Application of a crop-atmospheric model to assess the optimized nitrogen fertilizer rate for improving rice yield production.

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Abstract

To increase rice production, fertilizer plays a crucial role in rice yield. In this research, we applied the coupled atmospheric and crop model, which is based on the WRF and CERES-Rice models, to find the appropriate nitrogen fertilizer level for increasing rice yield production in northern Thailand. The model was conducted from October to December in 2011 to 2015. To evaluate the model capability, the output from the model, including meteorological data, i.e., precipitation and temperature, and rice production, was compared to actual observation data. The modeling system shows an acceptable level of output for statistical examination; for example, the R^2 values were 0.93, 0.76 and 0.97 for precipitation, temperature and rice production, respectively. To assess the optimization of the nitrogen fertilizer level, we designed 9 experiments: control cases and other cases that were multiplied by a factor of 2 – 10 times the nitrogen fertilizer levels. The model suggested that we can produce worthwhile rice yield production by approximately 4830 kg/ha if we increase the nitrogen fertilizer levels by 36 kg/ha.

Keywords: Rice yield production, Crop model, Nitrogen fertilizer, DSSAT, WRF

1. Introduction

Rice is an internationally important stable food that supplies more than 50% of the total population's consumers. According to the Food and Agriculture Organization (FAO), the most of the world’s rice is produced from Asia, with approximately 551-593 million tons of paddies (370-396 million tons of rice). Millions of tons of paddies are produced mainly for domestic consumption. On the world market, only 19 – 27 million tons of rice are produced each year, whereas the wheat trading volume reaches 93 – 96 million tons, of a total of 548 – 613 million tons. Approximately 22-23 million tons are produced in Thailand per year, with a famous aromatic and quality rice variety known as Khao Daw Mali 105 (KDML105). Rice is widely cultivated in Thailand in approximately 75% of the total area. Most of the cultivated area is in the northern and northeastern parts of Thailand. Over 50% of the rice areas are located in the northeast, and northern Thailand is a hilly mountainous area. Upland rice has a smallholding area in the northern hilly mountainous areas in the far northeast. According to the Thailand agriculture report, the proportion of rice production in the Northern Region in 2017 amounts to approximately 6 million tons or 25% of Thailand's total rice production. Rice cultivation in northern Thailand is based on a traditional method, which is inherited from generation to generation.

A number of meteorological and climate factors affect agricultural production, such as temperature, rain and solar radiation (Amnuaylojaroen and Chanvijit, 2019). Another factor is water management, particularly rice water, which is the main factor influencing traditional rice planting. Nutrients are also an important food for rice cultivation. Rice can use nutrients that usually consist of potassium (K), phosphorus (P), and nitrogen (N) through fertilizer. Nitrogen is the most constrictive control factor for crop production. It can enhance biomass, protein yield, and plant tissue concentration. With the initiation of rice, which reflects better amounts of gluteline and prolamine storage proteins, grain protein increases to improve nitrogen fertilization (De Datta et al., 1972; Nangju and De Datta, 1970; Cagampang et al., 1966). If the grain protein is >10%, a grain protein can increase the causes of the lysine content to decrease only slightly. The majority of commercial rice has less than 10% grain protein (Blumenthal et al. 2008).

