

## CARICE: A Rice Model for Scheduling and Evaluating Management Actions

Baird C. Miller,\* Theodore C. Foin, and James E. Hill

### ABSTRACT

Crop growth modeling can be useful in crop management, but previous rice crop models lack the morphologically accurate phenological detail needed for practical application. We designed a rice crop management model, CARICE, for scheduling management actions on the farm and evaluating consequences of alternative management strategies. A simple rice crop productivity model was expanded to include (i) phenology, based on leaf stage; (ii) tiller development, to establish yield components; (iii) assimilate partitioning by developmental stage, (iv) assimilate partitioning patterns of California cultivars; and (v) a direct-seeded cultural system. The key phenological events were accurately simulated: leaf stage development followed the expected pattern; predicted 50% heading was within 6 d of the actual heading dates; and grain filling predictions were within 1 to 11 d of field observations. Cultural management strategies simulated included delayed planting, and managing barnyardgrass (*Echinochloa* spp.; BYG) competition by increasing water depth and seeding rate. Simulated yield results were within the range of field observations, although total aboveground biomass was overestimated. The model simulated a 27% loss in grain yield from a 21-d delay in planting, which is close to the 21% loss measured in the field. At 11 and 54 BYG plants m<sup>-2</sup>, the model simulated 20.6 and 54.6% yield reductions relative to the control, as compared with 32.5 and 57.5% reported in the literature. The model predicted the interactive effect of rice seeding rate and water depth management for reducing barnyardgrass competition. The morphologically accurate phenology submodel and the yield-component approach to calculating yield are keys to using CARICE for scheduling and evaluating management actions and strategies.

RICE GROWERS AND RESEARCHERS are constantly striving to improve the effectiveness of management actions. Crop growth modeling can be a useful technique for evaluating the consequences of alternative management strategies. Several rice crop models, using different modeling approaches, are found in the literature. Yao and LeDuc (1980) and da Mota and da Silva (1980) used the empirical approach to develop weather-dependent yield prediction models. Iwaki (1975, 1977), van Keulen (1978), McMennamy (1980), McMennamy and O'Toole (1983), and Alocilja and Ritchie (1991) developed multilevel, process-oriented explanatory rice crop models. Stansel and Fries (1980), Angus and Zandstra (1980), and Hayes et al. (1982) generated predictive rice yield models, including significant physiological and process-oriented detail; these are described by Terjung et al. (1985) as examples of hybrid models, using both the empirical and mechanistic approach.

Of the numerous rice crop growth models cited, most were designed either to predict yield or to integrate current physiological knowledge for crop growth prediction, but they were not designed as management

tools: For a crop growth model to be a useful management tool, management strategies and the scheduling of management actions must be linked with the details of phenological and morphological development. For example, California rice producers typically schedule the following management actions based on crop phenology: (i) herbicide application, the timing of which is most accurately based on the leaf stage of both the crop and the target weeds; (ii) invertebrate pest control, which must take place prior to a given rice leaf stage; (iii) N topdressing, which is based on leaf tissue analysis at early, mid, and maximum tillering and also at panicle initiation; (iv) manipulation of water depth, such as increased depth at panicle initiation to reduce the incidence of cold-temperature-induced spikelet sterility; and (v) harvest, which is currently projected from the date of heading.

Previous rice crop models that include phenology still lack adequate detail of phenological and morphological events (such as leaf appearance, tiller development, and the events of reproductive growth) to link with management actions. Rice crop phenology is typically handled as (i) a deterministic function of chronological time, using days after planting (McMennamy and O'Toole, 1983, Iwaki, 1975); or (ii) as a discrete, discontinuous score of phenological events (Alocilja and Ritchie, 1991); or (iii) as a decimal fraction of the entire growth duration (van Keulen, 1978).

Our objectives were to design a rice crop management model to schedule management actions on the farm and to evaluate alternative management strategies. To this end, we developed a crop management model, CARICE, with a morphologically accurate phenology submodel to provide a link for scheduling management actions. The productivity submodel was based on a simple physiological model, modified to develop yield components that are influenced by important climatic and management factors.

### MODEL DESCRIPTION

#### Crop Productivity

The crop productivity submodel was based on a simple physiological rice growth model developed in Japan (Iwaki, 1975, 1977). The original model simulated dry matter accumulation of long-season cultivars, under flooded conditions, for 120 d following transplanting. Using California temperature and solar radiation data, our conversion of Iwaki's original model generated reasonable patterns of biomass production, and realistic final total biomass ranging from 1600 to 2000 g m<sup>-2</sup>.

In Iwaki's model, daily rates of gross photosynthesis (PG) are calculated for the rice canopy as a function of daily accumulated solar radiation, daylength, extinction coefficient of light within the leaf canopy, light transmissibility of single leaves, peak photosynthesis of a single leaf at light saturation, and leaf area index (LAI). This functional relationship for the calculation of gross photosynthesis was derived from Kuroiwa (1968). Respiration is based on daily photosynthesis, LAI, nonphotosynthesizing biomass, and mean temperature.

To accomplish our objectives, Iwaki's crop productivity model

B.C. Miller, Dep. of Crop and Soil Sciences, Washington State Univ., Pullman, WA 99164-6420; T.C. Foin, Div. of Environmental Studies, and J.E. Hill, Dep. of Agronomy and Range Science, Univ. of California, Davis, CA 95616. Research supported in part by the California Integrated Pest Management Program. Received 18 Nov. 1991. \*Corresponding author.

was modified by adding algorithms describing (i) phenology, based on leaf stage development; (ii) tiller development, to establish the critical yield components for grain yield; (iii) changes in assimilate partitioning at key developmental stages, (iv) overall assimilate partitioning, to account for grain yield and biomass production patterns of California rice cultivars; and (v) a direct-seeded cultural system. A flow diagram illustrating the basic components of CARICE and their interrelationships is presented in Fig. 1, using the conventions of Forrester (1961); abbreviations and variables are defined in Table 1.

### Phenology and Tiller Development

Vegetative development and the timing of reproductive events is based on the mainstem leaf stage. The leaf stage is defined as the number of fully expanded leaves plus a decimal fraction of the youngest visible expanding leaf blade (Matsushima, 1967). Matsushima (1967) also reported that numerous phenological events can be accurately predicted from leaf stage and leaf number index (LNI). LNI is calculated as the ratio of current mainstem leaf number to the flag leaf number (FLN). The LNI drives reproductive events such as panicle initiation (LNI = 0.70), spikelet differentiation (LNI = 0.85), and pollen development (LNI = 0.95). The LNI concept is based on the assumption that FLN is constant for most cultural conditions. Matsushima (1967) stated that cultural practices can change FLN, yet Yoshida (1981) reported that FLN for photoperiod-insensitive cultivars remained constant under most conditions. Since the very early and early maturity cultivars grown in California are considered photoperiod insensitive, FLN is cultivar specific, with a range of 12 to 14.

Air heat unit accumulation (HUA), base 10 °C, drives leaf development. Three thermal requirements for leaf development are used: (i) 38.5 HU leaf<sup>-1</sup> from seeding to the third leaf stage; (ii) 58.8 HU leaf<sup>-1</sup> from the third leaf to panicle initiation; and (iii) 161.3 HU leaf<sup>-1</sup> from panicle initiation to flag leaf. Field results have shown that the thermal requirements for leaf development, from the third leaf to panicle initiation and panicle initiation to flag leaf, remain relatively constant over a broad range of imposed management practices (Miller, 1989), including stand density and planting date, N fertility (Roberts, 1988) and water management (Tibbitts, personal communication, 1989).

