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The development, testing and application of crop models simulating the potential production of rice

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Preface

Crop growth simulation models are being increasingly used as tools to aid agricultural research in both developed and developing countries. Their ability to integrate the results of research from many different disciplines and locations allows agricultural scientists a cost-effective method of complementing traditional approaches to problem-solving. This is particularly attractive in developing countries, where scarce resources may limit effective agricultural research.

The Simulation and Systems Analysis for Rice Production (SARP) project is a collaborative effort between the International Rice Research Institute (IRRI), Los Baños, Philippines, the Research Institute for Agrobiology and Soil Fertility (AB-DLO), Wageningen, the Department of Theoretical Production Ecology (TPE) of the Wageningen Agricultural University, both in the Netherlands, and a number of national research centres in south-east Asia. Workshops are held at frequent intervals to allow collaborating scientists to exchange ideas and discuss research problems, and to familiarise themselves with new developments in the world of crop modelling.

The workshop described in these proceedings focused on the potential production of rice. The potential production of a crop is governed only by solar radiation, temperature, and characteristics of the particular variety used. It is assumed that water and nutrients are in abundant supply, and that there are no pests and diseases to affect the growth of the crop. While these conditions are not often met in field experiments, estimates of potential production provide a baseline for determining the likely gains to be made through improvements in varieties or management practices. The relative changes in potential yields can also be used to estimate the effects of future climate changes, and also to help in preliminary screening of new genotypes by accounting for possible genotype-environment interactions.

The workshop was particularly valuable in that the whole range of model-related activities were covered, from experimentation, to model building and development, experimental testing of the model, and finally to use of models as an aid in problem-solving. The participants, therefore, obtained a very good overview of all aspects of simulation modeling, even if they were not directly involved in all areas. Reflecting this, the papers presented in these proceedings have been arranged into three main sections. The first section describes experimental research conducted to collect data for development, calibration and verification of the models; the second section describes improvements and modifications made to the existing crop growth models, while the third focuses on the application of the models to help solve particular research problems faced by some of the teams, including their use to predict the effect of changes in the climate on rice production.

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Special thanks must also go to Say Calubiran-Badrina for her painstaking work in producing the figures for this publication.

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Systems analysis and agricultural development: basic needs and approaches

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Agricultural development is an important priority in the economies of many developing countries, and depends on improvements in crop production technology coupled with cost minimization and increased marketing potential. Improvements in the efficiency of input use, leading to reduced production costs per unit output, is a significant factor in stimulating agricultural development. However, the problems of increasing input use efficiencies vary between ecological environments, and range from the high cost of inputs to a large variation in yields. Nevertheless, improvements in input use efficiencies have been achieved in different parts of the world by breeding better crop varieties, distributing healthier seed, improving fertilizer application methods, more effective crop protection, and training of farmers in better management.

The high yield variability found in rainfed rice systems is often associated with low efficiencies of inputs, resulting in low economic returns. Land degradation due to overexploitation is a threat often linked with low input farming. Improvement of production systems subject to highly variable physical and biological stresses is particularly difficult because these stresses often interact, and a farmer's goals in evading risk are not necessarily the same as maximizing yield. At the other end of the scale, high input systems pose their own characteristic problems; environmental pollution, and long term instability due to pest buildup, soil fertility decline, micronutrient imbalances, and salinization are typical examples. Excessive use of external inputs to increase productivity can lead to low efficiencies of use, and side-effects often jeopardize sustainability. Both in low- and high-input systems, improvement of input efficiencies should be based on a sound understanding of the production system. This requires proper research methods tailored to specific local requirements.

Rice production in India has increased from 53.6 million tonnes in 1950-51 to 74.6 million tonnes in 1990-91 even though the area under rice cultivation only increased from 40.1 to 42.6 million hectares. There has even been a significant increase in the productivity of rice from 1.3 t ha^{-1} to 1.8 t ha^{-1} from 1980-81 to 1990-91. However, these yields are still below those obtained in most other Asian countries. To meet the needs of the growing population of the country, yields must be boosted to even higher levels.

Tamil Nadu, with 4.4% of the total area of rice cultivation in the country contributes 7.7% of total rice production, with a productivity of more than 4.0 t ha^{-1}. The Cauvery Delta Zone in Tamil Nadu shares nearly 25% of both cultivated area and production of rice in the State. Advances in technology have enabled many Tamil Nadu farmers to harvest yields of more than 10 t ha^{-1}. Yet to meet the demand, the total state production needs to be increased still further from the current 5.8 million tonnes to reach a target of 10 million tonnes of rice by the end of the century. This can only be done by increasing yields above present levels. However, there are considerable constraints on achieving these higher yields. Rice yields are higher during the dry season (June to September) due to higher incident solar radiation and temperature coupled with a lower incidence of pests and diseases, but scarcity of water limits production. On the other hand, the wet season (October-December) is characterized by cyclonic storms, low light intensity and a high incidence of pests and diseases.

Systems analysis may prove to be a useful tool in helping to optimize rice production in both of these seasons. The systems analysis approach provides a strong basis to study the interrelated problems in agricultural production. Although the relative importance of different factors varies between locations, only a limited number of basic processes operate to determine crop yields in all rice-based production systems. By using such a dynamic process-based approach rather than the traditional static production function methods, modern crop models can help predict the effect of individual parameters on crop production. Systems analysis has thus become an important tool in the quest for understanding the behavior of crops in various agroclimatic conditions, particularly in relation to crop production and management, crop protection, and in evaluating alternative or potentially sustainable agricultural systems.

The approach can also help to assess the options for improving efficiencies over the full range of environmental and input domains, a task that would be nearly impossible with traditional experimental techniques. Systems analysis can, therefore, be used to complement traditional and more empirical research. This allows knowledge obtained from basic research to be applied to a wider range of production situations than is possible with other methods. Systems analysis research should, therefore, enable a more efficient use of the limited research funds available in developing countries. In countries such as India, where the potential for increased production is high, the returns from simulation research should be rewarding.

Following the launching of this new concept of defining agricultural production systems in 1963 by Professor C. T. de Wit at Wageningen in the Netherlands, and due to the efforts of the Research Institute for Agrobiology and Soil Fertility (AB-DLO), Wageningen, the Department of Theoretical Production Ecology (TPE), Wageningen Agricultural University, and the International Rice Research Institute (IRRI), Los Baños, in the Philippines, the concepts of crop simulation in respect to rice have been made available to many rice scientists throughout south-eastern Asia.

The Systems Analysis for Rice Production (SARP) programme aims to study the important factors determining crop production and to incorporate these into process-based models. For convenience, a broad framework of themes, into which these factors may fit, has been defined:

1. *Agro-ecosystems:* issues at the cropping systems level: timing (planting, duration), cultural practices, and cropping patterns (crop type, rotations).
2. *Potential production:* issues related to radiation, temperature, and crop varietal characteristics that determine the crop's performance in a given physical environment.

3. Crop management: issues related to water availability and soil fertility.

4. Crop protection: issues related to pests, diseases and competition by weeds.

Our scientists who have been collaborating with the SARP network have been actively involved in all four research themes of the project. They have shown that simulation can aid in evaluating varietal performance in different locations using relevant weather data also obtained some useful results on the carbohydrate partitioning pattern in rice which is particularly influenced by growing conditions. They are also studying the effect of variable nitrogen supply on plant processes, with the aim of modifying the strategy of N supply. It has already been shown that by ensuring there is an adequate level of N in the leaves, the ripening phase can be extended, leading, in turn, to increased yields. The systems analysis approach has now been applied to investigate the damage caused by pests such as stemborer and leaf folder, and diseases such as bacterial leaf blight and paddy blast. Recently, research has also started on competition between crop and weeds.

Applied research activities in the third phase of the SARP project have been planned by giving priority to those issues that most of the participating National Agricultural Research Stations (NARS) have in common. Keeping in mind the various demands for simulation-based research, the following issues are considered relevant for the future.

a. Resource use efficiency in crop production: Many farmers are compelled to operate at sub-optimal levels of input use due to both poor technical knowledge and limited resource availability. Simulation models at the farm level will help to maximize returns from the resources available and increase the profitability of the farming enterprise.

b. Optimization of cropping patterns: There is an urgent need to make better use of available resources on the regional level to achieve a more productive and sustainable agriculture. An interdisciplinary team approach involving farm economists, agro-ecologists, agronomists, and rural sociologists should help achieve this goal. The SARP project has indicated that some NARS have indicated their interest in the use of optimization techniques at the cropping systems level. The Water Technology Centre of Tamil Nadu Agricultural University has already become involved in this approach.

The SARP concept has invoked considerable interest by many other scientists at our University who were not initially involved in the project, and already three more members have been added to the TNRRI team. In addition, five scholars of this University are using the system analysis approach as the basis for their Ph.D. research work. We are very grateful to the SARP project leaders for their sustained encouragement in this respect.

This workshop is being attended by many SARP rice scientists from Bangladesh, China, India, Korea, Malaysia, Indonesia, Japan, Netherlands and the Philippines. It is important not to forget that the ultimate goal of any rice research is to benefit the rice farmers of the world, and I hope that the deliberations of this workshop in the next few days will go some way towards achieving that.

Maximizing the yield of rice in Tamil Nadu, India

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Abstract

Field experiments using higher planting density and increased fertilizer applications were conducted at Aliyarnagar in Tamil Nadu, India, to determine the highest attainable yield of rice in the rice/rice/green manure cropping system under the prevailing soils and climate. The short duration rice variety IR50 and the green manure *Sesbania aculeata* were used. Treatments included two planting densities of rice (5×10^5 and 8×10^5 hills ha^{-1}), three fertilizer levels (150-50-50, 200-67-67 and 250-83-83 kg N-P_2O_5-K_2O ha^{-1}), and three times of fertilizer application (3, 4 and 5 splits). A maximum yield of 9.9 t ha^{-1} was obtained in the *kharif* season (June-Sept) with a treatment combination of 8×10^5 hills ha^{-1}, fertilizer application of 150-50-50 N-P_20_5-K_20 kg ha^{-1}, and incorporation of green manure at 12.5 t ha^{-1}. This yield represented an increase of 19.3% over that obtained from the current recommended practice. Higher levels of applied fertilizer or an increased number of splits beyond four showed no additional increase in yield.

Introduction

In recent years, higher crop yields have been achieved with the advent of new high yielding varieties and the widespread use of fertilizers coupled with better management of water and other resources. The maximum yield that a crop can attain under a given set of conditions is of interest in order to estimate the potential gains that can be achieved by further genetic and managerial improvements. Optimizing planting density and the timing of fertilizer application are two ways in which crop yields can be maximized (Nelson, 1981), and have been used to determine potential yields in maize and soybean (e.g. Saad et al., 1981; Sanchez, 1981).

In the Anamalai region of Tamil Nadu, India, the rice/rice/green manure cropping system is commonly practised in which rice is grown consecutively in the *kharif* (June-September) and *rabi* (September-January) seasons, followed by the planting of *Sesbania aculeata* for green manure in the next cycle. At present, the recommended practice is a planting density of 6.6 x 10^5 hills ha^{-1} with a fertilizer application rate of 100-50-50 N-P_20_5-K_2O kg ha^{-1}. In this study the effect of higher plant population and fertilizer levels on the productivity of the system was investigated.

Materials and methods

Field experiments were conducted from 1990 to 1992 at the Tamil Nadu Agricultural University Agricultural Research Station (TNAU), Aliyarnagar, Tamil Nadu. The soil was a red sandy loam with a pH of 8.1 and EC of 0.3 ds m^{-1}. It is rated low in available N (142 kg ha^{-1}), medium in P (15 kg ha^{-1}) and high in K (415 kg ha^{-1}). The treatments consisted of two population densities (5 x 10^5 and 8 x 10^5 hills ha^{-1}) and three fertilizer levels (150-50-50, 200-67-67 and 250-83-83 N-P_2O_5-K_2O kg ha^{-1}) in the main plots, and three application regimes in the sub-plots. These were as follows:

1. three splits (50% basal, 25% at active tillering and 25% at panicle initiation),
2. four equal splits (basal, active tillering, panicle initiation and heading stages) and
3. five equal splits (basal, early tillering, maximum tillering, panicle initiation and heading stages).

The treatments were replicated three times. The rice variety IR50, maturing in about 105 days, was used. Green manure (*Sesbania aculeata*) was applied at the rate of 12.5 t ha^{-1} one week before transplanting, and incorporated to a depth of 10-15 cm with a green manure trampler.

Results

Results of the trials are shown in Table 1. The maximum yield obtained was 9.9 t ha^{-1} during the *kharif* season (June-September) with the treatment combination of a population density of 8 x 10^5 hills ha^{-1}, and fertilizer application of 150-50-50 N-P_2O_5-K kg ha^{-1} coupled with the incorporation of 12.5 t ha^{-1} green manure. This treatment increased the yield by 19.3% over the current recommended practice. Higher levels of applied fertilizer or more than four splits showed no additional yield increase.

Table 1. Effect of different treatments on yields of rice (var. IR50) at Aliyarnagar for the 1991 and 1992 *rabi* and *kharif* seasons.

Treatment	Yield (t ha^{-1})		
	rabi	*kharif*	mean
Fertilizer (N-P-K kg ha^{-1})			
150-50-50	8.95	9.90	9.43
200-67-67	8.83	9.78	9.31
250-83-83	8.84	9.78	9.31
$LSD_{0.05}$	0.13	0.14	-
Population (hills ha^{-1})			
5 x 10^5	9.30	9.70	9.50
8 x 10^5	9.51	9.94	9.73
$LSD_{0.05}$	0.13	0.12	-
Applications			
3 splits	9.53	9.74	9.64
4 splits	9.18	9.83	9.51
5 splits	9.30	8.89	9.10
$LSD_{0.05}$	0.15	0.16	-

Table 2. Grain yield of rice (cv. IR50) in farmers' field trials at three locations.

Treatments	Grain yield (t ha^{-1})			
	Myladuthurai	Malaiandipattinam	Pinnalammantharai	Mean
Kharif season 1991				
Maximum yield	10.5	9.8	10.8	10.4
Recommended	9.2	9.2	9.1	9.1
Kharif season 1992				
Maximum yield	9.9	10.1	9.8	9.9
Recommended	8.7	9.7	9.1	9.2

Based on these results, three on-farm trials were conducted in farmers' fields at Myladuthurai, Malaiandipattinam and Pinnalammantharai, all in the Anamalai area, comparing maximum yield practices with the farmers' current practice. Results are shown in Table 2. The highest grain yield of 10.4 t ha^{-1} was obtained in the 1991 *kharif* season with IR50 using the maximum yield practice, compared to 9.1 t ha^{-1} obtained using current practices.

Conclusion

The results showed that for the short duration rice variety IR50 a plant population of 8×10^5 hills ha^{-1} (spacing 12.5 × 10 cm) is needed to obtain maximum yield. N-P-K application at the rate of 150-50-50 kg ha^{-1}, applied in four equal splits at planting, active tillering, panicle initiation and heading is adequate for obtaining highest yields. Green manuring with *Sesbania aculeata* at 12.5 t ha^{-1} is also essential for obtaining high yields.

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Potential production of some rice cultivars and advanced lines at Joydebpur, Bangladesh

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Abstract

Field experiments were conducted at Joydebpur, Bangladesh, to validate the rice potential production simulation model AMAN.CSM. Two varieties, BR11 and BR22, and three breeding lines, BR850-22-1-4, BR1870-1-1 and BR1725-13-7-1-6, were grown in 5.0×5.4 m plots. One half of the plot was used for sequential sampling while the other half was kept intact for final harvesting. Stem and leaf weights, leaf area index, and tiller densities were measured at 20-day intervals from transplanting until maturity.

Simulated yield and shoot weight corresponded well with that of the observed data, but tiller number was always overestimated by the model. Year to year variation in yields was explained satisfactorily by the model, which may allow plant breeders to use simulation techniques to remove the component of variation due to the environment, enabling them to evaluate their breeding lines over a wider range of agroclimatic conditions with fewer trials.

Introduction

Plant breeders, in developing new varieties, traditionally must evaluate large quantities of breeding materials for a number of years at many locations. This process is expensive, labour-intensive, and requires substantial physical and laboratory facilities. A well-developed simulation model could be calibrated with experimental field data and then be used to aid primary screening of breeding materials for further field evaluation. If this method gives results of acceptable accuracy, the cost of testing and time can be reduced.

In this paper, a rice growth model was used to calculate potential rice production which was compared to observed values, in order to evaluate the feasibility of using simulation techniques in a varietal development program.

Materials and methods

Field experiment

Two commonly grown rice cultivars (BR11 and BR22) and three breeding lines (BR850-22-1-4, BR1870-89-1-1 and BR1725-13-7-1-6) were grown in rainfed conditions at the Bangladesh Rice Research Institute (BRRI) farm, Joydebpur. The experiment was laid out in a randomized complete block design with three replications. Thirty-day old seedlings were transplanted on August 1, 1992, with a single seedling per hill at 25 × 15 cm spacing.

Table 1. Duration from transplanting to flowering and maturity of the five genotypes.

Genotype	Days to flowering		Days to maturity	
	Simulated	Observed	Simulated	Observed
BR11	113	116	139	146
BR22	132	131	158	161
BR850-22-1-4	116	115	142	143
BR1870-89-1-1	107	106	131	131
BR1725-13-7-1-6	112	112	138	138

Plot size was 5.0 × 5.4 m. Fertilizer at the rate of 100-18-33 kg N-P-K ha^{-1} was applied. One half of each of the plot was used for sequential sampling of leaves, stems and tillers at intervals of 15-20 days for measurements of dry weights. The other half of the plot was kept intact for a final harvest for determination of grain yield.

The model

The simulation model AMAN.CSM, developed by Sattar & Roy (1991), based on the L1Q module described by Penning de Vries et al. (1989), was used to simulate the potential production of the genotypes. The model assumes that there are optimum growing conditions with no diseases or pests, and the crop growth is only limited by the climate that prevailed during the growing period. Crop parameters obtained previously for IR36 were used in this study. To characterize the differences between the genotypes, the number of tillers and the development parameters were made genotype-specific. Weather data for the years 1989-90 and 1992, collected at BRRI at Joydebpur, were used for input to the model. The data consisted of daily values of solar radiation, maximum and minimum temperature, relative humidity, rainfall, and wind speed.

Results and discussion

Time to flowering and maturity

Simulated dates to flowering and maturity of all genotypes showed a good agreement with observed data as a result of adjusting the development parameters (Table 1).

Table 2. Simulated and observed grain yield (kg ha^{-1}) for 1989, 1990 and 1992.

Genotype	1989		1990		1992	
	Simulated	Observed	Simulated	Observed	Simulated	Observed
BR11	4774	5000	4937	4100	4856	4120
BR22	4652	5000	3885	4700	4618	4110
BR850-22-1-4	4417	4100	4507	4200	4444	4050
BR1870-89-1-1	4067	4400	4492	4600	3934	3610
BR1725-13-7-1-6	4289	4200	4660	4400	4225	3910

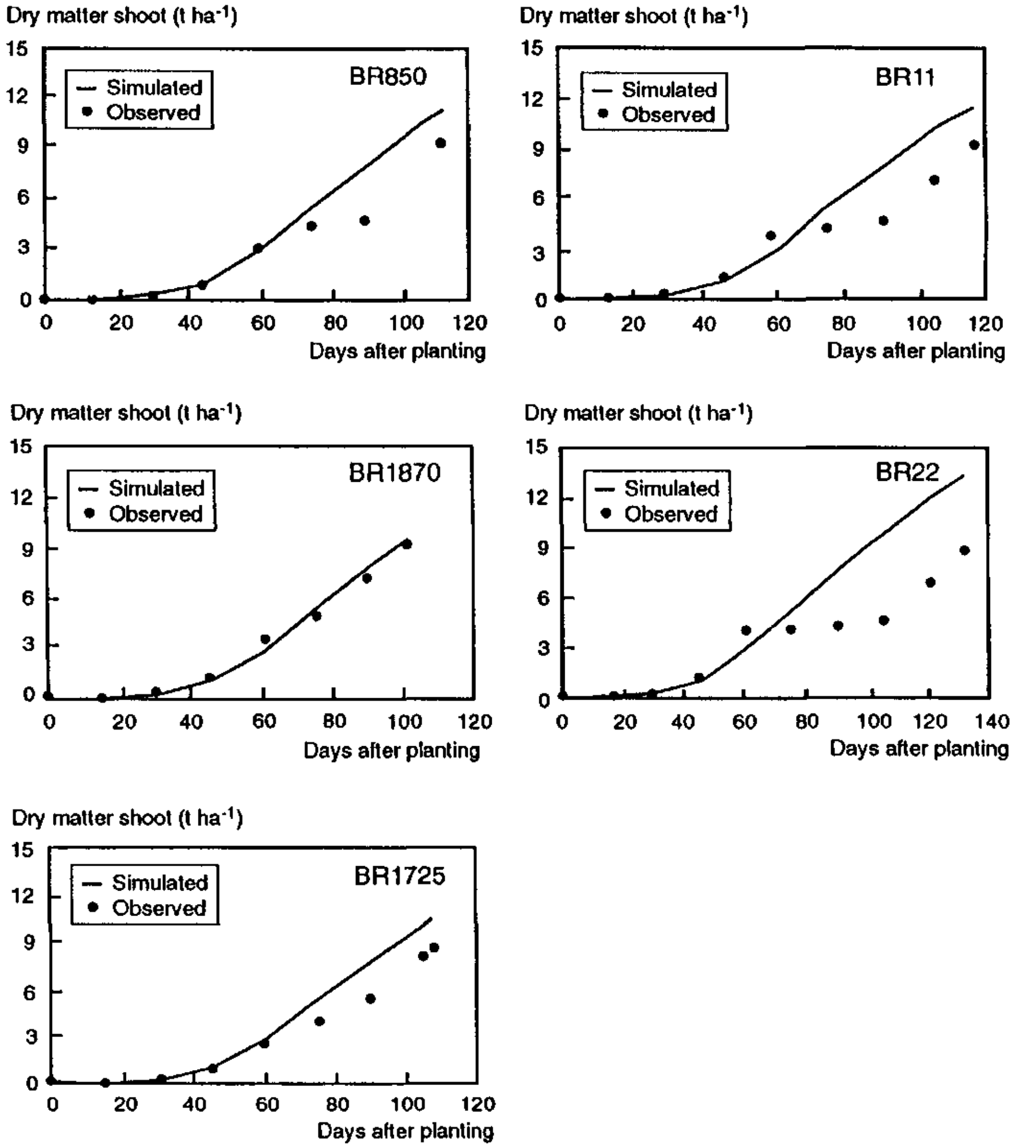

Figure 1. Comparison of simulated and observed shoot weights of the five genotypes used in the study.

