The Model ORYZA2000 to Simulate Growth and Development of Lowland Rice

B.A.M. Bouman[1], T.P. Tuong[1], M.J. Kropff[2] and H.H. van Laar[2]

[1] *International Rice Research Institute, Los Baños, Philippines (b.bouman@cgiar.org)*
[2] *Chair group Crop and Weed Ecology, Wageningen University, Wageningen, Netherlands.*

Abstract: The model ORYZA2000 simulates the growth and development of tropical lowland rice under conditions of potential production, and of water and nitrogen limitations. Under potential conditions, crop growth is determined by light, temperature and varietal characteristics for phenological, morphological and physiological processes. The model follows a daily calculation scheme for the calculation of growth rates of the plant organs, and the rate of phenological development. By integrating these rates over time, dry matter production is simulated throughout the growing season. Sink-sources relationships are accounted for in leaf growth and grain formation. Drought effects are modeled on: leaf rolling, spikelet sterility, leaf expansion, development rate, assimilate partitioning, root depth, leaf senescence and photosynthesis. Nitrogen (N) dynamics in the crop are calculated from crop N demand, which is derived from growth rates and target N contents of plant organs, N remobilization and N uptake from the soil. The N status of the crop affects leaf area growth, photosynthesis and senescence. The soil N balance is a simple book-keeping method of native soil N supply and fertilizer applications. The soil water balances included is PADDY. A data base is established for parameterization and validation of ORYZA2000. Evaluation results show a good fit with measured crop variables across a wide range in production situations.

Keywords: Crop simulation model; rice; water; nitrogen

1. INTRODUCTION

Crop growth simulation models play an important role in agricultural research. They are powerful tools to test our understanding of crop performance by comparison between simulation results and experimental observations, thus making gaps in knowledge explicit and helping to design experiments to fill these gaps. Well-tested models can be used in more application-oriented research such as yield prediction, exploring effects of climate change and the design of plant ideotypes.

The ORYZA model series was developed by the International Rice Research Institute (IRRI) and Wageningen University and Research Centre (WUCR) in the early nineties to simulate growth and development of tropical lowland rice [Drenth et al., 1994; Kropff et al., 1994; Wopereis et al., 1996]. Recently, the different ORYZA models were updated, extended and synthesized into one model, called ORYZA2000, and an effort was made to construct a data base of experiments for model evaluation. This paper outlines the basic principles of ORYZA2000 and presents new evaluation results.

2. THE MODEL ORYZA2000

ORYZA2000 is an exponent of the modeling "School of De Wit" [Bouman et al., 1996]. It simulates growth and development of lowland rice in situations of potential production, water-limitations and nitrogen-limitations:

- Potential production. Growth occurs in conditions with ample supply of water and nutrients; growth rates are determined by weather conditions only (radiation and temperature).
- Water-limited production. Growth is limited by water shortage over at least part of the growing period; nutrients are in ample supply.
- Nitrogen-limited production. Growth is limited by shortage of nitrogen (N) at least part of the growing season.

In all production situations, the crop is well protected against diseases, pests and weeds so that no reductions in yield take place. The main

calculation procedures are described below for each of the three production levels.

2.1. Potential Production

Under favorable conditions, light, temperature and varietal characteristics for phenological, morphological and physiological processes are the main factors determining the growth rate of a crop. The ORYZA2000 model follows a daily calculation scheme for the rates of dry matter production of the plant organs, and the rate of phenological development. By integrating these rates over time, dry matter production and development stage of the crop are simulated throughout the growing season.

The total daily rate of canopy CO_2 assimilation is calculated from the daily incoming radiation, temperature and the leaf area index. The model contains a set of subroutines that calculate the daily rate by integrating instantaneous rates of leaf CO_2 assimilation. The calculation is based on an assumed sinusoidal time course of radiation over the day and the exponential light profile within the canopy. On the basis of the photosynthesis characteristics of single leaves, which depend upon the N concentration, the photosynthesis profile in the canopy is obtained. The leaf N content is either read from an input file or obtained from routines that calculate the crop N dynamics (section 2.3). Integration over the leaf area index of the canopy and over the day gives the daily CO_2 assimilation rate. After subtraction of respiration requirements, the net daily growth rate in kg dry matter per ha per day is obtained. The dry matter produced is partitioned among the various plant organs, using empirically-derived partitioning factors as a function of development stage. Phenological development rate is tracked as a function of ambient daily average temperature and photoperiod.

