irrigation amount can understandably increase the WUE and significantly decrease percolation and leaching, while it slightly increases the yield and NUE. Reducing the fertiliser application rate can improve the NUE and decrease leaching slightly, but it also reduces the yield and the WUE. Furthermore, a reduced basal fertiliser amount achieved better performance than the heavy basal fertilisation mode for wheat (farmers' practice, S0).

Reducing the irrigation amount therefore not only increased the WUE, but also the NUE and yield. This is mainly because the N leaching was less than in the farmers' practice (S0). This confirms that less leaching can increase yield due to the increased plant uptake (Table 3, Figure 5). Most significantly, a rational irrigation strategy is more important for sustaining the yield and improving the WUE and NUE in the surface irrigation system. To summarise, reducing the irrigation and fertiliser rate together achieve the best results: a sustainable yield, a higher WUE and NUE, and considerably reduced percolation and leaching.

4. Discussion

Although surface fertigation is a promising and feasible technique to improve water and nutrient management practices in the NCP, a seasonal analysis of such practices is not well documented in previous studies. In this paper, we applied an integrated approach including a field experiment and modelling to evaluate current practices and develop alternative strategies regarding yield sustainability, WUE and NUE improvement.

The field experiment proved that reducing irrigation and, to a lesser extent, fertilisation amounts can significantly improve the WUE and NUE. This finding is in line with the analysis by [9], which also showed that irrigation was one of the main factors that decreased the WUE and NUE and increased the risk of N leaching. However, we found more N leaching in the wheat season than in the maize season, unlike other studies in the area, which found that leaching mainly occurred in the summer maize season when the rainfall was high. It is very likely that, in the farmers' practice scenario, irrigation was much higher in the wheat than in the maize season, leading to considerable water percolation. In addition, we surprisingly found that split N application showed no improvement compared to the farmers' practice (one top-dressing during the crop season). This finding contradicts other fertigation studies, which found that split application achieved better performance in a drip irrigation system [64]. Indeed, the rational strategy is to split N application in tandem with crop growth to meet the crop requirement [16]. However, this did not improve the yield or reduce N leaching in the surface irrigation system (Table 3), but did increase urea volatilisation during the top-dressing fertilisation (Figure 5) due to the increased exposure frequency of the fertiliser.

Irrigation is critical for improving the WUE and NUE while also decreasing percolation and leaching. Therefore, it is important and recommended for farmers to optimise the irrigation practice as a first step by optimising the irrigation schedule based on crop water requirements and the soil moisture status. To achieve this goal, we applied a modelling approach to determine the optimal scenario and feasible strategies. The simulation results achieved using the SWAP-WOFOST-N model were satisfactory compared to the field measured values (Figure 4), so that the detailed irrigation and fertilisation scenarios for surface fertigation practice could be compared regarding yield, WUE, NUE, percolation and leaching.

The simulated yield for wheat was 8.07 t/ha while an average measured yield was 7.11 t/ha, representing an increase of 13.5%, while for maize the increase was 7.3%: 7.42 t/ha to 7.96 t/ha. For the farmers' practice, the WUE for wheat (average 0.87 kg/m^3) was lower than for maize (1.31 kg/m^3), indicating over-irrigation during the winter (wheat) season. Both these figures are well below the average value in this region, which were 1.01 kg/m^3 for wheat and 1.51 kg/m^3 for maize [65], indicating that over-irrigation also takes place during the summer (maize) season. Not surprisingly, the corresponding NUEs were low, for both wheat (26.86 kg/kg) and maize (28.33 kg/kg). The WUE and NUE for the optimal scenario (S5) are however well above the efficiencies found in other studies. For example, the simulated WUE of wheat and maize (respectively, 1.68 kg/m^3 and 1.98 kg/m^3) all fit in the high water productivity category, which were 1.10 kg/m^3 for wheat and 1.75 kg/m^3 for maize globally [66]. This difference can be explained by the optimised irrigation and fertigation practice in the proposed scenario.