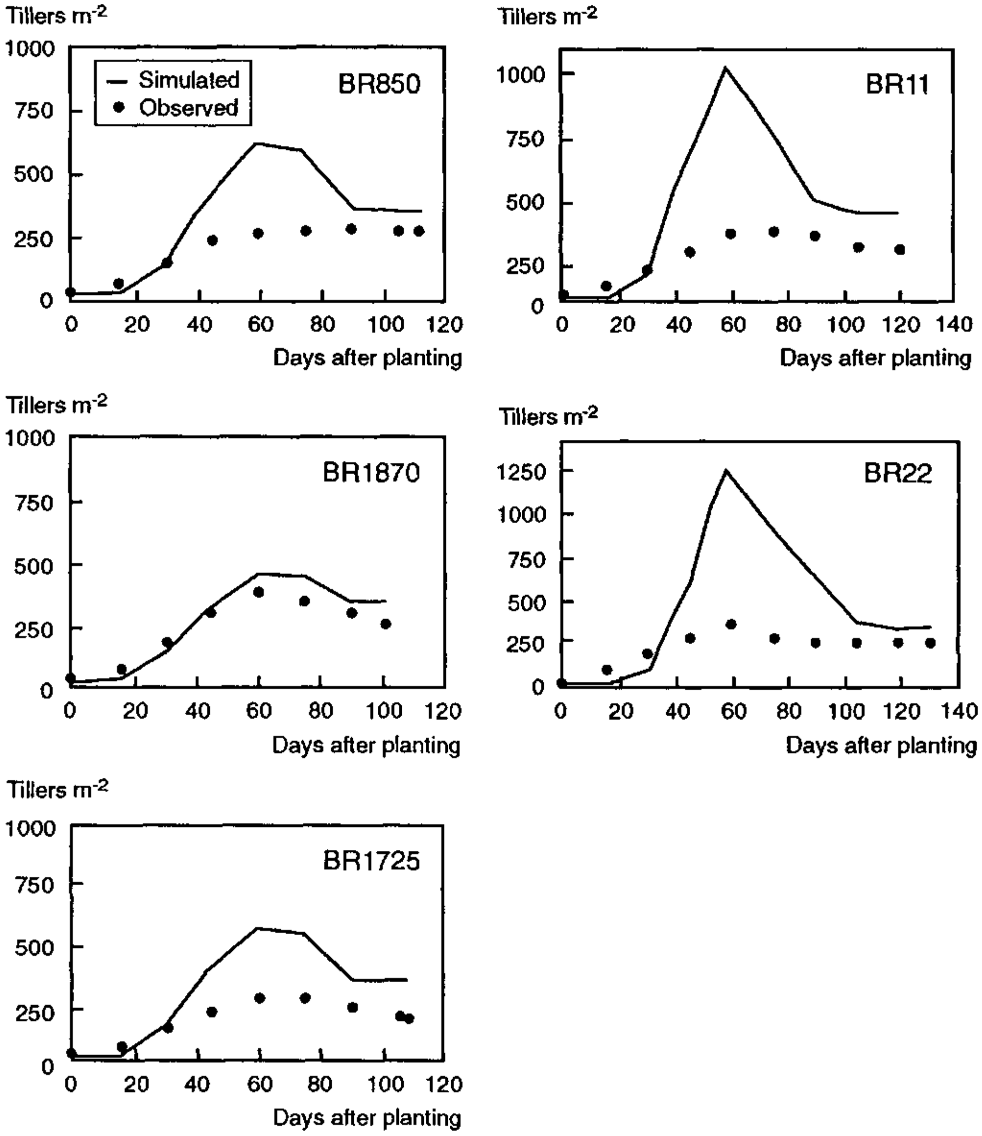

Figure 2. Comparison of simulated and observed tiller numbers of the five genotypes used in the study.

Shoot dry weight
The model had a tendency to overestimate the shoot dry weight at 60 days after transplanting (DAT) irrespective of genotypes, although for BR1870 and BR1725, two short duration lines, simulated results agreed reasonably well with observed data (Figure 1). For BR11 and BR22, simulated shoot weight showed poor agreement with the observed shoot dry weight, which remained more or less constant after 60 DAT. This may have been due to an overestimation of tiller production by the model compared to the field measurements (Figure 2).

Tiller production
In all genotypes except BR1870, the model overestimated tiller production, particularly between 40-90 DAT (Figure 2), indicating the need to improve the routines describing tiller production and survival. The suggestion of Pannangpetch et al. (1991) that high tiller numbers are caused by an overestimation of the carbohydrate production due to a too high rate of photosynthesis per unit leaf area, should also be investigated.

Grain yield
Simulated grain yield of all the tested materials agreed reasonably well with those of the observed data in 1992. Further simulation runs using weather data of 1989 and 1990 gave a satisfactory estimation of grain yields, except for BR22 in 1990, when about 1 t ha^{-1} difference was observed (Table 2).

Conclusion

These results show that the L1Q module of the AMAN.CSM model could be used reasonably successfully to simulate the potential grain production of rice genotypes. By using simulation techniques, plant breeders can evaluate promising materials and discard poor ones at a preliminary stage, thereby reducing the cost and time involved in developing new varieties.

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Influence of climate on rice productivity in the *kuruvai* season in Tamil Nadu, India

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Abstract

Grain yield in irrigated lowland rice grown in the Cauvery Delta Zone during the *kuruvai* season (June-September) was, in general, positively correlated with temperatures and levels of solar radiation during the cropping period, and negatively influenced by the occurrence of rainfall during flowering. Transplanting during the first week of July gave the highest grain yield. Yields were lower in 1992 than in 1991 probably due to a higher rainfall and higher relative humidity from panicle initiation to harvest, which resulted in higher spikelet sterility and lower grain size.

Introduction

In the Cauvery Delta Zone in Tamil Nadu, India, rice is double-cropped in the *kuruvai* (June-September) and *thaladi* (October-January) seasons depending both on the release of canal water from the Cauvery river and on support from ground water resources. In the *kuruvai* season, the date of planting varies from June to August depending on the receipt of canal water by the farmers. However, due to variation in climatic conditions over the period, the actual date of planting can markedly influence the yield obtained.

The present study was undertaken to investigate the influence of weather variables on the growth and yield of irrigated lowland rice, and to determine the optimum time of planting for the *kuruvai* season.

Materials and methods

Two field experiments were conducted at Tamil Nadu Rice Research Institute (TNRRI), Aduthurai, India (latitude 11°00' N, longitude 79°30' E, altitude 19.5 m) during the *kuruvai* season in 1991 and 1992 to study the influence of weather variables on the productivity of short duration rice. The soil was a fine Entic chromustert with a pH of 6.8. The treatments consisted of seven sowing dates: May 31, June 6, 14, 20, 27, July 4 and 10 during 1991, and May 29, June 5, 12, 19, 26 and July 3 and 10 during 1992. These are referred to hereafter as treatments T1, T2, T3, T4, T5, T6, and T7, respectively. Seedlings of the rice variety ADT 36 were transplanted on June 27, July 2, 8, 15, 19, 29, and August 5 during 1991, and on June 23, 29, July 6, 13, 20, 27, and August 3 during 1992, respectively, at a spacing of 15 × 10 cm in 20 m^2 plots arranged in a randomised block

Table 1. Growth and yield components of date of planting experiment, 1991 and 1992 *kuruvai* seasons.

Date of planting	Height at harvest (cm)	LAI at flowering	Tiller density (# m^{-2})	Panicle density (# m^{-2})	Filled grains (# m^{-2})	Unfilled grains (# m^{-2})	Grain size (mg $grain^{-1}$)	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})	Harvest index (%)
1991 season										
T1	90.1	5.8	450	436	47841	8397	21.5	7.5	7.3	50.8
T2	92.7	5.9	562	548	64980	9611	21.6	8.4	8.5	49.7
T3	93.8	6.1	497	474	50442	6821	22.2	7.2	7.3	49.9
T4	95.1	6.1	430	420	46554	5779	21.0	6.9	7.6	47.9
T5	98.5	6.3	385	375	43518	4254	21.0	6.7	6.7	50.0
T6	97.7	6.5	397	390	44473	4283	22.0	6.8	6.6	50.0
T7	96.3	6.2	374	364	40050	4085	21.7	6.6	7.3	47.5
Means	94.5	6.1	442	430	48266	6176	21.7	7.0	7.2	49.4
SE	0.52	0.38	8.74	10.37	3290	680	0.23	0.18	0.17	1.33
CD(P=0.05)	4.41	3.20NS	74.2	87.9	27912	5769	1.95NS	1.53	1.44	11.00NS
1992 season										
T1	91.3	6.0	425	410	43644	8190	20.8	6.1	6.2	49.9
T2	91.7	6.1	434	418	46828	8047	19.7	6.3	6.2	50.3
T3	92.3	6.4	497	480	54215	7854	19.8	7.1	7.1	50.1
T4	96.7	6.5	458	446	45792	6006	19.6	6.4	6.5	50.0
T5	100.7	6.5	425	414	42346	5543	19.6	6.3	6.7	48.5
T6	98.3	6.6	437	404	40371	5166	19.4	5.8	6.2	48.3
T7	97.3	6.4	422	385	37624	4916	19.2	5.3	5.7	48.2
Mean	95.5	6.4	440	418	44403	646	19.7	6.2	6.4	49.2
SE	0.49	0.43	3.86	9.5	1398	258	0.22	0.19	0.15	0.37
CD (P=0.05)	4.20	3.6NS	32.7	80.6	11861	2189	1.87NS	1.6	1.27	3.14NS

Table 2. Weather data from transplanting to harvest.

Treatment	Max temp (°C)	Min temp. (°C)	Cumulative solar radiation (MJ m^{-2})	Total rainfall (mm)	Mean relative humidity (%)
1991 season					
T1	35.0	25.9	1812	120.4	81
T2	34.5	24.4	1868	112.0	78
T3	34.4	23.2	1892	65.4	80
T4	35.2	26.2	1846	86.0	82
T5	32.7	24.2	1836	87.2	76
T6	32.9	23.1	1777	104.4	78
T7	35.3	26.0	1817	131.4	80
1992 season					
T1	34.1	24.8	1666	138.1	83
T2	33.8	24.8	1741	155.9	83
T3	33.7	24.5	1732	247.9	83
T4	33.5	24.3	1727	181.6	84
T5	33.3	24.2	1717	248.4	85
T6	33.0	24.0	1711	432.1	87
T7	33.0	24.0	1757	422.4	88

design with three replications. Daily weather data (maximum and minimum temperatures, solar radiation, rainfall, and relative humidity) from the day of sowing to harvest were recorded by the Agromet observatory of the Institute.

Results and discussion

Plant height ranged from 90.1 to 98.5 cm in 1991 and 91.3 to 100.7 cm in 1992 (Table 1), and was highest for the T5 planting and lowest in the T1 planting for both years. Similar plant heights were observed in the the T6, T7 and T4 plantings. There was no difference in leaf area index (LAI) at 50% flowering in either year.

The total number of tillers, number of panicles, and number of filled grains per area were higher when planted in the first week of July in both years. This was associated with high maximum and minimum temperatures, high levels of solar radiation, and low relative humidity (Oldeman et al., 1987). Tiller density ranged from 374-562 tillers m^{-2} in 1991, and 422-497 tillers m^{-2} in 1992, whereas panicle density ranged from 364-548 panicles m^{-2} in 1991 and from 385-480 panicles m^{-2} in 1992. The highest number of tillers and panicles was associated with the T2 planting in 1991 and the T3 planting in 1992. Similarly, the highest filled-grain number of 39262 and 35992 grains m^{-2} were recorded in T2 in 1991 and T3 in 1992 (both in the first week of July). The number of unfilled grains was high at early plantings in both years which may be due to the higher temperatures encountered. There was no effect of planting date on 1000-grain weight, but in 1992 the 1000-grain weight was 9.2% lower overall than in 1991. In general, vegetative growth was

Table 3. Correlation coefficients between grain yield and weather parameters from transplanting to harvest.

Variable	Max. temp	Min. temp	Solar radiation	Rainfall	Relative humidity	Yield
1991 season						
Max. temp	1.0000					
Min. temp	0.7434	1.0000				
Solar radiation	0.3137	-0.0454	1.0000			
Rainfall	0.3193	0.5073	-0.6920	1.0000		
Relative humidity	0.8496*	0.6155	0.2442	0.0579	1.0000	
Yield	0.2316	-0.0671	0.2253	0.1266	-0.0147	1.0000
1992 season						
Max. temp	1.0000					
Min. temp	0.9670**	1.0000				
Solar radiation	-0.5179	-0.3930	1.0000			
Rainfall	-0.9023**	-0.8695*	0.3936	1.0000		
Relative humidity	-0.0807	0.0278	-0.0537	0.3507	1.0000	
Yield	0.5646	0.5006	-0.0995	-0.5968	-0.2253	1.0000

* Significant at 5% level ** Significant at 1% level

higher in the later plantings whereas components of yield were higher in the early plantings for both years. This resulted in a lower harvest index in the late plantings.

The grain yield ranged from 6.6 to 8.4 t ha^{-1} in 1991, and from 5.3 to 7.1 t ha^{-1} in 1992

Table 4. Correlation coefficients between grain yield and weather parameters from transplanting to panicle initiation.

Variable	Max. temp	Min. temp	Solar radiation	Rainfall	Relative humidity	Yield
1991 season						
Max. temp	1.0000					
Min. temp	0.9151**	1.0000				
Solar radiation	0.2217	0.1377	1.0000			
Rainfall	-0.3016	-0.4244	0.1248	1.0000		
Relative humidity	-0.4626	-0.4455	-0.0539	0.3759	1.0000	
Yield	0.2791	0.4555	0.0754	-0.5591	0.3511	1.0000
1992 season						
Max. temp	1.0000					
Min. temp	0.9514**	1.0000				
Solar radiation	0.4193	0.1952	1.0000			
Rainfall	-0.2523	-0.3897	0.5176	1.0000		
Relative humidity	-0.2445	-0.2626	-0.3646	-0.0320	1.0000	
Yield	0.3707	0.3480	0.6093	0.5169	-0.7568*	1.0000

* Significant at 5% level ** Significant at 1% level

(Table 1). The highest grain yields of 8.4 and 7.1 t ha^{-1} were recorded in the July 2 planting during 1991 and in the July 6 planting during 1992. The higher grain yield in 1991 compared to 1992 was associated with higher maximum and minimum temperatures,

Table 5. Correlation coefficients between grain yield and weather parameters from panicle initiation to 50% flowering.

Variable	Max. temp	Min. temp	Solar radiation	Rainfall	Relative humidity	Yield
1991 season						
Max. temp	1.0000					
Min. temp	0.9544**	1.0000				
Solar radiation	-0.4176	-0.5642	1.0000			
Rainfall	0.5540	0.5922	-0.2980	1.0000		
Relative humidity	-0.8850**	-0.8795**	0.6193	-0.2070	1.0000	
Yield	0.6075	0.7754*	-0.6772	0.5569	-0.6222	1.0000
1992 season						
Max. temp	1.0000					
Min. temp	0.7633*	1.0000				
Solar radiation	0.1043	-0.4243	1.0000			
Rainfall	0.3282	-0.2440	0.8962**	1.0000		
Relative humidity	0.5639	-0.5765	0.7967*	0.8575*	1.0000	
Yield	-0.7513	-0.2347	-0.6593	-0.8051*	-0.5783	1.0000

* Significant at 5% level ** Significant at 1% level

Table 6. Correlation coefficients between grain yield and weather parameters from 50% flowering to harvest.

Variable	Max. temp	Min. temp	Solar radiation	Rainfall	Relative humidity	Yield
1991 season						
Max. temp	1.0000					
Min. temp	0.9970**	1.0000				
Solar radiation	0.6538	0.6256	1.0000			
Rainfall	-0.1011	-0.0842	-0.1138	1.0000		
Relative humidity	-0.6590	-0.6581	-0.5219	-0.2216	1.0000	
Yield	0.7909*	0.7907*	0.4182	0.3790	-0.3927	1.0000
1992 season						
Max. temp	1.0000					
Min. temp	0.3867	1.0000				
Solar radiation	0.4747	-0.1137	1.0000			
Rainfall	-0.6312	-0.2259	-0.3151	1.0000		
Relative humidity	-0.5645	-0.0135	-0.9390**	0.5932	1.0000	
Yield	0.4878	-0.2248	0.6793	-0.2185	-0.6155	1.0000

* Significant at 5% level ** Significant at 1% level

higher solar radiation, and lower rainfall and relative humidity.

Weather data for each of the treatments are presented in Table 2. Correlation analysis between grain yield and weather parameters from transplanting to harvest (Table 3) showed that the grain yield was influenced positively by the combined effect of maximum temperature and relative humidity (r = 0.8496) during 1991, whereas the joint effect of maximum and minimum temperature positively influenced the grain yield in 1992. This was also reported by Yoshida (1981). The interaction of rainfall with maximum and minimum temperature (r = -0.9670) negatively influenced the grain yield during 1992. Correlation analysis between grain yield and weather parameters from transplanting to panicle initiation (Table 4) showed that interaction of maximum and minimum temperature (r = 0.9151) positively influenced the grain yield in both the years whereas the relative humidity (r = -0.7568) negatively influenced the grain yield during 1992. Correlation analysis between the grain yield and weather parameters from panicle initiation to 50% flowering (Table 5) showed that the interaction of maximum and minimum temperature (r = 0.9544) positively influenced the grain yield in both the years whereas minimum temperature (r = 0.7754) alone positively influenced the grain yield in 1991. The joint effect of solar radiation and rainfall (r = 0.8692) and relative humidity (r = 0.7967) as well as solar radiation and relative humidity (r = 0.8576) positively influenced the grain yield in 1992. The occurrence of rainfall from panicle initiation to 50% flowering negatively influenced the grain yield during 1992. The correlation analysis between the grain yield and weather parameters from 50% flowering to harvest (Table 6) showed that the maximum (r = 0.7909) and minimum (r = 0.7907) temperatures both individually and jointly influenced positively (r = 0.9970) the grain yield during 1991 whereas the interaction of solar radiation and relative humidity (r = -0.9390) negatively influenced the grain yield in 1992.

Conclusions

Yields of rice in the *kuruvai* season were highest when transplanting was in the first week of July, with the yield declining for each week delay thereafter in planting. In general, maximum and minimum temperatures, and solar radiation, in association with rainfall and relative humidity, positively influenced the yield. Relative humidity and the occurrence of rainfall from panicle initiation to the 50% flowering stage were found to have a negative influence on grain yield.

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The uptake and distribution of nitrogen in the rice plant, and its effect on growth and yield

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Abstract

An experiment was conducted to determine the pattern of nitrogen uptake and distribution within the rice crop, the results of which were used to develop a subroutine describing N dynamics for inclusion in the MACROS rice simulation model. Seedlings of the rice variety RD6 were transplanted into 100 cm diameter pots, and nitrogen fertilizer applied in ten splits each at the rate of 12 kg N ha^{-1} at 10-day intervals from transplanting. Determinations of the N contents and the dry weights of plant tissues were also made at 10-day intervals until the plants reached maturity.

Results showed that the N content of the vegetative tissues reached maximum values at four weeks after transplanting and declined gradually thereafter, while that of the grain remained almost constant at 12 g kg^{-1}. However, total plant N reached a maximum at anthesis, decreasing thereafter. Leaf, stem, and root dry weights also reached their maximum values at the time of anthesis.

Based on this data, a model subroutine of N distribution, remobilization, and its effect on crop growth and yield was constructed. It was assumed that the amount of N distributed to each plant tissue is governed by the growth rate of that tissue, and that remobilization occurs when the total daily demand of N required for growth exceeds the rate of N uptake by the crop. N remobilization was assumed to occur only from the stems and leaves and to be proportional to their N contents. Remobilization also resulted in a reduction of photosynthetic area and consequently carbon assimilation. Aging of photosynthetic tissue occurred when no new tissue was produced, resulting in an increase in maintenance respiration.

The modified model indicated that yield increased asymptotically with an increase in N uptake, reaching a maximum value at a total N uptake of 107 kg N ha^{-1}. Further increases in grain yield could not be obtained by increasing nitrogen uptake. The increase in yield was due to both a higher grain growth rate and longer duration of grain filling.

Introduction

Environmental constraints on crop productivity in the northeast of Thailand are due mainly to erratic rainfall, low soil water holding capacity, and low soil fertility, all characterized by high variation at the microscale level (KKU-FORD, 1982). Such variation limits the transfer of agrotechnological research results to only those areas which have similar environmental conditions to the testing sites. To increase the efficiency of both research programmes and land use, agroecological zoning of the region has been initiated. Crop growth models and Geographic Information Systems (GIS) have been considered as tools to provide not only the basic information for defining agroecological zones, but also primary information on appropriate crop management within each zone. A prototype study linking a crop growth model and a GIS has already been applied to evaluate rice production under rainfed conditions of the five sub-districts of the district Phar Yuhn in Khon Kaen (Pannangpetch, 1991a). The results showed a significant correlation between simulated yield values and reported values, although the absolute simulated values were approximately twice as high as the observed values. The simulated values may be regarded as the potential production achievable under the rainfed conditions of the district. However, in order to provide further information for the optimization of crop management, especially under different soil fertilities, it was decided to develop the model further to include the effect of nitrogen status on the growth and yield of the crop.

Nitrogen can affect both the source and sink activities of the crop. Decreasing leaf nitrogen content reduces the rate of leaf photosynthesis. The relationship between leaf N content and leaf photosynthetic rate in rice can be described by a linear regression (Penning de Vries et al., 1990; Kropff et al., 1992; Pannangpetch, 1991b). Reduction of leaf nitrogen content occurs as a result of N remobilization during the leaf senescence process. This reduction can be rapid when leaf senescence is accelerated by various stresses; for example, when the rate of nitrogen uptake by the crop cannot fulfill the rate of N required by the biosyntheses of new tissues, N is remobilized from leaves and stems to the new growing tissues (Sinclair & de Wit, 1976). This effect of N status in accelerating leaf senescence is supported by the observation that leaf duration and maturation of field-grown rice are generally prolonged under optimal N application. For example, leaf senescence was delayed by up to 20 days in the variety Sasanishiki (Makino et al., 1984) and in the variety RD6 by approximately 10 days (Phalaraksh, pers. comm.). When grown under low N supply, early development of N deficiency in mature leaves is often observed (e.g. Marschner, 1986).

The low variation in N content in seeds of legumes grown under a wide range of contrasting nutritional and environmental influences suggests a priority for the allocation of N to growing tissues (Pates, 1983). In rice, up to 63% of the total nitrogen in a growing leaf can be from redistributed N (Mae & Ohira, 1981), and up to 40% of N content in grain can be derived from leaves and stems (Peoples & Gifford, 1990). The extent to which remobilization of N can meet the requirement for biosynthesis of new tissues probably depends on the balance between the 'N-retention' strength of the source and the 'N--withdrawing' strength of the growing tissue. If the supply of N cannot completely meet the requirement of the biosynthetic processes, the rate of biosynthesis is reduced below the maximum. This may result in an accumulation of carbohydrate which may in turn have a negative feedback effect on the rate of photosynthesis (Geiger & Giaquinta, 1982; Lafitte & Travis, 1984). Thus, inadequate N uptake can result in a reduction in canopy photosynthesis and consequently in growth and yield. On the other hand, when N uptake exceeds the requirement for growth, the excess N may be stored in forms of nitrate and free amino acids (Yoshida, 1981). The extent to which excess N can be stored depends on the feedback effect of shoot on root uptake.

As a first step toward modelling N distribution and its effect on the growth and yield, an experiment was conducted with the rice variety RD6 to measure changes in N uptake and distribution over time.

Materials and methods

Twenty-eight day old seedlings of the rice variety RD6 were transplanted on August 12, 1991, into concrete pots of 93 cm diameter and 40 cm depth, filled with soil of the Yasothon series (Mitsuchi et al., 1986). The seedlings were planted at a density of 13 plants per pot and arranged in radial fashion in each pot. There were three replicates, each consisting of ten pots. Natural light and temperature conditions were used throughout. The water level was maintained at approximately 1 cm above the soil surface throughout the experimental period. Nitrogen fertilizer was applied in ten splits at a rate of 12 kg N ha^{-1} at ten day intervals from transplanting. Total nitrogen fertilizer applied, therefore, was 120 kg N ha^{-1}, corresponding to the amount which was found to give the maximum dry matter and grain yield in the variety IR64 at a plant population density of 100 plants m^{-2} and four plants per hill (Dingkuhn et al., 1990).