To increase productivity in agriculture, crop production technology could be used to improve the amount of its product. The efficiency of crop production is based on the right decision in the right way at the right time. The Decision Support System for Agrotechnology Transfer (DSSAT) is an agriculture software program that uses for a broad array of agriculture studies at different spatial and temporal scales. It includes farming and precision management, regional climate variability impact assessment and climate change impact assessments, gene-based modeling and selection, water use, emissions of greenhouse gases, and long-term sustainability through the use of organic soil carbon and nitrogen balance. In over 150 countries, DSSAT has been used by many of researchers, educators, consultants, expanders, growers, and policymakers. DSSAT was chosen because the suitability of the DSSAT module to simulate crop growth and yields in smallholder farming systems has successfully been demonstrated through a wide range of land, management, and climate conditions (MacCarthy et al., 2012, 2017; Ngwira et al., 2014; Corbeels et al., 2016; Adnan et al., 2017a,b). For example, in 2003, Jactap and Abamu used DSSAT to evaluate the planting of maize in tropical savannah to determine the species' variety. They found that the seed yielding system and physiological properties were tested in close accordance with the actual values and that the OBA SUPER2 crop has a longer cultivation period that is more productive than TZUTSR-WC5, which has a moderate cultivation period. The results were found to be arbitrarily satisfactory for the duration of cultivation. Farmers with no fertilizer manufacturing strategies can achieve higher productivity than those with normal cultivation. In a system with high nitrogen fertilizers, the production is higher than in other plants. In 2013, Caviglia et al. used DSSAT to test the hypothesis that double wheat/soybean production would be used to grow crops, which could contribute to improving water capture and water production each year and reduce annual losses in nonearning water in southeastern Argentina. They found that the increase in water production has a relationship ($P < 0.0001$) with reduced water loss, mainly in the long run. The sequences of high intensity (ISI = 1.5 years - 1 year) are stable and extremely effective, as is the traditional series in our region based on summer wheat planting. In 2007, Saseendran et al. carried out a plant growth survey to enhance yield and nitrogen simulation using DSSAT in tissue flow in comparison to general effects on the water content of model administration.

To avoid costly long-term experiments, a common and well-accepted strategy of dynamic crop models is used. This research presents the application of a coupled atmospheric model based on the Weather Research and Forecasting Model (WRF) and a crop model based on CERES-RICE in the DSSAT modeling system. The meteorological output from the WRF model includes (maximum and minimum) temperatures, rainfall and solar radiation used as environmental factors in the crop yield calculation in DSSAT from October to December from 2011 to 2015.

2. Methodology

We used a coupled atmospheric model called the WRF model, version 3.8 (Skamarock et al., 2008) and a crop model called the CERES-RICE model (Ritchie, 1986) in DSSAT, version 4.7. WRF model has been performed the meteorological data including maximum and minimum of temperature, rainfall and solar radiation for DSSAT. The results from DSSAT were then used to analyze the proportion of nitrogen fertilizer used in rice production in northern Thailand. To test the performance of environmental factor from WRF model such as temperature and precipitation, they were compared with ground-based measurements data from the Thai Meteorological Department. Whilst the output from DSSAT was validated with on-farm dataset from the Department of Agriculture in Thailand.

2.1 Study area description

The northern parts of Thailand are marked by mountainous terrain, separated by the tectonic plates. The dominant river in this region is the Chao Phraya River, the origin of which is at a confluence of four rivers, the Ping, the Wang, the Yom and the Nan. Many kinds of natural disasters occur because of these characteristics. The mountain ranges in the north are steepened by deep river valleys and highlands in the middle region. These natural features have accommodated a wide variety of agriculture such as paddy cultivation in rice-growing valleys and moving cultivation in upland meadows. The mountains dominate the landscape which makes it a mountainous area. It contains the headwaters of our major rivers. The Ping, Wang, Yom and Nan are the smallest, middle and largest growers, respectively. In specific, particular, KDML 105, is globally recognized as the highest quality, with a total rice yield area of approximately 405,801 hectares and 1,487,506 tons per year. There is a great deal of paddy fields in this place. The rice crop is harvested annually from November to December.

2.2 WRF configuration

The WRF model has been used to investigate for several atmospheric researc. It is a nonhydrostatic mesoscale model that consists of many physical schemes. The CERES-RICE Model (Ritchie et al., 1986) in DSSAT was chosen for simulating the growth and yield of rice in northern Thailand. The Thai rice cultivar used in the study was KDML-105. In this paper, we configured two WRF domains with a grid spacing of 50 km and 10 km. In addition, the model was set the vertical levels by 30 levels up to 50 hPa. The outer domain mainly covered the most of the up of Southeast Asia and some parts from East and South Asia, such as South China and East India, as shown in Figure 1.