The data analysis of the two-year field experiments and model simulation with various irrigation and fertigation practice showed that differences in irrigation amount led to significant differences in WUE, NUE and N leaching. Therefore, optimising irrigation can significantly improve WUE and reduce N loss [67]. Reducing water and fertiliser application to decrease farming input while increasing field output is therefore a win–win strategy, while also eliminating adverse environmental effects.

Excessive irrigation leads to an increase in water stress and N stress, reducing crop yields. To achieve the best surface fertigation performance, optimising irrigation is the first step to take to sustain the yield and decrease water and N loss, especially in the wheat season. Reducing the amount of fertiliser applied and optimising the basal/top-dressing ratio can also increase the NUE, but results in a decrease in yield and then WUE. An optimised irrigation practice (improved irrigation operation with decreased irrigation depth and appropriate irrigation scheduling) combined with an optimal fertigation practice (reduced fertiliser rate and optimised basal/top-dressing ratio) therefore achieves the best performance in terms of sustainable yield, high WUE and NUE and minimal N loss. If the irrigation amount is far higher than the crop water requirement, reducing irrigation can not only reduce N leaching, but also slightly increase the crop yield.

It should be noted that the field experiment with a border strip set-up included spatial variations in soil characteristics and irrigation applied depth, thus some of the measurements may be invalid. In addition, as the uncertainty in hydraulic parameters tended to increase with depth and border length, we simulated the water and N movement in this one-dimensional vertical soil column based on the assumption that the water and N are distributed uniformly along the border length. This is applicable for simulating fertigation scenarios, as surface fertigation performs better than farmers' practice in terms of uniformity (can be as high as 90%) [43]. However, a lysimeter experiment is better for further validation of the model and broad application. On the other hand, Soil-N is a rough N balance module embedded in SWAP-WOFOST-N and can therefore only simulate the average of the N movement in the whole field rather than providing detailed spatial variation and soil layering, although in this study the soil mineral N concentrations were simulated with deviations within acceptable ranges. Despite these satisfactory results and applicability in first step scenario analysis, for fine-tuning fertigation scenarios, we might ultimately need a more sophisticated N-model. In principle, the SWAP-WOFOST-N output can be used as input for ANIMO [68], with which a more detailed post-analysis can be performed. Moreover, simulated yields were slightly higher than observed values, as limiting factors such as pest and disease management were not considered in the simulation.

5. Conclusions

Surface irrigation, in combination with broadcast fertilisation, is widely used but poorly managed by smallholder farmers in the North China Plain. The resulting low water and nitrogen use efficiencies (WUE and NUE) cause severe water and nutrient resource loss. Thus, a better understanding of current practices and developing alternative strategies for farmers is essential to improve the WUE and NUE. The following conclusions can be derived from the results of this study:

First, the integrated SWAP-WOFOST and extended Soil-N model is a useful tool to analyse water and nitrogen balance and seasonal performance in surface fertigation practices. The performance of the simulated soil water content (SWC) was good, the simulated soil nitrate content (SNC) was acceptable, and the simulated yields were close to measured yields. For wheat, the average measured yield was 7.11 t/ha compared to the simulated yield of 7.17 t/ha, and for maize, the values were 7.42 t/ha and 7.48 t/ha, respectively.

Second, analysis of the field experiments showed that the WUE for wheat (0.84 kg/m^3) and maize (1.26 kg/m^3) were lower than the regional average (1.01 kg/m^3 and 1.51 kg/m^3, respectively), indicating over-irrigation during the crop season, as the crop yield was comparable. Not surprisingly, the corresponding NUEs were low for wheat (34.92 kg/kg) and maize (30.39 kg/kg) due to excessive irrigation and fertilisation in the farmer's practice. At the same time, N leaching was also high due to excessive water percolation. We found, however, no significant difference in NUE between one top-dressing fertigation and split N top-dressing in surface fertigation system.

