# Fragile Lives in Fragile Ecosystems

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# Challenges and advances in simulation modeling of rainfed lowland rice systems

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Application of simulation modeling in rainfed lowland rice systems is confronted with temporal variability and spatial heterogeneity of the environment and the lack of data to describe this complexity. This paper reviews progress in simulation of rice growth in rainfed environments. It analyses important system properties unique to rainfed lowland rice ecosystems and discusses ways to model them. Special attention is given to crop responses to drought, field heterogeneity, changes in soil properties due to cracking of puddled soil, and dynamics of water table depth. Examples of different soil-water modeling approaches and applications are presented, and associated data needs and application domains are identified. Current shortcomings in rainfed rice systems modeling are discussed.

It is estimated that global rice production must increase by 65% by 2020 to keep up with the expected population growth (IRRI, 1993). Since most of the potentially suitable, and in some cases marginally suitable, land has been brought under production in the past years, increases in production have to come from increased yield levels. However, agricultural resources and inputs are becoming scarce in many places. In 2025, per capita available water resources will have declined by about 50% (Gleick cited in Hossain, 1994). Meanwhile, rice producing potential of rainfall is under utilized: rainfall in many areas, especially in the humid and subhumid tropics, is much higher than crop water requirement. However, substantial field water losses occur during land preparation and growing season. Improving field water use efficiency offers, therefore, a tremendous potential to increase rice production in rainfed lowlands. This can be done through 1) reducing field water loss, 2) optimization of planting time and selection of cultivars to match resource availability and plant needs, and

3) intensification and diversification via appropriate cropping systems. For any of these approaches, a thorough understanding of the system is needed.

Systems analysis and simulation have been used successfully in the past to evaluate the potential of different cropping systems for the diverse and variable rainfed lowland ecosystems. Angus and Zandstra (1979) used IRRIMOD to study the effect of climatic and environmental factors on rice growth and yield in different cropping systems. Bolton and Zandstra (1981a,b) developed PADIWATER to define areas and landscape positions suitable for double cropping of rainfed rice. Zandstra et al (1982) used the same model to determine the agronomic feasibility of major rice-based cropping patterns. Woodhead et al (1991) used the mechanistic soil-water flow model SAWAH (ten Berge et al 1992) to explain upland rice hydrology. Pannangpetch (1993) combined the crop growth model MACROS (Penning de Vries et al 1989) and the soil-water balance model SAWAH (ten Berge et al 1992) to evaluate rice production at the district level in northeast Thailand.

This paper discusses major aspects of rainfed rice land modeling and reports on research conducted at the International Rice Research Institute during the past 4 years to improve the quantitative understanding of the soil-crop-weather system in rainfed lowland rice ecosystems. Using the results of these studies, a process based simulation model, ORYZA_W (Wopereis et al 1995a), based on the ORYZA1 rice growth model developed for fully irrigated conditions (Kropff et al 1993) was developed.

All models which attempt to simulate rainfed rice yield consist of two parts: 1) the soil-water component, simulating water flow and water-status of the root zone, and 2) the crop component, relating root-zone water status to plant growth and yield. The discussion below is structured accordingly. Applications and further challenges in simulation modeling of rainfed lowland rice systems are discussed.

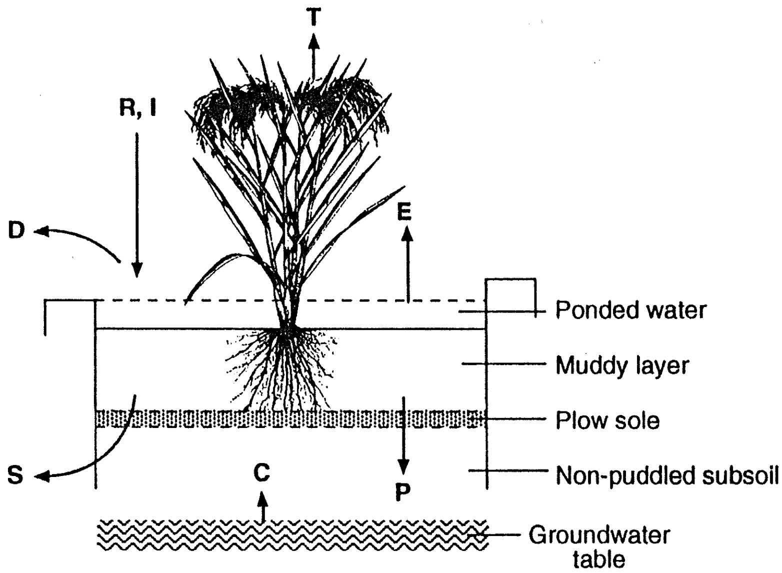
## Soil-water component

In Asia, contributing 90-95% of world production (Pathak and Gómez 1991), rice in lowland environments is mostly grown under flooded conditions. To achieve this, fields are bunded and soils are puddled by plowing, followed by harrowing and levelling at water-saturated conditions. The vertical profile of an irrigated puddled rice soil can schematically be described by a layer of ponded water, a muddy layer with little resistance to water flow, a "plow sole" with large resistance to water flow, and the non-puddled subsoil (Tuong et al 1994), as shown in Figure 1.

