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Modelling the Impact of Climate Change on Rice Production: An Overview

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Abstract: In modern agricultural research, crop modelling has become a critical tool which incorporates scientists' insights into the physiological and ecological processes by conducting crop growth into mathematical equations. The crop simulation models have been shown to be efficient in assessing the relationships between crop yield and environmental factors. They are able to determine the response of crop plants to change in weather. This study compares six different crop simulation models, namely RICEMOD, CERES-Rice, MACROS, RICESYS, SIMRIW and ORYZA series which can be used to evaluate the impacts of climate change on rice production. Comments are then made about the application and usefulness of these models.

Key words: Climate change, crop simulation model, rice production

INTRODUCTION

Climate change can have important effect on crop growth, development and yield by increasing carbon dioxide, temperature and uncertainty in rainfall. The relationship between climatic change and agriculture is an important issue, since the world's food production resources are already under pressure due to a rapidly increasing population. It also can affect the land use patterns and the productivity of crops. Thus good understanding of the processes of changes in climate and changes on the growth and development of crops is essential (Matthews and Wassmann, 2003).

The impact of climate change on rice production is of particular interest due to its importance as a food source in all over the world, especially in Asia. Hossain (1998) estimated that about 60% increase in rice yield would be likely needed by year 2020 due to population growth. Thus, attention to climate change issue is urgency, as it poses a significant threat to food supplies and security.

Crop modelling has become important tool in modern agricultural research. So far different models and methods have been employed in attempts to assess the impacts of climate change on rice production, such as crop production models, yield prediction and quantities of water or fertilizer consumed. Mechanistic crop production models are useful tools to study the impact of climate change on crop growth, development and yield in various agro-environments. The aim of this study is to review the possible crop production models to estimate the impacts of climate change on the rice production.

Every effort has been made to provide a comprehensive review and it is acknowledged that there may be some research, in both published and unpublished form which not explained in this review.

REVIEW OF CLIMATE CHANGE IMPACTS ON RICE PRODUCTION

Temperature effects: The major effect of temperature on crop growth is to control the duration of the period when growth is possible in each year. Furthermore, temperature may directly affect the other processes associated with the accumulation of dry matter such as leaf area expansion, respiration and photosynthesis (Olesen and Bindi, 2002). Increased temperature accelerates plant phonological development; however it can decrease the length of the grain filling period (Amthor, 2000; Bachelet and Gay, 1993). Hence, temperature increase may shorten the length of the growing period and thus reduce yield, if management practise is not changed.

In different parts of the world, climate change may affect agriculture differently. It depends on current climatic and soil conditions, the direction of change and the availability of resources and infrastructure to face with change. Rosenzweig *et al.* (1993) predicted that crop production are likely to decrease in the low-latitudes, however, could increase in the mid-and high-latitude

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regions. It is related to the current growing conditions. Since crops grow nearer their temperature tolerance limitation in low-latitude areas, any warming exposes them to higher stress. However, in many mid-and high-latitude regions, increased warming would be beneficial to crops which currently limited by cold temperatures and short growing seasons (Matthews *et al.*, 1997). For example global warming in Northern Europe will give more favourable conditions for crop production and hence can increase productivity of European agricultural system (Olesen and Bindi, 2002). Cure and Acock (1986), predicted the higher rice yield variability in cooler regions, particularly for rainfed rice. Jansen (1990) argued that yields would rise if temperature increases were small and instead, it would decrease if temperature increased more than 0.8°C per decade. In fact, the fertility of spikelet in rice plant is very sensitive to temperatures approximately 33°C and there is also a considerable variation between variability in tolerance to high temperature (Satake and Yoshida, 1978). The studies by Bachelet and Gay (1993) showed that potential rice yield will be lower by increasing in mean daily temperature due to global warming in many Asian countries. Nevertheless, it may also enable the northern limits of rice growing regions to expand, especially in northern China and Japan. The same study by Baker *et al.* (1992) and Vaghefi *et al.* (2013) indicated a sharp decline in grain yield and then potential negative effects on rice production in warmer regions if temperatures increase.

