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Optimizing Nitrogen Options for Improving Nitrogen Use Efficiency of Rice under Different Water Regimes

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Abstract: Major challenge in rice production is to achieve the goal of enhancing both food production and fertilizer use efficiency. Rice growth simulation model, ORYZA (v3) was used in the present study to evaluate the model under continuous flooded (CF) and alternate wetting and drying (AWD) regimes with different fertilizer nitrogen (N) rates with different N splits using a historical data of past 45 years. The model satisfactorily simulated crop biomass and nitrogen uptake at both irrigation regimes and fertilizers N rates and splits. The yield differences among the years were large due to climate change, but enhanced by N rates. The response of N curves was different at both water regimes. At 0 N rate, the slope for agronomic efficiency (AE) was high which tends to decrease with increase in N rates. With the one split basal application of N, lowest yield was found with high physiological efficiencies (PE), lowest fertilizer recoveries (RE) and lowest agronomic efficiency (AE). For both water applications and fertilizer levels, high yield with high nitrogen uptake, AE, RE and partial factor productivity (PFP) were witnessed high at four split (3:3:3:1), while having low physiological efficiency. The water productivity (irrigation + rainfall) WP_{I+R} at basal in one N split for AWD at 150 kg N ha^{-1} was 1.19 kg m^{-3} and for CF was 0.82 kg m^{-3}, whereas for 225 kg N ha^{-1} WP_{I+R} of AWD was 1.50 kg m^{-3} and 1.14 kg m^{-3} for CF. In general, AWD exhibited high WP_{I+R} with no rice yield penalty compared to CF. Splitting with the proper amount of fertilizer N resulted in good water productivity and nitrogen efficiencies, could lead to high rice yield.

Keywords: ORYZA (v3); rice; alternate wetting and drying; nitrogen use efficiencies; water productivity

1. Introduction

Rice (*Oryza sativa* L.) serves as a key nutritional crop and tends to feed almost worlds half population [1]. In the following three decades, overall worldwide utilization of rice is expected by another 116 million tons increase [2]. In China rice is considered the most vital food crop, nearly 30 million hectares of area is being occupied by rice [3]. In order to face the increasing demand for food and to fulfill the needs of a growing population, the production of rice must be enhanced up to 70% by 2050 [4]. Due to environmental deprivation and the lack of labors, the productivity of transplanted rice became susceptible [5,6]. To achieve the potential of high rice cultivar yields, advancement in crop management strategies are essential, which is independent of immense agronomic inputs.

To achieve potential rice yields, modern cultivars of rice require a large number of fertilizers. Among all fertilizers, nitrogen (N) is the most essential for plant development, growth and grain quality [7,8]. However, in developed economies, N use efficiency (NUE; defined as grain dry matter

per unit of N available from the soil, fertilizer included), is very low and estimated to be approximately 33% of the applied N source [9]. Thus, in Asia, Europe, and Northern America, intensive agricultural practices [10] have led to both higher production costs and greater risk from environmental hazards, such as ground and surface water pollution by nitrate leaching [11–13]. The main challenge for breeders is to minimize the applied amount of fertilizer N to the field without affecting yield, and also in selecting the cultivars that metabolize N more effectively. The average fertilizer N dose in China is roughly 180 kg ha^{-1} for the production of rice, which is 75% higher than the worldwide average [14]. Furthermore, application of around 300 kg N ha^{-1} is also practicing in different regions of China [15,16]. Also, over-utilization of N regularly initiates pest destruction and lodging, bringing a decrease in quality and quantity of rice yield [17,18]. Excessive use of N may induce the acidity of the soil [19], water contamination [20] and encourage nitrous oxide (N_2O) emission [21].

Because of the significance of nitrogen as a major nutrient for rice crop to attain high grain yield, it is crucial to determine the ideal amount and timing of N application for each rice cultivars and also the impact on agronomic parameters, for example, moisture content, plant height, lodging and other parameters [22]. Therefore, many researchers have identified different fertilization scheduling techniques to achieve the maximum N use efficiency in rice fields [23]. Subsequently, nearly each farmer supply N to get high yields [15] in one single split or up to four splits during crop growth critical stages neglecting crop N demand and temporal changes [24]. Furthermore, a basal dose application of N on transplantation day or day before transplantation has been followed [24]. The N loss likely to be at the basal application as rice take 7 days in recovering from transplanting shock and after developing root, rice N requirement is minimized during that period [25,26]. However, fertilizer application can increase the rice yield matching the indigenous N supply [24]. N splits with basal at panicle initiation irrespective of N rates can increase yield [27,28]. A study has been conducted by Prasad et al. (2018), revealed that four split (basal, tillering, panicle initiation and heading) limited the nitrate (NO_3) leaching loss from rice fields [29]. The adjusted splits could result in a reduction of fertilizer N input [30], splitting N can increase spikelet's per panicle, 1000 grain weight, ripened grain percentage and N uptake [31]. However, an increasing trend has been shown in N application doses in rice fields of China [32].

Water is crucial for the development and growth of rice crops. Though, the consequence of continuous flooding is a substantial amount of inefficient water losses by evaporation, percolation, and seepage [33,34]. Comparatively the production of rice in Asia is about 90%, nearly 80% of fresh water resources around the world is being consumed by irrigated water [35,36]. Because of climate change and rapid urbanization and industrialization, water for agricultural utilization turns out to be progressively scarce [37,38]. About 15 $\pm$ 20 million hectares area of irrigated rice in Asia will endure water shortage by the end of 2025 [39]. To handle the increasing demand for food for the rising population agriculturists are confronting a challenge to deliver more per unit area rice with constrained limit water amount. To maintain the food demand this is very crucial for the security of food, especially in dense populous countries like Asian countries, which are mainly depended on subsistence agriculture [40].

Simulation models for crop growth are valuable tools which give the chance to investigate the field data and inspecting the impacts of various crop management practices crosswise over various environment and seasons [41]. The form of any irrigation water [42] and N application [43] can be determined by modeling studies. There have been many studies conducting on different management strategies using different models ORYZA [35], CropSyst [44], DSSAT [45], Infocrop [46], and APSIM-ORYZA [47]. These models have been used for different scenario analysis, like climate change scenarios [48,49], nitrogen management [47,50,51], water management [52–54], plant densities [55,56], sowing time [57], splits fertilizers [24,58] and irrigation scheduling [42,59,60]. Hence no study has used a detailed analysis for split doses of N fertilizer with the interaction of different irrigation condition in a rice field.