From 21 days after transplanting (DAT) and continuing at intervals of ten days until maturity, plants in three pots were harvested. The plants were separated into the components of leaf blade, leaf sheath and stem, root, and panicle plus grain (subsequently referred to as leaf, stem, root, and grain respectively). They were then oven-dried at 75°C for 72 h, after which their dry weights were recorded. The nitrogen content of the uppermost leaf, remaining leaves, stems, roots, and grain were also determined. Tissue N content was determined according to the method described by Oweczkin & Kerven (1979) using a Technicon time-temperature programmed digestion block and a Technicon Auto Analyzer II.

Results and discussion

Nitrogen contents of leaves, stems, roots, and grain are presented in Table 1. The nitrogen contents of the vegetative parts generally attained their maximum values at 31 DAT, after

Table 1. Nitrogen content (g N $(100\ g)^{-1}$) of plant components of rice cv. IR6 at various stages of growth.

Days after transplanting	Uppermost leaves	Remaining leaves	Stems	Roots	Grains
21	4.58	3.61	2.53	1.65	-
31	4.88	3.79	2.84	2.11	-
42	3.12	3.14	1.40	1.24	-
52	3.25	3.06	1.04	1.06	-
63	3.48	2.87	0.95	0.74	-
73	3.30	2.60	0.76	0.75	1.30
84	2.59	2.08	0.52	0.64	1.36
94	1.62	1.05	0.45	0.50	1.29
105	1.48	1.12	0.52	0.56	1.38
115	1.03	0.84	0.43	0.64	1.30
$LSD_{0.01}$	0.93	0.86	0.27	0.29	0.17

Table 2. Dry weight (kg ha^{-1}) of the uppermost leaves, remaining leaves, stems, roots, and grains.

Days after transplanting	Uppermost leaves	Remaining leaves	Stems	Roots	Grains
21	64	114	167	66	-
31	46	547	486	217	-
42	81	1513	1752	958	-
52	78	2624	3896	1415	-
63	130	3460	8993	1778	-
73	82	3531	11624	1616	2553
84	113	3205	11012	1788	6287
94	164	3429	12386	2074	10238
105	201	3475	12172	2298	11607
115	198	3529	11749	2535	12015

which they declined gradually to their minimum values at maturation. The nitrogen content of the leaves was approximately 2.5 times higher than that of the stem and roots. Nitrogen content of the grain, however, remained almost constant throughout the reproductive period with slightly higher values during the middle of the period. The values of N content and the time course of N distribution found in the present experiment are comparable to those obtained for a number of IRRI rice varieties (e.g. Dingkuhn et al., 1990; Penning de Vries et al., 1990; Schnier et al., 1990), and for the variety Sasanishiki (Makino et al., 1984).

Dry weights of leaves, stems, roots, and grains are presented in Table 2. Total leaf and stem dry weight reached their maximum values at around the beginning of grain filling stage, but root dry weight continued to increase substantially until the crop matured. The dry weight of grain and vegetative tissues obtained in this experiment were considerably higher than those found under field conditions, which may have been due to the much greater penetration of light into the canopy in the pot experiment. The conversion of

Table 3. The cumulative N (kg N ha^{-1}) in leaves, stems, roots, grains, and total crop.

Days after transplanting	Leaves	Stems	Roots	Grains	Total
21	7.07	4.22	1.09	-	12.38
31	22.94	13.79	4.57	-	41.30
43	50.08	24.53	11.84	-	86.44
52	82.84	40.33	15.00	-	138.17
63	103.85	85.43	13.17	-	202.45
73	94.53	88.65	12.04	33.20	228.41
84	69.61	56.75	11.50	85.51	223.36
94	38.66	56.28	10.27	132.07	237.28
105	41.72	63.01	12.93	160.19	277.85
115	31.51	49.97	16.23	156.20	253.92

intercepted radiation to crop dry matter was also maintained at a high rate by an ample supply of water and nutrients. Nevertheless, the results suggest that if rice is not exposed to environmental stress during the heading stage, then source strength may be the factor preventing grain yield from reaching its potential level. The cumulative N content (kg N ha^{-1}) of each plant tissue was then derived from the product of its dry weight and fraction of its N content (Table 3). Total leaf N was calculated as the sum of all leaves, including the uppermost leaves. Total N uptake by the crop increased continually until maturity. The highest rate of N uptake occurred just before anthesis when the cumulative N of leaves, stems, and roots reached their maximum values. The leaves lost the greatest amount of N during the reproductive phase, but a substantial amount of N was also remobilized from stems during the grain filling stage. Nitrogen remobilized from leaves and stems together contributed about 70% of the final N content of the grains. Remobilization of N from the roots on the other hand was almost negligible, confirming a similar observation by Mae & Ohiri (1981).

Development of the nitrogen dynamics sub-model

Based on the results of the experiment, a sub-model of N distribution and its effects of growth and yield of rice RD6 was constructed. A relational diagram of the model structure is shown in Figure 1.

The amount of N available for crop growth processes is dependent primarily on the rate

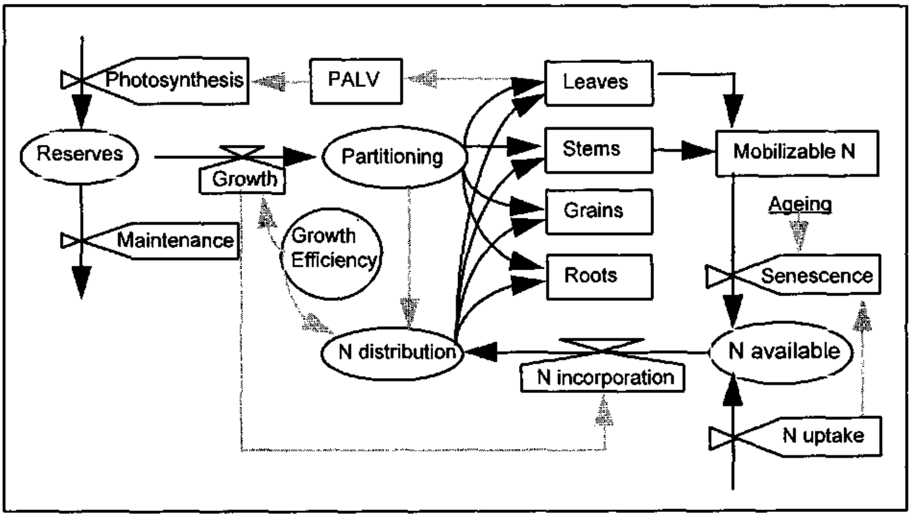

Figure 1. Relational diagram of N distribution and its regulation. Rectangles represent quantities (state variables); circles, auxiliary variables, underlined, driving variables; full lines, flows of materials; greyed lined, flows of informations (symbols according to Forrester, 1961).

of N uptake by the crop and the concurrent rates of leaf and stem senescence. However, when the amount of N available is not sufficient to meet the requirement for the biosyntheses of new tissues, senescence of leaf and stem is often accelerated to provide additional N. Sinclair & de Wit (1976) have suggested that the process of nitrogen and carbohydrate redistribution from the leaves is the major cause of senescence in leguminous crops. The depletion rate of the pool of available N in the crop is determined by the rate at which N is used by the biosynthetic processes, especially those related to the manufacture of protein. In the sub-model, the rate of biosynthesis, crop growth rate, is assumed to be a function of the amount of carbohydrate available for growth. Thus, net photosynthetic rate has a positive effect on N depletion.

It is assumed that the proportion of N distributed to each plant tissue is proportional to that of carbohydrates. This is based on the assumption that if solutes are translocated from their source to a sink mainly via the phloem and are driven by a concentration gradient according to mass flow, then the differences in the fraction of carbohydrate partitioned to each plant organ are proportional to the rate of translocation from the source to each sink. For given concentrations of carbohydrates and nitrogenous solutes in the phloem solution, therefore, a sink which receives a higher proportion of carbohydrate should also receive a greater proportion of nitrogenous solutes. However, the amount of N actually incorporated into a plant tissue depends on the type of tissue. For example, leaves, which normally have a higher protein content, incorporate more N for a given unit of dry weight increase than does the stem. In a tissue which has a slow rate of N incorporation, excess N may be re-exported via the xylem (Pates, 1983). To test these assumptions, the N requirement of the leaves, stems, and roots during the vegetative phase was estimated, based on the fraction of carbohydrates allocated to these tissues and their N composition.

In rice, the leaf protein fraction is usually about 20% w/w, and the N fraction of protein is around 15% w/w. The N content of the leaf is therefore about 0.03 kg N kg^{-1} leaf dry weight (Penning de Vries et al., 1989). Similarly, the N content of the stems, roots, and grain is about 0.012 kg N kg^{-1} dry weight. This gives a ratio of the leaf N content to that of the other components of 2.5, which agrees closely with the average ratio found in the present experiment. The fraction of carbohydrate partitioning was calculated as follows:

$$CP_{i,t} = (\delta Y_{i,t} \bullet CR_i) / \sum_{j=1}^{n} (\delta Y_{j,t} \bullet CR_j) \qquad (1)$$

where t is the time interval; δY_i is the increase in dry weight of tissue i over time interval t; n is the total number of tissue types; and CR_i is the amount of carbohydrates required for growth of tissue i (1.462 kg kg^{-1} for grain, and 1.326 kg kg^{-1} for leaves, stems and root (Penning de Vries et al., 1989)). The fraction of the total N requirement for each plant tissue was then derived as the product of the fraction of carbohydrate partitioning and the fraction of their N content. Estimated values of N distribution were then tested against the observed fraction (ND), which was calculated as follows:

$$ND_{i,t} = \delta N_{i,t} / \sum_{j=1}^{n} \delta N_{j,t} \qquad (2)$$

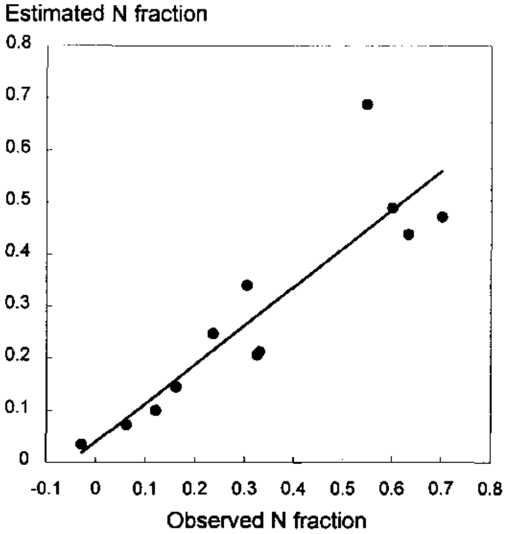

Figure 2. The relationship between predicted and observed N fractions (see text for details). The line is that fitted by regression (Y=0.039 + 0.74X; r = 0.894, n=12).

where δN_i is the increase in N of tissue i over time interval t, and n is the total number of tissue types. The relationship between the estimated and observed values is shown in Figure 2. There was a significant correlation (r^2=0.8), supporting the assumption described above. However it should be noted that the slope of the regression is less than unity. This could have been due to the temporary accumulation of nitrate or amino acids in the tissues as a result of an excess supply of N (Yoshida, 1981) which is not accounted for in the estimation. Another possibility is that the variety RD6 may have a higher protein content, or a higher fraction of N in protein, than was assumed above. Further investigation on the time course of the fraction of temporary storage of N in the form of free nitrate and amino acids may help to identify the causes of the deviation. The nitrogen content of the grain showed only slight variation during panicle development, ranging from 0.0129-0.0138 kg kg^{-1}. The values obtained from the experiment were slightly higher than the calculated values of the grain N requirement, 0.012 kg kg^{-1}, but comparable with those obtained by Chandra et al. (1986). The value of 0.012 kg kg^{-1} is used in the model.

The total amount of N in the crop can be subdivided into immobilisable N and mobilisable N. Immobilisable N is that which has been incorporated into the structural component of the plant tissues and remains in the senesced tissue. In rice, the ratio of immobilisable N to tissue dry weight in a given tissue varies only slightly. In the present experiment this ratio was 0.0084 for leaves, 0.0043 for stems, and 0.0064 for roots, which are somewhat higher than the values compiled by Penning de Vries et al. (1990). In the model, values of 0.01 for leaves, and 0.004 for other vegetative tissues, are used. Mobilisable N at any given time is defined as the difference between total N and the immobilisable fraction. Mobilisable N includes N in the form of protein, free amino acids and nitrate. Chloroplasts are the major source of remobilisable N from leaves (Morita, 1980). In the model, the contribution of nitrogen from leaves and stems to the total amount of mobilisable N is assumed to be proportional to the ratio of their mobilisable N content to the total mobilisable N. Any contribution from the roots was not included, as changes in root nitrogen were negligible compared with those in the leaves and stem.

The rate of removal of N from the available N pool depends on tissue age, and the difference between the rate of N supply and the rate of N requirement for growth. When the requirement exceeds the supply from both uptake remobilisation from senesced leaves, accelerated senescence can occur, resulting in an even further reduction of photosynthetically active tissues. The net change in photosynthetically active tissue is therefore the balance between the rate of new leaf growth and the rate of leaf senescence.

This approach implies that N uptake and mobilization exerts its effect on crop growth by regulation of the area of photosynthetically active tissue. At present, vertical profiles of leaf nitrogen content and photosynthetic capability in the canopy are not included in the model; instead it is assumed that N is equally distributed throughout the canopy, and thus all active leaves have the same photosynthetic capacity. Results from an earlier investigation into the relationships of N distribution and photosynthesis of leaf layers in a rice canopy and their effect on growth and yield (Pannangpetch, 1991b) have shown the validity of this assumption. Total photosynthesis (kg CO_2 ha^{-1} h^{-1}) of two canopies were simulated; one with a vertical gradient of leaf N content and leaf photosynthetic capability, and the other with N equally distributed at the fraction of 0.03 kg kg^{-1} throughout. Figure 3 shows a comparison of the two simulations. Gross photosynthesis of the canopy with equal N distribution was generally only slightly lower than that of the canopy with the

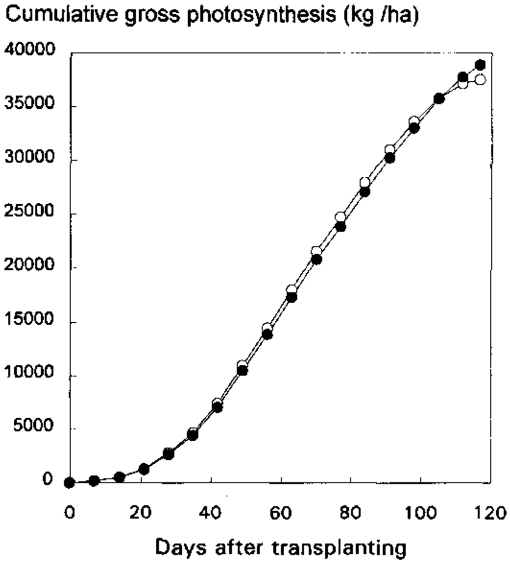

Figure 3. Comparison of the simulated cumulative gross photosynthesis of a canopy with the vertical decline of N content and leaf photosynthesis capability (open circles) and that of a canopy with equal distributed N content and photosynthesis (filled circles).

Table 4. Listing of the statements and parameters in CSMP notation (IBM, 1975) to be interfaced with the MACROS model.

```
INITIAL
  ALVI  = (WLVI/(SLC*AFGEN(SLT,DSI)))+(WSTI*0.5/SSC)
DYNAMIC
  WLVT  = INTGRL(WLVI,GLV-NRMLVT)
  WSTT  = INTGRL(WSTI,GST-NRMSTT)
  CELV  = PCGW-RMCR
  PALV  = INTGRL(ALVI,PGLA+PGSA)
  PGLA  = (GLV-SNLVT)/SLN
  PGSA  = 0.5*(GST-SNSTT)/SSC
  SNLVT,SNSTT,NRMLVT,NRMSTT=...
  SUNBAL(GLV,GST,GRT,GSO,WLVT,WSTT,NUCR,TIME,DELT)
  NUCR=NUCRMX*NUF
  NUCRMX=AFGEN(NUCRT,DS)
METHOD RECT
TIMER DELT=1.,TIME=0.,FINTIM=300.,PRDEL=1.,OUTDEL=1.
FINISH  DS=10.0, CELVN =3.0

PARAM NUF=  1.0
FUNCTION NUCRT = ...
0.22,0.31, 0.26,0.38, 0.31,0.54, 0.36,0.76, 0.42,1.25,...
0.47,2.11, 0.52,3.29, 0.58,4.58, 0.64,5.58, 0.68,5.82,...
0.75,6.00, 0.84,5.96, 0.91,5.83, 1.06,5.22, 1.16,4.34,...
1.27,3.34, 1.37,2.40, 1.47,1.62, 1.58,1.05, 1.68,0.66,...
1.78,0.40, 1.89,0.25, 1.99,0.15, 2.09,0.09, 2.20,0.05, 10.0,0.0
PARAMETER DATEB =224.0
PARAMETER WLVI  =25.0,  WSTI  =50.0, WSOI  =0.0
PARAMETER DSI   =0.22

END
STOP

      SUBROUTINE SUNBAL(GLV,GST,GRT,GSO,WLVT,WSTT,NUCR,TIME,DELT,
     $ SNLVT,SNSTT,NRMLVT,NRMSTT)
      IMPLICIT REAL(A-Z)
      IF (TIME .EQ. 0.0) THEN
       NRGLV=0.2*0.151
       NRGST=0.08*0.151
       NRGRT=0.08*0.151
       NRGSO=0.08*0.151
       WLVD=0.0
       NLVT=WLVT*0.03
       WSTD=0.0
       NSTT=WSTT*0.012
      ELSE
       WLVD=WLVD+(LVD+LVDC)*DELT
       NLVT=NLVT+(NAGLV-NRMLV-NRMLVC)*DELT
       WSTD=WSTD+(STD+STDC)*DELT
       NSTT=NSTT+(NAGST-NRMST-NRMSTC)*DELT
      ENDIF
```

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Table 4. (. . . con't.)

```
      PWLV=WLVT-WLVD
      FNPLV=(NLVT-WLVD*0.01)/(PWLV+1.0E-7)
      FNLV=NLVT/WLVT
      PWST=WSTT-WSTD
      FNPST=(NSTT-WSTD*0.004)/(PWST+1.0E-7)
      FNST=NSTT/WSTT
      SNLVC=AMIN1(PWLV,(370.0*1.0/100.0))
      NRMLVC=(FNPLV-0.01)*SNLVC
      LVDC=SNLVC-NRMLVC
      SNSTC=AMIN1(PWST,(1000.0*1.0/400.0))
      NRMSTC=(FNPST-0.004)*SNSTC
      STDC=SNSTC-NRMSTC
      NGLV=NRGLV*GLV
      NGST=NRGST*GST
      NGRT=NRGRT*GRT
      NGSO=NRGSO*GSO
      NGCR=NGLV+NGST+NGRT+NGSO
      NDIF=(NUCR+NRMLVC+NRMSTC)-NGCR
      IF (NDIF .LT. 0.0) THEN
       MXLVRM=(FNPLV-0.01)*(PWLV-SNLVC)
       MXSTRM=(FNPST-0.004)*(PWST-SNSTC)
       NRMLV=AMIN1(MXLVRM,(-NDIF*(MXLVRM/(MXLVRM+MXSTRM+1.E-7))))
       SNLV=(PWLV-SNLVC)*NRMLV/(MXLVRM+1.0E-7)
       LVD=SNLV-NRMLV
       NRMST=AMIN1(MXSTRM,(-NDIF*(MXSTRM/(MXLVRM+MXSTRM+1.E-7))))
       SNST=(PWST-SNSTC)*NRMST/(MXSTRM+1.0E-7)
       STD=SNST-NRMST
       NAG=NGCR
      ELSE
       NRMLV=0.0
       SNLV=0.0
       LVD=0.0
       NRMST=0.0
       SNST=0.0
       STD=0.0
       NAG=(NUCR+NRMLVC+NRMSTC)
      ENDIF
      NAGLV=NAG*(NGLV/NGCR)
      NAGST=NAG*(NGST/NGCR)
      NAGRT=NAG*(NGRT/NGCR)
      NAGSO=NAG*(NGSO/NGCR)
      NRMLVT=NRMLV+NRMLVC
      NRMSTT=NRMST+NRMSTC
      SNLVT=SNLV+SNLVC
      SNSTT=SNST+SNSTC
      RETURN
      END
ENDJOB
```

Table 5. Description and units of the variables used in the nitrogen sub-model.

Abbreviation	Description	Units
ALVI	initial area of leaves	ha ha^{-1}
CELV	carbohydrate export from leaves and stems	kg ha^{-1} d^{-1}
CELVN	days that CELV is negative	d
DATEB	date on which simulation starts	julian date
DELT	time interval for Euler integration	d
DS	developmental stage of the crop	-
DSI	initial developmental stage of crop	-
FNLV	average fraction of N in leaves	kg kg^{-1}
FNPLV	fraction of N in photosynthetically active leaves	kg kg^{-1}
FNPST	fraction of N in photosynthetically active stems	kg kg^{-1}
FNST	average fraction of N in stems	kg kg^{-1}
GLV	growth rate of leaves	kg ha^{-1} d^{-1}
GRT	growth rate of roots	kg ha^{-1}d^{-1}
GSO	growth rate of storage organs	kg ha^{-1}d^{-1}
GST	growth rate of stems	kg ha^{-1} d^{-1}
LVD	rate of accelerated leaf death	kg ha^{-1}d^{-1}
LVDC	rate of simultaneous leaf death, constant	kg ha^{-1}d^{-1}
MXLVRM	maximum N from accelerated leaf senescence	kg ha^{-1}
MXSTRM	maximum N from accelerated stem senescence	kg ha^{-1}
NAG	actual nitrogen available for growth of crop	kg ha^{-1}d^{-1}
NAGLV	actual nitrogen available for growth of leaves	kg ha^{-1}d^{-1}
NAGRT	actual nitrogen available for growth of root	kg ha^{-1}d^{-1}
NAGSO	actual nitrogen available for growth of storage organs	kg ha^{-1}d^{-1}
NAGST	actual nitrogen available for growth of stems	kg ha^{-1}d^{-1}
NDIF	difference between nitrogen requirement and available nitrogen	kg ha^{-1}d^{-1}
NGCR	nitrogen requirement for current growth of crop	kg ha^{-1}d^{-1}
NGLV	nitrogen requirement for current growth of leaves	kg ha^{-1}d^{-1}
NGRT	nitrogen requirement for current growth of roots	kg ha^{-1}d^{-1}
NGSO	nitrogen requirement for current growth of storage organ	kg ha^{-1}d^{-1}
NGST	nitrogen requirement for current growth of stems	kg ha^{-1}d^{-1}
NLVT	total nitrogen in leaves	kg ha^{-1}
NRGLV	coefficient of nitrogen requirement for growth of leaves	kg kg^{-1}
NRGRT	coefficient of nitrogen requirement for growth of roots	kg kg^{-1}
NRGSO	coefficient of nitrogen requirement for growth of storage organs	kg kg^{-1}
NRGST	coefficient of nitrogen requirement for growth of stems	kg kg^{-1}
NRMLV	nitrogen remobilized from leaves, accelerated senescence	kg ha^{-1}d^{-1}
NRMLVC	mitrogen remobilized from leaves, simultaneous senescence	kg ha^{-1}d^{-1}
NRMLVT	total nitrogen remobilized from leaves	kg ha^{-1}d^{-1}
NRMST	nitrogen remobilized from stems, accelerated senescence	kg ha^{-1}d^{-1}
NRMSTC	nitrogen remobilized from stems, simultaneous senescence	kg ha^{-1}d^{-1}
NRMSTT	total nitrogen remobilized from stems	kg ha^{-1}d^{-1}
NSTT	total nitrogen in stems	kg ha^{-1}
NUCR	rate of nitrogen uptake by the crop	kg ha^{-1}d^{-1}
NUCRMX	maximum rate of nitrogen uptake by the crop	kg ha^{-1}d^{-1}
NUF	nitrogen uptake fraction, modifier	-
PALV	photosynthetically active area	ha ha^{-1}
PGLA	net growth rate of photosynthetically active leaves	kg ha^{-1} d^{-1}
PGSA	net growth rate of photosynthetically active stems	kg ha^{-1} d^{-1}
PWLV	weight of photosynthetically active leaves	kg ha^{-1}

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Table 5. (. . . con't.)

