Physiology of Stress Tolerance in Rice

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MODELLING THE SOIL-PLANT-WATER BALANCE OF RAINFED LOWLAND RICE

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SUMMARY

A soil-water balance module (PADDY) and a module predicting the response of rice to drought (DSTRESS) were developed and linked with a crop growth simulation model (ORYZA1) to simulate rice growth and production in rainfed lowland rice ecosystems. The combined PADDY-DSTRESS-ORYZA1 model (ORYZA-W) was validated using two field experiments in the Philippines. Measured and simulated changes in ponded water depth under flooded soil conditions were in good agreement. In one of the field experiments, temporary drought was induced at different stages. The model satisfactorily predicted change in root zone water content, leaf area index, total aboveground dry matter, and panicle dry weight across drought treatments over time. The model was subsequently used to predict rainfed rice yield as a function of soil hydraulic properties and long-term weather data (25 yr) in Tarlac Province of Philippines. Risk involved in growing rainfed rice was quantified by calculating yield probability distribution for seven major soil types under rice cropping. Coupling ORYZA-W to a GIS allowed a spatial analysis of risk in Tarlac Province.

INTRODUCTION

Process-based simulation models can be used as a tool to unravel some of the complexity and variability of rainfed lowland rice ecosystems. Such models allow detail analysis of experimental data, or extrapolation of research findings to other environments.

Quantifying the responses of rice to drought stress is essential for predicting the impact of soil and weather conditions on rice production. For lowland rice, grown in puddled soils, there is little information on the link between soil-water status and crop response, although drought is generally seen as a major cause of yield loss in rainfed rice production system. Existing rice growth simulation models use standard drought stress responses often derived for other crops.

The man-made puddled layer in lowland rice soils is often effective reducing water loss through percolation to deeper soil layers. The effect of puddling on the

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hydraulic conductivity of the various layers is, however, not well understood. Drying of previously submerged rice soils creates cracks that may extend through the plow sole at the bottom of the puddled layer. This can cause a drastic and often irreversible increase in water losses due to increased percolation rates. Existing soil-water balance modules do not consider such changes and are not directly applicable to puddled rainfed lowland rice soils.

A new soil-water balance module, PADDY, and a 'drought stress' module, DSTRESS, were developed and coupled to the model ORYZA1, (Kropff *et al.*, 1993; IRRI, 1993) for use in rainfed ecosystems. The combined ORYZA1-DSTRESS-PADDY simulation model (ORYZA-W) was validated using two experiments conducted at IRRI in 1991 and 1992, and used to predict rainfed rice yield on a regional scale for a province in the Philippines.

MATERIALS AND METHODS

The crop simulation model ORYZA1 is documented elsewhere (Kropff *et al.*, 1993). Input requirements for ORYZA1 are :

* Geographical latitude ;
* Daily data on solar radiation and minimum and maximum temperature ;
* Plant density ;
* Date of crop emergence or transplanting ; and
* Parameters describing the morphological and physiological characteristics of the rice variety.

In water-limited environments, water availability, light, and temperature determine the crop growth rate (provided no nutrient limitations occur). Wopereis (1993) derived functions that describe a number of physiological and morphological responses of the rice crop to soil-water content of the root zone. These functions were incorporated in the module DSTRESS. The module PADDY was developed to predict the soil-water status of a puddled root zone. Both modules are described in detail below. The linkage between ORYZA1, PADDY, and DSTRESS is illustrated in Figure 1. PADDY and DSTRESS are written in FORTRAN and make use of the Fortran Simulation Environment (van Kraalingen, 1991). A detailed user's manual for ORYZA-W is in preparation.

Description of *PADDY*

An irrigated puddled soil profile consists of a muddy layer with little resistance to water flow, a less permeable plow sole and, the non puddled subsoil. The muddy layer gradually increases in bulk density with depth but is treated here as a uniform layer. In PADDY, it is assumed that the first two layers of the soil profile comprise the muddy layer and the plow sole, respectively. Time step of integration in PADDY is 1.