CO_2 effects: The first primary effect of CO_2 enrichment on plant is increasing photosynthesis. The second one is to reduce stomatal aperture and density which causes a reduction in stomatal conductance and transpiration. The third primary effect is the reduction of dark respiration. The resulting effects of these primary responses to increase atmospheric CO_2 concentrations are increasing resource use efficiencies for radiation, water and nitrogen and thus increasing productivity of plant (Olesen and Bindi, 2002). In general, the direct effect of increased CO_2 levels is beneficial to vegetation (Baker *et al.*, 1990; Bowes, 1993; Farquhar, 1997). Some previous studies indicated that elevated CO_2 would increase rice yield due to an increase in net assimilation rate and photosynthesis. However, this would be offset by the effect of the expected rise in temperature as a result of reduced length of the growing season and increased maintenance respiration rates, such that the two factors cancelled each other out (Baker *et al.*, 1995; Horie *et al.*, 1996; Kim *et al.*, 1996; Vaghefi *et al.*, 2011; Ziska *et al.*, 1997).

Again, higher levels of CO_2 accelerate the development rates of rice plant. However, in rice growing under increased CO_2 conditions, at first, there is a large response and then over time, this response decreases and go towards the rice growing under current CO_2 levels (Rowland-Bamford *et al.*, 1991).

Rainfall effect: Climate change may modify precipitation, runoff, evaporation and soil moisture strong. Changes in both total seasonal rainfall and its pattern of variability are very important (Olesen and Bindi, 2002). In a warmer climate, the demand for water for irrigation will be increased and thus more water will be needed per unit area under drier conditions.

Agriculture is extremely influenced by the availability of water. Topography and soil texture play an important role in defining the water availability of plant (Gupta and O'Toole, 1986). Rainfall and soil water availability can affect the duration of growth through effects on leaf area duration and also may affect the photosynthetic efficiency through stomatal closure (Olesen and Bindi, 2002).

Malabuyoc *et al.* (1993) found that, during the reproductive stage, rainfall can explain 38-67% of upland rice yields variation in the Philippines. In fact, under upland conditions, rice plant cannot maintain high yield performance under low rainfall. Saito *et al.* (2006) also found that rice yields are most associated with amount of rainfall during vegetative and reproductive growth stage.

CROP SIMULATION MODELS

Crop simulation models are widely used to assess the impacts of climate change on agricultural production which provide us with an opportunity of building scenarios of agricultural output in changed climates. They are recognized as useful tools in agricultural research. They can help to compare experimental research findings across sites, extrapolate experimental field data to wider environments, develop management recommendations and decision support systems, explore effects of climate change and make yield predictions (Jones *et al.*, 2003). They are useful tools to assess the complex interactions between weather, soil properties and management that affect crop performance (Timsina and Humphreys, 2003).

In general, crop models do not include all factors which may affect yield in a real situation and their input data requirements often are more than available databases. Hence, simpler models may be more suitable in such situations. Normally, the required input data for crop models are including the parameters of the environmental conditions (weather characteristics and CO_2 concentration), the soil characteristics, the cultivar and the agrotechnological management details (planting, fertilization, etc.) (Zalud and Dubrovsky, 2002).

Simulations can be an important step to specify the yield gap between farmers' yields and potential yields, assisting efforts to bridge the gap (Swain *et al*., 2007). However, there is a significant mismatch between the spatial and temporal scale of available data and the requirements of crop simulation models (Xiong *et al*., 2008). One of the most important practical limitations of using crop models in regional scale is the spatial coverage and enough quality of the input data (Heuvelink, 1998). In fact, application of crop simulation models depends not only on the availability of models and application software but also on the availability of information to run models for specific scenarios and to define the models accuracy for specific target regions as well (Hunt and Boote, 1998). Some models act better than others in specific contexts, for instance, when they applied to particular crops, climates, cropping patterns, soil quality indicators and management practices. Different crop growth simulation models exist for rice but thorough validation and evaluation reports are inadequate.

