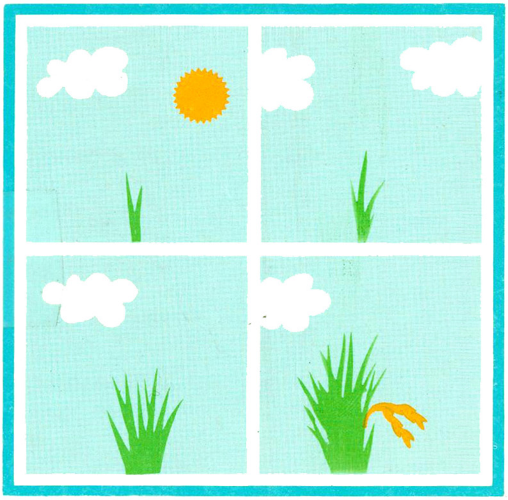
WEATHER AND RICE



International Rice Research Institute

WEATHER AND RICE

Proceedings of the international workshop on
The Impact of Weather Parameters on Growth and Yield of Rice
7-10 Apr 1986

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INTERNATIONAL RICE RESEARCH INSTITUTE
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The International Rice Research Institute (IRRI) was established in 1960 by the Ford and Rockfeller Foundations with the help and approval of the Government of the Philippines. Today IRRI is one of the 13 nonprofit international research and training centers supported by the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is sponsored by the Food and Agriculture Organization (FAO) of the United Nations, the International Bank for Reconstruction and Development (World Bank), and the United Nations Development Programme (UNDP). The CGIAR consists of 50 donor countries, international and regional organizations, and private foundations.

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The responsibility for this publication rests with the International Rice Research Institute.

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Foreword

Rice is cultivated under diverse climatic, hydrological, and edaphic conditions. Its wide adaptability is illustrated by rice cultivation at latitudes from 40°S to 53°N at elevations ranging from below sea level to more than 2,000 m; under upland conditions with no accumulated surface water and lowland conditions with no accumulated surface water and lowland conditions with 5 m deep water. Temperatures and humidity also vary widely. The importance of studies to determine the impact of weather variables on rice crop performance is apparent.

The Climate and Rice Symposium sponsored by IRRI in 1974 and the Agrometeorology of the Rice Crop Symposium sponsored by IRRI/WMO in 1979 helped summarize the progress made in explaining rice-weather relationships. In response to the recommendations made at the 1979 symposium, a coordinated series of rice-weather trials were carried out at several sites of the International Rice Testing Program (IRTP) during 1983-85. UNDP helped fund studies jointly organized by IRRI and WMO. The Ministry of Development Cooperation of the Government of The Netherlands made the services of an agroclimatologist available. Several rice scientists from national agricultural research programs in 16 countries in Asia, Africa, and Latin America conducted trials, using their own resources, and provided the valuable information suitable for a meaningful multilocation analysis of the impact of weather factors on rice yields.

A workshop on "The Impact of Weather Parameters on Growth and Yield of Rice" was organized at IRRI, 7-10 April 1986 to review the results of the multilocation IRRI/WMO rice-weather project and to exchange information about more recent research relative to crop-weather relationships. Proceedings from that workshop, including a report on the rice-weather project, form the content of this publication. I hope it will be useful to scientists involved in improving the productivity, stability, and profitability of rice-based cropping systems.

Dr. D.V. Seshu, IRRI plant breeder and International Rice Testing Program global coordinator, was chairman of the organizing committee for the workshop and served as technical editor of the proceedings. The volume was edited by Dr. M. LaRue Pollard, assisted by Emerita P. Cervantes.

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Opening remarks

Rice is the staple food of about half of mankind. At least 1.125 billion people, comprising 225 million rural families, depend on rice as their major crop; the majority of them are subsistence farmers.

National governments have long realized the importance of agricultural development to a country's economic well-being. Because agriculture is so vulnerable to weather and climate changes, a great deal of effort is being put into studies of the influence of weather and climate on crop growth and development.

In the Philippines, development of the countryside is hampered by the tropical climate. The low photosynthetic production of our rainfed crops is due to low solar radiation during the growing season. Yet these crops cannot be grown in the summer, when solar radiation is high, because of inadequate irrigation water. Rainfed crops also have high respiration rates or, in rice, a short grain-filling period because of the high mean temperature.

Crop yields are further reduced by such climatic extremes as typhoons and drought. On average, 19 tropical cyclones (depressions, storms, and typhoons) affect the country every year. The Bureau of Agricultural Economics statistics for the 15 yr 1968-82 show that 39% of rice and maize production losses were attributable to tropical cyclones and floods, 49% to drought, and 17% to weather-related incidence of insect pests and diseases.

An important and growing area of meteorological activity is the development of a sound and sustainable strategy for long-term agricultural planning. On the other hand, the farmer is faced with making day-to-day and week-to-week tactical decisions in which short-term weather conditions play a major role.

Explicit consideration of the weather in agricultural production, processing, storage, and distribution can optimize the output available from input. Waste of fertilizer and pesticide can be minimized if they are applied only when favorable weather is expected. Pollution of water bodies and the atmosphere by these inputs also can be minimized.

The World Meteorological Organization (the Philippines is an active member) has implemented a number of programs, including the World Climate Impact Studies (WCIP), to which the undertaking of this workshop is relevant.

The ultimate goal of the WCIP is to assist governments as they introduce climatic considerations into the formulation of national policies and to help them assess the vulnerability of their socioeconomic systems to climate change and variability, thereby developing strategies designed to reduce adverse impact and to exploit those that are favorable. Transfer of technology on climate impact assessment should be an important element within this program.

In the Philippines, specifically in the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), a system to assess climate impact for agriculture started in January 1985. Its objective is to provide a reliable and timely, yet inexpensive, weather-based information system that will continuously monitor and assess the impact of weather (such as drought, floods, typhoons, etc.) on rainfed agriculture.

Considering that the purpose of this workshop is to review the implications of studies on rice-weather relationships under irrigated conditions that have been carried out in selected rice-growing countries, the results should certainly contribute to the success of WMO programs in agricultural meteorology.

I am also pleased to note that part of the agenda of the workshop will deal with planning strategies for future research on rice-weather relationships under rainfed conditions. Results of such studies will undoubtedly be of immense value to agricultural development efforts, especially for less developed rice-growing countries that depend largely on rainfall for crop moisture requirements.

May I congratulate the UNDP and IRRI for organizing this workshop and assembling this group of experts to deal with this vital topic. May I wish all the participants every success in delineating research activities which will advance our understanding of the impact of climate on agriculture. My best wishes to all of you.

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Response of rice to weather variables

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Participants in the 1979 Symposium on Agrometeorology of the Rice Crop recommended that coordinated rice-weather experiments similar to previous international experiments on wheat and lucerne be undertaken (5). A project proposed by a joint IRRI/WMO working group had as its major objective:

> "to improve knowledge and understanding of the environment in which rice is grown so that the meteorological factors may be more fully used to develop further food production in the tropics. These studies will supplement information on varietal behavior of promising genotypes in different climatic environments and varietal differences in stability of yield performance in diverse environments as currently obtained from nurseries of the International Rice Testing Program (IRTP)."

The proposal suggested limiting the rice weather studies to fully irrigated areas, where water is not a constraint to the rice crop, and to areas where biological stresses and adverse soil conditions are negligible. Under those conditions, yield potential is related mainly to such atmospheric parameters as air temperature and solar radiation.

Rice weather studies were conducted at 23 sites in 16 countries within the International Rice Testing Program network. Appropriate meteorological equipment was installed at those sites where real-time weather observations did not provide information on solar radiation and temperature. During the 20-mo study, 65 trials were completed; data on daily rainfall, temperature, humidity, radiation, and wind speed were processed, and detailed information on phenological stages, yield, and yield components of 10 genotypes of rice (9 varieties plus a local check) were gathered. The technical report forms the basis of this summary (7).

Methodology

Seshu and Cady (8) demonstrated that, under full irrigation, the mean irradiance and mean minimum temperature during the postflowering stage of a rice crop correlated with economic yield. However, sparse data on certain radiation/ temperature combinations was a problem in estimating and interpreting weather-yield relationships. Also, the quality of radiation measurements and the availability of real-time weather measurements restricted location choices. Selecting representative sites and establishing agrometeorological stations with standards for uniform-quality weather data were the first concern.

Site selection

Sites studied should represent the wide variations in the climatic environments where rice is cultivated and should be free from such adverse soils problems as salinity, zinc deficiency, acid sulfate conditions, etc. With the help of national IRTP cooperators, the 5-yr FAO agroclimatic data bank, and the National Meteorological Services, climatic records for all the sites except Masapang were obtained. Mean monthly radiation during growing seasons ranged from 250 to >600 mWh/cm^2 per d and mean monthly minimum temperatures ranged from 12 to 26 °C.

The sites in 16 countries in Asia, Africa, and Latin America were grouped by annual fluctuations of mean monthly minimum temperature and mean monthly temperature of the coldest month of the year (Table 1).

Group 1, highly seasonal, has large seasonal minimum temperature fluctuations with a minimum temperature of less than 10 °C for the coldest month. Rice cultivation is restricted to one crop per year. Because of high latitude (more than 27 ° from the equator), seasonal solar radiation fluctuates widely. This group can be subdivided into arid zones with extremely high temperatures during the hot season and humid zones with much lower temperatures during the summer season.

Group 2, moderately seasonal, has moderate seasonal temperature fluctuations with a minimum temperature of more than 10 °C for the coolest month. Radiation fluctuations are less pronounced because the high potential radiation period coincides with the rainy season. Rice can be grown even in the cool season, although planting dates have to be selected to avoid cold spells during critical growth stages.

Table 1. Study sites arranged by seasonal temperature fluctuation.

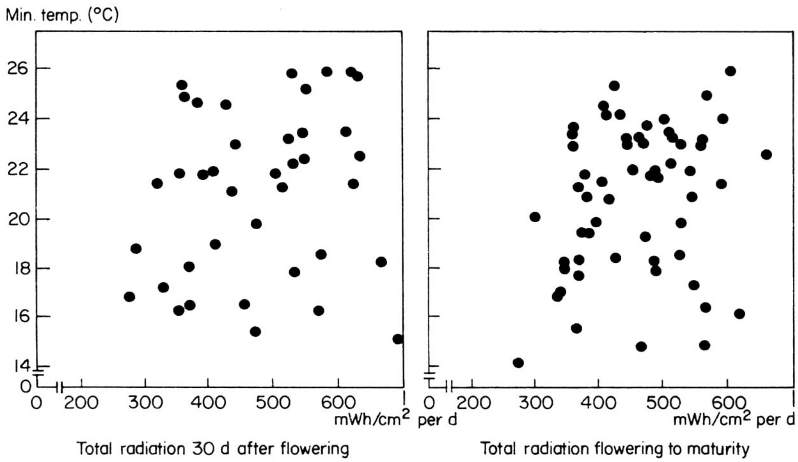
Site	Min temp (° Cd^{-1})	Max temp (° Cd^{-1})	Radiation (mWh/cm^2 per d)	Latitude	Altitude (m)
Group 1: Highly seasonal (minimum temperature fluctuation more than 10 °C and/or lowest minimum temperature less than 10 °C)					
Suweon, South Korea	–10.1 - +21.8	1.0 - 29.2	190-485	37°16'N	37
Milyang, South Korea	- 6.8 - +22.0	5.7 - 30.0	145-360	35°29'N	12
Nanjing, China	- 1.1 - +24.4	6.9 - 32.5	295-585	32°03'N	9
Kapurthala, India	5.2 - 25.7	18.6 - 39.2	350-700	30°56'N	247
Sakha, Egypt	6.0 - 19.0	19.3 - 34.0	290-725	31°05'N	20
Dokri, Pakistan	8.3 - 27.9	22.1 - 43.7	350-640	27°50'N	30
Parwanipur, Nepal	9.0 - 25.4	23.2 - 36.7	415-675	27°04'N	115
Group 2: Moderately seasonal (minimum temperature fluctuation 8-15 °C)					
Joydebpur, Bangladesh	11.4 - 26.2	25.1 - 32.8	395-610	23°54'N	8
Yezin, Burma	12.7 - 26.0	26.6 - 38.2	425-635	21°57'N	74
Sanpatong, Thailand	13.2 - 23.2	28.3 - 36.0	460-630	8°45'N	312
Hyderabad, India	13.2 - 26.1	27.7 - 38.6	355-650	17°25'N	545
Pingtung, Taiwan, China	13.6 - 24.8	24.6 - 32.5	330-440	22°40'N	24
Cuttack, India	14.3 - 26.3	27.6 - 39.2	350-520	20°30'N	23
Group 3: Weakly seasonal (minimum temperature fluctuation 3-8 °C)					
Coimbatore, India	18.4 - 22.3	28.9 - 35.3	445-620	11°02'N	431
Los Baños, (IRRI, Masapang), Philippines	21.2 - 24.2	28.0 - 32.6	350-635	14°10'N	21
Pattambi, India	22.2 - 26.5	30.3 - 33.5	390-645	10°48'N	25
Paranthan, Sri Lanka	23.3 - 27.1	28.1 - 31.9	450-650	8°59'N	4
Group 4: Nonseasonal (minimum temperature fluctuation less than 3 °C)					
Ibadan, Nigeria	22.0 - 23.7	27.3 - 33.8	450-545	7°34'N	200
Sukamandi, Indonesia	21.8 - 23.8	29.0 - 31.6	460-530	6°15'S	7
Muara, Indonesia	21.0 - 21.9	28.4 - 31.0	315-440	6°36'S	240
Palmira, Colombia	17.5 - 18.4	28.6 - 30.7	450-520	3°31'N	1006
Ahero, Kenya	13.1 - 15.1	28.5 - 31.4	630-720	0°09'S	1200

Group 3, weakly seasonal, has weak seasonal temperature fluctuations and seasonal fluctuations of wet and dry seasons; thus, seasonal radiation fluctuation becomes more important. If water is not a constraint, rice can be cultivated throughout the year.

Group 4, nonseasonal, is composed of sites located near the equator. With no seasonal temperature fluctuations, differences in temperature are related primarily to altitude. Seasonal radiation variations are much less pronounced than at locations farther away from the equator.

Trial date selection

To obtain maximum benefit from the selected sites, a minimum of two trials per calendar year was anticipated. Transplanting dates had to be selected to obtain the highest possible number of radiation/temperature combinations for the postflowering stage of the rice crop. Assuming that most of the genotypes selected would flower after a mean temperature sum of 1900 °C was accumulated, transplanting dates could be determined from available mean air temperature records. Figure 1 shows the expected and actual minimum



1. Estimated (a) and actual (b) mean minimum temperature and average total radiation for postflowering period for 65 trials at 23 sites.

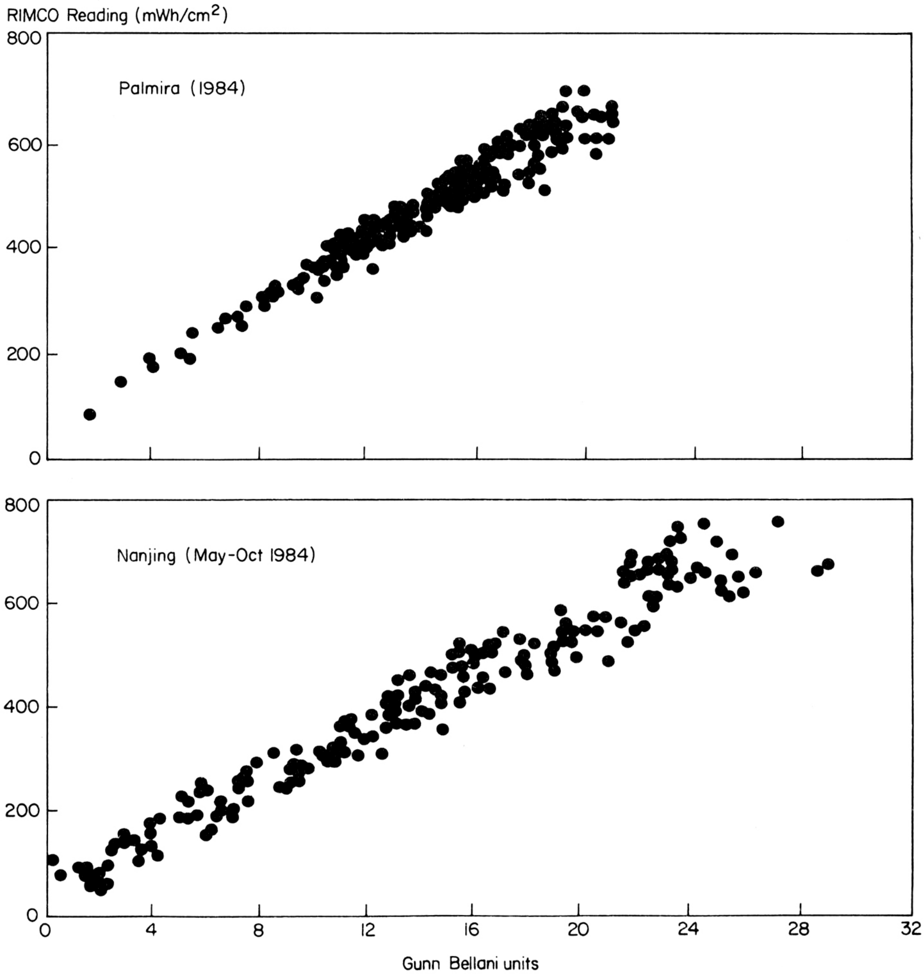
temperatures and total radiation for the postflowering period at all sites except Masapang. The two weather variables are statistically independent (r^2 = 0.12), although there is a weak tendency for minimum temperatures to be higher with higher total radiation.

Agrometeorological stations and global measurements

Because on-site monitoring of the most important weather variables is imperative for rice-weather studies, considerable effort was made to establish standard agrometeorological stations at sites where such a station was not available. Because it was considered desirable to measure global radiation directly instead of using such indirect measurements as sunshine duration, all 23 sites were equipped to measure global radiation. Criteria used to select the radiation measuring equipment included simple observation procedures, low maintenance, weatherproof under humid tropical conditions, no need for frequent calibration, and no need for a reliable source of electricity.

The RIMCO electronic integrating pyranometer type R/ET (Selbys Scientific Ltd., Oakleigh, Victoria, Australia) was chosen. It is self-contained. Built-in solar cells capture energy to charge the internal battery that drives the digital integrator, giving direct cumulative readings of total global radiation in mWh/cm^2. It is weatherproof under humid tropical conditions. Measurements with this pyranometer and the standard Kipp solarimeter correlated significantly.

The Gunn Bellani radiation integrator (Baird and Tatlock, Romford, Essex, England) was selected as a backup. Its method of integrating radiation also does not rely on electronic or mechanical devices. It provides a time-integrated assessment of radiation falling on a black body by measuring the volume of liquid distilled. Because the instrument does not record direct values,



2. Comparison of total radiation measured by Gunn-Bellani units and by RIMCO at Palmira and Nanjing.

it has to be calibrated against a direct recording solarimeter (Fig. 2). Its low cost makes this instrument particularly suitable for national agrometeorological networks.

Nursery composition

Each nursery was composed of nine varieties and lines selected from the best entries in the International Rice Yield Nursery (IRYN) and a local check. Entries originated from IRRI, Philippines, Sri Lanka, and Taiwan, China (Table 2). BG367-4, MRC603-303, IR13429-196-1, IR50, IR9828-91-2-3, and Taichung sen yu 285 ranked high for yield in earlier irrigated early maturity yield trials.

Table 2. Entries in the 1983-85 International Rice Weather Yield Nursery.

Entry	Cross	Origin
BG35-2	IR8-24-5//M307/H5	Sri Lanka
BG367-4	BG280-1*2/PTB33	Sri Lanka
MRC603-303	C12//Sigadis/TN1///IR24	Philippines
IR13429-196-1	IR4432-53-33/PT833//IR36	IRRI
IR36	IR1561-228/14*IR24/O. niv./// CR94-13	IRRI
IR50	IR2153-14-1-6-2/1R28//1R36	IRRI
IR9729-67-3	BG34-8/IR28/IR36	IRRI
IR9828-91-2-3	IR2071-559-2-4-6/ IR1820-52-2-4//1R36	IRRI
Taichung sen yu 285	Taichung sen shih 204/ Taichung sen shih 199	Taiwan, China
Local check		

Table 3. Minimum data set of daily weather and crop parameters.

Weather data	Crop data
Rainfall (mm)	Days from seeding to flowering
Max temp (°C)	Days from seeding to maturity
Min temp (°C)	Transplanting date
Dry bulb temperature (°C) (2× a day)	Plant height
Wet bulb temperature (°C) (2× a day)	Panicles per hill
Total global radiation (mWh/cm^2)	Filled grains per panicle
1. RIMCO electronic integrating pyranometer	Percent unfilled grains per panicle
2. Gunn Bellani radiation integrator	1,000-grain weight
Wind run (optional) (ms^{-1})	Plot yield (14% moisture)

BG35-2 ranked third and second in 1979 and 1980 upland yield trials, but had good phenotypic ratings in irrigated observational nurseries. IR9729-63-3 produced high yields in various very early irrigated yield trials. IR36 has been among the top 5 entries for yield in both irrigated and upland trials over the past several years. All entries are moderately resistant or resistant to some of the major insects and diseases (bacterial blight, blast, brown planthopper, stem borer).

Nursery management and layout

The experimental sites were required to have adequate irrigation facilities and be well-leveled and free from adverse soil problems. The plots, laid out in a randomized complete block design with 5 replications, were to be at least 10 m^2 for each entry, with seedlings spaced 15 × 20 cm. No blanket recommendations were given for site-specific management. N, P. K levels were those that would lead to maximum yields at the site. Seedbed and main crop were protected against insect pests and diseases to minimize biological constraints. Plots were kept as weed-free as possible.

Data collection

A minimum set of weather and crop data were collected and recorded in specially designed weather logbooks and nursery fieldbooks to ensure uniform sets of data that could be readily transferred into the computer data bank (Table 3). The weather data were processed and monthly weather reports were returned to the participating research sites for validation and for local use. A complete set of 5-d totals and means of the weather data for each trial and the complete results of the crop data for each trial are included in the special report (7).

Crop Performance

The mean yields for the 9 test entries (CV less than 20% for 55 of 65 trials) ranged from 4.4 t ha for IR9729-67-3 to 4.9 t/ha for IR9828-91-2-3; mean yields for the trials ranged from 2.2 t/ha in the third trial at Paranthan to 9.4 t/ha in the third trial at Suweon. This general result clearly indicates the significant impact of environment on yield.

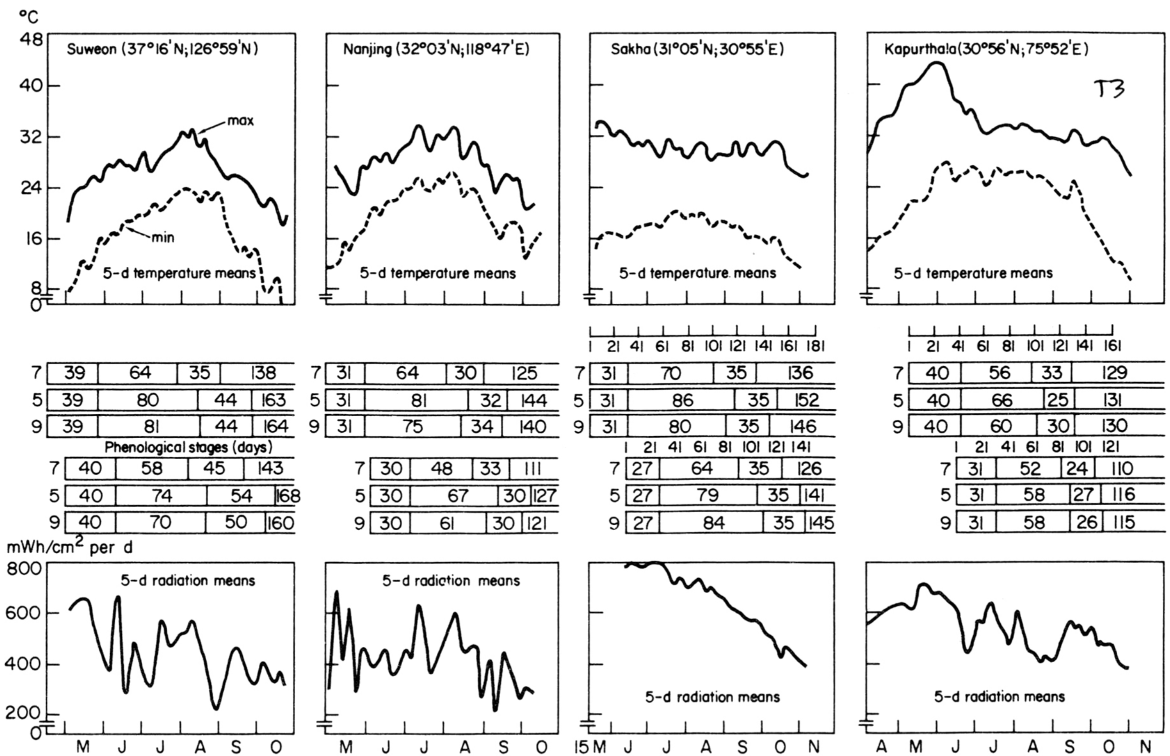
Agroclimatic region and yield

The regions are characterized by annual minimum temperature fluctuations and minimum temperature of the coldest month.

Group 1 — highly seasonal. The trials were in the temperate and subtropical regions (Suweon, Milyang, Nanjing, Kapurthala, Sakha, Dokri, Parwanipur). Because of low winter temperatures, only one rice crop can be cultivated a year. We compared normal planting dates and late planting dates (about 1 mo later).

Temperature and radiation values and length of phenological stages for Suweon, Nanjing, Sakha, and Kapurthala are shown in Figure 3. The low values for minimum temperature during seedbed and final ripening stages are striking. Radiation was rather low, particularly late in the growing season. Late planting at Suweon resulted in a very long postflowering period (54 d for IR36), which is obviously related to low temperatures. Despite the low temperatures, the crop at Nanjing was harvested by 30 d after flowering. This relatively short post-flowering period resulted in fewer filled grains and a lower 1,000-grain weight in the late trial than in the early trial (Table 4). The yield was greatly reduced in the late trial at Nanjing, but only moderately reduced in the Suweon and Milyang trials (Table 5).

Temperatures at Sakha did not fluctuate strongly during the growing season. The below 20 °C minimum temperature dropped to 15 °C toward the end of the growing season. What was significant at Sakha was very high radiation values, around 600 mWh/cm^2 per d during postflowering in the early trial but only around 450 mWh/cm^2 per d during postflowering in the late trial. This low radiation may be the primary reason for reduced yields in the second trial.



3. Maximum and minimum temperatures, total radiation, and length of phenological stage for three entries (7 = IR9729-67-3, 5 = IR36, 9 = Taichung sen yu 285) at Suweon, Nanjing, Sakha, and Kapurthala, 1984).

Table 4. Filled grains per panicle and 1,000-grain weights for trials 2 (early sowing) and 3 (late sowing) at Nanjing, 1984.

Entry	Filled grains/panicle (no.)		1,000-grain weight (g)	
	Early	Late	Early	Late
BG35-2	81	36	26	24
BG367-4	113	85	21	19
MRC603-303	59	31	25	23
IR13429-196-1	75	46	23	22
IR36	62	41	23	21
IR50	58	40	18	17
IR9729-67-3	78	51	25	23
IR9828-91-2-3	63	41	22	21
Taichung sen yu 285	79	58	24	23
Local check	73	71	24	24

Table 5. Real-time weather summary for flowering to harvest and yields for IR36 in early and late sowing trials at Suweon, Milyang, Nanjing, Sakha, and Kapurthala.

	Suweon	Milyang	Nanjing	Kapurthala	Sakha
		Early sowing			
Min temp (°C)	19.9	20.9	21.6	23.9	16.5
Radiation (mWh/cm^2 per d)	399	417	405	514	669
Postflowering period (d)	44	41	32	25	35
Yield (t/ha)	10.3	8.0	5.7	4.8	9.1
		Late sowing			
Min temp (°C)	15.6	17.8	18.0	18.7	14.8
Radiation (mWh/cm^2 per d)	368	373	345	501	467
Postflowering period (d)	54	45	30	27	35
Yield (t/ha)	8.2	7.6	3.7	4.4	4.9

At Kapurthala, very high maximum temperatures during seedbed and early growth in the early trial and an abrupt drop in minimum temperature during postflowering in the late trial were important. Despite high radiation levels, yields were consistently lower than at other sites in this group.

Because both radiation and temperature drop beginning in September, it appears that the earlier the crop is transplanted, the better yields will be, except at Kapurthala, where extremely high temperatures in May and June prohibit early transplanting.

Group 2 — moderately seasonal. This group includes Joydebpur, Yezin, Sanpatong, Hyderabad, Pingtung, and Cuttack. These areas are characterized by dry cool winters and warm to hot humid summers. Trials were conducted during both seasons. Minimum temperatures during preflowering of the cool dry season trials were relatively low, resulting in an extended vegetative period. Temperatures increased rapidly during postflowering. These conditions were reversed for the hot humid season trials.

Radiation from transplanting to harvest also increased in the cool dry season, but decreased in the hot humid season. The long vegetative period resulted in a higher number of panicles per hill. In combination with high radiation levels during postflowering, this resulted in relatively higher yields for the cool dry season trials than for the warm humid season trials (Table 6).

A higher incidence of insect pests and diseases during the warm humid season may have influenced yields.

Although mean monthly minimum temperatures during the cool dry season were above 10 °C, temperatures at Joydebpur during January occasionally dropped below 10 °C. This could cause some sterility if cold spells occur during panicle initiation to flowering. This actually happened in the first cool dry season trial at Joydebpur (transplanted on 5 Dec). The second cool dry season trial at Joydebpur (transplanted 20 Dec) escaped these cold spells and had significantly higher yields (Table 7).

Table 6. Real-time weather summary for transplanting (trpl) to flowering (flow) and flowering to harvest (harv) and yields of IR36 for the cold dry season and hot humid season at Joydebpur, Cuttack, Sanpatong, and Pingtung.

	Joydebpur	Sanpatong	Pingtung	Cuttack
	Cold dry season			
Min temp, trpl-flow (°C)	13.5	18.4	15.8	20.7
Radiation, trpl-flow (mWh/cm^2 per d)	434	541	390	501
Trpl-flow period (d)	108	68	89	76
Min temp, flow-harv (°C)	23.3	21.5	21.4	26.2
Radiation, flow-haw (mWh/cm^2 per d)	561	593	371	607
Flow-haw period (d)	23	19	26	24
Panicles/hill	14	10	20	16
Yield (t/ha)	5.5	5.3	4.4	5.4
	Hot humid season			
Min temp, trpl-flow (°C)	25.2	23.0	22.7	26.0
Radiation, trpl-flow (mWh/cm^2 per d)	427	496	317	532
Trpl-flow period (d)	72	59	71	66
Min temp, flow-haw (°C)	24.7	22.1	14.7	23.9
Radiation, flow-haw (mWh/cm^2 per d)	434	456	275	477
Flow-haw period (d)	23	28	36	25
Panicles/hill	19	15	12	12
Yield (t/ha)	2.6	2.9	1.7	4.8

Table 7. Yields of entries transplanted 5 and 20 Dec 1983, at Joydebpur.

Variety	Yield (t/ha)	
	Early (5 Dec)	Late (20 Dec)
BG35-2	3.7	4.9
BG367-4	3.5	4.7
MRC603-303	4.5	5.1
IR13429-196-1	3.8	4.4
IR36	4.3	5.5
IR50	4.1	4.9
IR9729-67-3	3.2	4.5
IR9828-91-2-3	3.8	5.0
Taichung sen yu 285	4.4	5.2
BR6 (Local check)	2.7	4.0

The 5-d weather data and length of phenological stages for 3 entries at Joydebpur, Cuttack, and Sanpatong are shown in Figure 4.

Group 3 — weakly seasonal. This group includes Coimbatore, Los Baños (IRRI and Masapang), Pattambi, and Paranthan. Seasonal fluctuations are related to the monsoon, with heavy rainfall during the wet season and virtually rainless periods during the dry season. With water for irrigation, rice can be cultivated throughout the year. Extremely heavy wet-season rainfall can sometimes lead to lodging. High humidity during the wet season and relatively high temperatures in both seasons are favorable for insect pests and diseases.

On the other hand, during the dry season, weather conditions, particularly high radiation levels, are favorable for rice. Yields during the dry season at Los Baños and Masapang were significantly higher than during the wet season. Despite high radiation levels, dry-season yields at Paranthan, although higher than wet-season yields, were still relatively low, possibly because of relatively high salinity in this area.

No dry-season trials were conducted at Coimbatore and Pattambi. In wet season trials, heavy rainfall at Pattambi during early growth stages, with a high incidence of pests and diseases, compared to relatively dry and moderately cool conditions at Coimbatore (at 430 m above sea level), possibly explains the higher yields at Coimbatore.

Figure 5 illustrates weather conditions and length of phenological stages at Los Baños. Table 8 summarizes weather and yield data for wet and dry seasons at Los Baños, Masapang, and Paranthan and for wet seasons at Pattambi and Coimbatore.

Group 4 — Nonseasonal. Sites in this group are located near the equator (Ibadan, Sukamandi, Muara, Palmira, and Ahero). Average minimum temperatures ranged from 23.5 °C at Sukamandi and Ibadan to 18.0 °C at Palmira and 14.8 °C at Ahero (1,200 m above sea level).

Heavy rainfall throughout the year at Muara leads to low radiation levels. Although Sukamandi has distinct wet and dry seasons, radiation levels do not differ significantly between the two seasons because the dry season coincides with the period of low potential radiation.

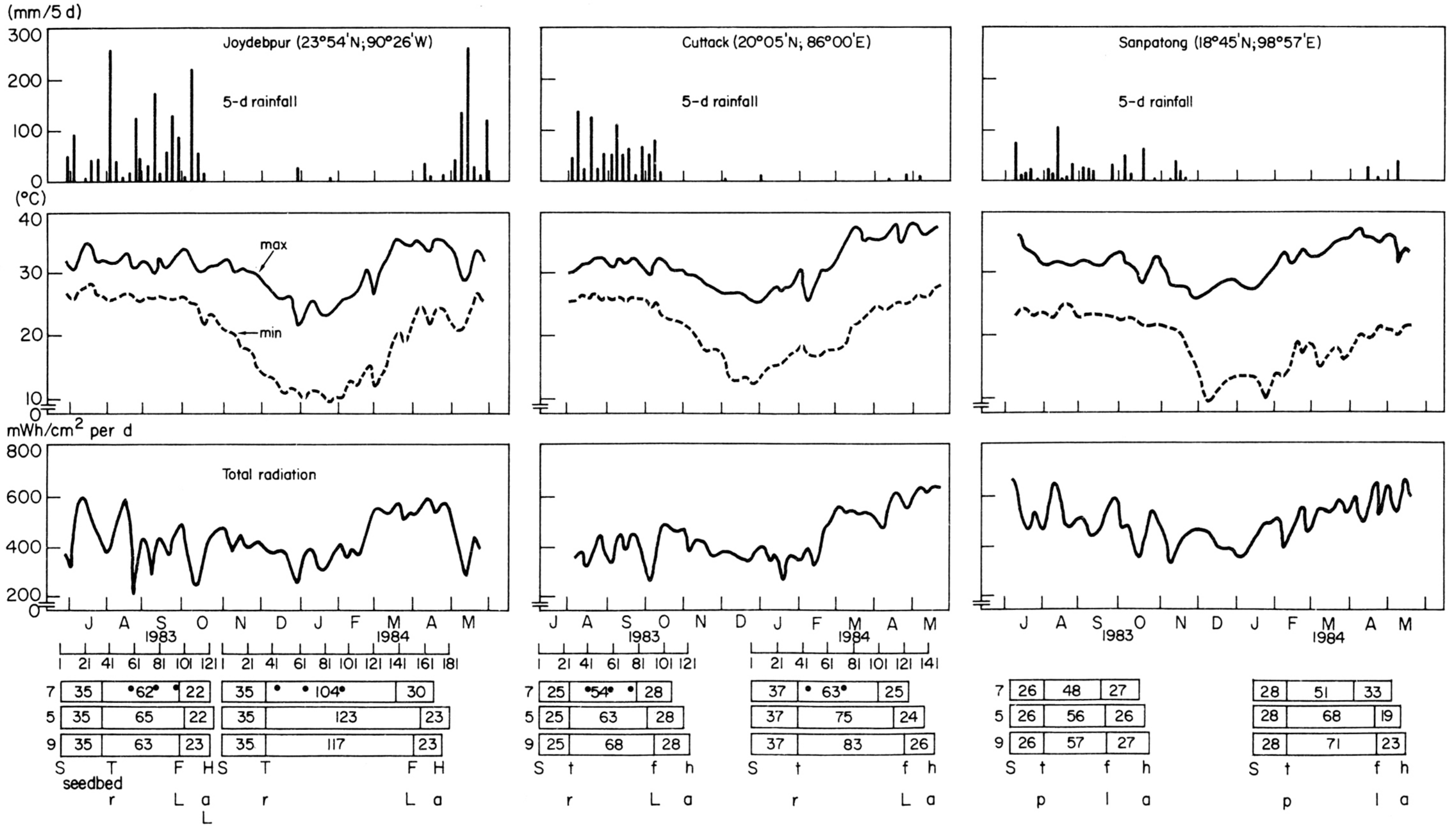
Weather conditions at Ahero are optimum for yield: low minimum temperatures, high daytime temperatures, and high radiation levels. Unfortunately, only one trial could be conducted at this site. Seed germination was poor, sufficient for only two or three replications. Despite the high variability among replications, trial yields indicate that weather conditions at Ahero are conducive to high production.

The Palmira site is in the middle: moderately high radiation levels and cool nights led to yields of 6-7 t/ha.

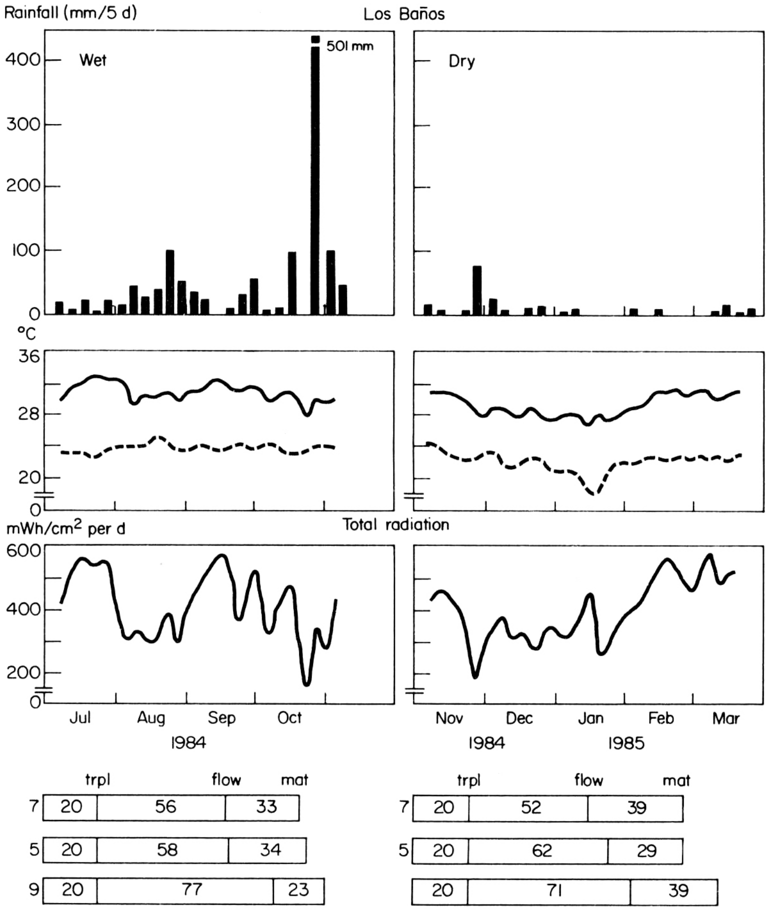
Table 9 summarizes weather and yield data for these five sites.

Length of phenological phases

Four characteristic times were examined: sowing date, transplanting date, flowering date, and date of harvest. The length of each period (sowing to transplanting, transplanting to flowering, flowering to harvest) are discussed



4. Rainfall, maximum and minimum temperatures, total radiation, and length of phenological stage for 3 entries (7 = IR9729-67-3,5 = IR36, 9 =Taichung sen yu 285) at Joydebpur, Cuttack, and Sanpatong.



5. Real-time weather variables (rainfall, maximum and minimum temperatures, and total radiation) and length of phenological phase for 3 entries (7 = IR9729-67-3,5 = IR36, 9 = Taichung sen yu 285) during wet and early dry seasons at Los Baños. tprl =transplanting, flow = flowering, mat = maturity.

separately. Growth duration from transplanting to flowering varied from 45-92 d for very early-maturing IR9729-67-3 to 54-108 d for IR36. The postflowering period ranged from 23-35 d for IR9729-67-3 to 23-44 d for IR36. Exact flowering dates are difficult to compare among sites because flowering percentage was not necessarily reported at the same level by different cooperators. Unfortunately, panicle initiation date was not recorded.

Sowing to transplanting. Temperatures during the seedbed period varied widely, from a minimum of less than 10 °C during the first 20 d of early sowing date trials at Suweon to a maximum of more than 40 °C at Kapurthala. Yoshida (9) indicated that seedlings are sensitive to temperature from the first week of postgermination growth. Growth rate increases linearly with temperatures between 22 and 31 °C but declines sharply above 35 °C. Nishiyama (6)

Table 8. Weather and yields of IR36 in different seasons at Los Baños, Masapang, Paranthan, Coimbatore, and Pattambi.[a]

	Coimbatore	Los Baños	Masapang	Pattambi	Paranthan
		Dry season			
Total rainfall, trpl-harv		289	15		154
Min temp, flow-harv		24.1	22.8		25.1
Radiation, flow-harv		509	606		571
Yield (t/ha)		6.6	5.6		3.2
		Wet season			
Total rainfall, trpl-harv	240	1039	1137	1346	1596
Min temp, flow-harv	19.4	23.6	23.3	23.1	23.1
Radiation, flow-harv	475	364	445	525	358
Yield (t/ha)	5.3	4.4	4.1	3.9	2.6

[a]trpl = transplanting, harv = harvest, flow = flowering.

Table 9. Weather and yields during postflowering at Muara, Sukamandi, Ibadan, Palmira, and Ahero for BG35-2, IR36, and IR7929-67-3.

Trial site	Elevation (m)	Min temp (°C)	Radiation (mWh/cm^2 per d)	Yield (t/ha)		
				BG35-2	IR36	IR7929-67-3
Ibadan	200	23.4	481	7.1	6.5	4.8
Sukamandi 2	5	22.7	518	3.8	3.7	3.3
Sukamandi 3	5	23.5	515	7.3	6.4	3.7
Muara	240	21.5	394	3.6	3.7	2.9
Palmira	1000	18.0	486	6.0	6.4	5.1
Ahero	1200	14.8	561	7.8	-	5.9

considered approximately 13 °C the critical mean air temperature for sowing rice. At temperatures higher than 35 °C, elongation of primary roots is strongly inhibited, even more than shoot growth.