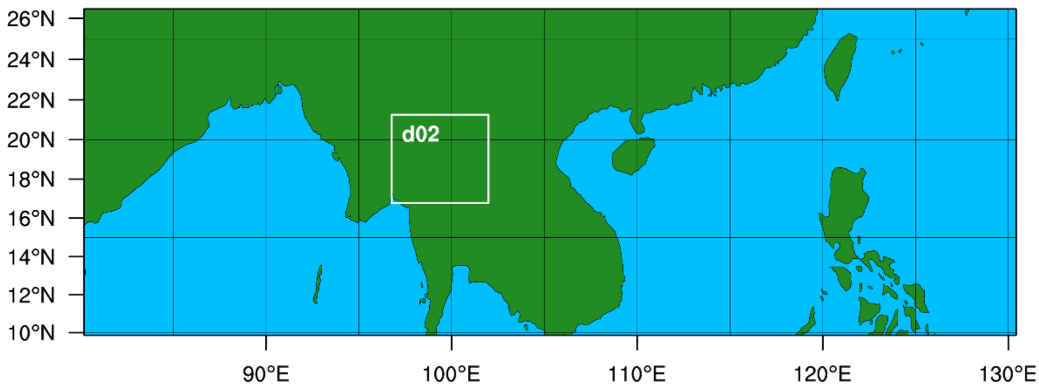

Figure 1. WRF domain configuration

The inner domain covered northern Thailand. The WRF configurations were similar to those of Amnuaylojaroen et al., 2019. The rapid radiative transfer model (RRTMG) was used for the evolution and feedback of atmospheric aerosol on both longwave and shortwave radiation in the model calculation (Iacono et al., 2008). At the same time, the feedback of aerosol affects on meteorology was included in the model through a computing in the Thompson scheme (Thompson et al., 2004). Grell-3 scheme was used for calculation the subgrid-scale atmospheric processes, while Noah Land Surface Model (Chen and Dudhia 2001) was responsible for the land and atmospheric interaction. Grid nudging technique (Stauffer and Seaman, 1990) was applied in the model configuration for accurate meteorology for all variables in the model with nudging coefficients of 0.0003 s^{-1} every 6 hours. The WRF model was performed from January to December from 2011 to 2015 to simulate the weather conditions for the DSSAT modeling system. The environmental factors, including maximum and minimum temperature, rainfall and radiation from WRF output in the rainy season between June and October, were used as inputs into DSSAT.

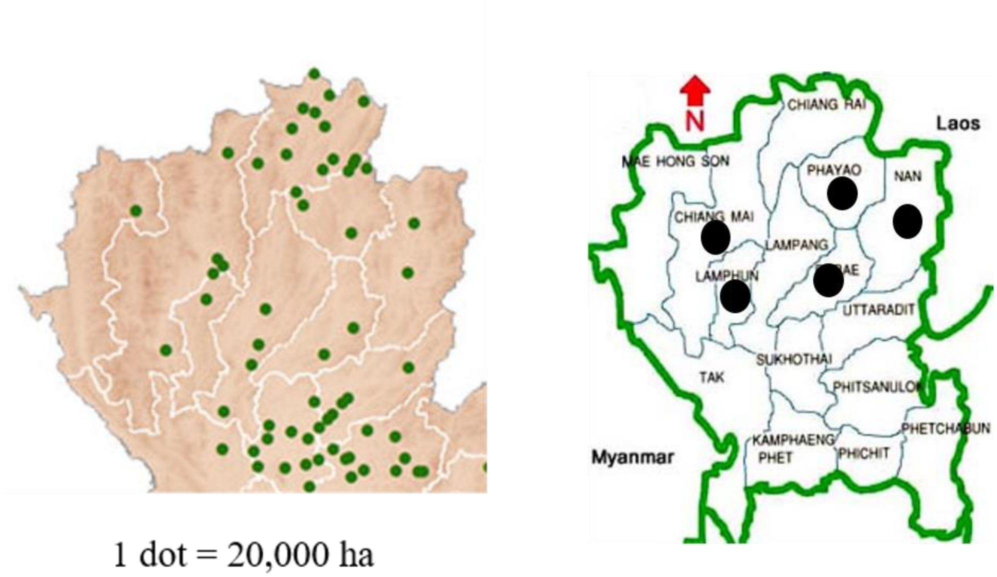

Figure 2. Rice plating areas in northern Thailand (left) (Ricepedia.org) and locations of the Thai Meteorological Department (TMD) (black dot) (right)