ORYZA (v3) is the advance release of ORYZA 2000 [61]. Many studies have been conducted using ORYZA model having different rice varieties under different N management, irrigation management, fertilizer splits, seedling age, plant density in the Philippines [62], China [24,26,63], India [42], Indonesia [64] or Iran [41]. However, most of the researchers have conducted the research of fertilizer N application with flooded water condition, but there was no specific study of fertilizer N dosages with N splits under alternate wetting and drying (AWD) condition by using ORYZA model. In the present study, we simulated the combined effect of N fertilizer rates with N splits, water regimes and their interaction in ORYZA (v3). The objectives of the study were: (1) To calibrate and validate ORYZA (v3) model for the different amount of N with water regimes. (2) Simulation of ORYZA (v3) model to identify optimum N rates with different N splits and water regimes and also their response to rice yield.

2. Materials and Methods

2.1. Experiment

Experiment with summer rice was carried out in 2007–2008 at Kunshan, irrigation and drainage experiment station. The experimental site is situated between at 31°15′15″ N and 120°57′43″ E in eastern China, having subtropical monsoon climate. The annual average temperature is 17.5 °C with an annual mean precipitation of 1397.1 mm. This study area has dark-yellow hydromorphic paddy soil and clay in texture (Table 1). Japonica Jia 04-33 rice variety, was transplanted to the fields on 27 June 2007 and 28 June 2008 and harvested on 27 October 2007 and 25 October 2008.

Table 1. Soil properties of the experimental site.

Characteristic	Value
Soil bulk density (g cm^{-3})	1.30
Soil organic matter (g kg^{-1})	21.88
Soil nitrogen (TN, g kg^{-1})	1.03
Soil phosphorus (TP, g kg^{-1})	1.35
Soil K (g kg^{-1})	20.86
pH	7.4

Experimental fields were assigned different levels of nitrogen and two types of irrigation flooded irrigation (FI) and deficit irrigation (DI), when the soil moisture reached to the lower irrigation threshold as measured by time-domain reflectometry (TDR, Soil moisture, Mitchell Instrument Company, Vista, CA, USA), DI paddies was irrigated to saturate the soil. The detailed explanation about DI irrigation regarding water content and root zone is provided in reference [65]. Similarly, irrigation volume for each plot was measured by water gauge mounted at the water supply pipes. Data on plant height and tiller dynamics have been recorded after every five days. Leaf area was calculated from selected three random plants while from roots, panicles, leaves and stem with sheaths was measured for biomass accumulation. CI 203 (CID INC, Camas, WA, USA) leaf area meter was used to measure individual leaf area, and summed for the leaf area index and the total leaf area. Samples of different organs (leaves, stems, and panicles) of rice plants were processed by H_2SO_4-H_2O_2 to measure their total nitrogen contents by indophenol blue spectrophotometric method [65]. Yield data was taken from each plot at harvesting. An automated weather station (WS-STD1, DELTA-T, Burwell, Cambridge, UK) was installed at the experimental site to record daily data on relative humidity (*RH*), air temperature (*Ta*), sunshine hours (*n*), atmospheric pressure (P_a), precipitation (*Pr*) and wind speed (*V*) every 30 min.

2.2. Model Description, Calibration, and Validation

2.2.1. The ORYZA (V3) Model

ORYZA (v3) is the most updated version of Oryza2000 model and was released in 2013 by international rice research institute (IRRI) Philippines. The model simulates a one-day time step, development, water balance and the growth of lowland rice for both limited and potential production scenarios of water and nitrogen. The model assumes that the crop doesn't undergo any other yield reduction stresses. For an explanation of the crop model see Reference [43]. The model summary description is given below.

The model simulates different daily dry matter (DM) growth and rate of phonological development of different plant organs. Leaf area grows exponentially as a function of thermal time at the relative leaf growth rate when the canopy has not yet closed. Then, leaf area grows linearly and is calculated from the increase in leaf weight times a specific leaf area. By assimilating these rates over time, developmental stages and dry matter production are simulated throughout the growing season. The daily income canopy CO_2 uptake is derived from the daily leaf area index, temperature, and radiation. The accumulated daily dry matter is obtained after subtracting respiration and maintenance requirements. The dry matter which is produced is then divided among stem leaves panicles using derived factors. The spikelet's number to first flowering period is calculated from total crop growth over panicle initiation. The spikelet's number at flowering at initial panicle to flowering is calculated from the growth of total crop [24].

The N potential daily demand is derived from the difference between N concentrations of each plant organ, growth rate, and dry weight. Vegetative organs are satisfied by getting their N from soil N uptake and panicles are satisfied with N getting their N uptake from leaves and stems after flowering stage by translocation. The availability of soil N is modeled from simulated with applied N, soil N and, deprived of simulating any N modification processes in soil.

The dynamics of water in the ORYZA (v3) model is estimated in three types of soil by water balance [42]. Which are poorly lowland drained soil, well-drained upland, and regular upland. Furthermore, percolation and evapotranspiration losses accounted for the water gains by irrigation or precipitation. Plant transpiration and soil evaporation on daily basis are combined from pond water layer, afterward from top soil layer and all root layers [35]. The water balance of lowland rice in ORYZA model includes:

$$dW = I + R + C - E - T - S - P - D, \quad (1)$$

where dW is stored water change in, I is irrigation supply, R is rainfall, C is a capillary rise, E is evaporation, T is transpiration, S is seepage, P is percolation, and D is surface drainage/runoff (all units are mm day^{-1}) [35].