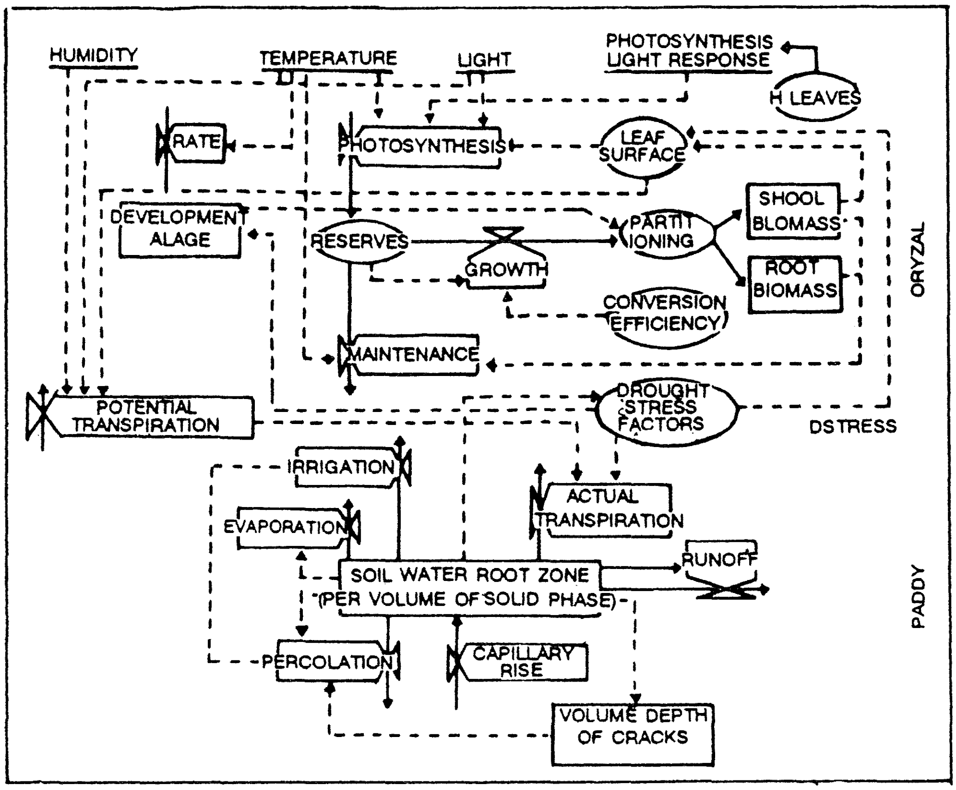


Fig. 1 : Linkage between the modules ORYZA1, PADDY, and DSTRESS

In PADDY, precolation rate can either be an input or can be calculated using an iterative Newton-Raphson Procedure (Wolfram, 1991) comparing fluxes through the plow sole and nonpuddled subsoil. Capillary rise is calculated based on integration of the Darcy equation for steady, upward, vertical flow (Gardner, 1958). Capillary rise can be ignored if the groundwater table is sufficiently deep, or if roots have not reached the nonpuddled subsoil (see for details Tuong et al., 1993). The potential rates of evaporation from soil and water and crop transpiration with soil background (dry field) or water background (wet field) are derived from the Penman reference evapotranspiration calculated from daily weather data (vapor pressure, temperature, wind speed) using a Penman type equation (Penman, 1948). Actual transpiration rate is estimated from the potential transpiration ratg and a drought stress factor calculated by DSTRESS, described below. Actual evaporation rate from soil is calculated by assuming that cumulative evaporation is proportional to the square root of time (Stroosnijder, 1982). The rate on the first day is assumed to be 60% of potential soil evaporation. In reality, puddled clay qoil will probably dry out faster because of the rapid appearance of shrinkage cracks, which may increase the evaporation surface to more than double in a puddled clay soil (Fujioka and Sato ,1986). This aspect has not been taken into account in PADDY.

The continuous drying of a puddled clay soil results in shrinkage cracks and subsidence of the soil surface. To simulate cracking of the puddled root zone, knowledge of the soil's shrinkage characteristic is needed (Fig. 2), where moisture ratio v is defined as the volume of water V_w over the volume of the solid phase Vs, and void ratio e is defined as the volume of pores Vp over the volume of solid phase. The shrinkage characteristic is used to calculate the volume of pores per volume of soil (ε, m^3/m^3), the volume of water per volume of soil (θ, m^3/m^3), the subsidence of the puddled soil surface, and the change in crack volume (Bronswijk, 1988). It is assumed in PADDY that shrinkage is irreversible and that the puddled muddy topsoil gradually regains structure, a process that usually is referred to as 'soil ripening'. Total porosity ε therefore, declines upon drying and will not increase if the water content of the root zone increases. In PADDY, cracks are assumed to have penetrated through the plow sole if its simulated moisture ratio drops below 1.2, which for IRRI soil is equivalent to a soil pressure potential h of - 100 kPa (IRRI, 1992).

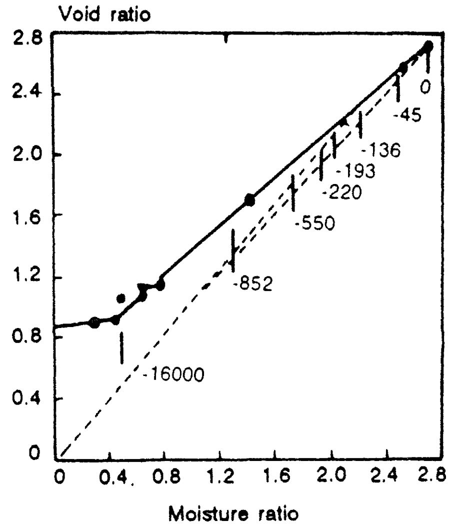


Fig. 2 . Soil shrinkage characteristic of a puddled clay soil. Values in diagram indicate soil pressure heads (cm).

If soil cracks have not yet reached the plow sole, it is assumed that all incoming water is used to replenish the first soil compartment but that cracks will not close. During this phase the percolation rate is zero. As soon as the water content of the top compartment has reached saturation, water starts ponding again and the percolation rate will be governed by the hydraulic conductivity of the plow sole. The amount of water that can be stored in the top compartment is calculated taking into account the changes in volume and porosity of the top compartment due to cracking. If cracks are deep enough to reach the plow sole (i.e.$h<-100$ kPa), all water in excess of field capacity will be drained from the top compartment. Because of the soil ripening process, the conventional field capacity concept (i.e. volumetric water content at h=-10 kPa) is hard to use for puddled soil conditions. The field capacity water content of the topsoil was, therefore, defined as 95% of total porosity. For the nonpuddled subsoil, the conventional definition for field capacity was used. In PADDY, water that drains from the cracked root zone will fill up soil layers below the root zone up to field capacity. Any excess water will be drained at a maximum rate equal to the saturated hydraulic conductivity of the subsoil horizon. The water content of soil compartments below the groundwater table depth is reset to saturation.

The required data for PADDY are :

* Saturated soil-water content of puddled topsoil;
* Saturated soil-water content of ripened topsoil and nonpuddled subsoil;
* Soil-water content at wilting point of the nonpuddled subsoil (h= -1.5 MPa);
* Soil-water content at field capacity of the nonpuddled subsoil (h=-10 kPa);
* Saturated hydraulic conductivity of the plow sole, or infiltration rate;
* Hydraulic conductivity characteristics of the subsoil (if groundwater table is relatively deep, or if roots cannot reach the subsoil because of a plow pan, capillary rise can be ignored and only the saturated hydraulic conductivity of the subsoil is needed);
* Groundwater table depth throughout the growing season (usually average groundwater table depths will be used);
* Soil shrinkage characteristics of puddled topsoil and nonpuddled subsoil (optional; if not available, default values will be used).

