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Assessment of climatic variability on optimal N in long-term rice cropping system

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Abstract

Climatic variability is one of the most significant factors influencing year-to-year crop production, even in high yielding and high-technology agricultural areas. Many studies have attributed variation in yield and crop response to N fertilizer in general terms to differences in varietal characteristics, but few attempts have been made to systematically disentangle the contributions of the genotype from other factors as climatic conditions. In this study, we used ORYZA V3 rice crop model to evaluate impact of climatic variability on optimum nitrogen application rate in rice cropping system. The results show that, solar radiation and N management practices play important roles in the response of N in grain yield. Maximum and minimum temperature has less effect on the grain yield compared to the solar radiation. Optimum N was higher in the dry season compared with the early wet season. Optimum N rate for the grain yield was around 200, 150 and 100. Nutrient use efficiency (NUE) was higher in early wet season (EWS) and late set season (LWS) in higher rate of nitrogen compared to the dry season (DS). Observed grain yield and simulated grain yield was almost similar in both seasons. The ORYZA simulation model performs well for estimating optimum N application.

Keywords: ORYZA v3, climatic variability, grain yield.

Introduction

Irrigated rice fields in Asia contribute about 70% to global rice production and provide the staple food to nearly half of the world's population (Bouman et al., 2007). Rice yields vary strongly (<2 - >15 MT ha⁻¹) across Asia depending on location and variety (Horie et al., 1997; Ying et al., 1998). Climatic variability is one of the most significant factors influencing year-to-year crop production, even in high yielding and high-technology agricultural areas. Dobermann et al. (2003) reported yields from different locations in Asia, ranging from 3.6 - 5.3 MT ha⁻¹ for local varieties without external nutrient inputs, which were probably limited by indigenous soil N supply (Cassman, 1999). The effect of N fertilization is variety-specific and depends on the climatic conditions (Van Keulen, 1977). Horie et al. (1997) and Ying et al. (1998) demonstrated that with sufficient N supply, yields were 40% higher in subtropical areas than in tropical areas.

Many studies have attributed variation in yield and crop response to N fertilizer in general terms to differences in varietal characteristics, but few attempts have been made to systematically disentangle the contributions of the genotype from other factors as climatic conditions. Simulation models, which are simplified representations of a complex reality, are useful tools to explore and disentangle effects of interacting factors on crop growth and development (Bauman et al., 1996).

In this study, we used the rice growth model ORYZA V3 to assess variation of N fertilizer rate and N use efficiency across seasons and years, as related to climatic conditions, to identify adaptation options for N adjustment, such as rate and distributions of N fertilizer with patterns of climatic conditions and to evaluate predictive capacity of historical weather data for different seasons in N management. We evaluated, as well, the variation among genotypes of these responses and we have attempted to develop specific association between climatic conditions and optimum nitrogen rate for our genotypes of study.

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Material and Methods

Methodological framework

Crop models help in the evaluation of cropping system productivity variations with long term variation of climatic conditions. In this study, we used ORYZA V3 rice crop model to evaluate impact of climatic variability on optimum nitrogen application rate in rice cropping system. Crop modeling is a useful tool to explore conditions that are not available within experimental field conditions. The model ORYZA V3 was then calibrated and validated using the data from the LTCCE IRRI (Embedded plots) field experiments. Rice yield under various nitrogen managements was simulated to estimate optimum nitrogen application for each year covering period from 1985 to 2015 (using long-term historical weather data).

Optimum nitrogen application rate (N optimum) was defined as the amount of total nitrogen applied at which an acceptable profitable grain yield is obtained and above which additional application of nitrogen will provide no significant benefit in yield or in profitability (Witt et al., 1998, 2000). N optimum was computed using linear and nonlinear regression between nitrogen application rates and simulated yield within the period from 1985 to 2015. Long term actual yield data from the LTCEE was also used to compare actual variability and the simulated N optimum to validate the approach and to define an approach assisting in developing recommendation for nitrogen management with changing climatic conditions. These simulations were run for the two varieties in this study.