PWST	weight of photosynthetically active stems	kg ha^{-1}
SNLV	rate of accelerated senescence of leaf	kg ha^{-1}d^{-1}
SNLVC	rate of simultaneous leaf senescence, constant	kg ha^{-1}d^{-1}
SNLVT	total rate of leaf senescence	kg ha^{-1}d^{-1}
SNST	rate of accelerated senescence of stem	kg ha^{-1}d^{-1}
SNSTC	rate of simultaneous stem senescence, constant	kg ha^{-1}d^{-1}
SNSTT	total rate of stem senescence	kg ha^{-1}d^{-1}
STD	rate of accelerated stem death	kg ha^{-1}d^{-1}
STDC	rate of simultaneous stem death, constant	kg ha^{-1}d^{-1}
SUNBAL	subroutine name of nitrogen balance	-
TIME	time of simulation	d
WLVD	weight of dead leaves	kg ha^{-1}
WLVI	initial weight of leaves	kg ha^{-1}d^{-1}
WLVT	weight of leaves since begining of simulation	kg ha^{-1}
WSOI	initial weight of storage organ	kg ha^{-1}d^{-1}
WSTD	weight of dead stems	kg ha^{-1}
WSTI	initial weight of stems	kg ha^{-1}d^{-1}
WSTT	weight of stem since beginning of simulation	kg ha^{-1}

vertical decline of N content, and the difference in total gross CO_2 assimilation between the two was not substantial. To keep the module simple, therefore, it is assumed that there is an equal distribution of nitrogen throughout the canopy.

Simulation

The listing of the N dynamics submodel and the associated parameters is given in Table 4. The rate of N uptake by the crop was derived from the observed values presented in Table 3, and used in the model as a driving variable. To simulate the effect of N uptake on crop growth and yield, a reducing parameter was used to reduce the rate of N uptake to various fractions of that derived from Table 3. A constant radiation level of 20 MJ m^{-2} d^{-1}, a maximum daily temperature of 30°C, and a minimum daily temperature of 25°C was used in the simulation for simplicity. Other crop parameters used were those from Penning de Vries et al. (1989), Pannangpetch (1991b) and Pannangpetch et al., (1991). The simulation started on August 12th, 1991, and terminated only when crop maintenance respiration exceeded crop gross photosynthesis for three consecutive days. The effect of N on yield of the variety RD6 was then simulated (Figure 4). When the total seasonal N uptake by the crop was less than 50 kg N ha^{-1}, canopy photosynthesis was not able to provide sufficient energy for maintenance respiration and resulted in premature cessation of growth. Grain yield attained at 105 days after transplanting increased with increases in N uptake until the uptake level reached 150 kg N ha^{-1} after which the effect of increasing N was less noticeable. However at the termination of the simulation, there was a strong linear relation between N uptake and rice yield. Differences between yields at 105 days and those at the termination were due mainly to prolonged leaf duration. With a total N

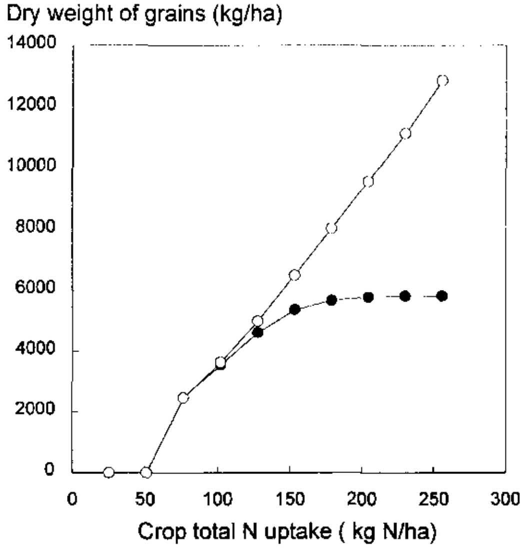

Figure 4. Simulated effects of N uptake on dry weight of grains and panicles at 105 days after transplanting (filled circles) and at the termination of simulation run when respiration exceeded photosynthesis for three consecutive days (open circles).

uptake of 250 kg N ha^{-1}, growth was extended to almost 300 days, although 80% of the final yield was obtained after 150 days. Detailed analysis showed that the extension of growth in this case was due to a high N accumulation (0.20 kg kg^{-1}) within the plant tissues when excess N was taken up. A high accumulation of N prolonged the onset of N removal from the flag leaf and resulted in an extended grain filling duration. However, in reality it seems unlikely that the leaves of rice could keep functioning for so long even with high levels of N. Such levels of N content have not been reported in the literature, the maximum value reported being 0.06 kg kg^{-1} (Penning de Vries et al., 1990). It is likely that N accumulation in the shoot is regulated via feed-back control on the rate of N uptake by the roots. To include such a mechanism in the model, however, it would be necessary to quantify the rate of N uptake as a function of tissue N content.

Acknowledgments

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Transplanting shock in rice

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Abstract

The effect of transplanting on the growth and development of rice (*Oryza sativa* L.) was studied by comparing transplanted and direct-seeded plants in two experiments. In the first experiment, the effect of various methods of transplanting and direct seeding were compared using the variety IR72, while in the second experiment the effect of transplanting in the cultivars IR72, IR64616H, and IR58109-113-3-3-2, was studied using 12-day-old dapog seedlings.

In the first experiment, transplanted seedlings were from dapog, nursery tray, and the traditional wetbed. In the first two methods, seedlings were transplanted at 12 days after sowing, and in the wetbed method, at 21 (WB21) and 30 days after sowing (WB30). The dapog, tray, and direct-seeded treatments had comparable tillering, leaf growth and dry matter yields and were superior to the wet-bed methods until the time of panicle initiation (PI). Tiller loss occurred for the first eight days after transplanting (DAT) in the wet bed treatments at the rate of 45 and 125 tillers m^{-2} for WB21 and WB30 respectively. At flowering, the number of tillers declined to similar levels in all treatments. The total dry matter yields were lowest in both wet-bed treatments. With the exception of the WB30 treatment, the mean N uptake of the direct-seeded crops was about 30 kg N ha^{-1} lower than those of the transplanted crops. There was a delay of six days to flowering and three days to maturity in the dapog and tray seedlings. Flowering and maturity were delayed by seven to nine days in the WB21 treatment and 11 days in the WB30 treatment.

In the second experiment, all three cultivars exhibited similar growth patterns. Early in the season, the transplanted crops had 200-320 tillers m^{-2} less than the direct-seeded crops and LAI development was delayed by 61-67 °Cd with 0N and 86-96 °Cd with 40 kg N ha^{-1}. After about 30 days from sowing, the transplanted seedlings recovered and exceeded the direct-seeded plants in LAI and the number of tillers and leaves.

Introduction

The traditional method of establishment of lowland rice by transplanting seedlings from a seedbed into the field provides significant advantages in terms of weed control and stand uniformity, but imposes considerable shock on the seedlings while they adjust to their new environment. Before the introduction of very early-maturing rice cultivars, the age of the seedlings at transplanting was not critical and the 'dapog' method, in which large numbers of seedlings are pre-germinated on a wet surface, was used for convenience rather than for higher yield (Cinco-Castro, 1985). The dapog method saves 20-30 man-days ha^{-1} compared to the conventional wet bed method (Pande & Mittra, 1968), in which seedlings are raised in a 'nursery' in a corner of the field. However, a number of experiments have shown that the severity of the transplanting shock increases with seedling age (Brown, 1958; Macalinga & Obordo, 1970; Cinco-Castro, 1985). The lower yields sometimes observed in transplanted rice compared to direct seeded rice (e.g. Adair et al., 1942) may be due to transplanting stress. Few studies, however, have sought to quantify this effect; it is the aim of the present work, therefore, to quantify the effect of transplanting shock for a number of transplanting methods, and in a number of rice cultivars, to provide a basis for its description in the ORYZA1 rice growth simulation model.

Materials and methods

Experiment 1: The effect of seedling establishment method on transplanting shock
Four seedling establishment methods, dapog, wet-bed, nursery tray, and direct-seeded, were used. For the wet-bed and direct-seeded methods, two dates of transplanting were also included, giving a total of six treatments. For all treatments, seeds of IR72 were pre-germinated before sowing by soaking in water for 24 h followed by incubation in a jute sack for 48 h. Further information specific to each treatment is as follows:

1. *Dapog (DP):* Following the method used by Vergara et al. (1972), a polyethylene sheet was laid on a slightly elevated seedbed in a paddy field and rice seeds spread on it at a density of 1 kg m^{-2}. The seeds were pressed lightly with a wooden board every morning and afternoon for five days to keep the roots in contact with the polyethylene sheet. The seed bed was periodically sprinkled with water to keep it from drying out. Seedlings were transplanted at 12 days after sowing (DAS).
2. *Wet Bed (WB21):* The seed bed was prepared in a paddy field by elevating the soil to about 5 cm above the natural soil level. Seeds were sown at a density of 100 g m^{-2}. The beds were splash-irrigated and after seedling emergence, surface water was maintained. The seedlings were removed at 20 DAS and transplanted the following day.
3. *Wet Bed (WB30):* A similar procedure to WB21 was followed, except that the seedlings were transplanted at 30 DAS.
4. *Nursery tray (NT):* Plastic nursery trays with cavities of 1.8 × 1.8 × 3.0 cm were used. Each cavity was partially filled with paddy soil, sown with five rice seeds, and a thin layer of soil added to cover the seeds. The trays were kept in a greenhouse and watered frequently to avoid moisture stress. Seedlings were removed with the soil surrounding the root system intact at 12 DAS for transplanting.
5. *Direct seeding (DS12):* Seeds were sown directly in the field at five seeds per hill to achieve a similar initial plant density to the other treatments. Sowing date was synchronized with that of the dapog and tray methods.
6. *Direct seeding (DS21).* Seeds were sown in a similar way to DS12 except that the sowing date was synchronized with that of treatment WB21.

The treatments were laid out in a randomized complete block design with four replications. The spacing between hills for all treatments was 20 × 20 cm. A basal dressing of superphosphate was applied at the rate of 16 kg P ha^{-1} together with urea at the rate of 30 kg N ha^{-1}. Further urea was topdressed at the rate of 30 kg N ha^{-1} at 25 days after transplanting (DAT), again at the stage of panicle initiation (PI), and a final application of

20 kg N ha^{-1} at the time of flowering. Plants were given maximum protection against pest and diseases.

Before transplanting, 50 plants were periodically taken at random from each treatment for growth measurements. After transplanting, periodic sampling of three hills for tiller count, six hills for leaf area measurement, and 12 hills for total dry matter measurement was made. The sampled plants were partitioned into leaf, stem and panicles before drying. At final harvest, samples were taken from a 3.2 × 2.8 m area in the centre of the plot for grain and dry matter yield estimation.

Experiment 2: Varietal response to transplanting shock

The effect of transplanting shock in cultivars IR72, IR58109-113-3-3-2 and IR64616H was studied in direct-seeded and nursery tray seedlings sown simultaneously and transplanted at 12 DAS. Experimental management was similar to that of Experiment 1. Starting at 4 DAT, tiller and leaf counts and LAI measurements were made at four-day intervals throughout the vegetative stage.

Results and discussion

Experiment 1

Tillering: Tillering was similar among the treatments, with the exception of both wet bed treatments which had consistently less tillers from about 30 DAT until the PI stage (Figure 1a). High tiller loss was a major reason for the low tiller counts of the wet bed seedlings. In both wet-bed treatments, tiller loss occurred until 8 DAT; about 45 and 125 tillers m^{-2} were lost in WB21 and WB30 respectively. At PI, the mean tiller density was about 810 tillers m^{-2} for the wet bed treatments and about 1000 tillers m^{-2} for the others. These results contrast with those of Calvo (1972), where there were less tillers in broadcast direct-seeded rice than in transplanted rice. After flowering, differences between

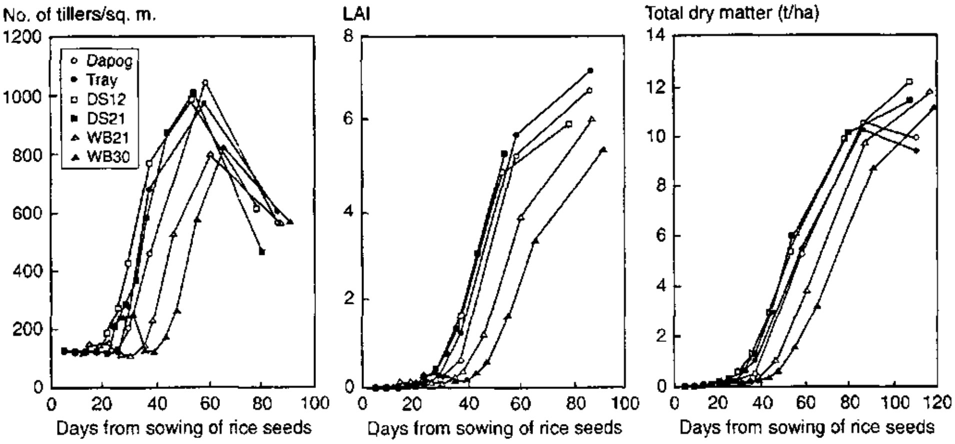

Figure 1. Effect of seedling establishment method on tiller numbers, leaf area index, and total dry matter.

Table 1. Dry weights of plant components of IR72 at flowering using different seedling establishment methods.

Establishment method	Stem wt (t ha^{-1})	Leaf wt (t ha^{-1})	Panicle wt (t ha^{-1})	Dead leaf wt (t ha^{-1})	Total wt wt (t ha^{-1})
Dapog	4.93	2.92	1.80	0.85	10.50
DS12	4.78	2.73	1.42	0.92	9.85
DS21	5.24	2.41	1.68	0.77	10.11
Tray	4.85	2.93	1.57	0.90	10.24
WB21	4.42	2.80	1.77	0.72	9.70
WB30	4.10	2.49	1.57	0.52	8.67
se	0.35	ns	ns	ns	0.59

ns = Not significantly different at the 5% level.

treatments disappeared, with the tiller number declining in all treatments to about 600 tillers m^{-2}.

Leaf area index (LAI): LAI was comparable between treatments until the PI stage, again with the exception of the wet-bed treatments (Figure 1b). The mean LAI of the wet-bed treatments was 3.6 compared to 5.3 for the other four treatments, the lower LAI values in the former probably being due to their higher tiller loss. Seedling age contributed to low LAI. The LAI in all treatments increased until flowering despite the decline in the number of tillers.

Dry matter production: Dry matter accumulation was not significantly different for plants grown from the nursery tray, the dapog seedlings, and the direct-seeded plants, but as with tiller number and LAI, was lower in the wet-bed plants (Figure 1c). However, part of the reduction was compensated for by a longer growth duration. The reduction was more marked when the seedlings were transplanted later (WB30). At flowering, the total dry matter weights were 8.67 t ha^{-1} in WB30 and 9.71 t ha^{-1} in WB21 compared to the 10.17 t ha^{-1} mean of the other four treatments (Table 1). After harvesting the WB30 and DS21 treatments, a typhoon occurred, causing the remaining crops, which were at the hard dough stage, to lodge. The dapog and tray treatments, being the last to mature, were particularly affected.

Nitrogen uptake: Early in the season, the direct-seeded crops had the highest rate of N uptake, but by flowering their N levels in the stem, leaves and panicles had become lower than in the transplanted crops. Over the whole season, the N uptake was lower in the direct-seeded crops by about 30 kg N ha^{-1} than in the transplanted crops, with the exception of the WB30 treatment (Figure 2). Adair et al. (1942) have suggested that transplanting stimulates root growth compared to direct-seeded rice, which may explain the observed differences in N uptake in the present work.

Harvest data: Accurate comparisons of the grain yields of the treatments could not be done due to the effect of the typhoon. The grain yield of DS21 was higher than that of the WB30 by 427 kg ha^{-1} (Table 2). The DS12 and WB21, both harvested at the same date, were near the physiological maturity stage when they lodged. The harvest indices of the treatments that lodged were much lower than those of the two treatments that were able to

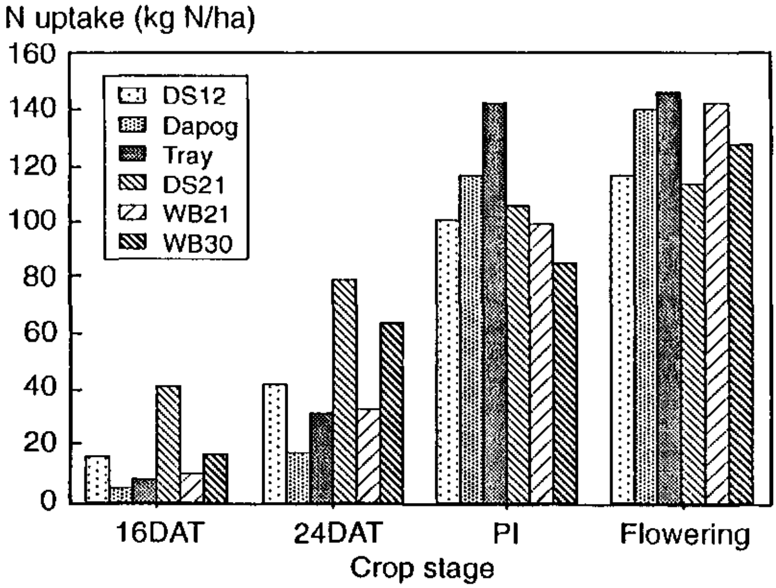

Figure 2. Nitrogen uptake of direct-seeded and transplanted rice at different growth stages.

escape the typhoon. Although dead leaves that decayed after lodging were not included in the total dry matter yield determinations, straw yields were still higher in some treatments that lodged. This may have been because stem carbohydrates had at that stage not been translocated to the seeds, an explanation that is supported by the low seed weights in the lodged treatments.

Phenology: Crop development was consistently more advanced in the direct-seeded treatments than in the transplanted (Table 3). The shock of transplanting delayed flowering by six days and maturity by three days when either dapog or tray method was used. Flowering and maturity were delayed by seven to nine days with WB21 and eleven days

Table 2. Grain yield, straw yield, harvest index, and seed weight of IR72 using different seedling establishment methods.

Establishment method	Grain weight (t ha^{-1})	Straw weight (t ha^{-1})	Harvest index (%)	Seed weight (mg grain^{-1})
Dapog	3.23	6.67	32.9	21.55
DS12	4.50	7.68	37.2	22.62
DS21	4.89	6.51	43.1	23.37
Tray	3.02	6.32	32.6	21.85
WB21	3.81	7.94	32.6	22.35
WB30	4.46	6.69	40.1	22.27
se	0.24	ns	2.6	0.32

ns = Not significantly different at the 5% level.

Table 3. Crop age at different growth stages of IR72 using different seedling establishment methods.

Establishment method	PI	Flowering	Maturity	Field Days (days)
	----------------	(days after sowing)	----------------	
Dapog	58	86	110	97
DS12	53	78	107	107
DS21	54	80	107	107
Tray	58	86	110	97
WB21	60	87	116	94
WB30	65	91	118	97

Maximum mean deviation is 1 day in all the variables.

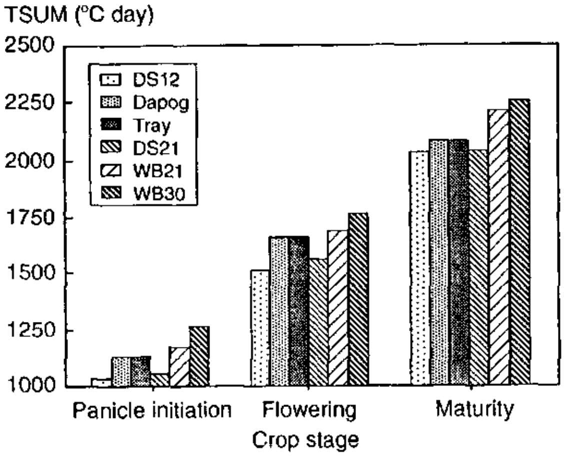

Figure 3. Temperature sum as a measure of delay in crop development attributed to the transplanting shock.

with WB30. The delay in development is indicated by the higher thermal time for the transplanted crops to attain a certain growth stage (Figure 3). Although all transplanted crops exhibited transplanting shock effects, these were more severe in the wet-bed method and with older seedlings.

Experiment 2

There was little difference in growth between the three cultivars and between the two nitrogen treatments. However, there were differences between the direct-seeded and transplanted treatments; at 20 DAS, when the cumulative thermal time since sowing (TSUM) was about 400 °Cd, tiller numbers were between 200-320 tillers m^{-2} higher in the direct-seeded treatments. Leaf numbers followed a similar trend. No significant tiller death could be attributed to transplanting shock, suggesting that low LAI increase rates in the early growth stage of transplanted seedlings was not due to loss of tillers but rather to the

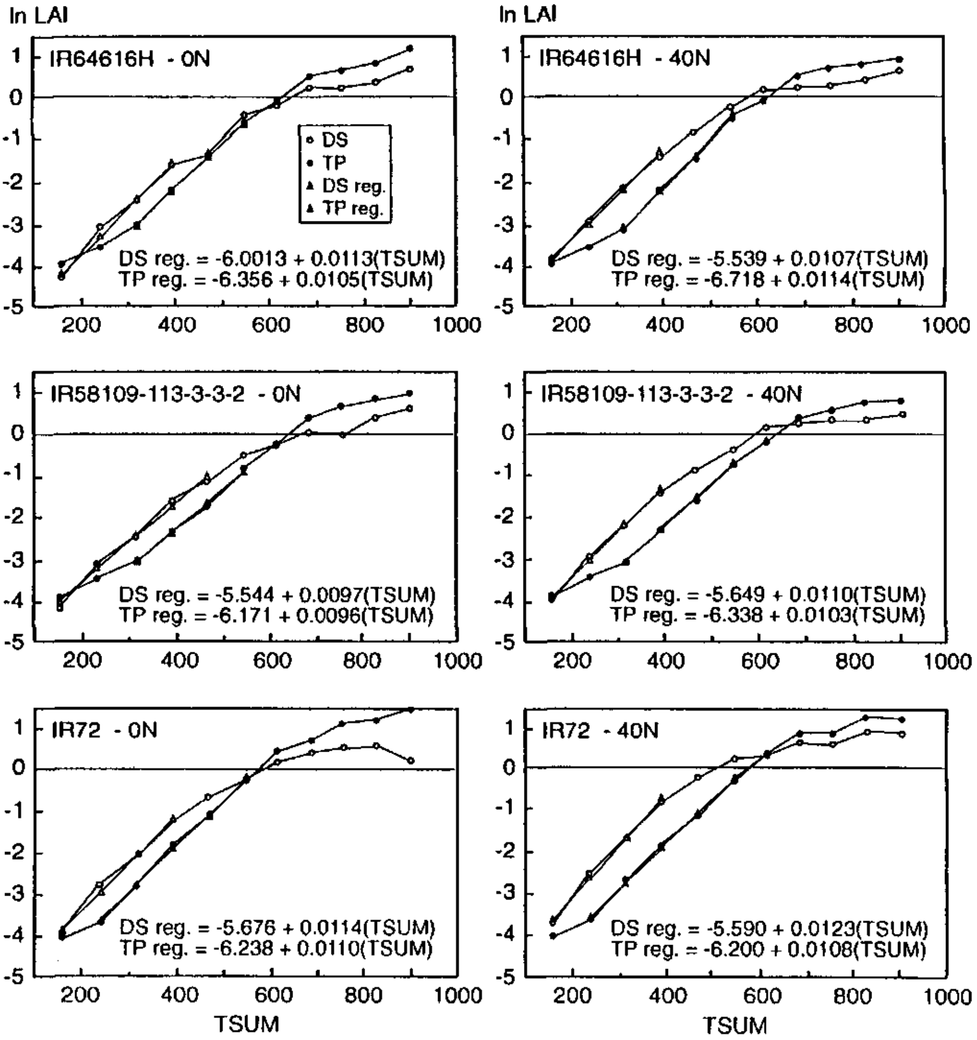

Figure 4. Transplanting shock effect on LAI of three rice cultivars.

initial rates of tiller production. The initial LAI development rate (Figure 4) was delayed by 61-67 °Cd in the 0N treatment and 86-96 °Cd with 40 kg N ha^{-1}. The higher growth rates of the direct-seeded crops occurred only during the first month of the crop. After this period, the transplanted seedlings recovered and surpassed the direct-seeded plants in tillering, leaf production and LAI. The differences in N uptake pattern between transplanted and direct-seeded treatments was similar to that observed in Experiment 1. Interplant competition in the seedbed had already caused some stress by the time of transplanting, resulting in a reduced growth rate per plant compared to the direct-seeded plants early in the season.