Third, the scenario simulation using SWAP-WOFOST-N implied that a considerable increase in yield, WUE and NUE can be achieved by improving irrigation and fertilisation practices. This increase can be achieved if the irrigation practice is changed from the current practice (irrigation is stopped when the water reaches the end of the border) to a feasible fixed depth per irrigation with a rational irrigation frequency (two irrigations for wheat and maize). The total irrigation application for wheat should be reduced to 2 × 95 mm (compared to the current 629 mm) and for maize to 2 × 80 mm (compared to the current 347 mm) under typical weather conditions for the NCP. If this improved irrigation practice is combined with optimal top-dressing fertigation (151 kg N/ha for wheat and 56 kg N/ha for maize), these high WUEs, NUEs, and corresponding yield increases can be achieved.

In conclusion, integrated SWAP-WOFOST-N modelling can be applied to optimise the performance of surface fertigation practices and improve water and fertiliser management in the North China Plain. Further research on the detailed N simulation and cost-benefit analysis are recommended to investigate the options for introducing this strategy in farmers' fields.

Author Contributions: Conceptualization, X.S., H.R. and P.H.; Data curation, X.S., Y.L., M.H. and J.v.D.; Formal analysis, X.S., Y.L., M.H. and H.R.; Funding acquisition, X.S.; Methodology, J.v.D.; Project administration, P.H.; Resources, H.R.; Software, Y.L. and J.v.D.; Supervision, H.R., P.H. and J.v.D.; Visualization, X.S. and Y.L.; Writing—original draft, X.S.; Writing—review and editing, Y.L., M.H., H.R., P.H. and J.v.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Innovation Project of Chinese Academy of Agricultural Sciences (CAAS-ASTIP-FIRI), the China Scholarship Council (No. 202003250036), the Central Public-interest Scientific Institution Basal Research Fund (No. Y2021YJ07), and the Key Grant Technology Project of Henan and Xinxiang (221100110700 and ZD2020009).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the author.

Acknowledgments: We sincerely appreciate the assistance from Joop Kroes, the late developer of the SWAP-WOFOST-N model. May he rest in peace. We also thank all the anonymous reviewers for the constructive suggestions during the review phase of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Detailed Field Observations and Data Measurements.

Measured Item	Sampling Information	Measuring Time	Measuring Method/Tool
Weather data	Solar radiation, Daily temperature, Air humidity, Wind speed, Daily rainfall	Every half hour	automatic meteorological station (Campbell Scientific, USA) placed within 100 m of the experimental field
Soil texture	Depth of 2 m at one random point with 20 cm increments each time, 3 replicate samples per soil layer	October 2017 and December 2019	BT-9300HT laser particle size analyser
Bulk density (BD)		September 2018	Cutting ring
Field capacity (FC)			Oven drying
θs [1]			Weighing
SWRC [2]	A total of 3 points in a random border located at 10 m, 100 m, 190 m along the field; 20 cm for each soil layer to 1 m deep	September 2020	Equitensiometer (Soilmoisture Equipment Corp., Goleta, CA, USA)
Ks [3]		December 2020	
Organic matter		October 2019	Laboratory analysis
Available N/P/K			
Irrigation amount	Recorded for each irrigation event	Before and after irrigation	Flowmeter
Fertilisation rate	As the set amount	Each fertigation event	Scale
Soil moisture	A total of 5 points in each border located at 10 m, 50 m, 100 m, 150 m, 190 m along the border, 100 cm deep in one point with 10 cm increments	Before and after irrigation	Oven drying Weighing
Soil NO_3-N concentration		Before and after fertilisation, before sowing and after harvest	Automatic discrete analyser (CleverChem Anna)
Leaf Area Index (LAI)	A total of 3 optional borders (one for each treatment group)	Each development stage	Manually for LAI [4] and CH in 2018 and SunScan (Delta-T) for LAI in 2019
Crop height (CH)	A total of 3 points in each border: 10 m, 100 m, 190 m along the field; 1 plant at each point		
Crop yields	All borders were harvested together by combine harvester Measured yield was an average of each treatment	After harvesting	Weighing

1: θs means saturated water content; 2: SWRC means soil water retention curve; 3: Ks means saturated hydraulic conductivity; 4: The manual measuring method for LAI = 0.86 × leaf length × leaf width.

Appendix B Calibrated Parameters

Table A2. Soil hydraulic parameters.