Model description

The rice crop model ORYZA V3 used for the simulation studies is an updated version of the model ORYZA 2000 (Bouman et al., 2001) which has been improved to account for the interaction of water and nitrogen on rice crop growth and with more mechanistic approach in rice crop functioning under limited environmental conditions (Li et al., 2016). This crop model simulates the growth, development and water balance of rice crop under potential, water-limited and N-limited environments with a daily time step.

Field experiments

The experiment was conducted during the early wet season 2015 and 2016, and dry season 2016 and 2017 in the embedded plots of the LTCCE (IRRI). Two contrasting varieties were used to evaluate variability among varieties in yield and N use efficiency. The experiment was designed in split plot with 3 varieties but only two varieties were included in this study. Variety was the main plot and 6 N rates were considered as the sub-plots. These treatments were replicated four times (total of 72 plotss) in each season and year.

Data used for model calibration and validation

The ORYZA V3 model required different data inputs to compute daily production of plant parts dry matter and phenological developmental rate during the cropping season. Among these data are variables characterizing the environmental conditions of production, namely, weather and the soil. The model required, as well, inputs providing details of the crop management and the variety.

Climatic data

Daily weather data on total solar radiation (KJ m^{-2} d^{-1}), average minimum and maximum temperature (^{0}C), vapor pressure deficit (kPa), windspeed (m s^{-1}), and total rainfall (mm d^{-1}) were collected from 1983 to 2015, from IRRI website (https://irri.org/climate).

Soil Data

Physical and chemical properties of the soil of the experimental field were characterized from soil samplings. Variables considered were soil texture (sand, clay content, and bulk density), pH, and Organic C, N at different layers.

Crop Data

Total above ground biomass at different key stages and the grain yield data were collected for early wet season (EWS) 2015 and 2016, dry season (DS) 2016 and 2017 from the embedded plots of the LTCCE, IRRI .

Date of sowing, emergence, transplanting, panicle initiation, flowering, and maturity were also recorded from these experiments. Data from DS 2017 and EWS 2016 was used for the model parameterization and for the crop parameters calibration. During these experiments, stem, green leaves, dead leaves and panicle dry weight, green leaf area and leaf area index, grain yield were collected. Data from DS 2016 and EWS 2015 was used for the model simulation outputs validation. These data are totals of above ground biomass and grain yield.

Model parameterization

We estimated the crop parameters needed for ORYZA V3 to simulate the two varieties of study, V4 (IRRI-146 which is also known as NSIC Rc 158) and V8 (IR2-10-L1-Y1-L). We followed the procedure described by Bouman (2007), using the calibration data set from EWS 2016 and DS 2017, to estimate the initialization value for the model crop parameters. DRATES application was used to calculate parameters related to the crop phenology using the recorded dates of emergence, panicle initiation, flowering, and maturity. PARAM application was used to calculate the factor of biomass partitioning among plant organs (stem, green leaves, dead leaves, and panicle).

Model calibration

Calibration is the process of definingand fine-tuning the model parameters to ensure model ability to simulate existing conditions of production. The calibration procedure for the ORYZA V3 model parameters is well described in the users' manual (https://irri.org)

We used the auto calibration application for ORYZA model V3 to calibrate the parameters of leaf growth and biomass partitioning set to obtain parameter values that minimize the errors between simulated and the observed data for the totals of above ground and panicle biomass.

Model Validation

The independent data set (2015 EWS and 2016 DS) of V4 and V8 varieties under the experimental conditions of the embedded plots of IRRI LTCEE was used to evaluate performance of the model simulating biomass production and grain yield. We computed the statistical parameters to assess the goodness of fit between observed and simulated values. The simulated and measured grain yield and total above ground biomass were graphically compared and the linear regression provided the slope (α), intercept (β), and coefficient of determination (R^2) of the linear regression between observed (X) and simulated (Y) values. The absolute root mean square errors (RMSEa) and normalized root mean square errors (RMSEn) were also calculated to evaluate the level of accuracy of the model in simulating rice crop growth and yield. These parameters were computed as following:

RMSE absolute $= \left(\sum_{i=i,...n}(Y_{I-}O_i)^2 \right)^{0.5} / \text{n}$

RMSE normalized (%) $= 100 \left(\left(\sum_{i=1,..n}(Y_i - O_i)^2/n \right)^{0.5}/\bar{O} \right)$

Where, Y_i and O_i are simulated and measured values, respectively, and O is the mean of all values, and n is the number of measurements.