Tiller appearance is closely synchronized with leaf development. Matsushima (1967) reported that a single tiller appears at each mainstem (or mother stem, in the case of secondary tillers) leaf stage  $n$ , from the leaf axil  $n - 3$ . The first tiller appears from the second leaf axil at the fifth leaf stage, the second tiller appears from the third leaf axil at the sixth leaf stage, and so on. Implementing these rules for a plant with FLN = 14 results in a plant with 10 tillers, inclusive of the mainstem. This is consistent with direct-seeded rice in a very low stand density. Miller et al. (1991) found that increasing stand density from 120 to 450 plants m<sup>-2</sup> linearly reduced the maximum tillers per plant (inclusive of the mainstem) from seven to three. This linear relationship is used in the model to determine the maximum tillers per plant from the initial stand density. Tillering continues until the tillering capacity, defined as the maximum tiller density (MTTLM2), is reached for a given plant density, or panicle initiation is reached. Tiller attrition typically observed after reaching MTTLM2 is approximated with a tiller survival function reported by Miller et al. (1991):

$$\text{final tiller density} = 233 + 0.41 \text{ MTTLM2.}$$

Plant survival and tiller appearance are influenced by the level of water management. Williams et al. (1990) found that established rice plant stand decreased with increasing water depth from shallow (2.5–7.5 cm) to moderate (10.2–15.2 cm) and deep (17.8–22.8 cm). The influence of water depth and the initial seeding rate are incorporated in the model to deter-

mine the plant survival and plant stand. Scardaci et al. (1987) reported that tillering is delayed with increasing water depth. Peterson et al. (1982) suggested that inhibition of tiller appearance in wheat is an indicator of a stressed plant. Visual observations confirm that the rice plant is stressed until the plant emerges from the water. Under deeper water management, the plant endures a longer stress period, resulting in tillers not appearing from the second and third leaf axils, thereby delaying tiller appearance. The phenology submodel incorporates this effect by delaying the initial tiller appearance from the fifth leaf stage under shallow water management to the sixth leaf stage under moderate water depth and to the seventh leaf stage under deep water management.

The number of days after seeding (DAS) to reach 50% heading is calculated by continuing leaf stage development one unit further than the FLN to account for panicle emergence. Grain filling duration is calculated as days from 50% heading to complete grain fill.

As Yoshida (1981) reported, the maximum yield of the rice crop is predetermined by the cultivar and the environment, and the yield components can be used to develop a target or potential yield for a given cultivar. Yield component analysis is also commonly used to characterize the influence of climate and cultural management on yield. In this model, potential grain yield (POTYLD) is calculated using the yield component parameters (plants per square meter, final tillers per plant, panicles per tiller, seeds per panicle, and grams per seed) from Miller et al. (1991). The number of seeds per panicle is a function of panicle density, while individual seed weight and panicles per tiller are constant. Grain filling stops and physiological maturity is reached either when the whole-field grain dry weight (GRAIN) equals the POTYLD or when the leaf area has senesced beyond the point of generating net photosynthate. GRAIN is adjusted to 14% moisture (w/w) and reported as grain yield.

Once CARICE has calculated POTYLD, detrimental within-season climatic and cultural management factors are incorporated to limit the yield components. Climatic and management factors known to affect yield are cool-temperature spikelet sterility (Board and Peterson, 1980) and barnyardgrass competition. The phenological stage corresponding to pollen development, from 7 to 21 d before 50% heading, is most sensitive to cool night temperatures. Miller (1989) reported that sterility increases after reaching a threshold of accumulated days below 14 °C during this period. The number of days with minimum temperatures <14 °C (cold temperature accumulation: CTA), from the start of pollen development (LNI = 0.95) through an 0.05 LNI equivalent beyond FLN, increases the background sterility (set in the model at 10%). For 5, 8, 10, and 13 accumulated cold-temperature days, background sterility increases to 12, 13, 31, and 49%, respectively.

Barnyardgrass is the most serious weed problem in California (Univ. of Calif. Statewide IPM Proj., 1983). The competitive effect of barnyardgrass is treated as a function of the barnyardgrass stand (BYGSTD) and the rice stand (RYCSTD). Every barnyardgrass plant established results in the loss of a rice plant. Barnyardgrass has a competitive advantage over rice: for every tiller developed by rice, barnyardgrass develops a number of tillers equal to BYGTEF (the barnyardgrass tiller equivalence factor). BYGTEF is a function of the relative BYGSTD in the total weed-crop stand (TOTSTD = BYGSTD + RYCSTD) (Carlson and Hill, 1985). The following function for BYGTEF is based on data from LeStrange (1985) and the analysis of Hill and LeStrange (personal communication, 1989).