Conclusions

1. Shock due to transplanting depressed the growth and delayed the development of transplanted seedlings to a quantifiable degree.
2. Wet bed seedlings, particularly older ones, suffered more growth depression and delay in phenology than seedlings from other methods of transplanting.
3. The shock of transplanting could be minimized by using tray or dapog seedlings.
4. Over the whole season, direct-seeded crops generally had less N uptake than transplanted crops.
5. Seedlings transplanted from seedling trays at 12 days after sowing had the ability to recover from transplanting and even surpass the growth of direct-seeded plants.
6. The results suggest that transplanting shock effects should be included in rice crop simulation models.

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Development of a model subroutine to describe tiller development in Korean rice

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Abstract

The number of panicles per unit area is an important yield component in rice, and depends on the number of tillers that are formed. Temperature is an important environmental variable influencing tiller formation. A controlled environment experiment was conducted to investigate the effect of temperature on various characteristics of tiller formation. The relative tiller growth rate (RTGR) depended on temperature and development stage, but the pattern of RTGR was similar for each temperature treatment. Based on these results, a tiller formation subroutine was developed and incorporated into ORYZA1, a simulation model describing potential production of irrigated lowland rice. Simulated tiller number agreed closely with observed values.

Introduction

Yields of rice are closely correlated with the number of spikelets per unit area (Matsushima, 1976), which in turn depends on the number of panicles per unit area. Increasing the number of panicles per unit area by higher planting density, however, does not always result in higher yields, as often the number of spikelets per panicle is decreased (Yoshida & Parao, 1972). Simulation modelling techniques can be used to explore the interrelations of these yield components, so that the optimum panicle density can be determined in order to maximize yields.

In rice, tillers develop from the node of the main culm, and are synchronous with leaf development (Yoshida, 1981). Factors such as spacing, light level, temperature, the amount of nitrogen applied and carbohydrate status in the plant are all known to affect the tillering pattern. The ability to understand and quantify the effects of these factors is essential in developing good management practices for rice cultivation in different climatic conditions. Due to low temperatures, early tiller development in Korean conditions is slow, with the result that final tiller numbers may be below the optimum for maximum yield. Temperature is therefore the most important environmental variable in determining tiller development at the potential production level in Korea.

This study investigates the effect of temperature on various characteristics of tiller formation, to provide a basis for developing a subroutine describing the growth of tillers for inclusion in the ORYZA1 potential production model (Kropff et al., 1993).

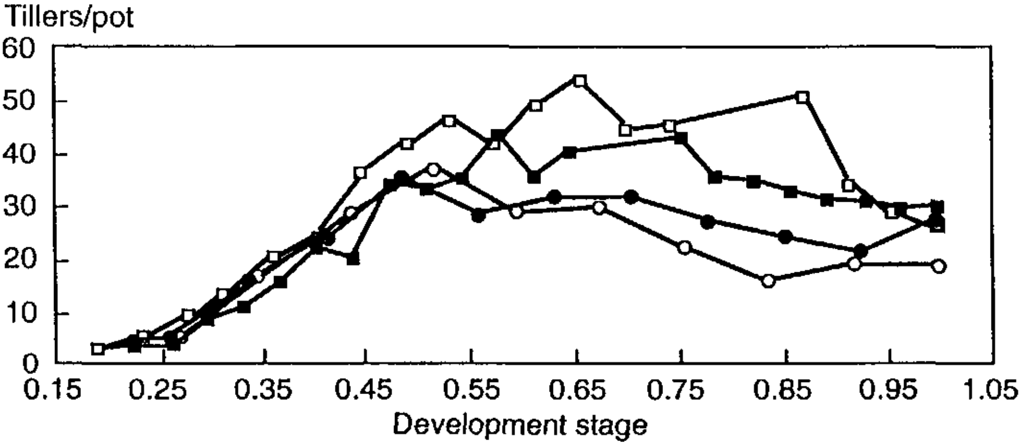

Figure 1. Effect of temperature on tiller number in the four treatments. Key: ■ 18/13 °C; □ 20/15 °C; ● 25/20 °C; O 30/25 °C.

Materials and methods

A phytotron experiment with four day/night temperature treatments of 30/25 °C, 25/20 °C, 20/15 °C and 18/13 °C was conducted in the summer season of 1992. Seedlings of the Korean *japonica* rice variety 'Hwaseongbyeo' were transplanted at the four-leaf stage into plastic pots and grown under the four temperature regimes. Tiller numbers and dry weights were recorded at one-week intervals from transplanting to heading.

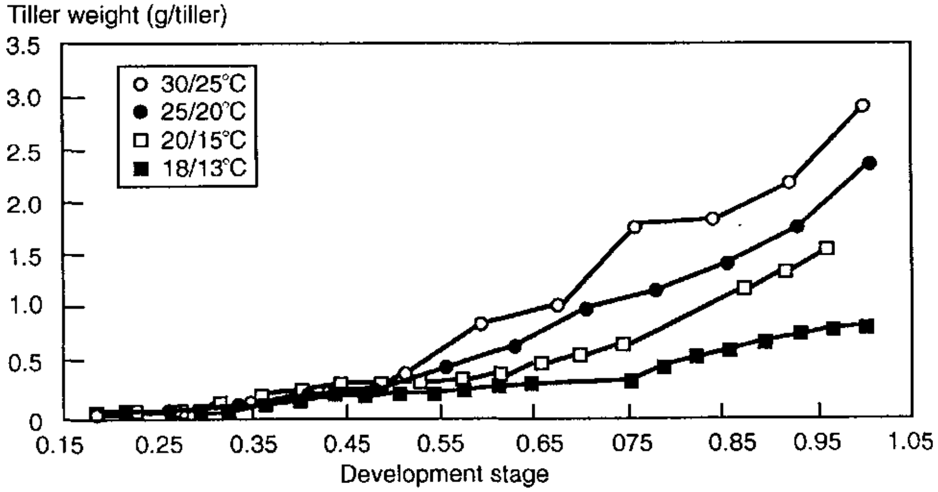

Figure 2. Effect of temperature on tiller weight in the four treatments.

Results

Figure 1 shows the change in tiller numbers for the four temperature treatments. The maximum tiller number reached was higher in the low temperature than in high temperature treatments. In contrast with the tiller number, tiller weight was greater under the higher temperatures than in the lower temperature treatments (Figure 2). Differences were particularly apparent after the development stage reached 0.4. The relative tiller growth rate (RTGR) was calculated as

$$\mathrm{RTGR} = \Delta W_t / W_t \tag{1}$$

where ΔW_t is change in tiller weight between one sample date and the next, and W_t is the mean tiller weight between the sample dates. Values for RTGR in each of the four temperature treatments are shown in Table 1. Higher temperatures increased the RTGR compared to the low temperature treatments.

Figure 3 shows the changes in the RTGR under different temperature treatments and the relationship between RTGR and development stage. The RTGR increased gradually in the early growth stages until DVS 0.35, thereafter decreasing. Values of RTGR for each developmental stage for the 30/25 °C treatment are shown in Table 2.

Table 1. Relative tiller growth rate (RTGR) as affected by different temperatures.

	Temperature			
	30/25 °C	25/20 °C	20/15 °C	18/13 °C
Mean RTGR(g g^{-1})	0.067	0.058	0.032	0.022
Relative value	1.00	0.87	0.48	0.33

Table 2. The relationship between relative tiller growth rate (RTGR) and development stage (DVS) shown in Figure 3 for the 30/25 °C temperature treatment.

	DVS						
	0.15	0.20	0.30	0.35	0.40	0.70	1.00
RTGR	0.046	0.065	0.103	0.112	0.104	0.060	0.016

Model development

Growth of the rice plant comes from carbohydrates produced by photosynthesis which are distributed to the various organs (Figure 4). Some of the carbohydrates produced are lost by respiration connected with the growth and maintenance of the plant, but the remainder is partitioned between the root and shoot for the production of new plant material. Total

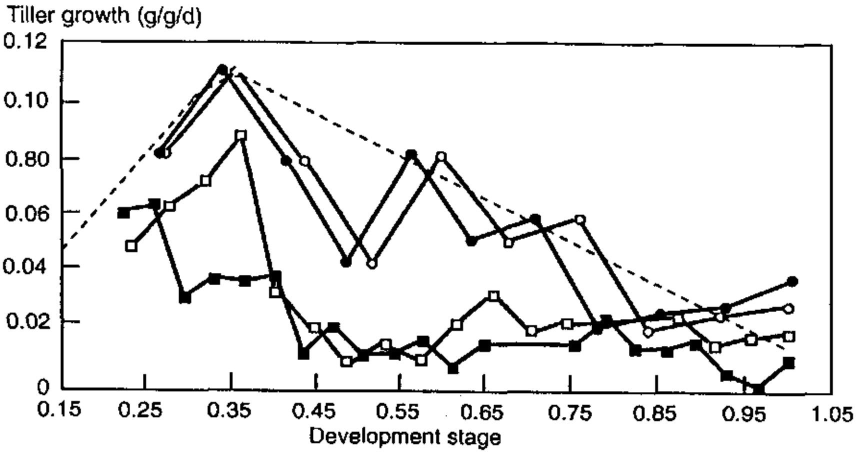

Figure 3. Effect of temperature on relative tiller growth rate in the four treatments. Key: ■ 18/13 °C; □ 20/15 °C; ● 25/20 °C; O 30/25 °C.

shoot growth is composed of the growth of the main culm, and that of any tillers that are produced. However, the priority of main culm and tillers in receiving this carbohydrate is different. It is assumed in the model that a new tiller is developed only if there are carbohydrates in excess of that required for growth of the main culm and existing tillers.

A listing of the tiller subroutine is shown in Table 3, and a description of the variables used in Table 4. The program is written in CSMP (Continuous Simulation Modelling Program) language, and is incorporated into the ORYZA1 rice potential production model. Daily dry matter production and that partitioned to the shoot (GCR•FSH) is calculated in ORYZA1. The amount of dry matter required for the growth of existing tillers (ANTF) is calculated by multiplying the amount of shoot mass (WAG) and the relative tiller growth rate (MRGRT) derived from the relationship between development stage and the RTGR (Table 2) and that between temperature and RTGR (Table 1). The difference between the daily dry matter production and that required for existing tiller growth is the amount of dry

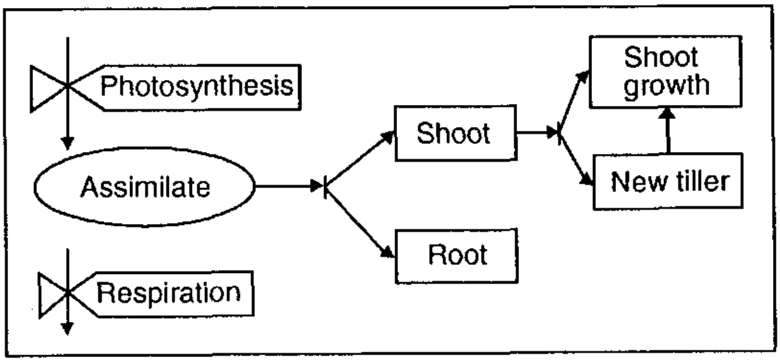

Figure 4. Diagram of dry matter flow for the formation of new tillers.

Table 3. Program listing of tiller formation subroutine

```
PARAM WPTILI=0.0001
    WPTIL=WAG/(NTILL+0.0001)
    MRGRT = AFGEN(RGRTB,DVS)*AFGEN(FRGRTB,TAV)
    NTILL = INTGRL(NTILI,NTILF)
    NTPH =NTILL/(NH*10000.)
    XNTPH=AFGEN(XNTTB,DOY)
PROCEDURE NTILF,ANTF,DCRF=PROTIL(MRGRT,GCR, FSH,TAV,DVS, WAG, NTILL)
 IF (WPTIL.LT.WPTILI) WPTIL=WPTILI
     ANTF = MRGRT*WAG
     DCRF=(GCR*FSH-ANTF)
  IF (DVS.LE.0.7) THEN
     IF (DCRF.GT.0.0) THEN
      IF (WPTIL.LT.WPTILI) WPTIL=WPTILI
      NTILF=DCRF/(WPTIL+0.0000001)
      IF (MRGRT.EQ.0.0) NTILF=0.0
      IF (WPTIL.EQ.0.) NTILF=0.
    ELSE
      NTILF=ANTF*0.05/(WPTIL+0.0000001)
      IF (MRGRT.EQ.0.0) NTILF=0.0
      IF (WAG.EQ.0.) NTILF=0.
    ENDIF
  ELSEIF (DVS.GT.0.7) THEN
    IF (DCRF.LT.0.0) THEN
    NTILF=DCRF/(WPTIL+0.0000001)
    IF (DVS.GT.1.0) NTILF=0.0
  ELSE
   NTILF=0.
  ENDIF
 ELSE
  NTILF=0.
 ENDIF
   IF (IDATE.LT.IDOYTR) NTILF=0.
ENDPRO

FUNCTION XNTTB   = 100.,3., 141.,3., 160.,3.8, 170.,16.3, 180.,25.3, 190.,27.7, 200.,24.6, 210.,19.7,
221.,19.2, 231.,19.1, 241.,16.6, 250.,16.6
FUNCTION RGRTB   = 0.0,0.0, 0.15,0.046, 0.35,0.112, 1.0,0.016, 2.1,0.0
FUNCTION FRGRTB  = 0.0,0.0, 8.0,0.0, 15.5,0.338, 17.5,0.48, 22.5,0.871, 27.5,1.0, 35.0,1.0, 45.0,0.0
```

matter available for new tiller formation (DCRF). The number of new tillers formed on a given day is calculated by dividing DCRF by the current mean tiller weight.

Model evaluation

The model, including the tiller subroutine described above, was run using 1989 weather data from Suweon and crop parameters derived for the variety 'Hwaseongbyeo' (CES,

Table 4. List of variables used in the tiller subroutine.

Variable name	Description	Units
WPTILI	single tiller weight at transplanting	kg tiller^{-1}
WPTIL	weight of a single tiller	kg tiller^{-1}
MRGRT	demand of dry matter for existing tiller growth	kg kg^{-1}
FRGRTB	table for the relation between RTGR and temperature (Table 1).	-
RGRTB	table for the relation between RTGR and development stage (Table 2).	-
NTILL	tiller density	ha^{-1}
NTILF	density of newly formed tillers	ha^{-1}
NTPH	number of tillers per hill	hill^{-1}
NH	hill planting density	hills m^{-2}
XNTPH	observed number tiller per hill	hill^{-1}
XNTTB	table of observed value of number of tillers per hill	hill^{-1}
ANTF	amount of dry matter needed for growth of existing tillers	kg ha^{-1}
DCRF	amount of dry matter available for the new tiller formation	kg ha^{-1}

1989). Figure 5 shows observed and simulated tiller numbers. The agreement is good, although there is a tendency for the model to underestimate numbers before the maximum tillering stage and overestimate after this stage. The time of maximum tillering is also later in the simulation. This may be a result of a difference in development stage between the simulated and observed data.

As a way of assessing the sensitivity of the tiller subroutine, ORYZA1 was also run using Suweon weather data for the 13 years from 1977 to 1989. Results indicate that tiller numbers are very sensitive to the variation in weather in the years tested (Figure 6).

Finally, to investigate the effect of temperature on tiller growth and development, the model was run using the 1989 Suweon weather data, but with the mean temperature altered by +3°C and -1.5°C respectively. The simulations indicated that higher

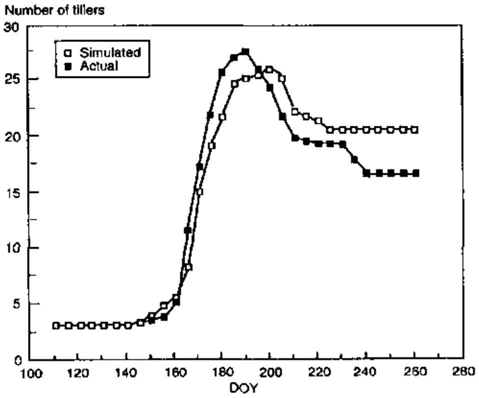

Figure 5. Comparison between simulated and observed tiller number with 1989 Suweon weather data.

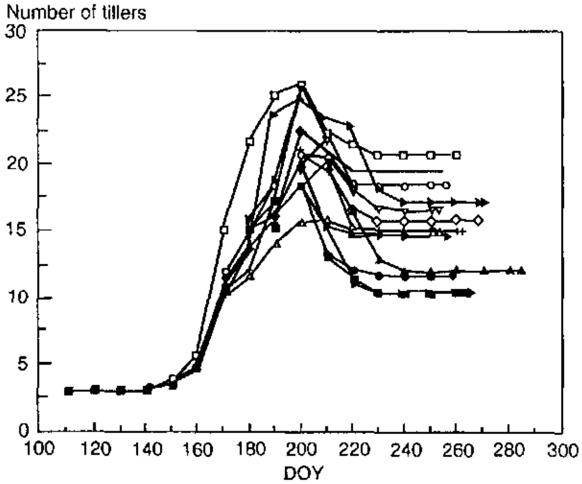

Figure 6. Sensitivity of simulated tiller numbers using 1977-1989 Suweon weather data.

temperatures resulted in markedly fewer tillers than in the normal conditions, although the maximum tillering stage was reached at the same time (Figure 7a). On the contrary, reduced temperatures did not alter simulated tiller numbers early in the season, but, because the maximum tiller stage was delayed for 20 days, the maximum tiller number was increased (Figure 7b).

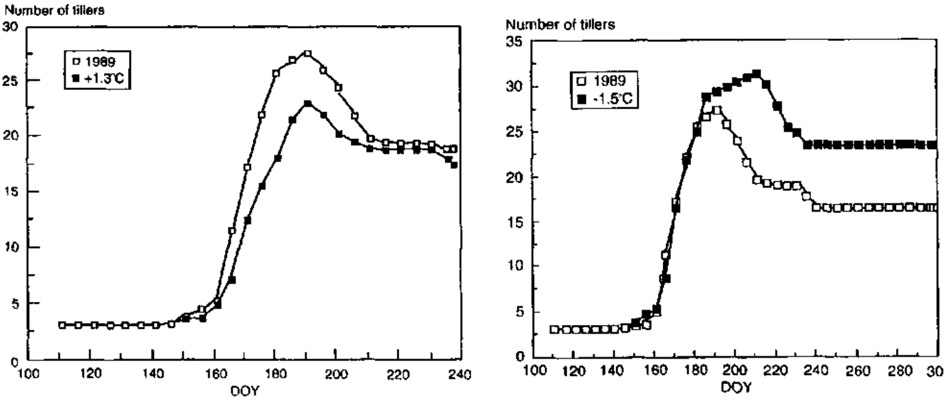

Figure 7. Effect of changes in temperature on tiller numbers. In each case 1992 Suweon weather data was used as a base, with (a) 3 °C added to maximum and minimum temperature, and (b) 1.5 °C subtracted from maximum and minimum temperature.

Thus it seems from these results that the tiller subroutine described is able to simulate tiller number reasonably accurately. This should provide a useful basis for further development of subroutines describing panicle formation and spikelet density, and for coupling to pest and disease models.

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Optimization of cropping patterns in tank irrigation systems, Tamil Nadu, India

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Abstract

In Tamil Nadu, India, tank irrigation systems account for over 30% of the total irrigated area in the region. However, tank water supplies are often below normal and optimization of the cropping patterns used is an important strategy to minimize risks in crop production. Linear programming models were used to indicate the optimal proportions of rice and non-rice crops in such systems. The results showed that by optimizing the crop pattern and water use, risk to income can be minimized. It was also shown that the entire command area could be irrigated even with deficit water supplies if non-rice crops were grown in the cropping system. Both government and voluntary organisations should therefore make efforts to introduce these crops into the cropping pattern of the tank irrigation systems.

Introduction

The tank irrigation systems of southern India are centuries old and today account for over 30% of the total irrigated area in the region. The tanks are mainly used to irrigate one rice crop in the *rabi* season between the months of September to December. However, several constraints limit the productivity of these tanks. Tank siltation, foreshore encroachment and poor maintenance of the structures are the major above-outlet problems; absence of water users' organizations, poor distribution systems and inadequate ground water supplies for supplementation are the major below-outlet problems (Palanisami & Flinn, 1989). In most years, farmers incur crop losses due to water scarcity, particularly at the end of the season. Since the tanks follow an uncertain filling pattern due to erratic and uncertain rains, farmers have no prior knowledge of the possible level of tank fillings and hence in most cases resort to late rice planting, thereby incurring crop losses (Table 1). However, experience has shown the feasibility of substituting rice with other crops such as maize, sorghum, groundnut, pulses, and cotton. Optimization of the cropping pattern of such systems is highly important. The present paper describes a study using compromise programming techniques to optimize the cropping pattern in tank irrigation systems.