A general representation of a lowland rice field water balance is:

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

in which (all units in L/T): $dW$ = change in stored water; $I$ = irrigation supply; $R$ = rainfall; $C$ = capillary rise; $E$ = evaporation; $T$ = transpiration; $S$ = seepage; $P$ = percolation; $D$ = surface drainage (bund overflow).




**1. Vertical profile of puddled soil in lowland environment: D = surface drainage, E = evaporation, I = irrigation, P = percolation, R = rainfall, S = seepage, T = transpiration, C = capillary rise from the groundwater table (from Wopereis et al 1995a).**

### Modeling approaches and data requirements

The dynamics of the various components of a field water balance (Eqn. 1) over time can be simulated using integral and differential soil-water balance models (ten Berge et al 1992). Integral models are those that describe water transport in soils partly by integrating calculations (over time and/or depth) rather than by solving the general flow equation, which combines Darcy's law and an expression for conservation of mass. Differential models solve the general flow equation numerically.

The CERES-Rice crop growth model (Singh et al 1993) and the WOFOST crop growth model (van Diepen et al 1988) use integral soil-water balance modules. IRRI-MOD (Angus and Zandstra 1980) and PADDYWATER (Bolton and Zandstra 1981a) assume a constant percolation rate through the puddled topsoil and are, therefore, also integral models.

Examples of differential simulation models are SWATRE (Belmans et al 1983), FLOCR (Bronswijk 1988) and SAWAH (ten Berge et al 1992). Such models require detailed knowledge of the soil's hydraulic properties, i.e. both soil-hydraulic conductivity and water retention data. The choice between integral and differential soil-water balance modules is dictated by data availability and data requirements as much as by the desired output of the model.

Mechanistic, differential models are useful for in-depth understanding of flow processes, e.g. flow through puddled soil (Wopereis et al 1994a) or in identifying the mechanisms of water loss in rice fields (Tuong et al 1994). Their use is limited by the data needs as they require both hydraulic conductivity and moisture retention data for each soil layer. Such information can be obtained only from high cost and time consuming measurements, either in situ (Wopereis et al 1992a) or in the laboratory (Adachi 1990). Heterogeneity in rice fields (Idachi and Ishiguro 1987, Wopereis et al 1992b), resulting in lateral or preferential flows also limit the applicability of these models.

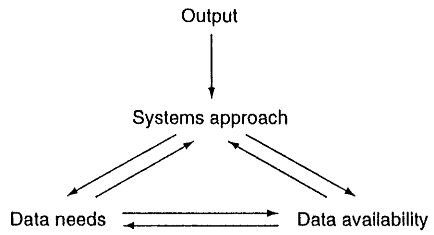
Field and simulation studies at IRRI (Tuong et al 1994) indicated that inclusion of a small area of non-puddled soil (in the order of 1% of puddled soil) increased field percolation losses by a factor of 5. Under-bund percolation, which results from lateral movement of water from the flooded fields into the bunds and then vertically down to the water table, increased percolation losses by a factor of 2-5, depending on field size. Under-bund percolation loss should be distinguished from lateral seepage, which is defined as horizontal flow through the bunds from one field to the other (Wickham and Singh 1978). While lateral seepage often results in no net loss to the field, except in peripheral fields, under-bund percolation may occur in every field, even in completely flat areas. Under-bund flow and losses through poorly puddled spots are expected to be important for rice soils that have a relatively permeable subsoil. Such soil conditions pose limitations to the practical use of SAWAH and similar mechanistic models that use point-measured soil hydraulic properties as input.

The need for data is greatly reduced by using integral soil-water balance modules that work with a constant field-average *SP* (i.e. $S + P$) rate—be it percolation, seepage and/or preferential flow—as input. The constant *SP* can easily be determined in the field from sloping gauge readings (corrected for *R*, *E*, and *T*). Using field-average *SP* rates, problems with field heterogeneity and spatial variation in location-specific *S* and *P* in the field (such as measured using double ring-infiltrometers) are overcome. Moreover, the *SP* rate measured with sloping gauges is a net value integrating water losses through vertical and lateral percolation (under-bund flow) and lateral seepage to neighbouring fields, and water gains through capillary rise and lateral inflow (seepage) from neighbouring fields.

Assumption of constant *SP* implies that losses are independent of the surrounding water regime (ponded water depth, PWD and ground water table, GWD). Sensitivity analyses using SAWAH showed that this assumption is valid for most lowland situations if the soil is well puddled (Bouman et al 1994). Losses greatly increase with increasing PWD and GWD when a poorly (or non) puddled topsoil overlies a relatively permeable subsoil or for non-puddled topsoil (Bouman et al 1994, Tuong et al

1993). For these soils, expressing SP as functions of PWD and /or GWD will improve the accuracy of the input parameters. These functions can be derived from measuring SP at several times during the crop season at different GWD and PWD.

In summary, the question of which model or approach to use, depends on the required output of the study, on data needs and on data availability (Fig. 2). Complex models can be used for in-depth research, and simple, but robust, rice crop models can be used for extrapolation.