$$\text{RW} = \text{BYGSTD}/\text{TOTSTD}$$

$$\text{RELYLD} = 99.8 - (377 \times \text{RW}) + (524 \times \text{RW}^2)$$

$$\text{BYGTEF} = (100 - \text{RELYLD})/(\text{RW} \times 100)$$

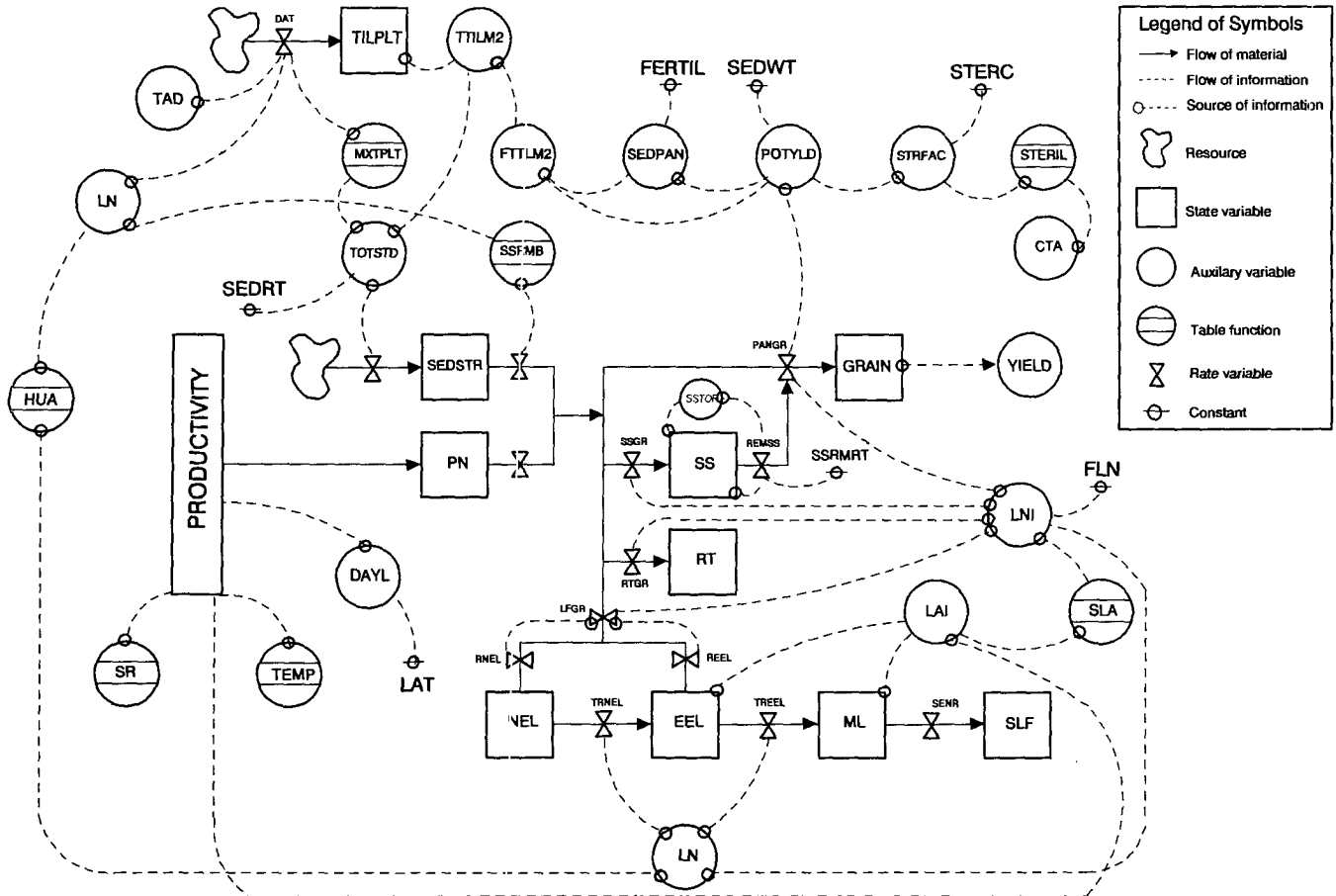


Fig. 1. CARICE, a rice model for scheduling and evaluating management actions: Flow diagram of the basic components and their interrelationships (conventions according to Forrester, 1961). Variables and abbreviations are as in Table 1.

For example, if  $BYGSTD = 20 \text{ plants m}^{-2}$  and  $RYCSTD = 396 \text{ plants m}^{-2}$ , then  $BYGTEF = 3.56$ . Therefore, for every tiller that develops in the RYCSTD, 3.56 tillers develop in the BYGSTD, thereby directly reducing the yield potential of the RYCSTD. In addition, gross photosynthesis (PG) is reduced by the ratio of barnyardgrass tiller density to total tiller density during the period from initial tiller appearance to pan-

icle initiation. Water depth provides additional control of barnyardgrass competition by reducing BYGSTD. The initial BYGSTD at the start of the growing season is reduced by 40% under moderate depth and by 70% under deep water levels (Williams et al., 1990).

**Assimilate Partitioning**

Net photosynthate (PN) generated from the productivity sub-model is allocated to live, photosynthesizing leaves (LF); stems, sheaths and panicle structure (SS); roots (RT); and grain (GRAIN). The leaf mass is further classified as nonemerged expanding leaves, emerged expanding leaves, mature leaves, and senesced leaves (Fig. 1 and 2). These leaf classes mimic the aging process, and separate the leaf mass that is dependent on assimilate import (nonemerged expanding leaves) and not contributing to leaf area, from the assimilate exporting leaves (emerged expanding and mature leaves). The LAI is calculated with a specific leaf area conversion of leaf mass.

Net photosynthate is partitioned among LF, SS, RT, and GRAIN using priority rules and temporal changes that are a function of developmental stage. Roots receive their fraction of PN first, and the balance is partitioned to the aboveground portion of the plant. The aboveground PN fraction is partitioned first to LF, then GRAIN, and the balance allocated to SS.

The temporal changes in allocation among these plant components are controlled by the LNI. Significant changes in dry matter partitioning take place at six developmental stages: initial tiller appearance ( $LNI = 0.35$ ); stem elongation and maximum tillering capacity ( $LNI = 0.65$ ); early boot ( $LNI =$

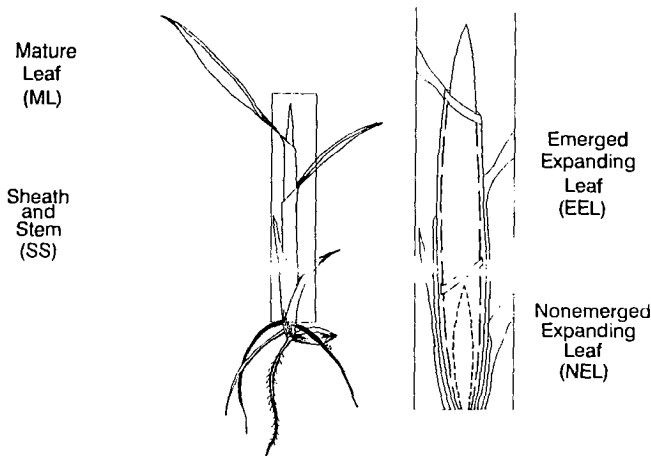


Fig. 2. Rice leaf mass classification as nonemerged expanding leaves (NEL), emerged expanding leaves (EEL), mature leaves (ML), and stems and sheaths (SS).

Table 1. Description of CARICE abbreviations and the variables shown in the flow diagram in Fig. 1.

Variable	Description	Units	Variable	Description	Units
AGWT	Total aboveground biomass	$g\ m^{-2}$	RT	Root weight	$g\ m^{-2}$
BYG	Barnyard grass	—	RTGR	Root growth rate	$g\ m^{-2}\ d^{-1}$
BYGSTD	Barnyardgrass stand density	$plants\ m^{-2}$	RYCSTD	Rice stand density	$plants\ m^{-2}$
BYGTEF	Barnyardgrass tiller equivalence factor	—	SEDPAN	Seeds per panicle	$seeds\ panicle^{-1}$
CTA	Cold-temperature accumulation: Accumulated days with minimum temperatures $<14\ ^\circ C$	d	SEDRT	Seeding rate of rice	$seeds\ m^{-2}$
DAS	Days after seeding	d	SEDSTR	Seed storage available for remobilization during seedling development	$g\ m^{-2}$
DAT	Daily rate of tiller appearance	$tillers\ d^{-1}$	SEDWT	Rice seed weight	$g\ seed^{-1}$
DAYL	Daylength	h	SENR	Leaf senescence rate	$g\ m^{-2}\ d^{-1}$
EEL	Exposed expanding leaf weight	$g\ m^{-2}$	SLA	Specific leaf area	$m^2\ g^{-1}$
FERTIL	Percentage of final tiller that produce panicles	%	SLF	Senesced leaf weight	$g\ m^{-2}$
FLN	Flag leaf number	—	SR	Solar radiation	langley
FTTLM2	Final tiller density prior to grain filling	$tillers\ m^{-2}$	SS	Stem, sheath, and panicle structure weight	$g\ m^{-2}$
GRAIN	Grain dry weight	$g\ m^{-2}$	SSGR	Stem and sheath growth rate	$g\ m^{-2}\ d^{-1}$
HU	Heat unit (base $10\ ^\circ C$ )	$^\circ C$	SSRMB	Seed storage remobilization rate	$g\ m^{-2}\ d^{-1}$
HUA	Heat unit accumulation	$^\circ C$	SSRMRT	Percentage of SSTOR available for remobilization during grain filling	%
LAI	Leaf area index of live photosynthesizing leaves	—	SSTOR	Total preanthesis photosynthate available for remobilization during grain filling	$g\ m^{-2}$
LAT	Latitude	$^\circ$	STERC	Minimum background spikelet sterility percentage	%
LF	Live photosynthesizing leaf weight	$g\ m^{-2}$	STERIL	Additional spikelet sterility percentage due to accumulated cool temperature days	%
LFGR	Total leaf growth rate	$g\ m^{-2}\ d^{-1}$	STRFAC	Final spikelet sterility percentage	—
LN	Main stem leaf number	—	TAD	Tiller appearance delay	$^\circ C$
LNI	Leaf number index	—	TEMP	Temperature	$^\circ C$
ML	Mature leaf weight	$g\ m^{-2}$	TILPLT	Potential tillers appeared per plant	$tillers\ plant^{-1}$
MTTLM2	Maximum tiller density	$tillers\ m^{-2}$	TOTSTD	Total plant stand including rice and barnyardgrass	$plants\ m^{-2}$
MXTPLT	Maximum tillers per plant	$tillers\ plant^{-1}$	TREEL	Transfer rate of exposed expanding leaves to mature leaves	$g\ m^{-2}\ d^{-1}$
NEL	Unexposed expanding leaf weight	$g\ m^{-2}$	TRNEL	Transfer rate of unexposed expanding leaves to exposed expanding leaves	$g\ m^{-2}\ d^{-1}$
PANGR	Panicle growth rate	$g\ m^{-2}\ d^{-1}$	TTTLM2	Actual total tiller density including rice and BYG	$tillers\ m^{-2}$
PG	Gross photosynthesis from productivity submodel	$g\ m^{-2}\ d^{-1}$	YIELD	Actual grain yield at 14% (w/w) moisture	$g\ m^{-2}$
PN	Net photosynthesis from productivity submodel	$g\ m^{-2}\ d^{-1}$			
POTYLD	Potential grain dry weight	$g\ m^{-2}$			
REEL	Growth rate of exposed expanding leaves	$g\ m^{-2}\ d^{-1}$			
REMSS	Rate of SSTOR remobilized during grain filling	$g\ m^{-2}\ d^{-1}$			
RNEL	Growth rate of unexposed expanding leaves	$g\ m^{-2}\ d^{-1}$			