Scenario Analysis

Simulation using the two varieties V4 (IRRI 146) and V8 (IR2-10-L1-Y1-L), and different rates of N was performed over 32 years (1983-2015). In addition of the six nitrogen management used in the LTCEE, 10 fertilizer N rates (0, 60, 90, 120, 150,180, 240, 300, 360 and 390 kg ha^{-1}) were used. The total amount was proportionally split into three application times (23, 44 and 57 DAT). Bilinear regression between simulated rice yield and the gradient of nitrogen rate application was done to define optimum nitrogen for each year.

Variability of the N optimum with years was then analyzed and correlation analysis of its variation with climatic variables as solar radiation, maximum and minimum temperature was perfomed using excel. Linear regression between optimum N and climatic variables was used to define the rate of variation of optimum N with unit of variation of the climatic variables. Validation of the linear and nonlinear regression between optimum N and climatic conditions was carried out using the long term yield data from the long term continuous cropping experiment (LTCCE) of IRRI. Grain yield data over the 32 years was then gathered from the historical records of the LTCCE of IRRI. As the rate of nitrogen and varieties were different in different years and season across the 32 years, the average yield was computed and collected for each rate, season and years.

Results

Climatic variability during the period 1983-2015

Daily solar radiation, rainfall, average minimum temperature and maximum temperature of 3 rice cropping seasons are shown in Figure 1. Incident solar radiation was observed higher during the dry season and was lower during the late wet season. Maximum and minimum temperatures were observed to be almost similar during the DS and EWS, whereas during LWS, mximum and minimum temperature was observed lower throughout the year except in 1996. The average rainfall was observed highest during the EWS and LWS and lowest during the DS. Rainfall fluctuated within the years both in the EWS and DS.
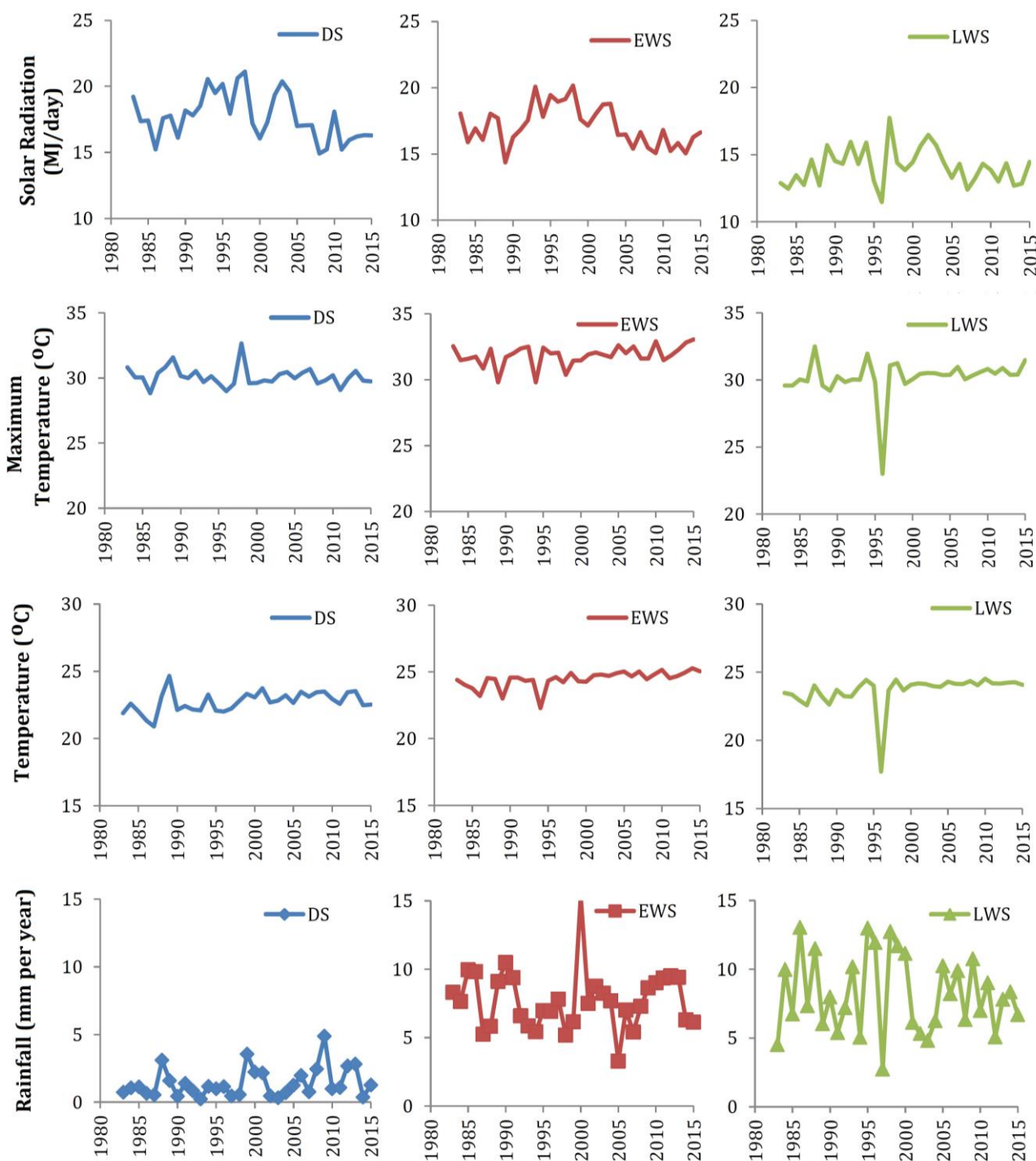
Figure 1. Trends of Solar radiation, maximum temperature, minimum temperature, Rainfall across 32 years in 3 different seasons.