OVERVIEW OF MODELS

The following section provides an explanation of the models for helping to determine which model is most appropriate for certain objective. In this study, six crop simulation models were selected based on their ability to simulate the effect of climate change: RICEMOD (McMennamy and O'Toole, 1983), CERES-Rice (Godwin *et al*., 1990), MACROS (Penning de Vries *et al*., 1989), RICESYS (Graf *et al*., 1990), SIMRIW (Horie, 1987) and ORYZA series (Ten Berge and Kropff, 1995). The key attributes of these crop simulation models are presented in Table 1.

RICEMOD: RICEMOD was developed at the International Rice Research Institute (IRRI) by McMennamy (1980) as a rice crop growth and yield simulation model to assess the completeness of knowledge about rice science. The main objective of this model is to explain the complex biophysical and biochemical systems interacting in a rice crop (Wu and Wilson, 1998). RICEMOD is based ecophysiological model for irrigated rice production. It includes a number of physical parameters which is designed to accommodate subroutines dealing with soil, plant chemistry and physical processes of the atmospheric environment. The components of this model include timings of plant growth initiation and harvest, maximum leaf area index, Harvest Index (HI) and Radiation-use Efficiency (RUE).

RICEMOD almost depends on soil, plant and atmospheric data derived from experiments at the IRRI. Photosynthesis, growth and maintenance respiration, partitioning of assimilates to different growth organs and the soil water balance are four soil-plant-atmosphere processes in this model (Rao and Rees, 1992). Daily weather data inputs for this model include maximum and minimum temperatures, precipitation, pan evaporation, solar radiation and day length which do not include the influence of CO_2 (Bachelet and Gay, 1993). In RICEMOD, photosynthesis is basically the process by which atmospheric carbon dioxide is fixed by the plant (McMennamy and O'Toole, 1983). It also assumes the best levels of nutrients and ignores the potential effects of typhoons and pests. In this model, the effect of temperature on photosynthesis is not considered and photosynthesis is a function of canopy structure, solar radiation and the ratio of leaf nitrogen weight to area. Leaf area is assumed to be consistent with leaf weight and leaf nitrogen content is assumed to be consistent with plant age (Bachelet and Gay, 1993).

Growth respiration is proportional to the photosynthesis rate during daylight hours and maintenance respiration is determined for the night hours of individual plant parts. The partitioning of assimilates is done through a distribution function approach by using partitioning coefficients which used to allocate the photosynthesis to different plant organs at different stages of plant growth. Based on the different rice variety and environmental conditions, the parameters of the various growth relationships used in the model will be different (Rao and Rees, 1992).

Calibration and validation of RICEMOD was done for high yielding rice variety IR 36 by McMennamy and O'Toole, 1983 in the Philippines. RICEMOD can be used to study the relative constraining effects of leaf blade nitrogen content, respiration rate, radiation and assimilate partitioning on rice plant growth. It would be also applicable to predict the future production scenarios. It has been used to indicate leaf water stress and predict the growth and yield component of different rice varieties in a number of rice-producing countries (McMennamy, 1980; Rao and Rees, 1992). In this model, more information is needed on respiration and the environmental effects on nutrient uptake and distribution, leaf blade thickness and plant growth control mechanisms, to predict growth precisely. RICEMOD could be more applicable, if it was sensitive to water and nutrient stresses (McMennamy and O'Toole, 1983).

CERES-rice: Crop Estimation through Resource and Environment Synthesis-Rice (CERES-Rice) is a generic and dynamic simulation model which was developed under the International Benchmark Sites for