0.85); late boot (LNI = 0.93); flag leaf (LNI = 1.0); and 50% heading. Preliminary results from field studies in California (Tibbitts, personal communication, 1987) confirm that these developmental events are closely associated with Matsushima's (1967) reported LNI values. The partitioning ratios for root weight (RT) were adapted from van Heemst (1986). The aboveground partitioning ratios (LF, SS, and GRAIN) were derived from Miller (1989) and are shown in Table 2. Linear interpolation is used to calculate the partitioning ratio between any two LNI values shown in Table 2. Specific leaf area, used to convert leaf mass to leaf area index, also changes with developmental stage and is based on the LNI. The leaf-age-dependent senescence in Iwaki's (1975) model was replaced with a partitioning function. Senescence rate is a function of the leaf growth rate from maximum tillering to panicle initiation, and a function of the total growth rate after panicle initiation. Field sampling indicates that senescence was not significant until maximum tillering, at which time canopy closure was complete.

The model of Iwaki (1975, 1977) was converted to describe a direct-seeded cultural system by adding initial seed carbohydrate storage and its subsequent remobilization during seedling establishment. The initial seed storage mass is calculated from the seed number required to establish the plant stand and a fraction of the seed weight assumed available for remobilization. Since 70% of rough rice is white rice (Barber and de Barber, 1980), this fraction of the seed weight is assumed to be available for remobilization. In addition, the germ makes

up  $\approx 2\%$  of rough rice, and this value is used to initialize the LF, SS, and RT weights.

The seed storage remobilization rate, adapted from Yoshida (1973), is a function of the relative growth, the fraction that PN contributes to the total growth rate, and leaf stage. The fraction that PN contributes to seedling growth logarithmically approaches 1.0 as the leaf stage approaches 4.0, when the plant becomes fully autotrophic. The fractional balance of the seedling growth rate is made up from seed storage reserves. Preanthesis storage of carbohydrate for grain filling is estimated as 15% of the SS mass at heading time. This stored carbohydrate is remobilized at 5% per day to approximate the 15% total remobilization that takes place during grain filling.

CARICE is written in the C language and runs on a daily

Table 2. Partitioning ratios for net photosynthate available to the aboveground portion of the rice plant (net photosynthate minus the mass partitioned to the roots). Linear interpolation is used to calculate the partitioning ratio between any two LNI values.

Aboveground plant component	Leaf number index						50% heading
	0.00	0.35	0.65	0.85	0.93	1.00	
Leaves	0.60	0.60	0.55	0.45	0.15	0.00	0.00
Stems and sheaths	0.40	0.40	0.45	0.55	0.75	0.55	0.00
Grain	0.00	0.00	0.00	0.00	0.10	0.30	1.00

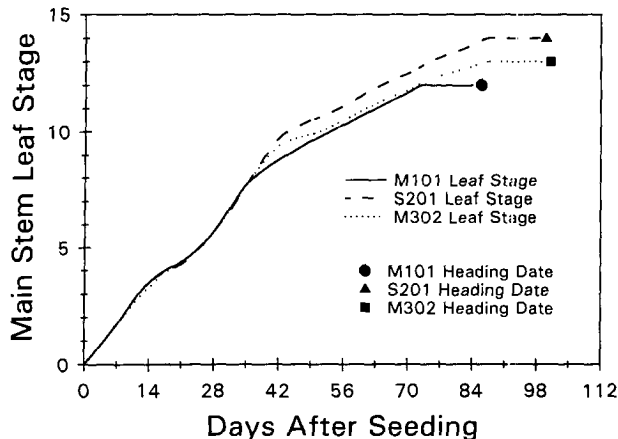


Fig. 3. Baseline simulation of mainstem leaf stage development and 50% heading for M101, S201, and M302 rice.

time step. The model simulates five cultivars, representing three maturity groups (very early: M101; early: S201, M201, and L202; and intermediate: M302), as well as three grain types (short: S201; medium: M101, M201, and M302; and long: L202). To illustrate the model's performance, the simulation results are presented for three cultivars differing in maturity (M101, S201 and M302). Unless otherwise noted, the simulations presented were based on the cultivar S201 (seeded at 600 seeds  $m^{-2}$  and grown under shallow water depth) and used 1985 temperature and solar radiation data from the Rice Experiment Station at Biggs, CA. The actual results, for comparison with simulated results, are from a planting date study (Miller, 1989).

The CARICE program code in C and a compiled executable file may be obtained by sending an IBM-compatible high-density floppy disk (either 5-1/4 inch or 3.5 inch, and formatted using MSDOS or PC-DOS) to the corresponding author.

## RESULTS

### Baseline Results

Leaf stage development, shown in Fig. 3 for the three cultivars M101, S201 and M302, followed the expected pattern of development reported by Miller (1989), with 50% heading taking place  $\approx 13$  d following the emergence of the flag leaf. Simulation of 50% heading in 1985 at the Butte and Colusa County trial sites, using leaf stage development and HUA, was within 6 d of the heading dates actually scored (Table 3). Results from Miller (1989) and preliminary efforts to predict 50% heading in the California statewide rice cultivar trials

Table 3. Actual vs. simulated phenological development of rice at Colus and Butte, CA, 1985.

Cultivar	50% heading			Grain fill duration		
	Actual	Simulated	Difference	Actual	Simulated	Difference
	DAS†			d		
	Colusa					
M101	84	88	4	41	37	-4
S201	98	102	4	32	33	1
M302	108	102	-6	39	34	-5
	Butte					
M101	81	86	5	39	41	2
S201	94	100	6	44	33	-11
M302	96	101	5	44	36	-8

† Days after seeding.

based solely on HUA or DAS resulted in differences at least this great. Grain filling duration, the period from 50% heading to complete grain fill, was simulated within 1 to 11 d of the actual results (Table 3). Generally, the simulated grain filling duration was shorter than observed.