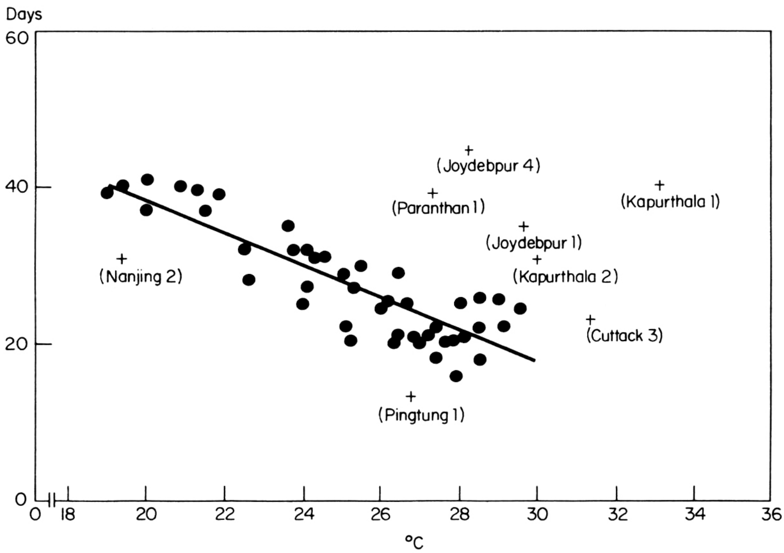
Figure 6 illustrates the relationship between mean air temperature and length of seedbed period. For 47 observations within a 19-28.5 °C temperature range and a 16-41 d seedbed period, the linear relationship: y = 81.24 - 2.14X (in which X is the mean air temperature in °C and y is the seedbed period in days) is highly significant (r^2 = 0.74). But a number of sites deviated from this relationship:

Kapurthala 1: The mean air temperature was 33.1 °C with maximum temperatures higher than 40 °C. This may have reduced seedling growth rates.

Cuttack 3: Maximum temperatures were consistently more than 35 °C throughout the seedbed period, delaying growth.

Paranthan 1: Although mean air temperature was 27.3 °C, drought stress may have delayed seedling development.

Joydebpur 4: Transplanting probably was delayed because of extreme heavy rainfall (44-d old seedlings were transplanted at a mean air temperature of 28.2 °C). No apparent reason can be detected for the late transplanting at



6. Relationship between mean air temperature and time from seeding to transplanting. + = not included in calculating linear regression.

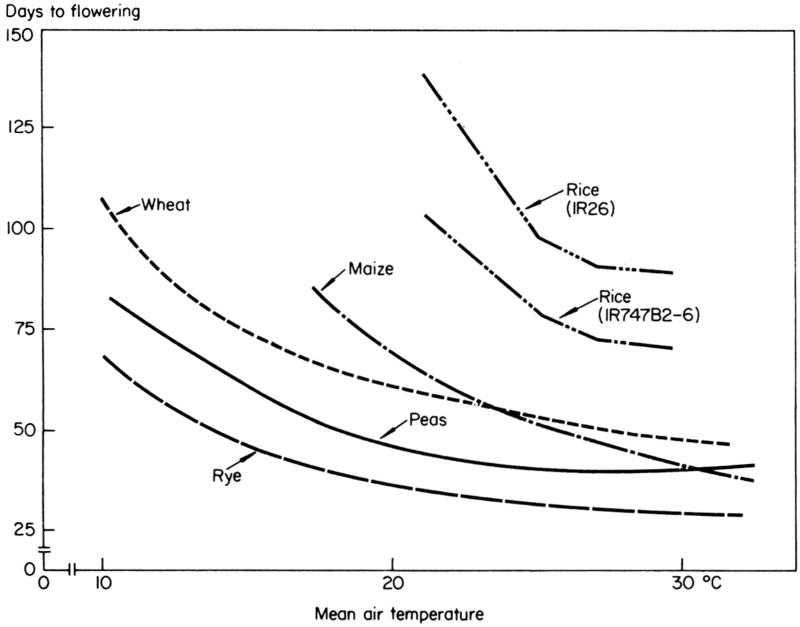
Joydebpur 1 (35 d at 29.6 °C) and Kapurthala 2 (31 d at 29.9 °C). Late transplanting where no temperature or drought stress is apparent may have resulted in tall, weak seedlings with reduced tillering capacity.

Transplanting to flowering. Higher temperatures accelerate the rate of development at all phenological stages. This implies that the length of a given phenological phase is shorter at higher temperatures. Van Dobben (8) collected data on the length of the period from emergence to anthesis for a number of crop species grown at different constant temperatures. The shape of the curvilinear relationship between mean air temperature and days to flowering (Fig. 7) suggests a constant product of days and temperature (also called heat units, heat sum, or degree days). Yoshida (9) found that the number of days to heading has a curvilinear relationship with temperature within a 21-30 °C range. His results for two photoperiod-insensitive rice varieties grown in temperature-controlled glasshouses are inserted into Figure 8.

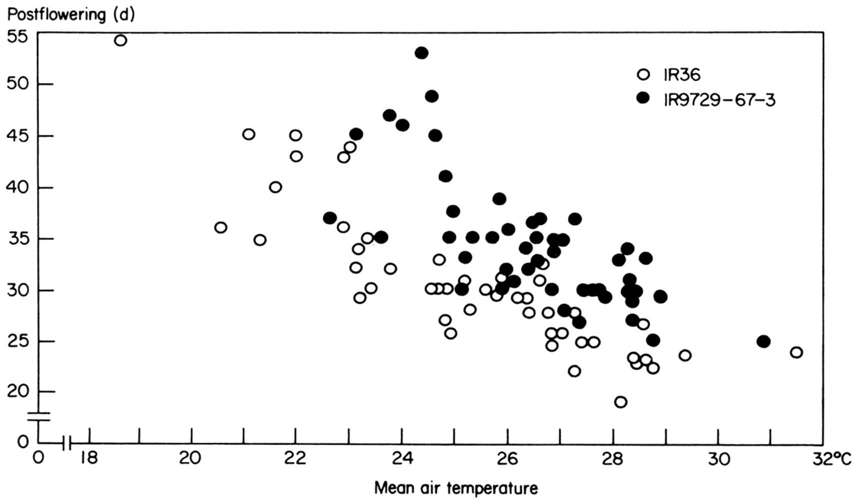
We observed somewhat similar relationships, although in field experiments these effects are confounded with other influences, such as seedlings at different stages of development when transplanted; uniform to continuously increasing/decreasing temperatures during transplanting to flowering; differences in exact flowering date.

Table 10 shows the length of the transplanting to flowering period for IR36 and IR13429-196-1 and mean air temperature and temperature sum for a number of sites at different latitudes.

Although temperature sums vary among sites, a greater temperature sum is required for IR36 than for IR13429-196-1, implying that IR36 is a longer-



7. Influence of temperature on length of preflowering period. Sources: For rice (10); for maize, wheat, peas, and rye (9).



8. Effect of mean air temperature on length of postflowering period of IR36 and IR9729-67-3.

duration variety. Separating sites by latitude clearly demonstrates that a smaller temperature sum is needed at lower latitudes than at higher latitudes. More days were needed for these rice entries to flower in sites characterized by longer days.

Table 10. Mean air temperatures, days to flowering, and temperature sums during transplanting to flowering for IR36 and IR13429-196-1 at sites 0-20° from the equator and north of 20°.

Site	Latitude	IR36			IRI3429-196-1		
		Air temp (°C)	Days to flowering	Temp sum (°C)	Air temp (°C)	Days to flowering	Temp sum (°C)
High-latitude:							
Pingtung 3	22°40'N	21.5	89	1913	21.2	82	1738
Suweon 3	37°16'N	23.9	80	1912	23.5	72	1692
Sakha 2	31°05'N	24.0	79	1896	24.1	69	1663
Milyang 3	35°29'N	24.5	77	1886	24.2	71	1718
Milyang 2	35°29'N	25.6	74	1894	25.6	68	1740
Nanjing 1	32°03'N	26.8	74	1983	27.1	68	1843
Nanjing 3	32°03'N	27.5	67	1842	27.8	61	1696
Cuttack 4	20°30'N	28.2	70	1974	28.4	66	1874
Parwanipur 2	27°04'N	28.4	67	1903	28.5	64	1824
Kapurthala 2	30°56'N	29.8	66	1967	29.8	61	1817
Mean temperature sum				1917			1760
Low-latitude:							
Palmira 2	3°31'N	23.5	67	1574	23.5	63	1480
Los Baños 4	14°10'N	24.8	62	1537	24.8	60	1488
Masapang 1	14°10'N	25.2	63	1588	25.1	59	1481
Paranthan 3	8°59'N	25.6	59	1510	25.5	56	1428
Pattambi 3	10°48'N	25.9	58	1502	25.9	54	1399
Muara 1	6°36'S	26.0	60	1560	26.1	54	1409
Sukamandi 2	6°15'S	26.9	57	1533	27.0	52	1404
Los Baños 3	14°10'N	27.6	58	1600	27.6	54	1490
Sanpatong 1	18°45'N	28.0	57	1596	28.0	55	1540
Los Baños 1	14°10'N	28.8	55	1584	28.8	53	1526
Mean temperature sum				1558			1464

This might indicate some photoperiod sensitivity. The temperature sum differences for IR36 are larger than for IR13429-196-1, implying that IR36 is somewhat more sensitive to daylength.

The Joydebpur cool-season sites are not included in these two sets of data. There, the transplanting to flowering period lasted much longer than would be expected from the mean temperature sums. But temperatures occasionally dropped to very low values, implying a critical value below which growth is significantly reduced. At a mean air temperature of 21.2 °C, IR36 took 108 d to flower, but temperatures fluctuated from 15.1 °C to 28 °C.

Flowering to ripening. Traditionally, the flowering to ripening period is considered to be about 30 d. But these trials clearly indicate that temperature determines its length. Therefore, a temperature sum can be calculated for this period. There was little difference among varieties and the difference between high- and low-latitude sites was not clear (Fig. 8). It appears that IR36 tends to mature a few days earlier than IR9729-67-3 under similar temperature regimes. Table 11 gives the temperature sums for the 2 phenological periods under long and short daylengths, represented by latitude locations above 20 °N, and below 20 °N, for the 9 entries.

Table 11. Temperature sums for transplanting (trpl) to flowering (flow), flowering to maturity (mat), and transplanting to maturity under long and short daylengths.

Entry	Short daylength (0-20° N)			Long daylength (20-40° N)		
	Trpl-flow	Flow-mat	Trpl-mat	Trpl-flow	Flow-mat	Trpl-mat
BG35-2			2370			2730
86367-4			2370			2680
MRC603-303			2550			2760
IR13429-196-1			2550			2690
IR36	1645	800	2445	1920	855	2775
IR50	1555	805	2360	1705	855	2560
IR9729-67-3	1485	845	2330	1625	865	2490
IR9828-91-2-3			2440			2750
Taichung sen yu 285	1780	810	2590	1950	840	2790

Although all entries were selected from irrigated early nurseries (only IR9729-63-3 was selected from the very early nurseries), there is still a difference of about 2 wk (or 200 degree days) among the entries. All entries appear to be somewhat photoperiod-sensitive, in particular BG35-2, BG367-4, IR9828-91-2-3, and IR36. A short-duration, less photoperiod-sensitive entry is preferred in regions where the growing period is limited by temperature.

Plant characteristics and yield components

Most of the trials reported plant height at harvest, number of panicles per hill, number of filled grains per panicle, percentage of unfilled or incompletely developed grains, and 1,000-grain weight. The analysis of these ancillary characteristics indicated both varietal differences and environmental differences.

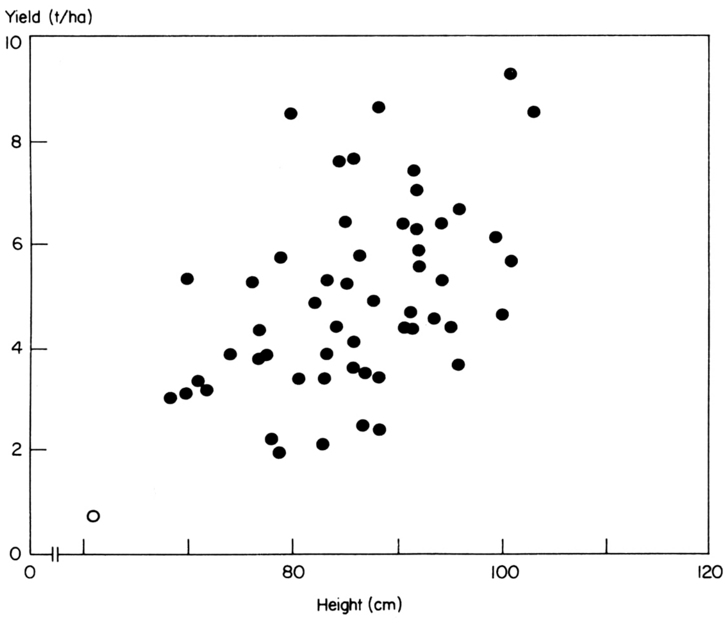
Plant height. All test entries were semidwarf plant types. However, differences in plant height were noted among the varieties, among sites, and between seasons and years at given sites. Site means for plant height varied from 65 cm at Yezin 2 to 103 cm at Suweon 3 and 4. The varietal mean across sites ranged from 78 cm for IR36 and IR9828-91-2-3 to 93 cm for Taichung sen yu 285. Plant heights were lower in the late-season trials than in the early-season trials at Sakha, Kapurthala, Nanjing, and Hyderabad, and in the cool-season trials than in the hot wet season trials at Pingtung, Joydebpur, and Cuttack (Table 12). In general, reduced temperatures and/ or reduced light intensity during the vegetative period appeared to reduce plant height.

Higher plant density also affected plant height. In Palmira, 30 × 30 cm plant spacing resulted in 84 cm plant height, but 15 × 20 cm spacing resulted in 92-cm-tall plants. Below-normal plant height also could be the result of low fertilizer application or of drought stress, as is evident in the Yezin and Paranthan trials, where average plant height was only 62 and 68 cm. Taller plants have a larger leaf area, thus larger photosynthetic activity, which could be a positive parameter in relation to yield (Fig. 9).

Panicle formation. Theoretically, under optimal conditions, 40 tillers could be produced by a single hill (9). However, all tiller buds do not necessarily develop into tillers. Some remain dormant. Spacing, light, nutrient supply, and

Table 12. Effect of transplanting (trpl) season on average plant height.

Site	Early/hot wet season			Late/cool dry season		
	Temp (°C) (trpl-maturity)	Radiation (mWh/cm^2 per d) (trpl-maturity)	Plant ht (cm)	Temp (°C) (trpl-maturity)	Radiation (mWh/cm^2 per d) (trpl-maturity)	Plant ht (cm)
Sakha	24.2	718	88	24.1	660	69
Kapurthala 1, 2	29.8	532	100	28.9	492	87
Nanjing 2, 3	26.9	456	102	25.7	466	96
Hyderabad 2, 3	26.8	515	92	26.3	551	76
Pingtung 1, 2	28.5	430	96	26.9	317	62
Joydebpur 1, 2	28.8	423	88	20.2	425	73
Cuttack (3, 2)	29.8	429	93	27.1	501	84



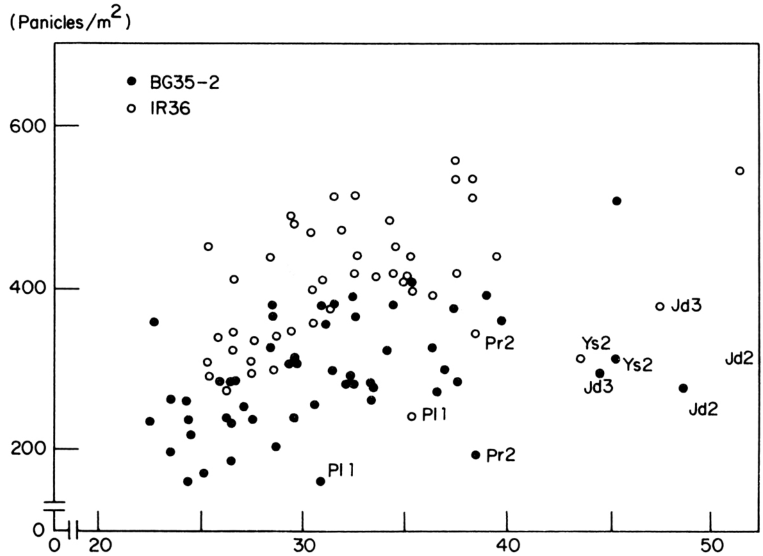
9. Effect of plant height on yield (means of nine entries].

other environmental and cultural conditions affect tillering. And not all tillers develop into panicles.

Number of panicles per hill means varied from 7 (Hyderabad 2, Pattambi 2, Cuttack 1) to 21 (Pingtung 1, Los Baños 4, Sakha 1). Overall means for different entries showed a narrow spread, from 10 panicles/ hill for BG35-2 to 15 for IR50. Although a standard plant spacing of 15 × 20 cm was recommended, some trials were conducted at wider (Palmira 1 30 × 30 cm; Pingtung 1 20 × 25 cm) or narrower (Coimbatore 2 10 × 15 cm) spacing. The results clearly show that an increase in plant density leads to a lower number of panicles per hill but a higher number of panicles per m^2 (Table 13).

Table 13, Average panicles per hill and panicles per m^2 at various plant densities, Palmira and Coimbatore.

Site	Spacing	BG35-2	BG367-4	MRC603-303	IR13429-196-1	IR36	IR50	IR9729-67-3	IR9828-91-2-3	Taichung sen yu 285	Local check
						Panicles/hill					
Palmira	30 × 30	15	15	20	19	22	26	16	21	16	18
	15 × 20	12	12	14	13	16	17	15	16	11	13
Coimbatore	15 × 20	9	8	10	8	10	11	11	10	9	9
	15 × 10	8	8	8	8	8	7	8	8	8	8
						Panicles/m^2					
Palmira	30 × 20	168	172	223	215	240	287	177	229	176	203
	15 × 20	386	408	461	442	523	560	491	520	381	440
Coimbatore	15 × 20	287	273	320	267	347	353	360	327	307	293
	15 × 10	507	547	547	520	533	493	533	547	533	507



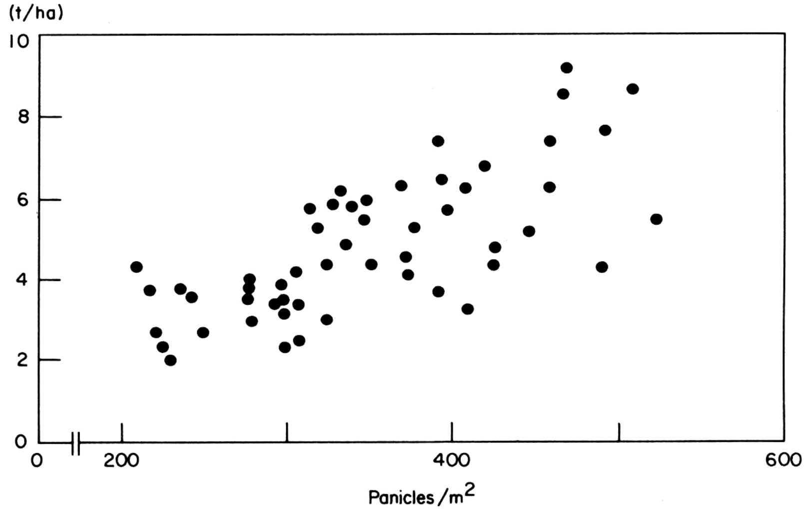
10. Relationship between radiation sum from transplanting to flowering and panicles/m² for BG35-2 and IR36. Pr = Paranthan; Jd = Joydebpur; Ys = Yezin; Pl = Palmira.

A long vegetative period and high radiation during this period is generally beneficial for tillering. This effect is illustrated in Figure 10. A higher total radiation sum from transplanting to flowering leads to more panicles per m². Exceptions were found in only five trials: Palmira 1, because of its wide spacing; Paranthan 2, because of very low N application; Yezin 2, drought stress, and Joydebpur 2,3 cool season, where the very long vegetative period at this site apparently did not produce a very high number of panicles.

Panicles per m^2 is an important yield component (Fig. 11) and the radiation sum from transplanting to flowering is an important weather variable in relation to yield. Such a relationship can be seen for the nine test entries and the local check (Table 14).

Filled grains per panicle. Yoshida (9) indicated that environmental factors (such as high or low temperatures during ripening or unfavorable weather during reduction-division and anthesis) and cultural practices (such as high plant density and protection against pests) determine the number of filled grains per panicle. Radiation levels are particularly important during the reproductive phase. Low radiation during postflowering reduces the number of filled grains.

About 50 trials reported the number of filled grains per panicle. Over all sites, BG367-4 had the largest average number of filled grains per panicle (114), followed by Taichung sen yu 285 (95). Other entries range from 75 to 85 filled grains/panicle. Site differences ranged from 40 (Pattambi 3) to 130 (Palmira 2, Los Baños 2, 4). A positive relationship between radiation during postflowering and number of filled grains per panicle is illustrated in Figure 12.



11. Effect of panicles/m^2 on yield. (Each dot represents mean of each of 9 entries.)

1,000-grain weight. IR50, with long slender grains, had the lowest mean grain weight (20 g); BG35-2, with bold grains, and IR9729-67-3, with medium long grains, had the highest (26 g). However, 1,000-grain weight varied widely among sites. Site means ranged from 21 g (Parwanipur 2) to 28 g (Cuttack 3).

Because this yield component is related to other yield components, its relationship with environmental parameters is more difficult to establish. A high number of panicles and a high number of filled grains might lead to a lower 1,000-grain weight. A long postflowering period or high radiation intensity during postflowering might influence 1,000-grain weight.

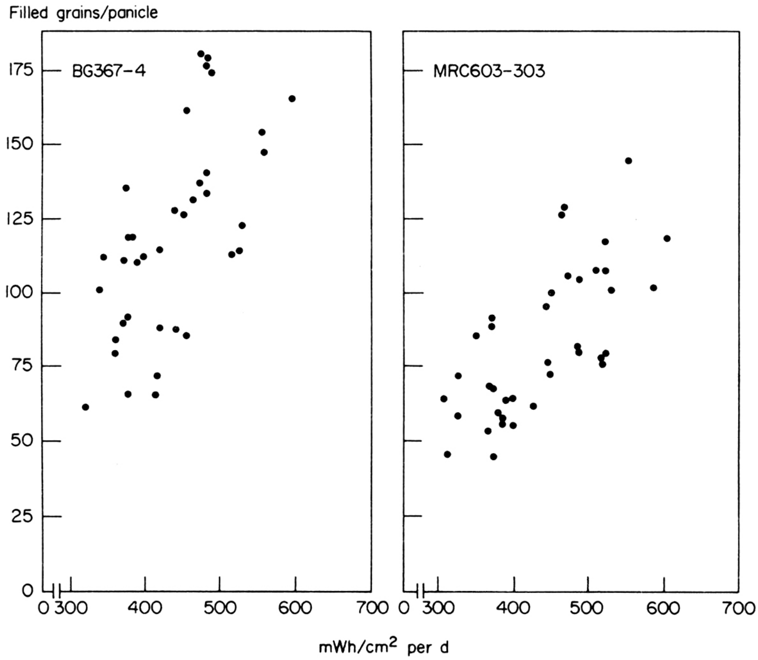
Impact of weather on yield

Although many attempts have been made to relate yield to weather variables, a major problem in estimating and interpreting yield-weather relationships is that data often are limited to only one site, province, or country. That can result in unwarranted correlations among weather predictor variables, causing problems in interpreting estimated relationships between yield and individual weather factors (7). This study, encompassing 23 sites in 16 countries and a period of almost 2 yr, provides 65 trials in which real-time daily weather data were recorded.

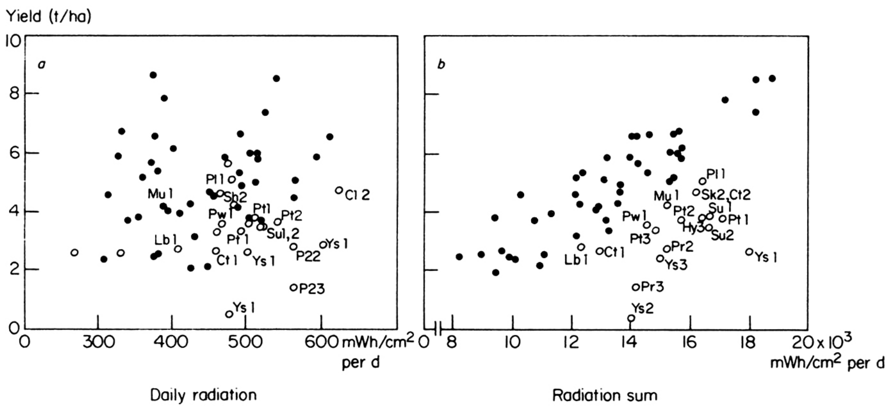
Although the problem of correlation among weather predictor variables was largely solved, 23 different field managers participated, with as many edaphic systems. A number of trials were affected by nonweather predictor variables, such as insect pest and disease problems (Pattambi 1,2,3; Sukamandi 2; Los Baños 1; Paranthan 3; Pingtung 2), drought stress (Yezin 2; Paranthan 1, 2), flooding (Cuttack 4; Paranthan 1), plant density (Palmira 1; Coimbatore 2), low fertilizer application (Cuttack 1,2,3,4; Paranthan 2), and

Table 14. Radiation sum, transplanting to flowering panicles per m^2, and yield in four trials.

Trial	BG35-2	BG367-4	MRC603-303	IR13429-196	IR36	IR50	IR9729-67	IR9828-91-2	Taichung sen yu 285	Local check
Sakha 1										
Radiation sum, $mWh/cm^2 \times 10^3$	55.4	56.6	59.6	56.6	60.8	54.1	50.9	55.4	57.2	52.3
Panicles/m^2	435	385	530	510	635	635	480	565	435	520
Yield (t/ha)	8.4	5.9	8.6	9.2	9.1	9.4	8.6	9.2	10.0	8.8
Milyang 3										
Radiation sum, $mWh/cm^2 \times 10^3$	38.9	35.8	38.0	34.6	38.3	30.5	28.0	38.3	37.6	34.6
Panicles/m^2	367	400	453	420	513	520	453	487	387	387
Yield (t/ha)	7.1	8.2	6.3	8.0	8.0	7.2	8.2	6.9	8.0	9.3
Coimbatore 1										
Radiation sum, $mWh/cm^2 \times 10^3$	31.3	36.4	42.8	36.4	38.5	35.8	34.5	37.5	42.7	32.0
Panicles/m^2	287	273	320	267	347	353	360	327	307	293
Yield (t/ha)	5.0	5.6	5.4	3.8	5.3	4.9	5.0	6.0	5.2	5.3
Cuttack 1										
Radiation sum, $mWh/cm^2 \times 10^3$	23.3	23.3	25.3	24.2	24.2	23.6	21.6	24.2	25.3	24.3
Panicles/m^2	163	174	231	221	233	333	228	277	182	238
Yield (t/ha)	2.5	2.6	2.6	2.9	2.9	2.9	2.7	3.1	2.3	2.4



12. Effect of radiation during postflowering on filled grains/panicle for BG367-4 and MRC 603-303.



13. Effect of daily mean radiation and radiation sum on yield of MRC603-303. The trials at Yezin 1,2,3 (drought, diseases), Palmira 1 (plant density 30 × 30). Cuttack 1,2 (cold stress, abnormal high temperatures), Sakha 2 (sharp drop in temperature toward ripening), Paranthan 2, 3 (drought, pests), Muara 1 (rats), Los Baños 1 (diseases), and Sukamandi 1 (rats and birds) were excluded in calculating linear regressions. Ct = Cuttack, Lb = Los Baños, Mu = Muara, Pl = Palmira, Pr = Paranthan, Pt = Pattambi, Pw = Parwanipur, Sk = Sakha, Su = Sukamandi, Ys = Yezin.

abnormal hot weather (Joydebpur 1 in seedbed; Kapurthala 1; Cuttack 2). These stresses, deviations from stipulated management practices, and abnormal weather conditions should be considered in interpreting correlations of real-time weather variables and yield.

Influence of radiation. The effect of total radiation on yield which is usually found was not clear in our trials. When radiation during postflowering is plotted against yield for MRC603-303, the pattern is scattered (Fig. 13). In Suweon, mean radiation during ripening was only around 380 mWh/cm^2 per d, but yields were around 8 t/ha. In Coimbatore, at a mean radiation level of 515 mWh/cm^2 per d. yield was only 5 t/ha.

Total radiation accumulated during ripening is more important. Length of the period depends mainly on temperature. At Suweon, the ripening period lasted 45-50 d, leading to a radiation sum of 17,500 mWh/cm^2. At Coimbatore, the period lasted 30 d, with a radiation sum of 15,000 mWh/cm^2. Plotting radiation sum against yield with these trials shows a much better correlation: y = 0.62X - 3.29 (r^2 = 0.85**).

Similar relationships were found for other entries (Fig. 14). The trend slopes for MRC603-303, IR13429-196-1, IR36, IR9828-91-2-3, Taichung sen yu 285, and BG367-4 indicate that sensitivity to radiation sum is not identical for all cultivars:

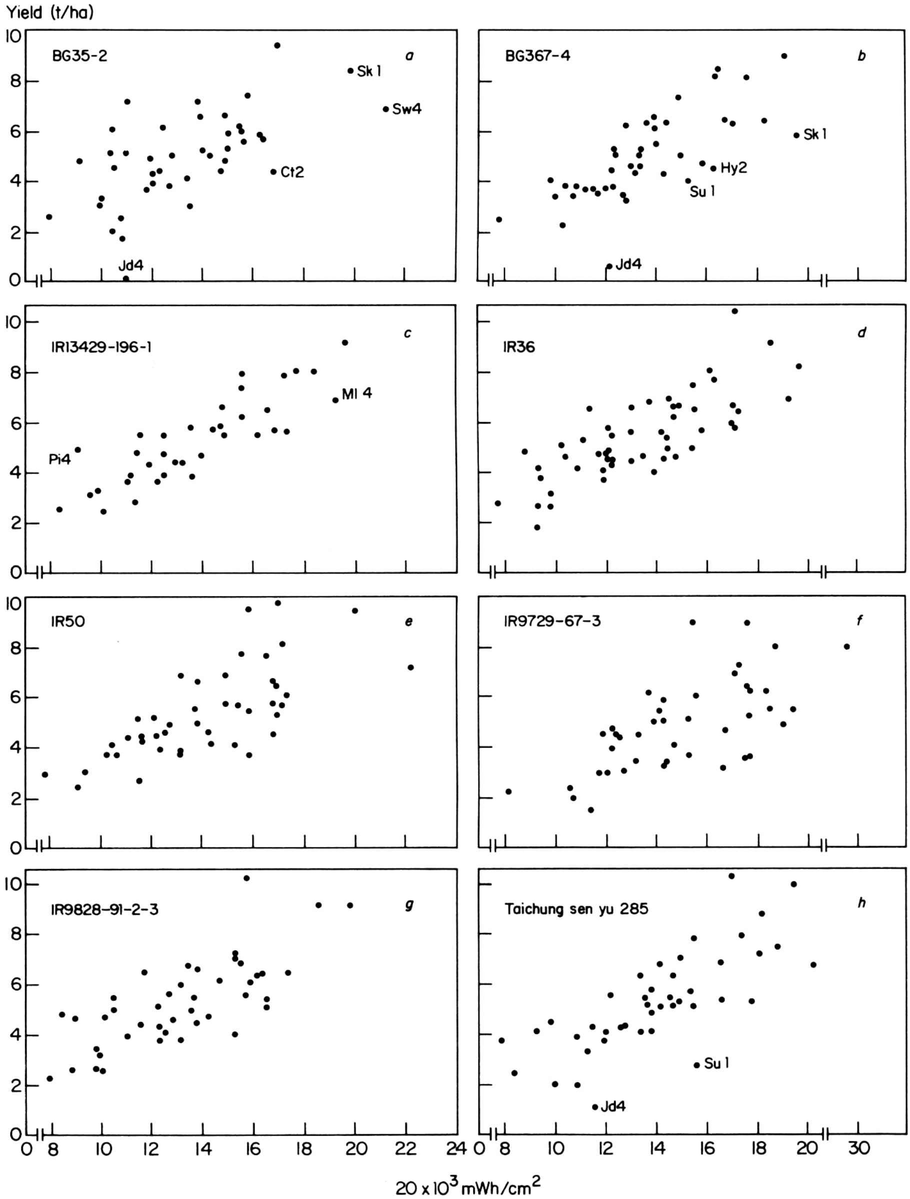
MRC603-303	:	Y = 0.62X - 3.24 (r^2 = 0.85)
Taichung sen yu 285	:	Y = 0.56X - 2.36 (r^2 = 0.73)
IR9828-91-2-3	:	Y = 0.43X - 0.51 (r^2 = 0.55)
IR36	:	Y = 0.36X + 0.73 (r^2 = 0.40)

IR36 and IR9828-91-2-3 produced relatively higher yields at low radiation sums during ripening than did MRC603-303 and Taichung sen yu 285; MRC603-303 and Taichung sen yu 285 responded relatively better to radiation after ripening.

The relationship between yield and radiation sum after ripening is less significant for BG35-2, IR50, and IR9729-63-3, particularly at high radiation sums. The wide scatter could indicate that other variables also influence yield.

Air temperature during post flowering. Lower night temperatures during postflowering correlate positively with yield. For MRC603-303, mean minimum temperature shows little correlation with yield (Fig. 15). But when the data are divided into two sets according to the slope of minimum temperature during ripening, the set with a sharp drop in minimum temperature toward ripening produced lower yields than the set without such a temperature drop, even though mean minimum temperatures during postflowering were similar. In all cases, minimum temperatures dropped from around 20 °C at flowering to 12 °C at harvest.

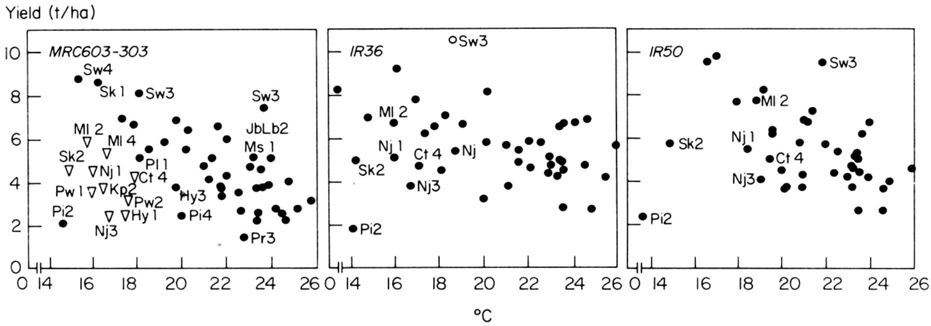
It is not completely clear whether these trials were harvested early because of the low temperatures or whether the low temperature itself had a negative effect on yield, although indications are that the trials were harvested prematurely. Yield in Suweon 4 was 8.7 t/ha, even though the minimum



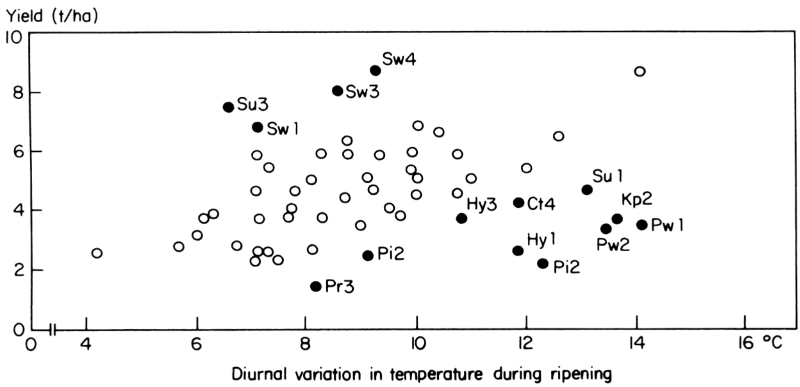
14. Effect of radiation sum during postflowering on yields of BG35-2, BG367-4, IR13429-196-1, IR36, IR50, IR9729-61267-3, IR9828-91-2-3, and Taichung sen yu 285. Ct = Cuttack, Hy = Hyderabad, Jd = Joydebpur, Sk = Sakha, Su = Sukamandi, Sw = Suweon.

temperature dropped from 23.5 to 7.5 °C over the 50 d from flowering to harvest.

The very low yields in Pingtung 2 and 4, which also appear out of place, may have been caused by very low radiation level (less than 250 mWh/cm^2)



15. Effect of minimum temperature during postflowering on yield. + = trials affected by sharp drop in minimum temperature. Ct = Cuttack, Hy = Hyderabad, Jb = Jhudan, Kp = Kapurthala, Lb = Los Baños, Ml = Milyang, Ms = Masapang. Nj = Nanjing, Pi = Pingtung, Pl = Palmira, Pr = Paranthan, Pw = Parwanipur, Sk = Sakha, Su = Sukamandi, Sw = Suweon.



16. Effect of diurnal variation in temperature during postflowering on yield of MRC603-303. Ct = Cuttack, Hy = Hyderabad, Kp = Kapurthala, Pi = Pingtung, Pr = Paranthan, Pw = Parwanipur, Su = Sukamandi, Sw = Suweon.

during the last 20 d before harvest. The relatively high yields in Cuttack 2 in relation to a high minimum temperature are probably due to high postflowering radiation (more than 600 mWh/cm^2 per d).

The high yield in Sukamandi 3 can be explained only as the result of the above-normal 1,000-grain weight (3-4 g/1,000 grains more than average); received radiation and/or air temperature were not high enough to account for yield. IR36 and IR50 show similar trends. IR36 yields seem to correlate less with minimum temperature than IR50 yields. IR50 has a shorter duration than IR36 and was harvested before the sharp drop in temperature experienced by longer-duration entries.

The relationship between yield and diurnal temperature range during postflowering is illustrated in Figure 16. A high diurnal difference leads to more efficient conversion and use of solar energy during photosynthesis, leading to a higher net photosynthesis. The trials at Suweon had higher yields than would be expected from the diurnal differences, possibly because of very high manage-

Table 15. Real-time variables during postflowering and yield of four entries at selected sites.

	Radiation sum	Min temp	Diurnal diff.	Yield (t/ha)
		IR9828-91-2-3		
Sakha 1	19757	16.5	13.2	9.2
Palmira 2	16071	18.0	10.3	6.4
Sanpatong 2	10444	21.7	12.5	5.6
Coimbatore 2	15700	21.2	9.4	5.6
Kapurthala 1	13672	23.8	8.2	4.5
Joydebpur 3	13542	23.4	10.9	5.0
Muara 2	12514	21.1	9.5	4.1
Cuttack 4	11621	16.9	12.3	4.5
Pingtung 4	9965	20.2	9.1	3.2
Joydebpur 1	7779	24.8	7.5	2.6
		IR36		
Sakha 1	18575	16.2	14.1	9.1
Palmira 2	15645	17.9	9.5	6.4
Sanpatong 2	11226	21.7	12.7	5.3
Coimbatore 2	15862	21.1	9.5	5.6
Kapurthala 1	12197	23.6	8.2	4.8
Joydebpur 3	131 13	23.0	11.1	5.5
Muara 2	12050	21.1	9.5	3.7
Cuttack 4	12070	17.1	12.2	4.7
Pingtung 4	9995	20.1	9.2	3.1
Joydebpur 1	7779	23.6	7.3	2.7
		Taichung sen yu 285		
Sakha 1	19412	16.3	13.7	10.0
Palmira 2	16505	17.8	10.4	6.9
Sanpatong 2	13560	21.5	12.8	5.5
Coimbatore 2	15493	21.3	8.9	5.2
Kapurthala 1	14218	23.9	8.1	5.1
Joydebpur 3	13639	23.6	10.8	5.2
Muara 2	1 1557	21.1	9.5	4.3
Cuttack 4	12070	17.1	12.2	4.2
Pingtung 4	10942	20.2	8.9	4.0
Joydebpur 1	8390	24.7	7.2	2.5
		IR50		
Sakha 1	20035	16.8	12.9	9.4
Palmira 2	16780	18.1	10.1	7.6
Sanpatong 2	16816	21.4	13.3	6.7
Coimbatore 2	17163	21.0	9.8	5.6
Kapurthala 1	15327	24.1	8.0	4.1
Joydebpur 3	12831	23.6	10.8	4.9
Muara 2	13105	21.1	9.6	3.7
Cuttack 4	12259	20.2	10.5	4.4
Pingtung 4	10229	20.4	9.0	3.7
Joydebpur 1	7779	23.6	7.3	–

ment levels (more N applied than in any other trial) and a high radiation sum combined with low minimum temperatures. Those trials with lower yields than would be expected from the diurnal difference are those that were stressed in some way.

Table 15 summarizes the effects of total radiation, minimum temperature, and the maximum-minimum temperature difference during postflowering for IR9828-91-2-3, Taichung sen yu 285, IR36, and IR50.

Practical implications

Some conclusions can be drawn from the studies:

- Environments with growing seasons limited by large seasonal temperature fluctuations, such as those located at high latitudes, can produce high yields, particularly when ripening coincides with decreasing air temperatures. Early sowing, even at mean air temperatures at or just below 15 °C, will give even higher yields. Short-duration varieties with minimum photoperiod sensitivity should be used. Planting dates should be adjusted to temperatures in the fall.
- Environments with mean minimum temperatures of at least 10 °C and distinct seasonal fluctuations of air temperatures are suitable for a cool dry season crop and a hot wet season crop. Yields in the cool dry season are significantly higher than yields during the hot wet season, not only because weather parameters are more favorable, but also because insect pest and disease occurrence is much lower in the cool dry season. Because temperatures in the cool dry season occasionally may drop below 10 °C, the probability of cold spells should be established.
- Environments with weak seasonal temperature fluctuations do not preclude rice production during any part of the year, provided water is available. Yields are higher during the dry season than during the wet season because of higher radiation levels. Also, insect pest and disease incidence is lower in the dry season. Dry season rice yields are more vulnerable to rat and bird damage, particularly if the surrounding area is not cultivated. It also appears that early wet season plantings are less damaged by insect pests and diseases than late wet season plantings.
- Varieties respond differently to light intensity. IR36 and IR9828-91-2-3 produced relatively better under low radiation; IR13429-196-1, BG367-4, and Taichung sen yu 285 produced better under high radiation.
- The length of the preflowering stage, and to a lesser extent the length of the postflowering stage, are influenced not only by temperature; these are also varietal characteristics. Even the photoperiod-insensitive entries used in this study appear to be influenced by daylength. Temperature summation appears to be a better characteristic to indicate earliness in a variety than the number of days from sowing to harvest. Low temperature sum entries are IR9729-67-3, IR50, BG35-2, and BG3674. Taichung sen yu 285, MRC603-303, and IR13429-196-1 have higher temperature sums under conditions of short days. IR36 and IR9828-91-2-3 fall between these two groups. BG35-2, IR36, BG367-4, and IR9828-91-2-3 are more sensitive to photoperiod than the other varieties.
- Although plant density and fertilizer application were not studied in these trials, it appears that establishing the relationship of radiation and temperature to these two management practices is extremely important. Where plant spacing was wider than recommended, yields were significantly lower. In some cases, yields were clearly reduced by low N applications; at other sites, the effect was less apparent.

Multilocational Analysis

A multilocational analysis of variance was calculated to evaluate the genotype-by-site interaction relative to the pooled experimental error (2). The interaction value (with 304 degrees of freedom) is large (a ratio of 5.8) and has to be considered important. Because solar radiation and temperature are believed to be the major environmental factors affecting grain yields in these trials, it is reasonable to expect that the interactions between these two weather factors and genotype account for a very significant proportion of genotype-by-site interaction.

Developing predictor models

Ideally, a model to predict rice yields on the basis of weather should include relatively few variables, predict yields within specified limits, predict for environments not included in the original data set, and have estimated coefficients reasonable in sign and magnitude.

Historically, variables have been selected using one of several stepwise regression programs in which variables are included or excluded one at a time, with decisions at any particular step conditioned by previous steps. Unfortunately, those variable selection procedures do not necessarily identify the best prediction model for a given number of variables (3).

Statistical programs for all possible regressions now available guarantee a series of prediction models for a given number of variables. In this study, an all-possible-regression procedure, PROC RSQUARE of the Statistical Analysis System (SAS) computing package, was used.