Soil Depth (cm)	Soil Texture	Residual Water Content (cm^3/cm^3)	Saturated Water Content (cm^3/cm^3)	Shape Factor α (cm^{-1})	Shape Factor n (−)	Saturated Hydraulic Conductivity (cm/d)	Exponent in Hydraulic Conductivity Function (−)	Bulk Density (mg/cm^3)
0–80	Silt loam	0.0334	0.4502	0.0137	1.5801	44.18	0.5	1510.00
80–100	Loam	0.0332	0.4406	0.0194	1.6383	54.76	0.5	1470.00
100–200	Sandy loam	0.0310	0.4352	0.0223	1.6801	66.04	0.5	1440.00

Table A3. Crop parameters for wheat and maize.

Parameter	Description	Unit	Calibrated Values			
			Winter Wheat		Summer Maize	
TSUMEA	Temperature sum from emergence to anthesis	°C	1160		1060	
TSUMAM	Temperature sum from anthesis to maturity	°C	920		910	
TDWI	Initial total crop dry weight	kg/ha	210		20	
SLATB	Specific leaf area as function of development stage	ha/kg	0.0	0.0020	0.0	0.0025
			1.0	0.0017	0.8	0.0020
			2.0	0.0016	2.0	0.0020
SPAN	Life span under leaves under optimal conditions	d	35		39	

Table A3. *Cont.*

AMAXTB	Max. CO_2 assimilation rate as function of development stage	kg/ha/hr	0.0 1.0 1.3 2.0	40 40 45 35	0.0 1.5 1.8 2.0	70 65 45 20
CVO	Efficiency of conversion into storage organs	kg/kg	0.779		0.601	
RDI	Initial rooting depth	cm	10.0		10.0	
RDC	Max. rooting depth crop/cultivar	cm	125.0		100.0	
DVSNLT	Development stage above which no crop nitrogen uptake occurs	/	1.5		1.8	
NMXLV	Max. N concentration in leaves as function of development stage	kg N/kg	0.0 0.4 0.7 1.0 2.0 2.1	0.06 0.04 0.03 0.02 0.012 0.012	0.0 0.4 0.7 1.0 2.0 2.1	0.06 0.04 0.03 0.02 0.018 0.018

Table A4. Soil-N parameters.

Parameters	Description	Unit	Calibrated Values
Temp_ref	Reference temperature at which the transformation rates have been established	°C	7.5
RateConNitrif_ref	Nitrification rate constant established at the reference temperature	d^{-1}	1.0
RateConDenitri_ref	Denitrification rate constant established at the reference temperature	d^{-1}	0.06
TCSF_N	Transpiration concentration stream factor	-	1.0
LaiCritNupt	Critical LAI value to calculate uptake rate based on the ammonium availability	-	0.1
dz_WSN	Thickness of the soil layer considered for the simulation of the soil organic matter and nitrogen dynamics	m	1.0