Description of *DSTRESS*

DSTRESS is largely based on data from a greenhouse experiment conducted at IRRI in the dry season (December - May) of 1992. In this experiment, the response of lowland rice cultivars IR20 and IR72 grown in puddled clay soil to temporary drought at different growth stages (transplanting, 2 wk after transplanting, mid-tillering, panicle initiation, and flowering) was studied. Morphological responses (inhibition of leaf production, leaf rolling, appearance of dead leaves) and physiological responses of the crop (reduction in transpiration rate and decrease in development rate) were expressed as a function of soil moisture ratio of the root zone. A similar approach was taken by Sinclair (1986) and McCree and Fernandez (1989). During the experiment, the degree of leaf rolling was visually examined daily at midday using a leaf rolling scale (1-5). A leaf score of 1 indicates the fipst sign of leaf rolling, whereas a score of 5 means that the leaf has completely rolled up (after O, Toole and Cruz, 1980). The experiment was repeated in the 1992 wet season. For reasons of brevity, only results from the drought at mid-tillering treatment conducted in the dry season are reported here (Fig. 3).

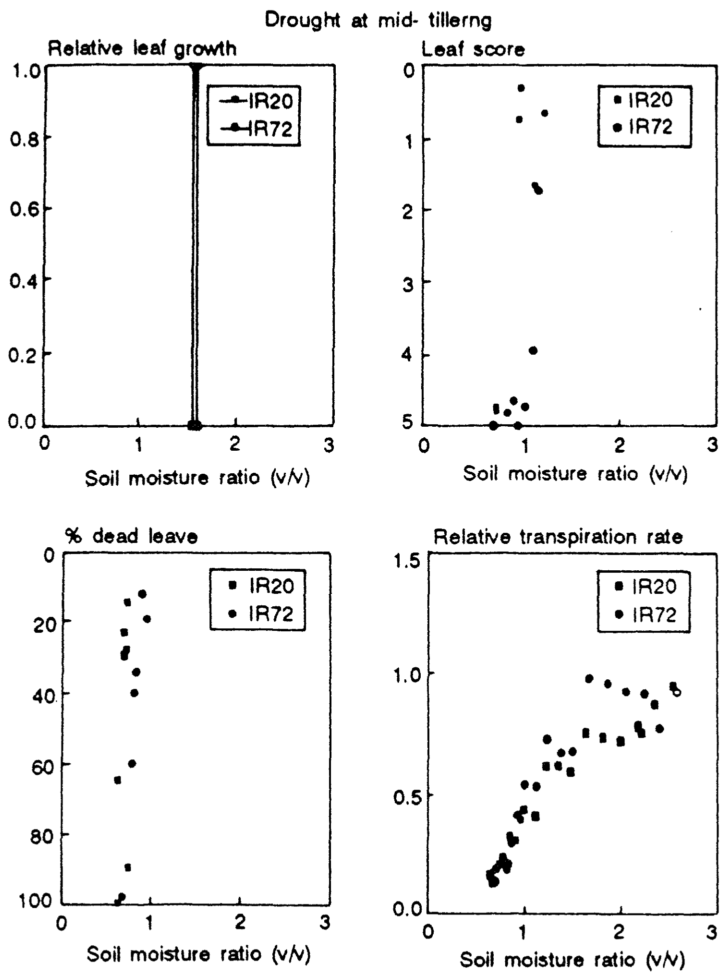


Fig. 3 . Relationships between soil moisture ratio (cm^3/cm^{-3}) and (a) relative leaf growth, (b) leaf score, (c) % dead leaves, and (d) relative transpiration rate in a greenhouse experiment conducted at IRRI in the dry season of 1992 (from Wopereis, 1993).

Relative leaf growth (defined as the ratio between the leaf growth of stressed plants and that of well-watered plants) decreased rapidly from 1 to 0 if soil moisture ratios dropped below 1.7, i.e. leaf expansion of plants subjected to drought stopped (Fig. 3a). Leaf rolling started at lower moisture contents, and leaf rolling score increased from 1 to 5 within a relatively narrow range of soil moisture ratios (Fig. 3b). As drought progressed, the percentage of dead leaves increased rapidly as well (Fig. 3c). Both leaf rolling score and percentage of dead leaves were linearly related to soil moisture ratio. Transpiration rate per unit of area of plants subjected to drought (T_d) remained equal to that of well-watered plants (T_w), even if soil-water status dropped nearly 50%. As soil-water content declined further, a decrease in relative transpiration rate (defined as T_d/T_w) was observed (Fig. 3d). Well-watered plants and plants that were temporarily stressed in the vegetative phase did not differ significantly in yield for either cultivar. However, flowering and maturity were strongly delayed. Severe drought in the reproductive phase greatly reduced yields. The following morphological and physiological plant responses to drought were quantified for the different growth stages : a) inhibition of new leaf production, b) leaf rolling, c) leaf senescence, d) decrease in relative transpiration, and e) decrease in development rate in the vegetative stage. Responses a, b, and c followed each other more or less sequentially, whereas response d) started at roughly the same soil-water content as response a) and declined to zero when leaves were dead (end of c) (Fig.3).

The effect of drought stress on development rate in the vegetative phase (e) could not be directly measured and is therefore not shown in Figure 3. In DSTRESS, the development rate in the vegetative phase used in ORYZA1 (Kropff *et al.*, 1993) is multiplied by a factor that increases from 0 to 1 between transplanting and flowering. This means that the closer the development stage is to flowering, the smaller the postponement effect. No delay in growth is simulated if drought occurs in the reproductive phase.

In the greenhouse study, production of new leaves was strongly inhibited than relative transpiration per unit leaf area during drought periods in the vegetative phase. This means that CO2 assimilation continues, but the C produced cannot be used for leaf production. In DSTRESS, excess C is stored in a pool and released for leaf production as soon as drought stress is released. The 1992 dry season experiment was repeated in the 1992 wet season.