The all-possible-regression procedure identified models with acceptable R^2 values and standard deviations ranging from 0.7 to 0.9 for the 9 entries. But taken individually, the estimated temperature coefficients in the resulting prediction equations were not reasonable in magnitude, and sometimes not in sign. Consequently, appropriate physiological information was used to supplement temperature, starting with preflowering.

The length of preflowering is known to be genotype-specific and is influenced by the temperature sum. Number of days is reflected in accumulated radiation units. Preflowering temperature variables included day-night temperature difference[1] because that difference is known to be related to

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[1] Day temperature and night temperature are values derived from observed maximum and minimum temperatures by: (5).

$$T_D = \frac{T_{max} + T_{min}}{2} + \frac{T_{max} - T_{min}}{4} \times \frac{11 + T_{n\,sin}}{12 + t_n}$$

$$T_N = \frac{T_{max} + T_{min}}{2} - \frac{T_{max} - T_{min}}{4} \times \frac{11 + t_{n\,sin}}{t_n}$$

in which T_D = day temperature; T_N = night temperature

T_{max} = maximum temperature; T_{min} = minimum temperature

$t_n = 12 - .05N$ (N = day length in hours)

$$= \frac{11 - t_n}{11 + t_n}$$

photosynthesis efficiency. Day temperature as the third predictor variable is not only reasonable from a physiological point of view; it also has a lower correlation with radiation sum and day-night temperature differences than other temperature variables.

Postflowering variables were restricted to two determinants. Radiation sum reflects the variable length of the ripening period. It did not correlate highly with preflowering radiation sum because the environments in this multi-locational study were specifically selected. Night temperature was chosen as the second postflowering variable (7).

The combination of physiological and statistical variable selection strategies resulted in a prediction model that is a compromise between finding the best-fit equation for this data set and developing a model with more interpretative weather variable relationships.

Interpreting estimated model coefficients. The prediction equations for each genotype are given in Table 16. Predicted yields were calculated from each set of partial coefficients. The individual coefficients are difficult to interpret because each weather variable was adjusted against other variables. Specifically, each preflowering variable is adjusted for each postflowering variable. Physiologically, yield potential is determined mainly by preflowering period weather variables; conditions during postflowering determine whether that yield can be realized or enhanced.

Table 16. Estimated coefficients for prediction equations using three preflowering explanatory variables: day temperature (TDB) °C, day-night temperature difference (DNB) °C, and accumulated radiation (RSB) 1000 mWh/cm^2; and two postflowering explanatory variables: night temperature (TNC) °C and accumuleted radiation (RSC) 1000 mWh/cm^2.

Entry	Intercept	TBD	RSB	DNB	RSC	TNC	R^2	SD	Mean
BG35-2	3.66 (2.44)	-0.11 (0.085)	0.088 (0.026)	0.54 (0.20)	0.10 (0.055)	-0.077 (0.052)	0.75	0.76	4.5
BG367-4	5.95 (2.98)	-0.073 (0.098)	-0.0014 (0.032)	0.76 (0.23)	0.20 (0.056)	-0.17 (0.073)	0.54	0.94	4.9
MRC603-303	5.73 (2.71)	-0.21 (0.092)	0.067 (0.028)	0.57 (0.23)	0.18 (0.065)	-0.069 (0.059)	0.71	0.88	4.6
IR13429-196-1	3.76 (3.23)	-0.061 (0.11)	0.074 (0.032)	0.48 (0.24)	0.18 (0.063)	-0.14 (0.073)	0.67	0.98	4.9
IR36	5.24 (2.42)	-0.16 (0.080)	0.068 (0.025)	0.49 (0.18)	0.22 (0.056)	-0.098 (0.053)	0.77	0.76	5.0
IR50	9.91 (3.18)	-0.19 (0.10)	0.064 (0.036)	0.56 (0.25)	0.15 (0.060)	-0.22 (0.096)	0.68	1.01	4.9
IR9729-67-3	9.98	-0.22	0.094	0.30	0.16	-0.20	0.68	1.05	4.5
IR9828-91-2-3	5.04 (2.43)	-0.17 (0.081)	0.077 (0.026)	0.51 (0.19)	0.19 (0.049)	-0.976 (0.053)	0.76	0.76	5.0
Taichung sen yu 285	7.40 (2.98)	-0.12 (0.10)	0.060 (0.028)	0.88 (0.23)	0.13 (0.063)	-0.24 (0.063)	0.77	0.90	4.9
Overall	6.12 (0.93)	-0.15 (0.031)	0.064 (0.0088)	0.57 (0.072)	0.17 (0.018)	-0.13 (0.022)	0.68	0.89	4.8

An alternative procedure for estimating the coefficients of the five-variable model in order to enhance interpretation is to first adjust the values of the postflowering weather variables for, any mathematical association between postflowering and preflowering. With this adjustment, each postflowering variable would be orthogonal to each preflowering variable (1). The *predicted adjustments* are calculated by regressing each postflowering weather variable on all preflowering variables, including an intercept term.

Accordingly, the model variables include the original three preflowering variables plus the two adjusted postflowering variables for radiation sum and night temperature. The least squares method was used to estimate the coefficients, but now the relationships of yield and preflowering weather variables are not influenced by postflowering variables (Table 17). The adjusted values for the postflowering weather variables, and the measured values, have to be used with the postflowering coefficients to calculate predictions.

As expected, radiation sum and day-night temperature differences have positive coefficients. The differences among the genotypes in coefficients for preflowering radiation relative to standard error are not large. Day temperature effect is negative. High day temperatures, combined with a low day-night temperature difference, is clearly not a favorable preflowering temperature

Table 17. Adjusted estimated coefficients for prediction equations using three preflowering explanatory variables: day temperature (TDB) °C, day-night temperature (DNB) °C, and accumulated radiation (RSB) 1000 mWh/cm^2; and two postflowering explanatory variables: night temperature (TNC) °C and accumulated radiation (RSC) 1000 mWh/cm^2.

Entry	TDB	RSB	DNB	RSC	TNC	Mean	SD	Stability
BG35-2	–0.21 (0.071)	0.11 (0.023)	0.45 (0.20)	0.10 (90.055)	–0.077 (0.052)	4.5	0.76	0.90 (0.054)
BG367-4	–0.24 (0.087)	0.046 (0.030)	0.73 (0.23)	0.20 (0.056)	–0.17 (0.073)	4.9	0.94	0.90 (0.068)
MRC603-303	–0.28 (0.084)	0.10 (0.026)	0.57 (0.23)	0.18 (0.065)	–0.069 (0.059)	4.6	0.88	0.96 (0.062)
IR13429-196-1	–0.25 (0.091)	0.11 (0.030)	0.52 (0.24)	0.18 (0.063)	–0.14 (0.073)	4.9	0.98	1.03 (0.044)
IR36	–0.28 (0.072)	0.12 (0.021)	0.37 (0.18)	0.22 (0.056)	–0.098 (0.053)	5.0	0.76	0.97 10.037)
IR50	–0.36 (0.089)	0.095 (0.033)	0.66 (0.25)	0.15 (0.060)	–0.22 (0.096)	4.9	1.02	1.09 (0.048)
IR9729-67-3	–0.43 (0.090)	–0.13 (0.034)	0.45 (0.24)	0.16 (0.061)	–0.20 (0.11)	4.5	1.05	1.10 (0.066)
IR9828-91-2-3	–0.28 (0.072)	0.12 (0.024)	0.43 (0.19)	0.19 (0.049)	–0.076 (0.053)	5.0	0.76	0.95 (0.43)
Taichung sen yu 285	–0.34 (0.084)	0.079 (0.025)	0.99 (0.23)	0.13 (0.063)	–0.24 (0.063)	4.9	0.90	1.11 (0.063)
Group 2 (Entries 3, 4, 5, and 6)	–0.27 (0.038)	0.11 (0.012)	0.49 (0.10)	0.19 (0.28)	–0.096 (0.028)			
Group 3 (Entries 6, 7, and 9)	–0.38 (0.050)	–0.089 (0.015)	0.73 (0.13)	0.15 (0.033)	–0.23 (0.047)			

environment. Low day temperatures, within the range of day temperatures of this study, and a high day-night temperature difference were conducive to high yields.

The result of the first condition would be a shortened preflowering period and a relatively low net photosynthesis because of the high day and relative high night temperatures. Conditions during Cuttack 1, seeded in July, are a good example. Day temperatures were around 29.7 °C and night temperatures were around 27.6 °C. The preflowering period was 63 d. In Sakha 1, seeded in May, day temperatures were around 26 °C and night temperatures were around 21.7 °C. The preflowering period was 74 d.

The postflowering radiation sum, adjusted for association with the three preflowering variables, shows larger response coefficients than the preflowering radiation sum. But the contribution to predicted yield is greater because of higher radiation sums during preflowering. BG367-4, MRC603-303, IR13429-196-1, IR36, and IR9828-91-2-3 appear to be more influenced by radiation than RG35-2, IR50, lR9729-67-3, and Taichung sen yu 285.

On the other hand, IR50, IR9729-63-3, and Taichung sen yu 285 appear to be more strongly affected by night temperature than BG35-2, IR36, and IR9828-91-2-3. To examine this conjecture, partial sums of squares for the five weather variables used in the predictor model were calculated (1). MRC603-303, IR13429-196-1, IR36, and IR9828-91-2-3 showed relatively high response to radiation variables, but relatively low response to temperature variables (Table 18). IR50 and Taichung sen yu 285 showed high response to temperature variables and low response to radiation variables. IR9729-67-3 showed high response to both radiation and temperature variables.

At Paranthan, entries behaved differently. BG35-2 showed low responses to both sets of variables. BG367-4 showed moderate response to temperature variables and low response to radiation variables.

Table 18. Partial sums of squares for two radiation predictor variables and three temperature predictor variables.

Genotype	Partial sum of squares	
	Radiation variables	Temperature variables
	Group 1	
MRC603-303	18.4	14.5
IR13429-196-1	21.2	15.5
IR36	25.7	13.1
IR9828-91-2-3	22.3	13.2
	Group 2	
IR50	14.7	29.8
Taichung sen yu 285	11.5	41.4
IR9729-67-3	23.6	32.9
	Group 3	
BR367-4	13.5	20.3
BG35-2	16.8	9.3

The need for individual genotype prediction equations relative to the three groups in Table 18 was examined. There is no statistical evidence for retaining nine genotype prediction equations, but there is statistical evidence (significance between 0.10 and 0.05) that group I entries should not be pooled with group II entries, particularly because of differences in response to night temperatures.

Table 19. Predicted yield (t/ha) and standard error (t/ha) on the basis of a 5-variable prediction equation with 3 preflowering explanatory variables: day temperature (TDB) °C, day-night temperature difference (DNB) °C, and accumulated radiation (RSB) 1000 mWh/cm^2; and two postflowering explanatory variables: night temperature (TNC) °C and accumulated radiation (RSC) 1000 mWh/cm^2.

Trial	DNB	TDB	RSB	TNC	RSC	Yield (t/ha)	Predicted yield (t/ha)	Predicted standard error (t/ha)
Joydebpur 1	2.1	29.8	26.791	26.2	7.997	2.49	2.45	0.12
Paranthan 1	1.4	26.1	16.852	24.5	9.998	2.40	2.53	0.15
Cuttack 1	2.1	29.7	24.516	25.8	12.497	2.74	3.13	0.085
Cuttack 3	2.8	31.1	28.587	27.3	12.060	3.82	3.31	0.10
Pingtung 4	3.3	28.9	17.626	23.4	10.170	3.21	3.42	0.14
Los Baños 3	2.6	28.8	25.803	25.7	11.511	4.37	3.48	0.071
Masapang 2	2.4	28.2	28.852	25.6	11.031	3.40	3.58	0.088
Pingtung 1	3.2	29.9	29.399	27.0	10.968	4.35	3.62	0.092
Sanpatong 1	2.9	29.4	27.801	25.7	12.014	4.28	3.77	0.067
Sukamandi 1	2.2	27.4	26.413	25.9	15.257	4.36	4.09	0.091
Cuttack 4	2.6	29.7	28.726	22.3	12.197	4.18	4.10	0.091
Kapurthala 1	3.0	31.1	32.055	26.3	14.107	4.63	4.12	0.10
Muara 1	2.9	27.0	24.060	24.8	12.760	3.51	4.13	0.080
Paranthan 2	2.3	30.5	36.070	26.9	15.074	3.01	4.14	0.13
Nanjing 3	2.8	28.9	28.674	20.1	10.203	4.30	4.30	0.12
Muara 2	3.2	27.8	24.831	24.2	12.892	4.33	4.35	0.072
Kapurthala 2	3.0	30.2	27.989	22.7	13.611	4.43	4.39	0.098
Pattambi 2	2.1	26.9	24.313	25.3	17.397	4.46	4.41	0.11
Los Baños 2	3.0	29.0	30.980	26.6	14.979	6.22	4.47	0.074
Parwanipur 1	2.5	30.1	30.947	21.9	14.276	3.49	4.52	0.11
Sukamandi 2	3.0	28.5	26.824	25.2	15.595	3.88	4.56	0.07
Pattambi 1	2.8	28.2	26.463	24.8	16.239	3.92	4.63	0.075
Nanjing 2	2.9	28.1	34.403	23.5	12.285	5.84	4.72	0.074
Hyderabad 2	3.2	23.3	31.170	24.7	16.611	5.34	5.22	0.068
Nanjing 1	3.1	28.3	32.774	19.1	11.926	5.21	5.23	0.12
Cuttack 2	4.6	29.5	38.355	29.4	14.970	4.69	5.41	0.16
Masapang 1	2.4	26.3	32.304	25.8	19.237	5.67	5.42	0.13
Coimbatore 2	3.0	27.1	36.402	24.1	16.306	5.57	5.65	0.082
Pingtung 3	3.9	23.4	33.071	23.5	10.874	4.45	5.68	0.18
Suweon 2	3.3	25.3	31.159	21.5	14.283	6.41	5.76	0.093
Suweon 4	3.2	25.7	29.632	20.7	15.135	5.87	5.80	0.093
Coimbatore 1	4.0	28.3	38.660	23.0	14.072	5.15	5.94	0.081
Milyang 3	3.6	27.1	32.336	20.0	15.162	6.86	6.09	0.096
Milyang 4	3.5	27.2	20.151	20.8	17.240	6.48	6.12	0.10
Palmira 2	3.5	25.2	30.347	21.2	16.093	6.44	6.18	0.099
Milyang 3	3.7	27.1	34.838	21.0	16.110	7.54	6.33	0.083
Sanpatong 3	6.0	29.6	35.379	25.4	13.838	5.92	6.35	0.20
Milyang 3	3.9	25.8	35.542	23.4	18.039	7.55	6.69	0.098
Sakha 1	4.6	26.2	56.301	20.7	19.580	8.72	8.97	0.19

Interpreting predicted values

The predicted yields for the 39 trials used in estimating the predictor model are shown in Table 19. Data for the 9 entries from 39 trials were pooled to estimate the weather coefficients in the prediction equation:

$$Y=4.8 + 0.5743 \text{ (DNB) - 3.1) - } 0.1492 \text{ (TDB -2.8)} + 0.06384 \text{ (RSB - 30.446)} + 0.1665 \text{ (RSC - 13.964)} - 0.1327 \text{ (TNC - 24.0)},$$

in which

yield average = 4.8 t/ha;
DNR = preflowering day-night temperature difference, average 3.1 °C;
TDB = preflowering day temperature. average 28.1 °C;
RSB = preflowering radiation sum, average 30.466 × 10^3 mWh/cm^2;
RSC = postflowering radiation sum, average 13.964 × 10^3 mWh/cm^2; and
TNC = postflowering night temperature, average 24 °C.

It is apparent that poor preflowering weather conditions result in yields of less than 4 t ha. But day temperatures and radiation sum during preflowering do not have to be in the upper quartile to have predicted yields greater than 6 t ha.

An interesting aspect is the ability of one or two weather variables to compensate for other weather variables. In the Sanpatong trial seeded in January, day temperature was high (29.6 °C), but the high day-night temperature difference (6.0 °C) compensated. The two postflowering weather variables also appear to have compensated for each other. For example, with Nanjing 1, the low radiation sum was compensated for by a low night temperature: with Masapang 2, a high night temperature was compensated for by a high radiation sum.

The predictor model based on 5 weather variables has reasonable estimated coefficients in sign and magnitude and predicted actual yields within 0.5 t/ha for more than half the trial data used. This prediction model should be tested for environments not included in the original data set.

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The FAO agroclimatological data base: its use in studying rice-weather relationships

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ABSTRACT

The development of FAO's agroclimatological data banks and their growth are described. Their potential in rice-weather relationship studies is projected.

The FAO agrometeorological data bank includes various components that were developed at different stages of its evolution (Fig. 1).

Monthly agroclimatological data base

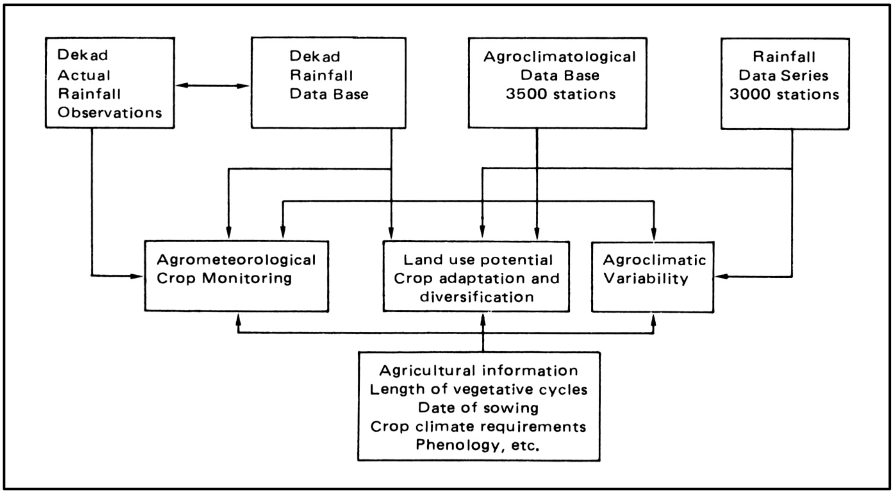
This component, the most important one, covers some 3,500 stations located primarily in developing countries. These stations are identified by name and country and a number of classifications based on the WMO system of codes, as well as the usual latitude-longitude and altitude coordinates.

For each station, these climatological parameters are assembled or calculated:

1. average monthly and annual precipitation in mm,
2. average monthly and annual maximum air temperatures in °C,
3. average monthly and annual minimum air temperatures in °C,
4. average monthly and annual mean air temperatures in °C,
5. average monthly and annual vapor pressures in mbs,
6. average monthly and annual wind speeds at the standard height of 2 m above ground in m/second, and
7. average monthly and annual relative sunshine durations in hours.

In addition to the basic climatological parameters, derived values useful for agrometeorological purposes include:

1. average monthly and annual day air temperatures in °C,
2. average monthly and annual night air temperatures in °C,
3. average monthly and annual global radiation in cal cm^2/d, and
4. average monthly and annual potential evapotranspiration in mm.



1. Components of the FAO agrometeorological data bank.

Day and night temperatures have been calculated using a formula developed by R. Petricevic, FAO Statistics Division. This formula uses maximum and minimum temperatures and daylength to calculate day and night temperatures, which are then used to further calculate gross and net photosynthesis rates. This information is used to assess biomass produced during the growing season.

Global radiation is calculated by the Angstrom formula, using radiation at the limit of the atmosphere and different sets of coefficients.

Potential evapotranspiration is calculated from a FAO-modified Penman equation, which considers the strong advection effects in semiarid areas.

The bank also provides data on the typical growing season for each station. This information is derived by computer from water balances during various parts of the year to present information on length of available growing season(s). The computer-derived information must, of course, be adjusted to particular tropical areas where a long rainy season presents two peaks, which normally signifies two distinct seasons for cereal crops.

Two volumes of agroclimatological data covering some 1,100 stations in Africa were published in 1984. Data covering some 800 stations in Latin America and the Caribbean were published in 1986; data concerning Asia are expected to be published by early 1987.

Monthly rainfall data

In addition to average agroclimatological data, FAO has started to collect a monthly rainfall series. A large part of this information has been obtained from the U.S. National Climatic Center in Asheville, North Carolina. This information contains the rainfall series recorded from the date a station was established to about 1980. Its quality ranges from the very best (those stations having more than 100 yr of accurate and reliable records) to very poor (those stations with less than 20 yr of incomplete records).

Computer programs have been designed to extract useful information on rainfall probability and coefficient of variability. This system provides information on the rainfall that may be expected in a given number of years out of 10.

Dekad rainfall data

Although the two types of agroclimatological tables are useful for characterizing agricultural environments by broad agroecological zones and cropping systems, monitoring crop behavior and its reaction to water availability has to be calculated over shorter intervals. In FAO, the standard time scale is the dekad. A third data bank is being developed on a time scale of ten days. This type of data bank has just been started for the Sahelian countries, in the framework of the Agrhymet Programme. It will be extended to other countries in the future.

Operational crop monitoring

Ten years ago, FAO started an operational agrometeorological monitoring of crops in the Sahelian area. This monitoring, now practiced in some 30 developing countries, is based on actual rainfall observations. It calls up climatological values of potential evapotranspiration filed in the agroclimatological monthly data base.

Other information, such as lengths of growing cycles of cultivated varieties, their crop coefficients or phases of their vegetative cycles, and soil water retention capacities, is obtained from local information.

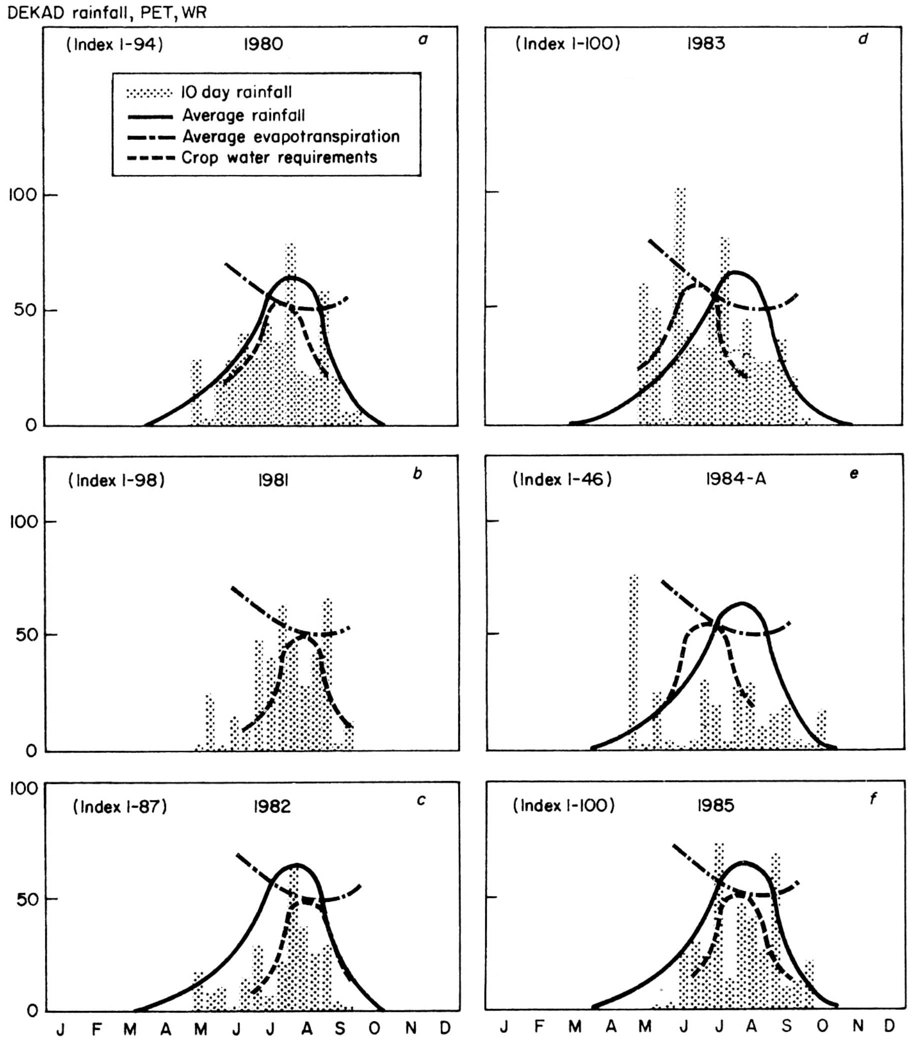
Figure 2 shows an example of agrometeorological crop monitoring analysis. The methodology also may be used in conjunction with the dekad rainfall data series to calculate, for example, the degree of adaptation of a 140-d cultivar in a given environment and the advantage to be derived with a shorter-duration, 110-d cultivar if the environment is known to be limiting.

Development Stage of Data Base Components

This type of information might be used in rice-weather relationships, with particular consideration of upland rice cultivated on dry land without water-retaining devices.

The monthly average agroclimatological data can be used to define broad areas suitable for rainfed rice cultivation by sorting information on available rainy season (preferably, the month receiving more than 150-200 mm of water) and minimum air temperature (which will condition the growth rate of the crop).

In conditions equally suitable from the point of view of water, it may be worthwhile to make a special sorting on total radiation received during the growing season (total radiation will be the factor influencing final yield, all parameters being equal).



2. Schematic crop monitoring and rainfall variability in NIAMEY.

Total radiation and temperature also will be important in delineating differences between growing seasons for rice, where yields differ importantly between clear and cloudy skies. However, that exercise will apply predominantly to areas where water is available for irrigation during the dry season.

Going into greater detail, examining the monthly rainfall series will show the variability of rainfall in the regions under study. In particular, it will show that during a given period, an apparent high average rainfall may hide dry periods occurring during the cropping season which might jeopardize rice cultivation.

This kind of assessment will highlight large gaps in rainfall distribution which would seriously distort the average rainfall calculated for a full month. These gaps might be obvious in the Asian zones at about 15-20º latitude which are directly affected by monsoon movements of wet and drier air masses.

In equatorial zones, where rainfall is more a convection type and where dry spells tend to be shorter, but still potentially can cause some water stress on rainfed upland rice, monitoring on a shorter time scale is necessary.

For this kind of assessment, the dekad rainfall data figures will provide the most useful information and, combined with climatological evapotranspiration data, will allow the construction of a cumulative water balance profile of the rice crop for each individual year, over a statistically significant number of years (say 30 or 40). The probability of carrying out the cropping season without major water stress problems will emerge from this water balance profile. The probability of reaping a good crop 7-8 yr out of 10 should be on the order of 0.70-0.80.

These are only a few of the applications of agroclimatological data in calculating a rice-weather relationship which now appear possible. It must be remembered that the FAO data bank, particularly in regard to the information collected for dekad periods, is still in development. The applications suggested only concern upland rainfed rice. Methods of cultivating rice are so diverse that many other applications could be envisioned for specific locations or methods of cultivation.

Agrometeorological aspects of growth, yield, and water relations, with special reference to rice

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ABSTRACT

The need for and feasibility of agrometeorological delineation of crop zones and crop growth periods, yield prediction, and irrigation scheduling are pointed out. Rice growth in relation to environment and rice and its weather requirements are detailed. Agrometeorological methodologies for delineating the optimum growth periods for various yield potentials and the maximum water availability periods for different crop durations are outlined. Points to consider in predicting yields of irrigated and upland rice are mentioned.

The optimum weather parameters for normal growth and development vary among crops and with crop stages. To derive maximum benefits, climate-oriented cropping technology needs to be developed. This is feasible if areas are zoned on a crop basis and if the feasible and best cropping times and durations are delineated for each crop zone.

It is possible to do this. For many crops, phenological development can be predicted from models using only meteorological inputs, often of a simple nature. For others, the primary and optimum range of the most important weather parameters, especially temperatures, have been determined,

Because weather vagaries during a crop season can affect yield potential considerably, yield predictions become important. Techniques for agrometeorological computation of actual biomass production have been given by Oldeman and Frere (19). However, the biomass going into yield can change in response to environmental fluctuations, especially for grain crops in which postfloral photosynthesis makes a large contribution to economic yields.

However, meteorological parameters during the reproductive phase of grain crops only provide a measure of photosynthetic opportunity. To account for the photosynthetic capacity available during the reproductive phase, it will be necessary to incorporate crop attributes into yield formulations.

The influence of a weather element on a crop varies widely with crop stages. Weather vagaries can bring about variations in phasic development. For real-time use, inputs of times and durations of crop phenological phases would need to be added in addition to an experimentally derived crop yield-weather models.

Because of its direct and indirect effects, weather emerges as the most important factor governing crop water needs. The loss of water that occurs as transpiration from crops and evaporation from soil surfaces, jointly called evapotranspiration (ET), constitutes the minimum crop water demand. The maximum water need of an extensive, short-vegetative-period, ground-covering crop with field capacity moisture status is referred to as potential evapotranspiration (PET). Methodology to determine PET from climatic data is available (6). PET for a given time and place is a conservative climatic parameter.

By expressing measured values of ET as ratios of ET/PET (called relative evapotranspiration [RET] or crop coefficient [K_c]), many of the apparently conflicting results on crop water needs in terms of a percentage of crop duration and growth stage can be reconciled (32). By the same procedure, it has been possible to develop agrometeorological methodologies for determining crop water needs (3) and for optimum distribution of the total crop water needs (33).

Rice Weather Features

The minimum accumulated day degrees (32.28 klx) required for rice is much higher than that required for any other crop. This may at first indicate a need for warmth in the rice plant. But the compensation point light intensity for rice is high and temperature dependent: 6.46 klx at 16 °C and 15.06 klx at 27 °C (20). When one realizes that many crop species tend to reach light saturation at 21.52 klx, the important role of light and temperature combinations in rice production becomes apparent.

Can differences in unit area yields be reconciled in terms of yield per day? Tanaka (29) found that differences in crop duration are reflected mainly at the vegetative lag stage. Coordinated rice trials in India show that the increased duration of rice in the winter season is due mainly to a longer vegetative stage. Moomaw and Vergara (15) found that medium-duration varieties gave better yields than long-duration varieties. Autumn, winter, and summer yields of a short-duration, photoperiod-insensitive variety rule out any explanation in terms of per day production (9).

In rice, the optimum leaf area index for maximum photosynthesis is 4.0 (16). Excessive tillering, leafy growth, and tallness are not conducive to photosynthesis. All these features would be suppressed more by lower early-season temperatures than by the temperatures that prevail in rainy weather. A large part of the starch in rice grain is formed from photosynthesis in the 6-wk period from 2 wk before flowering to 4 wk after flowering (16, 29, 36). Bright sunny weather with cool temperatures in later phases of the crop would be conducive to photosynthesis.

Rice stands wave and flutter in strong winds. This results in poor ascent of plant sap and drying of top leaves and ears. These conditions are not good for absorption of nutrients, photosynthesis, and retention of photosynthates. Winds are stronger and steadier and blow longer during the day in the rainy season than in the winter.

These features explain why the highest yields of rice are obtained in the high latitudes of both the southern and northern hemispheres and why varieties yield better in the clear, cool seasons than in the hot, clear seasons and yield lowest in the wet, warm, cloudy seasons.

Rice Weather Relationships

Crop duration

The optimum duration of a rice crop is reported to be 130-140 d (15, 27, 29). However, Seshu (25) pointed out that crop duration may be shortened due to agronomic exigencies and water availability. Incidence of cyclonic weather and the danger of biological setbacks may also reduce optimum durations (8). In dual monsoon areas, the longer rainy period makes it necessary to raise long-duration varieties, which reduces yield potential.

Sunshine

Sato (24) reports that sunshine during the last 2 mo of crop growth should total more than 400 h. Moomaw and Vergara (15) report that sunshine hours in the last month should total 220-240 h and that accumulated sunshine during the optimum growth stage should total 1,000 h.

Temperature

Optimum aerial temperatures for various growth processes are:

Germination: 22-31 °C (4);
Height: 25 °C (23);
Tillering: 32-34 °C (13);
Leaf emergence: 30 °C (23);
Flower initiation: 24-29 °C; 25-30 °C Day/20-25 °C Night (21);
Anthesis: 30 °C (21);
Ripening: 23 °C (17);
Fertility: Higher than 14 °C and less than 38 °C (1)
Transplanting: Higher than 15 °C (8)

These data show that temperatures optimal for leaf emergence, floral initiation, and anthesis would be lower than optimal for tillering and elongation. But suppression of tillering and elongation would not be yield depressing.

Techniques for computing day and night temperatures from data of maximum and minimum temperatures have been published by Oldeman and Frere (19).

Water and submerged soil temperatures

During its early stages, the growing rice plant remains submerged in water. Water temperature is more important than air temperature at active tillering. The optimum range is 25-30 °C (4). A submerged soil temperature of 32±5 °C at night has been reported optimal for all rice growth stages (2). Root growth is best at a water temperature of 23 °C and shoot growth at water temperatures of 28-35 °C (21).

In high latitudes, warming the water by using evaporation retardants is beneficial. In the tropics, the temperature of a freely evaporating surface does not exceed 33 °C (22) and there is no acute need to use expensive methods to cool the water of ricefields.

Extra Rice-Weather Relationships

For rice, puddling the field and meeting percolation losses by maintaining water depth constitute extra water requirements. Percolation loss is independent of season but not of soil type, waterhead, and perimeter of field area. Replacing rice with an alternate crop in the dry season and on soils where percolation loss is equivalent to or in excess of evapotranspiration needs would appear to be justified.

A saturated soil moisture regime is satisfactory in the rainy season (7), but the depth of standing water required is higher for the hot, dry season than for the cool, dry season. For upland rice, the advantages claimed for water submergence could be taken care of by using weedicides and sodium thioglycolates (11).

In rice evapotranspiration, peak RET ratios of 1.5±0.1 have been reported (5,28). This is attributable to the increased roughness of varieties. For such varieties, indications are that RET would increase after 20% of growth (28). A water shortage immediately after transplanting would be less serious. Indications are that there would be varietal variation in floral control on water consumption and that varieties in which peak water consumption is under floral control would show physiological senescence during maturity (31). Therefore, preharvest draining of the field should be based on the posttransplanting age of the crop. Varieties with no floral control on peak water consumption are better suited for late transplanting. Because the effects of lateness can be overcome by increased population densities, using such varieties would keep the period of below-peak consumption to a minimum.

Because rice often is preceded or followed by aerobic crops, a lysimetric system that provides for maintenance of subsurface and oversurface water tables has been detailed by Venkataraman et al (35). For aerobic crops, the subsoil depth of the water table in the lysimeter tank must be chosen carefully and the surrounding field must be irrigated properly to avoid moisture stress on the aerobic crop.

Rice-Climate Classification

The optimum duration of a rice crop is 4.5 mo, with a total sunshine requirement of 1,000 h. Such a crop would spend about a month in nursery and would have reproductive and ripening durations of a month each.

Isoquant plots giving curves of equal predicted yields for combinations of minimum temperature and solar radiation during ripening have been shown by Seshu and Cady (26). The sunshine requirement for the reproductive stage is reported to be the same as for the ripening stage. Temperatures during the vegetative stage influence photosynthetic capacity. Temperature requirements for various phases have been adequately quantified.

Data about the radiation network are sparse. Techniques are available for estimating solar radiation from sunshine hours (6) or even cloudiness data (3).

From climatic data of actual or derived radiation and minimum temperature, using the procedure of Seshu and Cady (26), one can determine yield potential on a monthly basis. The months with the highest potential delineate optimum ripening. The month preceding optimum ripening can be considered suitable for the reproductive phase if its radiation value is adequate and if its mean air temperature is 25-30 °C with a minimum temperature higher than 20 °C and a maximum temperature lower than 35 °C.

The next step would be to allocate the preceding 2.5 mo to reproduction and ripening in a way that, within the 4.5 mo, total sunshine is 1,000 h or more and mean air temperature is more than 20 °C in the first month and 25-30 °C in the next one and a half months.

That exercise can be repeated for lower and lower yield potentials. From overlapping of or discontinuity in optimum duration, one can arrive at the feasible duration of a rice crop season for different yield levels.

The problem of water availability during the optimum period must be considered. Even where rice is irrigated, the date of release of water is conditioned by the incidence of rainfall in the catchment areas. The local traditional season could give a real-time picture of the start of the rice season in irrigated areas.

In areas where the rice crop is entirely dependent on rainfall, one has to consider short period rainfall on a pentad, weekly, or decade basis. Saturation soil moisture, not standing water, is required for rice in the rainy season. To predict the probability of the start and end of the overall rainy season, Oldeman and Frere (19) used the forward and backward accumulations of rainfall for the decade. Because any rainfall would contribute to the evapotranspiration of a land-covering crop, the backward accumulation technique to find the end of the rainy season may be justified for rice.

However, with bare soil, short-period rainfall over a week or pentad has to meet the PET demand before moisture accretion for crop use can occur (30).

Accumulating weekly or pentad totals of rainfall in excess of PET to a value that would facilitate direct seeding or puddling would be better for fixing the start of the rice rainy season. Whether direct seeding or puddling is to be done would depend on the persistence of wet weeks; the weeks of moisture recharge could be analyzed for this.

To know the water availability picture for the season, a primary budgeting of short-period rainfall against the ET need of the rice crop is necessary. The ET can be taken as equivalent to PET in the first 50% of crop growth and 1.3 times PET for the last 50%. During periods when moisture storage exceeds saturation capacity or bunding height, losses to seepage, percolation, and spill-off can be allowed, using the interactive procedure suggested by Oldeman and Frere (19). If the analysis is done for crops of different durations, the maximum possible water availability period for rice can be defined. An estimate based on a year's time can be used to delineate the optimum water availability period for upland rice.

Rice crop rotation

The crops that can precede or follow rice for year-round cropping under varying weather situations have been detailed by Lomotan and Baradas (12). The only notable omission is a rice - wheat sequence. For wheat, and for almost all the crops they mention (maize, sorghum, peanut, cowpea, soybean), information on phasic climatic requirements is available. An analysis of pre- and postrainy season weather features can help identify the best rotation crops and their optimum growing periods. Venkataraman and Rahi (34) examined winter season climatology in India in relation to photothermal requirements of dwarf wheats. In Gangetic West Bengal, wheat after rice can be sown up to mid-December with little impairment to the development of the wheat crop.

Rice Yield Prediction

A yield prediction formula should be based on accurate inputs of crop phenological phases, meteorological parameters, and yield data and on well-established physiological concepts and crop-weather relationships. The methodologies for rainfed and for irrigated crops would be different.

For rice, multilocation sowing date trials, such as IRTP, can provide a foundation for yield predictions under irrigated conditions. For universal application, such formulations need to be critically evaluated. For example, Nishiyama (18) reported that average rice yields ranging from 3.4 to 5.4 t/ha in selected prefectures in Japan correlated closely with accumulated values of photosynthetically active solar radiation (PASR) in the range of 6,513-10,861 cal/m^2 during ripening (from average heading to average harvest dates), but not with temperature. The study obviously relates to irrigated crops having optimum heading temperatures during ripening at the places and during the seasons observed.

PASR is not a parameter that is measured very often. Fortunately, there is a strong relationship between PASR and solar radiation (14). Using solar radiation instead of PASR would be preferable for wider applications across time.

Seshu and Cady (26) have worked with yield data on nonstressed crops grown in a radiation range of 315-637 mWh/cm^2 with a minimum temperature range of 17.4-29.2 °C during ripening. They have outlined a formula for predicting yields from the levels of radiation and minimum temperature during ripening. The tacit assumption in the formula is that the development of photosynthetic capacity is optimum for all locations and years. This may not be the case when weather vagaries force deviations from the normal season. The suggestion of Kudo (10) to include growth attributes, such as spikelet number or dry weight at heading, deserves serious consideration.

In order to predict yields of rainfed rice, it will be necessary to assess the incidence of moisture stress in the season along the lines suggested by Oldeman and Frere (19), together with actual or derived information on planting and ready-for-harvest dates, and to consider the radiation and temperature regime during ripening. To account for temporal variations in rainfall distribution, IRTP for upland rice should provide for multisowing date trials each season of each year.

Conclusion

The existing information on climatic requirements of crops, methodologies for assessing crop water requirements and its optimum distribution, and archives of meteorological data can be used to determine optimum rice-based cropping systems for different areas. In predicting yield, care should be used in transposing formulas across locations, even for irrigated crops. Much more needs to be done for rainfed rice. For large areas, it would be prudent to determine the data set requirements and the infrastructure needed to make viable predictions.

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Implications of rice-weather studies for national programs

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ABSTRACT

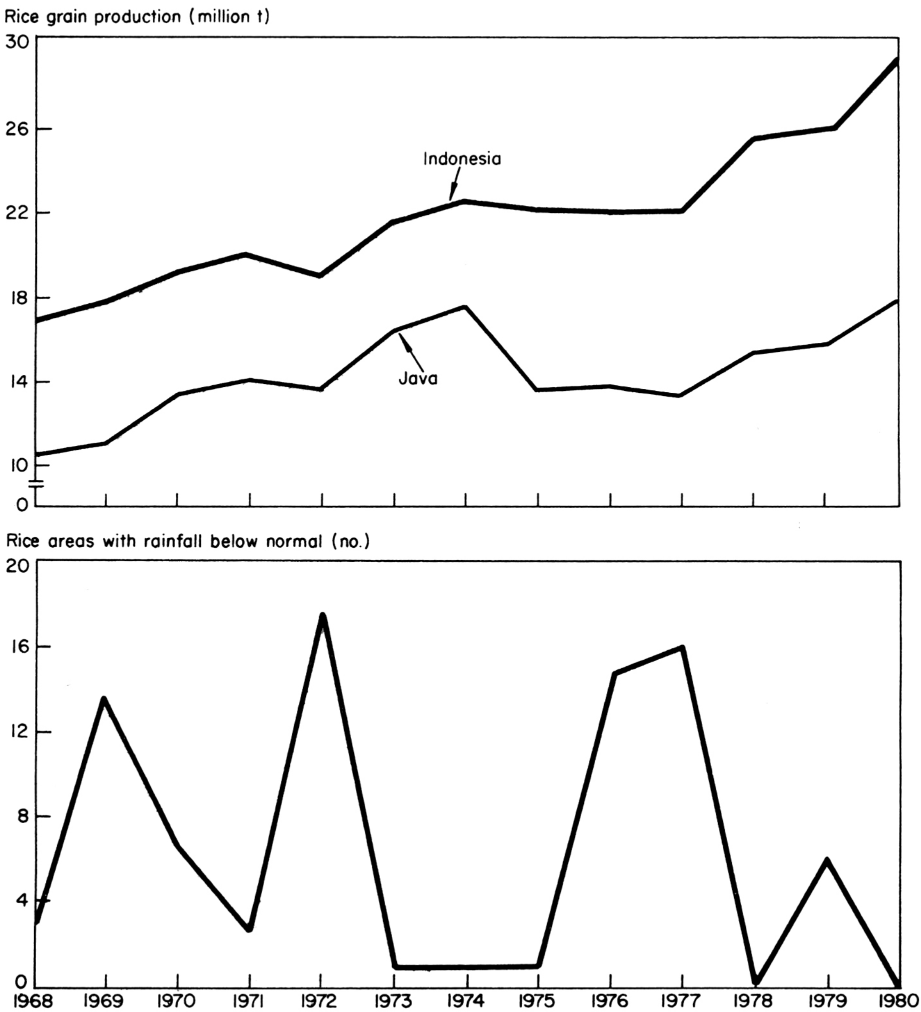
High variability in rainfall patterns and distribution is the main factor causing fluctuations in the growth of rice production under both rainfed and partially irrigated conditions in the tropics. Temperature and solar radiation are much less variable, but their effects on rice grain yield are only partially understood. Because of the interrelationships among the various physical parameters of weather, any fluctuation in rainfall affects the other parameters. Unstable weather parameters create difficulties in meeting future food production targets and dictate that more attention be paid to food security programs. These difficulties may be time and location specific. Climatic classifications based on rainfall have been developed for the humid tropics. Because rainfall is variable, it is important to improve the criteria for climatic classification by including soil water retention potential. Phenological phenomena may be used to improve the accuracy of weather forecasts. Stabilizing food production and its growth rate cannot be solved by better climate classification nor by more accurate weather forecasting. Appropriate technology suited to aberrant weather conditions must be developed. Reduced tillage practices, methods of conserving soil water, and water harvesting are alternatives to harnessing aberrant weather. Refining and testing such technology should be part of existing cropping systems and agroclimatic research.