References

1. Chen, X.; Cui, Z.; Fan, M.; Vitousek, P.; Zhao, M.; Ma, W.; Wang, Z.; Zhang, W.; Yan, X.; Yang, J.; et al. Producing more grain with lower environmental costs. *Nature* **2014**, *514*, 486–489. [CrossRef] [PubMed]
2. Strokal, M.; Biemans, H.; van Oel, P. The challenge to balance water and food objectives for sustainable development. *Curr. Opin. Environ. Sustain.* **2019**, *40*, A1–A4. [CrossRef]
3. Liang, H.; Hu, K.; Batchelor, W.D.; Qi, Z.; Li, B. An integrated soil-crop system model for water and nitrogen management in North China. *Sci. Rep.* **2016**, *6*, 25755. [CrossRef] [PubMed]
4. Fang, Q.X.; Ma, L.; Green, T.R.; Yu, Q.; Wang, T.D.; Ahuja, L.R. Water resources and water use efficiency in the North China Plain: Current status and agronomic management options. *Agric. Water Manag.* **2010**, *97*, 1102–1116. [CrossRef]
5. Kang, S.; Hao, X.; Du, T.; Tong, L.; Su, X.; Lu, H.; Li, X.; Huo, Z.; Li, S.; Ding, R. Improving agricultural water productivity to ensure food security in China under changing environment: From research to practice. *Agric. Water Manag.* **2017**, *179*, 5–17. [CrossRef]
6. Yao, L.; Zhao, M.; Xu, T. China's Water-Saving Irrigation Management System: Policy, Implementation, and Challenge. *Sustainability* **2017**, *9*, 2339. [CrossRef]
7. Zhang, X.; Qin, W.; Chen, S.; Shao, L.; Sun, H. Responses of yield and WUE of winter wheat to water stress during the past three decades—A case study in the North China Plain. *Agric. Water Manag.* **2017**, *179*, 47–54. [CrossRef]
8. Wang, J.; Li, Y.; Huang, J.; Yan, T.; Sun, T. Growing water scarcity, food security and government responses in China. *Glob. Food Secur.* **2017**, *14*, 9–17. [CrossRef]
9. Cui, Z.; Chen, X.; Zhang, F. Current nitrogen management status and measures to improve the intensive wheat-maize system in China. *Ambio* **2010**, *39*, 376–384. [CrossRef]
10. Li, Y.; Liu, H.; Huang, G.; Zhang, R.; Yang, H. Nitrate nitrogen accumulation and leaching pattern at a winter wheat: Summer maize cropping field in the North China Plain. *Environ. Earth Sci.* **2016**, *75*, 118. [CrossRef]
11. Ju, X.T.; Kou, C.L.; Zhang, F.S.; Christie, P. Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. *Environ. Pollut.* **2006**, *143*, 117–125. [CrossRef]
12. Lu, J.; Bai, Z.; Velthof, G.L.; Wu, Z.; Chadwick, D.; Ma, L. Accumulation and leaching of nitrate in soils in wheat-maize production in China. *Agric. Water Manag.* **2019**, *212*, 407–415. [CrossRef]
13. Jiao, X.-q.; He, G.; Cui, Z.-l.; Shen, J.-b.; Zhang, F.-s. Agri-environment policy for grain production in China: Toward sustainable intensification. *China Agric. Econ. Rev.* **2018**, *10*, 78–92. [CrossRef]