Model validation

The ORYZA-W model was tested for flooded soil conditions using data from a field experiment conducted at IRRI in the 1991 dry season (cv IR72) and described in detail by Wopereis *et al.* (1994) and Bouman *et al.* (1994). Input variables were rainfall, irrigation, evapotranspiration rate from daily weighing of pots installed in the field, and groundwater table depths measured using piezometers. Average and upper and lower extreme values for measured hydraulic conductivity of the plow sole and the non puddled subsoil were used. Simulated and observed changes in ponded water depth were compared.

For nonflooded soil conditions, the ORYZA-W model was tested using data from a second experiment (field experiment 2) conducted in the 1992 dry season on a 2,000 m^2 field (cv IR72). Four drought treatments in four replications were tested in a randomized complete block design in 10 x 5 m subplots. These subplots were separated by bunds and hydraulically isolated by plastic sheets placed 0.6 m into the soil. Prior to the start of the experiment, all plots were submerged for 10 d, then plowed three times and harrowed three times using a water buffalo.

Drought was initiated at transplanting (T1), at mid-tillering (T2), at panicle initiation (T3), or during the grain filling stage (T4) by simply draining the ponded water from the plots. For comparision, a well-watered treatment was included (T0). Two drought durations (D) were imposed based on the 1-5 leaf rolling scale of O'Toole and Cruz (1980). For D1, plots were rewatered to allow plant recovery from drought when leaves showed initial leaf rolling (leaf score = 1). For D2, plots were rewatered when leaves showed clear sign of leaf rolling (leaf score = 3).

All simulations were conducted using parameters obtained from the 1992 dry season experiment with IR72 reported in Kropff *et al.* (1993), except for the development rates of the vegetative and reproductive phase and leaf N concentration as a function of time, which were derived from the well-watered TO plots.

Model application

The ORYZA-W model was used to predict rainfed rice yield for the wet season (June-November) in the Province of Tarlac which is located in the northern part of the Philippines on the island of Luzon (Fig. 4). It covers an area of approximately 300, 000 ha and comprises 17 municipalities with a total population of about 740, 000 (BSWM, 1992).

A soil map of Tarlac Province (1:50, 000), which was provided by the Bureau of Soils and Water Management, Quezon City, Philippines, was digitized using the geographic information system (GIS). The total number of mapping units was reduced from 67 to 14 through generalization taking into account similarity in soil properties and importance of the unit in terms of surface area. A similar approach was taken by Bregt *et al.* (1989).

As a first qualitative step, soil unsuitable for rice growth, which included the mountainous area and light-textured soils, were eliminated from the analysis. However, light textured soils classified on the soil map as 'severely flooded' because of their proximity to a river were not excluded; it was assumed that rice grown on such soils does not suffer from drought stress. Simulations were conducted for potentially suitable soils only. Potential (irrigated) rice yield was simulated using the model ORYZA1 for 25 yr of weather data derived from a meteorological station in the center of the province.

Water-limited (rainfed) rice yield for the same set of 25 yr was simulated using the ORYZA-W model. Guided by the detailed soil map representative profiles for major soil type under rice cropping were located. The soil hydraulic properties needed in ORYZA-W were determined for all soil horizons in each representative profile. Procedures and results of these measurements are presented elsewhere (Wopereis *et al.*, 1993). Crop parameters for rice cultivar IR72 were derived from a wet-season experiment conducted at IRRI in 1991 (Kropff *et al.*, 1993). Simulations started at transplanting, assuming that seedlings were 30 days old. Initial leaf area index (LAI), temperature sum (sum of thermal units over a base temperature), and development stage of the seedlings were taken from field experiment 2. Initial rooting depth was assumed to be 0.05 m. After discussion with an expert from the Bureau of Soils and Water Management, Quezon City, Philippines (W. Sanidad, pers. commun.), transplanting of rice was assumed to start when cumulative rainfall exceeded 75 mm during seven consecutive days after 1 June. Thickness of the puddled topsoil was set to 0.15 m with the plow sole occurring between 0.15 and 0.20 m depth. At transplanting, the puddled topsoil was assumed to be saturated with an initial ponded water depth of 0.05 m. Subsoil horizons were assumed to be at field capacity (h= -10kPa).