Despite the impact of the green revolution on improving the rice situation in tropical Asia, it is apparent that the rice production growth rate is unstable. The forces of instability lead to greater concern for rice security and focus more attention on sustaining the rice production growth rate.

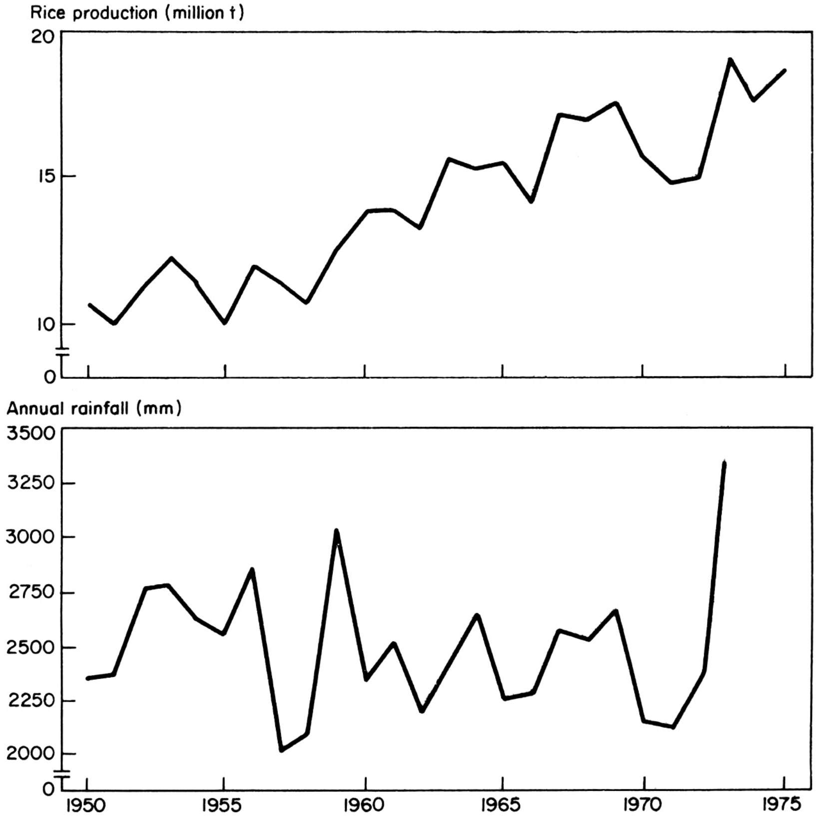
When green revolution technology was introduced, it was obvious that the tropical climate and the nature of the rice plant were propitious to a major scientific breakthrough. Unfortunately, the tropical climate also causes an uneven rice production growth rate.

In contrast to a sharp rise in rice production for tropical Asia, there has been a decline in rice production in tropical Africa. The constraints to increased food production in Africa are even more complicated than they are in Asia; it may not be possible to solve them by applying climate and crop-weather studies.

We review here the major physical parameters of the tropical climate as well as their potential for food crop production. Topics for rice-weather studies by national programs are proposed.



1. Annual rice production trends in Java and Indonesia, plotted against below-normal rainfall (11).



2. Bangladesh rice production, 1950-75, plotted against annual rainfall (21).

Major Weather Parameters Limiting Rice Yield

Rainfall

Because of high variability in monsoon rainfall, rice-growing regions in the tropics face problems in sustaining rice production growth rates. Variations in the start and end of rainfall, as well as in its intensity, greatly affect crop production.

In Java, Indonesia, for example, most rice areas are irrigated. But rice production from 1968 to 1980 fluctuated synchronously with the number of areas receiving below normal rainfall (Fig. 1) (11). In Bangladesh, where rainfed lowland rice is dominant, rice production from 1950 to 1971 fluctuated with annual rainfall (Fig. 2) (21). India achieved only a 16% gain in rice production between 1961-65 and 1971-75, because of little increase in rice yields in eastern India. Extensive areas of rainfed rice in this part of India are subject to drought and flood (3). Rice yields in Senegal, Africa, decreased rapidly when rainfall was less than average over a 10-yr period (9).

Reports from South and Southeast Asia and Africa suggest that rainfall fluctuations affect rice production under both irrigated and rainfed conditions.

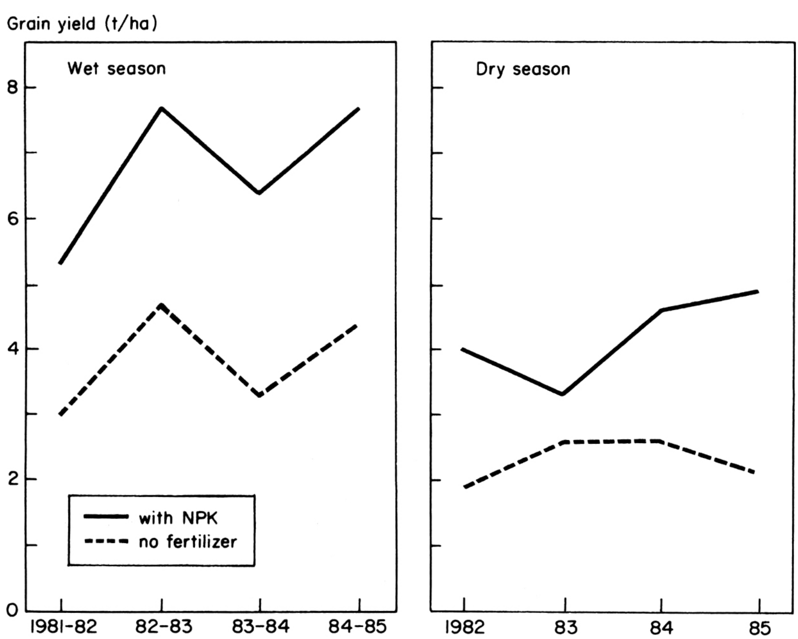
Temperature and solar radiation

Yield potentials of rice may be lower in the tropics than in the temperate regions because of the small diurnal changes in temperature in the tropics (4). But this is not necessarily true for improved indica rice varieties (20,34).

Usually, high rainfall intensity in the wet season in the humid tropics is associated with low solar radiation and relatively low temperatures, in contrast to conditions in the dry season. Studies at IRRI and elsewhere showed that rice yields were higher in the dry season than in the wet season (3,5,10). This tends to confirm that the positive effects of high solar radiation compensate for the negative effects of high temperature on rice yield. Discrepancies in the total effects of high solar radiation and high temperature have been observed with IR36 rice. Data from long-term fertility trials at the Sukamandi Experimental Farm (Vertic Tropaquults), Indonesia, show that IR36 planted in the dry season consistently gave lower yields than when planted in the wet season (Fig. 3), despite the higher N levels applied to the dry season crop (31).

The highest rice yields ever recorded in Indonesia (from annual yield contests) were 20.3 t/ha in West Nusatenggara, Bengkulu, and 21.5 t/ha in West Sumatera, on the basis of (pre-drying) harvest weight (Table 1) (12). Maximum recorded yields were 17.3 t/ha for India and 13.2 t/ha for Japan (33).

Time to flowering of restorer and male-sterile lines used for hybrid rice tend to vary from one year to the next. This phenomenon, observed at the



3. Grain yields of IR36 planted at the Sukamandi Experimental Farm in the wet and dry seasons. Data from long-term INSFFER trial (90 kg N/ha in the wet season, 120 kg N/ha in the dry season) (31).

Table 1. Grain yields in the 1981-82 Indonesian rice production contest (12).

Farmers' group	Farm size (ha)	Variety	Grain yield [a] (t/ha)	
			Lowest	Highest
Dewi Sri, W. Java	92	Cisadane	6.9	10.7
Bina Karya, C. Java	40	Cisadane	12.5	18.8
Sejahtera, E. Java	26	IR54	12.2	17.9
Jembrana, Bali	36	IR36	13.0	17.4
Setia Tani, W. Nusatenggara	26	IR36	10.0	20.3
Sentosa, Aceh	89	IR32	11.2	16.4
Dharma Karya, N. Sumatera	32	IR42	9.8	16.4
Kampung Sabalah, W. Sumatera	59	IR42	9.1	21.5
Karya Baru, Bengkulu	33	IR38	10.0	20.3
Giat Tani, S. Sumatera	66	IR36	5.1	9.7
Sejahtera, Lampung	33	IR36	11.2	14.1
Sumber Rejeki, S. Kalimantan	25	IR50	5.4	9.7
Harapan Java, C. Sulawesi	43	IR42	7.3	14.0
Masakini, N. Sulawesi	31	IR38	11.8	17.4

[a] Measured at harvest, before drying.

Sukamandi Experimental Farm, causes problems in producing hybrid rice (Dr. Bambang Suprihatno, Sukamandi Research Institute for Food Crops, 10 Mar 1986, pers. comm.).

Further investigations are needed to characterize environmental conditions in the tropics where 1) maximum recorded rice yields are higher than those in temperate regions, 2) higher solar radiation in the dry season did not result in higher rice yields, and 3) variations occur in the flowering times of hybrid parents.

Subjects for Rice-Weather Studies

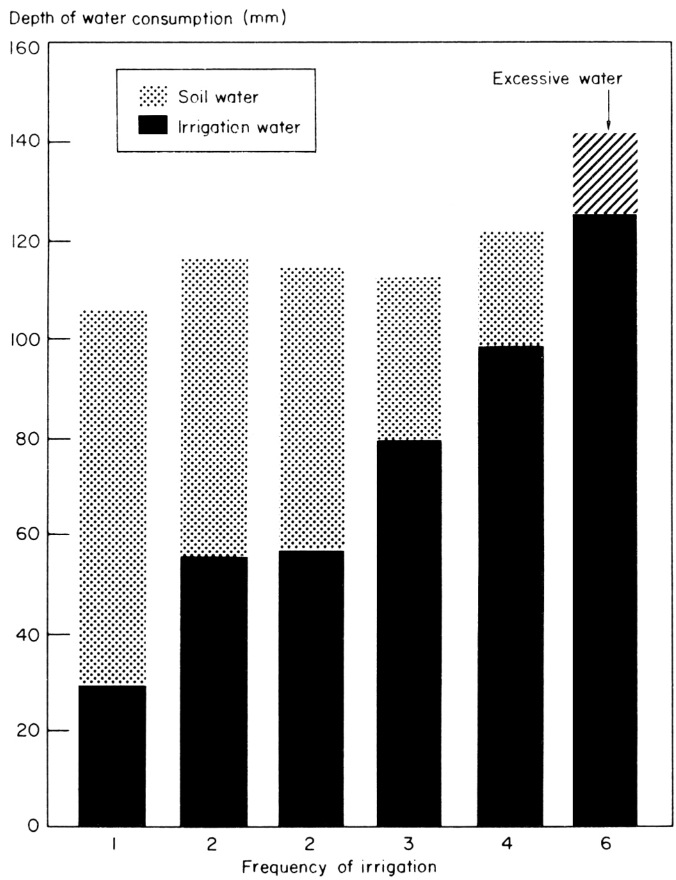
Agroclimatic classification

The agroclimatic classification developed by IRRI (15) for evaluating cropping systems potentials in Southeast Asian rice-growing regions used a wide range of wet and dry months. This classification delineated seven agroclimatic zones in Indonesia. A modification of this classification used narrower ranges for wet and dry months to identify 14 agroclimatic zones (25,26,27,28).

A monthly rainfall of 200 mm was considered sufficient for lowland rice and 100 mm for upland crops (25). The availability of these amounts of rain is largely dependent on the capacity of soils to retain water. Approximate amounts of available soil water for different soil textures are shown in Table 2 (29). The water table is also a potential source of available water for crops. Upward movement of water from the water table to the root zone depends on toposequence, water table depth, and soil texture (6,8). Studies on a clayey soil at the Sukamandi Experimental Farm showed that residual soil moisture supplied considerable water for mungbean planted in the dry season after rice (Fig. 4), minimizing the amount of irrigation water required (14).

Table 2. Available soil water in different soil textures and soil water retentions (29).

Soil texture	Available soil water (mm/m soil depth)			
	0.2 bar	0.5 bar	2.5 bar	15 bar
Fine-textured soils				
Heavy clay	180	150	80	0
Silty clay	190	170	100	0
Loam	200	150	70	0
Silt loam	250	190	50	0
Silty clay loam	160	120	70	0
Medium-textured soils				
Sandy clay loam	140	110	60	0
Sandy loam	130	80	30	0
Loamy fine sand	140	110	50	0
Coarse-textured soils				
Medium fine sand	60	30	20	0



4. Contribution of soil water (stored water + water table) to water requirement of mungbean planted in the dry season after rice grown with varied irrigation (14).

Table 3. Water balance classified on values for water retention potential and rainfall for shallow rainfed lowland rice in South and Southeast Asia (13).

Water retention potential				Rainfall			
Slope	Value[a]	Texture	Value[a]	5-mo rainfall	Value[a]	Growing season length	Value[a]
0-8	1.0	Fine	1.0	High to very high	1.0	Long (5-12 mo)	1.0
		Medium	0.6	(>1500 mm)		Medium (4 mo)	0.6
		Coarse	0.3			Short (0-3 mo)	0.3
8-30	0.6	Fine	1.0	Medium	0.8	Long	0.8
		Medium	0.5	(1200-1500 mm)		Medium	0.5
		Coarse	0.2			Short	0.2
>30	0.3	Fine	1.0	Low	0.5	Long	0.6
		Medium	0.4	(1000-1200 mm)		Medium	0.4
		Coarse	0.1			Short	0.2
				Very low	0.2	Medium	0.2
				(<1000 mm)		Short	0.1

[a]Water balance class (sum of 4 determinants): Favorable = 3.6-4.0, intermediate = 3.1-3.5, drought-prone = 2.4-3.0, highly drought-prone = 2.3.

The criteria for evaluating the suitability of environmental conditions for rainfed lowland rice proposed by Garrity et al (13) include water retention potentials of soils as well as rainfall regimes (Table 3). Evaluation of these criteria as additional criteria for crop suitability classifications is needed.

Weather forecasting

Climatic classifications developed for the humid tropics are usually based on rainfall. Because of the high variability of monsoon rains, recorded rainfall usually fluctuates widely. Fourier Descrete Transformation (FDT), a standard method for rainfall forecasting used by the Agency for Meteorology and Geophysics, Indonesia (32), is reported to be a promising methodology. The relationship between forecast rainfall using FDT and recorded rainfall results in a high coefficient of determination for a 1-mo forecast, but a lower coefficient for a 3-mo forecast. This method is highly accurate in evaluating rainfall characteristics or rainfall tendencies. The degree of accuracy depends on location (Table 4).

The physical parameters of weather and the mechanisms of the atmosphere that control weather are not stable. During a workshop on climate and crop production programs of Indonesia, it was proposed that *pranata mangsa* (traditional method of identifying seasons using phenological phenomena) be included. Using *pranata mangsa,* the climate of Java can be divided into 12 seasons (Table 5), instead of simply dry and wet seasons. In Lombok, West Nusatenggara, for example, rainfall is expected to come if sea worms, known locally as *nyale,* appear on the water surface. Once the *nyales* appear, farmers start preparing their fields for cultivation.

The instincts of plants and animals tend to integrate many environmental factors; studies of phenological phenomena could be important in improving the prognostic criteria for weather forecasting.

Table 4. Coefficients of the relationships between (a) forecast and recorded rainfall, (b) forecast and recorded rainfall characteristics, and (c) tendency of forecast rainfall (32).

Station of observation	1-mo forecasting	3-mo forecasting
Forecast vs recorded rainfall		
Cacaban reservoir, Tegal	90	89
Malahayu, Brebes	91	64
Southern Demak, Demak	-	65
Forecast vs recorded rainfall characteristics		
Cacaban reservoir, Tegal	88	75
Malahayu, Brebes	82	63
Southern Demak, Demak	-	66
Tendency of forecast rainfall		
Cacaban reservoir, Tegal	97	92
Malahayu, Brebes	92	96
Southern Demak, Demak	-	84

Table 5. Seasons in Java, Indonesia, as differentiated by *pranata mangsa* (phenological phenomena).

Name of season[a]	Duration (d)	Beginning of season
Kaso	41	22-23 Jun
Karo	23	2-3 Aug
Katigo	24	25-26 Aug
Kapat[b]	24	18-1 9 Sep
Kalimo	25	13-14 Oct
Kanem	27	9-10 Nov
Kapitu	43	22-23 Dec
Kawolu	26-27	3-4 Feb
Kasongo	25	1-2 Mar
Kasadoso	24	26-27 Mar
Dhesto[c]	23	19-20 Apr
Sodho	41	12-13 May

[a] In Java. [b] Wet season begins: wind blows from northwest; kapok trees are in flower, mammals are breeding, weaver birds are preparing nests, fish appear from hiding. [c] Dry season begins: wind blows from southeast; the second rice crop is harvested, tuber crops develop tubers, birds are hatching.

Appropriate Technology

In Niger, Africa, where only 12% of the land is suitable for agriculture, statistics show wide fluctuations in food production as a result of aberrant weather. Faced with that situation, President Seyni Kountche (17) asked: “Why have rural development strategies essentially been based on rainfall instead of promoting models suited to freeing agriculture from the fluctuations of climate?” President Julius K. Nyerere of Tanzania (24) considered the backwardness of agricultural methods, the use of primitive tools, and the lack of scientific knowledge as the main constraints to higher food crop productivity in Africa.

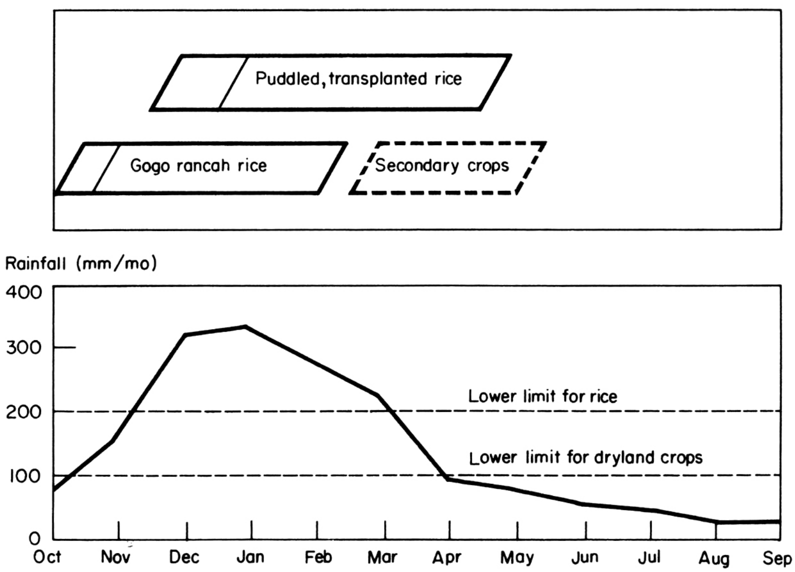
Gogo rancah rice

In Indonesia, a combination of traditional and modern technologies have helped boost rice production. In Lombok, 1,331 mm of annual rainfall is distributed irregularly, mostly within 3-4 mo (Fig. 5). Soil puddling aggravates the availability of rainwater to plants. Because of late planting, transplanted rice is often subjected to drought stress during its reproductive stages, resulting in low grain yields. As a result, rice production in Lombok could not meet demand. The gogo rancah system of rice cultivation (nonpuddled, dry-seeded, bunded rice) introduced in 1980-81 has increased rice production (Fig. 6) and changed Lombok from a food-deficient to a food-surplus area (7).

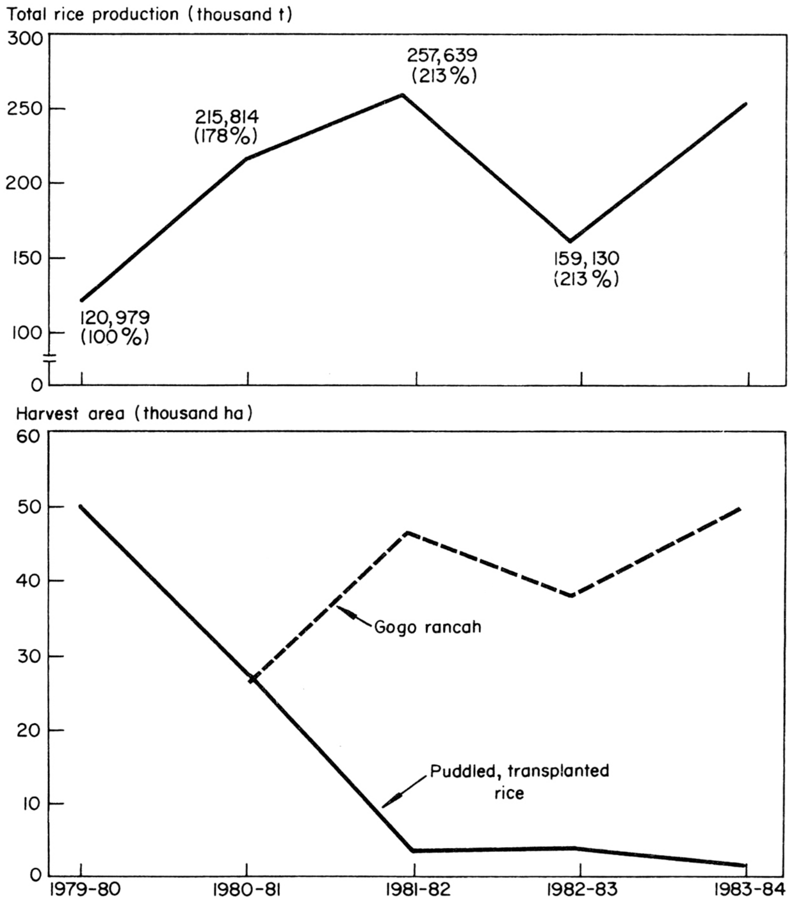
Walik jerami rice

Walik jerami is a minimum tillage transplanted rice management system typically used by farmers in Java. Rice is directly transplanted after harvest of the first crop. The second rice crop can be grown in the dry season on remaining rainfall and residual moisture. The practice is used widely on Tropaquept soils in the Indramayu area of West Java. This area is partially irrigated and flooding commonly occurs during the peak of the rainy season.

The gogo rancah technique for wet season rice permits earlier planting and enables the rice plant to grow tall enough to avoid flood damage during its reproductive growth. Walik jerami rice is planted immediately after harvest of the first rice crop. There is enough time to grow the walik jerami rice and possibly a following legume crop on residual moisture. Using such practices, cropping intensity and farm income have increased (Table 6) (18).



5. Working calendar for transplanted cultivation and introduced gogo rancah cultivation. Lombok, West Nusatenggara, Indonesia.



6. Annual rice production in Lombok and areas planted to gogo rancah rice since 1980-81 (7).

Reduced tillage practices also were reported to be promising for wheat, maize, and other cereals in South and Southeast Asia (2,19,23,30). They shorten turnaround time and increase cropping intensity under limited water supplies. Even in the United States, reduced tillage practices are gradually being adopted because they minimize energy consumption and production costs (1,22).

A more positive approach is needed to develop and assess reduced tillage systems for different crops, soils, and climates. Approaches must be pursued with the idea that newly devised systems will be used. It will be necessary to test and refine the technology so that it can be integrated into existing cropping systems in different agroclimatic zones.

Surjan

Surjan, a traditional farming system in Indonesia, consists of alternating broad raised beds of piled up soil with lowered beds. The technique is often used in

Table 6. Yield and economic return from farmers' and introduced cropping patterns. Indramayu, West Java, 1975-78 (18).[a]

Cropping pattern	Av yield (t/ha) with irrigation	
	7-9 mo	5-7 mo
Farmers' cropping pattern (1975-77)		
Transplanted rice	5.3	3.6
Transplanted rice	2.8	2.2
Net return ($)	590	309
Introduced cropping pattern (1975-77)		
Transplanted rice/gogo rancah[b]	5.6	4.8
Walik jerami rice	4.6	4.6
Legume	0.9	0.5
Net return ($)	993	524
Introduced cropping patterns (1977-78)		
Transplanted rice/gogo rancah[b]	7.2	3.4
Walik jerami rice	4.6	2.9
Soybean	0.610	-
Net return ($)	1,231	484

[a]1US$ = Rp 425 during 1975-78. [b]Gogo rancah technique was used in areas receiving 5-7 mo irrigation.

areas subject to flooding during the rainy season and drought during the dry season. During the wet season, water is collected on the lowered beds which are cultivated for lowland rice and/or fish. At the same time, the raised beds, which are too high to be flooded, are used for dryland crops. This system uses rainfall (or partial irrigation) efficiently. Water collected in the lowered beds permits crop production when there is a shortage of water in the entire area at the beginning and end of the rainy season. And, crops can be grown on the raised beds when there is flooding. Using this system, 160 mm rainfall per month is sufficient for lowland rice (16); the conventional system needs more than 200 mm/mo.

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A climatic classification for rice production in China

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ABSTRACT

Climates for rice production in China were classified according to a series of indices. A temperature index was used to divide China into two parts, potential and unsuitable rice production regions. Potential rice regions were further divided into humid, subhumid, and arid regions, using a rice aridity index based on a modified Penman equation. Based on modeling of rice growth duration and assessment of rice growing season, a compound index was established. With cross-reference to supplementary indices, such as topography, etc., China was finally delineated into 6 rice major climatic belts with 22 subbelts. This rice climatic classification was an effort to provide guidelines for utilizing land and water resources and for choosing suitable cropping systems and rice varieties.

China is the largest rice producer in the world, with a rice-growing area of more than 33 million ha and an annual yield in recent years of more than 144 million t. Greatly diversified climatic factors — temperature, moisture, and daylength, combined with topography — govern the climatic suitability of the rice-growing area in space and time.

The climate of China is generally favorable for rice cultivation. During the growing season, temperatures in the vast rice-producing areas are much higher than those at the same latitudes in other countries. Meanwhile, the monsoon carries abundant rainfall. The coincidence of ample precipitation, high temperatures, and high solar radiation is very beneficial to agriculture, especially to rice production.

On the other hand, unfavorable climatic constraints and disasters make it difficult for China to increase its rice production. Insufficient and unreliable rainfall causes extremely dry weather in the northwest. Spring droughts occur often in the north. Typhoons and floods occur frequently in the south. Injury due to low temperature is a major limiting factor in the north and northeast, and in most hilly regions throughout the country.

In addition to complex climatic conditions, the availability of reclaimable crop land is limited by adverse topography and dense population pressures. This means that China must adopt multiple cropping systems involving rice if production is to continue to grow.

We developed climatic classification to aid in increasing rice production. Crop characteristics (growth duration, sensitivity to temperature and daylength, water requirement, etc.) and environmental factors (temperature, moisture, daylength, topography, etc.) and their interactions were considered. Attention was focused on how the rice crop responds to environmental conditions and how existing environmental resources can be utilized most efficiently. The classification is designed to identify the optimum growth regions for different cropping systems and different rice varieties. This study reports the attempt to identify those climates best suited to rice production.

Ding (3) established the first regional division for rice production in China. In his classification, climate as an environmental factor was considered only roughly. No other climatic classification for rice production has been accomplished so far.

Methodology

To understand the relationship between environmental factors and rice production in China, an extensive investigation of different rice-producing regions was undertaken.

A series of environmental indices — temperature, moisture, a compound index for cropping system, topography, and rice growth duration, etc. — were chosen according to their importance in rice production. Each index was related to a particular problem in rice production: temperature index to the possibility of raising rice, moisture index to the irrigation conditions required for rice cultivation, etc.

These indices compared actual rice distribution and production and relevant climatic circumstances, especially those identified from field experiments (2,4,7). Most indices were not in a single form with a single element, but involved several related climatic factors. Computer models of these indices were built; the climatic data from different locations were also computerized. Locations with analogous climatic characteristics were grouped as rice regions.

Index Description

Temperature index

Rice growth and development in a given area depend primarily on temperature, which must be above a critical value. From experimental results (7) and field practices in the cool areas of the northeast, it is recognized that a mean daily temperature of 10 °C is the threshold for growing japonica varieties. Only when the mean daily temperature is equal to or greater than 10 °C for at least 110 consecutive days can extra-early maturing japonica rices be grown. From a survey in the Yunnan-Guizhou Plateau, Chang (1) reported that the early japonica varieties can reach booting, heading, and flowering below 20 °C but above 18°C mean daily temperature because of a rather wide daily temperature range. For example, rice grows in the Lijiang region (Yunman Province), where the elevation is 2,300 m and the highest mean daily temperature in summer is only 18-19 °C.

The two temperature indices (TI) recommended are:

1. at least 110 successive days with a mean daily temperature ≥10 °C, and
2. at least 30 successive days with a mean temperature ≥18 °C during booting and heading.

Rice can be grown in a given region (presupposing available water) if the thermal condition satisfies both those indices. Otherwise, rice crops will fail. TI was taken as the first-order index for the climatic classification in China.

Moisture index

Within a region with potential for rice production, water supply is another significant factor. The concept of a rice aridity index (RAI) was adopted as the second-order index. RAI is defined as

$$\mathbf{RAI = ET_R / P} \quad (1)$$

where:

ET_R = total evapotranspiration, in mm, from ricefields during the rice growing season, and

P = precipitation, in mm, during the same period.

ET_R can be found by

$$\mathbf{ET_R = K_R \cdot ET_o} \quad (2)$$

where:

ET_o = the reference crop evapotranspiration for the rice growing season considered, and

K_R = crop coefficient for rice (in the south, K_R = 1.05; in the north, K_R = 1.25) (9).

According to Doorenbos (5), ET, can be obtained from the modified Penman equation

$$\mathbf{ET_o = c \cdot [W \cdot RN + (1 - W) \cdot f(u).(e_a - e_d)]} \quad (3)$$

where:

W = temperature-related weighting factor,

Rn = net radiation (equivalent evaporation, in mm),

f(u) = wind-related function,

$(e_a - e_d)$ = difference between saturation vapor pressure at mean air temperature and mean actual vapor pressure of air (in mbar), and

c = adjustment factor to compensate for the effect of day and night weather conditions.

Table 1. Empirical coefficients a and b for equation 5.

Region	a	b
South to Huai River and Qin Mt.	1.0	0
North to Huai River and Qin Mt. but east to Xin-an Mt.	1.1	-0.1
The rest	1.2	-0.2

Net radiation Rn can be found by

$$Rn = (1 - \mathbf{a}) \cdot Q - 1 \qquad (4)$$

where:

Q = total incoming short-wave radiation;

a = short-wave reflection coefficient of the reference crop. It was assumed that a = 0.23 (8); and

I = effective net outgoing long-wave radiation obtained from the empirical equation

$$I = (a\frac{Q}{Q_0} + b) \cdot I_0 \qquad (5)$$

where:

Q_0 = total radiation from the Smithsonian Meteorological Table;

I_0 = effective outgoing radiation under conditions without cloudiness, obtained by Rosenberg's method (10); and

a,b = constants.

Table 1 gives empirical values of a and b for different regions (9).

Methods for calculating the other elements in the modified Penman equation [W, f(u). and c] followed Doorenbos (51). (e_a - e_d) were obtained directly from meteorological data.

The second-order moisture index for rice climatic classification can be described as:

1) Regions where the rice aridity index (RAI) during the rice growing season is greater than 2.0 are classified as the arid zone: rice production is limited by water stress, rice is cultivated only in areas where irrigation systems are perfect.
2) Regions where the RAI during the rice growing season is greater than 1.0 but less than or equal to 2.0 are classified as the subhumid zone: rice production depends, to a large extent, on irrigation.
3) Regions where the RAI is less than or equal to 1.0 are classified as the humid zone: rainfall usually can meet the needs of rice production but seasonal supplementary irrigation is occasionally necessary. All the important rice-producing regions are concentrated within the humid zone.

Compound index for rice cropping systems

The compound index for rice cropping systems (RCI) is defined as the ratio of the length of the rice-growing season (RGS), estimated on the basis of temperature, to rice growth duration from sowing to maturing (RGD), formulated by photothermal models of rice growth duration according to Gao et al (6; 1985 unpubl. data), plus the time interval between successive crops.

$RCI = RGS\ (RGD + T_i)$ For single rice crop only

$RCI = ARGS\ (\mathbf{S}RGD + \mathbf{S}T_i)$ For multiple cropping system

where:

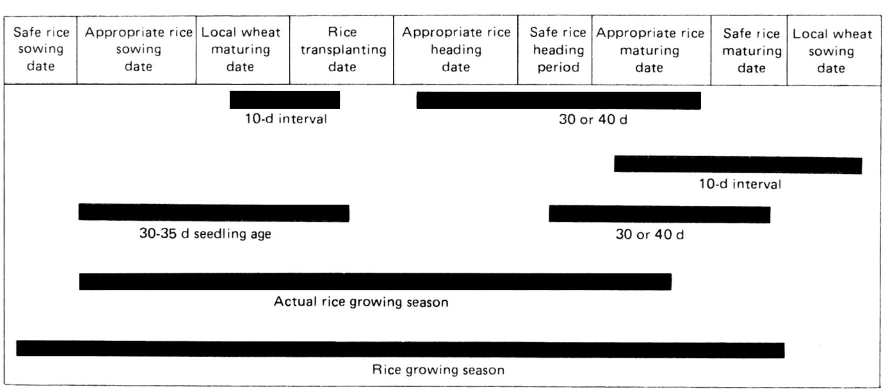
RCI = compound index for a rice cropping system;
RGS = rice growing season, in days. for a specific region;
ARGS = actual rice growing season, in days. for a specific region under a wheat + rice pattern or a wheat (barley) + double rice cropping system;
RGD = rice growth duration, in days. under different cropping systems, according to the photothermal models; and
T_i = time required, in days, for harvesting and preparing the field for the succeeding crop. For a single rice crop. T_i = 0; for a double cropping system, T_i = 10.

In computing RCI, two major procedures were performed.

1. Assessing the length of a rice growing season

Rice growing season (RGS) is defined as the total number of days from safe sowing date to safe maturing date. It is assumed that RGS is equal to the number of days from safe sowing date to safe heading date plus 40 d for japonica or 30 d for indica varieties. According to Gao et al (6), the safe sowing date is the time when the mean daily temperature is consistently above 10 °C, with 80% probability, for japonica, and consistently above 12 °C, with 80% probability, for indica. Gao et al (6) also defined the safe heading period as the time when the mean daily temperature is above 20 °C for 3 successive days for japonica and above 22 °C for 3 successive days for indica.

RGS can be obtained using these definitions. For a multiple cropping system, the procedure for assessing ARGS was based on local wheat maturing and sowing dates and 30-35 d seedling age (Fig. 1).



1. Rice growing season in a multiple cropping wheat + rice system.

2. Modeling rice growth duration

We (6; 1985 unpubl. data) used a multiple regression technique to develop photothermal models of rice growth duration for 3 major varietal types, based on crop data about 12 representative varieties grown at different locations throughout China and meteorological data taken from the same locations within the same periods. The validity of these models was tested statistically. The results showed that errors in estimating rice growth duration from sowing to heading were only 3-6 d across the whole extent of China. In comparison with the traditional temperature summation method, modeling reduced errors by about 3 d for early varieties, 6-12 d for medium varieties, and 18-20 d for late varieties.

Those models were used to estimate rice growth duration.

The rice growth duration models have these general forms (6; 1985 unpubl. data):

For early rice varieties:

$$\hat{D} = D' + b_1\Delta T + b_2\Delta\phi + b_3(\Delta T)^2 \quad (6)$$

For medium rice varieties:

$$\hat{D} = D' + b_1\Delta T + b_2\phi + b_3\Delta S' \quad (7)$$

For late rice varieties:

$$\hat{D} = D' + b_1\Delta T + B_2\Delta\phi + b_3\Delta S + b_4(\Delta T)^2 + b_5\Delta S \cdot \Delta\phi \quad (8)$$

or

$$\hat{D} = D' + b_1\Delta T + b_2\Delta\phi + b_3\Delta S \quad (9)$$

where

$\hat{D}$ = rice growth duration, in days, from sowing to heading;

D' = standard duration, or duration under standard conditions (T = 25 °C, ø = 30°N, and S = 1 Apr);

ΔT = temperature difference, in °C, between local mean temperature from sowing to heading and standard temperature (25 °C);

$\Delta\phi$ = latitude difference (in degrees) between local latitude and standard latitude (30°N). 4 is considered negative when latitude is ≤30°N and positive when it is >30°N;

ΔS = difference in days between local sowing date and standard sowing date (1 Apr). ø is considered negative when sowing date is before 1 Apr and positive when it is after 1 Apr;

$\Delta S'$ = no effect of sowing date in low latitude (ø£25°N), but considering sowing date in middle and high latitudes;

$\Delta\phi\Delta S$ = the interaction term between ø and S; and

b_i = the partial regression coefficients (i = 1,2....).

Using these models, rice growth duration (RGD) from sowing to maturing (D plus 40 d for japonica, D plus 30 d for indica) could be obtained.

The compound index RCI for representative varieties (early, medium, and late) under different cropping systems (single. double, and triple rice) were computed for all locations concerned. Those locations with the same or close values of RCI for a certain variety under a given cropping system were grouped into a rice region.

RCI were defined as:

- When RCI $\geq$ 1.0, the optimum rice planting area for certain representative varieties under a given cropping system;
- When RCI is less than 1.0 but greater than or equal to 0.9, a partial planting area for these varieties under this system;
- When RCI is less than 0.9, unsuitable planting area for these varieties under this cropping system.

Supplementary indices

Topography. The topography of rice-producing areas in China varies from plateaus to basins and from mountains to plains. Especially in the southeast, vertical differences in climate exist. In this classification, some ranges of big mountains and the bounds of plateaus were used as supplementary indices. For example, in the northeast part of the Sichuan Basin, the ranges of Daba and Mt. Wu were considered as the dividing lines. In the southeast part of the basin, the mountain chain of Dalou was taken as the boundary. Two regions in Yunman Province have an elevation of 2,000 m as their common boundary. Topography also was considered in dividing the Loess Plateau and the North China Plain.

Rice growing season. The length of the rice growing season (RGS) which could be estimated on the basis of temperature also was used as a supplementary index. When this index conflicts with the compound index for a rice cropping system (RCI), RCI should prevail.

Other associated indices. The isothermal lines of January mean temperature = 18 °C and January mean temperature = 14 °C were used as the dividing lines in South China because a mean January temperature of 18 °C satisfies the essential temperature requirement for rice booting, heading, and flowering, so that winter rice can grow well, and because the mean January temperature of 14 °C provides suitable conditions for a rice - rice - sweet potato cropping pattern.

Data Used

Crop data include sowing date, heading date, days from sowing to heading, etc. Some were obtained from the national rice ecological experiment conducted at eight locations 1962-63 under Ding (Coordinating Group of Rice Ecological Researches, 1978) and some from the Jiangsu Academy of Agricultural Sciences (1979-80).

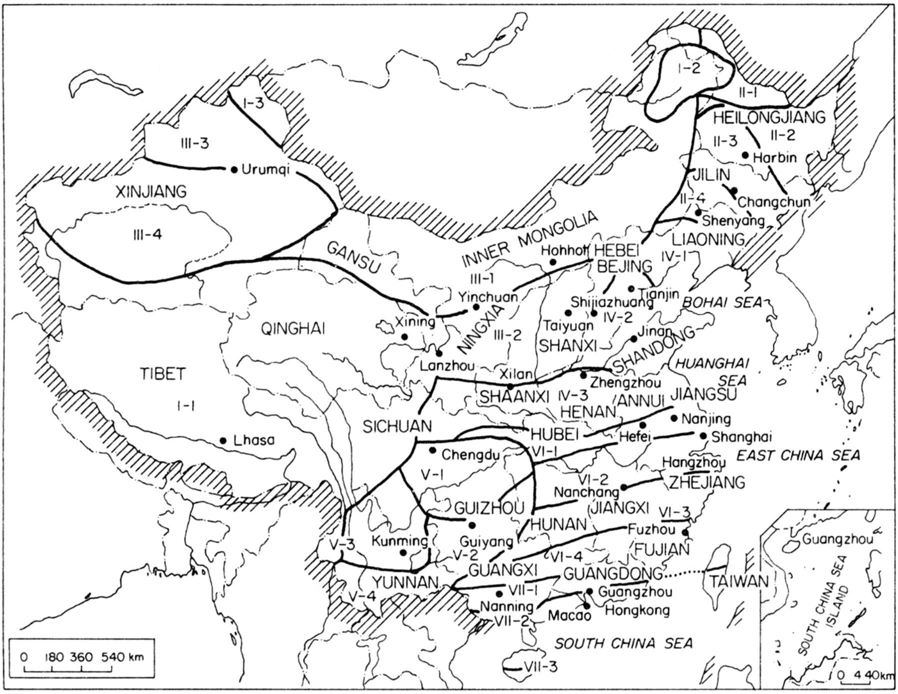
Environmental data include latitude, mean daily temperature, mean 10-d period atmospheric pressure, rainfall, solar radiation, wind speed, (e_a - e_d), etc. These records were obtained from the Centre Meteorological Service of China (1951-70).

Results

The climatic classification for rice production in China are presented in Table 2 and Figure 2.

Table 2. Major agroclimatic characteristics for different rice climatic belts and subbelts in China.

Rice climatic belt	Rice climatic subbelt	Agroclimatic characteristics			
		HI	RAI	RCI	RGS(d)
I. Belt without rice crop	I-1. Tibet		-	-	-
	I-2. Xinan Mt.	Unsatisfied	-	-	-
	I-3. Altai Mt.		-	-	-
II. Northeast China sub-humid — single crop-early rice belt	II-1. Heilung R.		0.9-2.0	For early japonica with early maturity <1.0	120
	II-2. Mudan R.	Satisfied	0.9-2.0	For early japonica with early maturity ≥11.0	120-130
	II-3. Songhua R.		0.9-2.0	For early japonica with medium maturity ≥11.0	130-140
	II-4. Yanbian		0.9-2.0	For early japonica with late maturity ≥11.0	140-160
III. Northwest China dry — single crop-early rice belt	III-1. Yellow R. irrig.		2.0-5.0	For medium japonica with early maturity ≥11.0	120-170
	III-2. Loess Plateau	Satisfied	2.0-5.0	For medium japonica with early maturity ≥11.0	130-180
	III-3. North Xinjiang		20-18.0	For early japonica with late maturity ≥11.0	120-160
	III-4. South Xinjiang		180-84.0	For early japonica with late maturity ≥11.0	160-190
IV. North China subhumid — single rice belt	IV-1. South Liaoning		1.0-2.0	For medium japonica with early maturity 1.0	160-180
	IV-2. Beijing-Tianjin	Satisfied	1.3-2.0	For medium japonica with medium maturity 1.0	180-190
	IV-3. Yellow R. & Huai R		1.1-2.0	For hybrid-indica 1.0	190-200
V Southwest China humid — single & double rice belt	V-1. Sichuan basin		0.5-1.0	For "wheat + hybrid indica" ≥1.0	200-240
	V-2. Guizhou Plateau	Satisfled	0.4-0.5	For hybrid indica ≥1.0	200-220
	V-3. N Yunnan and S. Sichuan		0.6-0.8	For "wheat + medium japonica" ≥1.0	170-200
	V-4. S Yunnan		0.5-0.7	For early triple maturity ≥1.0	200-240
VI. Central China humid — single-double rice belt	VI-1. Jiang-Huai R		0.9-1.0	For "wheat + hybrid indica" ≥1.0	200-210
	VI-2. Yangzi R	Satisfled	0.5-0.6	For early triple maturity ≥1.0	210-220
	VI-3. Jiangnan		0.5-0.6	For medium triple maturity ≥1.0	220-240
	VI-4. Middle-south China		0.5-0.8	For late triple maturity 1.0 < RCI ≥0.9	240-260
VII. South China humid — double-triple rice belt	VII-1. South of Nanjing		0.4-0.5	For late triple maturity ≥1.0	260-280
	VII-2. Pearl R.	Satisfied	0.5-0.9	For late triple maturity ≥1.0	280-290
	VII-3. Hainan Island		0.7-1.0	For late triple maturity ≥1.0	throughout the year



2. Classification of rice growing areas, based on climatic factors and cropping systems.

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Physiological responses

Physiological response of rice to light and to nitrogen

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ABSTRACT

The effect of deep placement of N at panicle initiation on yield and yield components was examined in dry and wet seasons at IRRI, using varieties with different growth characteristics. In the dry season, deep placement at panicle initiation increased N content and crop growth rate remarkably in medium-duration varieties IR8 and IR42. Spikelet numbers increased 5-8%, but filled grain decreased 3-14%. Late deep placement at panicle initiation did not significantly affect spikelet formation and yield in short-duration IR36. In the wet season, deep placement at 10 d after panicle initiation increased ripening and yield of medium-duration varieties. At IRRI, deep placement of N around panicle initiation apparently limited yield by encouraging more ineffective spikelets. Yield in unfertilized and standard fertilized plots wasconsistently lower than in previous studies, possibly due to impeded N uptake.