14. Zhang, Q.; Chu, Y.; Xue, Y.; Ying, H.; Chen, X.; Zhao, Y.; Ma, W.; Ma, L.; Zhang, J.; Yin, Y.; et al. Outlook of China's agriculture transforming from smallholder operation to sustainable production. *Global Food Secur.* **2020**, *26*, 100444. [CrossRef]
15. Zhang, X.; Uwimpaye, F.; Yan, Z.; Shao, L.; Chen, S.; Sun, H.; Liu, X. Water productivity improvement in summer maize—A case study in the North China Plain from 1980 to 2019. *Agric. Water Manag.* **2021**, *247*, 106728. [CrossRef]
16. Meng, Q.; Yue, S.; Hou, P.; Cui, Z.; Chen, X. Improving Yield and Nitrogen Use Efficiency Simultaneously for Maize and Wheat in China: A Review. *Pedosphere* **2016**, *26*, 137–147. [CrossRef]
17. Liu, B.-Y.; Zhao, X.; Li, S.-S.; Zhang, X.-Z.; Virk, A.L.; Qi, J.-Y.; Kan, Z.-R.; Wang, X.; Ma, S.-T.; Zhang, H.-L. Meta-analysis of management-induced changes in nitrogen use efficiency of winter wheat in the North China Plain. *J. Clean. Prod.* **2020**, *251*, 119632. [CrossRef]
18. Hagin, J.; Lowengart, A. Fertigation for minimizing environmental pollution by fertilizers. *Fert. Res.* **1996**, *43*, 5–7. [CrossRef]
19. Li, H.; Mei, X.; Wang, J.; Huang, F.; Hao, W.; Li, B. Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China. *Agric. Water Manag.* **2021**, *244*, 106534. [CrossRef]
20. Gao, X.; Du, S.; Zhong, Y.; Wu, Y.; Zhang, G. Development status and prospect of Fertigation. *China Agric. Inf.* **2015**, *4*, 14–19. (in Chinese).
21. Zhang, B.; Fu, Z.; Wang, J.; Zhang, L. Farmers' adoption of water-saving irrigation technology alleviates water scarcity in metropolis suburbs: A case study of Beijing, China. *Agric. Water Manag.* **2019**, *212*, 349–357. [CrossRef]
22. Ebrahimian, H.; Keshavarz, M.R.; Playán, E. Surface fertigation: A review, gaps and needs. *Span. J. Agric. Res.* **2014**, *12*, 820–837. [CrossRef]
23. Bai, M.; Xu, D.; Zhang, S.; Li, Y. Spatial–temporal distribution characteristics of water-nitrogen and performance evaluation for basin irrigation with conventional fertilization and fertigation methods. *Agric. Water Manag.* **2013**, *126*, 75–84. [CrossRef]
24. Chen, X. Influences of Different Fertilization Methods under Border Irrigation on Spatial and Temporal Distribution of Soil Water and Nitrogen in Winter Wheat-summer Maize Rotation Cropland. Master's Thesis, Graduate School of Chinese Academy of Agricultural Sciences, Beijing, China, 2017.
25. Zhang, S.; Xu, D.; Li, Y.; Bai, M. One-Dimensional Coupled Model of Surface Water Flow and Solute Transport for Basin Fertigation. *J. Irrig. Drain. Eng.* **2013**, *139*, 181–192. [CrossRef]
26. Xu, D.; Zhang, S.; Bai, M.; Li, Y.; Xia, Q. Two-Dimensional Coupled Model of Surface Water Flow and Solute Transport for Basin Fertigation. *J. Irrig. Drain. Eng.* **2013**, *139*, 972–985. [CrossRef]