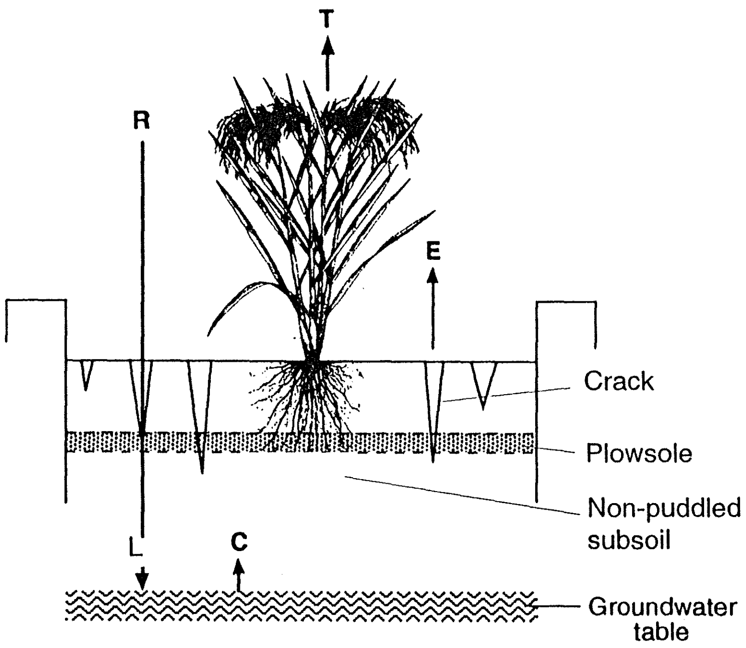



**2. Interdependency of output definition, selected systems approach, associated data needs and data availability in systems analysis (from Wopereis 1993).**

Decision trees can guide the user in selecting the appropriate model and associated "minimum data sets". Such approach was used in the ORYZA_W crop growth simulation model (Wopereis et al 1995a). It can handle any soil condition (puddled/non-puddled, free draining/impeded drainage, cracking/noncracking) in irrigated and rainfed rice-growing environments. It incorporates a *decision tree*, based on soil conditions, to help users identify data requirements. Depending on the decisions made by the user, data requirements to run ORYZA_W may vary from rather limited (non-puddled, freely draining, noncracking soils with a deep groundwater table) to substantial (puddled, cracking soils with a shallow groundwater table).

## Soil cracking

Deliberate or unavoidable drying of a previously submerged puddled soil creates cracks due to soil shrinkage. If drying-out of the puddled layer continues, cracks may develop that will broaden and widen in time. They eventually may extend through the puddled layer and plow sole into the subsoil (Fig. 3). Subsequent rainfall may flow through the cracks, bypassing the root zone. Water loss as a result of such preferential flow through deep soil cracks can be high (e.g. Wopereis et al 1994b), depending on the drainage capacity of the subsoil layers. Cracks may change the water balance of the rice field drastically. Knowledge on when cracking occurs and how much it changes seepage and percolation rate is important in soil-water balance studies of the rainfed rice environment.




**3. Vertical profile of a puddled soil in a rainfed lowland environment—cracks have penetrated into the subsoil. E = evaporation, R = rainfall, C = capillary rise and T = transpiration, L = water loss through crack (from Wopereis et al 1995a).**

ORYZA_W also takes a decision tree approach towards soil cracking. If the soil is not puddled (e.g. in dry seeded rice cultivation, Tuong et al 1995), soil cracking is not simulated. For puddled soils, the simulation passes through a subroutine which uses a semi-empirical approach to take into account the effects of cracks. A relatively simple approach, based on the soil-shrinkage curve (Bronswijk 1988) is used. A shrinkage factor, defined as the ratio of total porosity of puddled and non-puddled soil determines volume change. It is assumed that the puddled soil remains saturated during shrinkage, i.e. water loss equals volume change, until the total porosity is equal to that of nonpuddled soils. From that moment on, the soil pressure potential decreases and the rice plant may start to suffer from drought stress. Cracks are assumed to have penetrated through the plow sole if the simulated soil-pressure potential of the puddled topsoil drops below a critical value. For IRRI puddled soil conditions this was found to occur at about -100 kPa (IRRI 1992a). Water that drains from the cracked root zone will fill up soil layers below the root zone to field capacity. Any excess water will be drained at a maximum rate equal to the saturated hydraulic conductivity of the subsoil horizon. In heavy clay soils with a low drainage capacity, rainfall water may still get ponded on the surface, but in case of a relatively permeable subsoil, rainfall will drain quickly. Shrinking and cracking are irreversible, i.e. the puddled layer will not resume its earlier properties (until renewed puddling in the next season).

### Ground water table and capillary rise

Ground water contribution by capillary rise during a drought spell may represent up to a third of the input to the crop-soil water balance. Excluding the term may result in a 30% underestimation of actual yield at the 4 t/ha level and a 90% underestimation at the 1 t/ha yield level (Bolton and Zandstra 1981a). Unfortunately, capillary rise is difficult to measure. Simulating capillary rise requires data on groundwater table depth (GWD) and the soil's hydraulic conductivity characteristics with depth. Time series of groundwater depth fluctuations are usually not available. This poses a limitation to the extent with which models can be applied to simulation of rainfed lowland rice production. Reports on simulating GWD are limited. While it is clear that changes in GWD are affected by percolation rate and soil-specific parameters (Rashid 1993, Fukai et al these proceedings, Wopereis et al 1995a), existing approaches are not yet vigorously tested. Ten Berge et al (1992) suggested expressing groundwater table depth as an empirical and site-specific function of rainfall. Pannangpetch (1993) used this approach and expressed GWD as a function of GWD of the previous day, rainfall, and some soil-related parameters. Such empirical equations require, however, long term monitoring of the water table and are only applicable to the study site.