The model's simulation of GRAIN, LF, SS, and total aboveground biomass (AGWT), with no limiting conditions imposed, is compared with actual field results in Fig. 4. At the end of the growing season, CARICE had simulated 21% more AGWT than the observed 1915  $g m^{-2}$ . The model's overestimation of AGWT is principally due to an oversimplification of the leaf senescence function. Beyond 49 DAS, the model did not senesce the leaf area as fast as the rate of senescence observed in the field. As a result of modeling greater leaf mass and leaf area, the grain was filled at a faster rate and the grain filling duration was shorter than observed in the field. In spite of the overestimation of live photosynthesizing leaf weight (LF), CARICE's computation of GRAIN was only 5.3% above the actual 963  $g m^{-2}$ .

The model has a demonstrated ability to simulate leaf stage, critical reproductive stages (50% heading and grain filling), and tillering as a function of leaf stage. These key phenological events can then be used to schedule numerous management actions as shown in Fig. 5. For example, herbicide applications and invertebrate pest control depend on the rice leaf stage. The water level is raised in the field at panicle initiation to buffer against cool night temperatures, thus reducing spikelet sterility. The fertility status of the crop is evaluated with leaf tissue analysis at various stages. In addition to its utility in scheduling management actions, CARICE also can be used to evaluate several alternative management strategies.

### Delayed Planting

Staggered planting is a significant management decision for growers who need to spread out their planting and harvest operations due to large farm size. The effect of delayed planting was simulated for the three cultivars (M101, S201, and M302) and compared with the results from the 1985 planting date trial at the Rice Experiment Station at Biggs (Miller, 1989). Figure 6 shows that a 21-d delay in planting from 10 May 1985 resulted in an average of 21% less grain yield. The model was in close agreement, simulating a 27% loss in yield. The cultivar response to delayed planting was predicted with reason-

Table 4. Actual (Smith, 1968) vs. simulated yield reduction resulting from barnyardgrass (BYG) competition at two rice and two BYG densities.

Rice density	BYG density, plants $m^{-2}$				Difference due to increased BYG density	
	11		54		Actual	Simulated
	Actual	Simulated	Actual	Simulated		
108	40.0	29.4	66.0	66.3	26.0	39.6
334	25.0	11.9	49.0	43.0	24.0	31.1
Difference†	-15.0	-17.5	-17.0	-23.3		

† The percent difference is relative to the control.

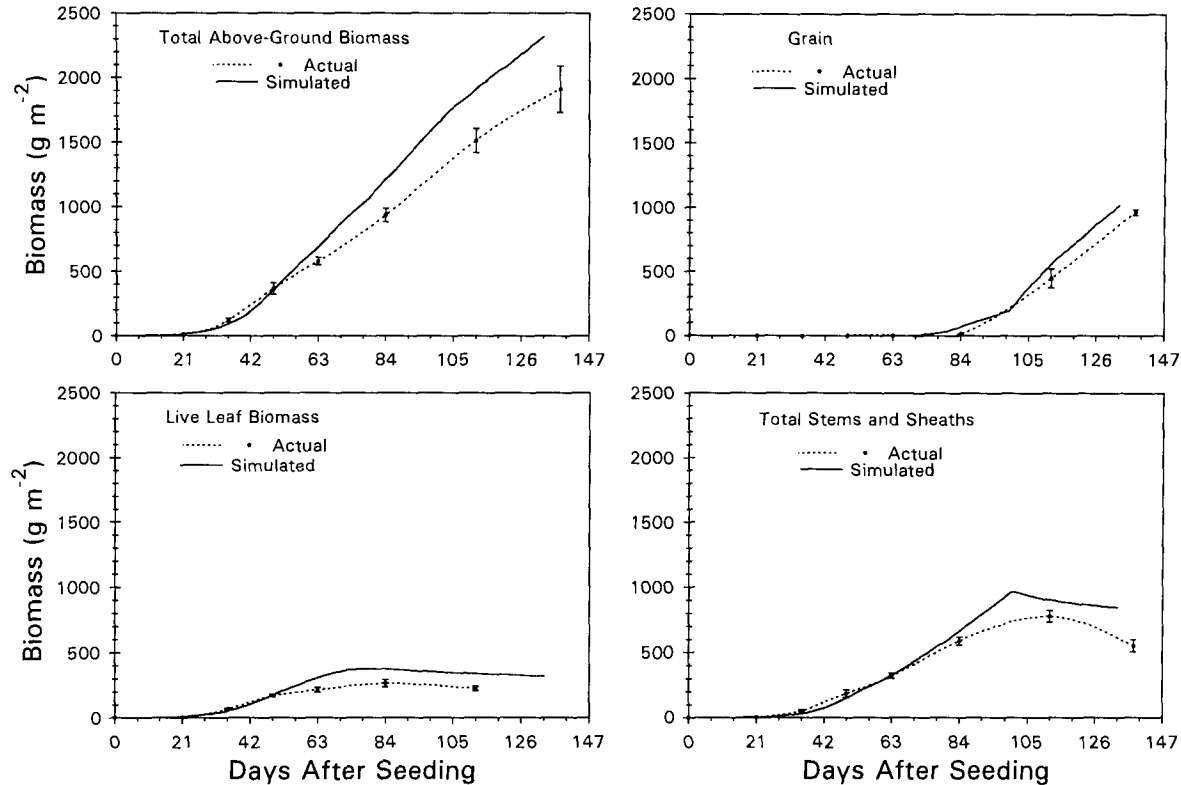


Fig. 4. Actual vs. simulated total aboveground biomass (AGWT), live leaf biomass (LF), total stem and sheath biomass (SS), and grain yield (YIELD) of rice. Bars indicate SE for actual values.

able accuracy. The model simulated an 11.3, 33.0, and 35.2% yield reduction, as compared with a 2.4, 32.3, and 26.2% yield reduction found in the field for delaying the planting of M101, S201, and M302. The very early maturing cultivar M101 was less sensitive to yield reductions than the later maturing S201 and M302. M101 avoided the cool night temperatures during pollen development and heading that increased sterility in S201 and M302 (Fig. 6). In addition to the increase in sterility, there was a reduction in aboveground biomass (AGWT) with delayed planting, in all three cultivars, as a consequence of the crop developing under shorter day-lengths and lower accumulated solar radiation.

### Interaction of Weed Competition and Cultural Management

Barnyardgrass infestation of rice fields is one of the most serious weed problems in continuously flooded, direct water-seeded cultural systems used in California. CARICE was used to simulate barnyardgrass competition with rice as an example of the application of the model to weed management in rice.

Barnyardgrass competition with rice was simulated at two rice and two barnyardgrass stand densities, and the results (Table 4) were compared with data given by Smith (1968). The simulated results follow Smith's findings very closely. At 11 and 54 BYG plants m<sup>-2</sup>, the model simulated 20.6 and 54.6% yield reductions relative to the control, as compared with reductions of 32.5 and 57.5% from Smith's report. At 11 BYG plants m<sup>-2</sup>, increasing the rice seeding rate from 108 to 334 plants

m<sup>-2</sup> lowered the actual yield reduction relative to the control by 15%; for the same conditions, the model estimated 17.5% lessening in yield reduction. At 54 BYG plants m<sup>-2</sup>, increasing the rice seeding rate from 108 to 334 plants m<sup>-2</sup> lowered the actual yield reduction relative to the control by 17% and the model estimated 23.3%. At 11 BYG plants m<sup>-2</sup>, the simulated results indicated lower yield reductions than what Smith reported. The difference in yield reduction was due in part to the lower tiller number per plant reported by Smith. Smith reported an average of 0.7 to 1.7 tillers plant<sup>-1</sup> excluding the mainstem, whereas the modeled results were 1.0 to 2.1 tillers plant<sup>-1</sup> at 11 BYG plants m<sup>-2</sup>. If CARICE were modified to simulate the lower rice tillering rate that Smith reported, the barnyardgrass competition at 11 BYG plants m<sup>-2</sup> would result in higher yield reductions, more closely approximating Smith's results. Additional unaccounted climatic and cultural management factors, such as the dry seeding in Arkansas (where Smith's work was done) vs. water seeding in California, could also contribute to the observed differences. However, the close agreement between the simulated and observed yield reductions by barnyardgrass competition suggests that the barnyardgrass tiller equivalence factor (BYGTEF) was an accurate predictor for the effect of barnyardgrass competition on rice grain yield.