In grain crops, the carbohydrate production (source size) in the grainfilling period can be higher or lower than the storage capacity of the grains (sink size). The latter is determined by the number and maximum growth rate of the grains. In experiments at IRRI, a good relationship was found between the total crop growth over the period from panicle initiation to first flowering and the number of spikelets at flowering. Spikelets turn into grains with crop growth. However, some spikelets become sterile due to either too high or too low temperatures and do not fill. The surviving spikelets are filled with the source-determined growth rate until their maximum grain weight is reached. In the case of sink limitations, the surplus of assimilates is partitioned to the stems.

Leaf area development includes a source- and sink-limited phase. In the early phase of growth, the leaves do not shade each other and leaf area development is not limited by the amount of available assimilates. In this phase, leaf area grows exponentially as a function of the temperature sum times a relative leaf growth rate. After the exponential phase (when the leaf area index is about 1), leaf area development is only determined by the amount of carbohydrates available for leaf growth. In this linear phase, the growth in leaf area is calculated from the increase in leaf weight times a specific leaf area that is a function of development stage.

2.2. Water-Limited Production

Drought affects the following processes of crop growth: leaf rolling, spikelet sterility, leaf expansion, development, assimilate partitioning, root depth, leaf senescence and photosynthesis. Based on pot experiments at IRRI, Wopereis et al. [1996] calculated drought stress factors as a function of the soil water tension in the root zone, which is the sum of the matric tension of the soil and the osmotic tension of the soil water. In our model, the matric tension is calculated by separate water balance modules (see below). The osmotic tension is calculated from the salt content.

All drought stress factors are multiplicative factors, and have values ranging from 0 to 1. The value 1 means that the growth process is not affected (resulting in potential production), and the value 0 means that the process has come to a complete stand-still.

Leaf rolling reduces the amount of intercepted solar radiation for photosynthesis. A leaf rolling factor of 1 indicates no leaf rolling, and a value of 0 indicates maximum leaf rolling. In the pot experiments, leaf rolling started at soil water tensions of 200-300 kPa, and was maximal at tensions of 400-1000 kPa. Drought stress in the reproductive phase, especially around flowering, enhances spikelet sterility. Turner et al. [1986] found a relationship between temperature increase due to drought and increased spikelet sterility, and related the increase in temperature to the leaf rolling score. We used their relationships to model increased spikelet sterility.

Leaf expansion rates of plants stressed in the vegetative phase decrease rapidly after an initial period of normal growth. In the pot experiments,

critical soil water tensions ranged from 50 kPa (upper limit of leaf expansion) to 260 kPa (lower limit of leaf expansion). In our model, a leaf expansion factor reduces leaf expansion between these two limits. Drought in the vegetative stage of development delays flowering. It was found that postponement of flowering was in reasonable agreement with the number of days between the date of zero leaf expansion and the recovery from drought. Therefore, we use the leaf expansion factor to simulate the effect on delayed flowering. Carbohydrate partitioning between shoot and root under water stress is generally altered in favor of the root biomass. When leaves stop expanding, photosynthesis still continues and the level of reserve carbohydrates increases, which makes more of them available for growth of the root system. Hence, in our model, the effect of drought on partitioning of assimilates between shoot and root and on root depth is again computed from the leaf expansion factor.

Drought accelerates the senescence and death rate of leaves. A dead leaf factor of 1 indicates no (drought-induced) dead leaves, and a value of 0 indicates that all leaves are dead. In the pot experiments, leaves started dying at soil water tensions of about 300 kPa and were fully dead at about 700 kPa. In our model, the dead leaf factor is multiplied with the leaf loss rate (due to normal senescence) to give the total leaf death rate.

Crops under drought stress close their stomata to reduce transpiration. This increases the resistance to the gas exchange of CO_2, which decreases the rate of photosynthesis. In our model, we adopt the assumption that there is a constant ratio of transpiration to gross photosynthesis under drought stress. The gross photosynthesis rate is reduced by a relative transpiration factor, which is defined as the ratio of the actual over potential transpiration. In the pot experiments, the relative transpiration rate started to decrease at soil water tensions of about 70 kPa, and approached 0 at tensions of about 1500 kPa. Potential transpiration rates are calculated using either the Penman-Monteith, the Priestley-Taylor or the Makkink equations (user-defined).

The soil water balance model incorporated in ORYZA2000 is PADDY [Wopereis et al., 1996].