The significance to yield increase of canopy photosynthesis during the reproductive and ripening stages has been linked to shading (17) and atmospheric CO_2 enrichment (1, 15). This is supported by correlation studies between climatic factors and yield (4, 10, 11, 13). Methods of applying N in different climatic conditions also are closely related to the physiology of yield-determining characters (3, 8, 9). The optimum level of N in a plant is always dependent on the intensity of solar radiation and the temperature at each growing stage.

At IRRI, solar radiation during the reproductive and ripening stages is positively related to yield (4, 5, 6, 7, 13). However, optimum N requirements differ significantly between the dry and the wet seasons.

In the dry season, solar radiation tends to increase from transplanting to harvest. Yield is not limited during ripening because of higher solar radiation during the reproductive and ripening stages (17). Maximizing yield in the dry season depends on improving spikelet number/ absorbed N. However, in warm climates, spikelet numbers cannot be increased by increasing absorbed N before heading (12).

In the wet season, solar radiation is comparatively higher before panicle initiation, declining toward harvest. A plant's N content tends to be higher at the early growth stage because favorable temperatures increase available N in the soil. Lack of available N and lower solar radiation at ripening is considered more yield limiting (5,6,7).

Broadcast topdressing of N has been the common practice to produce more spikelets in the dry season and better ripening in the wet season. But the resulting higher N content in the plant lasts only a short time. To sustain the N level, deep placement fertilization at the late growth stage was introduced. Late deep placement as a technique to promote high-yield was first tried in northern Japan (9). Yields in that temperate climate improved, even in indica variety Milyang 23 (2). However, Shiga et al (14) reported less response in IR26 and IR747 to late deep placement fertilization at IRRI.

N fertilization appropriate to a given solar radiation should increase sink size and ripening by increasing the photosynthetic activity of the canopy. Late deep placement fertilization to improve N nutrition at later growth stages would be a good strategy to increase sink size in the dry season and ripening in the wet season.

The effectiveness of late deep placement of N was analyzed in the wet and dry seasons at IRRI, using varieties with different growth characteristics.

Materials and Methods

In the 1985 dry season, 20-d-old seedlings of IR8, IR36, IR42, and Peta were transplanted 25 Jan at 3 plants/ hill, spaced 25 × 15 cm, on 20-m^2 plots. Basal fertilizer was applied at 0, 40, and 110 kg N/ha, in a randomized block design with 2 replications. Method, amount, and time of treatments are shown in Table 1.

Table 1. Method, amount, and time of N application to rice varieties differing in growth duration at IRRI, 1985 dry season.

Variety	Growth duration (d)	Method	N applied[a]			
			BT[b]	5 DBPI	5 DBF	Total (kg/ha)
IR36	108	No nitrogen	0	0	0	0
		Standard split	110	40	0	150
		Deep placement	40	110	0	150
IR8	132	No nitrogen	0	0	0	0
		Standard split	110	40	40	190
		Deep placement	40	150	0	190
IR42	132	No nitrogen	0	0	0	0
		Standard split	110	40	40	190
		Deep placement	40	150	0	190
Peta	141	No nitrogen	0	0	0	0
		Standard split	60	40	40	140
		Deep placement	40	100	0	140

[a] Complete fertilizer (12-12-12). [b] BT = before transplanting, DBPI = d before panicle initiation, DBF = d before flowering.

Plant height, tiller number, leaf area, and total dry weight were monitored every 2 wk. N uptake was determined at appropriate growth stages. Yield and yield components were measured at harvest.

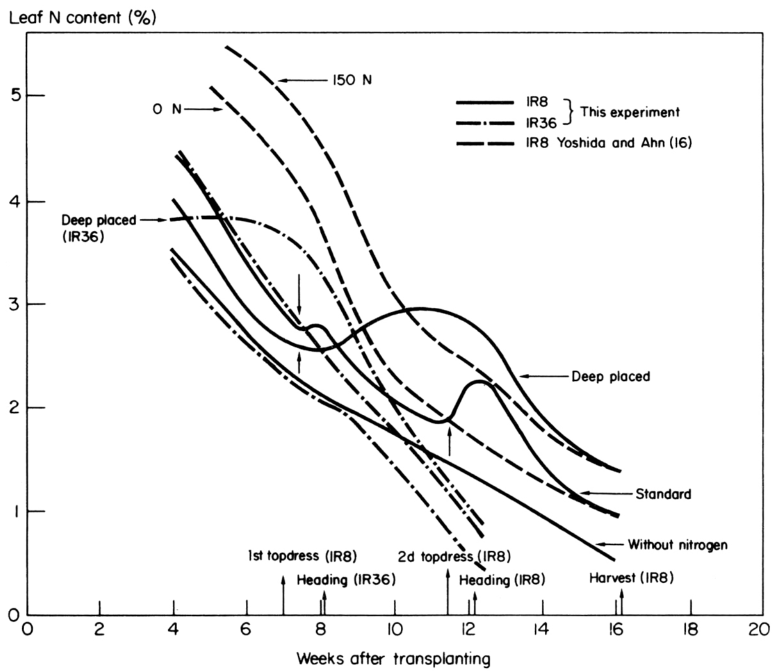
In the 1985 wet season, 20-d-old seedlings of IR42, IR48, and IR64 were transplanted 6 Aug at 2 plants/hill, spaced 25 × 10 cm, on 16-m^2 plots in a randomized block design with 2 replications. Basal fertilizer (urea) was applied at 80 kg N/ha. N was deep-placed at 80 kg N/ha −10, −5, 0, +5 and +10 d after panicle initiation, totaling 160 kg N/ha. Deep placement was manual, 10 cm below the surface at the center of each 4 hills.

Dry weight was measured at panicle initiation and flowering. Yield and yield components were measured at harvest.

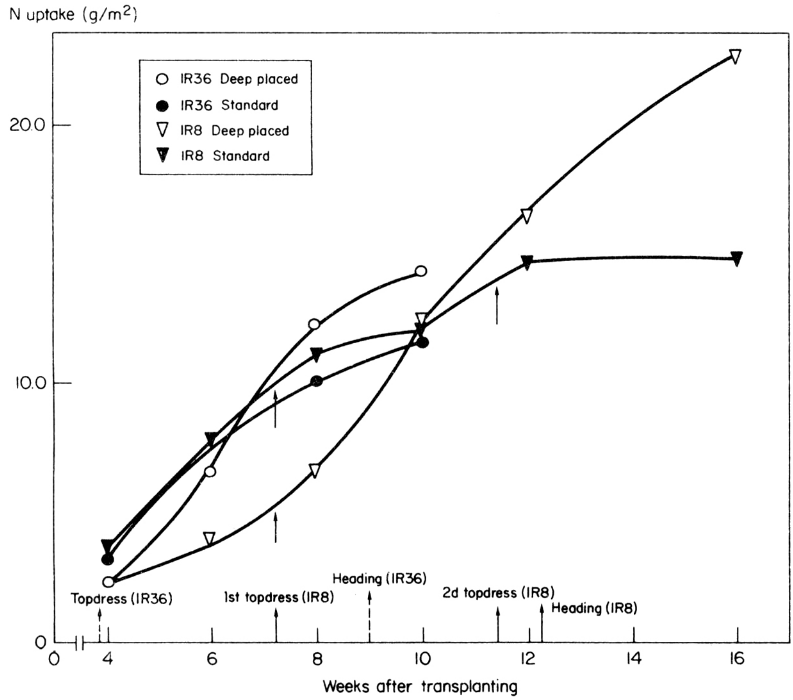
Results

Dry season field trial

In standard split placement, which showed the highest initial leaf N, leaf N increased slightly after each N topdressing, then declined rapidly (Fig. 1). However, deep placement increased leaf N from panicle initiation to maturity more than the standard method. Deep placement maintained higher leaf N at late growth stages and for a longer period.



1. Leaf N content of IR8 and IR36 under three N application methods. IRRI, 1985 dry season.



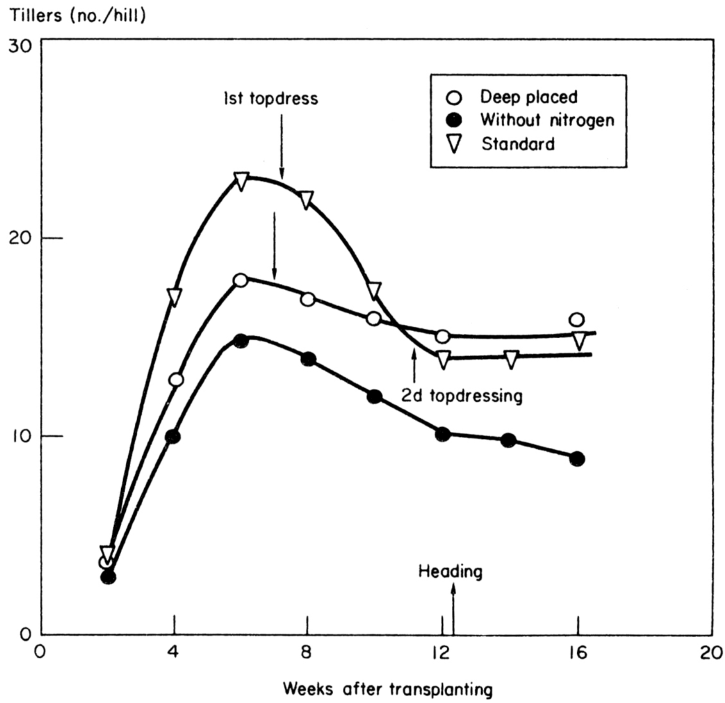
2. N uptake of IR8 and IR36 with N applied as standard and deep-placed fertilizer. IRRI, 1985 dry season.

Deep placement of N increased N uptake more than standard split placement from 3 wk after transplanting (WAT) to maturity (Fig. 2). The difference in N uptake was greater in IR8 and IR42, the medium-duration varieties, than in IR36. IR8 and IR42 showed the same patterns in N uptake, dry weight accumulation, and crop growth rate under standard split placement and deep placement.

Effective tiller number percentage was higher with deep placement than with standard placement (Fig. 3). Panicle number per m^2 also was higher (Table 2).

At the early growth stage, total dry matter production in all varieties increased rapidly, more with standard placement than with deep placement (Fig. 4). The difference was more pronounced in medium-duration IR8 and IR42. After heading, dry matter production in short-duration IR36 slowed down. In all medium-duration varieties except Peta, dry matter accumulation increased more with deep placement than with standard placement, after a slight lag before heading.

Initial crop growth rates (CGR) of IR8 and IR42 were higher with standard split than with deep placement (Fig. 5). This can be attributed to the high basal N applied in the standard split. However, a relatively low ceiling CGR of 15 g/m^2



3. Tiller patterns of IR8 under three N application methods. IRRI, 1985 dry season.

per d was reached with the standard split after basal application (7 WAT) and after the second topdressing (13 WAT). With deep placement, CGR increased continuously to 20 g/m^2 per d at 13 WAT, then gradually declined. Deep placement sustained more productive growth in the later growth stages of IR8 and IR42 than did standard split.

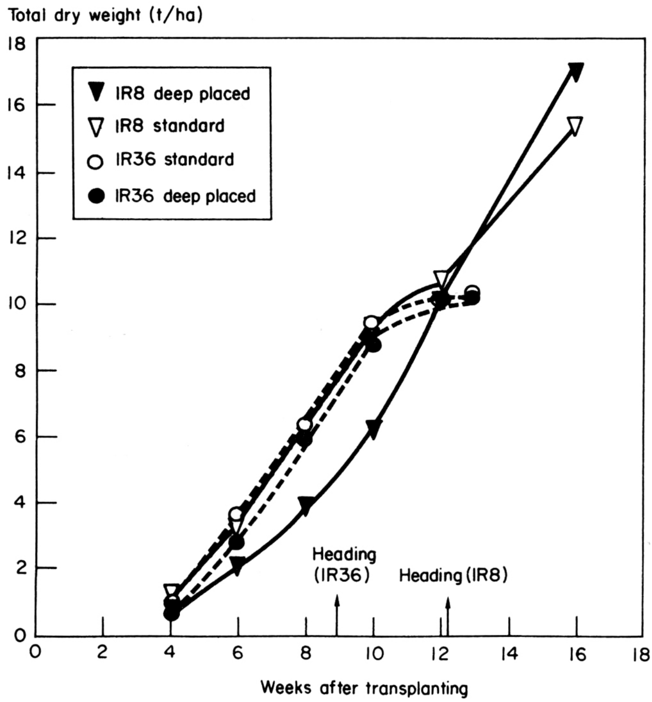
Standard split application influenced yield more than deep placement (Table 2). In both treatments, Peta lodged. With standard split placement, IR42 had the highest overall yield; with deep placement, IR8 yielded best.

Deep placement significantly increased panicle number per m^2 and spikelets per m^2, particularly in medium-duration IR8 and IR42. However, filled grain percentage declined and 1,000-grain weight decreased slightly (Table 2). Yield components of IR36 were not significantly affected.

Wet season field trial

Grain yield was higher with deep-placed 80 kg N/ha applied 10 d after panicle initiation (Table 3). Response was most apparent in medium-duration IR8 and least in short-duration IR64.

Influence on yield components of deep-placed N at different periods around panicle initiation varied (Table 3). At 10 d after panicle initiation,



4. Dry matter production of IR8 and IR36 with standard and deep-placed N application. IRRI, 1985 dry season.

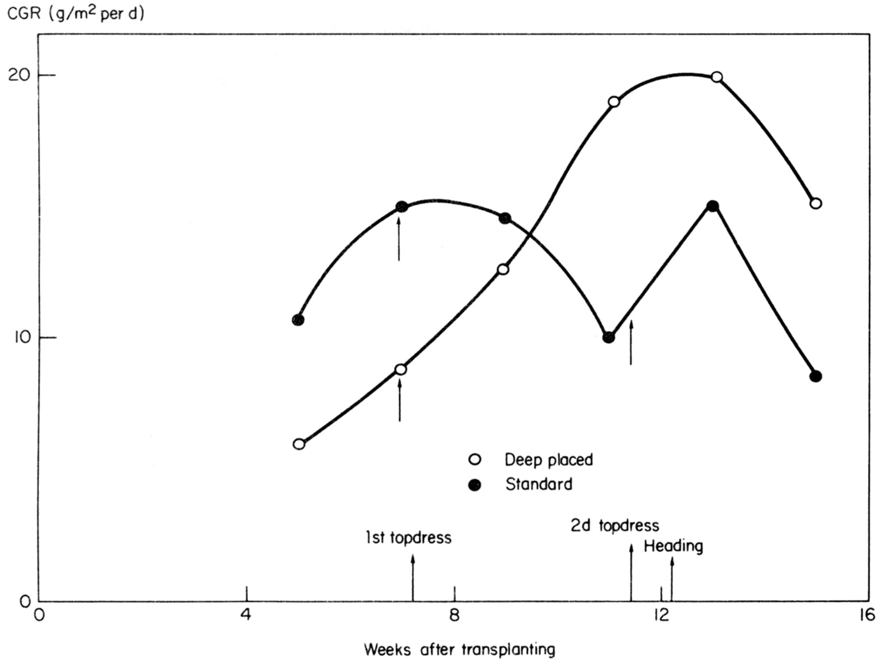
spikelet filling was enhanced except in IR42, which had moderate spikelet filling. Filled spikelet percentages of the three varieties tested at this stage were comparable.

Across treatments, spikelets per m^2 decreased in short-duration IR64, but changed only slightly in medium-duration IR48 and IR42. Grain weight changed slightly in all varieties.

Discussion

When N was topdressed as deep placement at later growth stages, N content in the plant stayed at a higher level longer (Fig. 1). This favorable N condition in the plant at later growth stages affected differentiation of spikelets, degeneration of spikelets, and ripening. The extent of effect depended on the variety.

In the dry season experiment, topdressing by deep placement around panicle initiation in short-duration varieties had a minimum effect on spikelet formation and yield. This was similar to the results of Shiga et al (14). The lower response in spikelet formation and spikelet filling of short-duration varieties, regardless of the method of N topdressing, is attributed to the relatively higher N content at later growth stages resulting from their shorter vegetative growth period (Fig. 1).



5. Crop growth rate (CGR) of IR8 with deep-placed and standard N application. IRRI, 1985 dry season.

High correlations among vegetative growth rate, spikelet formation, and yield in short-duration varieties (5,6,7) also suggest the comparatively lower contribution of late growth to yield. These facts strongly indicate that efficient basal application of fertilizer could be the only way to improve yields of short-duration varieties.

In medium-duration varieties, N content in the plant at later growth stages decreases considerably. But N content increased remarkably, for a longer period, when N was topdressed by deep placement around panicle initiation (Fig. 1). This favorable N in the plant at later growth stages increased crop growth rate and number of panicles and spikelets per m^2 (Table 2), probably by preventing spikelet degeneration or by enhancing differentiation. However, ripening decreased, even though crop growth rate during ripening was high (Fig. 5).

This apparent discrepancy can be attributed to less effective sink size. That is, deep placement around panicle initiation enhanced the total number of panicles and spikelets per m^2. However, spikelets which survived and contributed to increased spikelet numbers were physiologically poor in filling ability. These spikelets are generally located in secondary and tertiary rachis and are supposed to degenerate in standard plots. The lower activity of these late-developing spikelets, coupled with the limited spikelet filling period caused by rapid senescence in tropical conditions, seemed to have contributed to the

Table 2. Influence of N deep placement on yield and yield component. IRRI, 1985 dry season.

Variety	Growth duration (d)	Method	Panicles (no./m^2)	Spikelets ($X10^3/m^2$)	Filled grain (%)	1,000-grain wt (g)	Yield [a] (t/ha)	Total dry wt (t/ha)	Harvest index
IR36	108	No nitrogen	320	17.4	83.2	21.9	3.6	5.9	0.54
		Standard	587	39.5	66.0	21.8	6.3	10.0	0.55
		Deep placement	640	38.7	65.3	21.2	5.9	10.0	0.52
IR8	132	No nitrogen	240	19.2	83.7	25.6	4.6	7.8	0.52
		Standard	373	34.8	72.3	26.8	7.4	15.2	0.43
		Deep placement	400	36.5	69.0	25.8	7.2	17.0	0.37
IR42	132	No nitrogen	286	23.8	85.3	18.3	4.1	7.0	0.51
		Standard	454	44.4	85.2	18.6	7.7	16.0	0.42
		Deep placement	533	47.7	71.1	18.2	6.8	15.3	0.39
Peta	141	No nitrogen	240	23.0	68.7	24.7	4.5	10.5	0.38
		Standard	267	32.0	39.5	24.5	3.5	- [b]	-
		Deep placement	294	44.7	17.3	24.6	2.2	— [b]	-

[a] At 14% moisture content. [b] Lodged at heading.

Table 3. influence of N deep placement around panicle initiation stage on yield and yield components. IRRI, 1985 wet season.

Variety	Growth duration (d)	N treatment around PI[a]	Grain yield (g/m^2)[b]	Panicle number ($/m^2$)	Spikelet ($\times 10^3/m^2$)	Filled grain (%)	1,000-grain wt (g)
IR64	117	-10	410	453	24.3	63.1	23.4
		-5	400	448	23.9	59.8	23.9
		0	420	416	22.2	67.3	24.8
		+5	430	438	22.2	70.2	24.2
		+10	440	376	21.1	75.5	24.4
IR48	131	-10	419	260	23.3	62.2	25.5
		-5	395	277	23.1	60.6	24.6
		0	420	257	23.1	66.2	24.0
		+5	469	246	23.8	69.4	24.8
		+10	500	248	23.7	72.8	25.2
IR42	133	-10	450	295	28.7	76.8	18.0
		-5	428	385	28.4	70.6	18.6
		0	417	382	20.0	67.6	19.4
		+5	419	323	25.9	76.3	18.7
		+10	457	357	28.0	74.5	19.2

[a]80 kg N applied basally plus 80 kg N/ha deep-placed at 10-15 cm depth around panicle initiation (estimated at 60 d from maturity). [b]Adjusted for 14% moisture content.

Table 4. Comparison of leaf N content and yield of IR8 and Peta (16).

Variety	Treatment	1968[a] Leaf N (%) Panicle initiation	1968[a] Leaf N (%) Heading	1968[a] Yield (t/ha)	1985[b] Leaf N (%) Panicle initiation	1985[b] Leaf N (%) Heading	1985[b] Yield (t/ha)
IR8	No N	3.7	1.7	5.3	2.2	1.5	4.6
	With N	4.6	2.8	8.2	2.7	2.4	7.4
Peta	No N	1.8	1.5	6.6	1.8	1.3	4.5
	With N	2.6	1.8	7.5[c]	2.4	1.6	3.5[d]

[a]150 kg N as basal. [b]110 kg N + 40 kg N at 5 d before panicle initiation + 40 kg N 5 d before flowering. [c]Significant difference. [d]Lodged at heading.

poor filling. In cool regions, where the spikelet filling period is longer due to slower senescence, these spikelets ripened well (2).

Topdressing by deep placement might have failed to improve effective sink size, even though spikelet number increased. In tropical conditions where spikelet number is the main factor limiting yield, better yields could be achieved by N fertilization which improves effective sink size or by using rice cultivars with high effective sink sizes.

In the wet season, when solar radiation lessens toward harvest and when high N uptake occurs at early growth stages, deep placement at 10 d after panicle initiation was effective in increasing yield (Table 3). N topdressing hardly affected spikelet number at this stage. Higher photosynthesis due to higher N content favored spikelet filling and resulted in a higher filled spikelet percentage.

Mimoto (9) showed that, with late deep placement fertilization, yield increases of “panicle weight” type varieties which have fewer panicles per m^2 were higher than increases of “panicle number” type varieties which have more panicles per m^2. In the dry season, IR8, with fewer panicles per m^2, responded better to late deep placement than IR42, with more panicles per m^2 (Table 2). In the wet season, IR48, with fewer spikelets. showed a higher ripening percentage than IR42 (Table 3). Differential response to late topdressing needs further analysis in terms of panicles per m^2 and panicle morphology.

Yields of IR8 in the dry season at IRRI have been reported to increase in proportion to spikelet number per unit land area: percentage of filled spikelets did not inhibit yield (18). Similar associations were found in the standard plot of IR8, but filled spikelet percentage and spikelet number were always lower than previous results. N content of leaves in unfertilized and standard fertilized plots of IR8 and Peta also was much lower than had been reported earlier (Table 4). And, yields were lower.

Because climatic factors did not significantly change between 1967 and 1985, they could hardly have contributed to the variation of leaf N content and lower spikelet number. The lower spikelet number and filled spikelet percentage of IR8 in standard application and no N plots of this experiment may be attributed to the lower N content in the plant throughout growth, especially at early growth stages. This could be due to some impediment to normal N uptake. Rice yields at IRRI in the dry season have been declining since IRRI’s inception (4). Limited N content in the plant tissue might be a factor contributing to this yield decline.

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Impact of low-light stress on growth and yield of rice

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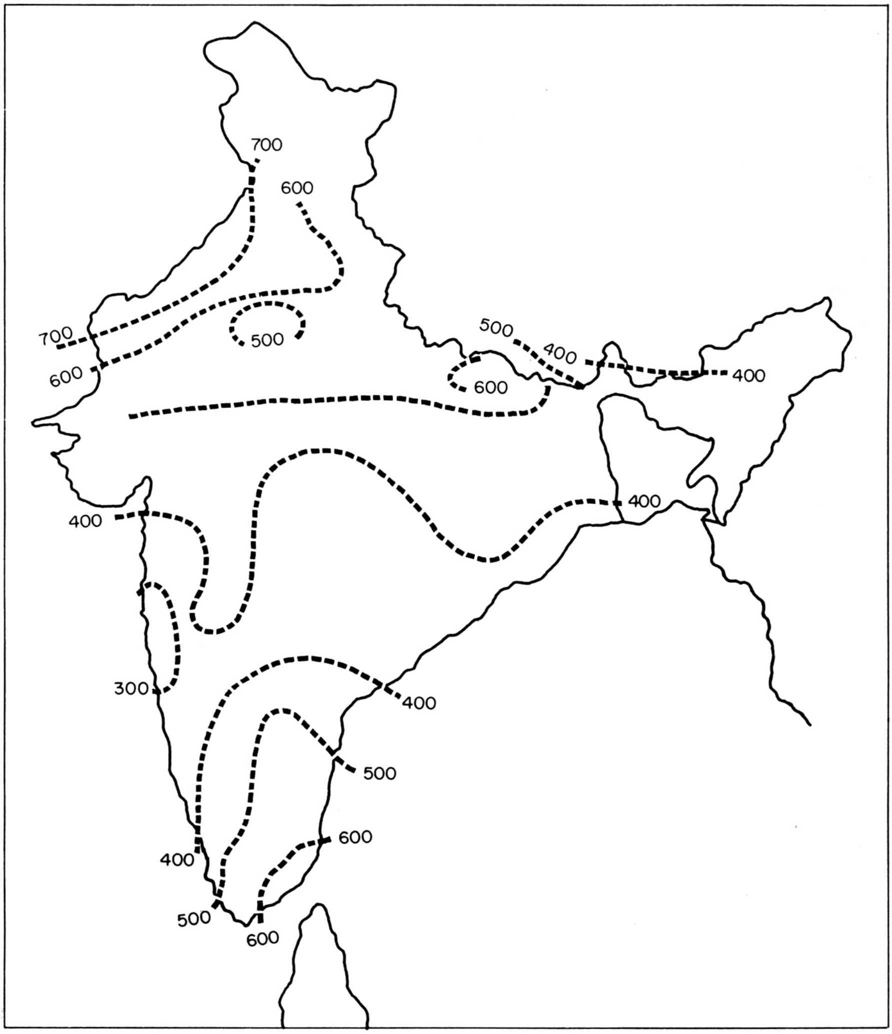
ABSTRACT

Poor grain yield during the wet season is attributed to low incidental light, which reduces grain number per panicle in short-duration rice varieties, increases spikelet sterility in medium-duration varieties, and decreases panicle numbers in long-duration varieties. Low light at anthesis leads to high spikelet sterility and low harvest index. Under low light at flowering, carbohydrate content, protein synthesis, and proline and cytokinin accumulation decrease and gibberellins and soluble N in the panicle increase, leading to high spikelet sterility. Leaf chlorophyll increases but photosynthetic rate declines due to impaired RuBP carboxylase activity. Varieties PTB10, Mahsuri, T90, and NC1281 (tall indicas) and Pallavi and Vijaya (short varieties) are less affected in these parameters and are better adapted to low-light stress. Parameters that are useful for isolating varieties tolerant of low-light stress are: higher survival rate of 10-d-old seedlings in complete darkness for 7 d, lower reduction in dry weight and specific leaf weight of 2-wk-old seedlings in 30% normal light for 15 d, high chlorophyll band photosynthetic rate in blue light at vegetative stage, and greater accumulation of reserve carbohydrates in shoot at flowering, with low sterility.

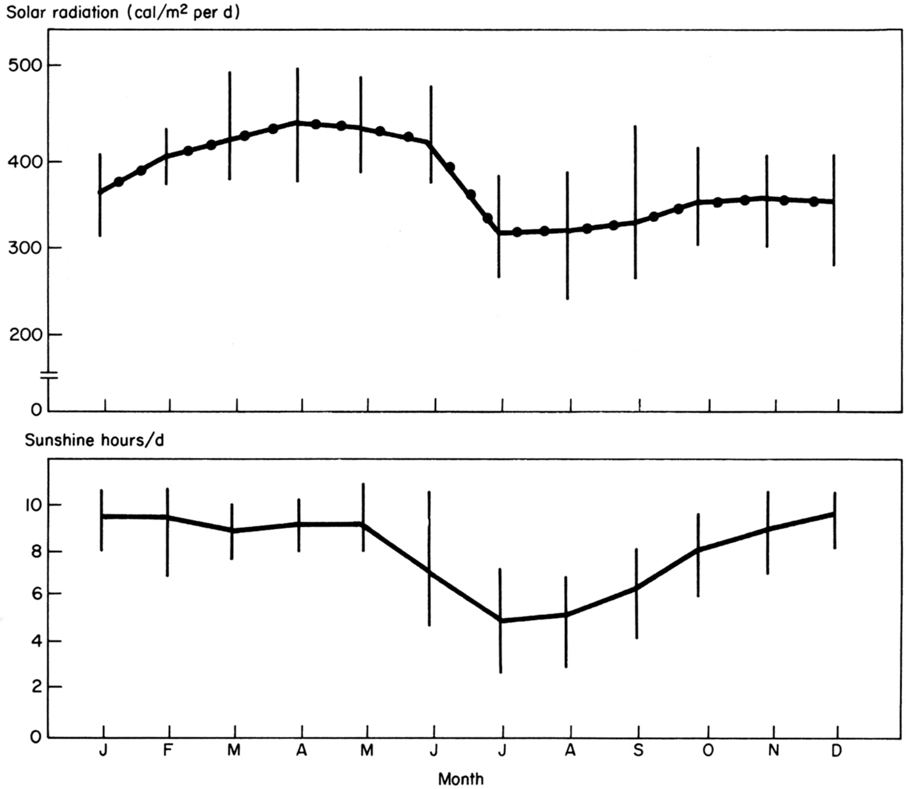
The high yield potential of improved rice plant types is mostly expressed with adequate solar radiation during the dry season. Grain yield is comparatively low during the wet season due to cloudy days with inadequate light intensity (2,24,28). Grain yield correlates positively with solar radiation, especially during later stages of crop growth.

It is estimated that a cumulative solar radiation of 14,000 g cal/cm^2 or 200 h bright sunshine during the 30 d before harvest would be optimum for grain yield. Vamadevan and Murty (25) reported that the traditional rice growing areas in India are exposed to less than 450 h of bright sunshine from July to September. The west coast and major parts of eastern and northeastern India receive less than 300 h of sunshine during this period (Fig. 1). Productivity potential is closely associated with solar radiation during the crop season (9).



Seasons

The majority of the rice grown in India is monsoon-dependent. It is grown during the wet season (July-November) in the traditional rice-growing areas of eastern India. Solar radiation is about 300 cal/cm^2 per d, with wide fluctuations in day-to-day radiation (60-420 cal/cm^2 or 2-5 bright sunshine hours per d). However, during the dry season, mean solar radiation is about 450 cal/cm^2 and sunshine hours vary from 9 to 10 h/d, indicating 1.5-2 times more solar radiation and sunshine hours in the dry season than in the wet season (Fig. 2). Grain yields



follow the same seasonal pattern. A major limitation to higher productivity in the wet season is the natural low light intensity during crop growth.

The lower yields in the wet season than in the dry season, even with the same variety, are attributed mostly to reduction in grain number per panicle or per unit land area, which is a consequence of high spikelet sterility (Table 1). Panicle number and 1,000-grain weight are less affected. During the wet season, leaf area index (LAI) is not impaired but dry matter production (DMP) is reduced 20-30%. DMP after flowering is even more reduced and grain development depends mostly on the contribution of reserve carbohydrates or dry matter production before flowering (4). The partitioning of dry matter to panicle is also poor during the wet season due to high spikelet sterility, resulting in a lower harvest index (19, 21). A wide gap between spikelet number and number of filled grains is apparent during the wet season due to the poor supply of carbohydrates from source leaf and the associated high spikelet sterility (26).

The canopy photosynthetic rate shows a linear trend with LAI during the dry season; during the wet season such a relationship is asymptomatic beyond

Table 1. Seasonal influence on growth and yield attributes of early rice varieties (mean of 8 varieties) (20). [a]

Component	DS	WS	WS/DS × 100
Yield (t/ha)	5.41	3.52	65.2
Panicles per m^2	346	411	119.2
Grains per panicle	77	50	63.2
Grains per m^2 x 100	260	200	77.7
Sterility (%)	13.5	31.6	247
1,000-grain weight (g)	22.1	21.2	96.7
Dry matter at flowering (t/ha)	5.37	4.72	91.8
Dry matter at harvest (t/ha)	9.10	7.57	83.7
Harvest index	59.8	46.3	77.3
Leaf area index at flowering	2.85	3.44	124
N % at flowering panicle	1.35	1.50	111
N % at flowering leaf	2.83	3.24	115
N % at harvest panicle	1.21	1.39	116
N % at harvest leaf	1.08	1.50	141
N productive efficiency (Yield per unit N absorbed)	61.0	38.7	63

[a] DS = dry season, WS = wet season.

3 LAI. Population photosynthesis in the wet season is also 20% less at flowering (3).

N uptake at flowering is relatively high in the wet season and is reduced only after flowering. Thus, the N concentration in shoot and panicle at flowering is considerably higher in the wet season than in the dry. The high sterility during the wet season is partly attributed to a greater accumulation of N, especially soluble N in the panicle during anthesis and at early stages of grain development (20).

Low light during reproductive and ripening stages is much more detrimental to yield. Low light is commonly experienced by short- and medium-duration rice varieties during August and September. However, in long-duration varieties, such low-light stress synchronizes with the vegetative lag phase and results in considerable tiller mortality and fewer productive panicles per m^2. Spikelet sterility is more apparent in short- and medium-duration varieties than in long-duration varieties because flowering in short- and medium-duration varieties synchronizes with the lowest light intensity of the season, about 250 cal cm^2 per d (6). The major constraints to yield during the wet season are low grain numbers per panicle in short-duration varieties, high spikelet sterility in medium-duration varieties, and low panicle numbers in long-duration varieties (7) (Table 2).

The correlations of growth and yield components during the two seasons indicate that yield is related to LAI (r = 0.68**) and dry matter (r = 0.88**) at flowering (source size) during the wet season. Grain number (sink size) has a high correlation with yield during the dry season (r = 0.78**) (8). Grain yield, grain number per panicle, and spikelet fertility also correlate positively with cumulative solar radiation during ripening (60-90 d after planting) in short-duration rice varieties (22).

Table 2. Yield components and growth duration of varieties during wet season (50 kg N/ha) (7).

Component	Early	Medium	Late
Yield (t/ha)	4.21	3.77	3.70
Panicles per m^2	431	296	226
Grains per panicle	44	58	83
Sterility (%)	28	45	28
Dry matter at harvest (t/ha)	7.84	10.21	9.24
Harvest index (%)	54	38	40

Induced Low Light

Because reduced light is one of the major constraints to yield during the wet season, several researchers have attempted to analyze the influence of induced low light on growth and yield parameters of different rice varieties. Low light during primordial initiation (PI) to flowering or from flowering to harvest reduces grain yield considerably (26). In general, varieties are uniformly susceptible to low light during PI to flowering, although some varieties, such as Vijaya, tolerated low light during ripening better than others. Grain yield decreases when light intensity is reduced from normal to 25% of normal (29). Low grain yield under reduced light intensity is attributed to the cumulative influence of fewer panicles per m^2 and grain numbers per panicle and lower 1,000-grain weight and higher percentage of spikelet sterility (17) (Table 3). Under low light, dry matter is reduced mostly by impaired photosynthesis (15). Under low light, a considerable proportion of grain carbohydrate is contributed by reserve assimilates at flowering (4). The direct influence of low solar radiation on percentage of spikelet sterility has been amply demonstrated (19, 20). The impaired translocation under subdued light of carbohydrates from source to developing grain during ripening is yet another factor in high sterility (18).

Low light from 10 d before anthesis to 20 d after anthesis is highly critical: it induces high spikelet sterility, resulting in poor grain yields (13). Recent work has shown that low solar radiation on the day of anthesis, and especially during the period of anthesis, is crucial in causing sterility (18) (Table 4).

Chlorophyll content increases more under low light than under normal light (6) (Table 3). Among the chlorophyll fractions, the increase is more prominent in chlorophyll b, leading to a lower Chl a/b ratio. Low light-adapted varieties, such as Vijaya and Pallavi, show higher chlorophyll b and lower Chl a/b ratio (16). Under low light, the relative proportion of blue light is higher and, because of its affinity with chlorophyll b, varieties with higher chlorophyll b are considered to be more adapted to low light (15).

The reduction of photosynthesis under low light can be attributed to high stomatal and mesophyll resistance to CO_2 exchange (Table 3). Shading from flowering to harvest reduces leaf and panicle photosynthetic rate and photo respiration (18). RUPB carboxylase activity decreases under low light. The lower photosynthetic rate despite higher chlorophyll content under low light is attributed to reduction in the activity of RUPB case (16).

Table 3. Effect of light intensity on yield and physiological attributes (17).

Character	Variety[a]	Normal light (NL)	70% NL	50% NL	30% NL	Mean
Yield (t/ha)	IR8	4.91	2.78	2.34	1.24	2.82
	Vijaya	4.92	3.16	2.53	1.87	3.12
Sterility (%)	IR8	12	25	36	55	32
	Vijaya	11	22	30	35	24
Harvest index (%)	IR8	55	42	34	25	39
	Vijaya	60	46	40	35	45
Chlorophyll (%)	IR8	3.2	3.9	3.7	3.7	3.6
(Flowering)	Vijaya	3.9	4.5	4.2	3.4	4.3
Photosynthetic rate	IR8	41.5	26.6	17.2	12.8	24.5
(mg CO_2/dm^2 per h)	Vijaya	43.8	33.2	24.2	18.7	30.0
Translocation index	IR8	50.8	60.1	43.9	38.1	48.2
	Vijaya	59.3	72.6	50.9	39.2	55.5

[a]IR8 is shade susceptible and Vijaya is shade tolerant.

Table 4. Effect of low light intensity during anthesis on spikelet sterility (1978 wet season) (10).

Treatment[a]	Sterility (%)			
	25% normal light		50% normal light	
	Ratna	Pallavi	Ratna	Pallavi
T_1	47.7	35.3	40.9	32.4
T_2	60.3	40.2	52.9	40.4
T_3	49.0	41.4	46.7	34.1
T_4	56.2	43.8	50.4	44.1
T_5	58.6	44.8	52.7	41.6
T_6	62.1	45.9	53.9	44.0
Normal light	40.6	27.5		

[a]T_1 = low light 1 h before anthesis; T_2 = low light 1 h during anthesis; T_3 = low light 1 h after anthesis; $T_4 = T_1 + T_2$; $T_5 = T_2 + T_3$; $T_6 = T_1 + T_2 + T_3$.

Photo assimilates accumulate initially in the stem and sheath in low light-adapted varieties. Under low light, those stored carbohydrates contribute substantially to grain filling (4) (Table 3). A reduction in light of up to 30% does not impair translocation of photosynthates; 50% or more does (5).

Under shade, total sugars (mostly nonreducing sugars and starch) are markedly reduced in all plant parts. Total, soluble, and amino N, especially in shade-susceptible varieties like Ratna, are enhanced (4). High sterility under low light is ascribed to disturbed N metabolism and accumulation of higher concentrations of soluble N in the panicle, which is toxic to normal grain setting (14).

Reduced light from flowering reduces auxins and cytokinins and increases gibberellins (GA) in the spikelets. Shade-intolerant Ratna showed higher GA and lower cytokinin in the spikelets than shade-tolerant Pallavi (12) (Table 5).

Table 5. Effect of low light intensity from flowering to 11 d after flowering on sugars, nitrogen, growth regulators, and proline (11, 12).[a]

Component	Ratna		Pallavi	
	Normal light	50% light	Normal light	50% light
Total sugar % (panicle)	2.6	1.8	3.2	2.4
Soluble N % (Panicle)	0.16	0.22	0.09	0.15
Auxins (µg IAA 10^{-3} spikelets)	95.7	85.2	144.4	76.5
Gibberellins (µg GA_3 10^{-3} spikelets)	30.9	102.5	53.3	74.0
Cytokinins (ppm kinetin equivalents)	20.4	13.9	21.5	18.4
Proline in panicles (µg/g dry weight)	220	183	288	224

[a] Ratna is susceptible to low light and Pallavi tolerant of low light.

Under low light, proline content decreases in the panicle and increases in the leaf and culm, especially in shade-susceptible Ratna (Table 5). Such low proline content in the panicle is attributed to translocation impairment and also to an increase in proline oxidation caused by the depletion in carbohydrates in the shade. Proline deficiency in the spikelets may also be a factor in higher sterility (11).

Under low light at flowering, very high spikelet sterility (30-50%) is apparent. Such sterility is attributed mostly to low carbohydrate availability, impaired protein synthesis and accumulation of high soluble N (nearly 40% of the total N), poor proline mobilization to panicle from shoot, low cytokinin activity, and lower cytokinin/gibberellin ratio in spikelets soon after anthesis. Exogenous feeding with proline or growth regulators such as 2,4-D and kinetin (10 ppm) helps mobilize carbohydrates, proline, and growth substances to the spikelets and aids normal development of fertilized grain (7,13).

Screening For Low Light

Characters useful in screening for low light adaptability are:

1. survival of 10-d-old seedlings under complete darkness for 7 d (23).
2. lower reduction in dry weight and specific leaf weight of 2-wk-old seedlings under 30% normal light (30 klx) for 15 d, high photosynthetic rate of both leaf and panicle and high chlorophyll b content under 30% normal light, and relatively high efficiency in photosynthesis under blue light at vegetative stage (18).
3. greater accumulation of dry matter at flowering with high efficiency in translocation and high proline and cytokinin content in the panicle with low sterility under reduced light at flowering (12).

Tall indicas PTB10, Mahsuri, T90, and NC1281 and semidwarfs Pallavi and Vijaya have those traits and are consistently efficient under subdued light. Vijaya, a hybrid derived from T90/IR8, showed high adaptability to low light, especially during ripening. IR8 was intolerant of reduced light, indicating that the low-light adaptability in Vijaya has been derived from the tall parent T90. Selective breeding for low-light adaptability may be useful (18).

Strategies

The high yielding varieties program has not been all that successful in the traditional monsoon season; often, traditional local varieties are more productive than high-yielding varieties. More concerted efforts are needed to breed specific varieties for the wet season by utilizing appropriate donors, such as tall indicas PTB10 and T90 and semidwarfs Pallavi and Vijaya, which are tolerant of low-light stress. The selections should be carried forward only during the wet season or using advanced generation techniques in low light. The ultimate selection should be based on such desirable traits as high photosynthetic rate under low light or blue light, high light harvesting efficiency, high cholorophyll content, greater dry matter production with high reserve carbohydrates at flowering, and high harvest index.