Growing rice under deeper water is an effective method for controlling barnyardgrass. Figure 7 shows the predicted influence of water depth (shallow, 2.5–7.5 cm; moderate, 10.2–15.2 cm; and deep, 17.8–22.8 cm) on grain yield for a range of initial barnyardgrass densities. The model predicts a near-linear decrease in yield

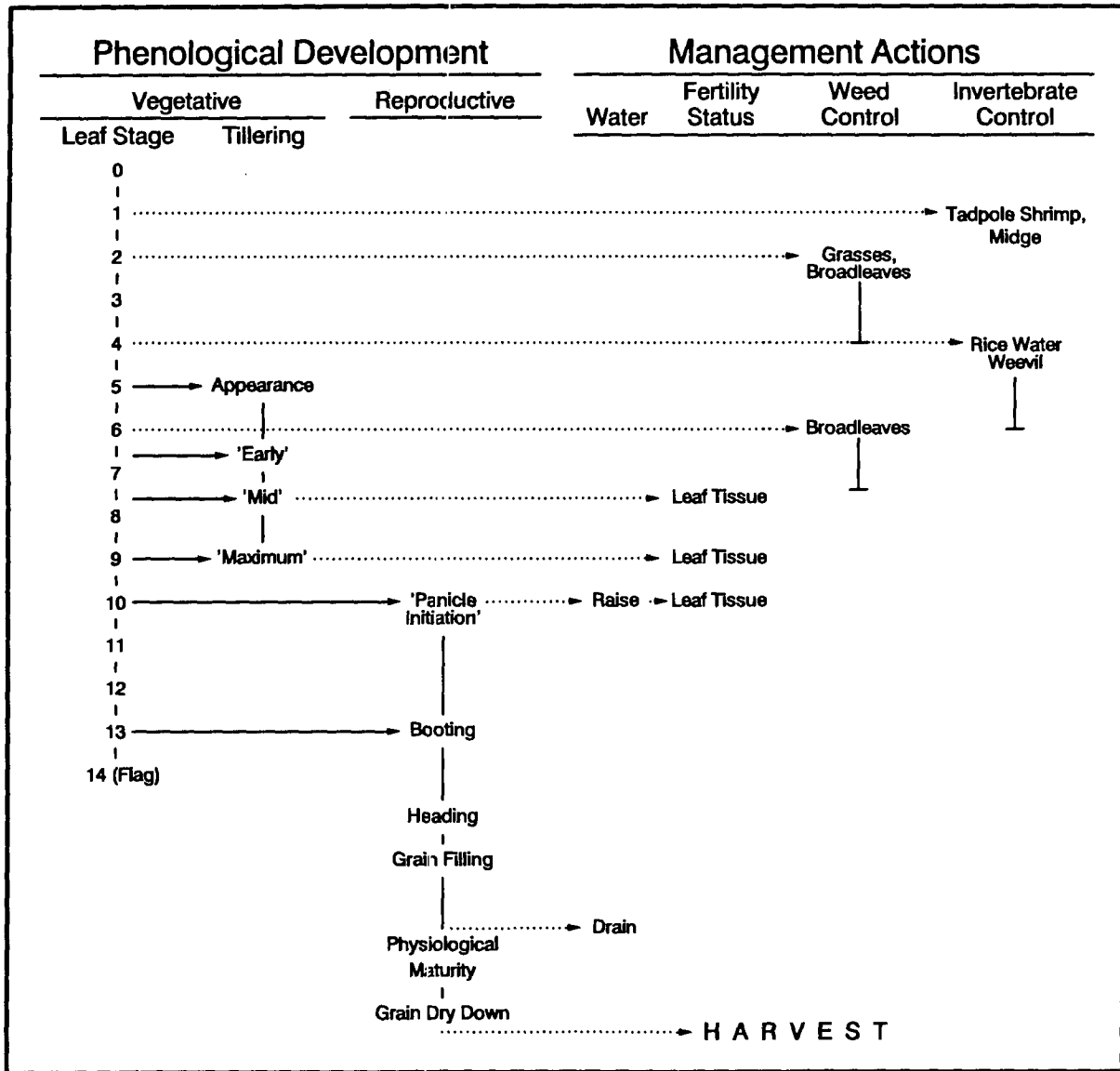


Fig. 5. A schedule of management actions for rice based on phenological development predicted by the CARICE model.

throughout the range of increasing barnyardgrass densities. Increasing water depth from shallow to deep for the entire growing season reduces barnyardgrass competition by reducing the weed stand, which in turn increases rice tillering and enhances grain yield. For example, the weed stand of 80 BYG plants  $m^{-2}$  present at the start of the growing season was reduced to 24 BYG plants  $m^{-2}$  as a result of the deep water treatment (Fig. 7), resulting in a grain yield gain of 3.38 Mg  $ha^{-1}$ .

An alternative management strategy growers could use to reduce weed competition is to increase the rice seeding rate and resulting established plant stand. Figure 8 shows the predicted results of increasing seeding rate on rice grain yield for a range of barnyardgrass densities. A curvilinear yield response was found, with a threshold for improved grain production at  $\approx 400$  rice seeds  $m^{-2}$ . Similar responses were reported by Hill et al. (1990). Whether 400 is the optimal seeding rate depends on other environmental factors, as reported by Miller et al. (1991).

The interactive effect of seeding rate and water depth

management in reducing barnyardgrass competition was predicted (Fig. 9). BYGSTD was reduced with increasing water depth, as noted above. Higher water depth delayed tiller appearance and, at the low seeding rates, resulted in lower final tiller density and rice grain yield. Increasing the seeding rate compensated for the reduced tillering and minimized the negative impact on rice yield caused by increased water depth. Therefore, the combined management actions of increased seeding rate and water depth could minimize the influence of barnyardgrass competition on rice yield.