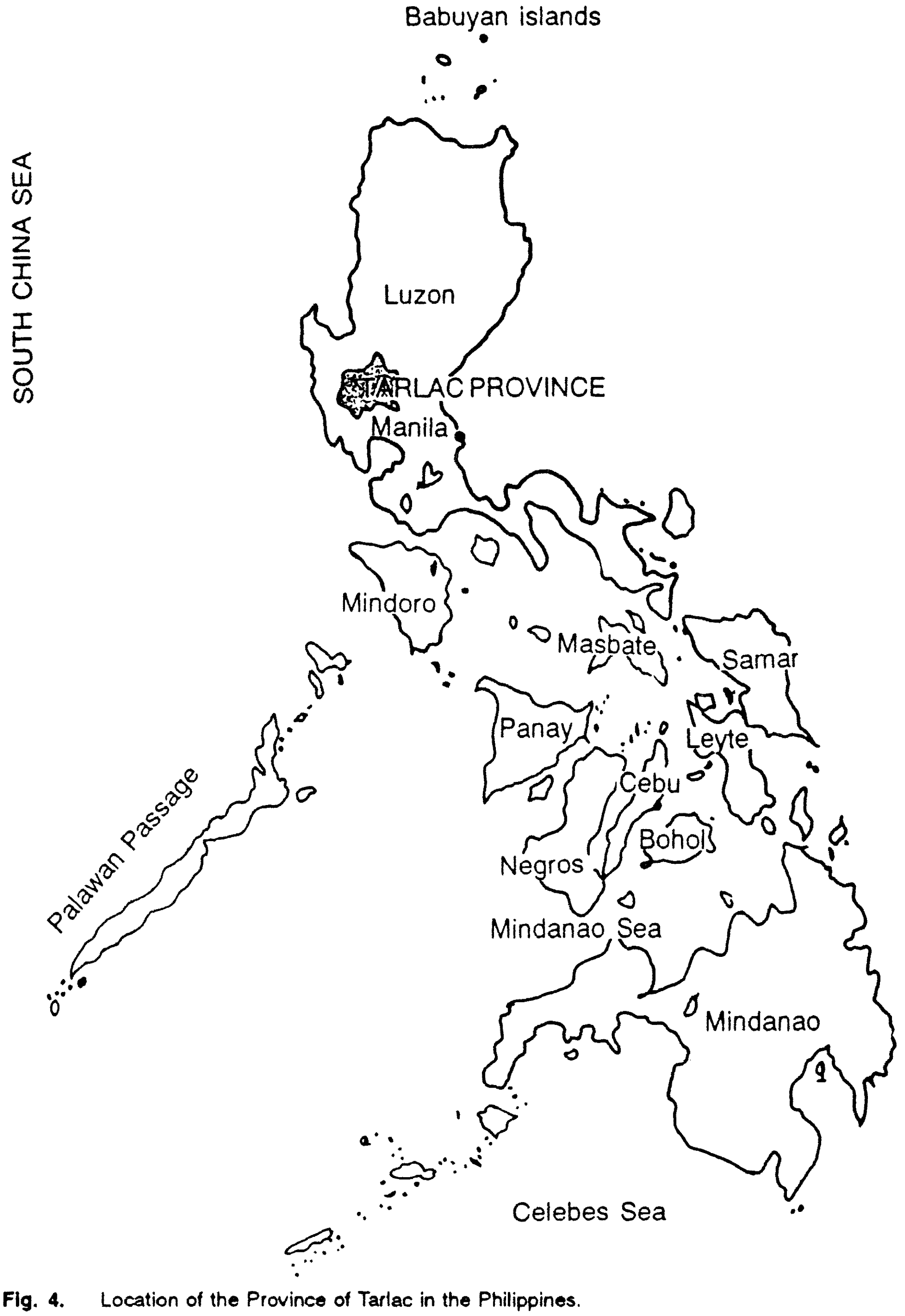


Fig. 4. Location of the Province of Tarlac in the Philippines.

The impact of groundwater table depth and thoroughness of puddling on rainfed rice yield was investigated for each of the major soil types under rice cropping. Groundwater table depth was varied between 0.5 and 1.0m. Wopereis *et al.* (1992) determined the saturated hydraulic conductivity of the least permeable layer (i.e. plow sole) in the top 0.2 m of a puddled clay soil at the experimental farm of the International Rice Research Institute. Average value was 0.036 cm/d, with 95% confidence limits at 0.027 and 0.045 cm/d. In this study, two classes of puddling (poorly puddled and well puddled) were considered and expressed in terms of the hydraulic conductivity k_s of the plow sole: well puddled, K_s (plow sole) = 0.01 cm/d and poorly puddled K_s (plow sole) = 0.10 cm/d. Combined with the two water table depths, four simulation series were created:

1 : K_s plow sole=0.01 cm/d; water table depth = 0.5m

2 : K_s plow sole=0.01 cm/d; water table depth = 1.0m

3 : K_s plow sole=0.10 cm/d; water table depth = 0.5m

4 : K_s plow sole=0.10 cm/d; water table depth = 1.0m

Probability distributions of rainfed rice yield for all soil types under rice cropping were estimated. Maps of simulated rainfed rice yield at different levels of cumulative probability were produced using the GIS software.

RESULTS AND DISCUSSION

ORYZA-W validation

The water balance module PADDY accurately predicted the changes in ponded water depth for field experiment 1 (Fig. 5). Wopereis *et al.* (1993) tested the more

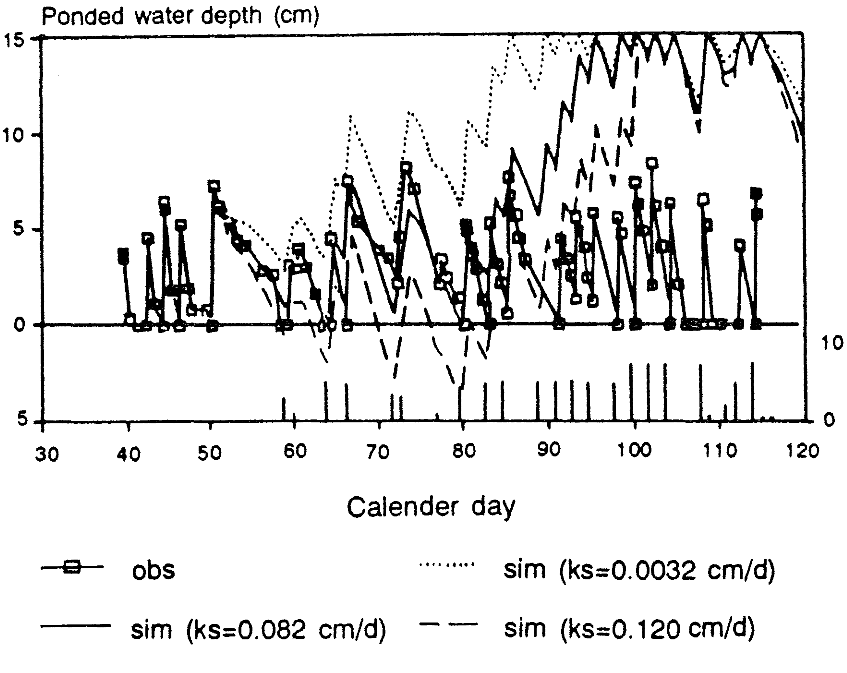


Fig. 5. Simulated and observed changes in ponded water depth in field experiment 1 using soil-water balance module PADDY.