2.2.2. Parameterization

The ORYZA (v3) model was parameterized following Bouman and Van Laar [43]. For calibration and evaluation, experimental data of 2007 was calibrated and evaluated with experimental data of 2008. Data of various plant traits, soil properties, cultivation practices, nitrogen contents in different crop organs and weather data (daily basis) were used as subjected input data to in ORYZA (v3) model. The model output is comprised of partitioning total biomass into various components; leaf area index; yield; nitrogen content in leaf, stem, and panicle. Developmental rates and dry biomass partitioning were calculated using DRATES and PARAM of ORYZA (v3) model. The calibrated parameters were: Developmental rates (DVR), partitioning factors of leaf (FLV), partitioning factors of stem (FST), partitioning factors of storage organ/panicle (FSO), partitioning factors of death rate of leaf (DRLV) and partitioning factors of stem reserves fraction (FSTR). Calibrated parameters for nitrogen uptake related were: Residual N concentration in leaves (RFNLV) and residual N concentration in stems (RFNST), storage organ/panicle N maximum concentration (NMAXSO) and storage organ/panicle

N minimum concentration (NMINSO). The calibrated values were additionally fine-tuned manually (refining the parameters values until simulated values best match with observed values). It's worth mentioning that this calibration of model parameters based on field experimental data is very crucial. Because some crop parameters are accommodative standard (likewise IR72) and can be used for all varieties whereas, some parameters are variety and environment specific. The detailed explanation about calibration is provided in reference [43]. The model was calibrated and validated for parameters, including weight of above ground biomass (WAGT), weight of storage organ/panicle (WSO), weight of stem (WST), weight of green leaves (WLVG), amount of nitrogen in leaf (ANLV), amount of nitrogen in stem (ANST) and amount of nitrogen in storage organ/panicle (ANSO). Moreover, the coefficient of determination (R^2) and normalized root mean square error (*RMSEn*) was used to evaluate the uniformity between observed and simulated values [66].

$$R^2 = \frac{\left(\sum_{i=1}^{N}\left(X_i - \frac{1}{N}\sum_{i=1}^{N}X_i\right)\left(Y_i - \frac{1}{N}\sum_{i=1}^{N}Y_i\right)\right)^2}{\sum_{i=1}^{N}\left(X_i - \frac{1}{N}\sum_{i=1}^{N}X_i\right)^2 - \sum_{i=1}^{N}\left(Y_i - \frac{1}{N}\sum_{i=1}^{N}Y_i\right)^2} \quad (2)$$

$$RMSEn = \frac{100\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2}}{\frac{1}{n}\sum_{i=1}^{n}X_i} \quad (3)$$

where X_i is the observed value and Y_i the corresponding simulated value, N is the number of values.

2.3. Scenario Analysis

Different scenario analysis was carried out to evaluate different water and nitrogen inputs for yield and nitrogen uptake. In simulation set 1 historical data from 1961 to 2005 was run to observe the yield and nitrogen uptake along with different years. The water management scenarios were continuous flooded (CF) and alternate wetting and drying (AWD) with 70 kpa threshold soil water potentials. For AWD regime, about 30 mm of irrigated water was applied to the field after reaching the soil water potential threshold. The AWD management regime was executed after 8 days of transplanting. Different nitrogen rates (0, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300 kg ha^{-1}) were used under CF and AWD conditions. For simulation set 2 different splits ratios (5:5, 6:4, 7:3, 6:2:2, 5:3:2, 4:4:2, 5:2:2:1, 3:3:3:1, 4:3:2:1) were used. N fertilizer ha^{-1} were applied at transplanting and tillering, for 3 doses N fertilizer ha^{-1} used at transplanting, tillering and panicle initiation while for 4 doses N fertilizer ha^{-1} used at transplanting, tillering, panicle initiation and booting stage.

The output of the model was utilized to investigate N number use efficiencies i.e., partial factor productivity (PFP), fertilizer N recovery (RE), Agronomic efficiency (AE) and physiological efficiency (PE), [24]:

$$PFP = (Y_o/N_r) + (\Delta Y/\Delta N_p)(\Delta N_p/N_r), \quad (4)$$

$$PE = \frac{\Delta Y}{\Delta N_p}, \quad (5)$$

$$AE = \frac{\Delta Y}{N_r}, \quad (6)$$

$$RE = \frac{\Delta N_p}{N_r}, \quad (7)$$

where Y_o is the yield (kg ha^{-1}) without fertilizer N input, N_r is the N rate (kg ha^{-1}) applied, ΔY is the incremental increase in yield (kg ha^{-1}) resulting from N application, ΔN_p is the increase in crop N accumulation (kg ha^{-1}) resulting from N application.

Water productivity for the simulation of the model was calculated as the ratio of grain yield to the total supplied water [67].

3. Results

3.1. Model Calibration and Validation

3.1.1. Biomass Attributes and Leaf Area Index

Evaluation of observed and simulated crop biomass attributes are presented in Figure 1 for calibration and in Figure 2 for validation data sets. The observed data fell close or on the simulated lines in biomass attributes and leaf area index (LAI) for both calibration and validation period (Figures 1 and 2). The results for a total above ground biomass represented an adequate agreement between observed (Table S1) and simulated (Table S2) data sets. The total above ground biomass R^2 and *RMSEn* noted for calibrated data set was 0.98 and 10.40% and for validated data set was 0.99 and 6.60%. Panicle biomass displayed a high correlation between measured and simulated data having R^2 and *RMSEn* for calibration was 0.98 and 18.0%, and for validation was 0.99 and 11.89%. Similarly, model exhibited a good relation between observed and simulated data for LAI. The observed R^2 was 0.88 and 0.84 and *RMSEn* was 21.68% and 23.41% for calibration (Table S1) and validation (Table S2) of LAI, respectively. Overall, in between observed and simulated dry whole crop and dry weight organs presented a satisfactory agreement. The dynamic crop variables for goodness-of-fit parameters displayed in Tables S1 and S2. In both data sets the Student's test displays that all observed values were identical to simulated values with 95% confidence (Tables S1 and S2).