Assessment of grain yield across the year and season

Grain yield of 3 different seasons across the 32 years is shown in Figure 2. Observed grain yield declined until 1992, both in the DS and EWS. In the LWS, grain yield fluctuated within the years. In the DS, grain yield was observed higher with higher N rate application. In the EWS and LWS, grain yield was almost similar in all treatment levels of nitrogen except in the 0 level of nitrogen.

Adaptation options for N adjustment to pattern of climatic conditions.

Figures 3a and 3b show the grain yield and nitrogen use efficiency under different rates of nitrogen. In the DS, we observed an in increasing nitrogen trend towards the grain, giving the high yield with highest rate of nitrogen (200 kg ha-1). Similarly, the nitrogen use efficiency (NUE) was higher in the 100 kg h-1 of nitrogen and stared to shift downward with higher rate of N. In the EWS and LWS, N response functions started to shift downward at 150 and 100 kg ha-1 of N for grain yield. Similarly, the slope shifted downward at 50 kg ha-1 of N for the NUE both in the EWS and DS.
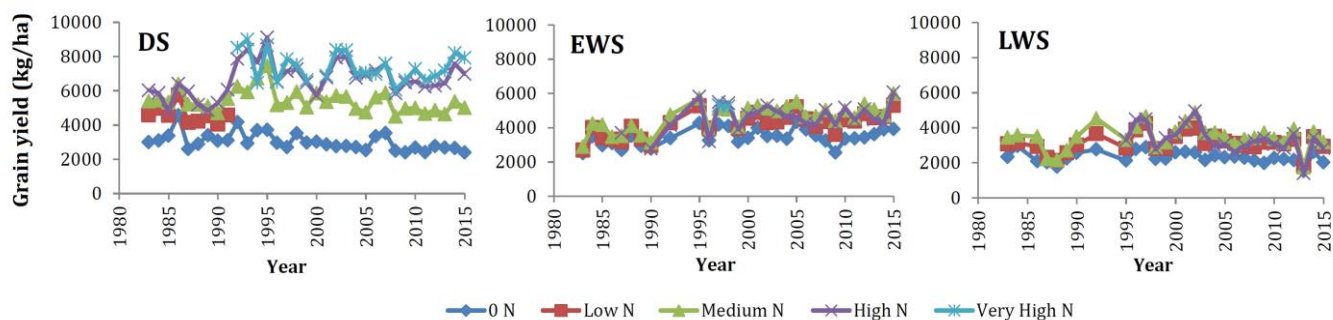
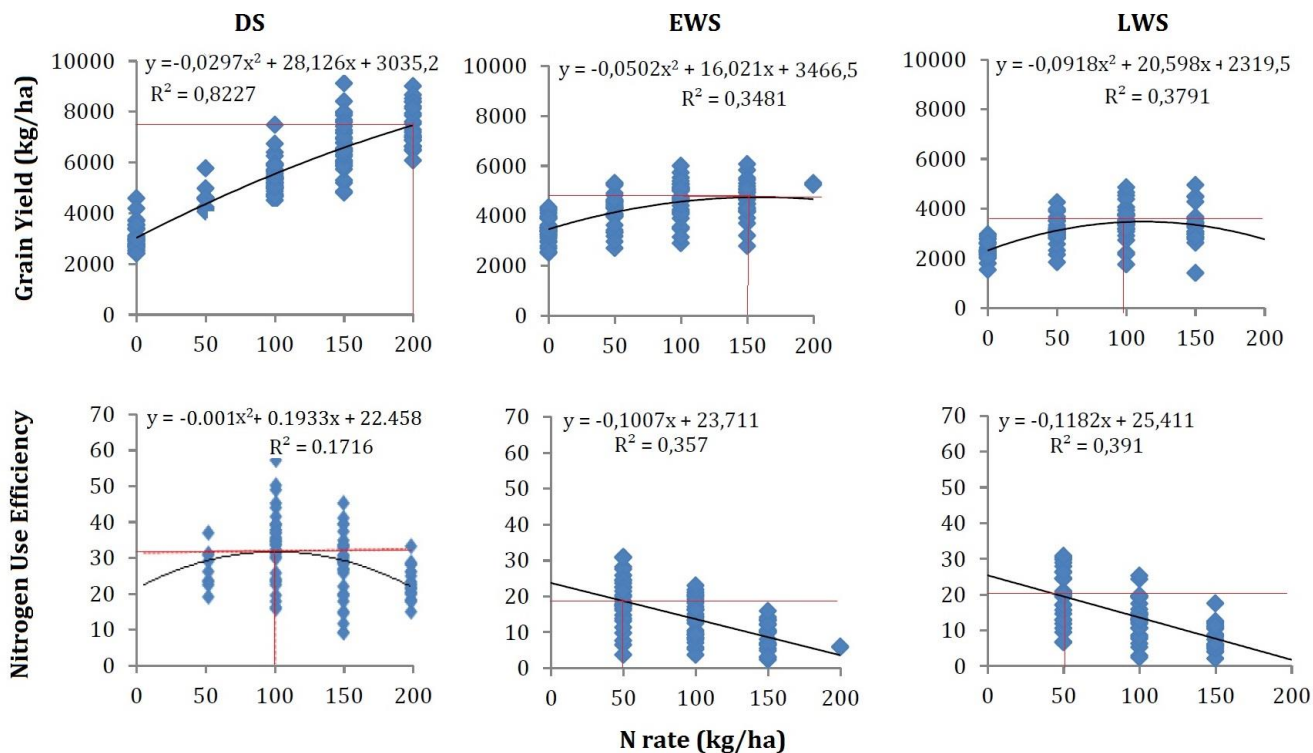Figure 2. Trends of grain yield in 3 different seasons across the 32 years from LTCCE of IRRI.

Figure 3. Grain yield (a) and Nitrogen use efficiency (b) in different rates of nitrogen in long term experiment IRRI