2.3 DSSAT configuration

To simulate crop yield production, we performed the Decision Support System for Agrotechnology Transfer (DSSAT), version 4.7.5, from June to December from 2011 to 2015. June to October is defined as the planting period, while November to December is defined as the harvesting period. The seasonal run involved crop development, growth, and yield along with changes in water, soil, carbon and nitrogen balance under the cropping system (Jone, et al., 2003). These calculations were based on CERES-RICE, which is an individual submodule embedded in DSSAT that simulates phonology, daily growth, plant nitrogen and carbon demands, and senescence of plant material. Based on complete information on total crop production, we selected 5 provinces, including Phrae, Chiang Mai (CM), Nan, Lamphune, and Phayao, to analyze rice production. We chose the location of rice planting areas as shown in Figure 2 in 5 provinces to estimate rice production. The crop model configurations including water demand, fertilizer level and soil analysis, were similar to Amnuaylojaroen et al., 2021. The water demand for the growing rice in each month was configured as shown in Table 1 (Intaboot, 2020). The fertilizer level was used according to the report of the Department of Agriculture of Thailand with N: 6 kg/ha, P_2O_5: 7.5 kg/ha, and K_2O: 7.5 kg/ha. The soil analysis layers were set up with bulk density of 1.035 g/cm^3, organic carbon by 1.46%, total nitrogen by 0.601%, pH in buffer of 5.63, pH in water of 6.59, extractable phosphorus of 5.766 mg/kg, exchangeable potassium of 5.766 cmol/kg and stable organic of 1.46%.

Table 1. Water demand for the grown rice in each month.

Month	Water demand (mm/month)
June	274
July	67.8
August	49.3
September	58.5
October	32.2

The cultivars that were used in the paper was KDML105. The genotype coefficients for the cultivars KDML105 is calculated by Buddhaboon et al. (2020) as listed in Table 2. Genetic coefficients from the analysis "KDML105" of Jongkaewattana and Vejpas, 2020, were used. They performed a monthly planting experiment from May 1997 to May 1998, at the Multiple Cropping Center, University of Chiang Mai. The data used was obtained using the standard procedures of The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). Data from the experience were used to estimate the genetic parameters by using the "genotype coefficient calculator" given by the DSSAT shell (Tsuji et al., 1994).

Table 2. Genotype coefficient of Khao Dawk Mali 105 (KDML105)

Cultivar	P1	P2	P5	P2R	P2O	G1	G2	G3	G4
KDML105	502.30	-	386.50	1233.00	12.70	45.47	0.027	1	0.95

P1: Time period (Growing Degree Days, GDD) of basic vegetative phase; P2: extent to which development is delayed for each hour of increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (12.5 h); P5: thermal time from silking to physiological maturity (above a base temperature of 8 °C); P2R: extent of phasic development (GDD); P2O: critical photoperiod (hours); G1: potential spikelet number; G2: single-grain weight; G3: tillering coefficient; G4: temperature tolerance coefficient.

3. Results

3.1 Model evaluation

To evaluate the model's ability, we compared the model output to the ground-based measurement from the Thai Meteorological Department (TMD) and total rice yield production from the Department of Agriculture. The model reliability can be indicated by statistical analysis, including correlation determination (R^2), mean absolute error (MAE), and standard deviation (SD).

The R-square is calculated from the correlation coefficient (r) in (2).

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2][n\sum y^2-(\sum y)^2]}} \qquad (2)$$

where n is the number of model and observation data points, x is the model data, and y is the observation data.

The mean absolute error (MAE) is calculated in (3)

$$MAE = \frac{\sum_{i=1}^{n} |M-O|}{n} \quad (3)$$

where O is the observational data, M is the model data, and n is the number of model and observational data points.