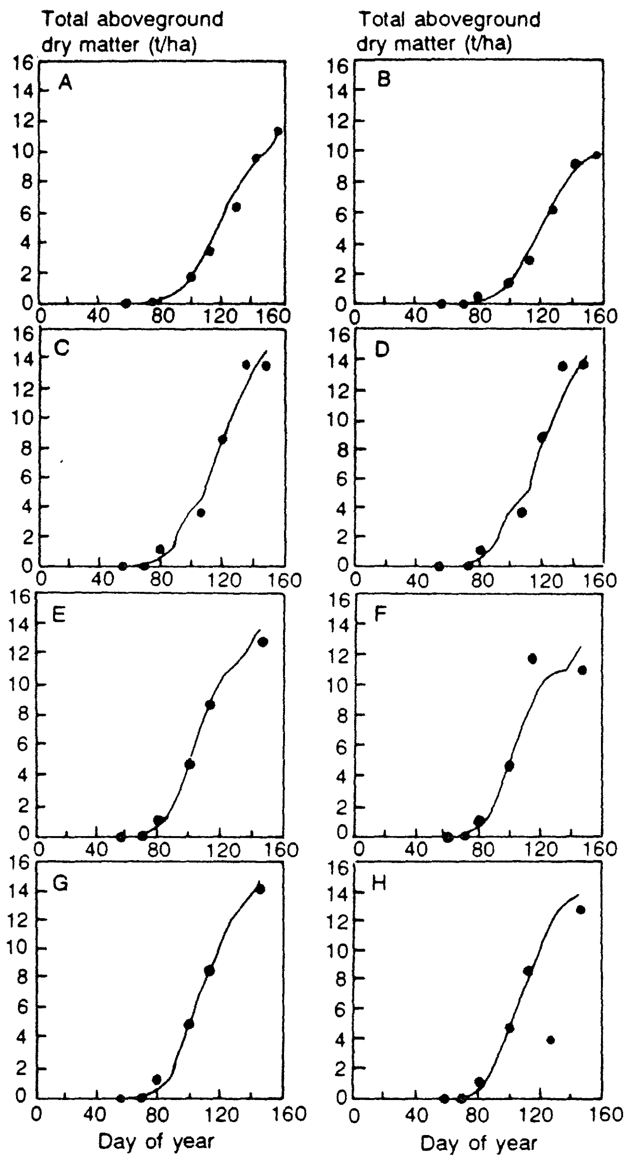


Fig. 6. Simulated (lines) and observed (symbols) total dry matter weights (t ha^{-1}) for cv. IR72 in field experiment 2 for all drought treatments : A is drought at transplanting, early recovery; B at transplanting, late recovery; C at mid-tillering, early recovery, D at mid-tillering, late recovery; E at panicle initiation, early recovery; F at panicle initiation, late recovery; G at flowering, early recovery; H at flowering, late recovery.

complicated differential SAWAH soil-water balance module (ten Berge *et al.*, 1992) using the same field data. Results from this study showed that the iteration procedure used in PADDY to calculate the flux through the soil profile under flooded soil conditions was as effective as the small time step calculations used in SAWAH. The observed and simulated total above ground matter (Fig. 5), LAI, panicle dry weight, and root zone water content (Fig. 6) were compared. The results indicated that ORYZA-W could satisfactorily explain the differences in biomass production and soil water content across drought treatments, although for root zone, water content predictions were less good at severe stress and for drought at flowering.

Tarlac simulations

Potential yields in Tarlac Province varied from 5.4 to 6.7 t/ha (Fig.7), which are considerably higher than the irrigated rice yields (2.5-3.5 t/ha) reported by BSWM (1992). This discrepancy may be due to a number of factors, e.g. lack of fertilizer, incidence of pest and diseases, etc. that were taken into account by the ORYZA-W model.

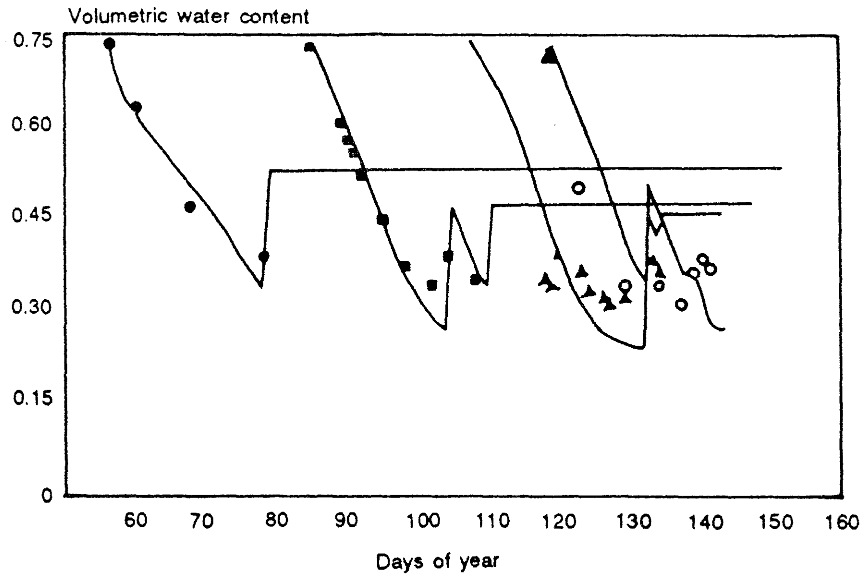


Fig. 7. Simulated (lines) and observed (symbols) soil water content m^3/m^{-3} for cv. IR72 in field experiment 2 for drought at transplanting (0-5 cm, late recovery, closed circles), drought at mid-tillering (0-10 cm, late recovery, squares), drought at panicle initiation (0-10 cm, late recovery, triangles), and drought at flowering (0-10 cm, no recovery, open circles).