## SUMMARY

CARICE was designed for use as a management tool. Two keys to CARICE's successful use as a management tool were our addition of a morphologically accurate phenology submodel and incorporation of the yield-component approach to calculating grain yield. The phenology submodel is essential for scheduling management

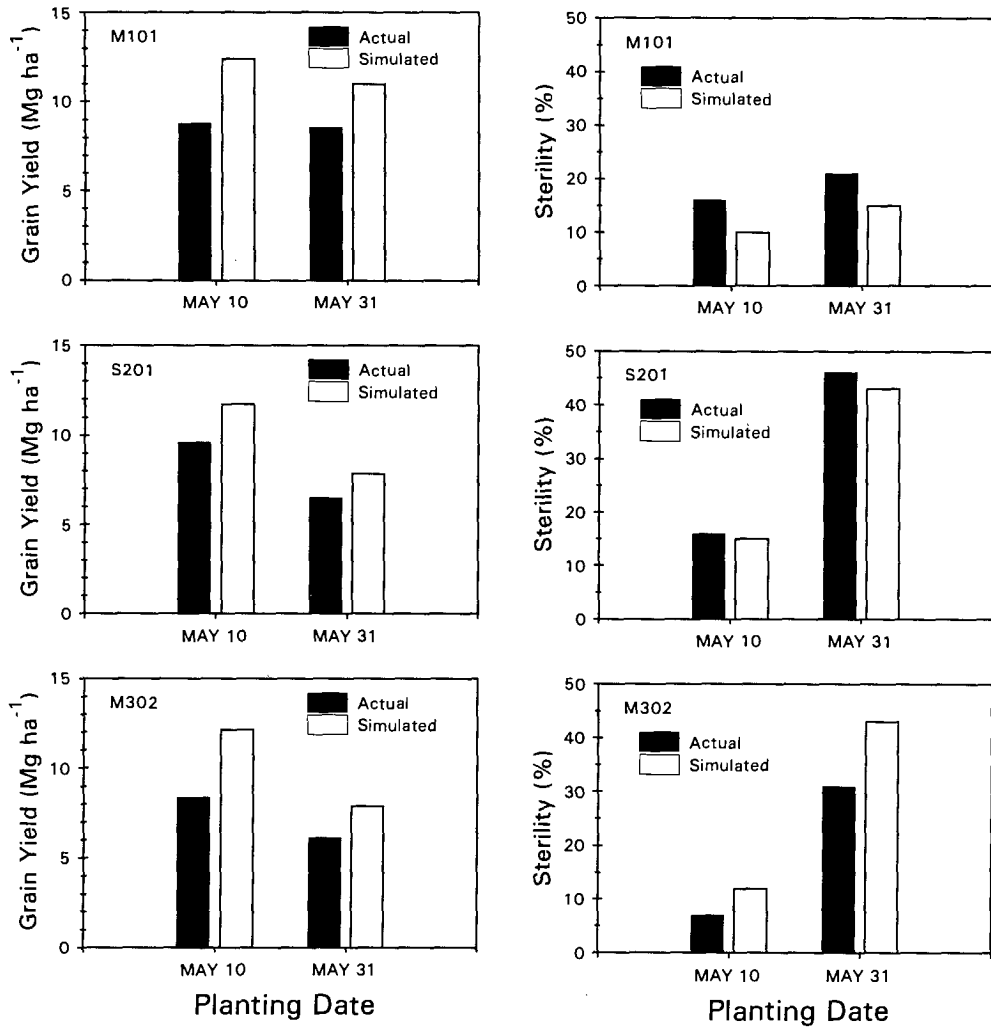


Fig. 6. Grain yield (YIELD) and spikelet sterility (STRFAC) of M101, S201, and M302 rice for two planting dates.

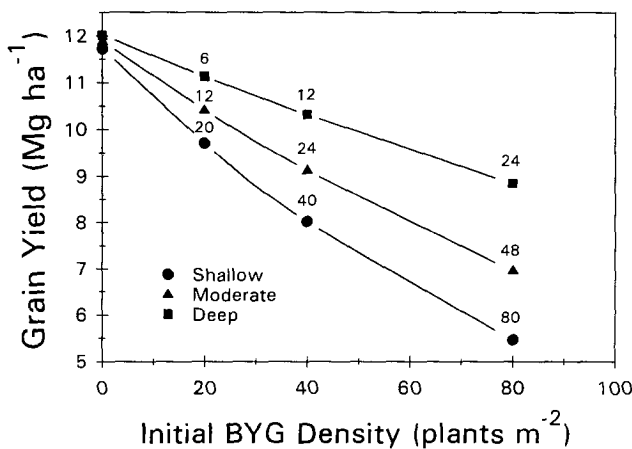


Fig. 7. Predicted rice grain yield (YIELD), as influenced by the initial barnyardgrass density (BYGSTD) and water depth. Numerical values above data points indicate the final barnyardgrass density established (plants m<sup>-2</sup>).

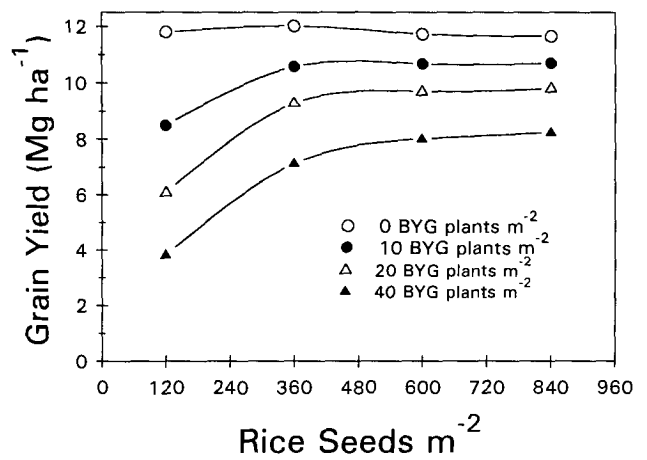


Fig. 8. Predicted rice grain yield (YIELD), as influenced by barnyardgrass density (BYGSTD) and rice seeding rate (SEDRT).

actions. The model predicts the development of leaf, tiller, and reproductive stages from which the timing of herbicide applications, invertebrate pest control, evalu-

ation of fertility status, and water management can be scheduled. Simulation of 50% heading as an extension of leaf stage development generated results similar to the



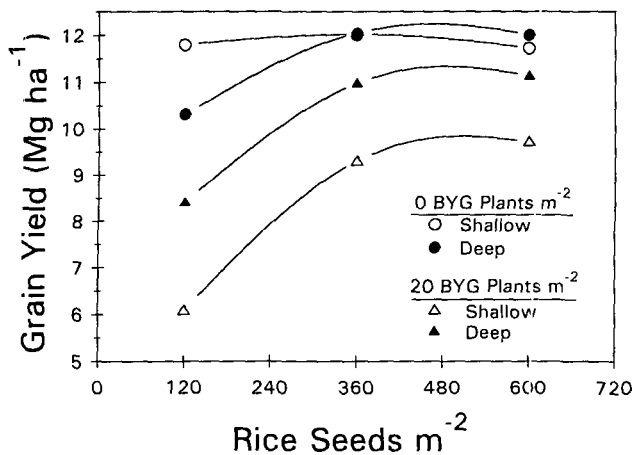


Fig. 9. Predicted rice grain yield (YIELD), as influenced by barnyardgrass density (BYGSTD), rice seeding rate (SEDRT), and water depth.

field measurement of 50% heading based on days after seeding. In addition, the leaf stage method may provide an avenue for improving the predictability of heading, which regression analysis using days after seeding is not likely to achieve.

CARICE is also capable of evaluating alternative management strategies and interactions among several management actions. For example, the cultivar response to delayed planting was simulated with reasonable accuracy. Simulation of barnyardgrass competition at different rice densities closely followed the results reported by Smith (1968). The interactive influence of water management and seeding rate on barnyardgrass competition was also predicted, and the results suggest that the combination of deep water and increased seeding rates could be used for limiting barnyardgrass competition in flooded rice culture.

Incorporating the yield components into the model was the key to being able to evaluate the influence of management and environmental factors on grain yield, such as delayed planting, seeding rate, water depth, and BYG competition. Delayed planting resulted in spikelet development during a period with cooler night temperatures, such that spikelet sterility increased and yields declined, a common observation in California. Barnyardgrass competition with rice was accurately predicted by assuming that each barnyardgrass tiller replaced rice tillers by a factor of BYGTEF. The control of barnyardgrass with increasing water depth resulted from delaying tiller appearance for the barnyardgrass, ultimately reducing the number of barnyardgrass tillers produced. The detrimental effect of increased water depth on rice tillering was overcome by increasing the seeding rate and thus increasing rice plant and tiller density. Clearly, simulating yield-component dynamics in CARICE was an effective way to evaluate realistic field management scenarios.