Because high spikelet sterility is the major constraint in low-light situations, emphasis has to be given to selecting varieties with low sterility by exposing the plants to low-light stress at flowering. In addition to carbohydrates, the growth regulators (cytokinins and auxins) are also involved in spikelet fertility. Efforts to explain the role of growth regulators would be useful.

N is poorly utilized. Nitrate reductase activity is associated with N use efficiency (1). Selecting for high NRA under reduced light may be rewarding.

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Using ethylene to monitor the influence of adverse climatic factors and to predict plant performance

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ABSTRACT

Two approaches were used to monitor the influence of adverse climatic factors on plant performance, one based on the ability of the ethylene-forming enzyme (EFE) to convert a saturating dose of 1-aminocyclopropane-1-carboxylic acid (ACC) to ethylene (C_2H_4) and one based on the ability of EFE to produce C_2H_4 via ACC by increased activity of ACC-synthase. Rice seeds subjected to a rapid-aging environment (40-43 °C, 95-100% RH) developed seedlings with low vigor, which produced low levels of C_2H_4 in the presence of ACC. The capacity of seedlings to produce ACC-derived C_2H_4 was a varietal trait and correlated well (r = 0.92) with resistance to aging (determined by shoot growth). High temperature (35 °C) applied during seedling establishment also reduced ACC-dependent C_2H_4 production; the predictiye value of C_2H_4 for shoot growth in a large population of rice varieties was evident. The rapid elongation capacity of the top two leaves and corresponding sheaths in several deep water and floating rices depended on enhanced ACC-synthase activity and correlated well with high C_2H_4 production. A requirement of gibberellin (GA) for rapid elongation also was indicated, as tetcyclacis, an inhibitor of GA biosynthesis, strongly reduced elongation growth; the inhibition was reversed by adding GA. Hormonal interaction studies suggest that rices may produce varying amounts of C_2H_4, GA, and a stress inhibitor; C_2H_4 production and/or action may be related to the removal of the inhibitory block, while GA action may be related directly to the promotion of growth.

A strong knowledge base is needed to increase and stabilize rice yields under diverse climatic conditions. New approaches to identifying physiological and biochemical responses to components of climate are needed. These responses could be used to predict plant behavior and to develop varieties adaptable to a specific set of climatic conditions.

Identifying biochemical and physiological markers does not appear to be difficult; rices are known to thrive under a wide range of soil and climatic variables and to tailor their physiological responses to climatic requirements. Such responses are good indicators of mechanisms underlying wide adaptability to diverse climatic conditions.

For example, the ability of traditional rices to tolerate high temperatures, salinity, and drought at seedling establishment suggests a common mechanism related to preventing water withdrawal. Areas related to water withdrawal could include osmoregulation, selective hormone action, changes in membrane structure and function, and continued functioning of key enzymes.

The ability of rices in flood-prone areas to rapidly elongate when submerged suggests a hormonal mechanism to avoid submergence stress. Elongation is a well-known characteristic of gibberellin (GA)-treated plant tissues.

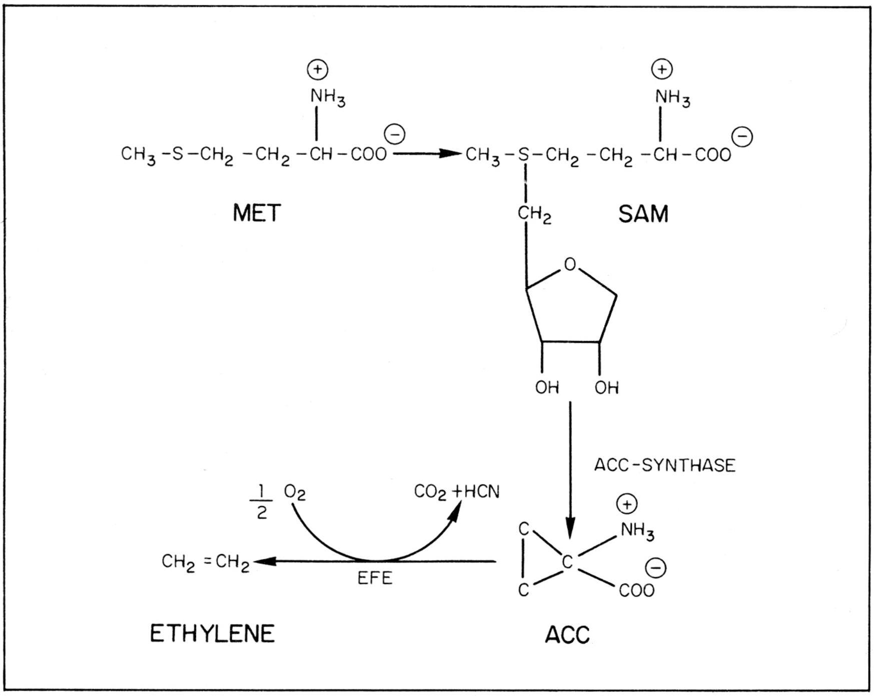
Identifying a biochemical marker associated with a favorable or an unfavorable plant response would be of immense help to breeders striving to develop a variety adapted to a particular set of soil and climatic conditions. Such markers could be used to screen a large breeding population of a crop such as rice. Lack of suitable markers continues to be a major stumbling block in conventional plant breeding.

To be an effective marker, a chemical should be able to meet one or both of these requirements: its level or activity should be related to growth changes under a particular situation and it should elicit a growth response when applied to a plant. We endeavor here to show that 1) the biosynthesis of ethylene (C_2H_4) in intact rice seedlings is strongly influenced by adverse climatic factors, 2) the amounts of C_2H_4 produced can be used to monitor the influence of adverse climatic conditions, and 3) C_2H_4 can serve as an effective marker to screen varieties for improved growth under adverse climatic conditions.

Ethylene Biosynthesis in Rice

The pathway of C_2H_4 biosynthesis in plants has been elucidated by Adams and Yang (1) (Fig. 1). Ethylene is synthesized from methionine via S-adenosylmethionine (SAM) and 1-aminocyclopropane-1-carboxylic acid (ACC). The two key enzymes regulating C_2H_4 synthesis are ACC-synthase and the ethylene-forming enzyme (EFE), which oxidizes ACC to C_2H_4. Rice varieties show a great deal of diversity in C_2H_4-producing capacity. C_2H_4 production under adverse soil and climate conditions may determine whether a rice plant can establish itself successfully or survive (14,16).

Ethylene is synthesized in stem internode sections of floating rice in response to submergence (20); the synthesis is believed to be triggered by reduced oxygen level (25). There is evidence from rice and other plants that C_2H_4 response is GA-dependent (22,26).



1. Pathway of ethylene biosynthesis in plants (1).

Development of Monitoring Procedures

ACC-dependent ethylene production

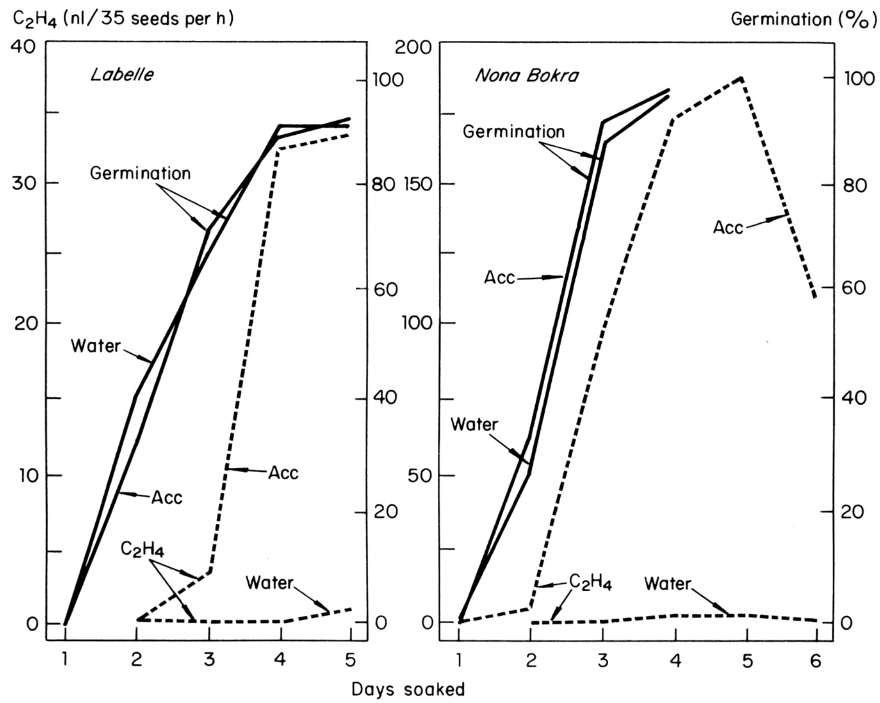
Rice seeds produced little C_2H_4 before germination (radicle protrusion) and the level remained low in 2- to 6-d-old seedlings. Aminoethoxyvinylglycine (AVG), a specific inhibitor of ACC synthase (1), had no effect on rice germination, indicating that C_2H_4 production may have little to do with germination. This had been noted previously (6,27). However, ethylene was clearly implicated in growth, particularly under stress situations.

Because adding ACC markedly enhanced C_2H_4 production in young seedlings, ACC-mediated C_2H_4 production seemed like a good candidate for both monitoring and screening purposes. However, several questions needed to be resolved before ACC-mediated C_2H_4 production could be used as a monitoring procedure:

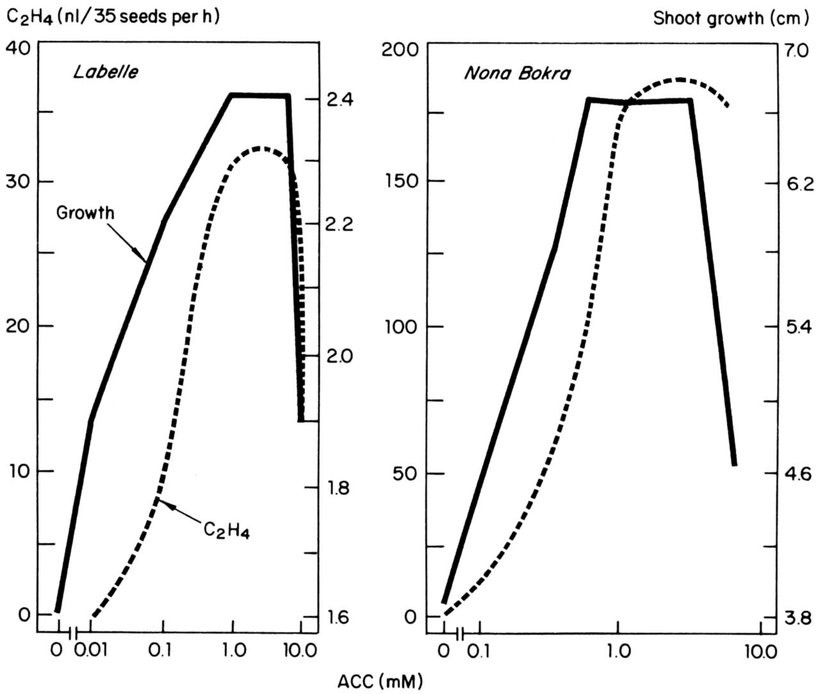
1. When does EFE activity peak during seedling growth?
2. What is the nonlimiting concentration of ACC at which the ACC to C_2H_4 step depends solely on the level and/or activity of EFE?
3. What is the effect of ACC on shoot growth?
4. Is the utilization of ACC the same or different under stress and nonstress?

5. How can one be sure that the endogenous ACC is not being synthesized, contributing to ACC (exogenous)-derived C_2H_4?
6. Is EFE a constitutional enzyme. as in other systems, or is it synthesized *de novo* during seedling establishment?

To develop a procedure to monitor C_2H_4 production during seedling establishment and to detect differences among rice varieties and breeding lines, it was necessary to work with small amounts of seeds producing reasonably high amounts of C_2H_4. The time pattern of C_2H_4 production and germination in the presence and absence of 2 mM ACC in rice varieties. Labelle and Nona Bokra, is shown in Figure 2. The production of C_2H_4 in 2- to 6-d-old seedlings was low (1-2 nl/35 seeds) but was enhanced considerably with ACC. Little C_2H_4 was detected until 48 h, when germination had begun, indicating that C_2H_4 was not needed for germination. The rate of C_2H_4 production peaked at 96 h, remained nearly constant to 120 h, then declined.



2. Time course of C_2H_4 production and germination in rice cultivars Labelle and Nona Bokra. After soaking in 2 mM ACC or water for indicated times, 35 seeds (2 replications) were transferred to a 28-ml tube and capped with a rubber septum. Ethylene content was determined from a 1 ml gas sample taken with a hypodermic syringe and injected into a Packard 437 gas chromatograph equipped with a hydrogen flame ionization detector and a 100- × 0.2-cm glass column containing poropak N. For C_2H_4 production and seedling development, 40 seeds (2 replications) were soaked in 8 ml test solutions in 16-oz jars at alternating 25/30 °C and 12 h photoperiod.



3. Effect of concentratton of ACC on shoot growth and C_2H_4 production of rice cultivars Labelle and Nona Bokra. Growth (av of 20 seedlings) was determined after 4 d and C_2H_4 content after 6 d.

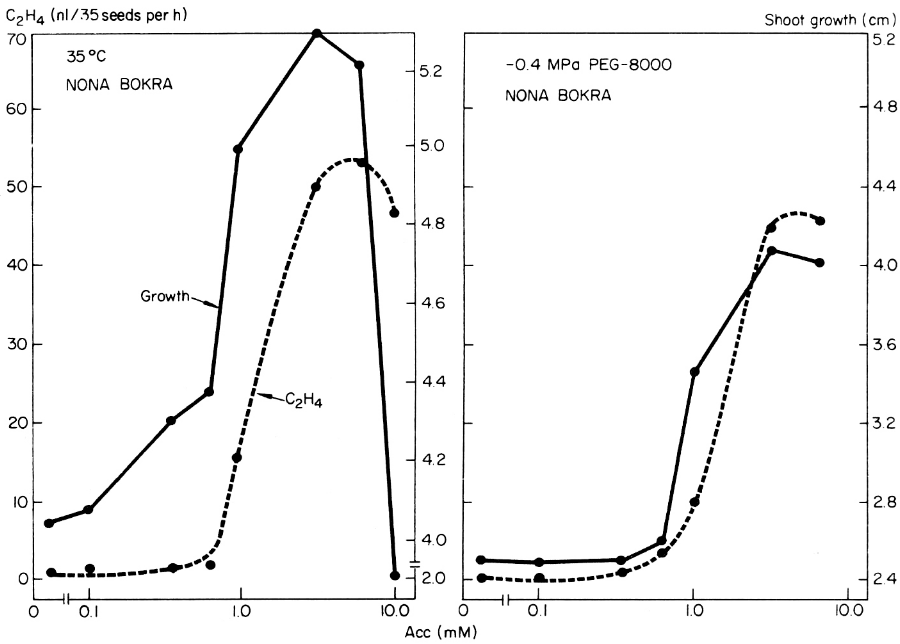
To measure the differences in EFE activity catalyzing ACC (substrate) to C_2H_4 (product), it was necessary to select a nonlimiting concentration of ACC. This was found to range from 1 to 2 mM for the varieties used (Fig. 3). The increase in C_2H_4 production with increasing concentrations of ACC paralleled an increase in shoot growth, indicating that C_2H_4 was needed for shoot growth. At 10mM and higher ACC, both C_2H_4 production and growth were inhibited.

To determine if endogenously produced ACC contributed to C_2H_4 derived from exogenous ACC, seeds were grown with AVG, an inhibitor of the SAM to ACC step (1) and Co^{2+}, an inhibitor of the ACC to C_2H_4 step (17). Both AVG and Co^{2+} strongly inhibited C_2H_4 production and substantially reduced shoot growth when no ACC was added (Table 1). At 2 mM ACC, only Co^{2+} was effective in reducing growth and C_2H_4 production; AVG had little or no effect. Thus, endogenous ACC did not contribute to the C_2H_4 produced at a saturating dose of externally applied ACC. Under stress conditions, such as high temperature and drought, the saturation level of ACC remained about 2 mM, although both C_2H_4 production and shoot growth diminished noticeably (Fig. 3, 4).

Table 1. Effect of aminoethoxyvinylglycine (AVG) and $CoCl_2$ on shoot growth and C_2H_4 production in rice Nona Bokra at 25/30 °C.[a]

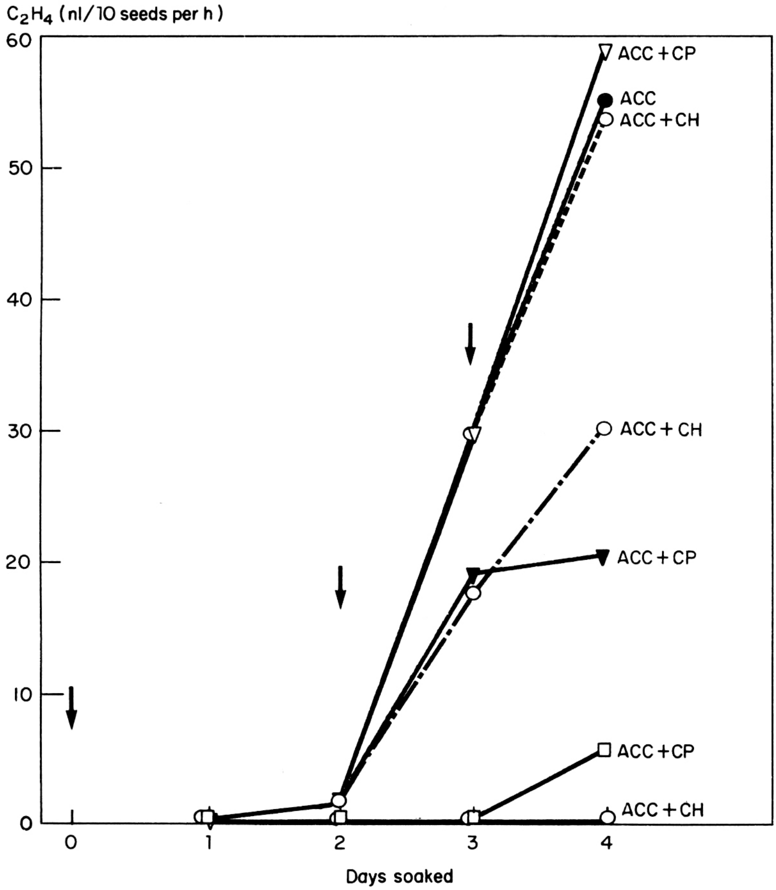
Treatment	Shoot growth[b] (cm)	C_2H_4nl/35[c] seeds per h
Water	6.3 (100)[c]	3.5 (100)
AVG, 0.1 mM	2.3 (36)	ND (0)
AVG, 0.01 mM	3.8 (60)	ND (0)
Co^{2+}, 2 mM	3.0 (47)	ND (0)
Co^{2+}, 1 mM	4.2 (67)	ND (0)
ACC, 2 mM	7.1 (100)	150.1 (100)
ACC, 2 mM + AVG, 0.1 mM	6.8 (96)	148.0 (99)
ACC, 2 mM + AVG, 0.01 mM	6.9 (97)	188.0 (125)
ACC, 2 mM + Co^{2+}, 2 mM	4.1 (58)	28.6 (19)
ACC. 2 mM + Co^{2+}, 1 mM	5.0 (70)	47.8 (32)

[a]Six-d-old seedlings, 2 replications of 10 seedlings each. Figures in parentheses are percentages of control value. ND = not detectable.



4. Influence of 35 °C temperature and low water potential (-0.4 MPa PEG-8000) on C_2H_4 production and shoot growth of rice cultivar Nona Bokra at different concentrations of ACC. Seedlings were analyzed for both growth and C_2H_4 production after 4 d.

EFE activity was strongly inhibited in Nona Bokra by 1 mM cordycepin (RNA synthesis inhibitor) and 0.1mM cycloheximide (protein synthesis inhibitor) (Fig. 5). When cordycepin and cycloheximide were present from the beginning of seed soaking, C_2H_4 production was strongly inhibited. When they



5. Effect of RNA and protein synthesis inhibitors on C_2H_4 production in rice cultivar Nona Bokra. CP = cordycepin, CH = cycloheximide.

were applied after 2 d of soaking, production was inhibited about 50%; when applied after 3 d, they had no effect.

These studies indicate that EFE is not a constitutive enzyme in seeds but is synthesized de novo during seedling development and requires RNA synthesis.

Stress-induced ethylene production

A number of plant tissues, when subjected to stress (wounding, drying, flooding, insect infestation, viral infection, chilling, etc.), produce large amounts of so-called 'stress C_2H_4' in a few minutes or hours. This increase is soon followed by a decrease in the rate of production (34). The production of this C_2H_4 is largely dependent on increased activity of ACC-synthase. Because large amounts of C_2H_4 are produced when deep water and floating rices are immersed, it appeared that C_2H_4 could be used to monitor the elongating capacity of these rices and to distinguish varieties with differing capacities to elongate under submergence stress.

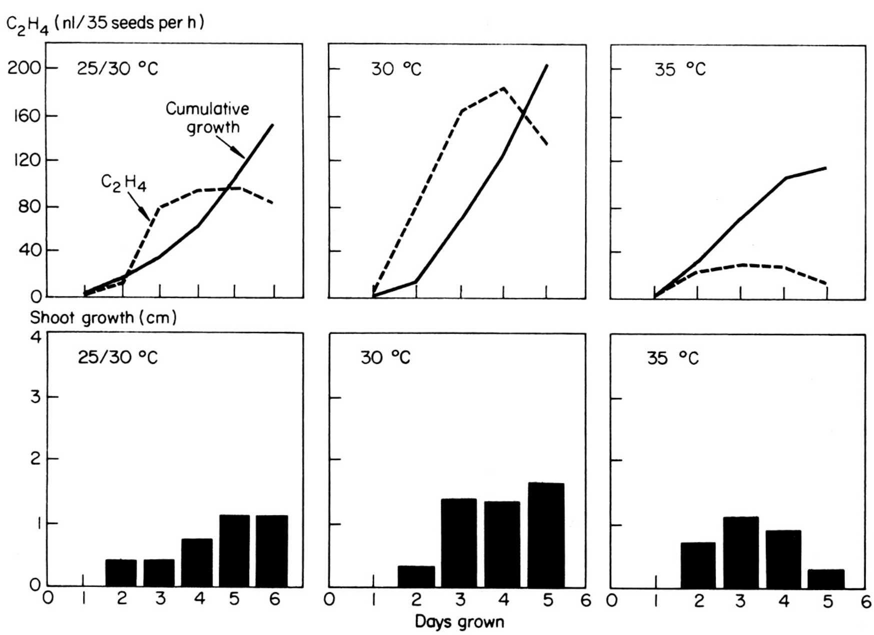
The method developed consisted of growing plants for, about 3 wk in the nutrient culture solutions of Yoshida et al (35). then immersing them in different depths of water or nutrient solution at 30 °C for one to several days. To study effects on elongation during submergence, growth regulators and other bioactive chemicals can be added directly to water or nutrient solution.

Two to four plants were transferred into 130-ml glass tubes and the hourly rate of C_2H_4 production was determined. Plants were measured before and after submergence for changes in height and length of the top two leaf blades and their corresponding sheaths. An elongation index (EI), defined as the cumulative increase in length of the top two leaf blades and corresponding sheaths, was used to distinguish elongating ability.

Monitoring the Influence of Adverse Climatic Factors and Predicting Plant Performance

High temperature

The effect of temperature on ACC-derived C_2H_4 production and shoot growth was studied. Both growth and C_2H_4 production rate were higher at constant 30 °C than at alternating 25/30 °C or at constant 35 °C temperatures (Fig. 6). Growth was more closely related to C_2H_4 production at 35 °C than at 25/ 30 °C or at 30 °C, as is shown by the daily growth rate.



6. Effect of temperature on C_2H_4 production and shoot growth in cultivar IR28. Hatched areas show daily growth rate.

Table 2. Effect of $CoCl_2$ on shoot growth and C_2H_4 production in rice Nona Bokra at 35 °C.[a]

Treatment	Shoot growth[b] (cm)	C_2H_4 (nl/ 35 seeds per h)[c]
Water	2.56 (100)	3.13 (100)
Co^{2+}, 2 mM	0.88 (34)	ND (0)
Co^{2+}, 1 mM	1.20 (47)	ND (0)
ACC, 2 mM	4.04 (100)	60.0 (100)
ACC, 2 mM + Co^{2+}, 2 mM	1.27 (31)	3.1 (5)
ACC, 2 mM + Co^{2+}, 1 mM	2.55 (63)	10.3 (17)

[a]Figures in parentheses are percentages of control value. ND = not detectable. [b]4-d-old seedlings, 2 replications of 10 seedlings each, [c]Analyzed at 4 d, 2 replications of 35 seeds each.

A closer relationship between C_2H_4 production and shoot growth at 35 °C than at 25/30 °C also was indicated from studies with Co^{2+}, which had a greater inhibitory effect on both growth (69 vs 42%) and C_2H_4 production (95 vs 81%) at the higher temperature (Table 1,2). ACC also improved growth over water to a greater extent at 35 °C (58 vs 13%) than at 25/30 °C, indicating a greater need for C_2H_4 at the higher temperature. These data suggest that at lower temperatures, factors other than C_2H_4 may have an overriding influence on growth. At supraoptional temperatures, C_2H_4 seems to be the dominant factor and can be used to monitor growth changes.

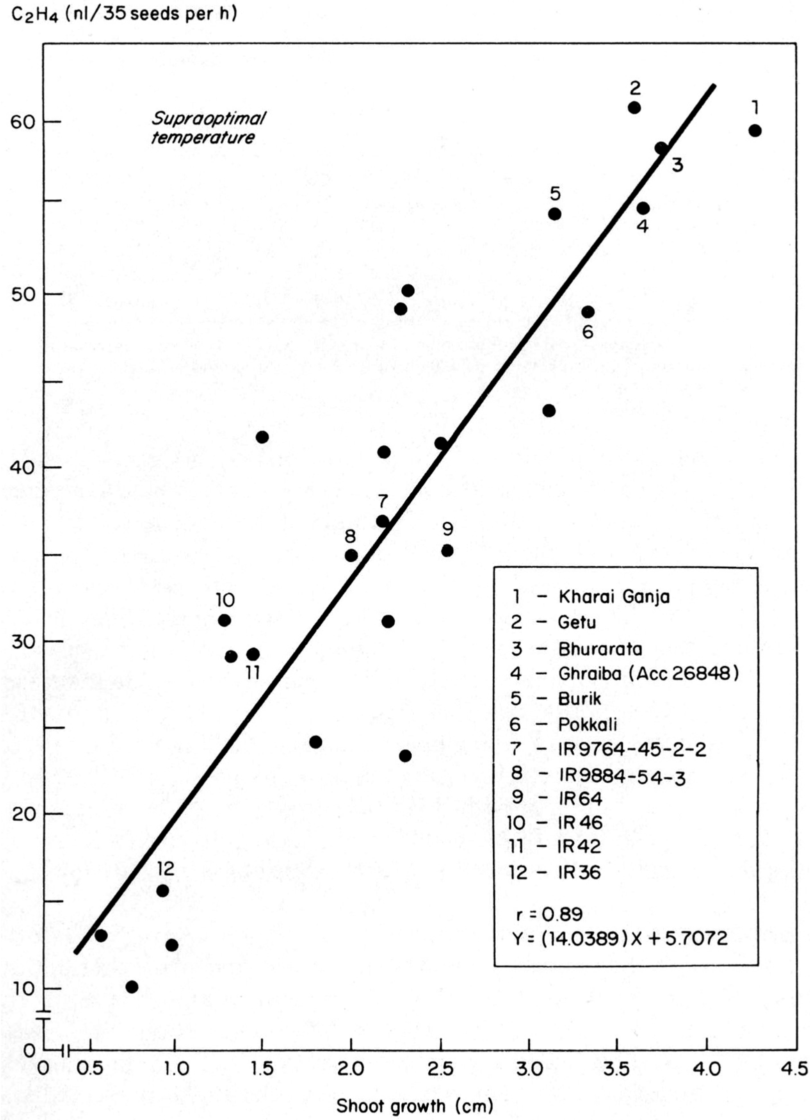
The predictive value of C_2H_4 production for seedling establishment at 35 °C is illustrated in Figure 7. Rice varieties showed a great deal of diversity in C_2H_4 production and shoot growth. Traditional varieties, such as Getu, Kharai Ganja, Bhurarata, Ghraiba, Burik, and Pokkali, outperformed IRRI-developed varieties and breeding lines IR36, IR42, IR64, IR9884-54-3, and IR97644.5-2-2.

High temperature plus high humidity

In large areas of the rice growing regions, temperature and atmospheric relative humidity (RH) are high. At 90% RH and 25 °C temperature, the equilibrium moisture content of rice is 18.3% (8); at 100% RH, about 26% (Khan, unpublished). In subtropical and tropical areas with high humidity and temperature, seeds may lose vigor within a few weeks under ambient climatic conditions. In these areas, seeds for shipping, processing, and storing must be transferred to low RH and temperature immediately after harvest to prevent deterioration.

It is essential to know how to monitor the level of seed deterioration in different seed lots and to predict their planting value. Recent studies with snap beans indicate that seed vigor is highly correlated with C_2H_4 production and seedling establishment (28). Two studies were designed to determine if C_2H_4 could be used to monitor level of vigor of rice grains and to determine varietal differences in resistance to aging.

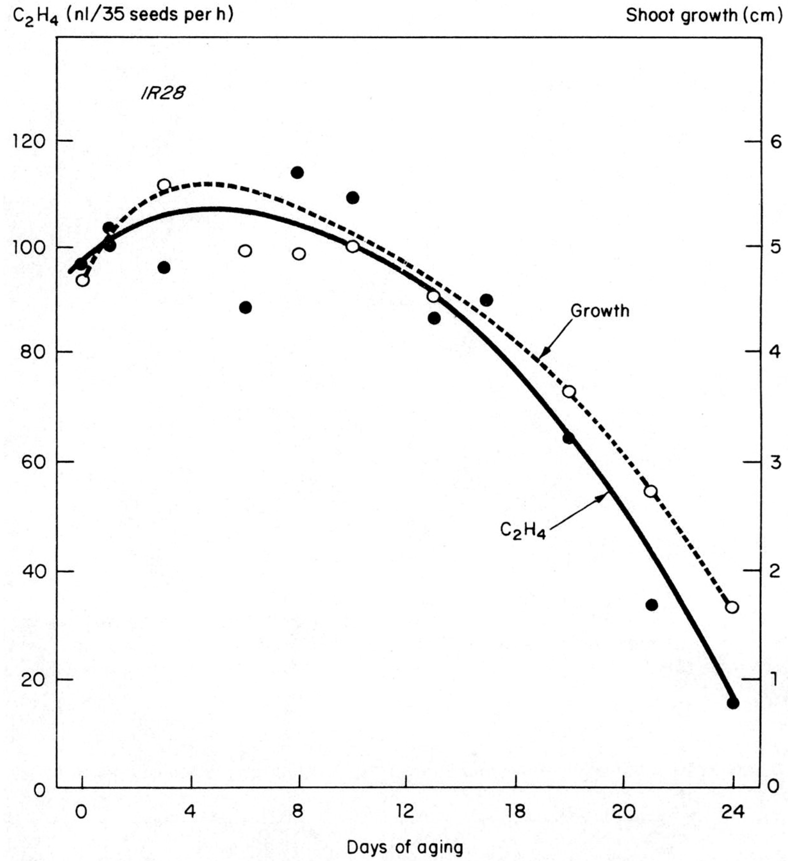
To obtain different vigor levels, rice seeds were subjected to a rapid-aging environment (40 °C and 100% RH) for different lengths of time, as described by



7. Scatter diagram of C_2H_4 production and shoot growth in 25 rice cultivars and lines. Seeds were soaked at 35 °C in 2 mM ACC. Seedlings were analyzed for C_2H_4 and shoot growth after 4 d.

Delouche and Baskin (5). ACC-dependent C_2H_4 production and shoot growth were determined in seedlings derived from aged seeds.

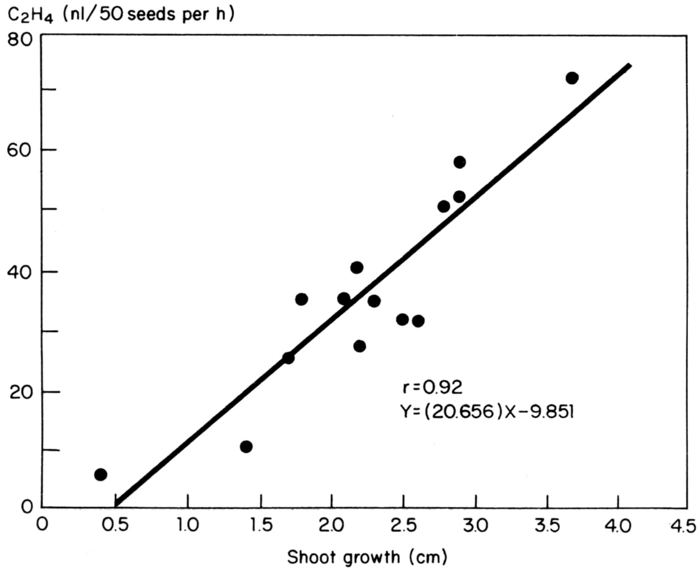
Both C_2H_4 production and shoot growth declined as seed deterioration increased (Fig. 8). With relatively short aging (1-3 d), some promotion of growth occurred. This may be related to the breaking of dormancy and to the



8. Effect of accelerated aging treatments of IR28 seeds at 40 °C and 100% RH on C_2H_4 production determined after 4 d and shoot growth determined after 6 d.

improvement of growth potential by the mobilization of stored reserves. This is common with freshly harvested rice seeds. Assuming that natural and rapid aging affect seed deterioration in a similar fashion, C_2H_4 production can be used to monitor the vigor level of seeds subjected to adverse climate and storage environments.

Aged and unaged seeds of some of rice varieties and breeding lines were compared for C_2H_4 production and shoot growth (Table 3). Based on C_2H_4 production, IR36, IR480-5-9-3, C22, and Nam Sagui were classified as resistant to aging and M148 and Kinandang Patong as susceptible. Varieties with intermediate values were classified moderately resistant. The value of C_2H_4 in predicting varietal survival and performance of seeds is illustrated in Figure 9. These studies emphasize a close relationship between stressed (aged) tissues and C_2H_4 production. A relatively poor correlation (r = 0.63) was found between C_2H_4 production and shoot growth in unaged seeds.



9. Scatter diagram of C_2H_4 production and shoot growth from aged seeds for 14 rice cultivars and lines. After aging at 43 °C and 95% RH for various times, seeds were soaked at 25 °C in 2 mM ACC. Ethylene was analyzed after 4 d and shoot growth after 6 d.

Table 3. Effect of rapid-aging environment on C_2H_4 production and shoot growth of some rice cultivars.[a]

Cultivar/ breeding line	Vigor[b]	Days aged			
		0 d		7 d	
		C_2H_4 (nl/50 seeds per h)	Shoot growth (cm)	C_2H_4 (nl/50 seeds per h)	Shoot growth (cm)
IR5	M	168	3.2	32	2.5
IR8	M	77	2.5	36	2.1
IR36	R	88	2.8	59	2.9
IR480-5-9-3	R	151	3.2	53	2.9
IR1529-430-3	M	77	2.6	35	1.8
M1-48	S	24	3.0	6	0.4
C-22	R	144	3.2	51	2.8
Kinandang Patong	S	35	3.1	11	1.4
Dular	M	88	3.0	32	2.6
BPI 76 (NS)	M	157	2.9	36	2.3
N22	M	70	2.6	28	2.2
Surjamukhi	M	101	2.7	41	2.2
Nam Sagui	R	187	4.3	73	3.7
Labella	M	26	2.5	26	1.7

[a] Ethylene production and growth were determined in 4- and 6-d-old seedlings, respectively. Seeds were aged et 43 °C and 95% RH. [b] R = resistant, M = moderately resistant, S = susceptible.

Submergence stress

Large tracts of land in Asia are subject to annual monsoon floods. These areas contribute little to production to meet increasing local food needs because of their very low rice yields. To accelerate breeding programs for flood-tolerant varieties, mechanisms for plant elongation and submergence tolerance need to be identified. Studies were conducted with intact 3-wk-old rice plants to determine if C_2H_4 production is related to elongation and whether C_2H_4 could be used to monitor and predict the elongation capacity of rices under submergence stress.

A good relationship was found between elongation ability and C_2H_4 production in several varieties subjected to submergence stress (Table 4). Elongation was largely due to growth of the topmost leaf blade and its corresponding sheath (data not shown, to be reported elsewhere). C_2H_4 production was highest in the floating rices with high elongation capacity (TCA177, TCA4, Jaladhi 1, FRRS 43/3). Deep water rices with moderate elongation ability (Pichar, Janaki, IR11288-B-B-69-1) produced intermediate amounts of C_2H_4. Nonelongating IR36 and IR42, and submergence-tolerant BKNFR76106-16-0-1 had the least C_2H_4 production and elongation. An increased rate of C_2H_4 production and elongation occurred in TCA177 as early as 30 min after submergence, peaked at 24 h after submergence, then declined (data not shown).

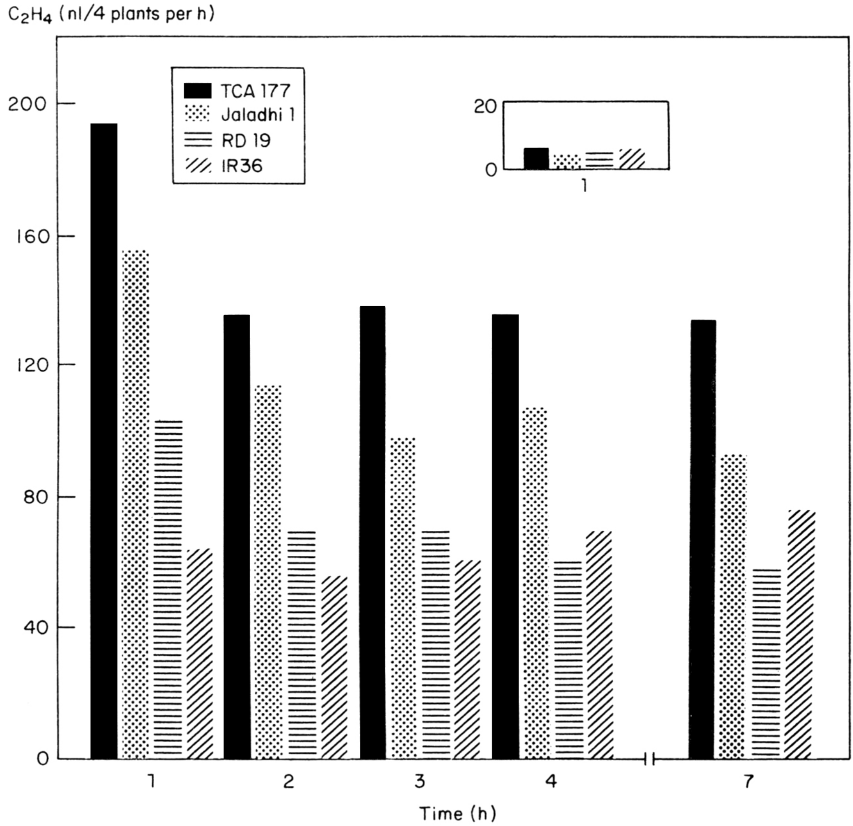
Following 24 h submergence, C_2H_4 production was highest during the first hour in TCA177, Jaladhi 1, RD19, and IR36, then declined slowly (Fig. 10). These results indicate that C_2H_4 production in the first hour following a 24-h submergence may be an effective way to monitor varieties for C_2H_4-producing capacity and for predicting elongating ability.

In general, floating rices submerged a few centimeters below the water surface elongated more rapidly than those submerged 70 cm below the surface. Ethylene production declined soon after the leaves protruded above the water surface. Activation of C_2H_4 production, elongating ability of floating rice, and escape from submergence stress are illustrated schematically in Figure 11. These results again underscore the importance of C_2H_4 for growth under stress.

Table 4. Effect of 1-d submergence 8-10 cm below the water surface on plant height and ethylene production of some rice cultivars (Thakur et al, unpubl. data).

Cultivar[a]	Increase in height (cm)			C_2H_4 (nl/4 plants per h)		
	Control	Submerged	Difference	Control	Submerged	Difference
Jaladhi 1	1.8	11.3	9.5	3	52	49
TCA 177	2.3	13.6	11.3	6	71	65
Janki	1.6	6.6	5.0	8	61	43
IR42	2.8	4.6	1.8	6	32	26
IR36	1.3	1.8	0.5	9	23	14

[a]Twenty-one-d-old plants grown in nutrient culture at 29/21°C submerged at 30 °C in 200-liter metal drums equipped with a thermostat and a pump for maintaining continuous aeration and uniform temperature.

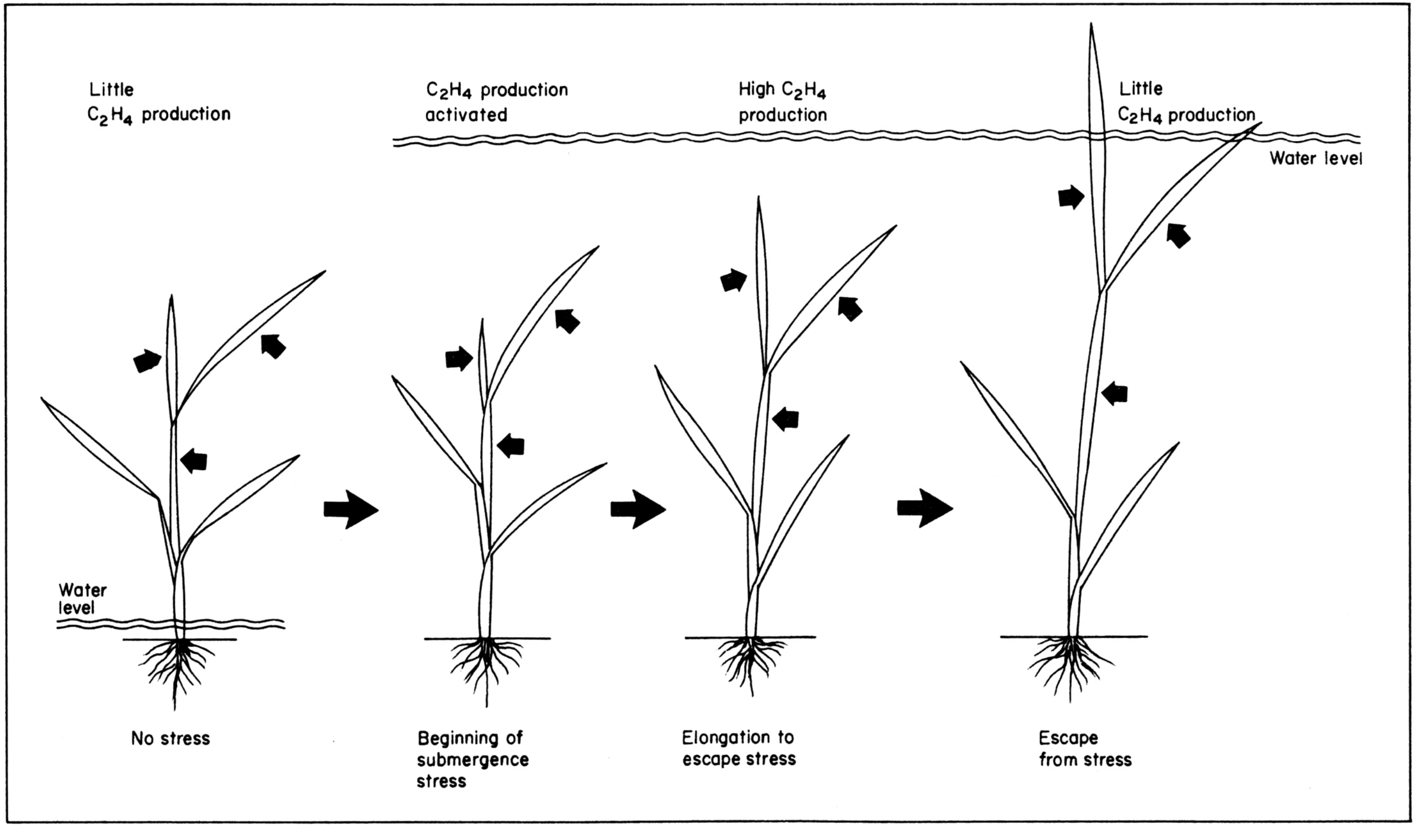


10. Hourly rate of C_2H_4 production in 4 rice cultivars. After submergence at 30 °C for 1 d, 4 plants (2 replications) were analyzed for C_2H_4 production. Insert shows C_2H_4 production during 1 h in nonsubmerged controls (Thakur et al, unpubl. data).