Model Evaluation for Optimum N

Figure 4 shows the results of the simulated optimum N for 32 years. Here, we can see that the simulated Optimum N is in the range of 170 to 200 kg ha^{-1} in DS except 2007. In the EWS, simulated optimum N is in the range of 120 to 170 kg of N ha^{-1}.
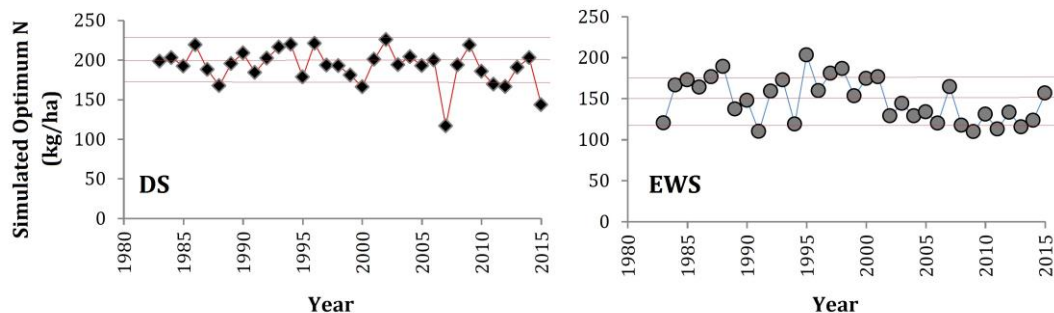

Figure 4. Simulated Optimum N across the 32 years in DS and EWS.

Relationship between simulated optimum N v/s climatic parameters

The Optimum N required was estimated from Oryza 2000 V3. Average climatic parameters such as radiation, minimum air temperature and maximum air temperature were calculated for the period between transplanting and physiological maturity (harvesting time). The correlation between simulated N requirement and the above mentioned climatic parameters are shown in Figure 5 and Figure 6. Significant