The productivity model from Iwaki (1975) was modified by the addition of net photosynthate partitioning ratios based on phenological stage. CARICE overestimated the development of leaf mass and area, which in turn caused an overestimate of the aboveground biomass. Leaf mass was overestimated because of an underesti-

mate by the leaf senescence submodel. Differences in aboveground biomass resulted primarily from changes in the accumulated solar radiation as planting date was delayed and from the competitive effect of barnyardgrass. These differences in aboveground biomass inversely affected the grain filling duration; however, yield was not necessarily altered by changes in aboveground biomass. Final yield was dependent primarily on the yield components determined from phenological and morphological development, and the management strategies that affected these yield components.

## REFERENCES

- Alocilja, E.C., and J.T. Ritchie. 1991. A model for the phenology of rice. p. 181-189. In T. Hodges (ed.) Predicting crop phenology. CRC Press, Boca Raton, FL.
- Angus, J.F., and H.G. Zandstra. 1980. Climatic factors and the modeling of rice growth and yield. p. 189-199. In Agrometeorology of the rice crop. Proc. Symp. World Meteorol. Org. and IIRI, Los Baños, Philippines. 3-7 Dec. 1979. IIRI, Los Baños, Philippines.
- Barber, S., and C.B. de Barber. 1980. Rice bran: Chemistry and technology. p. 790-862 (817). In B.S. Luh (ed.) Rice: Production and utilization, AVI Publ. Co., Westport, CT.
- Board, J.E., and M.L. Peterson. 1980. Management decisions can reduce blanking in rice. Calif. Agric. Nov.-Dec. 1980:5-7.
- Carlson, H.L., and J.E. Hill. 1985. Wild oat (*Avena fatua*) competition with spring wheat: Plant density effects. Weed Sci. 33:176-181.
- da Mota, F.S., and J.B. da Silva. 1980. A weather-technology model for rice in Southern Brazil. p. 235-238. In Agrometeorology of the rice crop. Proc. Symp. World Meteorol. Org. and IIRI, Los Baños, Philippines. 3-7 Dec. 1979. IIRI, Los Baños, Philippines.
- Forrester, J.W. 1961. Industrial dynamics. MIT Press, Cambridge, MA.
- Hayes, J.T., P.A. O'Rourke, W.H. Terjung, and P.E. Todhunter. 1982. A feasible crop yield model for worldwide international food production. Int. J. Biometeorol. 26:239-257.
- Hill, J.E., S.K. De Datta, and J.G. Real. 1990. *Echinochloa* competition in rice: A comparison of studies from direct-seeded and transplanted flooded rice. p. 115-129. In Proc. Symp. on Weed Management, Bogor, Indonesia. 7-9 June 1989. SEA-MEO-BIOTROP, Bogor, Indonesia.
- Iwaki, H. 1975. Computer simulation of vegetative growth of rice plants. p. 105-121. In Y. Murata (ed.) Crop productivity and solar energy utilization in various climates in Japan. Jpn. Int. Biol. Prog. Syn. Vol. 11. Univ. of Tokyo Press, Tokyo.
- Iwaki, H. 1977. Computer simulation of growth process of paddy rice. JARQ 11:6-11.
- Kuroiwa, S. 1968. Theoretical evaluation of dry-matter production of a crop under insolation and temperature climate. In Proc. Reading Symp. UNESCO, Paris.
- LeStrange, M. 1985. Competition between rice (*Oryza sativa*) and barnyardgrass (*Echinochloa* sp.): The influence of rice stature, barnyardgrass density, and nitrogen fertility. M.S. thesis. Univ. of California, Davis.
- Matsushima, S. 1967. Crop science in rice. 2nd ed. Fuji Publ. Co., Tokyo.
- McMennamy, J.A. 1980. Dynamic simulation of irrigated rice crop growth and yield. p. 213-221. In Agrometeorology of the rice crop. Proc. Symp. World Meteorol. Org. and IIRI, Los Baños, Philippines. 3-7 Dec. 1979. IIRI, Los Baños, Philippines.
- McMennamy, J.A., and J.C. O'Toole. 1983. RICEMOD: A physiologically based rice growth and yield model. IIRI Res. Pap. Ser. 87.
- Miller, B.C. 1989. A study of rice growth and development designed to develop CARICE: A rice growth model for scheduling management actions and evaluating management strategies under California's direct seeded, continuously flooded culture. Ph.D. diss. Univ. of California, Davis.
- Miller, B.C., J.E. Hill, and S.R. Roberts. 1991. Plant population effects on growth and yield in water-seeded rice. Agron. J. 83:291-297.
- Peterson, C.M., B. Klepper, and R.W. Rickman. 1982. Tiller development at the coleoptilar node in winter wheat. Agron. J. 74:781-784.
- Roberts, S.R. 1988. The effects of nitrogen on the growth and

- development of California rice varieties. M.S. thesis. Univ. of California, Davis.
- Scardaci, S., J.E. Hill, D.G. Crosby, A.A. Grigarick, R.K. Webster, and R.K. Washino. 1987. Evaluation of rice water management practices on molinate dissipation and discharge, rice pests and rice production. Univ. of California, Davis, Agronomy Prog. Rep. 200.
- Smith, J.R., Jr. 1968. Weed Competition in rice. *Weed Sci.* 16:252-254.
- Stansel, J.W., and R.E. Fries. 1980. A conceptual agromet rice yield model. p. 201-212. *In* Agrometeorology of the rice crop. Proc. Symp. World Meteorol. Org. and IRRI, Los Baños, Philippines. 3-7 Dec. 1979. IRRI, Los Baños, Philippines.
- Terjung, W.H., J.T. Hayes, H-Y. Ji, P.E. Todhunter, and P.A. O'Rourke. 1985. Potential paddy rice yields for rainfed and irrigated agriculture in China and Korea. *Ann. Assoc. Am. Geogr.* 75:83-101.
- Univ. of California Statewide Integrated Pest Management Project. 1983. Integrated pest management for rice. Univ. of California Statewide IPM Project, Div. Agric. Sci. Publ. 3280.
- van Heemst, H.D.J. 1986. Crop phenology and dry matter distribution. p. 27-40. *In* H. van Keulen and J. Wolf (ed.) Modeling of agricultural production: Weather, soils and crops. PUDOC, Wageningen, Netherlands.
- van Keulen, H. 1978. Simulation of influence of climatic factors on rice production. p. 345-358. *In* Climatic change and food production. Proc. Int. Symp. Univ. of Tokyo Press, Tokyo.
- Williams, J.F., S.R. Roberts, J.E. Hill, S.C. Scardaci, and G. Tibbitts. 1990. Managing water for weed control in rice. *California Agric.* 44(5):7-10.
- Yoa, A.Y.M., and S.K. LeDuc. 1980. An analogue approach for estimating rice yield in China. p. 239-247. *In* Agrometeorology of the rice crop. Proc. Symp. World Meteorol. Org. and IRRI, Los Baños, Philippines. 3-7 Dec. 1979. IRRI, Los Baños, Philippines.
- Yoshida, S. 1973. Effects of temperature on growth of the rice plant (*Oryza sativa* L.) in a controlled environment. *Soil Sci. Plant Nutr.*, 19:299-310.
- Yoshida, S. 1981. Fundamentals of rice crop science. IRRI, Los Baños, Philippines.