Table 1: Key attributes of the crop simulation models

Model	Input parameters	Output parameters	Application	Advantages	Disadvantages
RICEMOD	• Soil data • Crop characteristics • Weather data (e.g., maximum and minimum temperatures, precipitation, pan evaporation, solar radiation and day length)	• Total area index (e.g. LA1, leaves, stem) • Growth rates • Dry weights • Dry matter partitioning • Grain yield • CO_2 assimilation • Amount of radiation absorbed by the canopy	• To indicate leaf water stress and predict the growth and yield component of different rice varieties in a number of rice-producing countries	• Useful for predicting future production scenarios	Does not include the influence of CO_2
Cress-rice	• Weather data (e.g., solar radiation, maximum and minimum temperatures, precipitation) • Management information (e.g., plant population, plant genetics, planting and harvest dates, row spacing, fertilizer application amounts and dates) • Environmental factors (e.g., soil type saturated hydraulic conductivity, drained upper and lower limits) • Genetic coefficients	• Biomass at different stages of crop growth • Yield parameters • Harvest index • Grain yield • Biomass nitrogen	• To simulate crop growth and yield responses to scenarios of field management changes • Assessing regional climate change impacts • Gene-based modelling to simulate yield responses to environment	• Standardized inputs (soil and climate) and has a strong analyzing component • Simulates more realistic responses to temperature • Simulate the long term consequences of potential climate change on rice production	Needs many input data
MACROS	• Weather data (e.g., maximum and minimum temperature, precipitation, solar radiation, air humidity, wind speed, daylength) • Soil data • Crop characteristics	• Harvest index • Water use efficiency • Grain yield	• To study the climate change impact • To schedule the time of planting and estimate the yield	• Provides a development tool to apply models for various applications such as management of water, nutrients and pests	Is poor at predicting CH_4 emissions
RICESYS	• Weather data	• Grain yield • Harves index	• To assess the effect of climate change • To explain the dynamics of rice growth and development • To represent the effect of delays in transplanting date and planting density on growth and yield of rice plant	• Assesses the effect of climate change on the rice plant, its weeds and herbivores • The model is structurally a well documented program and can be easily modified	Does not include the influence of CO_2
SIMRIW	• Water data • Crop characteristics • Soil data	• Dry weight • Grain yield	• To evaluate the climatic productivity and overall cultivation technologies in rice production in different locations of the world • To predict the optimal cropping season and/or a most suitable genotype under given climatic conditions	• Is useful in a large area simulation without regional parameters • Simple and little meteorological data is needed	The effect of water and nitrogen stress cannot be simulated by this model
ORYZA2000	• Water data • Geographical latitude • Crop management (e.g., plant density, crop emergency date)	• Dry weight • Grain yield	• To assess the climate change impacts, Nutrient management and water management	• Improved and integrated all previous versions of ORYZA series into one model	It does not consider any effect of either [CO_2] or N on dry matter partitioning hence, it overestimates leaf biomass and LAI under elevated [CO_2]. It also cannot be used for the modelling of upland rice

Agrotechnology Transfer (IBSNAT) project (Ritchie *et al*., 1987). It is part of the Decision Support System for Agrotechnology Transfer (DSSAT) system. All the DSSAT models are continuously being refined, calibrated, validated and applied by the scientists and their collaborators who developed the models. CERES-Rice is a physiological-based and management-oriented model which can simulate the growth and development of rice under optimal, nitrogen-limited and water-limited conditions (Timsina and Humphreys, 2003).

CERES-Rice was designed to estimate yield as constrained for alternative technology and new growing sites, by different characteristics, soil water and nitrogen. It is able to reduce time and cost of agrotechnology transfer of new varieties and management (Bachelet and Gay, 1993). The model is able to compute the growth and development of rice plants in a homogeneous area on a daily time step. The final crop yield can also be calculated on the date of harvest (Xiong *et al*., 2008). It can estimate the potential yield by combining the properties of crops, weather and soil (Wikarmpapraharn and Kositsakulchai, 2010). CERES- Rice simulates detailed soil and water N dynamics under changing hydrological conditions (Timsina and Humphreys, 2003). The inputs required to run the model are weather variables (daily solar radiation, maximum and minimum temperatures and precipitation), management information (plant population, plant genetics, planting and harvesting dates, row spacing and fertilizer application amounts and dates) and environmental factors (soil type, saturated hydraulic conductivity, drained upper and lower limits, etc.). This model does not consider the effect of typhoons and it is assumed that the crop is well protected against insects, weeds and diseases.