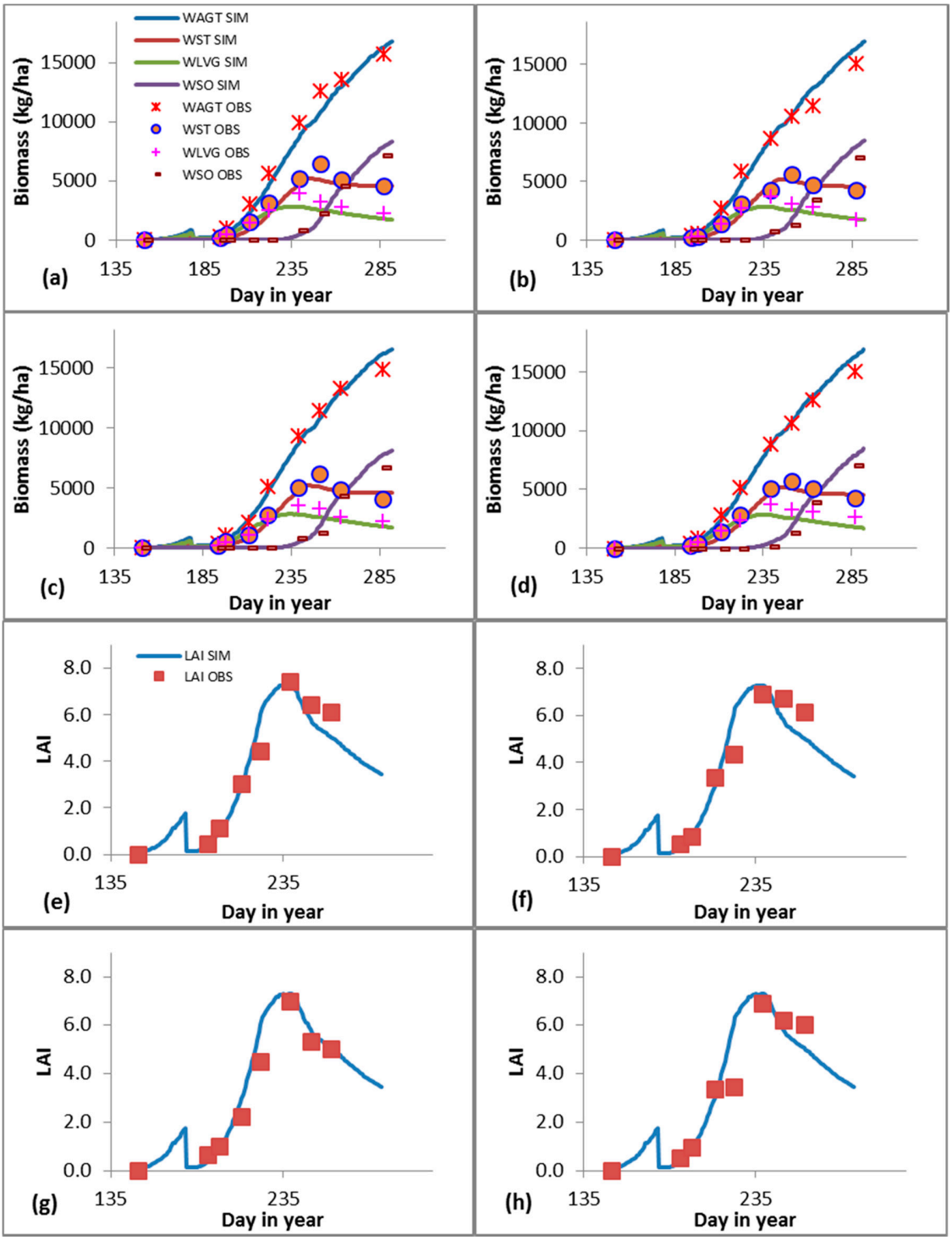


Figure 1. Simulated and observed total biomass (WAGT), green leaves (WLVG), stems (WST), storage organs/panicles (WSO) are presented in (**a**–**d**) and leaf area index (LAI) is presented in (**e**–**h**), for calibration period 2007, in Kunshan, Nanjing, China.