Several studies were conducted to identify the mechanism for elongation during submergence stress. An application of AVG during submergence nearly stopped subsequent C_2H_4 production and reduced the elongation index (EI) 62%, indicating that the C_2H_4 produced is dependent on the ACC synthesized and is needed for elongation (Table 5). Similarly, tetcyclacis (TCY), an inhibitor of GA biosynthesis (23), strongly inhibited the EI. The inhibitory effect was reversed by adding GA, indicating that elongation is dependent on the synthesis of GA (Table 6).

Hormonal interactions involving GA, C_2H_4, a stress inhibitor, and cytokinins may control elongation in floating rices. An attempt was made to test this hypothesis by applying these hormones externally to TCA177 during submergence.

Application of abscisic acid (ABA) strongly inhibited both C_2H_4 production and elongation (Fig. 12). Although kinetin completely reversed ABA



11. Schematic of events leading to C_2H_4 activation, C_2H_4 production, shoot elongation, and escape from submergence stress. Arrows show plant parts that are elongated.

Table 5. Effect of 1-d submergence with and without aminoethoxyvinylglycine (AVG), on elongation growth of floating rice (cv FRRS 43/31 (Khan et aL, unpubl. data).[a]

Treatment[b]	Plant ht (cm)	Top leaf plus sheath (cm)	Penultimate leaf plus sheath (cm)	Eiongation[c] index (EI)	C_2H_4 (nl/4 plants per h)
- AVG	1.3	9.8	4.5	14.3	140.8
+ AVG, 0.05 mM	1.3 (0%)[c]	3.8 (61%)	1.3 (71%)	5.1 (65%)	5.5 (96%)

[a]Figures in parentheses are percentages of inhibition. [b]Twenty-five-d-old plants grown in nutrient culture at 29/21 °C submerged 8-10 cm below the surface in test solutions at 30 °C in 122 × 6 cm glass cylinders. [c]Elongation index is defined as the cumulative increase in length of top leaf plus sheath and penultimate leaf plus sheath.

Table 6. Effect of tetcyclacis (TCY) and gibberellin (GA_{4+7}) on elongation during 1-d submergence of floating rice TCA177, and subsequent ethylene production (Khan et al, unpubl. data).

Treatment[a]	Plant ht (cm)	Top leaf plus sheath (cm)	Penultimate leaf plus sheath (cm)	Elongation Index (EI)[b]	C2H4 (nl/4 plants per h)
Water	6.8	13.5	2.7	16.2 (100)	64.1
GA_{4+7}, 0.1 mM	8.5	16.7	0.2	16.9 (104)	43.9
TCY, 1 µM	2.0	6.9	0.3	6.2 (38)	45.1
TCY, 1 µM + GA, 0.1 mM	5.1	15.9	0.3	16.2 (100)	43.1

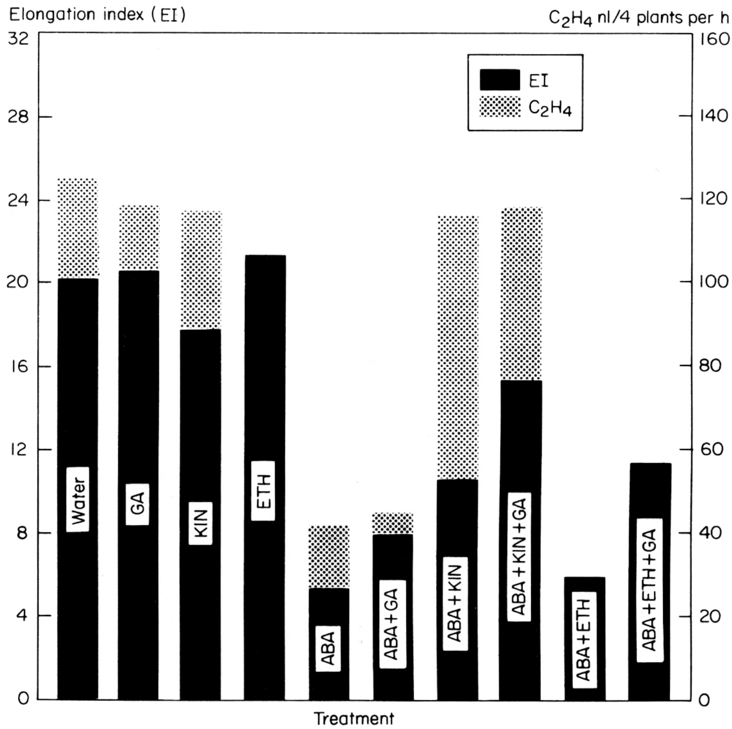
[a]Twenty-three-d-old plants grown in nutrient solution at 29/21 °C submerged in nutrient solution supplemented with test chemicals at 30 °C in 122- × 6-cm glass cylinders at 30 °C and grown for 1 d. [b]Figures in parentheses are percentages of control value.

inhibition of C_2H_4 production, it only partially removed inhibition of elongation. Unlike kinetin, adding GA to ABA failed to reverse the inhibition of C_2H_4 production. Further, GA was less effective than kinetin in reversing the ABA inhibition of elongation. Adding kinetin plus GA increased C_2H_4 production to a level higher than it was in water or GA treatment and caused the maximum reversal of growth inhibition by ABA. Ethephon, a C_2H_4-releasing compound, was less effective than kinetin in reversing the ABA inhibition.

Taken all together, these results suggest that GA, an inhibitor, probably ABA, C_2H_4, and cytokinins may all participate in the process of elongation under submergence. This suggests that the production and/or action of C_2H_4 may be related to the removal of an inhibitory block, permitting GA to induce elongation. It is easy to visualize how a change in the level of any one of these regulators during submergence would have a profound effect on elongation.

Cooperative Role of Ethylene In Alleviating Environmental Stress

The results of this study indicate that C_2H_4 may be important in regulating growth when plants or seeds are subjected to a stress. In both young seedlings

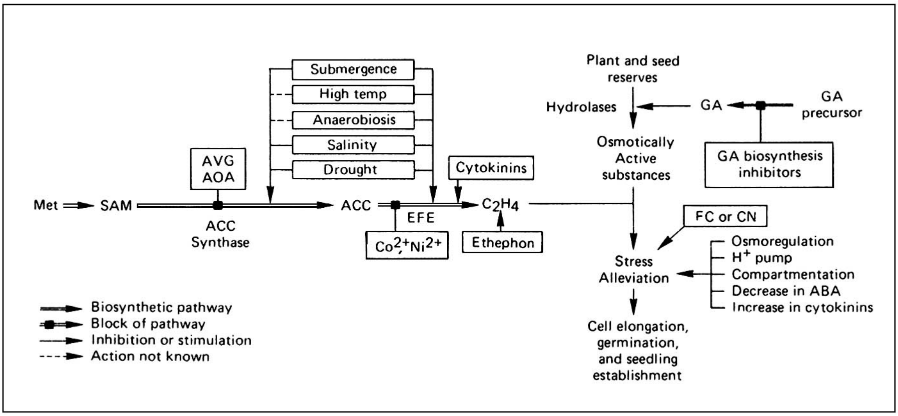


12. Interaction of GA_{4+7}, kinetin, ethephon, and ABA in C_2H_4 production and growth (EI) in 21-d-old floating rice TCA177 during 1-d submergence stress. Ethylene contents in treatments containing ethephon were very high and are not shown. Concentrations: GA_{4+7} = 0.1 mM, kinetin = 0.05 mM, ethephon = 0.05 mM, ABA = 0.01 mM.

and older plants, greater C_2H_4-producing capacity may allow rice plants to survive a stress situation. When C_2H_4 production is inhibited, exogenous C_2H_4 (or an ethylene-releasing compound) may be necessary to alleviate different types of stress.

Ethylene or ethephon are known to alleviate stresses caused by high temperatures (3,11,24), anaerobiosis (9,31), low water potential (3), and salinity (3,33). In a number of stress cases, C_2H_4 production is inhibited (2,4,7,11,30,36). A synergism between the actions of cytokinins and C_2H_4 or ethephon has been demonstrated to alleviate various stresses on germination, suggesting that C_2H_4 and cytokinins may interact (24,29).

In many cases, C_2H_4 production increases under a stress (34). Rice stem internodes, as well as young rice plants with undifferentiated internodes, produce C_2H_4 when subjected to submergence stress (20) (Table 4). Water stress applied to detached wheat leaves caused an increase in both ACC and C_2H_4 (18). These studies indicate that C_2H_4 production or availability may be an essential component of a stress removing mechanism.



13. Schematic showing the cooperative roles of ethylene and gibberellin in stress alleviation and growth promotion. Met = methionine, SAM = S-adenosul-methionine, ACC = 1-Aminocyclo-propane-1-Carboxylic acid, AOA = (Ammooxy) acetic acid, AVG = Aminoethoxyvinylglycine, GA = gibberellin, FC = fusicoccin, CN = cotylenin E, ABA = abscisic acid, EFE = ethylene-forming enzyme.

The fact that C_2H_4 production is inhibited by ABA during germination and that adding a cytokinin alleviates this inhibition indicates that an inhibitor-C_2H_4 or inhibitor-cytokinin interaction may occur during stress alleviation (10). Stressed wheat leaves treated with a cytokinin produced increased levels of C_2H_4; when treated with ABA, C_2H_4 decreased (18). In our studies, ABA inhibited C_2H_4 production in intact rice plants; kinetin reversed its inhibition (Fig. 12). A reciprocal increase in ABA and decrease in cytokinin occurs in plants subjected to water deficit, salinity, and other stresses (13,21,32). There may be a greater need for C_2H_4 and/or cytokinins in plants under stress than under normal situations.

Evidence presented here and elsewhere indicates that stress alleviation by C_2H_4 and cytokinins, although essential, may not account for the growth ability of plants. GA is primarily responsible for inducing cell elongation and growth (12,13).

A scheme to illustrate how C_2H_4 biosynthetic events are influenced by different stresses is shown in Figure 13. The continued availability of C_2H_4, produced endogenously or by applying exogenous substances (e.g., cytokinins and ethephon), and of GA may be essential for cell elongation, germination, and growth under stress. Relief of stress by C_2H_4 and/or cytokinins may depend upon the removal of a stress inhibitor, such as ABA. The preexisting or newly synthesized GAs may induce growth following the removal of stress. The GA action may be related to mobilization of storage reserves and production of osmotically active substances. This, in turn, could lead to improved water uptake, germination, and growth.

How C_2H_4 and/ or cytokinins alleviate a stress is not known. It may involve activation of an energy-linked H^+ pump and changes in membrane structure and function may be involved. This is suggested by the similarities between the actions of fusicoccin or cotylenin with cytokinins and C_2H_4 in alleviating stresses (3,15,19). Ethylene and cytokinin action and/or production may be closely related to alleviation of stress, while GA may serve as a primary stimulus for events related to germination and growth, with little direct influence on stress alleviation (12,13).

Acknowledgments

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Biological stresses

Climate and rice diseases

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ABSTRACT

Climate is one of the factors that limit the potential distribution, spectrum, and development of rice diseases. About 80 diseases occur on rice; their distribution varies with climate and geographic location. Some diseases are endemic to one continent or region, others are cosmopolitan. Most rice diseases occur in Asia, where rice is grown in both tropical and temperate climates. Bangladesh, which has a tropical monsoon climate, is used as a case study. The appearance of various diseases in Bangladesh is related to seasonal climatic changes. Examples are tungro, bacterial blight, bacterial leaf streak, blast, sheath blight, and damping-off. The relationship between climatic parameters (especially microclimate) and the biology of a pathogen are important in predicting disease occurrence in new areas and in forecasting outbreaks in areas where a disease is already present. Two approaches to gathering such information for the tropics are suggested and some potential benefits of knowledge of climatic influences on diseases are discussed.

Rice is grown under a wide range of climatic conditions, including temperate, subtropical, and tropical regions of Asia, Africa, Australia, and the Americas. These different climates influence not only growth and yield, but also the spectrum and development of rice diseases. Plant pathologists began to research climatic influences on disease development comparatively late; not until early in the 20th century did pathologists “rediscover the weather” (3). An approach that looks at the causes of spatial disparities of disease occurrences, including the comparison of different climatic regimes, was designed by Reichert and Palti (19) and Weltzien (22), but few studies have been done on this subject.

Disease, Climate, and Environment

Disease is the result of interactions of host, pathogen, and environment. Climate, as part of the abiotic environment, must be considered on different scales of time and space. For epidemic development of a disease, weather patterns are important. For assessing the risk of a disease occurrence, climatic data are sufficient.

This discussion deals with the meteorological definitions of macroclimate (the climate within large areas), mesoclimate (the climate within an area of a few square kilometers), and microclimate (the conditions in the layer within 2 m of the surface). But for many diseases, the important conditions inside the crop canopy are difficult to correlate with observations made by standard meteorological equipment placed at 2 m height. Plant density, topography, exposure, soil conditions, and cultural practices greatly influence the microclimate of the crop canopy.

Pathogeography and Disease Prediction

Geophytopathology focuses interest on spatial phenomena influencing disease distribution and intensity (19,22). Climate is one factor that limits the potential distribution of a plant disease. The actual distribution of a disease can also be limited if 1) the pathogen has not been introduced in all conducive areas, 2) susceptible hosts are not available, 3) cultural practices make the environment unsuitable, 4) disease vectors are not present, or 5) alternate hosts are not available.

If other factors limiting disease occurrence are removed, knowledge of climatic requirements makes prediction of disease occurrence possible. A striking example is the prediction of a sugar-beet mildew outbreak in the USA. Drandarevski (4) investigated the climatic requirements of the pathogen, then mapped the sugar-beet growing regions of the world and their climates. He noticed that the southwestern part of the USA had a suitable climate, but had not experienced a mildew outbreak. In 1974, this region was hit by a heavy epidemic (22).

For smaller areas and shorter times, forecasting has to be based on more detailed biological and meteorological information. Empirical forecasting systems use observations of previous epidemics to identify weather factors that occur long enough before an outbreak to allow the application of chemical protectives. Statistical analysis is applied to construct forecasting formulas using specific weather factors (for example, the amount of rain in the last 5 d of July). These are valid only for the particular region.

A more elaborate approach tries to relate knowledge of the climatic requirements of a pathogen at a critical stage of its development to the easily predictable circulation patterns in the atmosphere available from synoptic weather maps (2).

The most accurate tools for forecasting disease are system-analysis models, such as EPIVEN, the simulator for apple-scab epidemics (12). In these models, the environmental influences at every stage of the epidemic cycle are analyzed. Integrating this information leads to a simulation of the epidemic. Considerable knowledge of the biology of the pathogen must be accumulated before such a model can be constructed; the use of computers is absolutely necessary.

Rice Diseases, Distribution, and Climate Zones

About 80 diseases have been reported on rice. Not all are economically important, but at least 20 cause losses at certain locations and in certain seasons (Table 1). Among the 80, 22 are caused by viruses or virus-like pathogens, 10 by bacteria, 40 by fungi, and 8 by nematodes. Some of the diseases are endemic to one continent or region: hoja blanca in the Americas, yellow mottle in Africa, tungro in tropical Asia, dwarf and stripe in temperate Asia, and root needle nematode in Australia. Others are cosmopolitan: blast, brown spot, leaf smut, stem rot, sheath blight, and bakanae. The endemic diseases are mostly insect-borne or soil-borne; the cosmopolitan diseases are either airborne, seedborne, or both.

The greatest number of rice diseases occurs in Asia (Table 1). To examine the distribution of diseases, the Asian rice growing countries have been grouped according to the climate type occurring in the major portion of the country (Table 2). The delimitations of the four principal climatic belts of the rice-growing regions follow the modified Koeppen map by Trewartha and Horu (21). This rough division of climatic belts is used because reports of rice disease occurrence in Asia usually do not mention the climatic regions where the disease was found.

About 10-12 diseases are of concern in each climatic belt (Table 2). Some are common problems in the rice areas of Asia: bacterial blight, blast, brown spot, sheath blight, leaf scald, bakanae, sheath rot, grain spot, false smut, kernel smut, leaf smut, Cercospora leaf spot, white tip, and yellow dwarf. Others are specific to certain climates: tungro, orange leaf, bacterial leaf streak, ufra, seedling blight, stackburn, and sheath blotch in tropical forest and tropical monsoon regions; transitory yellowing, wilted stunt, and rusts in subtropical areas, and dwarf, stripe, black-streaked dwarf, bacterial halo blight, sheath net blotch, red blotch of grain, and speckled blotch in the temperate regions (13,18).

Differences occur not only across the climatic belts, but also between and within countries within a climatic belt, perhaps in part because of differences in mesoclimate. To help interpret these gross differences in distribution, information on the influence of environment (microclimate) on disease development, as well as knowledge of the prevailing macroclimate during the rice crop season and how this macroclimate relates to the microclimate, is necessary.

Tropical Monsoon Climate — a Case Study of Bangladesh

Bangladesh was used as a case study to focus on the relationship between disease occurrence and such climatic parameters as temperature, humidity, rainfall, and dew period. Bangladesh, situated 20.5° to 26.5° north latitude, has a typical tropical monsoon climate with two predominant seasons: hot and wet (April-October) and dry and cool (November-March). The land is mostly a plain, with a network of rivers and fertile soils.

Table 1. Occurrence of rice disease on different continents.

Continent[a]	Diseases present (no.)					Economic problem[b]
	Virus and viruslike	Bacteria	Fungus	Nematode	Total	
Africa 35°N-35°S	2	2	26	7	37	YM, BB, Bl, BS, CLS, LSc, ShB, ShR, GS
America 35°N-45°S	3	1	29	3	36	HB, BB, Bl, BS,ShB, SR, CLS, DO
Asia 45°N-10°S	16	10	37	7	70	Tg, GSt, Dw, TY,Str, BB, BLS, Bl, BS,ShB,SR, ShR, LSc, DO, GS, Uf
Australia and Oceania 10-40°S	-	3	19	2	24	NM, CLS, Bl
Europe 35-45°N	1	1	14	1	17	El, SR, BS
Total	22	10	40	8	80	

[a]Includes rice growing areas only. The climate in Africa is tropical and subtropical; in America, tropical and subtropical; in Asia, tropical rainforest, tropical monsoon, subtropical, and temperate; in Australia and Oceania, tropical and subtropical; and in Europe, subtropical mediterranean and temperate. [b]BB = bacterial blight, Bl = blast, BS = brown spot, BLS = bacterial leaf streak, CLS = Cercospora leaf spot, DO = damping-off, Dw = dwarf, GS = grain spot, GSt = grassy stunt, HB = hoja blanca, LSc = leaf scald, NM = needle nematode, ShB = sheath blight, ShR = sheath rot, SR = stem rot, Str = stripe, Tg = tungro, TY = transitory yellowing, YM = yellow mottle, Uf = ufra.

Table 2. Occurrence of diseases on rice crops in relation to climate in different countries of Asia.

Climate[a]	Diseases prevalent (no.)					Major problem[b]
	Virus and viruslike	Bacteria	Fungus	Nematode	Total	
Tropical						
Tropical forest	8	5	27	4	44	Tg, GSt, BB, BLS, Bl, BS, ShB, ShR, LSc, SR, Bk, GS, Uf
Tropical monsoon	7	3	27	7	44	Tg, BB, BLS, Bl, BS, ShB, LSc, SR, Bk, ShR, GS, Uf
Subtropical	9	6	25	3	43	TY, BB, Bl, BS, ShB, SR, ShR, LSc, Bk, GS
Temperate	10	9	26	5	50	DW, Str, BB, Bl, BS, ShB, SR, DO, Bk, LSc
Total	16	10	37	7	70	

[a]Tropical forest = coolest months above 18 °C, constant moist, rainfall throughout the year, little change of solar radiation during the year (Indonesia, Malaysia, Philippines, Thailand, Vietnam, Cambodia); Tropical monsoon = short dry winter and wet summer, rainfall and high solar radiation during summer months (Burma, Bangladesh, Bhutan, Nepal, S & E India, Sri Lanka); Subtropical = mesothermal forest climates, coolest months between 0-18°C, warmest above 22 °C (China, Taiwan, Laos, NW India, Pakistan); Temperate = microtherm I snowforest climates, coldest months below 0 °C, warmest above 22°C. constantly moist, rainfall throughout the year (Japan, Korea, N. China). [b]BE = bacterial blight, Bl = blast, BS = brown spot, Bk = bakanae, BLS = bacterial leaf streak, CLS = Cercospora leaf spot, DO = damping-off, Dw = dwarf, GS = grain spot, GSt = grassy stunt, HE = hoja blanca, LSc = leaf scald, NM = needle nematode, ShB = sheath blight, ShR =sheath rot, SR = stem rot, Str = stripe, Tg = tungro, TY = transitory yellowing, Uf = ufra.

Four types of rices are grown during three seasons a year (Fig. 1), with at least two crops raised on the same land. The rice crops are: boro (November-May), aus (April-July), broadcast aman or deep water rice (March-November), and transplanted aman (July-December).

The general patterns of rainfall, temperature, and humidity during the year are shown in Figure 1. The time of onset of the monsoon and the severity of cold weather during winter months vary with year and region (15).

Virus and viruslike diseases

The occurrence of such diseases as dwarf, stripe, and black-streaked dwarf in temperate regions; tungro, grassy stunt, ragged stunt, and transitory yellowing in tropical regions, and yellow dwarf in both temperate and tropical regions seems to depend on the temperature requirements of the various insect vectors.

High tungro incidence has been related to high temperature (25-30 °C). Moderate to low temperature (15-25 °C) favors dwarf, stripe, and black-streaked dwarf. Temperature affects probing frequency, acquisition feeding, movement, and transmission of the virus by the vector (10,18).

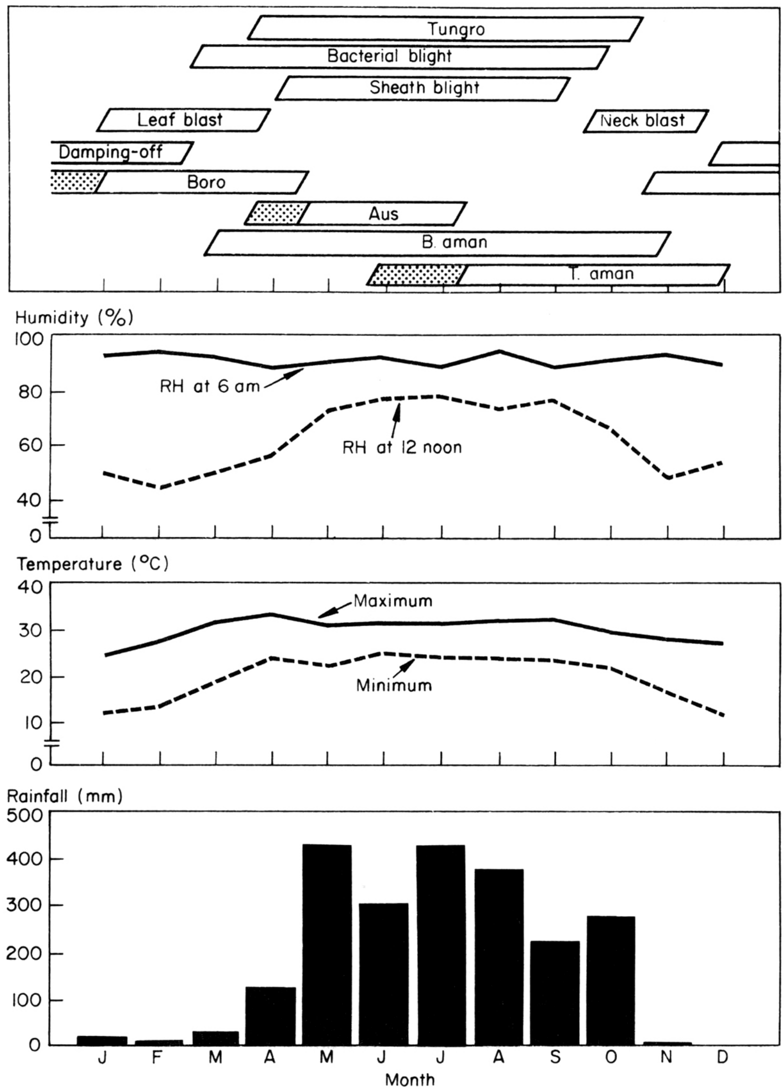
Both tungro and yellow dwarf diseases occur on rice in Bangladesh. Tungro, a complex disease caused by two virus particles, is severe on aus and aman crops. The disease, transmitted by the green leafhopper (GLH), appears in March, with the seasonal rise in temperature, and continues into October, when temperatures decrease (Fig. 1). The GLH population starts to increase in March, then suddenly decreases in April due to the advent of monsoon rains and wind. However, the population quickly rebuilds to a peak in July (1).

Tungro incidence tracks the vector population and is prevalent only during the summer months, not during the cool dry winter from October to February when low temperatures suppress the GLH population. This suggests that high temperature is necessary for the GLH population buildup which is ultimately responsible for the spread of tungro.

Bacterial diseases

The relationships of atmospheric temperature to the development of bacterial blight, bacterial leaf streak, black rot of grain, and brown sheath rot have been studied. High temperature (25-35 °C) favors lesion development for bacterial blight (17), leaf streak (18), and black rot of grain (8).

Three bacterial diseases, bacterial blight, bacterial leaf streak, and stalk rot, occur in Bangladesh (15). Although bacterial blight appears on all crops, maximum severity is on crops grown during the summer months. Bacterial leaf streak usually appears after the first monsoon rain in April, when the boro crop is at the booting to heading stage (Fig. 1). Although the late boro crop is often infected with leaf streak, damage is not severe. Aus and transplanted aman crops are badly affected, especially if a hailstorm is followed by monsoon rain, high temperature, and high humidity. This clearly indicates that these two bacterial diseases prefer hot, moist climates.



1. Temperature, humidity, rainfall pattern plotted against rice crops grown, and disease occurrence during the year in Bangladesh (1)

Although black rot of grain is a high-temperature disease, its absence in Bangladesh may be because the causal organism is not present. If low temperatures prevail for 5-7 d, rice plants are likely to be attacked by the brown sheath rot bacterium (16). This low-temperature requirement perhaps explains its occurrence in temperate areas, but not in Bangladesh. There is no work on the effect of humidity or leaf wetness period on these diseases, but it is known that high rainfall and strong wind increase their spread (18).

Fungal diseases

In a 1979-81 survey, fungal diseases found in Bangladesh included blast, brown spot, sheath blight, sheath rot, leaf scald, stem rot, bakanae, Cercospora leaf spot, stackburn, false smut, grain spot, seedling blight, and damping-off (15). Most of these diseases occur in all seasons. Seedling blight and damping-off appear only in boro seedbeds; false smut appears only in the aman crops. In general, the different times of appearance of the various diseases seem to be related to the onset of certain environmental conditions.

Blast is a cosmopolitan disease, occurring in almost all rice-growing regions of the world except California, USA (18). This wide occurrence suggests that the pathogen can survive in almost all types of climates. In tropical climates, the period of leaf wetness, either from dew or rainfall, may be the most critical microclimatic factor determining epidemic development (18). The minimum period of wetness required for infection of rice leaves by *P. oryzae* ranges from 6 to 14 h, depending on temperature (6,9).

Blast appears in Bangladesh during two periods, January-March and October-November (Fig. 1), when night temperatures are low, humidity in the morning is high, and the dew period is longer than at other times of the year. These are the conditions most favorable for blast (14). Blast occurrences in the northeastern India states of West Bengal, Orissa, and Assam follow the same pattern.

Blast is a more serious problem in upland rice, which is grown in aerobic soil, than in lowland rice, which is flooded during growth of the crop. This phenomenon is due not only to longer periods of leaf wetness in upland rice, but also to the increased susceptibility of the rice plant after a period of water stress, a common occurrence in many upland rice environments.

Aside from these effects of climate on blast disease, such factors as soil type, cultural practices, and cultivar resistance may greatly influence disease development. These other factors could explain why the disease is of relatively little importance in certain environments where the climate is otherwise favorable.

Sheath blight is a soilborne fungal disease which, like blast, is cosmopolitan, occurring in most rice growing countries of tropical, subtropical, and temperate regions (18). The disease is favored by high temperatures and high humidity, especially below the crop canopy (Table 3). In Bangladesh, the disease appears during April, when the boro crop is at the flowering to milk stage, and continues to increase in aus and transplanted aman crops until mid-September (Fig. 1). Its occurrence coincides with the high temperatures and high humidity during those months.

This climatic condition is apparently the reason the disease is severe on the aus crop but not on boro and aman crops. The disease cannot develop on the boro crop due to low temperature until about flowering, at which stage it causes little damage. Although the disease appears on the aman crop during early growth stages, its development stops after mid-September because the temperature decreases (Fig. 1). As with the boro crop, not much loss occurs. However, late-sown boro and early-sown aman crops often encounter severe damage.

In temperate Japan, sheath blight appears in July in early season crops and in August in normal season crops. Disease progress coincides with the rise in temperature; the early season crop is affected more than the normal season crop because the temperature begins to decrease during the heading stage in the later crop (7). This is also the case in the transplanted aman crop in Bangladesh.

In Japan, within this century, sheath blight developed from an endemic disease in the southwestern part to a severe problem affecting 32-50% of the rice-growing area. The main reason for this spread seems to be the change in microclimatic conditions caused by the introduction of modern varieties and fertilizers. Increased plant density leads to a relative humidity near saturation, especially during the maximum tillering stage. The temperature still follows the macroclimatic pattern (11). In a similar way, the intensification of rice culture in certain tropical environments has led to increases in sheath blight severity.

Damping-off, caused by *Achlya* spp., is another soilborne fungal disease. In Bangladesh, the disease is found in boro seedbeds raised during December-January, especially when the minimum temperature is 15 °C or less (20) (Fig. 1). The pathogen prefers low soil and irrigation water temperatures. Because of this, it is also an important problem in wet seedbeds in temperate Japan and in early water-seeded rices in California, Louisiana, Texas, and Arkansas, USA (18). In the USA, early water-seeded rices are sown during February-March. The sprouted seeds remain submerged in cool water for about 5-7 d. Such conditions favor proliferation of the water mold and the infection of the germinating seeds results in reduced stands. Because of the cold-weather requirement of the pathogen, the disease is rare in the tropical monsoon climate of Bangladesh and appears only when cool weather prevails.

Other diseases for which high temperature has been related to high incidence and severity are leaf smut, stackburn, bakanae, sheath spot, false smut, and grain spot. Downy mildew occurs under low temperatures in temperate regions. Brown spot is not much influenced by temperature, although it favors high humidity and high rainfall for sporulation and spread (18).

Nematode diseases

Ufra, white tip, root knot, root, stunt, and ring nematode diseases are reported in Bangladesh (15,18). Ufra is the most destructive, occurring on rice grown in the Brahmaputra-Meghna-Ganges floodplains. In the past, ufra was considered only as a disease of deep water rice, but now it has been detected in all rice culture types in the country.

White tip is prevalent in the aus and aman crops. Root knot occurrence is observed on boro and aus seedlings during November-April, when the temperature is low and soil moisture is below field capacity. High temperatures and high humidity have been found to favor ufra and white tip development and spread, which explains their appearance during the summer months. Unlike ufra and white tip nematodes, the root knot nematode seems to thrive at lower temperatures and under dry soil conditions (18).

Table 3. Influence of climatic parameters on the development of different rice diseases.

Disease	Causal organism/ vector	Climatic parameters favoring disease					Remarks
		Temperature[a]	Humidity[b]	Dew (leaf wetness period)[c]	Rainfall[d]	Wind[e]	
Virus and viruslike diseases							
Tungro	*N. virescens* and other species	High	-	-	Low	-	Increase probing frequency and movement
Dwarf	*N. cincticeps* and other species	Moderate	-	-	-	-	Acquisition feeding higher at 25 °C
Strips	*L. striatellus* and other species	LOW	-	-	-	-	Viruliferous insects and trans-mission are high
Black streaked dwarf	*L. striatellus* and other species	LOW	-	-	-	-	Viruliferous insects and trans-mission are high
Bacterial diseases							
Bacterial blight	*X. c.* pv. *oryzae*	High	?	?	High	Strong	Helps multiplication and spread
Bacterial leaf streak	*X. c.* p.v. *oryzicola*	High	?	?	High	Strong	Helps multiplication and spread
Black rot of grain	*P. itiona*	Hilgh	?	-	-	-	Helps in infection and development
Brown sheath rot	*P. syringae* pv. *syringae*	LOW	-	-	-	-	Helps in infection and development
Fungal diseases							
Blest	*P. oryzae*	LOW	High	Longer	High	Mild	Helps in sporulation infection and spread
Brown spot	*D. oryzae*	Wide	High	?	High	-	Helps in sporulation infection and spread

Downy mildew	*S. macrospora*	Low	?	?	-	-	Helps in sporulation infection and spread
Leaf smut	*E. oryzae*	High	?	Longer	High	Mild	Helps in infection and development
Stackburn	*T. padwickii*	High	High	-	-	-	Helps in infection and development
Bakanae	*F. moniliforme*	High	-	-	-	-	Helps in infection and development
Sheath blight	*R. solani*	High	High	-	-	-	Helps in infection and development
Sheath spot	*R. oryzae*	High	High	-	-	-	Helps in infection and development
Damping-off	*Achlya* sp.	Low	-	-	-	-	Helps in sporulation infection and development
False smut	*U. virens*	High	High	-	-	-	Helps in infection and development
Grain spot	Many organisms	High	High	-	-	-	Helps in infection and development
Diseases caused by nematodes							
Ufra	*D. angustus*	High	High	-	-	-	Helps in multiplication infection and development
White tip	*A. besseyi*	High	High	-	-	-	Helps in multiplication infection and development
Root knot	*Meloidogyne* sp.	Low	Low	-	-	-	Helps in multiplication infection and development

[a]High = 26-36 °C, low = 16-26 °C, moderate = 20-30 °C, wide = 16-35 °C. [b]High = 89% relative humidity, ? = not clearly known. [c]Longer = 6 h. [d]Low = infrequent and less amount/day, high = frequent and high amount/day. [e]Mild = low speed or soft, strong = high speed or strong type.

Conclusion

The information available on macroclimate and rice diseases is adequate to identify gross differences in disease occurrence across climate belts. Some information from experimental studies on microclimatic influences on blast, sheath blight, bacterial blight, tungro, and damping-off is available (6,7,17, 18,20). While the microclimate is influenced by the macroclimate, it is not yet possible to establish a quantitative relationship between ambient climate and microclimate of a particular area or plot. This makes applying the results of laboratory studies to disease management in the field difficult.

The system analytic model of Hashimoto et al (5) for rice blast is perhaps the only example where the results of experimental studies were used to construct a forecasting model for rice diseases. The empirical forecasting models used in Japan and Korea are based on accurate disease incidence records and severity measurements recorded in climatically different regions for many years. In the tropics, such data are scarce.

The survey conducted in Bangladesh is one of only a few published examples where disease occurrence and severity have been studied in farmers' fields in tropical regions (15). Even basic information on the distribution of diseases within countries is lacking.

To gather these data, two approaches are possible: 1) develop a uniform methodology and conduct appropriate disease surveys in farmers' fields within regions representing various climates and rice culture types, and 2) conduct multilocation trials in such regions to measure diseases and associated damage to yield in relation to the prevailing microclimate.

Knowledge of climatic influences on diseases has some potential benefits. As the intensity of agricultural practice increases in the tropics, system analytic forecasting models developed in the temperate countries could be modified for use in the tropics. When information on disease occurrence in climatically similar regions is available, it should be possible to predict changes in the relative importance of certain diseases as cultural practices change. This information would be useful in defining breeding for resistance objectives. Information on the climatic limits of diseases could be integrated into land suitability maps and environmental classifications.

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Using weather data to forecast insect pest outbreaks

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ABSTRACT

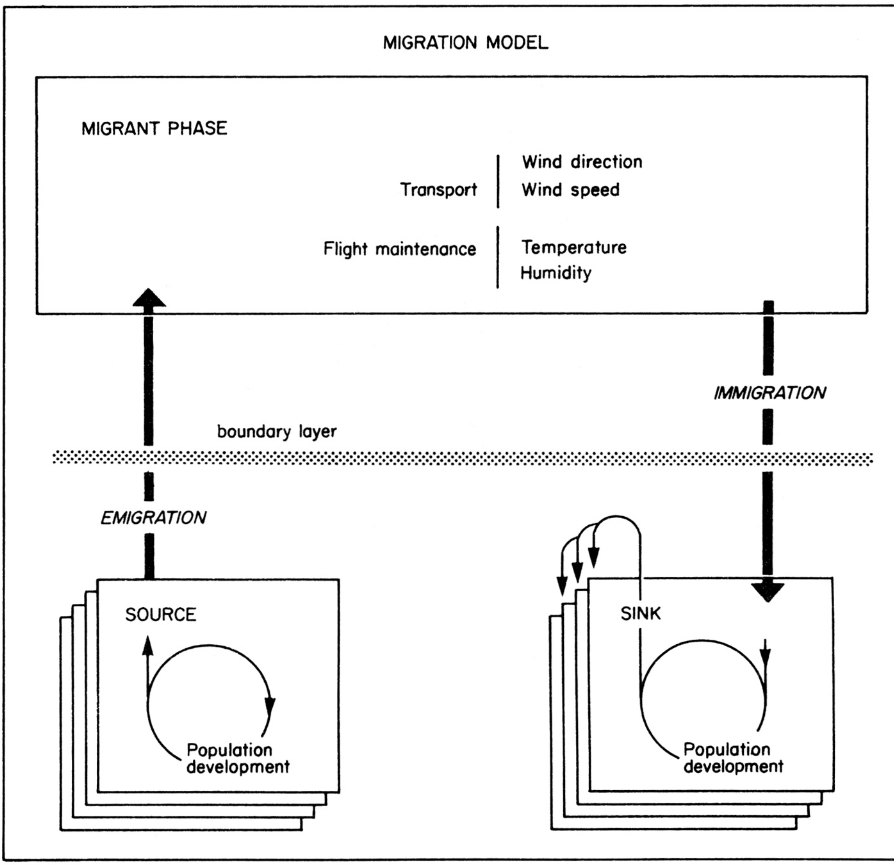
Weather data have been used to predict outbreaks of certain important migrant tropical pests, notably the desert locust *Schistocerca qreqaria* and the African armyworm *Spodoptera exempta.* How weather influences the bionomics of migrant pests is examined and the application of this examination to forecasting outbreaks is discussed. The situation for rice pests is considered, particularly the application of weather data to forecasting outbreaks of brown planthopper *Nilaparvata lugens.*

The development of forecasting systems to manage outbreaks of migrant pests is becoming increasingly important. Such systems normally are based on integrating meteorological and entomological data into a conceptual model that relates the probability of occurrence of outbreaks to a particular series of events which can be monitored. The advantages of this approach to forecasting are both tactical and strategical: those concerned with pest control can plan ahead to ensure that appropriate resources and the means to deploy them effectively are available where and when they will be needed. A strategic advantage of major importance is the potential for limiting the spread of outbreaks through timely control of early infestations, reducing the production of further migrants.

Pest Dynamics and Weather

In considering the relationship between weather and forecasting, it is helpful to construct a simple model of a generalized migrant pest. This makes explicit the points at which weather interacts with the pest system to influence its success (Fig. 1). The model has three major components: the source population, the transient or migrant phase, and the sink,

Source and sink are horizontally separated in space to a degree determined by the time spent in, and displacement characteristics of, the transient phase. In wind-borne migrants, source and sink are vertically separated from the transient



1. Schema of components involved in constructing an insect population forecasting model.

phase by what has been termed the boundary layer. This is the height at which the insect loses its capacity for directional flight and is passively transported by air movement for as long as it is able to remain buoyant. It is important to recognize that this involves active flapping of the wings to maintain altitude. There may be a gliding component, but without wing-beating, insects will sediment in the manner of inert particles (13).

Various strategies are adopted by insect groups to improve buoyancy and to increase dispersal. Some flightless forms have adaptations that make them capable of considerable wind dispersal (for example, the secretion of silken threads by coccid 'crawlers' and first-instar lepidopterous larvae; spiders also disperse in this way). In some insect species, migration is conducted wholly within the boundary layer. Such migrations may cover very large distances, as with the monarch butterfly *Danaus plexippus* (22) and the Great Southern White *Ascia monuste* (7). However, wind-borne migrants are the dominant category and certainly the more economically important.

Weather is important at all stages of the model. Microscale weather may be a determinant of successful population growth at either source or sink by acting directly on the insect or through host plant quality. For the source population, this will influence both the abundance and the fitness of emigrants, and thus the potential migrant range. At the sink, the same factors will govern the ability of the population to express its full potential for increase and dispersal, giving rise to outbreaks.

Forecasting must take into account two situations: status of the source population and favorability of the sink habitat. Weather may be an important contributory factor. In particular, this is likely to be the case where migration is associated with the seasonal expansion of an insect's range that exploits the changing distribution of the host plant.

Redistribution of migrants at the sink habitat is related to local and mesoscale weather conditions; long-distance transport is most often associated with macroscale climatological events (11). Throughout migration, weather conditions interact with the physiology and behavior of the insect to determine the expression of migration potential.

This can be illustrated by the rice brown planthopper (BPH) *Nilaparvata lugens.* Take-off for this insect occurs under well-defined meteorological conditions. It is bimodal and crepuscular in the tropics, where temperature is not limiting (14). But when late season temperatures in Japan fall below the take-off threshold of 17 °C, morning activity is often suppressed (10). Winds greater than 3.1 m/s also inhibit take-off.

Rosenberg and Magor (16) reviewed data on flight duration once BPH have become airborne. They used trajectory analysis to investigate movement from China to Japan. Synoptic weather charts and catches in nets on weather ships in the East China Sea and light traps in Japan were studied and backtracks constructed from the ship to possible source areas in China and Taiwan. Forward trajectories from the ship to landfall in Japan or South Korea also were constructed. In their simulation, flights of 30 h or less linked all captured samples to potential sources when trajectories were projected at heights of 10 and 1,500 m. The 30 h is considerably longer than laboratory estimates of flight duration (1,9,12), but this may be a function of sample size.

Forecasting

Forecasting entails drawing conclusions about the expected severity of a pest problem on the basis of observation of factors (such as weather) identified as important in its buildup. Normally, a forecast will include the probability of damaging infestations occurring within a particular time and location.

Short-range forecasting

Forecasts in the short range are often based on current or past weather and the relationship established between weather and the progress of infestations, usually within a given season and often in terms of weeks. Such short-range forecasting can be completely empirical, such as the use of environmental cues reported from Japan, where the date of the first blooming of cherry blossoms and the mean March temperature were used to predict peak emergence of the rice stem borer *Chilo.*

It is more usual to base forecasts on cumulative degree days. Temperature has a profound effect on the rate of insect development; temperature changes can markedly influence the course of an infestation.