Model Description

A flow chart of the tank irrigation system simulation model is shown in Figure 1. Inputs to the model are of three types. The first are weather-related factors such as rainfall, run-off,

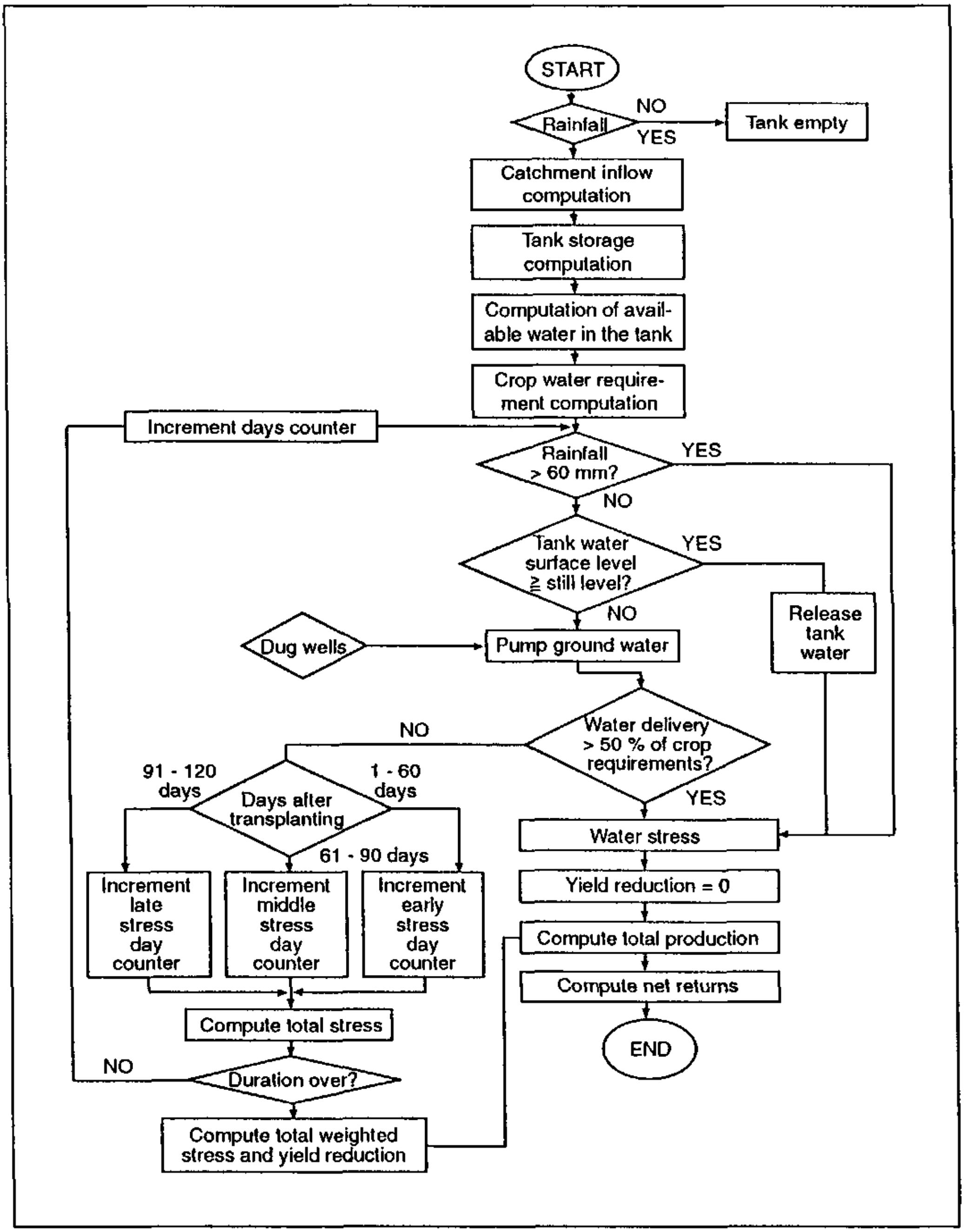

Figure 1. Flow chart of the tank simulation model.

Table 1. Frequency of failure of the rice crop in tank irrigation systems, Tamil Nadu, India.

Probability	Probability of tank storage	Number of farmers who planted rice (Total = 602)	Percent failure
Surplus	0.1	594	0
Full	0.2	578	19
Deficit	0.5	556	39
Failure	0.2	234	76

and evaporation. The second type are tank hydrology-related factors such as tank catchment area, seepage, sill level of the surplus weir, full tank capacity and the number of sluices. The third are farmer-related factors such as crop area, water deliveries to crops, well output, and the number of wells.

Water balance: The model, programmed in FORTRAN IV, operates in a daily basis. The daily tank water balance is computed by adding the inflow from rainfall in the catchment to the previous day's water balance, and subtracting tank outflows, seepage and percolation losses for that day. The elevation of the tank water surface is calculated to enable the estimation of possible outflows from each of the four tank sluices. The model can calculate both when the tank will be empty and when overflows will occur. Simultaneous use of tank and well water is permitted. Pumping may take place when the tank water level is below the sill level of the sluice, or when the sluices are closed as part of tank water management. The quantity of water pumped on any day is dependent on (a) the groundwater level which is a function of the tank storage level, and (b) the number of wells in the command area. This relationship is as follows:

$$GWAT_{sk} + f\,(TSTO_k) \bullet Nw_s \qquad \begin{aligned} s &= 1 \text{ to } 4 \text{ sluices} \\ k &= \text{daily increments} \end{aligned} \tag{1}$$

where $GWAT_{sk}$ = groundwater pumped in sth sluice on the kth day.
$TSTO_k$ = tank storage on kth day.
NW_s = number of wells in sth sluice.

Stress days and yield reductions: A drought-stress index, with units 'stress-days', was empirically estimated as the number of days in excess of three that the tank or ground water supply for the rice crop was less than half of its field water requirements, for each period of drought stress which occurs. The impact of stress at different periods of crop growth (i.e. vegetative, panicle development and grain filling) was empirically estimated from field level observations of rice yields and stress periods observed in farmers' fields. Farmers were requested to keep records of key information such as the dates of irrigation, fertilization and harvest details, which were collected by research staff at weekly intervals. Based on the survey data, the drought-stress index for non-rice crops was defined as the number of days in excess of six days that the tank or ground water supply for the crop was less than half of its field water requirements, for each period of stress which occurred. The equation for estimation of yields was:

$$Y_t = a_t + b_t \cdot SD_t \qquad t = 1...3 \qquad (2)$$

where Y_t = crop yield in t ha^{-1} given the stress days in period t
a_t = base yield given no stress days in period t
SD_t = number of stress days observed in period t, and
b_t = estimated yield reduction per day of stress in period t

To permit accumulation of stress days in the three phases of crop growth, coefficients for the yield reduction per day of stress in phase t (W_t) were calculated as

$$W_t = b_t / b_3 \qquad t = 1...3 \qquad (3)$$

where b_3 is the coefficient for yield reduction per day of stress in phase 3. This permitted the estimation of the weighted stress days (WSD_s) for sluice s, given observations of actual incidence of stress in different sluices and crop growth periods, as:

$$WSD_s = (SD_{st} \cdot W_t) \qquad s = 1...4, t = 1...3 \qquad (4)$$

These weighted stress days were then used in the final yield equation in the simultaneous equation system to calculate the actual yield.

$$Y_{sk} = c_k - d_k \cdot WSD_s \qquad s = 1...4, k = 1...3 \qquad (5)$$

where Y_{sk} = actual yield in sluice s, location k
c_k = crop yield without moisture stress, location k, as derived from the 'simultaneous equation system'
d_k = estimated coefficient of the yield reduction due to weighted stress days, location k, as derived in the 'simultaneous equation system'

Table 2. Net income (10^6 Rs) for the four cropping systems.

Year	Probability	Cropping combination*			
		X1	X2	X3	X4
Surplus	0.1	.848	.845	.783	.721
Full	0.2	.798	.798	.780	.748
Deficit	0.5	.615	.779	.781	.789
Failure	0.2	.096	.167	.187	.192
Exp. margin¶		.571	.667	.645	.654

* X1, X2, X3, and X4 refer to the crop combinations (rice:non-rice ratios) where X1 is 100:0, X2 75:25, X3 50:50, and X4 is 25:75.

¶ Exp. margin = net income × probability of the occurrence of different tank filling years.

The 'simultaneous equation system' is used to study the interrelationships between variables when the relationship between the dependent and independent variables could not be captured in a single equation model (Palanisami, 1993).

The total crop production of the group of farms ($TOTPRN_{sk}$) in location k, sluice s, is:

$$TOTPRN_{sk} = Y_{sk} \bullet ARE_{sk} \tag{6}$$

where ARE_{sk} is the total crop area (ha) in the group of farms in location k, sluice s.

Finally, the net return, in \$ ha^{-1}, to the group of farms in location k, sluice s, is:

$$NETRN_{sk} = (TOTPRN_{sk} \bullet PR) + VBP_{sk} - COSTHA_{sk} \tag{7}$$

where $NETRN_{sk}$ = net return per ha to the group of farms in location k, sluice s
PR = crop price, in \$ t^{-1}
VBP_{sk} = value of by-product, in location k, sluice s
$COSTHA_{sk}$ = cost of production per ha, in location k, sluice s.

Optimization - application of the COMPROMISE programming model

Earlier, the MOTAD (minimization of total absolute deviation) model was used to optimize the crop pattern in the tank-irrigated systems using crop gross margins (Table 2). The model indicated that risk-averse farmers always prefer to have a combination of crops instead of rice only. However, most of the farmers in the command area expressed interest to maximizing both their net income and their employment potential, as for much of the time they are underemployed. Since the two objectives of income and employment maximization cannot be achieved in the MOTAD model, the COMPROMISE programming technique was employed to optimize the two objectives simultaneously. Compromise programming techniques seek to simultaneously optimize a number of objectives subject to a given set of constraints, and therefore have considerable potential in handling more realistic and complete farming systems. Sankhayan (1988) used this model in Punjab agriculture.

The basic model is described as follows:

$$\text{Max } Z(X) = Z_1(X), Z_2(X) \tag{8}$$

$$g_i(X) \geq 0 \quad i = 1, 2, ..., m \tag{9}$$

$$X_j \geq 0 \quad j = 1, 2 \tag{10}$$

where $Z(X)$ is a two-dimensional objective function
X is a 'm' dimensional vector of decision variables
$g_i(X)$ are constraints associated with the problem

For each of the income and employment maximization objectives, optimal values should be arrived at using linear programming models. Then deviations were arrived for solving

Table 3. Input use per hectare in different cropping options.

Crop pattern	Water used (ha cm)	Labor used (days)	Capital (Rs)
X1	158	85	1900
X2	131	64	1721
X3	103	51	1453
X4	76	37	1123

1 US $ = Rs27; See Table 2 for description of X1, X2, X3, X4.

the compromise programming. The steps involved are:

1. *Deriving the income and employment deviations:* For establishing the ideal points, the optimal values of the income maximizing plan (LP 1) and the employment maximizing plan (LP II) were taken. The corresponding income of LP II and corresponding employment of LP 1 were taken as anti-ideal points. As the objective is to compromise between ideal and employment maximizing plans, the difference between ideal and anti-ideal values were taken to calculate the income and employment deviations.

2. *Deviations of weights:* Income and employment deviations were taken and using different weights, compromise plans were calculated.

3. *Compromise programming models (CPM):* CPM-1 refers to what would be the crop allocation when equal importance is given to income and employment; since income is comparatively important, weights were given for income deviation. In CPM-2 the income was multiplied by three and in CPM-3, the income was multiplied by five keeping the employment deviation as such.

Ideal and anti-ideal values:

Model	Income	Employment
LP - I	I1	E1
LP - II	I2	E2

where I1 and E2 are ideal points (optimal values from LP I and LP II) of income and employment. I2 and E1 are anti-ideal values of income and employment using the calculated differences. The deviations can be derived as follows:

$$d_j = (Z^*_j - Z_j(X)) / (Z^*_j - Z_{*j}) \qquad j = 1, 2 \qquad (11)$$

where d_j = deviations for income and employment
Z^*_j = ideal value
Z_{*j} = anti-ideal value
X = the vector of the decision variables
$Z_j(X)$ = jth objective function used.

4. *Solving compromise programming:* The compromise farm plan was obtained by solving the following model using the linear programming basic matrix with given input requirements (Table 3).

$$\text{Min } L = d \text{ subject to } \quad \begin{array}{l} \delta_1 (Z^*_1 - Z_1(X)) / (Z^*_1 - Z^*_1) < d_1 \\ \delta_2 (Z^*_2 - Z_2(X)) / (Z^*_2 - Z^*_2) < d_2 \end{array} \qquad (12)$$

where L = the maximum of individual deviations
d_1, d_2 = the income and employment deviations
δ_1, δ_2 = weights.

Results

The results shown in Table 4 indicate that with CPM-1, rice and non-rice combinations such as groundnut and pulses entered the optimal plan, but that rice occupied a negligible area; when the income weight was increased to 2.0 (CPM-2), the optimal rice area increased while the area under non-rice crops was reduced. When the income weight was further increased to 5.0 (CPM-3), the rice area increased to 123 ha, indicating that crop return dominated the risk. In the MOTAD model, both return and risk are directly related and rice has not entered the optimal plan as the possibilities of crop failure due to water scarcity in the tank irrigation systems. Keeping the employment objective, the COMPROMISE plans indicated that rice may be one of the dominant crops in the crop pattern. Since the labour requirement for non-rice crops is almost half that of rice, it is important in the rural areas to give importance for employment generation. Employment increased to about 20,000 man-days in the season in the CPM-3 compared to other models, except in the existing situation (LP model) where rice is the dominant crop with crop failures. Though employment generation was comparatively lower compared to the existing plan, the latter has higher crop failure due to more area being allocated to rice, as water may not be sufficient for the entire command area. The COMPROMISE programming models have combined the rice and non-rice crops in such a way that water may not be such a constraint for crop production.

Table 4. Results of the Programming Models.

Model	Areas sown to each crop combination (ha)				Total income	Employment
	X1	X2	X3	X4	(Rs)	(man-days)
LP	366.0	-	35.0	-	416543	32895
MOTAD			200.5	200.5	481601	17643
CPM-1	3.5	-	249.5	88.0	465432	16278
CPM-2	45.7	-	204.7		484307	14324
CPM-3	123.5	-	189.3		488438	20152

1 US $ = Rs 27; See Table 2 for description of X1, X2, X3, X4.
LP = Linear Programming model; MOTAD = Minimization of Total Absolute Deviation model;
CPM-1, CPM-2, CPM-3 = Compromise Programming Models 1,2,3 respectively (see text for details).

Conclusion

Tank water supplies are below normal in most of the periods and optimization of the crop pattern in tank irrigation systems is one of the important strategies being normally recommended, particularly to minimize risk in crop production. The results of the MOTAD and COMPROMISE programming models have clearly indicated that by optimizing the crop pattern and water use, risk in income will be minimized. Also the model demonstrated that the entire command area can be irrigated even with deficit water supplies if non-rice crops are grown. Since it is difficult to convince the farmers to grow non-rice crops in the short run, both government and voluntary organisations can make efforts to introduce these crops in the cropping pattern of the tank irrigation systems.

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Effects on growth and yield of rice by control of tillering through induced mild drought stress

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Abstract

Panicle number is an important component of yield in rice, and depends largely on the number of tillers that are formed. However, many tillers do not produce panicles, and therefore consume resources that could be more profitably diverted to productive tillers. Management techniques that reduce the number of unproductive tillers may therefore be of importance in increasing yields of rice.

Inducing mild drought stress on the crop in the vegetative phase has been shown to reduce the number of late tillers formed, thereby increasing the proportion of productive tillers. It is planned to further refine this technique by using simulation and systems analysis approaches to determine the optimum timing, duration and intensity of this drought stress for a range of environmental conditions. As the first step of this study, a pot experiment was conducted to determine the optimum duration and intensity of the drought stress. Results showed that appropriate tillering control measures can raise the grain yield by 8-15%. The optimum stress treatments were to keep the soil water content at field capacity for 12 days or at 75% field capacity for three days. Both the leaf area per stem and specific leaf weight were also found to increase under mild drought stress, and it was suggested that these effects may have been responsible for the higher yields by increasing the supply of assimilates.

Introduction

Tiller production in rice has a major influence on both the vegetative growth and the reproductive growth of the crop. The final grain yield is determined by the grain size, the number of grains per panicle, and the number of panicles per unit ground area. The number of tillers produced can influence all three components of yield, particularly the latter. Not all tillers that are produced form panicles, particularly those that emerge near the transition to the reproductive phase. In general, up to 40% of the maximum number of tillers produced may be unproductive. Although such tillers make no contribution to the final grain yield, they do consume soil nutrients and assimilates produced by the plant in the middle stages of growth, thereby reducing the resources available for grain filling later.

It has been found that the rate of tillering can be influenced to some extent by controlling the amount of water available to the crop (Jiang Pengyian et al., 1985, 1987, 1990). Draining the standing paddy water at an appropriate time to induce mild drought stress can reduce the number of later-produced tillers, thereby reducing the number of tillers that do not produce panicles. However, most models of rice growth do not yet incorporate this effect, as little is known quantitatively of the mechanism involved.

Table 1. Description of drought stress treatments. ✓ indicates an intensity/duration combination used in the experiment. Treatments referred to in the text as intensity:duration combination (e.g. III-6).

Drought duration (days)	Drought intensity (soil water content) CK SAT	I (SAT+FC)/2	II (FC)	III (75%FC)	IV (50%FC)
3	✓	-	-	✓	✓
6	✓	-	✓	✓	✓
9	✓	✓	✓	✓	-
12	✓	✓	✓	✓	-

CK = control; SAT = saturated water content (54.5%); FC = field capacity (30.3%)

In the present study, a pot experiment was carried out to investigate the effect of mild drought stress on control of tillering in rice, to provide a basis for recommendations on water management in rice systems, and to propose a possible mechanism that may be useful to include in rice growth models.

Materials and methods

A pot experiment was conducted in the greenhouse during June-September 1992 using the hybrid rice variety SY-69. Nutrients (225 kg ha^{-1} N, 90 kg ha^{-1} P_2O_5, and 195 kg ha^{-1} K_2O) were mixed with 7.5 kg of a silty loam soil contained in 15 litre drainable buckets. On 25 June, four rice seedlings were transplanted into each bucket. The seedlings had an average of 4.5 leaves each. Fifteen treatments (including the control), representing various degrees of intensity and duration of drought stress, were imposed from the time when 80% of the estimated maximum tiller numbers had emerged. The degree of drought stress was manipulated by allowing the buckets to drain until their soil moisture content reached specified values ranging from saturation to 50% of field capacity, at which they were held for a specified duration ranging from three to twelve days. Details of each treatment are shown in Table 1.

Results and discussion

Effect of drainage on tillering and grain development

There were significant differences between treatments in the rate of tiller production (Figure 1). In the control treatment, the maximum tiller number produced was 29.5, with 18 of these also producing a panicle. However, in the drought stress treatments, while the numbers of productive tillers remained similar to those in the control treatment, the maximum numbers of tillers produced were 22-25% lower, resulting in the proportion of panicle-bearing tillers rising from 61% in the control to 75.5% in the II-12 treatment. Mild drought stress appears only to affect the unproductive tillers.

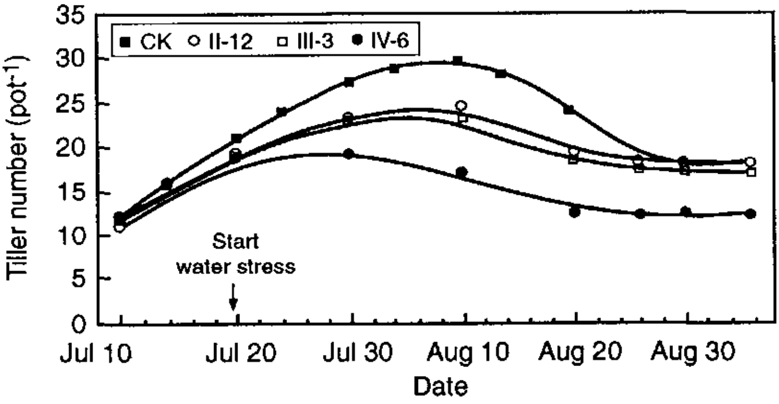

Figure 1. The effect of different drought stress treatments on tiller number.

A lower proportion of unproductive tillers should lead to a lower maintenance respiration burden on the rest of the crop, resulting in more nutrients and assimilates becoming available for those tillers that do produce panicles. Indeed, grain number per panicle in the II-12 treatment increased by 25% over that in the control treatment (Figure 2a, Table 2). Grain number was highly correlated with grain yield (Figure 2b).

Effect of drought stress on leaf development

Although there was a slight decrease in the total leaf area per bucket in the drought stress treatments, most of this decrease was from the smaller, later-formed tillers, with the result that mean leaf area per stem actually increased (Figure 3b). For example, leaf area per stem in the III-2 treatment was 16.7% higher than the control. There was also an increase in specific leaf weight, particularly in the later stages of development (Figure 3a), which

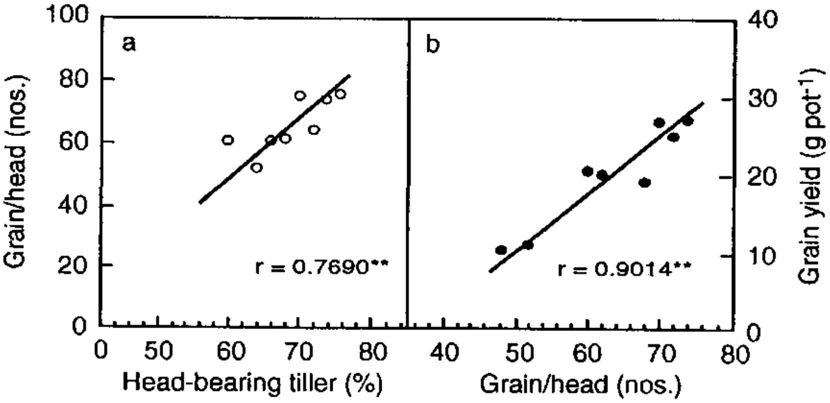

Figure 2. Relationship between % productive tillers, grain numbers per panicle, and final yield.

Table 2. Effect of drought stress on tillering and grain development.

Treatment	Tillers		Grain		
	max. no.	productive tiller no.	no./panicle	1000-gr wt (g)	total wt (g pot^{-1})
Control	29.5	18.0	60.3	20.01	20.55
I-9	25.0	17.0	61.4	20.47	20.17
I-12	27.0	18.0	60.3	21.37	23.02
II-6	24.5	18.0	70.8	21.30	27.01
II-9	22.5	16.0	75.0	20.25	24.39
II-12	23.0	18.0	75.5	20.23	27.15
III-3	23.0	17.0	73.4	21.87	27.33
III-6	20.0	15.5	74.6	21.79	25.02
III-9	22.0	16.0	63.9	18.39	18.89
III-12	20.0	13.5	69.2	20.66	19.37
IV-3	19.0	13.0	52.9	16.17	11.10
IV-6	19.0	12.0	51.7	16.12	10.33

could increase the rate of photosynthesis. Effects on both of these characteristics should increase the supply of assimilate to each panicle.

Optimum drought stress for grain yield

Figure 4 shows the effects of both the intensity and duration of the drought stress treatments. The treatment resulting in the highest proportion of productive tillers was where the soil moisture was held at field capacity (FC) for 12 days, followed by 75% FC for three days, FC for six days, and 75% FC for six days. The corresponding yield increases in these treatments compared to the control ranged from 34.5 to 21.7%. Excessive drought stress, however, severely reduced yields.

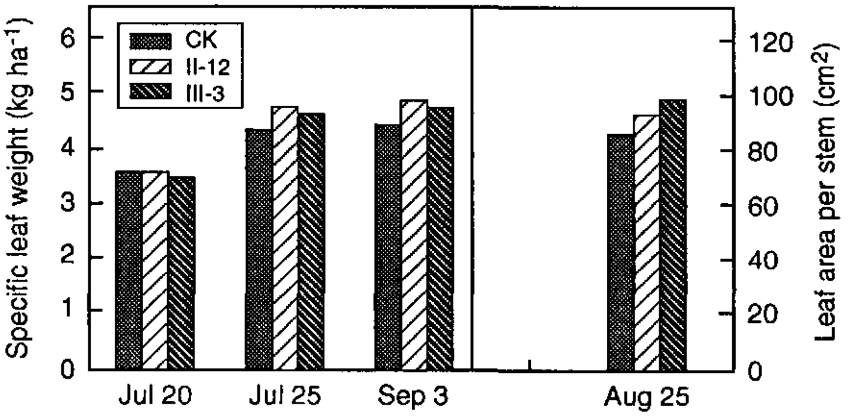

Figure 3. Effect of drought stress on specific leaf weight and leaf area per stem.