The standard deviation of residuals is calculated following (4).

$$SD = \sqrt{\frac{\sum[(x_O - X_M) - (\overline{X_O} - \overline{X_M})]^2}{n}} \quad (4)$$

where X_O is observation data, X_M is model data, $\overline{X_O}$ is the mean of observation data, $\overline{X_{MO}}$ is the mean of model data and n is the number of model and observation data points.

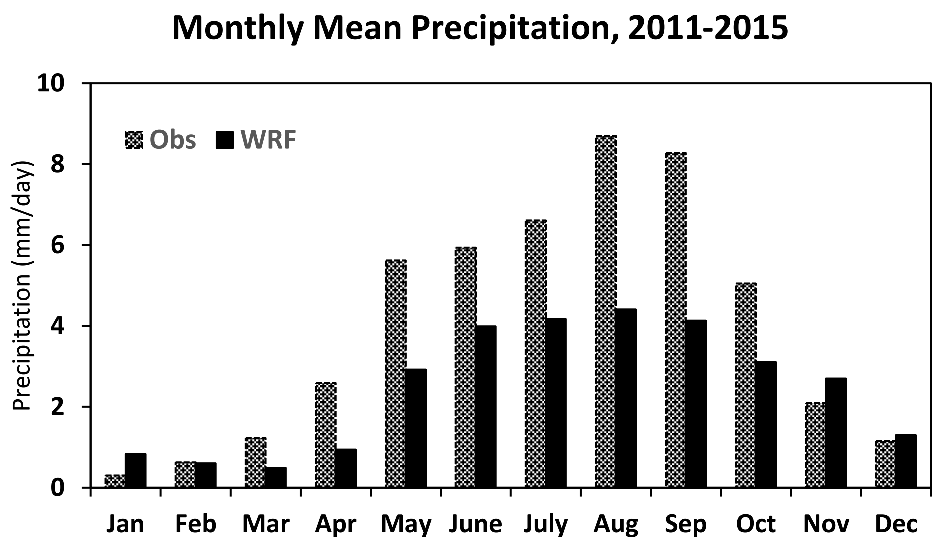

Figure 3. Monthly mean precipitation (mm/day)) averaged over 2011–2015 based on 5 station locations of the Thai Meteorological Department (TMD) (dot) and the WRF model (black).

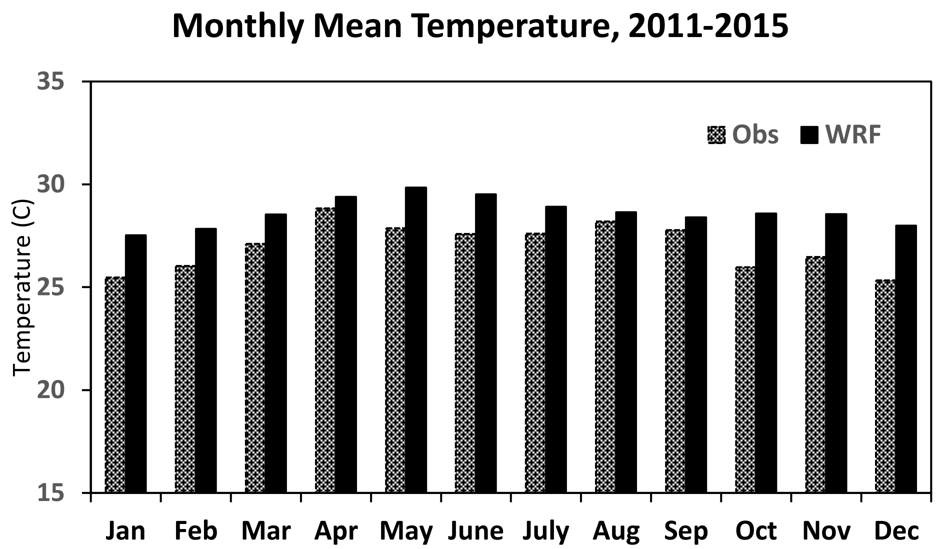

Figure 4. Monthly mean temperature (°C)) averaged over 2011–2015 based on 5 station locations of the Thai Meteorological Department (TMD) (dot) and the WRF model (black).