In different studies, CERES-Rice has been used to simulate the effects of weather, soil properties, plant genetics and management practices on the yield, growth and development of rice plants (Kumar *et al*., 2010; Mahmood, 1998; Saseendran *et al*., 2000; Xiong *et al*., 2008). This model has been widely used to assess the impact of climate change on rice production worldwide (Amien *et al*., 1999; Basak *et al*., 2010; Felkner *et al*., 2009; Mall and Aggarwal, 2002; Van Oort *et al*., 2011).

MACROS: MACROS (Modules of an Annual CROp Simulator) was developed in Wageningen in the Netherlands and has been applied for educational purposed, specifically in developing countries (Bachelet and Gay, 1993). It was developed as a part of the Simulation and Systems Analysis for Rice Production (SARP) project for crops in the semi-humid tropics. One of the objectives of this project was transferring the technology of simulation and system analysis to multi-disciplinary teams of scientists in Southeast Asia. MACROS supported these objectives in two ways. First, as a training instrument to transfer the agrotechnology and system analysis and second, as a tool to apply the models in the ‘cropping system’, ‘nutrients, water and roots’, ‘potential production’ and ‘diseases, pests and weeds’ research areas (Bouman *et al*., 1996). In fact, studies on the climate change impacts on rice production began at IRRI in the late 1980s, by using MACROS crop simulation model (Penning de Vries *et al*., 1990). The model simulated the potential rice production by determining the daily rates of photosynthesis, transpiration, respiration and phonological development, by considering the effects of temperature, air humidity, wind speed and radiation as well. It was modified to consider the response to changes in temperature and CO_2 level, on the basis of a number of crops summarised by Kimball (1983), Cure and Acock (1986) and Matthews and Wassmann (2003).

MACROS is a generic crop growth model based on comprehensive physiological processes which consist of parameter sets for crop. It can simulate crop growth and development under conditions of water limitation and potential production. The model is well adapted to the study of response to the environmental changes and has been widely used in crop growth simulations for rice (Bachelet *et al*., 1993; Jansen, 1990), soybean (Eitzinger *et al*., 1996) and wheat. It focuses on the biochemical aspect of plant physiology on the basis of growth limitation factors. This model is included a set of equation which can explain the relations between the main physiological processes and the environment. Main physiological processes refer to respiration, photosynthesis, biomass accumulation and partitioning, phenological and leaf area development and the structure of the canopy. The environment also refers to radiation, temperature and CO_2 concentration which radiation and CO_2 affect photosynthesis and temperature affects photosynthesis, respiration and the rate of phenological development (Penning de Vries, 1993). The daily weather inputs in MACROS model are as follows: Maximum and minimum temperature, precipitation, solar radiation, air humidity, wind speed, daylength and vapour pressure.

The model includes series of basic modules for potential and water limited crop growth and for the water balance of soils as well. There are two different modules for water balance of soils which the first one is for free draining soils (SAHEL) and the second one is for soils with impeded drainage (SAWAH). MACROS provides a development tool to apply models for various application, such as management of water, nutrients and pests

(Jones *et al*., 2001). In fact, this model can be run in one of three different situations where (1) Nutrients and water are in optimum conditions and pests, weeds and disease are absent, (2) Water stress may be occur because of limiting water availability, (3) Plant production may be restricted by water and nitrogen during part of the year. However, the carbon fraction in dry matter and the biochemical composition are fixed in all situations (Bachelet and Gay, 1993).

RICESYS: RICESYS is an ecosystem model for predicting the inter-species and herbivores competition between rice and weeds which provides an applicable tool for integrated pest management studies. In other word, this is a demographic model for rice growth and development as affected by temperature and solar radiation and does not include CO_2 effects. The demographic component of this model consists of bookkeeping device for births, deaths, growth, ageing of mass and numbers of plants subunits. This structure prepares a base for the linkage of insect pest and weed model. Furthermore, to simulate the competition with weeds, the model should be included the dynamics of nutrients (Graf *et al*., 1990). In RICESYS, all nutrients, except nitrogen and water, in the irrigated paddies, are assumed to be non-limiting. The model also ignores the effects of typhoons and assumes there are no other pests except herbivorous leafhoppers.