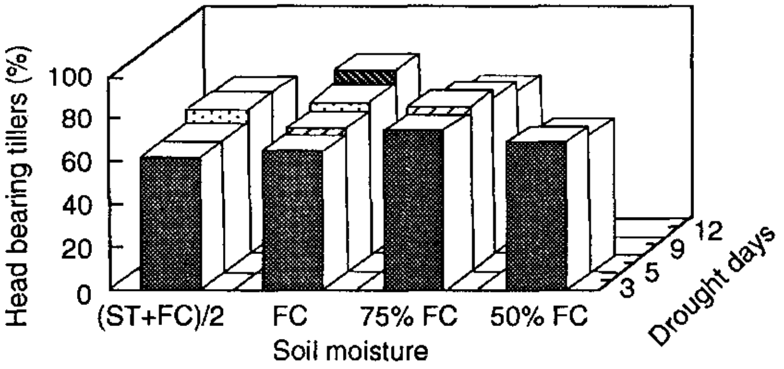

Figure 4. Effect of drought stress on the ratio of productive tillers.

Conclusions

The use of induced mild drought stress is an efficient technique to reduce the proportion of unproductive tillers, and hence their respiratory burden, in irrigated rice production. It appears that specific leaf weight and leaf area per stem are also increased in such circumstances, suggesting that in addition to a reduction in unproductive sinks, there is also an increase in the assimilate supply. A corresponding increase in the number of grains per panicle was also observed. The results of the present experiment suggest that the optimum intensity and duration of induced drought is to keep the soil water content at field capacity for 12 days or at 75% field capacity for three days. The grain yield for these two treatments were more than 30% higher than the control treatment.

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Simulation modelling as a tool to study wheat productivity in a rice-wheat cropping system in Bangladesh

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Abstract

Much of the wheat produced in Bangladesh is grown as part of a rice/wheat cropping system, and most of this is sown after the transplanted *aman* rice crop. After the rice is harvested, there is a period of about 105-110 days available for wheat, but because the weather is very variable during this period, the risk associated with growing it is high. Experimental results have indicated a yield reduction of over 1% per day of planting after December 1, which represents a substantial reduction in potential national production. An understanding of the factors responsible for this reduction will help to indicate the likely progress that could be made by selecting for improved wheat cultivars for inclusion in the system.

The MACROS L1D crop simulation model was used to simulate the growth and yield of wheat sown at different dates following the *aman* rice crop in a rice/wheat cropping system in Bangladesh. The model could explain the observed decline in yields caused by a delay in sowing in terms of solar radiation and temperature alone.

Introduction

Wheat is the second major cereal crop in Bangladesh, accounting for about 12% of the cereal grain production. However, as all major cropping patterns are rice-based, it is important that wheat fits into these in order for it to play a significant role in crop production activities. Survey results from greater Dinajpur, Kustia, and Jessore districts indicate that the rice/wheat cropping system covers about 87% of the wheat area in these districts (Saunders, 1990, 1991). The productivity of the system is low due to lack of appropriate rice and wheat cultivars that can be grown in the rotation under the given climatic conditions, lack of improved management practices, and poor infrastructure.

The presently available wheat varieties yield around 2 t ha^{-1} at the farmers level, although yields vary greatly depending upon the region and the year. Within the rice/wheat cropping cycle, there is a period of about 105-110 days available for wheat, but because of the large yearly climatic variation, the risk associated with growing it during this period is high. It has been estimated that about 75% of the annual wheat crop is planted in December and of that about 60% is planted during the last two weeks of the month (Ahmed et al., 1985). Most of the wheat sown this late is after the transplanted *aman* rice crop. Experimental results have indicated a yield reduction of over 1% per day of planting after December 1, thus suggesting a substantial reduction in potential national production.

There is a need to develop wheat cultivars that are able to tolerate variability in the climate, and yet still produce an acceptable yield in the time frame permitted. A comparison of the potential and current yields of wheat under such circumstances can indicate the progress that could be made by such a breeding program. Crop growth models are a useful tool to quantify the environmental limits to crop production, and provide the advantage that their use minimizes the requirement for costly and lengthy experimentation. Therefore, an attempt was made to determine the potential yields of wheat following rice in Bangladesh by using simulation modelling techniques.

Environmental constraints to wheat production in existing cropping systems

The optimum temperature for vegetative wheat growth is between 20-25°C (Ray & Nathan, 1985). High temperatures (>28°C) in the vegetative phase result in a poor stand, poor tillering, and attack by insects and diseases. However, the optimum temperature for grain development lies within the day/night temperature range of 15/10°C to 18/13°C.

The rainfall pattern is also a major factor influencing a farmer's decision whether to grow wheat in rainfed conditions. For rainfed wheat cultivation, if the monsoon rains cease early, the residual soil moisture at the normal time for sowing wheat may be low, and farmers will usually decide not to plant wheat due to the risk of poor emergence and subsequent crop failure. The crop may also be subjected to high temperatures at an early vegetative stage resulting in less or no tillering, premature heading, smaller heads and lower yield. At the other extreme, excess rainfall towards the end of the monsoon season results in excessively wet soil conditions, particularly in heavy soils, thereby preventing ploughing. This results in late planting, with the result that the grain filling period is shortened through exposure to the higher ambient temperatures in late February and early March. This in turn leads to lower yields through the reduction of the number of grains per spikelet and individual grain weight (Chowdhury & Wardlaw, 1978).

The model and simulation procedure

The MACROS L1D crop simulation model (Penning de Vries et al., 1989) was used with crop parameters for winter wheat. The model simulates the physiological processes of photosynthesis, respiration, crop development, carbohydrate partitioning, photosynthetic area, and senescence, in response to the environment. The potential production version of the model uses only solar radiation intensity and maximum and minimum temperatures as weather inputs, and it is assumed that other factors such as water, nutrients, and pests and diseases, do not limit growth. The daily increase in dry matter is partitioned into leaves, stem, roots, spikes and grains as a function of the stage of development. The model, written in CSMP (Continuous Simulation Modelling Program), was run on an IBM PC/AT compatible computer.

Output from the model was compared with data from experiments conducted at Joydebpur, Bangladesh, during 1990-91. Simulation runs were also made for four planting dates starting from November 15 at fifteen-day intervals with four years' historical weather

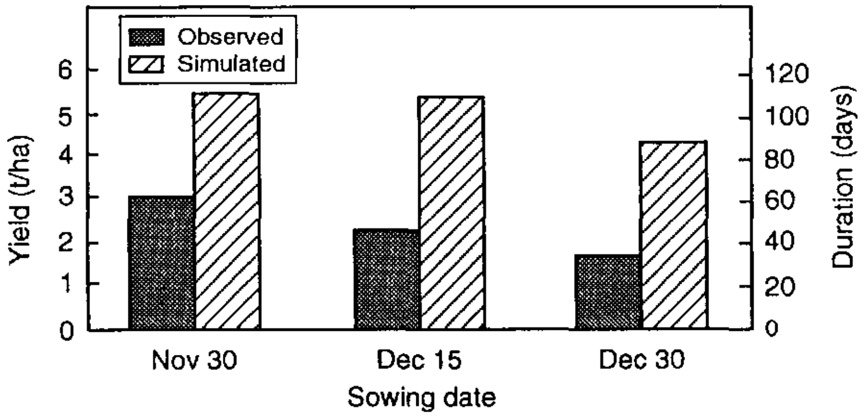

Figure 1. Yield (bars) and growth duration (lines) of the wheat cultivar Kanchan at Joydebpur, 1991.

data from Joydebpur and with one year's weather data from two other locations, Rajshahi and Barisal.

Results and discussion

Model evaluation

The simulated and measured grain yield and growth duration of the wheat cultivar Kanchan are presented in Figure 1. The predicted and observed values for both yield and growth duration showed similar trends for the three planting dates, although the predicted

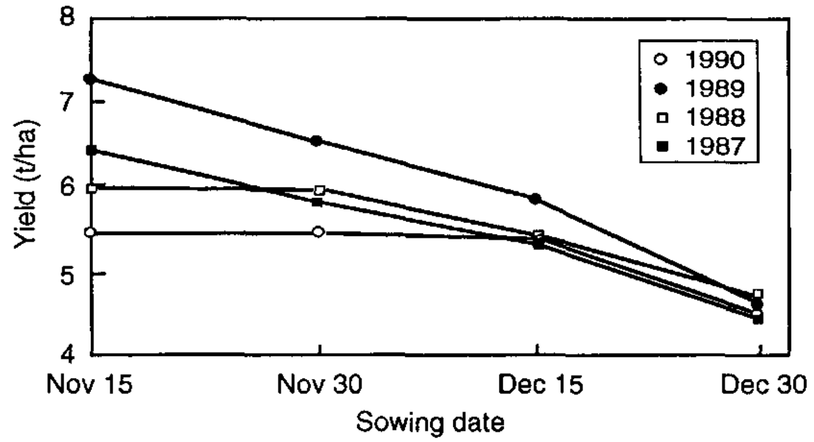

Figure 2. Simulated wheat grain yields for different planting dates at Joydebpur.

yields were 1.8 to 2.6 times higher than the observed yields. This indicates that the temperature effect is simulated well by the model, but that other stress factors are causing a significant yield reduction. The increasing trend of the difference between predicted and observed yields for the later plantings may have been due to an increase in moisture stress later in the season, a factor not at present included in the model. The overall growth duration was predicted accurately by the model.

Model application

The simulated grain yields of Kanchan using four years' weather data from Joydebpur for various sowing dates are shown in Figure 2. In all years, similar trends for the predicted yields were observed. For the early sowing dates, the yields were very variable between years, probably due to the variability in incident radiation and temperature at these times. For the late sowings, the yields were low in all the years; the lower yield variability compared to the earlier sowings may have been due to the shorter growth period, or to less variability in the weather. However, these results need to be confirmed further with weather data spanning a longer period of time.

The three locations, Rajshahi, Joydebpur and Barisal, represent three different thermal zones in Bangladesh. The simulated grain yields of the cultivar Kanchan during 1989 at each site are shown in Figure 3. In all three locations the yields showed a similar trend for different sowing dates. The ranking of yields for each sowing date was consistently higher in Rajshahi, followed by Joydebpur and Barisal, reflecting the differences in mean temperature at each location.

Conclusion

It was found that the MACROS L1D simulation model could be used to explain variation in yields of crops sown at different dates. The high variability in yields observed between

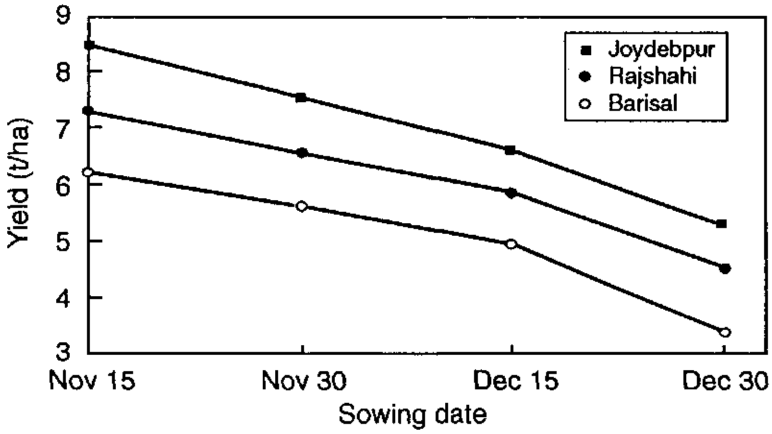

Figure 3. Simulated yields for wheat sown at different planting dates at three locations.

years was also predicted by the model, indicating that this is due to variability in solar radiation and temperature. The model predicted yields considerably higher than was achieved in practice, indicating that the crop parameters used in the model at present need to be revised for the particular cultivars being used. This was particularly the case for the dry matter partitioning coefficients. As much of the wheat in the rice/wheat cropping system is grown under moisture-limited conditions, a water uptake sub-model should also be included in future versions of the model.

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Predicting the effects of increased temperature and elevated CO_2 on rice yields in Japan

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Abstract

The effects of CO_2 on growth and high temperature on spikelet fertility were incorporated into the SIMRIW rice growth simulation model to investigate the effects of elevated atmospheric CO_2 concentration and global warming on rice yields in Japan. The effect of CO_2 on growth was accounted for by adjusting the radiation use efficiency (RUE). On the basis of experiments in temperature gradient tunnels and also on information from the literature, RUE was estimated to increase by 24% under doubled CO_2 concentration. A logistic function was used to describe the relationship between average daily maximum temperature and the degree of high temperature-induced spikelet sterility over the flowering period.

Although the model predicted only the potential yield for a given environment, actual farmer's yield was calculated by multiplying this by a 'technology factor'. This approach was able to explain annual yield variations well in Hokkaido (northern Japan), Gumna (central Japan) and in Miyazaki (southern Japan). The model, calibrated in this way, predicted that the combined effects of increased CO_2 and temperature would be to increase the average yield of irrigated rice by about 20% and 10% in Hokkaido and Miyazaki respectively. Year-to-year variation in yields would be reduced in the north, but in southern Japan, variability would double due to increased spikelet sterility caused by higher temperatures.

Introduction

Climate and varietal characteristics determine the potential yield of crops in different regions. The currently increasing CO_2 concentration in the atmosphere and the anticipated climate change due to global warming are likely to affect future crop production, although the effects may vary between crops and regions. It is essential to assess the effects of global climate change on the production of major crops in each region, to form a basis for developing methods to deal with the changes (e.g. cultivar improvements, alterations of crop species and cropping seasons, provision of irrigation systems, etc.). Although several attempts have been made using computer models to predict the effects of global environmental change on the yield of crops at various locations (e.g. Williams et al., 1988; Horie, 1988; Barry & Geng, 1991), the results remain hypothetical due to the uncertainty associated with assumptions used in the models. Moreover, most predictions are either of direct effects of elevated CO_2 on the crop, or of the indirect effects of climatic change, and models for predictions of both these effects are very limited. Thus, there is a need for the development of reliable models for prediction of both direct and indirect effects of global climate change on crop yields.

Our previous model SIMRIW (Simulation Model for Rice-Weather Relationships; Horie, 1987; Horie et al., 1992) satisfactorily explained locational and yearly variations of rice yields in Japan and the USA using daily weather data. The objective of the present study was to expand the ability of SIMRIW to predict the effects of climate change on rice production, particularly in Japan. For this purpose, we incorporated into the model the effect of CO_2 on growth and yield and the effect of high temperature on spikelet fertility. This paper describes these improvements and the results obtained from the use of the revised model to predict the effect of climate change on rice yields in northern and southern Japan.

General structure of the SIMRIW model

SIMRIW is a simplified process-model for simulating rice growth and yield in response to weather. A schematic representation of the processes of growth, development and yield formation used in the model is shown in Figure 1. Phenological development is represented by the developmental stage (DVS), defined to be 0.0 at emergence, 1.0 at heading and 2.0 at maturity. The value of DVS at any moment of crop development is calculated by integrating the developmental rate DVR with respect to time. DVR is calculated from a nonlinear function of daily mean temperature and daylength as described by Horie & Nakagawa (1990).

The conservative relationship between dry matter production and cumulative absorbed radiation (Monteith, 1977) is used as a basis for calculating daily increments in biomass. This relationship is characterized by one parameter, the radiation conversion

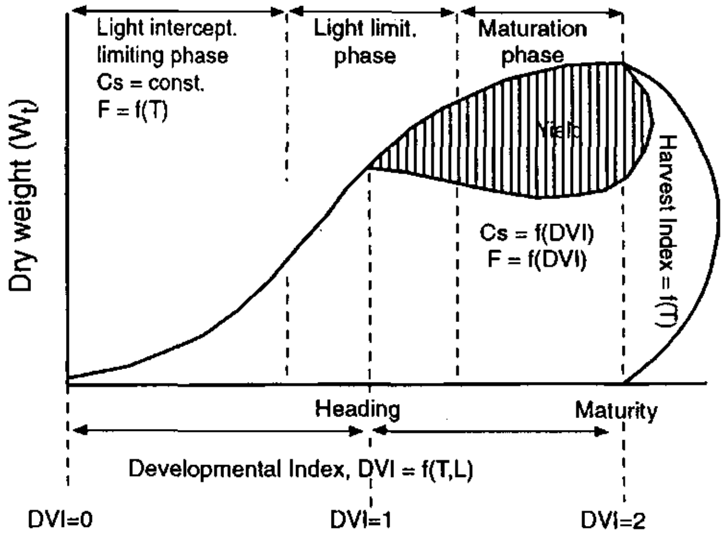

Figure 1. Schematic representation of processes of growth, development and yield formation of rice, as modelled in SIMRIW (after Horie, 1992).

efficiency (RUE). It is assumed that RUE is constant until flowering (DVS=1), declining thereafter with respect to DVS to account for senescence. Leaf area growth is modelled independently and assumed to be a function of temperature. This contrasts to the approach used in the Wageningen MACROS models in which leaf weight increments are derived from partitioning fractions, and leaf area calculated using the specific leaf area. Leaf area growth and leaf weight growth have previously been found to be largely independent of each other (Horie et al., 1979).

Grain yield is calculated in SIMRIW by multiplying total biomass by a partitioning index. This index is a function of DVS and takes into account the fraction of sterile spikelets. The partitioning index/DVS relationship enables dynamic simulation of the yield formation process, particularly the premature cessation of growth when the crop encounters low temperatures (e.g. in the autumn). The sterile spikelet fraction is a function of the time spent below a reference temperature (Uchijima, 1976) during the sensitive period from DVS=0.75 to DVS=1.2.

SIMRIW predicts the potential yield of a rice cultivar under irrigated and optimal cultivation technologies. However, Horie (1987) showed that a close linear relationship existed between the simulated potential yield (Y_p) and actual yield (Y_a) for locations in Japan and the USA, described by

$$Y_a = \alpha \, Y_p \tag{1}$$

in which α can be regarded as a parameter describing the level of rice production efficiency, or the 'technology factor'. Eq. 1 can be used to estimate farmers' yields from the yield predicted by the model.

Modification of SIMRIW to include the effects of CO_2 and high temperature

For SIMRIW to be able to predict the effects of anticipated global climate change (elevated CO_2 and warming) on rice production, two important processes needed to be incorporated into the model: that of the direct effect of CO_2 on growth and yield, and that of the effect of high temperature on grain formation. It has been shown that CO_2 enrichment has little or no effect on leaf area development in rice (Imai et al., 1985; Baker et al., 1990b; Nakagawa et al., 1992), so we assumed that the effect of CO_2 concentration on growth acts through an enhancement of the radiation use efficiency (RUE). We have obtained information on the effect of temperature and CO_2 on RUE and grain formation, both from long-term experiments using a newly-devised temperature gradient tunnel (Horie et al., 1991), and from already published experimental data in the literature.

CO_2 concentration and RUE: Analysis of canopy photosynthesis data of Baker et al. (1990a) showed that a rectangular hyperbola described well the relative response of RUE (g MJ^{-1}) to changes in CO_2:

$$RUE \;=\; 1 + [(R_m - 1) \bullet (C_a - 330)] \,/\, [(C_a - 330) + k_c] \tag{2}$$

where R_m (g MJ^{-1}) is the asymptotic response limit of RUE, C_a is the ambient CO_2 concentration (ppm) and k_c the value of C_a at which RUE = $(R_m - 1) / 2$. Eq. 2 is the same

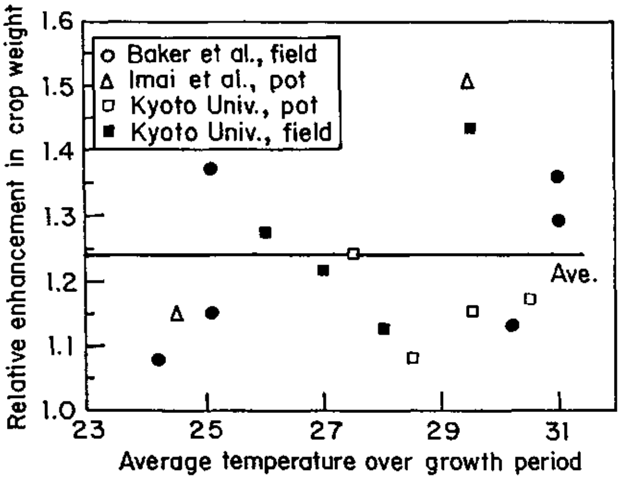

Figure 2. Relative responses in crop dry weight of rice to near-doubled CO_2 concentration as a function of temperature. (Sources: Imai et al., 1985; Baker et al., 1990b; and data from temperature gradient tunnel experiments in Kyoto).

as the one used by Allen et al. (1987) for the response of soybean seed and biomass yield to CO_2.

Figure 2 shows the relative response of total crop biomass to increased levels of CO_2 as a function of temperature for rice subjected to long-term CO_2 acclimation experiments, including data of Imai et al. (1985), Baker et al. (1990b), and our data derived from two experiments conducted in 1991 and 1992 in Kyoto. The 1991 experiment used two temperature gradient tunnels with ambient (350 ppm) and elevated (690 ppm) CO_2 concentrations. The temperature gradient tunnel creates a temperature gradient along the long axis (25 m) of the tunnel while maintaining natural daily and seasonal temperature variations. The plants were grown in pots which were distributed evenly in the tunnel at a density of 20 pots m^{-2} for the entire growth period (Kim et al., 1992). The 1992 experiment was conducted in temperature gradient tunnels in the field, but was otherwise similar to the 1991 experiment. The variety Akihikari was used in both experiments.

There was a mean increase of 24% in relative crop biomass when the CO_2 concentration increased from ambient to 690 ppm, although there was a large range (9-51%) between experiments (Figure 2). There was, however, no consistent trend in the effect of temperature on the response to CO_2. The relative responses obtained from pot experiments tended to be lower than those from field experiments, with the exception of one crop by Imai et al. (1985). This may have been due to the limited rooting space in the pots reducing the photosynthetic response to elevated CO_2. For this reason, we omitted pot experiment data in subsequent analysis. On this basis, the best estimates of the parameters in eq. 2 were $R_m = 1.54$ g MJ^{-1} and $k_c = 1787$ ppm. These values were used in the model.

High temperature sterility of spikelets: Rice spikelets are known to be very sensitive to both high and low temperatures. SIMRIW already takes into account the effect of low temperature on spikelet sterility, but the effect of high temperatures has not previously been simulated. Spikelet sterility is due to a marked decline in the level of

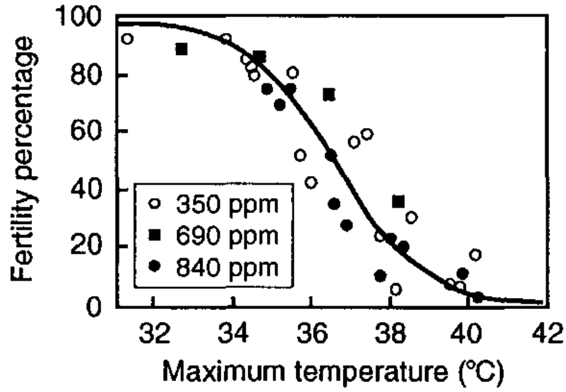

Figure 3. Relationship between average maximum temperature during the flowering period and the spikelet fertility percentage for rice growing in different CO_2 concentrations.

pollination at temperatures in excess of 35°C; the highest sensitivity is therefore at anthesis (Satake & Yoshida, 1978; Matsui & Horie, 1992).

Figure 3 shows the relationship between the percentage of fertile spikelets and average daily maximum temperature over the flowering period (DVS = 0.96 to DVS = 1.2) for Akihikari grown in TGT's with both ambient and elevated CO_2 concentrations. There was no apparent effect of CO_2 concentration on the temperature/fertility relationship. The relation shown in Figure 3 can be described by the following equation

$$\delta = 100 / [1 + e^{0.853\,(T_{max} - 36.6)}] \qquad (3)$$

where δ is the fertility percentage and T_{max} the average daily maximum temperature during the flowering period. As rice spikelets usually flower during daylight hours, daily maximum temperature is a better parameter than daily mean temperature. Using eq. 3 together with a linear relationship between δ and the harvest index (Horie, 1987), the effect of high temperatures on rice yield can be simulated.