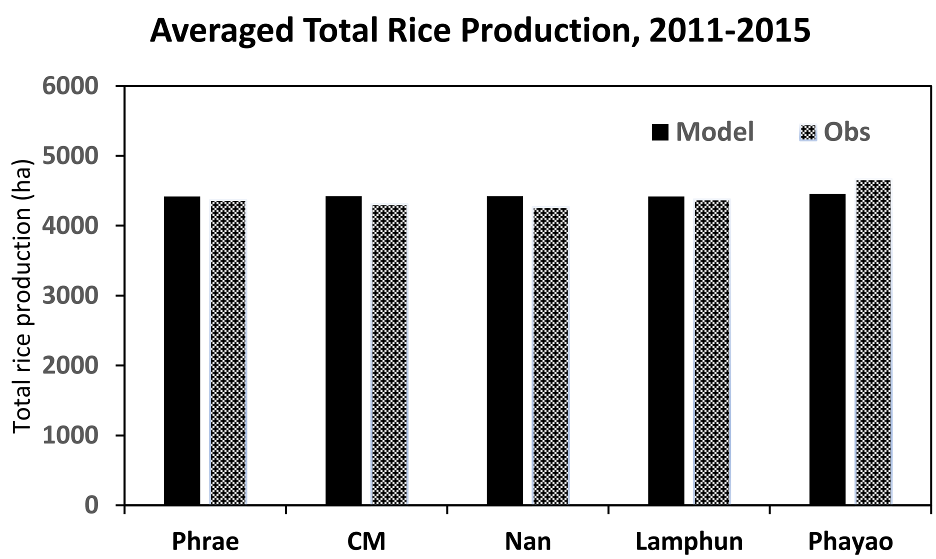

Figure 5. Average total rice production over 2011–2015 based on location in Figure 2 between the DSSAT model (black) and information from the Department of Agriculture.

Table 3 Statistics comparing the model and observations.

Variables	R^2	SD	MAE
Precipitation	0.93	2.43	1.55
Temperature	0.76	1.21	1.62
Rice Production	0.87	100.61	30.49

The monthly validation of the model and observations averaged over 2011-2015 based on 5 station locations of TMD in Phrae, Chiang Mai, Nan, Lamphune, and Phayao is illustrated in Figure 2. In general, the meteorological factors such as temperature and precipitation from the WRF model were agreeable well predicted compared with the TMD data. However, the monthly average temperature from WRF was higher than observation from TMD by 2 – 3 °C. While modeled precipitation agreed fairly well with the ground-based data from TMD. However, the WRF model predicted underestimate of precipitation by 1 – 5 mm/day compared to observation in the dry season (May – September). The total rice yield production of DSSAT based on the CERES-Rice submodule was compared to information from the Department of Agriculture in Thailand. Total rice production was averaged from a location in Figure 2 in each province, including Phrae, Chiang Mai (CM), Nan, Lamphune, and Phayao. As a result of model comparison, the model showed a good simulation of rice production, with slightly high totals of crop yield at the five sites (Figure 5).

The statistical analysis between the model and the observed data were averaged over 2011-2015 from 5 station locations of TMD annually, as shown in Table 3. Rice yield production was estimated in the location of the planting area (Figure 2) in five provinces. The model had an acceptable ability to capture temperature, precipitation, and rice production, which are indicated by R-squared values ranging from 0.7 – 0.9. The modeled temperature and precipitation were underestimated compared to observations, with a mean absolute error of 1.62 °C, 1.55 mm and 30.49 kg/ha for temperature, precipitation, and rice productions, respectively. The standard deviations of the model are 1.21, 2.43 and 100.61 for temperature, precipitation, and rice productions, respectively.