Graf *et al*. (1990) in their study used (Frazer and Gilbert, 1976) functional response model to predict photosynthesis. This approach permits the simulation of energy acquisition at different nutrition level which energy acquisition is a function of resource availability, demand and the search rate. Therefore, photosynthesis is a function of temperature, solar radiation, Leaf Area Index (LAI) and total demand of plant for carbohydrate. The product of photosynthesis was used first for respiration and then for reproduction, growth and reserves, respectively.

RICESYS is a useful model to explain the dynamics of rice growth and development and to represent the effect of delays in transplanting date and planting density on growth and yield of rice plant. The model was designed to simulate growth and development of the rice variety Makalioka 34 from Madagascar under irrigated condition but other rice varieties in other location can also be simulated via simple parameter changes. The model is structurally a well documented program and can be easily modified.

SIMRIW: SIMRIW (Simulation Model for Rice and Weather- relationship) is a simplified process model for rice which developed by Kyoto University to estimate the potential rice growth and yield from climate and weather variation. It can predict the growth and yield of rice under the best managements of pests, diseases, nutrients and good condition of an irrigated paddy field. This model was developed by a reasonable simplification of the underlying physiological and physical process of the rice growth; hence, it needs just a limited number of crop parameters which can be obtained from field experiments. Because of this, SIMRIW is useable for a wide range of environment. It can be executed as a Web application by displaying the optimal transplanting date, the potential for cultivation and the maximum yield on a map. The original SIMRIW model was developed for researchers; however, the Web application can be used as a decision support system tool for policy makers and farmers (Tanaka *et al*., 2010). The actual farmers' yield at a given location can be obtained by multiplying the simulated potential yield by a technological coefficient which describes the current level of rice cultivation technology, such as fertilizer applications, pest management, soil, water, etc. (Horie *et al*., 1995).

Previous studies show that the model has adequate capability to explain the locational variability and special distribution of rice yield based on the respective climate (Horie, 1987; Tanaka *et al*., 2010). It can also acceptably explain the yearly variations in yield at different regions based on the weather (Horie *et al*., 1992). In spite of its good applicability, the model has limited capability in climate acclimatization.

SIMRIW program consists of a subroutine to input weather data and one main program to calculate the equations. It also needs two external files. One of them is CROPARAM.DAT, for specification of cultivar specific crop parameters and the other one is a weather data file which includes daily weather data. The required weather data for this model is temperature and solar radiation which can be easily obtained and does not need any regional parameters (Horie *et al*., 1995). Although solar radiation data are a little difficult to obtain than precipitation and air temperature data but a sunshine hours solar radiation conversion model is available in SIMRIW to support the requirement of solar radiation data. The model determines the maturity or heading as a crop growth stage by using Developmental Index (DVI) which integrates the Developmental Rate (DVR). Since SIMRIW just simulates potential growth in irrigated and fertilized paddy field, so the effect of water stress and nitrogen stress cannot be simulated by this model (Tanaka *et al*., 2010).

A sensitivity analysis of SIMRIW can be done by testing responses of simulated yield to daily mean temperature, CO_2 concentration and solar radiation, under constant environmental conditions and over the whole growth season.

ORYZA series: International Rice Research Institute (IRRI) in cooperation with Wageningen University developed the ORYZA model series to simulate tropical lowland rice growth, development and water balance under conditions of potential production, water limitations and nitrogen limitations. They have been developed from MACROS model and SUCROS (Simple and Universal CROp growth Simulator) model (Spitters *et al*., 1989) to serve specific application. ORYZA1 (Kropff *et al*., 1994) was the first model for potential production which derived largely from the MACROS model, followed by ORYZA-W (Wopereis *et al*., 1996) for water-limited production and by ORYZA-N (Drenth *et al*., 1994) and ORYZA1N (Aggarwal *et al*., 1997) which was partly based on ORYZA-N, for nitrogen-limited production (Bouman and Van Laar, 2006).