negative correlation between optimum N and minimum air temperature was observed in EWS for V8. However, positive correlation was observed in all treatments between optimum N and solar radiation. Negative correlations were observed between optimum N and air temperature (both minimum and maximum air temperatures) all cases except for V4 during EWS.

Early wet season

Linear regression between simulated optimum N and weather parameters for early wet season are shown in Figure 5. We observed a positive and strong relationship between optimum N and solar radiation. However, we could not find a strong relationship between optimum N and air temperature in any cases, except for V8 with minimum air temperature.
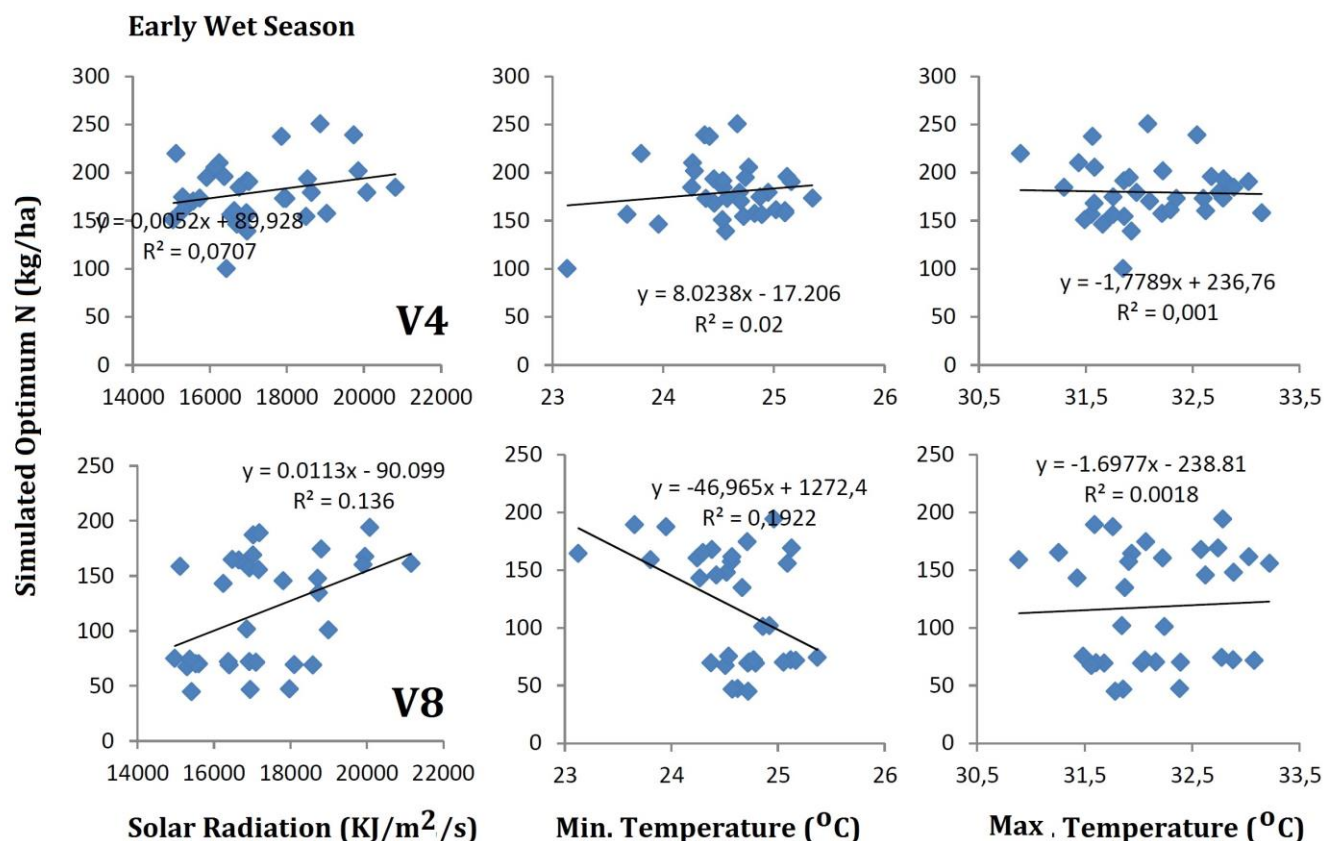