## Crop component

### Modeling of drought stress response in rice

Morphological and physiological responses of rice to drought stress have long been investigated. Morphological responses include reduction of leaf expansion and leaf area, leaf rolling, and early senescence (e.g. O'Toole and Cruz 1980, O'Toole and Baldia 1982). Physiological processes that are affected by drought are closing of stomata, reduction of photosynthesis, and reduced translocation of assimilates to the grains (e.g. Fukai et al 1985, Turner 1986). Drought that develops before anthesis also delays the phenological development of the rice plant (Chaudry and McLean, cited in De Datta et al 1973, Puckridge and O'Toole 1981, Turner et al 1986, Inthapan and Fukai 1988).

For lowland rice, responses to drought have rarely been expressed as functions of root zone water status. Because of the lack of such data, rainfed rice simulation models often use standard relationships that have been derived for other upland crops (Penning de Vries et al 1989), upland rice (Fukai et al these proceedings), or other simpler approaches and assumptions.

Predictive equations based on the accumulation of stress days (days without standing water) have been used by Wickham (1973) to determine the benefits of irrigation. The stress day concept was also used by Rashid (1993) to evaluate the long-term yield stability of rainfed lowland rice as a function of the interactive effects of nitrogen and water stress. The value of this simple approach in rainfed areas is, however, questionable, since the stress day concept does not take into account the intensity and timing of the drought stress (Cablayan and Wickham 1978).

In more mechanistic rainfed rice models, drought stress is often simulated through its physiological responses. The rate of photosynthesis under water-limited conditions is calculated by multiplying the potential photosynthesis rate with the ratio of actual over potential transpiration (Bolton and Zandstra 1981a, McMennamy and O'Toole 1983, Penning de Vries et al 1989, Fukai et al these proceedings). The relationship between soil moisture status and actual transpiration provides the link between soil-water balance and the crop growth module. Simulation results are sensitive to the effect of water shortage on transpiration rate under water stress conditions. This effect is often modeled by assuming that the ratio $T_r$ of actual transpiration $T_a$ over potential transpiration $T_p$ is a function of soil water volumetric content ($V$) over the rooting zone (Bolton and Zandstra 1981a, McMennamy and O'Toole 1983, Penning de Vries et al 1989, Fukai et al these proceedings). As $V$ decreases from field capacity ($V_{FC}$ defined at $h = -10$ kPa) to wilting point ($V_{WP}$, often defined at h = -1.5 MPa), $T_a/T_p$ stays equal to 1 until V reaches a threshold or critical value, $VC$. $T_a/T_p$ decreases from 1 to 0 as $V$ decreases from $V_C$ to $VWP$. The ratio $(V_{FC} - V_C)/(V_{FC} - V_{WP})$ is often taken between 0.5 and 0.7 for other crops than rice (Saugier and Katerji 1991). $V_C$ for lowland rice is often set to $V_{FC}$ (Penning de Vries et al 1989), or very near to saturation point (Bolton and Zandstra 1981a, Fukai et al these proceedings). The models thus assume a very sensitive response of $T_r$ to soil-water content. This sensitive response implies a very early closure of stomata.

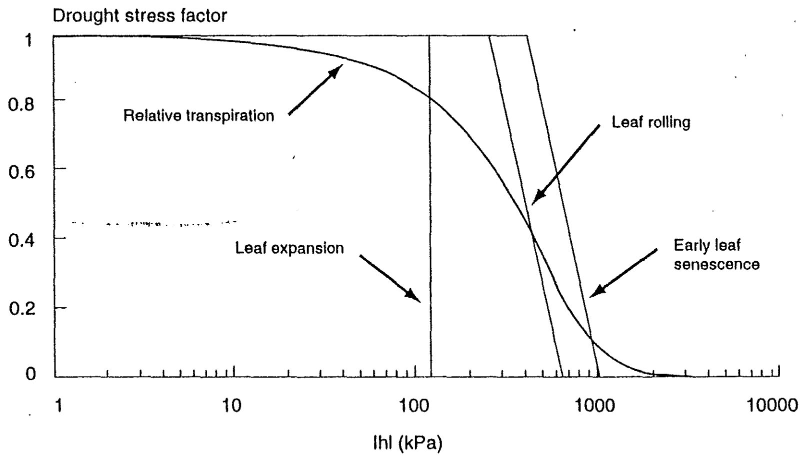
Delay in phenological development is also often neglected in simulation models. This delay is, however, an important mechanism for the rice plant to compensate for reduced biomass accumulation during stressed periods. Neglecting the delay may result in underestimation of total dry matter production. Accurate modelling of the delay, which sometimes may go up to 40 days (Puckridge and O'Toole 1981, Inthapan and Fukai 1988), is also important if the models are used to test cropping calendars.