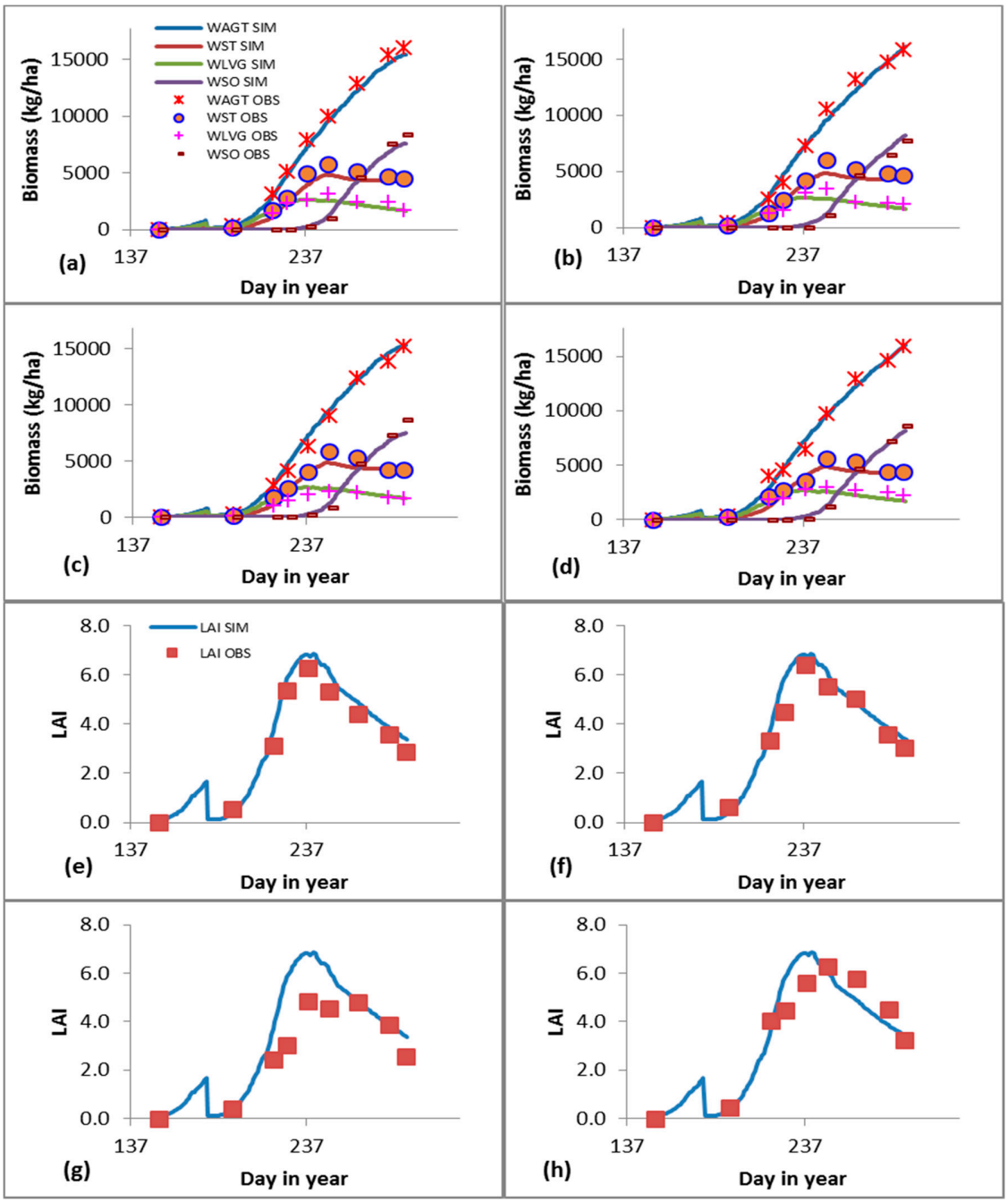


Figure 2. Simulated and observed total biomass (WAGT), green leaves (WLVG), stems (WST), storage organs/panicles (WSO) are presented in (**a**–**d**) and leaf area index (LAI) is presented in (**e**–**h**), for validation period 2008, in Kunshan, Nanjing, China.

3.1.2. Crop N-Uptake Attributes

Comparison between observed and simulated crop N uptake attributes are displayed in Figures 3 and 4. The ORYZA model showed a good response ($p > 0.01$) to N attributes except for leaf N uptake between observed and simulated data which was higher than those in the crop biomass attributes, reflects high values for *RMSEn* while low for R^2 in calibration (Table S1) and validation period (Table S2). Nevertheless, values of *RMSEn* and R^2 for total crop N uptake were 12.35% and 0.90 for calibration, for validation were 11.63% and 0.96 respectively. In calibration and validation, for panicle N uptake *RMSEn* was 13.38 % and 18.96%, for R^2 were 0.98 and 0.97. However, for leaf N

uptake, *RMSEn* was 18.21% and 27.56%, while for R^2 leaf N uptake was 0.67 for calibration and 0.92 for the validation period. In addition the statistical evaluation like root mean square error (RMSE) student test (Pt) values, intercept (α), slope (β), for calibration and validation of nitrogen uptake can be found in Tables S1 and S2.

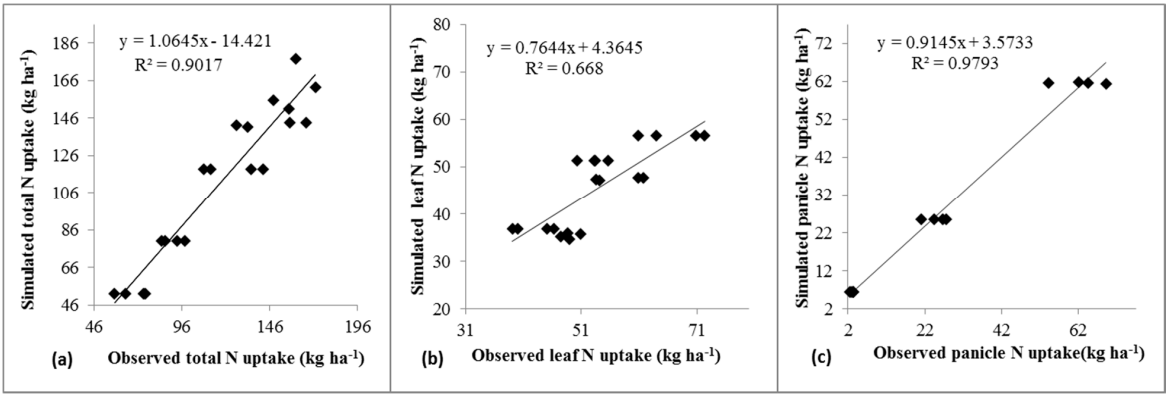


Figure 3. Simulated vs. observed total N uptake, leaf N uptake and panicle N uptake, (**a**–**c**) for 2007 calibration period, in Kunshan, Nanjing, China.

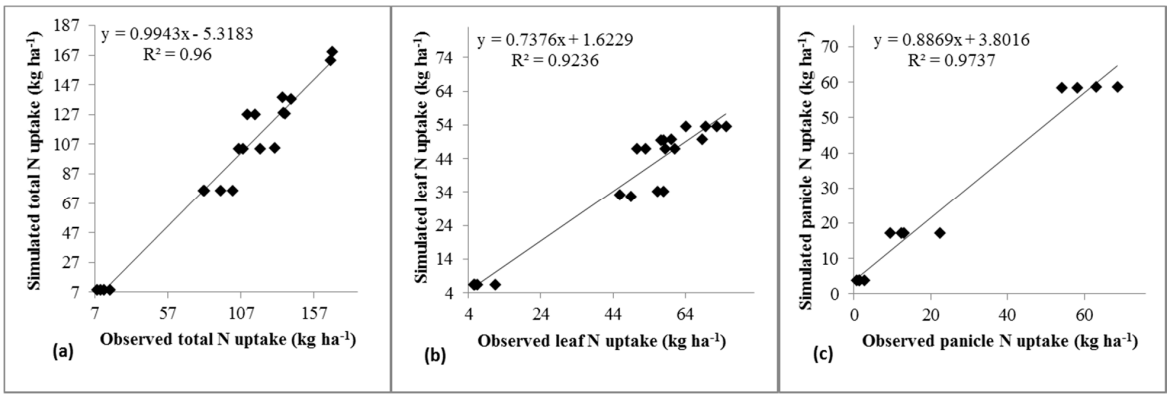


Figure 4. Simulated vs. observed total N uptake, leaf N uptake and panicle N uptake, (**a**–**c**) for 2008 validation period, in Kunshan, Nanjing, China.