27. Dai, W.; Zhang, S.; Xu, D.; Bai, M.; Shi, Y. Efficient Simulation of Surface Solute Transport in Basin Fertigation. *J. Irrig. Drain. Eng.* **2017**, *143*(11), 1–7. [CrossRef]
28. Tenreiro, T.R.; García-Vila, M.; Gómez, J.A.; Jimenez-Berni, J.A.; Fereres, E. Water modelling approaches and opportunities to simulate spatial water variations at crop field level. *Agric. Water Manag.* **2020**, *240*, 106254. [CrossRef]
29. Karandish, F.; Šimůnek, J. An application of the water footprint assessment to optimize production of crops irrigated with saline water: A scenario assessment with HYDRUS. *Agric. Water Manag.* **2018**, *208*, 67–82. [CrossRef]
30. Ranjbar, A.; Rahimikhoob, A.; Ebrahimian, H.; Varavipour, M. Simulation of nitrogen uptake and distribution under furrows and ridges during the maize growth period using HYDRUS-2D. *Irrig. Sci.* **2019**, *37*, 495–509. [CrossRef]
31. Farmaha, B.S.; Pritpal, S.; Bijay, S. Spatial and Temporal Assessment of Nitrate-N under Rice-Wheat System in Riparian Wetlands of Punjab, North-Western India. *Agronomy* **2021**, *11*, 1284. [CrossRef]
32. Fang, Q.X.; Ma, L.; Yu, Q.; Hu, C.S.; Li, X.X.; Malone, R.W.; Ahuja, L.R. Quantifying climate and management effects on regional crop yield and nitrogen leaching in the north china plain. *J. Environ. Qual.* **2013**, *42*, 1466–1479. [CrossRef]
33. Groenendijk, P.; Boogaard, H.; Heinen, M.; Kroes, J.; Supit, I.; de Wit, A. Simulation nitrogen-limited crop growth with SWAP/WOFOST. In *Process Descriptions and User Manual*; Report 2721; Wageningen Environemntal Research: Wageningen, The Netherlands, 2016.
34. 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. *SWAP Version 4, Theory Description and User Manual*; Report 2780; Wageningen Environmental Research: Wageningen, The Netherlands, 2017.
35. Kroes, J.; van Dam, J.; Supit, I.; de Abelleyra, D.; Verón, S.; de Wit, A.; Boogaard, H.; Angelini, M.; Damiano, F.; Groenendijk, P.; et al. Agrohydrological analysis of groundwater recharge and land use changes in the Pampas of Argentina. *Agric. Water Manag.* **2019**, *213*, 843–857. [CrossRef]
36. Huo, Z.; Feng, S.; Dai, X.; Zheng, Y.; Wang, Y. Simulation of hydrology following various volumes of irrigation to soil with different depths to the water table. *Soil Use Manag.* **2012**, *28*, 229–239. [CrossRef]
37. Li, P.; Ren, L. Assessing the feasibility of sprinkler irrigation schemes at the regional scale using a distributed agro-hydrological model. *J. Hydrol.* **2022**, *610*, 127917. [CrossRef]
38. Ma, Y.; Feng, S.; Huo, Z.; Song, X. Application of the SWAP model to simulate the field water cycle under deficit irrigation in Beijing, China. *Math. Comput. Model.* **2011**, *54*, 1044–1052. [CrossRef]
39. Li, Y.; Bai, M.; Zhang, S.; Wu, C.; Li, F. Development in improved surface irrigation in China. *Irrig. Drain.* **2020**, *69*, 48–60. [CrossRef]