## New developments

To be effective in predicting the impact of soil and weather conditions on rice production process-based crop simulation models must, in addition to the physiological responses, take into account morphological and phenology-delay responses of the rice plant under water stress conditions. At IRRI, greenhouse experiments were conducted to quantify these responses in relation to root-zone soil-water pressure potential $h$ for rainfed rice simulation models. Three rice varieties were used: IR20, IR72, and PSBRC14. Responses during the drought period itself and after recovery (i.e. re-irrigation) were investigated. Details are given in Wopereis et al (1995b) and U. Singh et al (these proceedings, pages 507-519). Results obtained for different varieties, soil materials, and conditions (puddled and non-puddled) were quite similar, indicating the potential of the root-zone soil-water potential $h$ to act as an indicator for drought in different soil types. The first observed response, if drought was initiated in the vegetative phase, was a relatively abrupt decline in leaf expansion. Leaf rolling and senescence of leaves followed at lower soil moisture contents and were linearly related to log $|h|$ The initial reduction of transpiration of stressed plants as compared with well-watered plants was caused by a reduction of LAI, resulting from morphological responses to drought. Closure of stomata occurred at a lower soil moisture content. Logistic functions could be used to describe the decline in relative transpiration, corrected for differences in LAI between well-watered and stressed plants, as a function of log $|h|$. By neglecting morphological responses to drought, simulations tend to overestimate the LAI of stressed plants, leading to an overestimation of the transpiration rate when stress is relieved.

The information gathered from the experiments conducted at IRRI was used to further develop ORYZA_W (Wopereis et al 1995a). Drought stress responses (leaf rolling, leaf senescence, relative transpiration, leaf expansion) are modeled as stress factors, defined as a function of the log $|h|$ of the root zone (Fig. 4). For each response, critical log $|h|$ values can be defined: an upper limit, that indicates the start of stress (stress factor = 1) and a lower limit (stress factor = 0), that indicates 100% stress (completely rolled up leaves, 100% dead leaves, zero transpiration). For leaf expansion, a step function was assumed (Fig. 4). Log |h| of the root-zone is calculated from soil-water balance modules. If log |h| drops below the critical value (upper limit) for a certain drought stress response drought stress starts. The critical log |h| values apply for the whole crop growth duration, although in reality plant age influences drought stress responses as a function of soil-water pressure potential to some extent (Wopereis et al 1995b).

Rooting depth is an important variable in calculating root zone water content and water uptake for transpiration by the plants. Roots can be modeled as growing with a constant daily root growth rate to a user-specified maximum depth (e.g. in Penning de Vries et al 1989, Wopereis et al 1995a). There is a wealth of literature showing root length densities of rice as a function of soil depth. From such data an estimate of root growth rate can be made. Usually this is in the range of 0.01-0.02 m/day depending, among other things, on rice variety, soil texture, soil tillage, and presence of hard layers. The volume of water taken up by the roots, i.e. the transpiration of the crop needs to be divided over the rooting depth. The maximum uptake $S_{max}$ is assumed constant over depth in most of the present models. This means that, under optimal water conditions, the transpiration load of the crop is divided equally over all soil layers. Another option would be to assume that $S_{max}$ declines with increasing rooting depth. At present, insufficient experimental information on root water uptake versus soil depth is available.




**4. Relationship between soil-water pressure potential and drought stress factors for rice variety IR20 (adapted from Wopereis et al 1995b).**

The delay in flowering due to water stress in the vegetative phase as observed in the IRRI experiments was in reasonable agreement with the number of days between the date of zero leaf expansion and the recovery date. This may indicate that, if the soil is too dry to produce new leaves, the development rate of the crop is brought to a standstill as well. The development rate of the crop, as simulated by ORYZA_W stops, therefore, if the water content of the root zone drops below the critical log lhl value for leaf expansion. No delay in development is simulated when drought occurs in the reproductive phase.

The reduction factor on daily total gross $CO_2$ assimilation of the crop due to drought stress used in ORYZA_W is again calculated as the ratio of actual canopy transpiration over potential canopy transpiration. With drought stress, photosynthesis no longer leads to leaf production (vegetative phase); "excess" carbohydrates are allocated to the roots. In reality, part of the "excess" carbohydrates will probably be stored in the stem or the leaves as well. Without leaf expansion, this will lead to thicker leaves and, therefore, a smaller specific leaf area (i.e. leaf area/leaf weight per unit area of land, SLA). Upon recovery from drought, such thick leaves may expand quickly while increasing their SLA. Such drought responses need further study.

The modeling approaches used in ORYZA_W were validated with experiments reported by Hasegawa and Yoshida (1982) and Wopereis (1993) for both puddled and non-puddled soil. Good agreement was found between simulated and observed results for soil-water status and plant dry matter accumulation (Wopereis 1993, Wopereis et al 1995a).

## Applications

**Identification of limiting factors for low yield of rainfed rice**

Rainfed rice is characterized by low and unstable yield. Simulation models can be used as a first step to identify key factors responsible for the low yield, and ways to alleviate them, in a certain environment. Simulation studies by Fukai et al (these proceedings) identified the importance of rainfall, deep percolation, and soil fertility in determining rice yield under rainfed lowland conditions in northeast Thailand. Regional rice yield losses due to drought in the wet-season in the province of Tarlac, Philippines were estimated (Wopereis et al 1993) by simulating the difference between potential rice yield under fully irrigated and water limited conditions, while assuming optimal N supply. The analysis indicated which soil types were most susceptible to drought and would benefit most from improved irrigation facilities. In models where soil nitrogen transformation and crop response to nitrogen are not included (e.g. ORYZA_W, Wopereis et al 1995a), the effects of nitrogen shortage can also be simulated by assuming a lower N content in the canopy. If measured nitrogen content and leaf area index (LAI) over time are used as an input to the model, differences in simulated and actual yield indicate differences due to factors other than water, nitrogen, and solar radiation (e.g. P and/or K shortage, pest and diseases).