3.2 Sensitivity analysis of nitrogen fertilizer on rice production

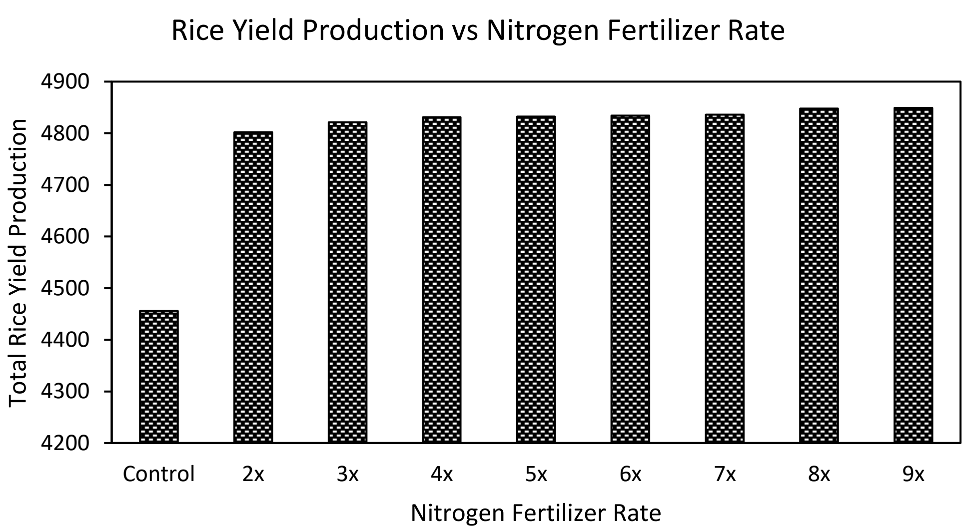

Figure 6. Sensitivity of nitrogen fertilizer rate on rice yield production in northern Thailand.

Table 4. Percentage of rice growing when the level of nitrogen fertilizer increased.

Experiment	Nitrogen level (kg/ha)	Percentage of rice growing (%)
Control	6	-
Exp. 1	12	7.76
Exp. 2	18	8.19
Exp. 3	24	8.42
Exp. 4	30	8.44
Exp. 5	36	8.48
Exp. 6	42	8.53
Exp. 7	28	8.80
Exp. 8	54	8.82

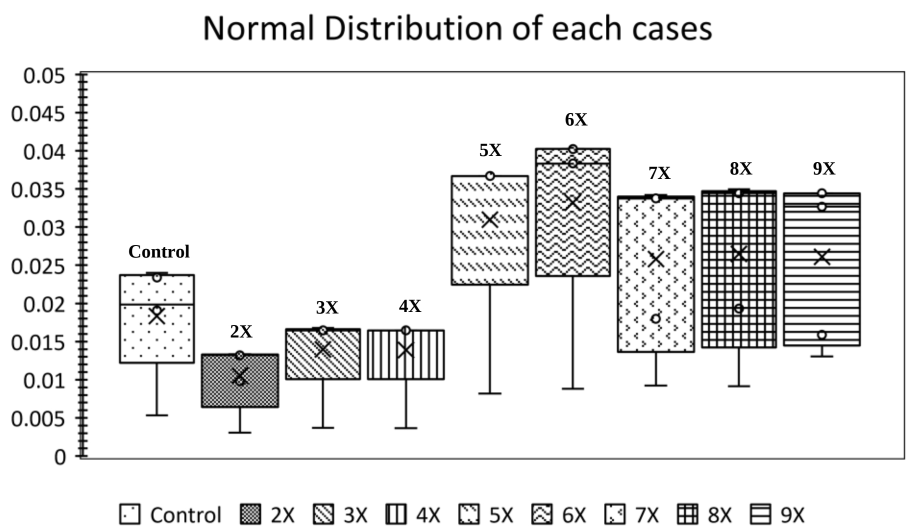

Figure 7. Normal distribution of nitrogen fertilizer rate on rice yield production in northern Thailand.

To examine the sensitivity of the level of nitrogen fertilizer on rice yield products, we designed 8 experiments, as listed in Table 4, and a control case, which is the normal fertilizer level during rice growth, according to the report of the Department of Agriculture of Thailand (N: 6 kg/ha, P_2O_5: 7.5 kg/ha, and K_2O: 7.5 kg/ha). The modeled rice production was averaged from five locations, including Phrae, Chiang Mai, Nan, Lamphune, and Phayao, from 2011 to 2015. The sensitivity of nitrogen fertilizer levels to rice production is shown in Figure 6. Compared with the control case, Exp. 1 with nitrogen fertilizer at 12 kg/ha tended to significantly increase rice products up to 4800 kg/ha, while other cases also increased the same amount of production.