3.2. Scenario Analysis Set 1

3.2.1. Simulation with 0 and 300 N Rates

The graphical example of yields simulated for the past 45 years (1961–2005) of evaluation at four combinations of CF and AWD and low (0 N) and high (300 kg N ha^{-1}) fertilizer rates are presented in Figure 5. The yield differences among the years were large, due to climate change but also enhanced by N rates. The differences in yield were witnessed at high (300 kg N ha^{-1}) fertilizer rate. The fluctuation in yield was observed between 8000 and 11,000 kg ha^{-1} with some year exceeding 12,000 kg ha^{-1}. At Low application rates (0 N), the variation in crop yields at AWD were relatively high than CF and vary between 2500 kg ha^{-1} and 4000 kg ha^{-1}. The effect of AWD at low fertilizer N (0 N) was high compared to CF. However, the differences in yield at high fertilizer N (300 kg N ha^{-1}) were found close between AWD and CF.

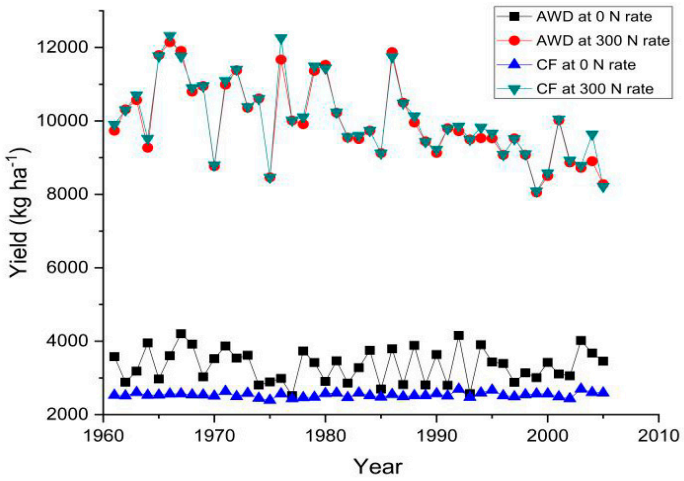


Figure 5. Simulated yields between 1961 and 2005, with AWD and CF conditions with 0 and 300 fertilizer N rates.

3.2.2. Various Fertilizer N inputs with AWD and CF conditions

The results in Figure 6 display simulation of different nitrogen inputs at AWD and CF, using values averaged over the 45 years simulation. The response of N curves was different at both water regimes. Yield increases linearly with the input of nitrogen. The slope of the curve between nitrogen input and yield, agronomic efficiency, is high at low N rates and decreases with the increase of nitrogen input. At both water supply AWD and CF there is yield gap at lower fertilizer rates ranged from 0 to 200 kg ha^{-1} but the difference became very low at high N rates and at above 300 kg N ha^{-1} were almost plateau. The simulated yield at 225 kg N ha^{-1} for AWD was 9356 kg ha^{-1} and for CF was 9015 kg ha^{-1}. Figure 7 showcase the same trend for nitrogen uptake at CF and AWD with different N rates. The increase in N uptake directly proportional to N rates and no significant difference at high fertilizer N (above 225 kg N ha^{-1}) rate at both irrigation regimes. In both CF and AWD partial factor productivity, physiological and agronomic efficiencies decrease with the increase of nitrogen input (Figure 8). Water productivity increases with the increase of fertilizer N rates. However, AWD showed high water productivity compared to CF. The WP_{I+R} at 0 kg ha^{-1} fertilizer N rate was 0.5 kg m^{-3} for AWD and 0.3 kg m^{-3} for CF while at 300 kg ha^{-1} fertilizer N rate, WP_{I+R} was 1.52 and 1.16 kg m^{-3} (Figure 9) for AWD and CF, respectively.

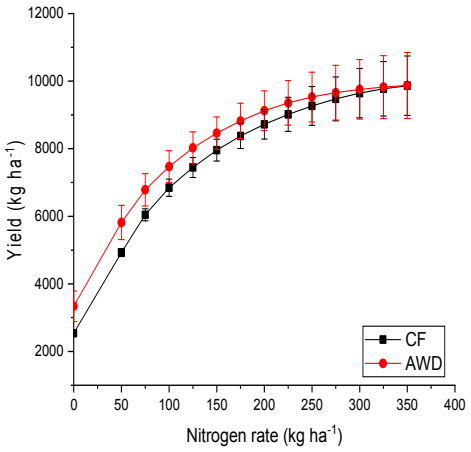


Figure 6. Simulated yield and applied fertilizer N, with AWD and CF conditions. Each value is the average of 45 years between 1961 and 2005. The bars show the standard deviation among years for each N rate.

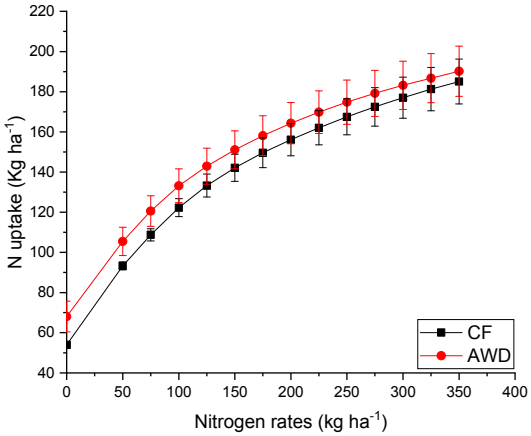


Figure 7. Simulated Nitrogen uptake and applied fertilizer N, with AWD and CF conditions. Each value is the average of 45 years between 1961 and 2005. The bars show the standard deviation among years for each N rate.

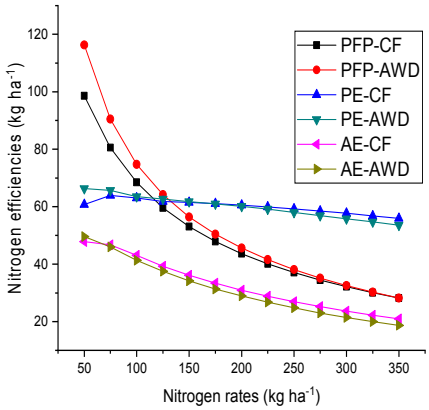


Figure 8. Simulated different nitrogen efficiencies and applied fertilizer N, with AWD and CF conditions. Each value is the average of 45 years between 1961 and 2005.