Simulated and observed yearly variations of rice yield

To evaluate the accuracy of SIMRIW in explaining annual variation in rice yields at different locations in Japan, the three prefectures of Hokkaido, Gunma and Miyazaki were selected to represent northern, central and southern Japan, respectively. For each prefecture, weather data (consisting of daily solar radiation, and maximum and minimum temperatures) from one weather station for the period 1979 to 1990 were used for input into the model.

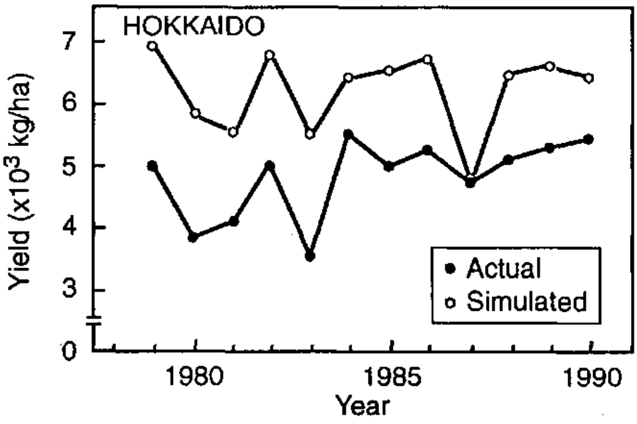

Figure 4. Simulated and actual yearly variations in rice yields in Hokkaido, Japan.

Figure 4 shows the simulated and measured rice yields in Hokkaido' for the period. Although the potential yield predicted by SIMRIW is much higher than the measured values, the difference between the two decreases over time, indicating an improvement inrice production technology, as represented by the technology factor α in eq. 1. If it is assumed that α increases linearly with time, actual yields (Y_a) may be calculated from simulated yields (Y_p) as

$$Y_a = Y_p \bullet [b_0 + b_1 (N - 1)] \tag{4}$$

where N is the years since 1979, and b_0 and b_1 are regression coefficients. Values for b_1 of

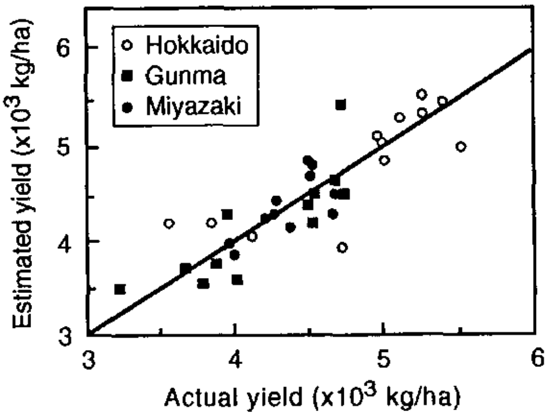

Figure 5. Comparison between actual farmers' yields and that estimated by multiplying predicted yields by the technology factor, α, for three different prefectures in Japan.

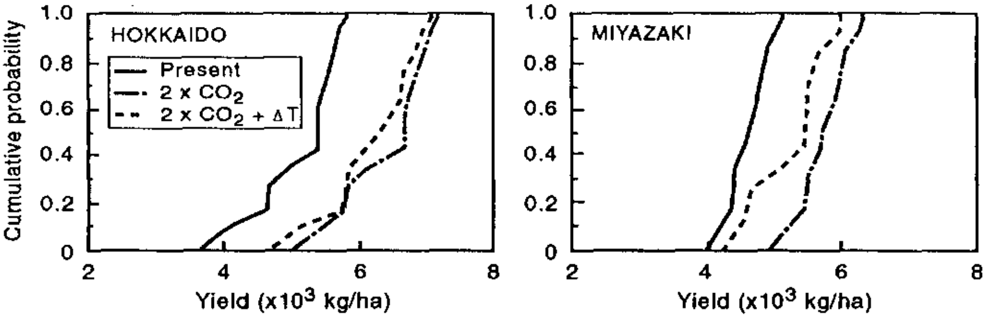

Figure 6. Cumulative distribution functions for rice yields simulated by SIMRIW in Hokkaido and Miyazaki for three scenarios of global climate change.

1.3, 1.7 and 0.9% were obtained as rates of yearly yield increases due to technological advancement in Hokkaido, Gunma and Miyazaki, respectively.

Using eq. 4 to transform model output gave predictions of farmers' yields close to those actually obtained in the three prefectures (Figure 5) suggesting that the model is able to explain weather-induced variations in rice yield reasonably accurately.

Prediction of the effects of climate change on rice yields in Japan

The modified SIMRIW model was also used to predict the effects of a global rise in CO_2 and an associated temperature increase on rice yield in Japan. Three scenarios were compared: (1) the current climate, (2) the current climate but with double CO_2 levels, and (3) with the temperature increases predicted by the GISS general circulation model (Hansen et al., 1984) under doubled CO_2 levels (2xCO_2). Again, the three prefectures of Hokkaido, Gunma and Miyazaki were used. For the current climate, we used daily maximum and minimum temperatures and daily solar radiation data for the 1979-1990 period recorded at Sapporo (43.03°N, 141.20°E) in Hokkaido prefecture, Maebashi (36.24°N, 139.04°E) in Gunma prefecture, and Miyasaki (31.55°N, 131.25°E) in Miyazaki prefecture. For the 2xCO_2 climate, we incremented the recorded temperature measurements by the monthly mean temperature rise predicted by the GISS model. These values were 3.0-4.0°C, 2.8-3.1°C and 2.9-3.1°C monthly mean temperature rises for the rice growing season at Sapporo, Maebashi and Miyazaki, respectively.

Simulations were made for the 12-year period for the three scenarios at each location. All predicted yields were normalized using eq. 4 to the yields at the production efficiency in 1990. Figure 6 shows the predicted cumulative probability of obtaining a given yield for the Hokkaido and Miyazaki prefectures. In Hokkaido, yields varied under the present climate from 3.4 to 6.0 t ha^{-1} indicating that production is very unstable. By doubling CO_2

alone, the model predicted that yields should increase by 24% without changing the variability. Doubling CO_2 and increasing the temperature predicted average yield increases of 22% and a reduction in variability. This reduction in variability at higher temperatures may have been due to there being less years in which there is spikelet sterility due to low temperatures, as happens frequently under the present climate at this location.

In Miyazaki, yields varied under the present climate from 4.0-5.2 t ha^{-1}, indicating stable production. A doubling of CO_2 alone increased predicted yields by 24% with no change in the variability, but increasing the temperature in addition increased predicted yields by 14% above the present level, but also doubled the variability. This increase in variability in Miyazaki was probably due to an increase in spikelet sterility due to higher temperatures during the flowering period in warm summer years.

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Effects of elevated temperature and CO_2 on the growth and competitive ability of irrigated broadcast-seeded rice in Malaysia

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Abstract

The modified COMPETITOR model previously adopted for simulation of weed interference in broadcast seeded rice under Malaysian conditions was used to study the effects of elevated temperature on the potential production of rice, and determine the sensitivity of the predicted competitive ability of the crop to elevated temperatures. The analysis was performed with ten years of historic weather data during the main growing season for the three major rice growing regions of Tanjung Karang, Telok Chengai and Kemubu in Malaysia.

A 2°C rise in maximum temperatures during the main growing season resulted in a 2-18% increase in leaf area index, while potential grain yields declined by 2-10%, depending on location and year. Mean increases in LAI and reductions in grain yield were 8.9% and 8.6%, 12.0% and 7.1%, and 13.7% and 7.3% for Tanjung Karang, Telok Chengai and Kemubu respectively. Yields declined from 7143, 7057 and 6683 kg ha^{-1} to 6537, 6561 and 6196 kg ha^{-1}, respectively. An increase in the maximum photosynthetic rate (P_{max}) from 41 to 47 kg ha^{-1} h^{-1} coupled with a 2°C increase in maximum temperatures showed a 23% increase in LAI, and reduced the loss in grain yield to 2% or less, suggesting that yield decreases due to elevated maximum temperatures would be minimal under increased CO_2 levels. The dominance index for rice at flowering, computed from simulated dry matter values in the presence of weeds, remained relatively constant at between 0.59 and 0.63 for all of the specific crop-weed densities studied.

Introduction

Increasing levels of atmospheric CO_2 have stimulated the development and use of simulation models to predict the response of the climate and vegetation to changes in CO_2 concentration (Allen & Belladi, 1990). Effects of elevated temperature and carbon dioxide on the physiology and growth of rice have also been extensively studied and reviewed (Baker et al., 1989, 1990; Allen et al., 1991).

The major objective of this study was to investigate the response of growth, potential production and competitiveness of rice to elevated temperatures and CO_2 on using a crop-weed competition model (Rabbinge et al., 1989), which was previously adapted and validated to simulate the effects of weed interference in broadcast-seeded rice in Malaysia (Rajan, 1991).

Materials and methods

The growth response of rice (var. MR84) to elevated daily maximum temperature (2°C higher then recorded) and CO_2 (achieved by increasing the maximum leaf photosynthesis value (P_{max}) from 41 to 47 kg ha^{-1} h^{-1}) was simulated using ten years of weather data for the main growing season at three major rice growing locations, Tanjung Karang, Telok Chengai and Kemubu, in Malaysia. The computed summed dominance ratios (average of the sum of relative dry matter and relative density) at the panicle emergence stage was used as a measure of potential competitiveness. Only responses in potential leaf growth, grain yields, development rate, and computed dominance potential are discussed in this paper.

Results and discussion

In general, a 2°C rise in daily maximum temperatures resulted in a 2-18% increase in LAI, while potential grain yields declined by 2-10% depending on location and year. The overall mean yield loss was 7.7%. Yield declines for Tanjung Karang, Telok Chengai and Kemubu ranged between 7.6-10.0%, 5.2-8.6% and 2.0-10.0% respectively. The corresponding increases in LAI values were between 2.0-16.1%, 9.4-13.6% and 4.0-17.9% (Tables 1, 2 and 3).

Yield declines of 7-10% per 1°C rise at constant daytime temperatures in the range 26-36°C have been recorded previously (Baker et al., 1989, 1990). The competition model predicted 8.6%, 7.1% and 7.3% declines in yield for Tanjung Karang, Telok Chengai and Kemubu respectively, for a 2°C rise in maximum daily temperatures. The maximum daytime temperatures for these locations were in the range 32-35°C.

Table 1. Effect of elevated temperature on simulated LAI, WSO and development rate, for broadcast seeded rice (var. MR 84) at Tanjung Karang during the main season, 1980-89.

Parameter	Temp. change	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	Mean
LAI	Nil	2.55	2.71	3.00	2.65	2.80	2.50	2.35	2.80	2.80	2.81	
	+2°C	2.96	2.94	3.06	2.97	2.85	2.80	2.68	2.86	2.95	3.21	
	% change*	16.1	8.5	2.0	12.1	2.0	12.0	14.0	2.3	5.4	14.2	8.9
WSO	Nil	7164	6930	7079	7250	7362	7146	7268	7013	6770	7430	
	+2°C	6506	6408	6467	6657	6668	6574	6607	6385	6262	6831	
	% change*	-9.2	-7.6	-8.9	-8.2	-9.5	-8.0	-9.2	-10.0	-7.5	-8.1	8.6
Reduction in days to PE	+2°C	3	2	2	3	2	1	3	3	2	2	

LAI: Leaf Area Index (ha ha^{-1}) at DVS=2.0; WSO: Potential dry grain yield (kg ha^{-1}); PE: Panicle Emergence; * % change relative to current temperature

Table 2. Effect of elevated temperature on simulated LAI, WSO and development rate, for broadcast seeded rice (var. MR 84) at Telok Chengai during the main season., 1980-89. Abbreviations as in Table 1.

Parameter	Temp. change	1980	1982	1983	1984	1985	1986	1987	1988	1989	Mean
LAI	Nil	2.60	2.65	2.55	2.72	2.70	2.60	2.52	2.50	2.45	
	+2°C	2.87	3.01	2.87	3.05	2.99	2.95	2.85	2.83	2.68	
	% change	10.4	13.6	12.6	12.1	9.7	13.5	13.1	13.2	9.4	12.0
WSO	Nil	7021	7338	7146	7413	7005	7273	6675	6920	6725	
	+2°C	6457	6795	6679	6910	6529	6653	6926	6364	6380	
	% change	-8.1	-7.4	-6.6	-6.8	-6.8	-8.6	-5.7	-8.1	-5.2	7.0
Reduction in days to PE	+2°C	3	2	2	3	3	2	2	3	1	

Increase in P_{max} from 41 to 47 kg ha^{-1} h^{-1} had a beneficial effect on potential grain yield, while an increase in temperature had a negative effect (Table 4). An increase in P_{max} from 41 to 47 kg ha^{-1} h^{-1} coupled with a 2°C increase in maximum daily temperatures showed a 22-23% increase in LAI, and reduced the yield loss to 2% or less. The higher P_{max} value had little or no effect on development rate (days to maturity) in comparison to the temperature increase. These responses are in agreement with findings from physiological

Table 3. Effect of elevated temperature on simulated LAI, WSO and development rate, for broadcast seeded rice (var. MR 84) at Kemubu during the main season, 1983-91. Abbreviations as in Table 1.

Parameter	Temp. change	1983	1984	1985	1986	1987	1988	1989	1990	1991	Mean
LAI	Nil	2.29	2.58	2.51	2.38	3.02	2.39	2.37	3.05	2.29	
	+2°C	2.65	2.98	2.96	2.80	3.14	2.79	2.78	2.85	2.66	
	% change	15.7	15.5	17.9	17.6	4.0	16.7	17.3	6.6	16.2	14.2
WSO	Nil	6497	7230	6765	6657	6543	6344	6857	6473	6777	
	+2°C	5967	6757	6208	6153	6100	5887	6223	6371	6100	
	% change	-8.2	-6.5	-8.2	-7.6	-6.8	-7.2	-9.3	-2.0	-10.0	7.3
Reduction in days to PE	+2°C	2	2	2	2	2	1	1	2	3	

Table 4. Effect of elevated temperature and CO_2 on simulated LAI, WSO and maturation date in broadcast seeded rice (var. MR84) at Tanjung Karang during the main season 1980/1990.

Year	Parameters	PMAX = 41.0 (current CO_2 level)		PMAX = 48.0 (elevated CO_2)	
		current temp.	Temp + 2°C	current temp.	Temp + 2°C
1980	LAI	2.55	2.96	2.70	3.13
	% change		16.1	5.9	22.8
	WSO	7164	6506	7734	7010
	% change		-9.2	8.0	2.2
1990	LAI	2.50	2.91	2.65	3.08
	% change		15.9	6.0	22.7
	WSO	7371	6746	7962	7278
	% change		-8.5	8.0	1.3
	Maturation (days)	120	115	120	115

studies (Baker et al., 1989, 1990). The temperature effect reduced the time to panicle emergence by one to three days depending on the year and location, while the total growing period was reduced by about five days. The dominance index for rice (at DVS=1.0), as a measure of the crop's competitive ability, computed from simulated dry matter values in the presence of weeds, in all cases remained relatively constant at between 0.59 and 0.63. This assumed a proportionate increase in photosynthetic rate to the temperature rise in both rice and the weed species.

While there was a general trend towards increased LAI and reductions in yield due to rises in temperature, there was also significant variation, probably indicating the need to incorporate the influence of expected changes in the quantity and quality of solar radiation for a more reliable prediction of the effect of climate change on potential production of rice in the tropics.

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Simulation of the effect of elevated temperature and CO_2 on growth and yield of rice in Peninsular Malaysia

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Abstract

The current increase in CO_2 concentration of the earth's atmosphere and the associated global warming could have significant effects on the growth and production of rice in the tropics. The MACROS module L1QT was used to simulate the effects of elevated temperatures of +4°C above ambient and increased CO_2 concentrations of up to 450 ppm on the growth and yield of transplanted rice for three major rice growing areas of Peninsular Malaysia.

Increased daily maximum temperatures resulted in yield reductions of 5-11%, due mainly to the shortening of the maturation period by two to four days. Spikelet sterility increased by as much as 12% when current temperatures were increased by +4°C. Increasing CO_2 concentrations generally mitigated the detrimental effects of higher temperatures; for example, when CO_2 concentrations were raised to 450 ppm at the higher maximum temperatures, yields were 5-15% higher than at present.

Introduction

The current increase in atmospheric CO_2 concentration and associated warming of the earth's climate have stimulated considerable interest in the agricultural research community in estimating the likely effects on crop production. Rice is the most important food crop in Asia where more than 90% of the world's rice growing area is found. It is also the staple food for the people of Malaysia. It is, therefore, important to estimate the potential effects of climate change on rice production in Malaysia, particularly as it is currently a net importer of rice. Baker et al. (1992b) have reported that increased CO_2 concentrations are likely to be beneficial to rice growth and yield but that potentially large negative effects are possible if maximum daily air temperatures also rise.

The objectives of this study were to simulate the effects of elevated temperatures and increased CO_2 concentrations on the growth and yield of transplanted rice for three major rice growing regions of Peninsular Malaysia.

Materials and methods

The response of the rice variety MR84 to elevated maximum daily temperatures (+2°C and +4°C above current daily values) and CO_2 concentrations (400 and 450 ppm, achieved by increasing the maximum leaf photosynthesis value (P_{max})) was simulated using the

MACROS module L1Q including the tillering sub-model of Penning de Vries et al. (1989). MR84 is a popular variety grown extensively over the entire country. Three major rice growing regions in Malaysia were chosen for this study: Muda Agricultural Development Authority (MADA) in the north, Kemubu Agricultural Development Authority (KADA) in the northeast, and Tanjung Karang in the southwest. All three areas are double cropped with rice and equipped with drainage and irrigation facilities. Ten years of weather data for Tanjung Karang and MADA, and eight years of data for KADA, was used in the simulations. The model was calibrated and validated previously by Singh et al. (1991). Only effects on maturation period, grain yield and spikelet fertility are discussed in this paper.

Results and discussion

The simulated effect of elevated temperature and CO_2 concentration on the maturation period, grain yield and spikelet fertility are shown in Tables 1, 2 and 3, for Tanjung Karang, MADA and KADA, respectively.

The maturation period was shortened by about three to four days during the main season and about two days during the off season with a 2-4°C increase in daily maximum temperature at all sites. However, increasing CO_2 concentrations together with the temperature did not show any effect on the maturation period. Yoshida & Hara (1977) also reported a hastening of the maturity of rice with an increase in temperature, while Baker et al. (1992a) showed that the maturation period could be shortened by as much as ten days under their temperature treatments.

At the current CO_2 level of 340 ppm, grain yield was reduced by 5.4-6.6% during the main season and 4.6-5.2 % in the off-season with a 2°C increase in temperature, and by as much as 11.3% with a 4°C increase in temperature, with Tanjung Karang showing the lowest reduction. When CO_2 was also increased to 400 ppm together with a 2°C rise in

Table 1. Simulated effect of elevated temperature and CO_2 on maturation period, grain yield and spikelet fertility of variety MR84 at Tanjung Karang, Malaysia.

CO_2 level (ppm)	Temperature increment (°C)	Maturation period (days) Main	Off	Grain yield ($kg\ ha^{-1}$) Main	Off	Spikelet fertility (%) Main	Off
340	+0	102.7	100.6	6413	6991	89.9	89.9
340	+2	100.3	98.8	6067	6670	86.3	85.8
340	+4	99.2	98.0	5816	6344	81.5	81.4
400	+2	100.3	98.8	6729	7467	85.5	84.9
400	+4	99.2	98.0	6483	7121	80.5	80.5
450	+2	100.3	98.8	7193	8040	84.5	84.0
450	+4	99.7	97.4	6893	7673	79.5	79.6

Main = main planting season; Off = off season

Table 2. Simulated effect of elevated temperature and CO_2 on maturation period, grain yield and spikelet fertility of variety MR84 at Telok Chengai (MADA), Malaysia.

CO_2 level (ppm)	Temperature increment (°C)	Maturation period (days) Main	Off	Grain yield (kg ha^{-1}) Main	Off	Spikelet fertility (%) Main	Off
340	+0	102.3	99.4	6456	6822	87.7	87.1
340	+2	100.0	97.8	6070	6466	83.4	82.6
340	+4	98.6	97.1	5768	6098	77.2	77.1
400	+2	100.0	97.8	6772	7299	82.3	81.0
400	+4	98.6	97.1	6458	6904	76.1	75.6
450	+2	100.0	97.8	7212	7788	81.1	79.6
450	+4	98.6	97.1	6895	7428	75.0	74.2

maximum temperature, a 5-7% increase in yield was predicted. But when temperature was further increased to 4°C, only Tanjung Karang showed a slight increase in grain yield during the off season while yield at the other sites declined slightly or was the same as that observed under current conditions. However, increasing the CO_2 concentration to 450 ppm resulted in a higher simulated grain yield at both elevated temperatures at all sites. Rowland-Bamford et al. (1991) reported an increase in net canopy photosynthesis as CO_2 concentration increased up to 500 ppm, beyond which there was a levelling off. Baker et al. (1990) reported increases in grain yields by as much as 50%, when the CO_2 level was doubled from 330 to 660 ppm, but in a later study (Baker et al. 1992a) obtained no response of grain yield to CO_2 enrichment. They attributed this result to the lower levels of solar radiation in the second experiment.

Table 3. Simulated effect of elevated temperature and CO_2 on maturation period, grain yield and spikelet fertility of variety MR84 at Kemubu (KADA), Malaysia.

CO_2 level (ppm)	Temperature increment (°C)	Maturation period (days) Main	Off	Grain yield (kg ha^{-1}) Main	Off	Spikelet fertility (%) Main	Off
340	+0	103.7	99.4	6396	6638	91.3	90.8
340	+2	101.2	98.0	5977	6310	89.3	88.5
340	+4	99.7	97.4	5677	5901	85.6	84.7
400	+2	101.2	98.0	6697	7072	88.1	87.5
400	+4	99.7	97.4	6303	6551	84.9	83.5
450	+2	101.2	98.4	7066	7550	86.5	86.2
450	+4	99.7	97.4	6723	7128	82.8	81.9

Spikelet sterility increased with increasing temperatures. At the current level of CO_2 a 2°C rise in temperature resulted in a 2.0-4.3% increase in spikelet sterility during the main season and 2.3-4.5% during the off season over all sites. On the other hand, a 4°C rise in temperature increased spikelet sterility by 5.7-10.5% and 6-10% in the main and off seasons, respectively. With increasing CO_2 concentrations, simulated spikelet sterility was only very slightly affected (less than a 1% reduction in fertility), but coupled to the higher temperature, spikelet sterility was further increased. Satake & Yoshida (1978) reported that spikelet sterility caused by high temperatures was induced almost exclusively on the day of anthesis with temperatures in excess of 35°C. Baker et al. (1992a) also reported a highly significant effect of temperature, resulting in an increase in spikelet sterility when temperatures were raised by 9°C in combination with an elevated CO_2 concentration of 660 ppm. However, the simulated spikelet sterility was not as high as that observed by Baker et al. (1992b), the reason being that temperatures used in the simulation were not as high as those used in their experiments.

Conclusions

From our results, it can be seen that the model predicted changes in maturation time, grain yield and spikelet sterility at elevated temperatures. However, the magnitude of changes simulated were small compared to that reported by Baker et al. (1992a, b). Thus the model may require further modification for a more reliable simulation of reported observed effects.

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