2.3. Nitrogen-Limited Production

The daily potential demand for N is calculated from the growth rates and the N contents of the plant organs. The basic assumption is that the crop strives to maintain the N content in its

organs close to the potential values. The N demand of the leaves and stems is calculated from the difference between the potential and actual amount of N in the existing and newly formed biomass. The potential amount of N in the leaves is determined by its maximum N content, which changes with development stage (Figure 1).
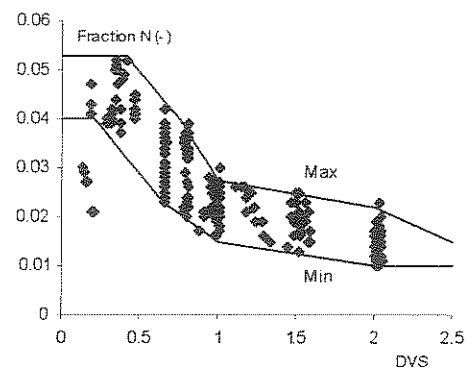
Figure 1. Mass fraction N in leaves versus development stage (0 = emergence, 1=flowering, 2 = harvest). Data from 5 experiments with different N regimes; IR72 in the wet and dry seasons of 1991-1993, IRRI.

The stem N content is half the leaf N content [Drenth et al., 1994]. The maximum content of N in the storage organs is independent of development stage, and fixed at 0.0175 kg N kg^{-1} dry matter.

Next, the amount of N that can be translocated from leaves, stems and roots to the storage organs is computed. All N allocated to the storage organs is assumed to be supplied by translocation. For leaves and stems, the daily potential 'translocatable' amount of N is determined from the total amount of N in the organ, minus the residual N content at maturity times the weight of the organ, divided by a time coefficient of 10 days. For leaves, the residual N content was found to be 0.004, and for stems, 0.0015 kg N kg^{-1} dry matter. Since no N balance for roots is modeled, it is estimated that the roots contribute a fraction (0.15) of the amount of N translocated from leaves and stems combined [Aggarwal et al., 1997]. The total amount of daily 'translocatable' N is subtracted from the daily potential demand to get the daily crop N demand for uptake from the soil. The actual crop N uptake is limited by the maximum uptake rate of the crop and the daily extractable amount of N from the soil. Rice plants are physiologically limited in the daily amount of N they can take up. Peng and Cassman [1998], observed N uptake in tropical rice at IRRI on a

two-day basis and calculated that maximum N uptake rates at panicle initiation were as high as 9-12 kg ha^{-1} d^{-1}. In our model, the average maximum N uptake rate by the crop is user-defined, and a value of 8 kg ha^{-1} d^{-1} is used for conditions at IRRI.

Daily soil N available for uptake is modeled as a simple bookkeeping routine and does not compute the dynamics of N transformation processes in the soil. The sources of N taken into account are indigenous soil supply and fertilizers. The root zone is considered a single soil compartment in which all mineral N is available for uptake by the crop. The indigenous soil N supply is determined by mineralization of organic matter and biological N fixation. Typical values for tropical rice soils vary from 0.5 to 0.9 kg N ha^{-1} d^{-1}. Fertilizer N is multiplied with a recovery fraction to calculate the uptake potential. The recovery of N depends on the development stage of the crop, with relatively low values at transplanting to high values at panicle initiation. For the IRRI farm, we use a linearly increasing recovery of 0.35 at transplanting to 0.75 at panicle initiation and thereafter [Aggarwal et al., 1997].

The leaf N content affects the photosynthesis rate (section 2.1) and the relative area growth rate of leaves in the exponential phase of growth. From experiments at the IRRI farm, we found a maximum relative leaf growth rate of 0.0085 °Cd^{-1} with no N limitations, and a minimum of 0.0045 without any N fertilizer. The minimum value occurred when the N content in the leaves was 90% or less of the maximum value. The actual relative growth rate is derived by scaling the leaf N content between the maximum and minimum values.

The total amount of N in the crop affects the loss rate of leaves after flowering. A stress factor is calculated from the ratio of the actual over the potential amount of N in the crop. This potential amount is calculated from the weights of the plant organs times their maximum N contents.

3. EVALUATION

Previous versions of ORYZA were extensively validated under conditions of potential production [Kropff et al., 1994]. The effects of drought stress on growth and development were derived from pot experiments and literature, and only one example is published of field validation of ORYZA under water-limited conditions at the IRRI farm [Wopereis, 1993]. Since the simulation of N

dynamics as presented here is new, no validation results have yet been published (although validation of earlier concepts was presented by Drenth et al. [1994]). Therefore, in 2000 a major effort was undertaken to collect data of experiments of lowland rice grown under water- and N-limited production.