40. Dai, X.P.; Zhang, X.H.; Han, Y.P.; Huang, H.P.; Geng, X. Impact of agricultural water reallocation on crop yield and revenue: A case study in China. *Water Policy* **2017**, *19*, 513–531. [CrossRef]
41. Gao, Y.; Shen, X.J.; Li, X.Q.; Meng, Z.J.; Sun, J.S.; Duan, A.W. Effects of pre-Sowing Irrigation on Crop Water Consumption, Grain Yield and Water Productivity of Winter Wheat in the North China Plain. *Irrig. Drain.* **2015**, *64*, 566–574. [CrossRef]
42. Sun, X.; Ritzema, H.; Huang, X.; Bai, X.; Hellegers, P. Assessment of farmers' water and fertilizer practices and perceptions in the North China Plain. *Irrig. Drain.* **2022**. [CrossRef]
43. Sun, X. Optimizing surface fertigation practices for application in farmers' field in the North China Plain. 2022; Unpublished.
44. Van Dam, J.C.; Groenendijk, P.; Hendriks, R.F.A.; Kroes, J.G. Advances of Modeling Water Flow in Variably Saturated Soils with SWAP. *Vadose Zone J.* **2008**, *7*, 640–653. [CrossRef]
45. Richards, L.A. Capillary Conduction Of Liquids through Porous Mediums. *Physics* **1931**, *1*, 318–333. [CrossRef]
46. Van Genuchten, M.T. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Sci. Soc. Am. J.* **1980**, *44*, 892–898. [CrossRef]
47. Mualem, Y. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.* **1976**, *12*, 513–522. [CrossRef]
48. De Wit, A.; Boogaard, H.; Fumagalli, D.; Janssen, S.; Knapen, R.; van Kraalingen, D.; Supit, I.; van der Wijngaart, R.; van Diepen, K. 25 years of the WOFOST cropping systems model. *Agric. Syst.* **2019**, *168*, 154–167. [CrossRef]
49. Van Genuchten, M.T.; Leij, F.J.; Yates, S.R. *The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils*; Report no. EPA/600/2–91/065; U.S. Environmental Protection Agency: Ada, OK, USA, 1991; p. 85.
50. Pei, H.; Shen, Y.; Liu, C. Nitrogen and water cycling of typical cropland in the North China Plain. *Chin. J. Appl. Ecol.* **2015**, *26*, 283–296.
51. Cai, G.X.; Chen, D.L.; Ding, H.; Pacholski, A.; Fan, X.H.; Zhu, Z.L. Nitrogen losses from fertilizers applied to maize, wheat and rice in the North China Plain. *Nutr. Cycl. Agroecosyst.* **2002**, *63*, 187–195. [CrossRef]
52. Li, P.; Ren, L. Evaluating the effects of limited irrigation on crop water productivity and reducing deep groundwater exploitation in the North China Plain using an agro-hydrological model: I. Parameter sensitivity analysis, calibration and model validation. *J. Hydrol.* **2019**, *574*, 497–516. [CrossRef]
53. Li, P.; Ren, L. Evaluating the effects of limited irrigation on crop water productivity and reducing deep groundwater exploitation in the North China Plain using an agro-hydrological model: II. Scenario simulation and analysis. *J. Hydrol.* **2019**, *574*, 715–732. [CrossRef]
54. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *T Asabe* **2007**, *50*, 885–900. [CrossRef]
55. Janssen, P.H.M.; Heuberger, P.S.C. Calibration of process-oriented models. *Ecol. Model.* **1995**, *83*, 55–66. [CrossRef]
56. Allen, R.; Pereira, L.; Raes, D.; Smith, M. *Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; FAO: Rome, Italy, 1998; p. 300.
57. Yin, Y.; Zhao, R.; Yang, Y.; Meng, Q.; Ying, H.; Cassman, K.G.; Cong, W.; Tian, X.; He, K.; Wang, Y.; et al. A steady-state N balance approach for sustainable smallholder farming. *Proc. Natl. Acad. Sci. USA* **2021**, *118*. [CrossRef] [PubMed]
58. Van Halsema, G.E.; Vincent, L. Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism. *Agric. Water Manag.* **2012**, *108*, 9–15. [CrossRef]
59. Dobermann, A. Nutrient use efficiency–measurement and management. In *IFA International Workshop on Fertilizer Best Management Practices*; IFA: Brussels, Belgium, 2007; pp. 1–28.
60. Cassman, K.G.; Dobermann, A.; Walters, D.T. Agroecosystems, Nitrogen-use Efficiency, and Nitrogen Management. *AMBIO A J. Hum. Environ.* **2002**, *31*, 132–140, 139. [CrossRef] [PubMed]
61. Qin, W.; Hu, C.; Oenema, O. Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: A meta-analysis. *Sci. Rep.* **2015**, *5*, 16210. [CrossRef]
62. Zhang, F.S.; Wang, J.Q.; Zhang, W.F.; Cui, Z.L.; Ma, W.Q.; Chen, X.P.; Jiang, R.F. Nutrient use efficiencies of major cereal crops in China and measures for improvement. *Acta Pedol. Sin.* **2008**, *45*, 915–924.
63. Peng, Z.; Liu, Y.; Li, Y.; Abawi, Y.; Wang, Y.; Men, M.; An-Vo, D.A. Responses of Nitrogen Utilization and Apparent Nitrogen Loss to Different Control Measures in the Wheat and Maize Rotation System. *Front. Plant Sci.* **2017**, *8*, 160. [CrossRef]
64. Abubakar, S.A.; Hamani, A.K.M.; Chen, J.; Traore, A.; Abubakar, N.A.; Usman Ibrahim, A.; Wang, G.; Gao, Y.; Duan, A. Optimized Drip Fertigation Scheduling Improves Nitrogen Productivity of Winter Wheat in the North China Plain. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 2955–2968. [CrossRef]
65. Xie, J.; Qin, W.; Zhang, X. Improving water use efficiency in grain production of winter wheat and summer maize in the North China Plain: A review. *Front. Agric. Sci. Eng.* **2016**, *3*. [CrossRef]
66. Foley, D.J.; Thenkabail, P.S.; Aneece, I.P.; Teluguntla, P.G.; Oliphant, A.J. A meta-analysis of global crop water productivity of three leading world crops (wheat, corn, and rice) in the irrigated areas over three decades. *Int. J. Digit. Earth* **2019**, *13*, 939–975. [CrossRef]

67. Cui, M.; Zeng, L.; Qin, W.; Feng, J. Measures for reducing nitrate leaching in orchards:A review. *Environ. Pollut.* **2020**, *263*, 114553. [CrossRef]
68. Groenendijk, P.; Renaud, L.V.; Roelsma, J. Prediction of Nitrogen and Phosphorus leaching to groundwater and surface waters. In *Process Descriptions of the Animo 4.0 Model*; Alterra–Report 983; Alterra: Wageningen, The Netherlands, 2005.