However, the result was unclear regarding the extent to which nitrogen fertilizer improves rice products. For a highly visually effective way of finding a clear summary of the results, we applied the box plot of the rice product in each experiment, as shown in Figure 7. The box plot displays the normal distribution of rice production in all cases compared with the control case. The plot shows that Exp. 5 tended to increase the maximum rice product with a nitrogen fertilizer level of approximately 36 kg/ha (6-fold compared with the control case). The mean rice yield production shows the maximum level of rice production compared to all cases.

4. Discussion

The analysis of the significant output of the WRF and DSSAT encourages us to determine the optimal level of nitrogen fertilizers that would enhance rice production while also being profitable. The model performance was initially evaluated by comparison with actual data for both environmental factors from WRF and rice production from DSSAT. The WRF model shows an acceptable performance to represent the environmental facfors in this region. It simulates the patterns of precipitation and temperature in the whole year well. In particular, the modeled precipitation, however, underestimate compared to observations in the rainy season. It likely due to the atmospheric model uses grid nudging to keep the constant values of large-scale meteorology from the global model; thus, it is vital to discuss the error from initial and boundary conditions. Another possibility is lack of a soil moisture estimation in the model calculation that plays an important role in the simulation of precipitation in tropical regions.

In this case, variability in weather simulation causes impact on crop simulation. The environmental temperature did not contribute a large amount to crop model uncertainty but had a major effect on the range of wheat period that could be generated. The lack of precipitation could raise concerns for nitrogen emissions in the field. Nitrogen fertilization is a crucial input for rice growth in the region. In humidified soil, the N losses can vary greatly. Traditional midseason crops normally require more nitrogen than rice crops. Moreover, Deng et al., 2012, also suggested that highlands and regions that struggle with irrigation water sources are likely to undergo more rainy seasons. The dissolved fertilizer N contained in surface water has risen by 89% in 2003 and 73% in 2004 of the previous application. The rate dropped to 1% of the total N submitted 6–7 days after submission. If surface water runoff occurred within a week of fertilization, up to 79 percent of nitrogen from urea fertilizer will be lost to the groundwater. Moreover, Woli et al. (2004) recorded that river N concentrations increased significantly during the rice-planting season in central Hokkaido, Japan.

5. Conclusion

In this paper, we used a coupled atmospheric-crop modeling system to optimize the nitrogen fertilizer level to produce the maximum rice yield production in upper northern Thailand. To obtain the answer, we designed 10 experiments: the control was N: 6 kg/ha, P_2O_5: 7.5 kg/ha, and K_2O: 7.5 kg/ha, while we increased the nitrogen fertilizer level by factors of 2 to 10 for other cases. We performed the Weather Research and Forecasting Model (WRF) for meteorological inputs such as precipitation and temperature into a crop model that is based on the Crop-Environment Resource Synthesis)-Rice (CERES-RICE) model. The modeled precipitation and temperature from the WRF model were compared to a dataset from ground-based measurements from the Thai Meteorological Department (TMD) in Thailand. The rice yield production of the model was compared to information from the Department of Agriculture of Thailand. Reliability in the modeling system was examined using statistical analysis, including correlation determination (R2), standard deviation (SD), and mean absolute error (MAE). The statistical values indicate that the output from the model shows an acceptable level compared with real information. The R^2 values are 0.93, 0.76 and 0.87 for precipitation, temperature and rice production, respectively. The MAEs were 1.55±2.43, 1.62±1.21 and 30.49±100.61 kg/ha, respectively. The results found that the optimal nitrogen level for improving the maximum rice production in northern Thailand is taking the nitrogen fertilizer by 6 times compared to the normal level. It tends to produce the maximum rice yield production by approximately 4830 kg/ha.

Acknowledgments

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