3.1. Water-Limited Conditions

Rice variety IR64 was grown under irrigated and rainfed conditions in 1995 and 1996 at Jakenan, Indonesia, as part of the research program of IRRI's Lowland Rice Research Consortium. The irrigated treatments of 1995 and 1996 were used to derive the variety-specific crop characteristics. The required soil input parameters were collected in the field. Daily weather parameters were obtained from the weather station at the site.
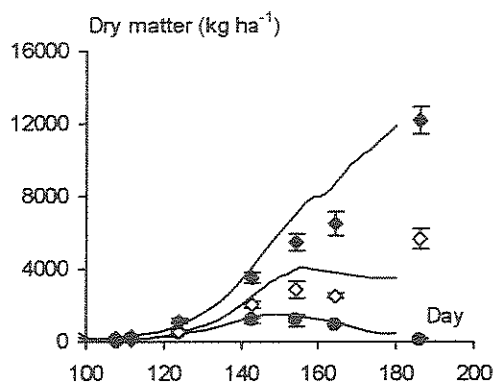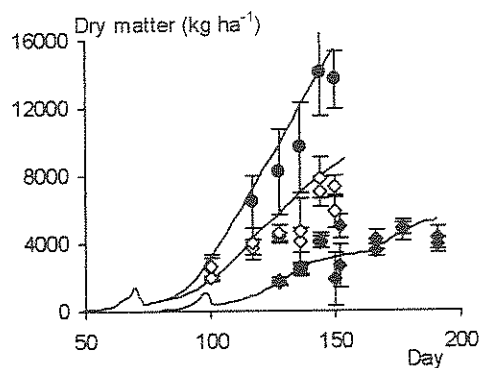

Figure 2. Observed and simulated biomass (lines) of total above ground dry matter (♦), green leaves (●) and stems (◊). Rainfed IR64, Jakenan, Indonesia, 1995. The bars indicate standard deviations.

Examples of ORYZA2000 simulations are given for biomass of plant organs in 1995 (Figure 2), and for above-ground biomass (Figure 3) and soil water potential (Figure 4) in 1996. Levels and trends in soil water potential, crop growth and development were satisfactorily reproduced. Only under severe drought (transplanting at April 9, 1996; Figure 3) did ORYZA2000 considerably overestimate grain yield (data not shown). Whereas the model partitioned all assimilates produced in the reproductive phase to the storage organs, it was observed that, in reality, the crop produced new tillers instead of filling the grains.

Figure 3. Observed and simulated (lines) above-ground biomass of IR64 at Jakenan, 1996. Transplanted March 10 with irrigation (●) and rainfed (◊), and transplanted April 9 rainfed (◆). The bars indicate standard deviations.
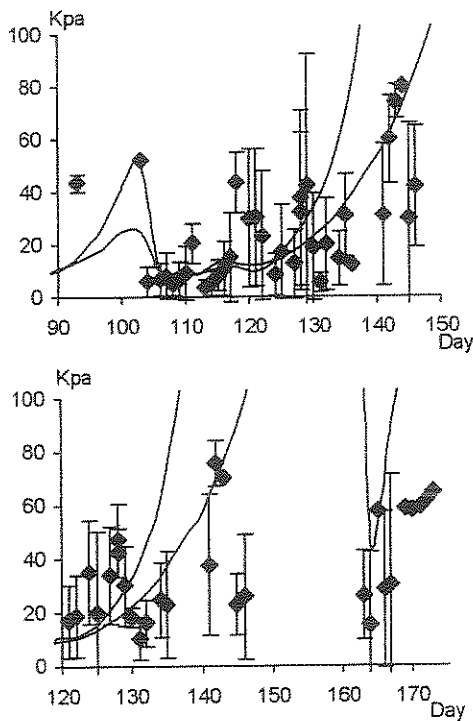

Figure 4. Observed soil water tension at 20 cm depth (◆; with standard deviation bars) and simulated values at 15 and 25 cm depth (lines). Rainfed IR64, Jakenan, 1996. Transplanted March 10 (top) and April 9 (bottom). At days 147-163, the soil was too dry to measure tension.