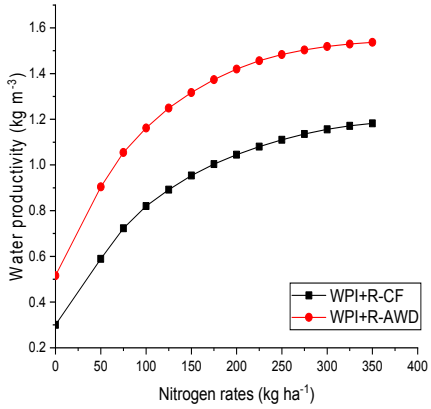


Figure 9. Simulated water productivity and applied fertilizer N, with AWD and CF conditions. Each value is the average of 45 years between 1961 and 2005.

3.3. Scenario Analysis Set 2

The simulation scenario set 2 (Table 2) was carried out with different splits and timing of N rates, which has a significant effect on yield for both AWD and CF. However, there were no significant differences between AWD and CF. At basal fertilizer N application in one split, lowest yields were found with high physiological efficiencies and lowest fertilizer recoveries and agronomic efficiencies.

For both water application and fertilizer levels, the highest yield, agronomic efficiency, fertilizer recovery, and partial factor productivity were witnessed high at four splits (3:3:3:1), while these indexes were found low at basal in one split application N fertilizers (Table 2). A similar trend was observed for nitrogen uptake indicated that with the increase of fertilizer splits, nitrogen uptake increased specially under AWD regime. Also, the highest nitrogen uptake was observed 182 kg ha^{-1} and 162 kg ha^{-1} at split 3:3:3:1 with 225 kg N ha^{-1} and 150 kg N ha^{-1} for AWD as compared to CF (Table 2). However, agronomic efficiency at 150 kg N ha^{-1} and 225 kg N ha^{-1} for CF was higher than AWD (Table 2). High N rates with splitting showed lower agronomic, physiological, fertilizer recovery efficiency and partial factor productivity (Table 2) at both water application as compared to low fertilizer N rates with different splits. Water productivity (irrigation + rainfall) was increased with the amount and splitting fertilizer N rates at both AWD and CF. The WP_{I+R} at basal in one split N application for AWD at 150 kg N ha^{-1} was 1.19 kg m^{-3} and for CF was 0.82 kg m^{-3}, whereas for 225 kg N ha^{-1} WP_{I+R} of AWD was 1.50 kg m^{-3} and 1.14 kg m^{-3} for CF (Table 2). In general, AWD exhibited high WP_{I+R} compared to CF. Splitting in proper amount and timing of fertilizer N resulted in good water productivity and nitrogen efficiencies, could lead to high yield.

Table 2. Simulated grain yield Means, N use efficiency parameters N uptake and water productivity at different N splits, rates with AWD and CF, analyzing 45 years historic weather data from 1961 to 2005.

Irrigation Application	Fertilizer N Rate (kg ha^{-1})	Fertilizer N Splits) (kg ha^{-1})	Grain Yield (kg ha^{-1})	Total N Uptake (kg ha^{-1})	PFP (kg kg^{-1})	Y_o/Nr (kg kg^{-1})	AE (kg kg^{-1})	PE (kg kg^{-1})	RE (%)	WP_{I+R} (kg m^{-3})
CF	150	Basal	6878	122	46	17	29	64	45	0.82
		5, 5	7412	132	49	17	32	63	52	0.89
		6, 4	7310	130	49	17	32	63	51	0.88
		7, 3	7206	128	48	17	31	63	49	0.86
		6, 2, 2	7773	139	52	17	35	62	57	0.93
		5, 3, 2	7865	141	52	17	36	62	58	0.94
		4, 4, 2	7958	142	53	17	36	61	59	0.95
		5, 2, 2, 1	8383	149	56	17	39	62	63	1.00
		3, 3, 3, 1	8671	156	58	17	41	60	68	1.04
		4, 2, 3, 1	8447	150	56	17	39	61	64	1.01
	225	Basal	7847	139	35	11	24	62	38	0.94
		5, 5	8436	150	37	11	26	61	43	1.01
		6, 4	8327	148	37	11	26	61	42	1.00
		7, 3	8212	146	36	11	25	62	41	0.98
		6, 2, 2	8837	158	39	11	28	60	46	1.06
		5, 3, 2	8928	160	40	11	28	60	47	1.07
		4, 4, 2	9016	162	40	11	29	60	48	1.08
		5, 2, 2, 1	9424	172	42	11	31	58	52	1.13
		3, 3, 3, 1	9688	179	43	11	32	57	56	1.16
		4, 2, 3, 1	9487	173	42	11	31	58	53	1.14
AWD	150	Basal	7704	137	51	22	29	63	46	1.19
		5, 5	8082	144	54	22	32	63	50	1.25
		6, 4	8011	143	53	22	31	63	50	1.24
		7, 3	7943	141	53	22	31	63	49	1.23
		6, 2, 2	8338	149	56	22	33	62	54	1.29
		5, 3, 2	8399	150	56	22	34	62	55	1.30
		4, 4, 2	8458	151	56	22	34	62	55	1.31
		5, 2, 2, 1	8790	157	59	22	36	61	60	1.36
		3, 3, 3, 1	9015	162	60	22	38	60	63	1.40
		4, 2, 3, 1	8837	158	59	22	37	61	60	1.37
	225	Basal	8616	154	38	15	23	61	38	1.33
		5, 5	9006	162	40	15	25	60	42	1.40
		6, 4	8938	160	40	15	25	61	41	1.38
		7, 3	8863	159	39	15	25	61	40	1.37
		6, 2, 2	9263	167	41	15	26	60	44	1.43
		5, 3, 2	9313	169	41	15	27	59	45	1.45
		4, 4, 2	9365	170	42	15	27	59	45	1.45
		5, 2, 2, 1	9630	178	43	15	28	57	49	1.49
		3, 3, 3, 1	9752	182	43	15	29	56	51	1.51
		4, 2, 3, 1	9656	179	43	15	28	57	49	1.50

The fertilizer splits are applied at transplanting for one split, at transplanting, tillering for two splits, transplanting, tillering and panicle at three splits, transplanting, tillering, panicle and booting for four splits. PFP is partial factor productivity for applied N; Y_o is grain yield at 0 kg N ha^{-1}; *N*r is the amount of applied fertilizer N; PE is physiological N efficiency; RE is fertilizer recovery, and AE is agronomic N efficiency, WP_{I+R} is the water productivity.