**Detailed analysis of data from field experiments and extrapolation of results**

Simulation models were used to investigate if shallow flooding of paddy rice fields increases water use efficiency as claimed by Tabbal et al (1992) and Hardjoamidjojo (1992). Analyses using the differential SAWAH simulation model (ten Berge et al 1992) showed that savings depend on the hydraulic conductivity of the subsoil and the thoroughness of puddling of the topsoil (Bouman et al 1994).

**Optimization of cropping systems**

Simulation models can be used to investigate risk associated with varietal selection and adoption of various cropping systems/calendars for specific environments. Palanisami (1993) used simulation models to derive the optimum cropping pattern and to improve irrigation water conveyance efficiency and scheduling of centuries old tank irrigation in Tamil Nadu, India. Fukai et al (these proceedings) suggested that late planting should be avoided as much as possible as it resulted in low rice yield under rainfed conditions in northeast Thailand. Early planting is, however, constrained by inadequate water accumulation for transplanting. One possible way to overcome this constraint is to make use of the dry seeded rice systems. Dry seeded rice can be established early because it effectively makes use of premonsoon rains (Tuong et al 1995). Its early harvest also enhance crop intensification, diversification, and productivity of rainfed rice ecosystems. Dry seeding is already successfully used in Vietnam and Indonesia (Fujisaka et al 1993). More experimental work and combined use of simulation modeling and GIS may identify other areas where this new technique may be adopted.

### Analysis of physiological requirements for increased yield potential

The drought stress experiments at IRRI summarized above were conducted with semidwarf lowland varieties. Dryland rice varieties are known to be more "pessimistic" (Bradford and Hsiao, cited in Dingkuhn et al 1989) in their drought responses as they show leaf rolling at higher leaf water potentials (e.g. Turner et al 1986, Dingkuhn et al 1989). They also tend to have a deeper root system than lowland rice varieties (Yoshida 1981) and may therefore be more effective in exploring soil-water resources. Mechanistic models, such as ORYZA_W, which incorporate important physiological, morphological, and phenological responses, can be used to quantify the impact of plant traits on varietal performance in rainfed environments.

## Challenges and conclusions

### Validation of models

A model is truly workable only when it is validated for a wide range of environmental conditions, different from where it has been developed and parametrized. Few rainfed rice models have been vigorously validated. Validation of models includes the selection of well founded data sets and/or implementation of well designed and well managed experiments. The Rainfed Lowland Rice Research Consortium (IRRI 1992b) could serve as an excellent vehicle for model validation and application. This could be achieved by conducting, at each consortium key site, a standard experiment, with clear sampling and measurement protocols. The diverse environments of the key sites offer wide conditions for vigorous model validation.

### Drought and nutrient interactions

Certainly one of the greatest challenges in rainfed rice modeling will be to include N uptake under water-limited conditions. The CERES-Rice model (Singh et al 1993) has built in a subroutine predicting N transformations and uptake under water-limited conditions. The subroutine has, however, not been tested for rainfed lowland rice conditions (U. Singh 1995, pers. comm.). The ORYZA_W model can handle N limited conditions by assuming different N profiles in the canopy, but is thereby skipping the N uptake process completely and cannot assess how far drought stress in rainfed environments is compounded by N deficiency and vice versa.

**Knowledge on drought stress responses**

Further research needs to be devoted to drought stress effects on sink size formation (e.g. spikelet formation, ratio of filled-unfilled grains), phenology, dry matter partitioning, and root growth. The effect of increased soil strength during drought must also be taken into account.

**Slopes and water table dynamics**

A large area of rainfed rice is on sloping land. Most of the available rainfed rice models are one-dimensional. Developing soil-water balance models that take into account the effect of toposequence on water table dynamics in terraced or sloping land is urgently needed.

**Data and database development**

What is lacking most for effective application of models at the regional level are suitable input data necessary for simulation studies. National and international agricultural research centres should work together to optimize the number of field monitoring sites in research networks. Key sites in such consortia should be carefully selected. It is better to have fewer but well-maintained sites that are carefully monitored. Only if good data sets are available, can simulation models be used to extrapolate new technologies or to identify constraints to rice production. Minimum data sets for key site characterization and standard methodologies for collecting soil and climate data should be identified. Installation and maintenance of weather stations should be stimulated.

One of the major problems for application of rainfed simulation models is the lack of data on soil hydraulic functions. Data bases are needed that relate these functions to soil characteristics that can be derived from soil survey data. At IRRI a hydraulic functions database developed by the US Soil Salinity Laboratory is used.

There is also a need of methods—such as the decision tree approach used in ORYZA_W)—to guide the user in selecting the appropriate model and associated "minimum data sets" and to assess the effect of variability of model input parameters on simulated output. An important development in this respect has been the contribution by Bouman (1994) who developed a framework to deal with uncertainty in input parameters in crop yield simulation.

## References cited

Adachi K (1990) Effects of rice-soil puddling on water percolation. Pages 146-151 *in* Transactions of the 14th International Congress of Soil Science. ISSS, Kyoto, Japan.