3.2. Nitrogen-Limited Conditions

Variety IR72 was grown at the IRRI farm in the wet and dry seasons of 1991-1993 under optimal water supply but under different fertilizer N regimes. Five experiments were conducted with a total of 39 N treatments. Specific characteristics of IR72 were derived from the maximum N treatments in 1991-1992. Daily weather data were obtained from the weather station at the site. Figure 5 gives the simulation of the growth of plant organs in the 0-N and 225-N (in 4 splits) treatments in the dry season of 1992. There is a close agreement between simulated and observed values.
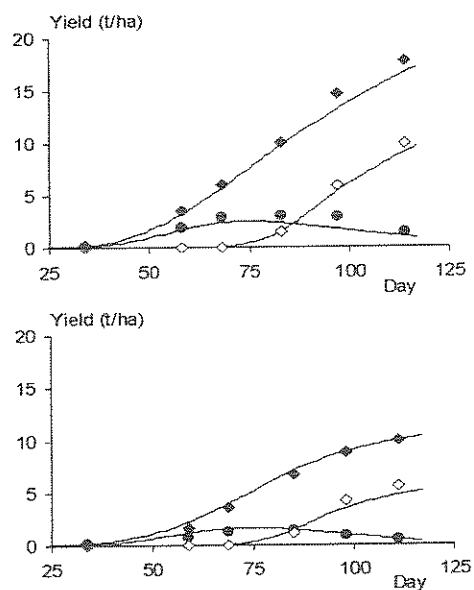
Figure 5. Observed and simulated (lines) biomass of total above ground dry matter (◆), green leaves (●) and panicles (◊) of IR72 at IRRI in the dry season, 1992, with 225 (top) and 0 kg N ha^{-1} (bottom).

Figure 6 shows a 3-quadrant diagram of observed and simulated values of yield and total N uptake versus N supply for one of the experiments in the dry season of 1993. This experiment had 17 treatments with N application rates ranging from 0 to 400 kg N ha^{-1} and a number of splits from 1 to 7 [Wopereis et al., 1996]. In general, the model reproduced the observed trends in yield and N uptake fairly well, though N uptake was often slightly overestimated. Yields were overestimated by about 2 t ha^{-1} in the two treatments where 150 and 300 kg N were applied around flowering (with 0 N before that). Since total N uptake was simulated well (150 kg in both cases, versus 130 and 155 kg observed), the effect of this late N uptake on yield production was overestimated in the model.
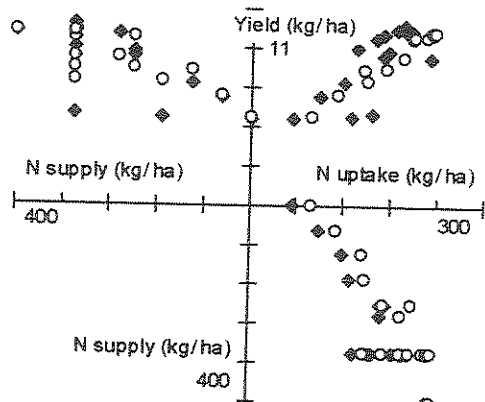
Figure 6. Three-quadrant graph of observed (◆) and simulated (○) N uptake and yield versus fertilizer N supply. Data from IR72 in the dry season of 1993, at IRRI, under 17 N regimes.

Figure 7 shows the simulated and observed yields of all 39 treatments from 1991-1993. The mean difference between simulated and observed values is 0.7 t ha^{-1} over a range of 3.6-10.2 t ha^{-1}.
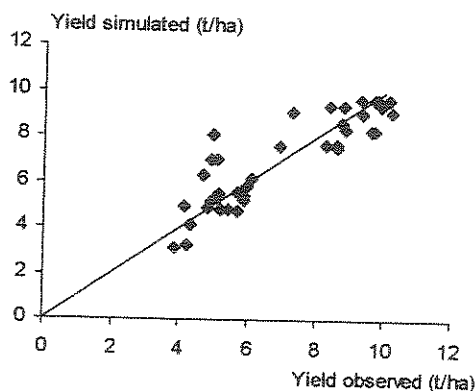

Figure 7. Simulated versus observed yields of irrigated IR72, 1991-1993 at IRRI, under various N management regimes. N=39.

4. CONCLUSIONS

The model ORYZA2000 simulates the growth and development of tropical lowland rice under conditions of potential production and of water and nitrogen limitations. It is an update, extension and integration of previously published models of the ORYZA series. A major new element is the dynamic simulation of crop N dynamics. Evaluation results show a good fit with observed crop variables across a wide range in production

situations, but also show where insights in crop growth processes need further improvement.

5. REFERENCES

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