ORYZA1 is an ecophysiological model for irrigated rice production which was modified from different models such as SUCROS, LID module of MACROS, INTERCOM (Kropff and van Laar, 1993) and GUMCAS (Matthews and Hunt, 1994). The required environmental and crop management data of the model are included daily weather data (such as minimum and maximum temperature and solar radiation), geographical latitude, plant density, crop emergency date, transplanting date and parameter values which explain the morpho-physiological characteristics of rice. The model estimates daily growth rates for dry matter production of plant organs, phonological development and leaf area. Daily canopy CO_2 assimilation is estimated based on leaf area index and the climate variables such as temperature and solar radiation. This model assumes that nitrogen and water are non-limiting factors (Olszyka *et al*., 1999). ORYZA1 includes a carbon balance check, to make sure that the total net assimilated carbon equals the carbon fixed in dry matter and the carbon lost due to maintenance respiration and growth. The model has been successfully calibrated and evaluated by using data from previous experiments carried out at IRRI (Kropff *et al*., 1995). The results of Olszyka *et al*. (1999) show that under high temperature and normal CO_2 scenarios, ORYZA1 over predicted by about 70%. However, under normal temperature and high CO_2 level, the over prediction was about 7%. It shows that simulations based on the ORYZA1 model may overestimate rice yield and it is not able to predict the absolute values. These results are consistent with the findings of Matthews and Wassmann (2003). Hence, the model needs some improvements and integration of modelling to provide more accurate prediction.

In 2001, ORYZA2000 was released as a product of the modelling ‘‘school of De Wit’’ (Bouman *et al*., 1996) that improved and integrated all previous versions into one model which was a new version in the ORYZA model series (Bouman *et al*., 2001). Hence, ORYZA2000 can simulate growth and development of lowland rice in situations of potential production, water limitations and nitrogen limitations. The model assumes that, in all these situations, there are complete control of growth factors such as pests, weeds, disease and other management variables and that no decreases in production take place. From Bouman and Van Laar (2006) evaluation, they concluded that ORYZA2000 was adequately accurate in the simulation of yield, LAI and biomass of crop organs over time for irrigated rice. The ORYZA2000 model also simulates the increases of daily Dry Matter (DM) in phonological development progress and plants organs (Artacho *et al*., 2011).

DISCUSSION

Matthews and Wassmann (2003), in their article reviewed the characteristics of three crop simulation models, ORYZA1, SIMRIW and CERES-Rice which can be applied to simulate the potential rice production. They found that SIMRIW needed fewer crop parameters than ORYZA1 which all of them can be obtained easily from well defined field experiments; because SIMRIW was based on underlying physiological processes involved in the growth of the rice crop. In addition, CERES-Rice model has routines describing the main crop components involved in CH_4 dynamics, i.e., organic matter decomposition, root growth and death and root exudation, along with routines describing the relevant crop management options such as water management and applications of organic and inorganic fertilisers. It can be then noted that SIMRIW is simpler than CERES-Rice and ORYZA model.

In fact, in global studies, it is required to choose a rice simulation model which does not need regional parameters, because it is not feasible to do the cultivation experiment to predict the rice cultivation possibility throughout the world. SIMRIW fulfils this requirement, because it already obtained good result in a simulation of large area without any regional parameters. It does not use regional parameters and just uses temperature and solar radiation as meteorological data. It is beneficial that small amount of meteorological data is required to run the model. These characteristics make it suitable to predict the possibility of rice cultivation in areas all over the world.

Bachelet and Gay (1993) compared the performances of four rice crop simulation models namely MACROS, CERES-Rice, RICEMOD and RICESYS, about their ability to simulate the effects of climate change on rice growth and productivity. They found that the first two were the most suitable for climate change studies, because they simulated more realistic responses to temperature and CO_2 than the others. On the other hand, RICEMOD and RICESYS did not simulate the effect of CO_2 level. RICESYS is able to assess the effect of climate change on the rice plant, its weeds and herbivores, that is to say, at the system level of the plant. This model consists of competition between rice and its natural herbivores and weeds, under condition of increased temperature only. Hence, it can simulate more realistic yield than CERES-Rice which simulates pest-free yield and MACROS which estimates potential yield. Making a choice between MACROS and CERES-Rice depends on which the scientist was familiar with (Matthews and Wassmann, 2003). Based on Bachelet and Gay (1993) findings, RICEMODE simulated the smallest decrease in yield among these models. CERES-Rice also predicted a lower impact of temperature (18% from 25-30°C) than MACROS (62% from 25-30°C). However, CERES-Rice predicted a higher increase in yield due to a doubling of CO_2 (without temperature increase) than MACROS model (Bachelet and Gay, 1993).