Angus J F, Zandstra H G (1980) Climatic factors and the modeling of rice growth and yield. Pages 189-199 *in* Agroclimatology of the rice crop. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Belmans C, Wesseling J G, Feddes R A (1983) Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrol. 63:271-286.
Bolton F R, Zandstra H G (1981a) A soil moisture based yield model of wetland rainfed rice. IRRI Research Paper Series 62. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.
Bolton F R, Zandstra H G (1981b) Evaluation of double-cropped rainfed wetland rice. IRRI Research Paper Series 63. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.
Bouman B A M (1994) Uncertainty in soil and management parameters in crop growth modelling on regional scale. Pages 58-72 *in* SARP research proceedings, agro-ecology of rice-based cropping systems. B.A.M. Bouman, H.H. van Laar, and Wang Zhaoqian, eds. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.
Bouman B A M, Wopereis M C S, Kropff M J, ten Berge H F M, Tuong T P (1994) Understanding the water use efficiency of flooded rice fields. II. Percolation and seepage losses. Agric. Water Manage. 26:291-304.
Bronswijk J J B (1988) Modeling of water balance, cracking and subsidence of clay soils. J. Hydrol. 97:199-212.
Cablayan D, Wickham T (1978) Modeling the performance of two crops of rainfed rice. Irrigation Water Management Department, International Rice Research Institute, P.O. Box 933, Manila, Philippines.
De Datta S K, Abilay W P, Kalwar G N (1973) Water stress effects in flooded tropical rice. Pages 19-36 *in* Water management in Philippine irrigation systems: research and operations. International Rice Research Institute, P.O. Box 933, Manila, Philippines.
Dingkuhn M, Cruz R T, O'Toole J C, Dörffling K (1989) Net photosynthesis, water use efficiency, leaf water potential and leaf rolling as affected by water deficit in tropical upland rice. Aust. J. Agric. Res. 40:1171-1181.
Fujisaka J S, Moody K, Ingram K T (1993) A descriptive study of farming practices for dry seeded rainfed lowland rice in India, Indonesia, and Myanmar. Agric. Environ. Ecosyst. 45(1-2):115-128.
Fukai S, Kuroda E, Yamagishi T (1985) Leaf gas exchange of upland and lowland rice cultivars. Photosynthesis Res. 7:127-135.
Hardjoamidjojo S (1992) The effect of depth of flooding and method of water application on water requirements and yield of wetland paddy. Pages 63-71 *in* Soil and water engineering for paddy field management. V.V.N. Murty and K. Koga, eds. Irrigation Engineering and Management Program, Asian Institute of Technology, Bangkok.
Hasegawa S, Yoshida S (1982) Water uptake by dryland rice root system during soil drying cycle. Soil Sci. Plant Nutr. 28(2):191-204.
Hossain M (1994) Recent developments in Asian rice economy: emerging trends and prospectives. Paper presented in a seminar in the University of Gothenburg, Sweden, November 1994.
Idachi K, Sihiguro M (1987) Water requirement and percolation. Pages 35-48 *in* Physical measurements in flooded rice soils: the Japanese methodologies. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.
Inthapan P, Fukai S (1988) Growth and yield of rice cultivars under sprinkler irrigation in south-eastern Queensland. 2. Comparison with maize and grain sorghum under wet and dry conditions. Aust. J. Exp. Agric. 28:243-248.

IRRI—International Rice Research Institute (1992a) Program report for 1991. International Rice Research Institute, Los Baños, Philippines.

IRRI—International Rice Research Institute (1992b) Challenges and opportunities in a less favorable ecosystem: rainfed lowland rice. IRRI Information Series No. 1. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

IRRI—International Rice Research Institute (1993) Rice research in a time of change. IRRI's medium-term plan for 1994-1998. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Jones A C, O'Toole J C (1987) Application of crop production models in agro-ecological characterization: simulation models for specific crops. Pages 199-209 in Agricultural environments. Characterization, classification and mapping. A.H. Bunting, ed. CAB International, Wallingford, UK.

Kropff M J, van Laar H H, ten Berge H F M, eds (1993) ORYZA1, a basic model for irrigated lowland rice production. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

McMennamy J A, O'Toole J C (1983) RICEMOD: a physiologically based rice growth and yield model. IRRI Research Paper Series 87. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

O'Toole J C, Baldia E P (1982) Water deficits and mineral uptake in rice. Science 22:1144-1150.

O'Toole J C, Cruz R T (1980) Response of leaf water potential, stomatal resistance and leaf rolling to water stress. Plant Physiol. 65:428-432.

Palanisami K (1993) Optimization of cropping patterns in tank irrigation systems in Tamil Nadu, India. Pages 413-425 *in* Systems approaches for agricultural development. F.W.T. Penning de Vries, P.S. Teng, and K. Metselaar, eds. Kluwer Academic Press, Dordrecht, The Netherlands.

Pannangpetch K (1993) Application of a simulation model to evaluate rice production at the district level. Pages 16-25 *in* SARP research proceedings, agro-ecology of rice-based cropping systems. B.A.M. Bouman, H.H. van Laar, and Wang Zhaoqian, eds. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Pathak M D, Gomez K A (1991) Rice production trends in selected Asian countries. IRRI Research Papers No. 147. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Penning de Vries F W T, Jansen D M, ten Berge H F M, Bakema A (1989) Simulation of ecophysiological processes of growth in several annual crops. Simulation Monographs 29. IRRI, Los Baños and Pudoc, Wageningen.