Figure 5. Linear regressions between simulated optimum N and weather parameters during early wet season

Dry season

Linear regression between simulated optimum N and weather parameters for dry season are shown in Figure 6. Strong and positive relation between optimum N and solar radiation was found for V4 only. V8 found weak and positive relationship between optimum N and solar radiation. The relationships between optimum N and air temperatures were significant in the dry season.

Discussion

The yield decline was observed until the 1991 DS. (Flinn and De Datta, 1984) explained that the reason for the decline in grain yield before 1992 was because of the B toxicity and Zn deficiency and alkaline irrigation water. After 1992, various changes occurred in the design of the long term experiment and its crop management (Dobermann, 2000). In 1993 and 1994, chlorophyll meter (SPAD 502, Minolta, Ramsey, NJ) readings of the uppermost fully expanded leaf (Y-leaf) were used to determine the timing of N topdressings based on thresholds established by Peng et al. (1996). In the 1994 and 1995 DS, $ZnSO_4$ was also applied as a blanket application to the plots to provide 10 kg ha^{-1}. Yield increase after 1992 do not support the hypothesis that B toxicity or Zn deficiency had much effect on the yield decline and reversal. The irrigation water source has not been changed and is not among those known for occasional high B concentrations at the experimental site (Cayton, 1985).

Improved crop N supply (increased N supply from fertilizer to the root system, increased N rate and timing etc.) might be the major factor responsible for increased rice yields after 1991. The Dry Season (DS) yield was higher compared to the EWS and LWS which can be the result of the higher solar radiation in DS