MACROS and CERES-Rice are both physiologically-based models and both of them are based on the concept of a generic crop growth model. MACROS needs a greater number of climatic inputs compared to CERES-Rice, however its code is structurally easier to modify and well documented than CERES-Rice. MACROS can be used as training tool because of its obvious modular structure which allows scientist to select and combine suitable crop growth and water balanced modules for addressing their particular production situations and research questions.

Actually, the most commonly used rice models are ORYZA2000 and CERES-Rice models which are very similar in terms of processes included (Van Oort *et al*., 2011). However, these two models have some limitations. These models, like any other crop simulation models, are built on specific assumptions. It assumed that weeds, insects and diseases are entirely controlled. It is also assumed that there are no nutrient insufficiencies, except for nitrogen. In addition, crop losses which may increase due to extreme events such as droughts, floods, frosts and heat waves are not taken into account in the model. The damaging effects of catastrophic weather events and deteriorated soils are not considered as well.

CERES-Rice and ORYZA1N are two popular rice growth models for the same input conditions. The main objective of CERES-Rice model is to evaluate how the weather and genetic characteristics can affect the rice production yield at a given location under a certain management scheme (Lal *et al*., 1998). This model is able to simulate the effects of CO_2 on photosynthesis and water use. But, it cannot compute gross photosynthesis and respiration separately as it can be done in ORYZA1N. CERES-Rice can estimate net photosynthesis (CARBO) based on a constant radiation use efficiency (RUE), Leaf Area Index (LAI), extinction coefficient (k) and light absorption (IPAR) by the canopy (Mall and Aggarwal, 2002). Hence, photosynthesis sensitivity in CERES-Rice is greater than ORYZA1N which could probably be due to separate estimation of gross photosynthesis and maintenance respiration in the ORYZA1N model.

ORYZA1 which is a derivative of MACROS model and SIMRIW have been successfully tested and compared in Matthews *et al*. (1995). It was concluded that both models were suitable to predict changes in rice yield caused by changes in temperature and atmospheric CO_2 concentration. However, ORYZA1 is poor at predicting CH_4 emissions (Olszyka *et al*., 1999). On the other hand, CERES-Rice model which already included soil organic matter decomposition routing and routines describing the relevant crop management, is capable to evaluate the effects of any changes of these on both rice yields and CH_4 emissions.

Although all of these models have been well tested for the model validity but there are some uncertainties with the results of simulations which could be due to many assumptions that built into the model used. For example, in most of them the influences of water, nutrients, pests and diseases are not included in the models. In addition, most of the relationships about the effect of temperature and CO_2 on rice plant processes obtain from experiments which its environment was changed for just part of the season. Thus, crop's acclimation to changes in its environment is not taken account in the model.

CONCLUSION

Based on physiological and physical perception, RICEMOD was quite simple and did not received extensive attention. For assessing the effect of temperature and CO_2 changes on rice production, CERES-Rice and MACROS should be preferred over RICEMOD and RICESYS. For climate change impacts studies that just examine the effect of temperature without changes in CO_2 level, the more realistic model between these models is RICESYS, because it considers the effect of climate change at plant system level as well. For large area and global rice yield prediction, SIMRIW model is more preferable. At the regional level, ORYZA2000 and CERES-Rice are the most commonly used models, especially in Asian countries. However, CERES-Rice received more attention than ORYZA2000, because it has been well tested in a range of environments and could simulate the growth and development of rice crop under both upland and lowland conditions. The rice simulation model should be simple; however, it should be comprehensive enough to predict the growth of various varieties under different agroclimatic conditions. The use of crop simulation models to predict the likely impact of climate change on rice production is a developing science and knowledge on the limitations of each crop model can help to make a better prediction.

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