4. Discussion

4.1. Model Evaluation

In our study, we evaluated that ORYZA (v3) performed satisfactory in simulating results from both calibration and validation experimental data sets. The goodness of parameters between observed and simulated values like *RMSEn*, R^2 and the graphical analysis of the results of our experimental data were in good comparison to japonica variety Wuxiangjing and IR72 [24,43]. The *RMSEn* for the biomass partitioning was good as compared to nitrogen uptake especially for leaves, it may be because of the high *RMSEn* value for LAI, which is also reported in reference [35,55] which might be due to the insufficient precise evidence regarding soil N indigenous supply and soil organic matter in different layers of soil.

4.2. The Response of Sifferent N Fertilizer Rates

For scenario analysis, there was a decreasing trend in historical simulation (Figure 5). AWD has displayed more yield compared to CF at 0 fertilizer N rate, nevertheless exhibited no significant difference at high fertilizer N rates. At 0 N rate, the increase might be due to low leaching of nutrients into the soil, runoff, and drainage [68]. The highest yields at high fertilizer N rates had no significant difference at both AWD and CF. These results are in confirmation with Tan et al. (2013) who reported that the extremely shallow groundwater table guaranteed the success of AWD on grain yields and no significant yield penalty under AWD and an increase in water productivity by 17% as compared with continuous flooding irrigation treatment [69]. Another study also revealed that the adaptation of AWD can conserve around 38% of water without adversely affecting their yields [70]. The yield margin above 225 kg N ha^{-1} fertilizer N rates was very low (Figure 5) in both AWD and CF [24], also the results are in confirmation with Peng et al. (1999) [71], who reported curvilinear response of rice yield to nitrogen fertilizer applied rate. Linear response of rice to nitrogen rate below 150 kg N ha^{-1}, and a plateau off when the applied N rate is greater than 150 kg N ha^{-1} was reported by Harell et al. (2011) [72]. Moreover, in China southeast the fertilizer application is more than 260 to 300 kg N ha^{-1} having 6000–8000 kg ha^{-1} rice yields [73]. Our study suggested that there is still a scope of high yield with less nitrogen and water application.

4.3. Fertilizer N Splits, Efficiencies and Water Productivity

Application of fertilizer N in China is normally to apply all fertilizer in one either two splits at transplantation or 10 days after transplantation. Our study suggested that splitting the fertilizer N resulted in high N use efficiencies at both AWD and CF conditions. Same reports were also suggested for flooding irrigation in reference [24,74], that N use efficiency can be enhanced by increasing the number of splits and late applications. Small doses of frequently fertilizer application were also suggested by Reference [75]. In AWD the high nitrogen uptake might be the reason of low nitrogen leaching which resulted in high N uptake and yield with high nitrogen efficiencies compared to CF. Re-watering can enhance the photosynthesis process in later stages, increases carbon remobilization from vegetative tissues to grains, increases root biomass associated with high yields and nitrogen uptake [76].

However, agronomic efficiency at CF was higher than AWD which was reported in reference [67]. Nevertheless, yield was increased in AWD, it might be an inferior grain yield in CF conditions which were mainly accredited to a lesser percentage of filled grains at HN (high amount) than at NN (normal amount), although either more spikelet number per panicle or more panicles contributed in the AWD to a higher yield [76]. Partial factor productivity was high at the AWD compared to CF at both high and low fertilizer N rate. Same results were reported in reference [6,67].

The lowest WP_{I+R} values under both irrigation regimes were obtained under zero nitrogen application, and WP_{I+R} increased with applied nitrogen rate [67]. WP_{I+R} at 150 kg ha^{-1} was observed highest 1.16 kg m^{-3} at AWD regime with four split (3:3:3:1) and lowest at basal N application

0.94 kg m^{-3} while for CF was 1.04 kg m^{-3} and 0.82 kg m^{-3} respectively. These results are with an agreement with [77,78], who also reported that WP_{I+R} can be increased under intermittent irrigation whereas, it also reported a decline in WP_{I+R} under AWD [79]. The implementation of AWD at field and schemes levels should consider local climate, soil type, rice genotype and season for the improvement of WP_{I+R}.

5. Conclusions

This study concluded that ORYZA (v3) performed satisfactorily the interaction of water and nitrogen conditions. The model simulated biomass partitioning well match with the observed values and also nitrogen related partitioning. The model overestimated the simulated LAI compared to observed data, however it was statistically in the accepted range. ORYZA (v3) can be adopted, to run under different climatic conditions. For scenario analysis from 45 years, historical data indicated that AWD can be adopted as the main irrigation method under optimum fertilizer rates. The study also suggested that N rates should be applied in more splits with the later application. The better split identified was (3:3:3:1) that was at transplanting, tillering, panicle initiating and booting stage. However, splits N doses in AWD performed better as compared to CF. Partial factor productivity was high at AWD and agronomic efficiency was high at CF. High yield was associated with AWD, but there were no significant differences between AWD and CF. AWD can save more water could save energy and labor cost, and with no production reduction. The study suggested that there might be more investigations, essential to explore the effects of different rice genotypes, and their interaction with fertilizer N and AWD under different climatic and soil conditions and also for the future climatic scenarios and its response to yield and biomass of rice crop.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/9/1/39/s1, Table S1: ORYZA (v3) evaluation results for crop growth variables simulations for calibration data set over the entire growing season; Table S2: ORYZA (v3) evaluation results for crop growth variables simulations for validation data set over the entire growing season.

Author Contributions: J.X. conceived and designed the experiments; F.H collected data for model input Q.L., S.F.R., Q.W., experimental work; F.H., J.X., and S.F.R., analyzed the data and model calibration and paper writing; Q.W. and A.u.R.K., concise the paper. All authors have read and approved the final manuscript.

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