Rainfed rice yields ranged from 0 to 6.7 t/ha. For reasons of brevity, the variability of rainfed rice yield over 25 years for the four simulation series is shown in Fig. 8 for two distinct soil types only : Zaragoza clay loam (light texture) and Padapada clay soil series (heavy texture). Potential yields are also shown for comparison.

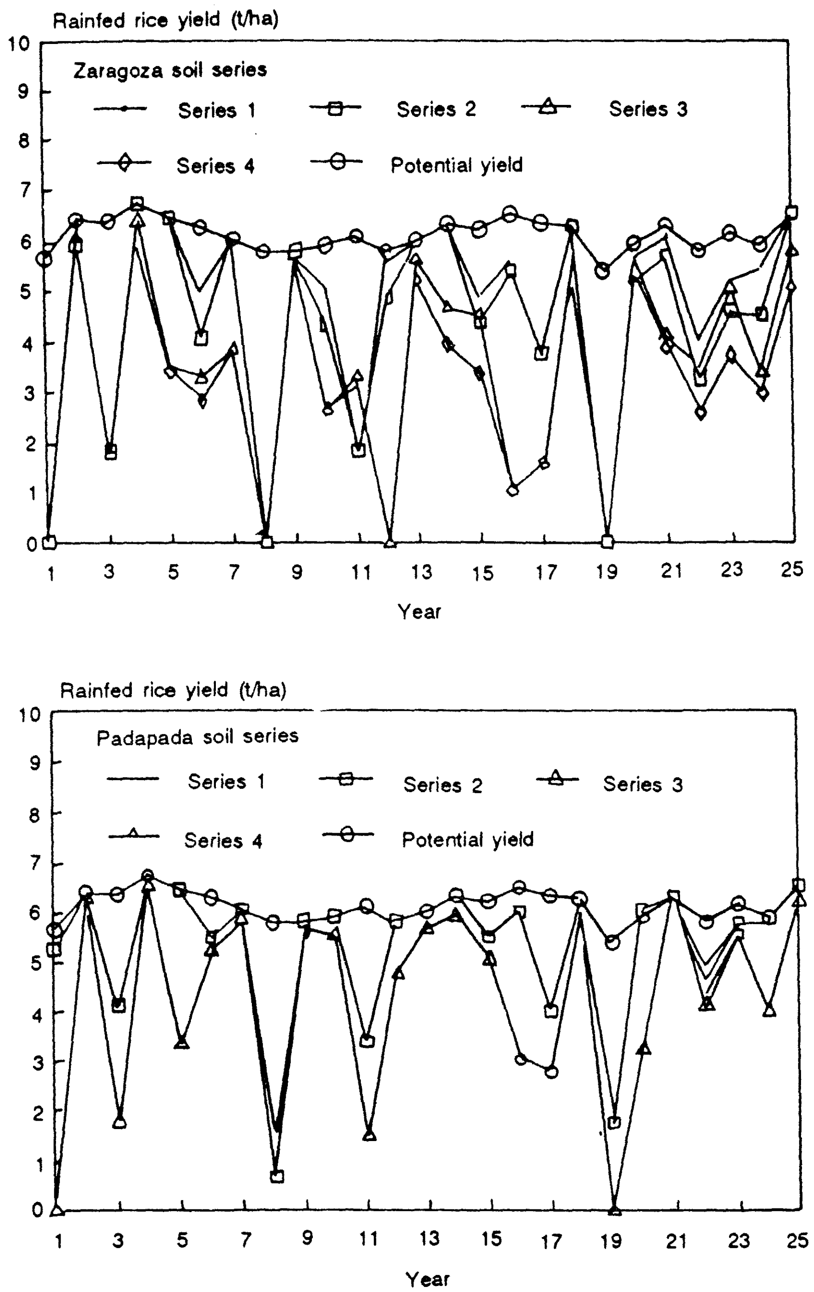
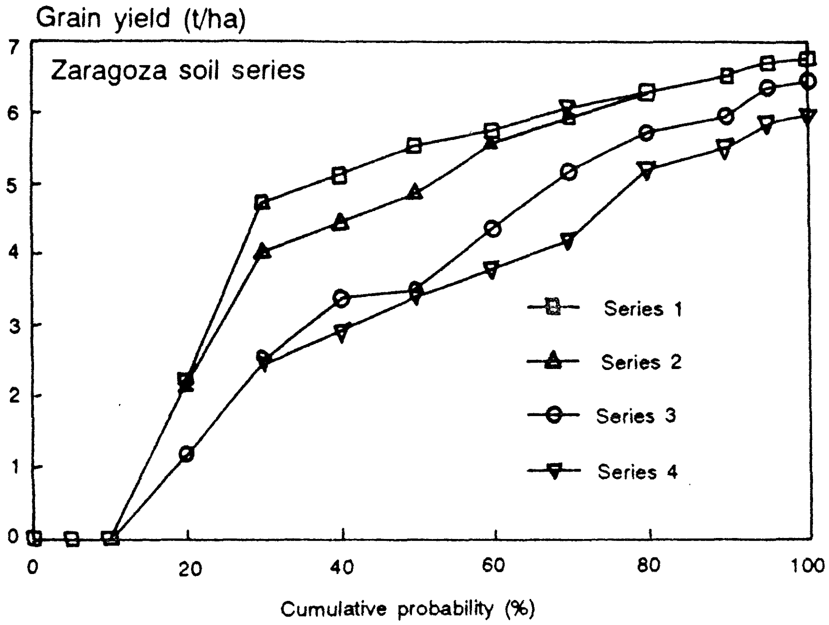


Fig. 8. Potential and rainfed rice yield calculated for 25 consecutive wet seasons and four simulation scenarios on Zaragoza and Padapada soil.