Puckridge D W, O'Toole J C (1981) Dry matter and grain production of rice, using a line source sprinkler in drought studies. Field Crops Res. 3:303-319.

Rashid M A (1993) A simple water balance model and the long term yield stability of rainfed lowland rice as interactive effects of nitrogen and water stress. Ph.D. thesis, the University of the Philippines at Los Baños, College, Laguna, Philippines.

Saugier B, Katerji N (1991) Some plant factors controlling evapotranspiration. Agric. Forest Meteorol. 54:263-277.

Singh U, Ritchie J T, Godwin D C (1993) A user's guide to CERES-Rice - V2.10. International Fertilizer Development Center, P.O. Box 2040, Muscle Shoals, Alabama, USA.

Tabbal D F, Lampayan R M, Bhuiyan S I (1992) Water-efficient irrigation techniques for rice. Paper presented at the international workshop on soil and water engineering for paddy field management, Asian Institute of Technology, Bangkok, 28-30 Jan 1992.

ten Berge H F M, Jansen D M, Rappoldt K, Stol W (1992) The soil water balance module SAWAH: user's guide and outline. CABO-TPE Simulation Report Series, no. 22. CABO, Wageningen, The Netherlands.

Tuong T P, Ingram K T, Siopongco J D, Confesor R B, Boling A A, Singh U, Wopereis M C S (1995) Performance of dry seeded rice in response to agrohydrology and N-fertilizer management. Pages 141-155 *in* Rainfed lowland rice: agricultural research for high-risk environments. K.T. Ingram, ed. International Rice Research Institute, P.O. Box 933, Manila, Philippines.

Tuong T P, Wopereis M C S, Marquez J, Kropff M J (1994) Mechanisms and control of percolation losses in puddled rice fields. Soil Sci. Soc. Am. J. 58:1794-1803.

Tuong T P, Wopereis M C S, Singh A K, Kropff M J, ten Berge H F M (1993) Modeling lowland rice agrohydrology. Presented at the 14-17 Dec 1993 ASAE International Meeting. Paper No. 932528.

Turner N C (1986) Crop water deficits: a decade of progress. Adv. Agron. 39:1-51.

Turner N C, O'Toole J C, Cruz R T, Namuco O S, Ahmad S (1986) Responses of seven diverse rice cultivars to water deficits. I. Stress development, canopy temperature, leaf rolling and growth. Field Crops Res. 13:257-271.

van Diepen C A, Rappoldt C, Wolf J, van Keulen H (1988) CWFS crop growth simulation model WOFOST. Documentation Version 4.1. Centre for World Food Studies, Amsterdam–Wageningen, The Netherlands.

Wickham T (1973) Predicting yield benefits in lowland rice through a water balance model. *In* Water management in Philippines irrigation systems: research and operations. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Wickham T H, Singh V P (1978) Water movement through wet soils. Pages 337-357 *in* Soils and rice. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Woodhead T, ten Berge H F M, de San Agustin E M (1991) Modeling upland rice hydrology. Pages 53-60 *in* Systems simulation at IRRI. F.W.T. Penning de Vries, M.J. Kropff, P.S. Teng, and G.J.D. Kirk, eds. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Wopereis M C S (1993) Quantifying the impact of soil and climate variability on rainfed rice production. PhD Thesis Wageningen Agricultural University.

Wopereis M C S, Bouman B A M, Kropff M J, ten Berge H F M, Maligaya A R (1994a) Understanding the water use efficiency of flooded rice fields. I. Validation of the soil-water balance model SAWAH. Agric. Water Manage. 26:277-289.

Wopereis M C S, Bouma J, Kropff M J, Sanidad W (1994b) Reducing bypass flow through a dry, cracked and previously puddled rice soil. Soil and Tillage Res. 29:1-11.

Wopereis M C S, Bouman B A M, Tuong T P, ten Berge H F M, Kropff M J (1995a) ORYZA_W: rice growth model for irrigated and rainfed environments. SARP Research Proceedings (in press).

Wopereis M C S, Kropff M J, Maligaya A R, Tuong T P (1995b) Drought stress responses of two lowland rice cultivars to soil-water status. Field Crops Res. (in press).

Wopereis M C S, Kropff M J, Hunt E D, Sanidad W, Bouma J (1993) Case study on regional application of crop growth simulation models: Tarlac province, Philippines. Pages 27-46 *in* Agro-ecology of rice-based cropping systems. B.A.M. Bouman, H.H. van Laar, and W. Zhaoqian, eds. SARP Research Proceedings.

Wopereis M C S, Wösten J H M, Bouma J, Woodhead T (1992a) Hydraulic resistance in puddled rice soils: measurement and effects on water movement. Soil and Tillage Research 24:199-209.

Wopereis M C S, Stein A, Bouma J, Woodhead T (1992b) Sampling number and design for measurement of infiltration rates into puddled rice fields. Agric. Water Manage. 21:199-209.

Yoshida S (1981) Fundamentals of rice crop science. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

Zandstra H G, Samarita D E, Pontipedra A N (1982) Growing season analyses for rainfed wetland fields. IRRI Research Paper Series 73. International Rice Research Institute, P.O. Box 933, 1099 Manila, Philippines.

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