compared to the EWS and LWS. Dobermann et al (2000) also reported that 54% of the change in rice yields was due to increase in solar radiation in the long term continuous rice cropping system of IRRI. Yang et al (2008) explained the yield gap between dry season and wet season with the higher radiation in dry season.
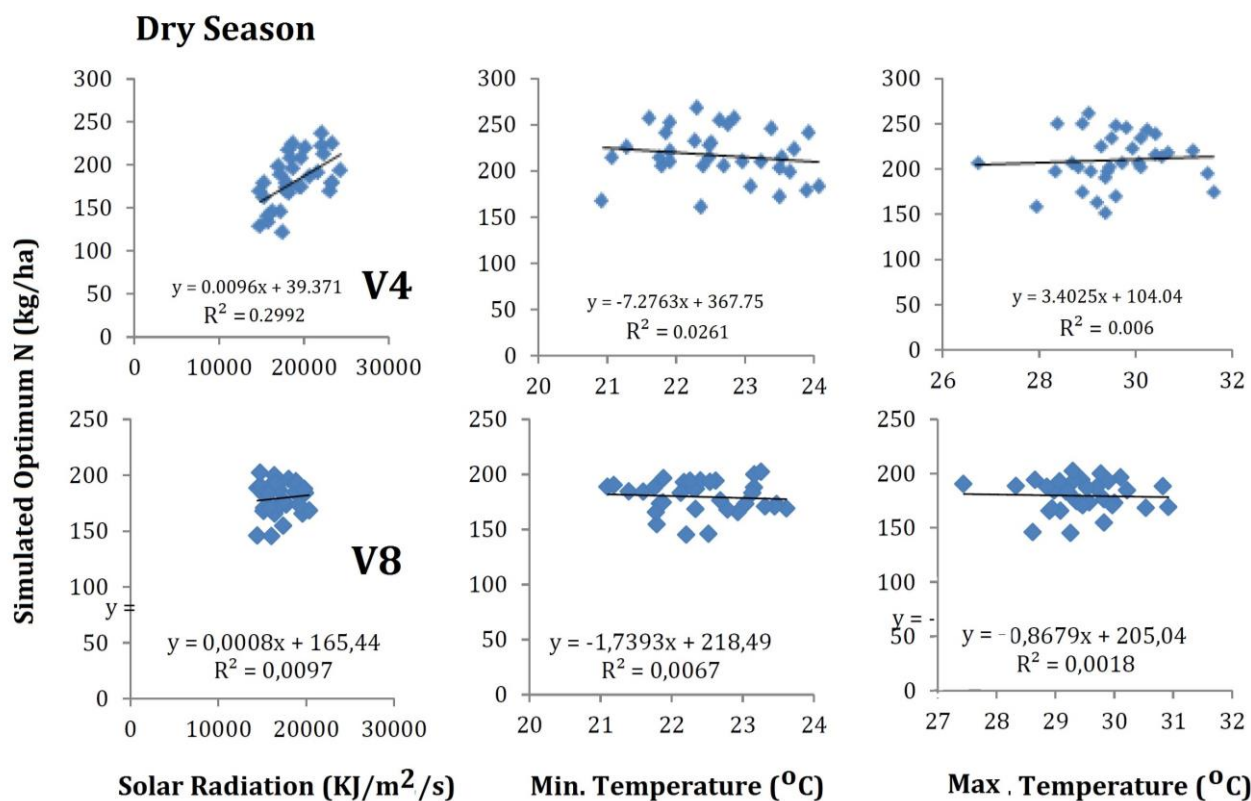

Figure 6. Linear regressions between simulated optimum N and weather parameters during dry season.

In the DS, with increased rate of nitrogen, the grain yield also increased. Based on these results, we can say that in the DS, to get the higher grain yield, we can apply N by up to 200 kg ha^{-1}. However, in the EWS, grain yield increased up to the 150 and started to shift downward. Moreover in the LWS, grain yield was maximum in 100 kg ha^{-1} and after that started to decline. Hence, our results indicate that the optimum N for EWS is 150 kg ha^{-1} and 100 kg ha^{-1} for LWS.

Greater NUE was achieved in the DS with 100 kg ha^{-1} and the NUE has decreased after 100 which indicates that, with higher rates of the nitrogen application, the NUE decreases. In the EWS and LWS, the NUE was greater at 50 kg ha^{-1} and also decreases with increased N rate. Decreases in N uptake efficiency at higher N rates have also been reported by Eagle et al. (2001) and Timsina et al. (2001) .

Optimum N from the observed data (Figure 2) and optimum N from simulated data (Figure 4) shows the similar results both in the DS and EWS. The optimum N in observed data and optimum N in simulated data in the DS and EWS were ±200 kg ha^{-1} and ±150 kg ha^{-1} respectively. If we compare between the DS and EWS, the optimum N in the DS shows higher optimum than in the EWS. This explains that the Oryza 2000 V3 model performs well for optimum N application. Small anomalies between years explain the sensitivity of Oryza 2000 V3 while estimating optimum N.

Conclusion

From our study, we can say that solar radiation and N management practices play important roles in the response of N in grain yield. Maximum and minimum temperature have less effect on the grain yield compared to the solar radiation. Optimum N was higher in the dry season compared with the EWS. Optimum N rate for the grain yield was around 200, 150 and 100. NUE was higher in EWS and LWS in higher rate of nitrogen compared to the DS. Observed grain yield and simulated grain yield was almost similar in both seasons. The ORYZA simulation model performs well for estimating optimum N application.

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