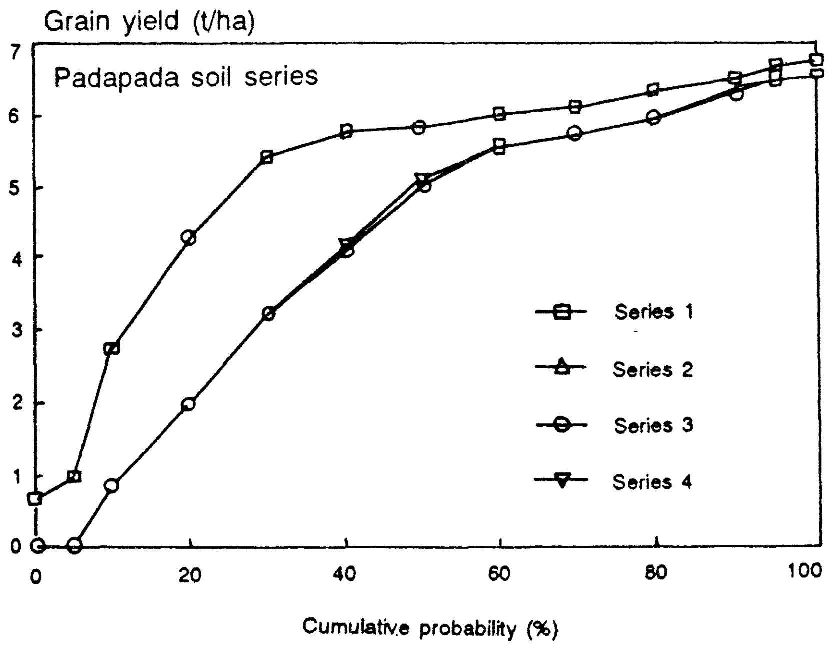


Fig. 9. Cumulative distribution functions for rainfed rice yield on Zaragoza and Padapada soil.

Comparison of rainfed rice yield with potential yields quantifies the yield gap between fully irrigated and rainfed production. This information indicates the yield loss farmers will experience due to lack of irrigation water, under otherwise optimal growing conditions. Production risk was quantified by calculating cumulative probability functions for rainfed rice yield for each soil type (Fig. 9). For Zaragoza, a shallow groundwater table had a positive effect on grain yield due to increased capillary rise to the root zone. For Padapada, this effect was almost non- existent. Poor puddling resulted in yield losses for both soils, especially for Zaragoza.

The hydraulic conductivity of the plow sole was an important determinant of rainfed rice yield for light-textured soils with a relatively permeable subsoil, like the Zaragoza soil series. If no information on this soil parameter is available, a constant percolation rate determined for the various soil types may be used as an input for the PADDY soil-water balance module (Wopereis *et al.*, 1994; Bouman *et al.*, 1994). Tuong *et al.* (1994) showed that percolation losses toward and into bunds, and the effect of poorly puddled sites may be important in areas with a relatively permeable subsoil. More complex numerical models that allow for lateral flow into the bunds (e.g. Walker and Rushton, 1984) are needed under these circumstances. On a regional scale, one-dimensional models, such as the PADDY soil-water balance module can still be used, provided a constant percolation rate is assumed, incorporating both vertical and lateral percolation losses.

Simulated rainfed rice yield was mapped at the 10 and 90% cumulative probability levels using the GIS software. Simulations were conducted assuming average ks values of the plow sole determined in the laboratory and a water table depth of 1.0 m. The Zaragoza soil series occupies a large part of the potential rice-growing area in Tarlac Province (Wopereis, 1993). Growing rice under rainfed conditions in that province is, therefore, risky.

The approach outlined above can only result in a broad overview of yield losses due to drought in Tarlac. Soil types were characterized using measurements conducted at one representative site only. Spatial variability of soil hydraulic properties or thickness of soil horizons was not taken into account.

CONCLUSION

The GIS and crop simulation modelling can be used to quantify rice yield losses due to drought at a regional level. Rainfall variability has a strong impact on yield variability in Tarlac Province. Field experiments conducted for 1 or 2 yr in such environments may give misleding results. Long-term weather data are needed to determine probability distributions of crop yield to perform an economic evaluation (Anderson, 1991). Unfortunately, there is a lack of long-term weather data in many rice-growing countries in Asia as was also the case for the study presented here (detailed weather data were only available for one station in the entire province).

Supplementary irrigation increased wet-season rainfed rice yields and reduced yield variability. Irrigation may also increase the potential for a dry-season crop (e.g. mungbean), which would boost total production and income per year relative to rainfed conditions. The scope for a dry-season crop after rice could be investigated using the PADDY soil-water balance and good explanatory model for the dry-season crop.

FUTURE RESEARCH NEEDS

One of the major problems in the application of crop-soil models is the lack of data on soil hydraulic functions. Data bases, that relate these functions to soil characteristics derived from soil survey data, are needed. Maintenance and installation of weather stations should be promoted partly through research consortia. It is important to have a few well-selected and well-maintained sites that can be carefully monitored. Only if good data sets are available can simulation models be used to extrapolate new technologies or to identify constraints or opportunities in rice production. More research is needed on how to deal with limited data in crop modelling studies.

The rainfed rice model ORYZA-W can be used to investigate yield losses due to drought in rainfed, puddled environments and may also be used to quantify the benefits of improved irrigation facilities. ORYZA-W is also a starting point for simulation studies on rice upland crop rotations. The model, however, needs further validation for a broader range of environmental conditions and for different rice varieties. PADDY needs to be expanded to include simulation of water table depth. Sensitivity analyses to investigate the importance of variability in model-input parameters must be conducted.

The increased water-use efficiency of rice-based cropping systems is becoming increasingly important. This can be done by improving irrigation facilities, introducing water-saving techniques, and adjusting the planting time and/or cropping system to maximize rainfall utilization. For any of these approaches, a thorough systems analysis to evaluate the different solutions for different environments is needed. One of the most promising water-saving techniques is dry seeding of rice. The drought stress functions used in this study were all derived for puddled soil conditions. More research is therefore needed on drought stress responses of dry seeded rice and their relation to root zone water content. Special attention should be paid to root development and the effect of drought on root growth.

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