It is clear that in short-term forecasting of this type, weather parameters can provide important information, although the actual severity of a problem - including such basics as presence or absence - can only be predicted with knowledge about the level of colonization. The importance of appropriate monitoring systems to collect those data cannot be overemphasized. Short-range forecasting allows those concerned with pest control to develop appropriate seasonal tactics to contain outbreaks.

Medium-range and long-range forecasting

Medium-range forecasting deals with the overall impact of a pest within a particular season. It may be based on recent climatological data or on extended weather forecasts. Extended weather forecasts are becoming more useful as they become more reliable.

Long-range forecasting is based on long-term trends identifiable in climatological data and is concerned with the probable development, extension, or modification of a pest problem.

The great advantage of medium-range and long-range forecasting is their potential for developing strategies to minimize the expression of a pest problem, such as changes in cropping practices, development of effective quarantine procedures and control technology, development of strategies for pesticide use to guard against pesticide resistance, and exploitation of resistant crop cultivars.

Some Examples of Forecasting

While the principles and justification for forecasting outbreaks of insect pests are well established, only a few operational systems provide good illustrations of its potential and of the part that weather can play. In general, forecasting that is heavily dependent on weather parameters has been more successful in predicting outbreaks of fungal and bacterial pathogens than outbreaks of insects. Complications are introduced through the insect’s own behavioral responses. The problem is compounded in the epidemiology of vector-borne virus diseases.

Forecasting is particularly important for epidemic pests that appear irregularly. Such pests often are exploiting a variable food resource, which may in turn be dependent on weather conditions — particularly rainfall. Therefore, weather is a very good indicator of potential pest outbreaks.

The desert locust *Schistocerca gregaria* provides a good example of an epidemic pest for which forecasting has been developed and refined on a regional level. Weather parameters play a major role in the forecasting model.

The desert locust is a highly mobile insect; migration is essential to maintain the species in a predominantly arid environment that experiences only brief flushes of vegetation in association with seasonal rains. Early observations indicated a close relationship between the movement of locust swarms and seasonal wind and rainfall. That suggested the use of synoptic weather data to forecast locust movements.

A World Meteorological Organization Technical Assistance Mission was established in 1954-55 to undertake a detailed study of widespread locust infestations and related weather data over the entire invasion area. It was concluded that the movements of desert locusts are to a large extent determined by corresponding low-level wind fields (15). Locusts are carried downwind. Populations may be concentrated in areas of convergence to give rise to swarms, or may be dispersed through divergent wind flow. Between May and October, downwind movement and the cohesion of swarms tend to maintain the insects in areas where rainfall allows oviposition to occur, leading to further aggregation and increased size of swarms. Forecasting is able to give several days notice of impending swarms.

Figure 2 illustrates a situation in India in 1964, where convergence concentrated scattered locusts.

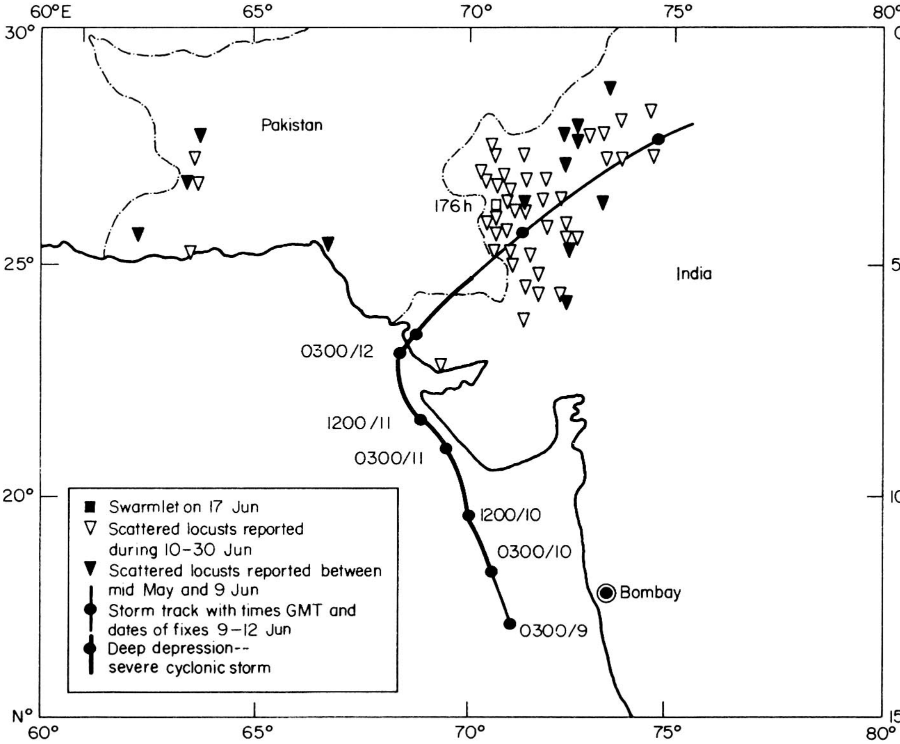
Short-term forecasting of swarm behavior and structure is also of considerable importance in guiding control operations, such as effective and economic deployment of aircraft spraying operations.

The African armyworm *Spodoptera exempta* is another pest for which a regional forecasting system has been developed. In east Africa, the Desert Locust Control Organisation (DLCOEA) collects data on the abundance and current distribution of this noctuid moth from a network of light and pheromone traps. The data are used in conjunction with synoptic weather charts to provide a weekly forecast of the likelihood of outbreaks (8).

Forecasting also relies heavily on historical analogs. Detailed studies have been conducted since 1961 on the epidemiology of outbreaks (2). Armyworm populations appear to persist throughout the dry season, in perennially moist areas along the coastal plains and inland mountain and lake systems. Moths arising from such low density populations concentrate in convergence zones during early-season rainfall (20), leading to mass oviposition and emergence of damaging populations of larvae. Young larvae are inconspicuous and control tends to be undertaken too late, hence the need for a forecasting system to alert farmers to the need for careful monitoring.

In addition to the specific relationship between rainfall and breeding sites, analysis of long-term records shows a more general association between early-season rainfall and the number of outbreaks occurring over the remainder of the season (21). Seasons with more than average numbers of outbreaks often follow poor early season rains and vice versa. The biological basis for this relationship of rain pattern to pest population may be related to virus infestation under high moisture or to physical dislodging of larvae from plants by heavy rainfall.

There is considerable promise for introducing a longer term component



2. Storm track of a 1964 cyclone in the Arabian Sea and its effect on desert locust dispersal. The likely path of the cyclone to the NNW was forecast on 10 Jun, with a recommendation to monitor developments in the locust situation. The storm concentrated scattered locusts, including the formation on 17 Jun of a swarmlet in Indian desert areas.

into armyworm forecasting. Weather data are a major contribution to both short- and medium-range forecasts. Early outbreaks of armyworm that often occur in Kenya or Tanzania, and then move north with the ICTZ, can cause serious infestation and crop loss as far north as Yemen. Forecasting early outbreaks on both crop and pasture and subsequently controlling them is extremely important in limiting the spread of the insect.

Forecasting rice pest outbreaks has been largely confined to seasonal rice in temperate latitudes, particularly in China, Japan, and Korea. The most important species considered have been BPH and the Oriental armyworm *Mythimna separata.* Movements of these insects as they migrate northward to exploit the seasonal expansion of rice production are well documented (3,5) and are very closely linked with movements of frontal systems.

Although it is possible to predict (on a fairly coarse scale) the temporal and spatial distribution of some pests, weather per se, while it determines the context within which outbreaks may occur, has been of little value so far in forecasting outbreaks. Levels of immigration and agronomic practices are the critical factors.

For Japan, at least, there is a good relationship between numbers caught in pan, light, and net traps early in the season and the subsequent development of infestations (6). When a mass immigration is recorded (more than 150 in a water pan trap), the need for chemical control can be predicted. Pesticide is applied to emerging nymphs 20-25 d after the immigration is observed. But Cook and Perfect (4) found that such a prediction/control system could not be applied in the tropics because there was no consistent relationship between immigration rate and population development.

A forecasting system based on general patterns of BPH movement has been operating in China since 1977. Five main rice-growing zones are recognized. Information is collected on times of macropter (long-winged migrant forms) production, rice growth stage, and meteorology. These data are used in conjunction with light trap and field survey data in developing forecasts. The forecasts have been successful, although heterogeneity in invasion and successful colonization has led to scattered infestations for which no treatment had been recommended. Further studies are under way to improve this situation.

Detailed information on movements of BPH and rice roller *Cnaphalocrosis medinalis* has been collected from a large number of forecasting stations in China by light trapping, alpine nets, and field observations. The researchers hope to construct a computerized forecasting model using trajectory analysis of data on source populations and synoptic weather data to predict local concentrations of insects.

Studies of BPH population development in relation to weather in Guangdong Province (18) point to the importance of temperature in determining the number of insect generations during the summer and the size of the infestation of the second rice crop. High temperatures in July and August and low rainfall in September are associated with low numbers in the 6th and 7th generations. When average temperatures are less than 28 °C in July and August, when high rainfall in September continues into October, and when temperatures remain above 24 °C, serious infesfations result.

Conclusion

There is great potential for using weather data to forecast outbreaks of insect pests, particularly because our ability to access and process information from remote-sensing systems is increasing rapidly. FAO routinely uses satellite pictures for information on rainfall and vegetation to identify potential breeding sources of the desert locust. It is likely that this will expand to other pests, such as the African armyworm.

However, it appears that weather parameters are a critical factor in outbreak development, and thus a good predictor, only in situations where they represent a population-limiting factor. This is seen most frequently with temperature in the temperate zone and rainfall in the tropics.

In many situations, weather may play a very important part in determining the precise epidemiology of an outbreak, although it is not in itself a determinant of the outbreak. Rice leafhoppers and planthoppers and the virus diseases they transmit are an example.

The study of weather systems against the background of the ecology, behavior, and physiology of the insect pest and the distribution of the host plant can lead to improved predictions of dispersal patterns. This type of information can be of great value in developing appropriate management strategies. The development of computer-based migration and population models for particular insects will be important in exploiting that forecasting potential.

It is worth emphasizing that climatological studies can also be of great value in examining such phenomena as the likely frequency of interchange between populations in relation to virus transport or to genetic shifts of populations which may lead to the breakdown of varietal resistance. This technique has been investigated for BPH by Rosenberg and Magor (17) and could be extended to other rice insects.

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Climatic factors affecting the occurrence of insect pests

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ABSTRACT

Many abiotic factors affect the distribution and bionomics of rice insect pests. Temperature extremes, water, and wind influence distribution. To a large extent, temperature and photoperiod regulate phenology. In temperate zones, multiple generations develop during warm weather. A few insects *(Agromyza* and *Oulema)* cause more damage at lower temperatures. In tropical areas, heavy rainfall can wash small insects off foliage. Outbreaks of locusts, armyworms, and leaffolders may follow prolonged drought. Outbreaks of *Mythimna separata* occur in ricefields after flooding. Low relative humidity and plant moisture are detrimental to most insects other than aphids, thrips, and mealy bugs. Combinations of climatic factors are known to be related to the occurrence of *Scirpophaga incertulas, Laodelphax striatellus,* and *Tetraneura ulmi.*

Climatic factors affect rice insect pests directly, by limiting or expanding their distribution, growth, reproduction, diapause, and dispersal, and indirectly, through plant mechanisms and natural enemies that regulate insect populations. Applied insecticides may be washed off plants during rainy periods or may degrade under high temperature and high solar radiation. This is not a negligible factor, because when insecticide application has been delayed by rain or when it has rained heavily just after application, stem borer control frequently has failed.

Insect pest outbreaks may be stimulated by the climatic parameters believed to be governed by sunspot frequency. In China, outbreaks of the Oriental migratory locust *Locusta migratoria* in the Hwai-Ho basin were recorded 236 times in the 1,000 yr between 957 and 1956. Although correlations between the periodicity of annual relative sunspot numbers and the outbreaks were weak, 2 population peaks every 10 yr or 5 peaks every 20 yr were quite evident, corresponding roughly to periodic climate variations in certain locations (66).

In Japan, outbreaks of the whitebacked planthopper *Sogatella furcifera,* with or without the brown planthopper *Nilaparvata lugens,* were recorded 111 times in the 1,258 yr between 697 and 1955 (113). In southwestern Japan, outbreaks were more frequent in years with more days of sunshine in June. In Korea, outbreaks of *S. furcifera,* with or without *N. lugens,* were recorded 39 times in the 1,908 yr between 18 and 1923 (92).

The outbreaks in Japan seemed to have no relationship to those in Korea (Mochida, unpubl. data). In all cases, climatic factors in certain areas might be related to the outbreaks, but major climatic factors did not correlate directly.

To analyze climatic effects on pest occurrences, macroclimatic factors in normal years were compared with those in years with pest outbreaks. (The method is based on the same rice varieties, cropping patterns, and crop management.) Biotic changes affected the occurrence of the striped stem borer *Chilo suppressalis* in Japan (40,50) and *N. lugens* in Indonesia (81) much more than did climatic conditions.

Although there are little data, drought may be the most important climatic factor in the tropics; in the temperate zone, temperature or combinations of climatic factors may affect the occurrence of a rice insect pest more than drought.

Single Climatic Factors

Temperature

Rice is grown in areas where mean monthly temperatures across the growing season range from 23.3 to 27.7 °C, within daily minimum temperatures of 15 °C and maximum temperatures of 39 °C (33). These temperatures are well within the favorable range for rice insect pests. Temperature mainly affects distribution, development rate, and phenology of rice pests.

Species distribution is affected by insects' tolerance of temperature extremes at their most sensitive growth stage. Some insects overcome temperature extremes by hibernating or aestivating (Table 1), seeking shelter, or dispersing (Table 2).

At optimum temperatures, accelerated development means more insect generations per crop, and more damage (118).

Phenology — the appearance or absence of pests — is frequently dictated by temperature. An example is early emergence after a mild winter. Temperature changes also trigger the onset and termination of diapause, a physiological dormancy triggered by signals from nature in advance of the actual stress. Overwintering is a direct response to low temperatures.

Low temperature limits the distribution of the yellow stem borer *Scirpophaga incertulas.* Overwintering larvae cannot survive in stubble at temperatures lower than –6.0 °C (54). Adult male and female moths die at 44-48 °C (42). Temperatures during winter (Feb-Apr) were correlated positively with the first moth appearance in light trap catches of the overwintered generation in three prefectures in Japan (38); similar tendencies were observed in other prefectures (r = + 0.8 to 0.98) (39).

Table 1. Rice insect pests that undergo dormancy.

Pest	Reference	
	Hibernation	Aestivation
Diptera		
Agromyza oryzae	59	
Chlorops oryzae	32	
Coleoptera		
Colaspis flavida	98	
Echinocnemus oryzae	117	
Leucopholis irrotata		64
Lissorhoptrus oryzophilus	83, 121	
Oulema oryzae	48	
Lepidoptera		
Chilo suppressalis	24	
Diatraea saccharalis		23
Maliarpha separatella		7
Parnara guttata	84	
Pelopidas mathias	115	
*Scirpophaga incertulas**	39	
Scirpophaga innotata		41
*Sesamia inferens**	69	
Hornoptera		
Laodelphax striatellus	51	
Nephotettix cincticeps	91	
Heteroptera		
Leptocorisa spp.		41, 100
Nezara viridula	53	
Oenalus pugnax		87
Scotinophara lurida	34	
Orthoptera		
Hieroglyhus spp.		28
Locusta spp.		28
Oxya spp.		28
Patanga succincta		28
Schistocerca gregaria		28

*Probably not in larval diapause, but in quiescence.

Table 2. Rice insect pests that disperse over long distances.

Species	Reference
Lepidoptera	
Cnaphalocrocis medinalis	76
Mythimna separata	89
Parnara guttata guttata	85
Spodoptera exempta	97
S. mauritia acronyctoides	99
Hornoptera	
Nilaparvata lugens	53
Rhopalosiphum padi	18
Sogatella furcifera	53
Orthoptera	
Locusta migratoria	90

Ishikura (38) and Fukaya and Nakatsuka (24) reviewed the effects of climate on *C. suppresalis.* Correlations between temperature in May and light trap catches of 1st moth appearance from the overwintered generation in Tokushima, Japan (r = −0.98) and between temperature in July and light trap catches during the 2nd moth appearance from the 1st generation in Hyogo Prefecture, Japan (r = −0.5 to −0.92) were highly negative.

Correlations between temperatures from December to March and in July and 2nd-generation larval rice skipper *Parnara guttata* densities in Nagano Prefecture, Japan, were positive (r = +0.56 to 0.84) (38,107). Second-generation outbreaks were frequent when December to March temperatures were high.

Adult rice stem maggot *Chlorops oryzae* populations of the overwintered generation were correlated positively with March temperatures (r = +0.97), but those of the 2nd generation were correlated negatively with temperatures in August (r = −0.74). Insect numbers increased under the warmer spring temperatures but decreased under high summer temperatures (38,55).

Under low temperatures, frequent outbreaks of the rice leaf miner *Agromyza oryzae* were observed in Tohoku and Hokkaido in northern Japan (38,58).

Kuwayama (58) pointed out that, when lower temperatures occur in summer, severe damage to the rice crop occurs due to higher numbers of rice leaf beetle *Oulema oryzae* eggs and extended adult longevity.

Suenaga (112) pointed out that *S. furcifera* usually occurs in rice growing areas in Japan where average monthly temperatures are 20 °C or higher in July and August; outbreaks were frequent in northern Japan when it was warmer. Mochida (78) pointed out that temperatures in June from 1896 to 1963 were not related to outbreaks of this pest in Kyushu, southwestern Japan.

One important factor in the control of green leafhoppers and tungro virus in South Sulawesi was choosing a planting time when green leafhopper numbers were seasonably low, partially because of low temperatures (70).

The aphid *Rhopalosiphum prunifoliae* was more abundant on upland rice in years with warmer minimum temperatures, especially in July (111).

Rainfall

It is not surprising that those insects that have specialized on rice have also adapted to flooded fields (Table 3).

Rainfall is the ultimate source of water for rice, regardless of whether fields are rainfed or irrigated. The more rainfall, the wetter the environment. Certain rice pests, such as the caseworm *Paraponyx stagnalis* (123), the water weevil *Lissorhoptrus oryzophilus* (37), chironomid midges (14), and whorl maggots *Hydrellia* spp. would die without flooded fields. *Paraponyx* larvae have tracheal gills and die out of water. *Lissorhoptrus* larvae have hooks on their backs which are tubes connected to their tracheal respiratory system. The hooks are inserted into rice roots to tap air sacs. Air sacs shrink in nonflooded fields and the larvae dry up. *Hydrellia* spp. flies are attracted to flooded fields. Pests like *S. incertulas* have evolved the ability to seal off their tunnels (108), allowing them to survive underwater within the stems of deep water rice (10).

Table 3. Rice insect pests that prefer flooded rice fields.

Species	Reference
Diptera	
Chironomid spp.	6, 12, 14
Hydrellia griseola	27
H. philippina	21
Orseolia oryzae	22
Coleoptera	
Dicladispa armigera	60,116
Lissorhoptrus brevirostris	75
L. oryzophilus	37,121
Oryzophagus oryzae	72
Lepidoptera	
Chilo polychrysus	41
Paraponyx stagnalis (=Nymphula depunctalis)	123
Scirpophaga incertulas	47
Homoptera	
Nephotettix virescens	26
Nilaparvata lugens	15,88
Sogatella furcifera	61,86

Heavy rainfall is detrimental to green leafhoppers *Nephotettix* spp. (53). Thrips flourish on upland rice during low rainfall; their feeding injury causes leaves to roll, mimicking the rolled leaves caused by drought stress. The thrips frequently are not noticed. However, heavy rain washes thrips off foliage (Fig. 1). Plants protected from rainfall by plastic cages harbored high thrips numbers.

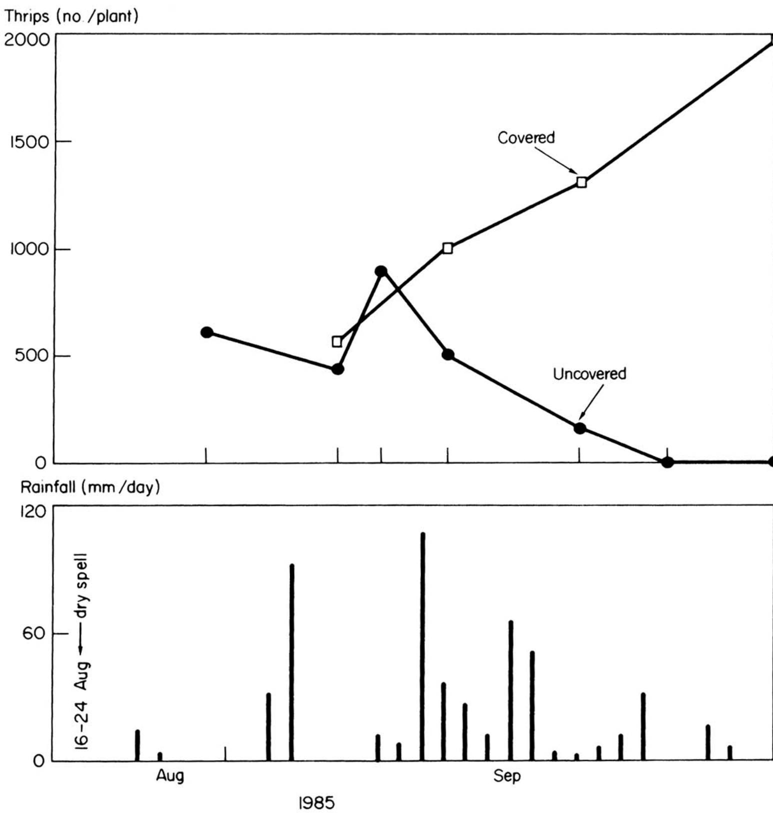
Enormous numbers of egg clusters of *S. incertulas* were destroyed during violent storms by the mechanical force of rain (108).

Rainfall and monthly light trap catches of the adult black bug *Scotinophara coarctata* were correlated negatively in Sabah, East Malaysia (r = −0.39**) (77).

Outbreaks of the armyworm *Mythimna separata* are frequently observed in flooded ricefields in Japan (114).

Heavy rainfall from typhoons may cause resurgence of *N. lugens* (36). A strong typhoon in the Cagayan Valley, northern Philippines, Oct-Nov 1980, flooded about 1,000 ha of single crop, photoperiod-sensitive, traditional rice for several days. The floodwater came like a river current and washed insects and other arthropods away. Ants *Solenopsis geminata* formed large, baseball-size balls of solid nests which floated away with floodwaters. This social behavior ensured the survival of reproductively active ants. The spiders that washed away hit land and formed sheets of webbing over nearby shrubs and grasses.

Two months later, after a 2-generation cycle of planthoppers, 30 ha of rice were hopperburned by *N. lugens* and *S. furcifera.* Large catches were found in light traps, but suction sampling showed low numbers of spiders. Possibly the flood had physically removed the spiders. After the flood subsided, planthoppers immigrated and rapidly increased in numbers under conditions of very low natural enemy pressure.



1. Effect of rainfall on rice thrips. Siniloan, Laguna, 1985 (Barrion and Litsinger, unpubl.).

Nephotettix did not resurge, perhaps because it was less able to disperse and might not have been able to recolonize in sufficient densities to multiply quickly.

This phenomenon may explain some planthopper outbreaks in traditional rice. Pesticides and fertilizers are rarely used on the drought- and flood-prone crops in this part of the Cagayan Valley.

In lowland areas with high rainfall, granular insecticides can be broadcast in the water of flooded fields if the bunds are sufficiently high to retain the water. Broadcast granules have little effect if the water is free-flowing or if the depth is under 5 cm (9).

Relative humidity

The literature is full of reports correlating relative humidity (RH) with insect development, phenology, and survival. Most are based on macro-scale measurements. But other abiotic and biotic phenomena also change with RH, clouding the issue. More experiments are needed to observe development and survival of insects under a range of conditions.

Numerous citations, but only circumstantial evidence, state that *N. lugens* prefers high humidity. One reason cited for the planthopper's meteoric rise to the status of a major pest of rice is the high tillering ability of modern rice varieties, which blocks the air flow through the rice canopy and raises the RH. Recent studies have related the increased pressure of *N. lugens* more to the expansion of irrigation systems, eliminating the dry season fallow (65), and to insecticide resurgence (44). A RH study in the IRRI phytotron showed that *N. lugens* had low survival at 80% RH and, in fact, was more comfortable at 50-60% RH (35). High RHs are favorable for fungal pathogens, which need 12 h of free moisture on the surface of the insect for their spores to grow through membranous tissues into the insect's body. But in more recent studies, RH variations within normal field limits were not critical to population increases (19).

On the other hand, low vapor pressure deficit (VPD) is detrimental to many insects, particularly at the egg stage. Laying eggs on plant surfaces exposes them to desiccation. Some insects insert their eggs into plant tissue to ensure adequate moisture, but this behavior also exposes eggs to the harsh biochemical environment of the plant. An insect whose eggs are particularly sensitive to low VPD is the gall midge *Orseolia oryzae* (93).

Drought

Soil-inhabiting insect pests attack rice only in dry soil. This group includes numerous seed and root pests and stem borers *Elasmopalpus lignosellus* and *Acigona* spp. Seedling maggots *Atherigona* spp. are an exception. Locusts are adapted to dry areas, *Patanga* spp. and *Schistocerca* spp. rarely attack lowland rice.

After favorable rainfall following a long drought, outbreaks of locusts, armyworms, and leaffolders often occur. The drought kills rice and other host plants, which in turn kills the rice insect pests and their natural enemies, creating a vacuum. Once the rains return, grassy weeds flourish in response to the N flush caused by mineralization of organic N in the soil. The insect pests recolonize and multiply under better crop nutrition and in the absence of natural enemies. The natural enemies eventually recolonize and multiply to contain the pests, but not before severe crop damage (Litsinger, unpubl. data).

Although no research is available on the interactions between rice plants and insect pests, drought may affect pests indirectly, through the plant.

Secondary compounds. Antiherbivory in plants has been ascribed to many causes; one is the accumulation of allelochemics (chemicals not needed directly for growth and development) which act as repellents, feeding deterrents, or toxins. The only exception seems to be the condensed tannins, but they have not been reported to be positive insect attractants (30). Under water stress, antibiotic activity due to increased titres of condensed tannins affects herbivore fitness by decreasing survivorship and growth rates or by deterring herbivore grazing (29).

Plant moisture content. Phytophagous insects normally feed on plants with high water content and suffer if their dietary moisture is not relatively high (124). Many researchers have observed that feeding on wilted foliage has adverse effects (46).

The moisture content of plant leaves varies within seasons and researchers believe that low moisture content reduces the suitability of leaves as food for defoliators (20,57,74,106).

The importance of leaf water content and its effects on N utilization by various species of lepidoptera have been shown by Scriber (103,104,105) and Reese and Beck (96).

Plant turgor pressure. The xylem feeders — aphids, scales, and mites — are affected by turgor pressure (109). Plant water status and osmotic pressure effects on aphids were reviewed by Van Emden et a1 (122). There is considerable evidence that aphids are affected by plant-water relationships. Aphids suffer adverse effects on both well-watered and water-deficient host plants. These effects probably are closely connected with the nutritional requirements of aphids. Two mechanisms are involved in plant turgor:

- Lower plant turgor pressure and/or increased sap viscosity reduces food uptake.
- Higher soluble N content in the sap from the reduced protein synthesis and increasing hydrolysis of starch leads to an increase of sucrose in older leaves (25).

The first mechanism is dominant and is detrimental to aphids during continuous severe water stress (45). The second mechanism is dominant and is beneficial during less severe or intermittent water stress (71). The responses of aphids to plant-water status still require clarification but clearly involve different characteristics among aphid species.

Nitrogen. N mobilization by plants in response to water stress stimulates insect growth and abundance. Stress, particularly that caused by drought, can cause complex changes in the quality, distribution, and composition of a plant's N content. Protein synthesis decreases and existing proteins are converted into water-soluble forms (43,94,101), increasing the water-retaining capacity of the plant tissues. Total N content and carbohydrate increase has been observed in drought-stressed plants (5).

The stability of a host plant as food for pests is governed by a complex interaction of factors (106). Total N levels are highest in young leaves, decreasing in older mature foliage (20,74). The quality of foliar N can greatly alter the suitability of plants for herbivores (68). Moisture stress on a host plant, through its impact on N uptake and metabolism, can significantly alter its food quality for herbivorous insects (73).

These *mechanisms* may influence insect numbers:

- Water stress causes the conversion of starch to sugar and the accumulation of high concentrations of proline (62). These biochemicals act as phagostimulants to the green leafhopper *Nephotettix virescens* (82) and grasshoppers (13,63).
- Increased N titres during physiological plant stress due to water shortage or leaf senescence may increase the chances of insect survival (126) and high fecundity of leafhoppers (31,95). An increase in free amino acids and amides, the major sources of dietary N, may favor aphids, scales, and

mealy bugs (8,16). Phloem feeders recognize differences among tissues and focus feeding on high nutrient tissues (16,95). When food plants became a source of N due to random fluctuations of weather, outbreaks of many phytophagous insects occurred (49,126,127,128). The number of defoliators generally decreases with higher levels of N fertilization (67).

Radiation

Suenaga (110) pointed out that outbreaks of *S. furcifera* were frequently observed in southwestern Japan in years when sunshine durations in June were longer than those in normal years.

Kenmore (44) stated that hopperburn from planthoppers accelerates under low incidental radiation. Stylet sheaths produced during feeding block the phloem. During cloudy weather, leaf stomata close and N accumulates in the plant, eventually turning into ammonia. Hopperburn may be the result of ammonia toxicity induced by cloudy weather. High incident radiation and open stomata allow the toxic ammonia to escape. However, his hypothesis should be confirmed experimentally.

Photoperiod

In the temperate zone, photoperiodism controls diapause in many rice insect pests, usually in combination with temperature and host plant condition. Although daylength is seasonally determined at each location, its effect on the occurrence of rice insect pests is combined with temperature (affecting the time of adult appearance in the overwintered generation), cropping patterns, rice varieties, and crop management. Tsuzuki et a1 (121) showed that adult females of *L. oryzophilus* emerging at Nagoya, Japan, (N 35°24') after 29 Jul or under less than 14-14 h 30 min daylength enter reproductive diapause over the winter.

Photoperiodism also affects insect polymorphism. *P. guttata* produced larger eggs in response to longer (14 h) photoperiods. Large eggs overwinter and produce larger larvae in spring (85).

Wind

Wind is a factor in the dispersal of rice insect pests (Table 2). Migratory insects have the advantage of being able to quickly colonize a young rice crop and multiply rapidly before natural enemies can reinvade.

Reviews by Kisimoto and Dyck (53) and Kisimoto (52) describe the migration of *N. lugens* and *S. furcifera.* Their long distance dispersal was confirmed in China (1,2,3,4,11,17,125) and over the East China Sea into Japan (79). In China, adults were collected from airplanes at 300-2500 m altitudes in summer and 100-500 m in autumn; 3.9 *N. lugens* adults/ 1000 m^3 air and *S. furcifera* 1.4 adults/ 1000 m^3 were collected at 1500 m (17). Saxena and Justo (102) detected the movement of hoppers within the Philippine Archipelago.

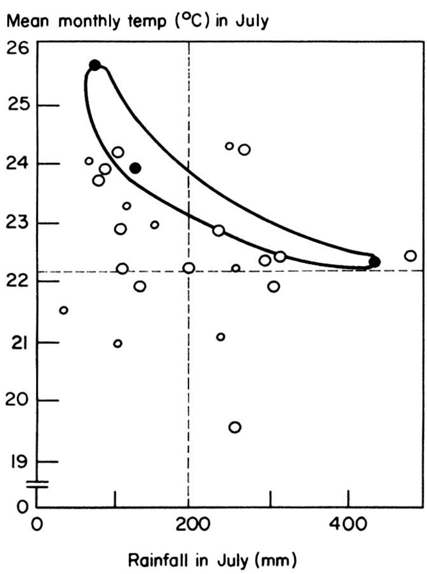
Adults of *S. furcifera* also have been found outside rice-growing areas (80). This means wind is related to the spread of the planthopper. However, there is no report that wind affects hopper outbreaks directly.

Combinations of Climatic Factors

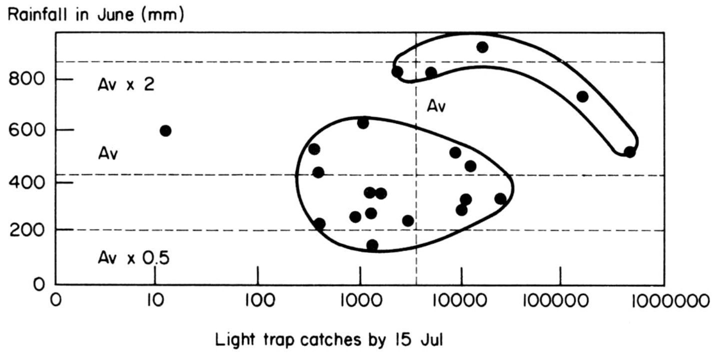
Temperatures between 24 and 29 °C with about 90% RH are ideal for both oviposition and hatching of *S. incertulas* (118). Outbreaks of *S. incertulas* were observed in Zhejiang, China, in 1923, 1925, 1928, and 1929. Tsai (119) compared the climatic factors in those 4 yr to those in 1927. Temperatures in the previous autumn of each of the years were higher, with higher RHs. Previous winters were mild with lower RHs.

Johraku (40) used light trap data to examine factors related to the fluctuation of *C. suppressalis* in Toyama Prefecture, Japan, 1941-66. Light trap catches of adults in the 1st generation were correlated with days when maximum June and July water temperatures in paddy fields were higher than 35 °C (r = −0.986**) and to rainfall (r = +0.772**). Catches were not highly correlated with maximum air temperatures and sunshine durations. He suggested borer populations tended to increase with increased rainfall during egg to larval growth in the 1st generation in June. He also showed that stem borer populations are influenced not only by climatic factors, but also by cultivation practices, early cultivation, use of early-maturing cultivars, early reaping cultivation, and insecticide application. Similar phenomena were suggested by Kiritani (50).

In Akita (North) and Kagoshima (South), Japan, occurrence of *S. furcifera* and *N. lugens* was related to rainfall and early summer temperatures (Fig. 2,3) (78). The frequency of migration of *S. furcifera* and *N. lugens* from China across the East China Sea to Japan may be due to combinations of the frequency of weather fronts, the locations of such fronts, and the presence of massive adult



2. Interactions among occurrence of *S. furcifera,* a rainfall, and temperatures in Akita, Japan, July 1937-62 (78).



3. Interactions among light trap catches of *S. furcifera* in early summer and rainfall in Kagoshima, Japan, 1941-63 (78)

populations of the hoppers on rice in May to July in China (Mochida, unpubl. data).

Cool temperatures with high rainfall might suppress population growth of the smaller brown planthopper *Laodelphax striatellus* in southwestern Japan (78).

In North China, less precipitation and longer sunshine durations in July and August probably were the main factors that stimulated the 1959 autumn outbreak (120). The aphid *Tetraneura ulmi* was more abundant on upland rice in Japan in years that had warmer minimum temperatures and less rainfall from mid-July to mid-September (111).

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Effect of weather on weeds and their control with herbicides

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ABSTRACT

All vegetation is in a continuous state of flux, as individual plants die and are replaced. The rate of change varies with the life span of the species. Apart from this natural fluxuation, a particular vegetative community may be in a state of relative stability or instability that is largely governed by the environment. All plant species are affected by climatic, edaphic, and biotic factors. Even minor changes in these factors may cause important changes in plant associations. In the tropics, adequate moisture in the soil surface, rather than temperature, is the factor that determines weed seed germination. Weeds have higher leaf water potentials than rice, indicating that they have greater root system development. Temperature and moisture before, during, and after application have a great deal to do with the success or failure of a herbicide treatment. For postemergence herbicide applications, weed control is best when prespraying soil moistures and temperatures have favored uniform and rapid growth. Degradation of preemergence herbicides increases with increasing temperature or moisture, or both.

No two vegetation communities are ever exactly alike. The combinations and proportions of the different species in each community differ. The properties of a community depend on the properties of the individual plants growing in it. The vegetation of an area is the result of selection by an environment fluctuating in time and varying in space or of plants arriving there by a fluctuating process of immigration.

Each plant is subjected to the diverse and changing aspects of temperature, moisture, oxygen, and carbon dioxide supply; to the physical and chemical conditions of the soil, and to the interrelationships with other plants and other living organisms. These vary with latitude, altitude, meteorological conditions, topography, and soil characteristics. The effects of such natural forces can be modified to varying degrees by such practices as irrigation, drainage, tillage, and date of planting. However, the major factors of crop production (air, light, temperature, precipitation, and soil) are largely outside human control.

According to Harper (9), the supply of water to an area of land is often the least reliable (in time) of all the resources needed for plant growth. Even in areas of high annual rainfall, rainy days are difficult to predict; even within a rainy season, there is much day-to-day variation. All plant species are affected by climatic, edaphic, and biotic factors. Even minor changes in these factors may cause important changes in plant associations (19).

The availability of moisture after land preparation or planting will greatly influence such factors as crop performance, weed flora, weed intensity, crop-weed competition, and herbicide performance.

Weed Intensity

Roberts and Potter (23), in experiments conducted over a 4-yr period, found that soil disturbance resulted in a flush of weed seedlings, 90% of which appeared within 10 wk after cultivation in early spring and within 3 wk after cultivation in summer. Each year, there was a spring flush of seedlings, probably associated with rising soil temperatures; subsequent flushes were related to the rainfall pattern.

Each year there were periods when lack of soil moisture restricted emergence: this appeared to be the overriding factor determining seedling numbers. When cultivations were followed by long dry periods which prevented germination, the numbers of seedlings appearing when rain fell were no different from the numbers appearing when the soil was disturbed just before rainfall.

In the tropics, moisture may have the greatest influence on weed seed germination and weed emergence. Wiese and Davis (32) reported that more weeds emerged from wet soil than from dry soil. However, the emergence differential was greater at lower temperatures because germination was slower and because soil surface drying occurred shortly after watering ceased. Hoveland and Buchanan (10) found that weed species differed widely in their ability to germinate under simulated drought. Garcia (6) reported that the optimum moisture content for germination of six weed species was at or above saturation. Suzuki et al (30) reported that weed occurrence decreased sharply when the soil moisture content was below 70%. Janiya and Moody (15) found that weed density and weed weight increased linearly with increasing amounts of water applied.

Terasawa et a1 (31) observed differences in the response of two weed species to different soil moisture levels. The vegetative growth of *Digitaria sanguinalis* (L.) Scop. var. *marginata* Fernal. was greatest at 50% of maximum water-holding capacity, that of *Portulaca oleracea* L. was greatest at 25% of maximum water-holding capacity. Growth of *D. sanguinalis* var. *marginata* was greatly depressed at 12% of maximum water-holding capacity. The greatest depression in growth of *P. oleracea* was observed at 100% of maximum water-holding capacity.

Weed Flora

Maiti (1977, cited in [19]) reported that weed vegetation correlates well with such meteorological conditions as temperature, rainfall, and humidity. Hanafiah et al (7) concluded that weed community distribution is determined by variations in such environmental factors as soil, climate, altitude, and cultural techniques. It is common knowledge that certain weed species present in the wet season are absent in the dry season, and vice-versa (19).

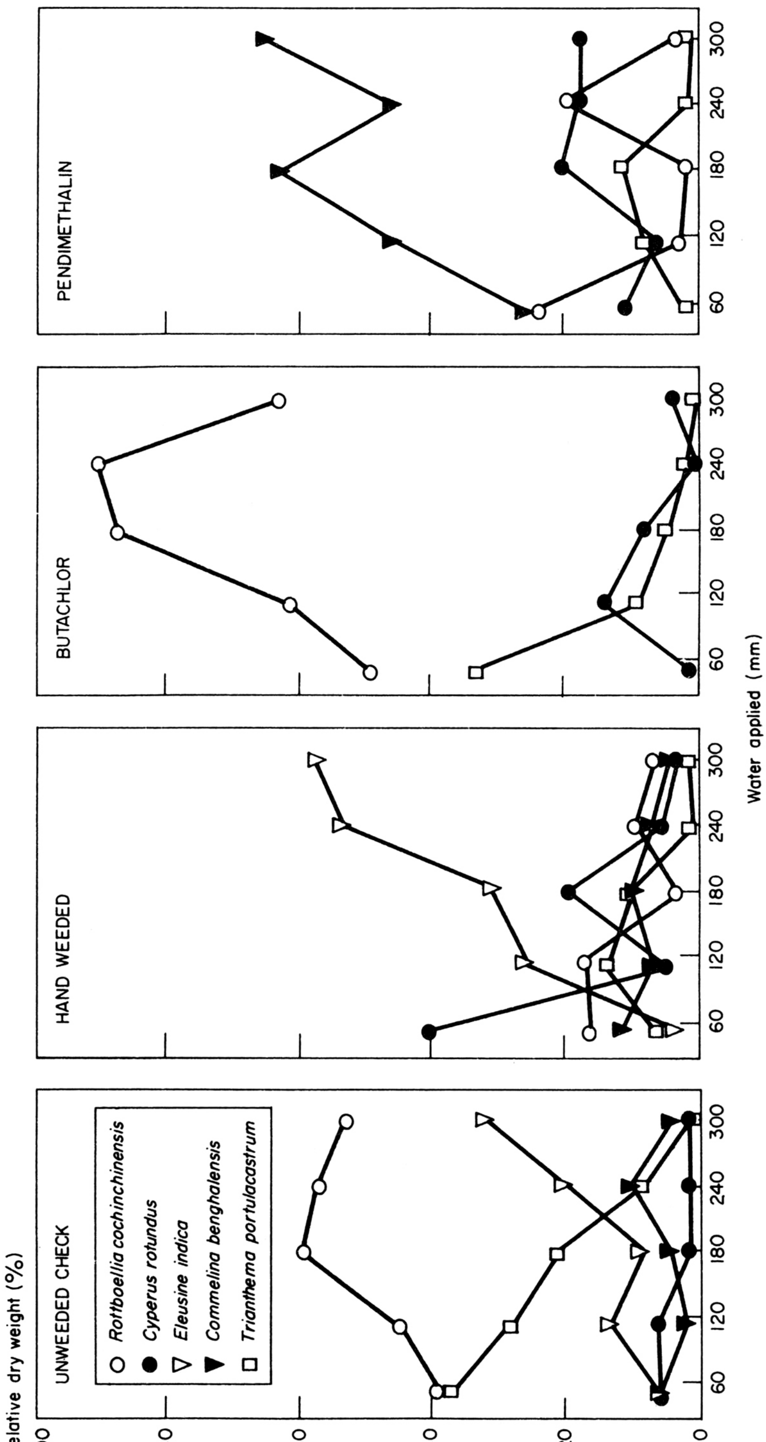
Janiya and Moody (15) used a line source sprinkler system (8) to provide different levels of irrigation to 30 d after emergence (DE). They found that the weed flora was affected by irrigation level and weed control treatment. The relative dry weight (RDW) of *Rottboellia cochinchinensis* (Lour.) W.D. Clayton in unweeded plots ranged from 50 to 60% when 179-298 mm of water was applied, but decreased to about 40% when 50 mm was applied (Fig. 1). The RDW of *Eleusine indica* (L.) Gaertn. increased as amount of water applied increased; *Trianthema portulacastrum* L. showed a corresponding decrease. In pendimethalin-treated plots, the RDW of *Ipomoea triloba* L. decreased. *Commelina benghalensis* L. became a more dominant component of the weed flora with an increase in the amount of water applied. Sankaran and De Datta (27) reported that the density of *R. cochinchinensis* was not influenced by the application of 214-811 mm water, but its weight increased as the amount of water applied increased.

Rice-Weed Competition

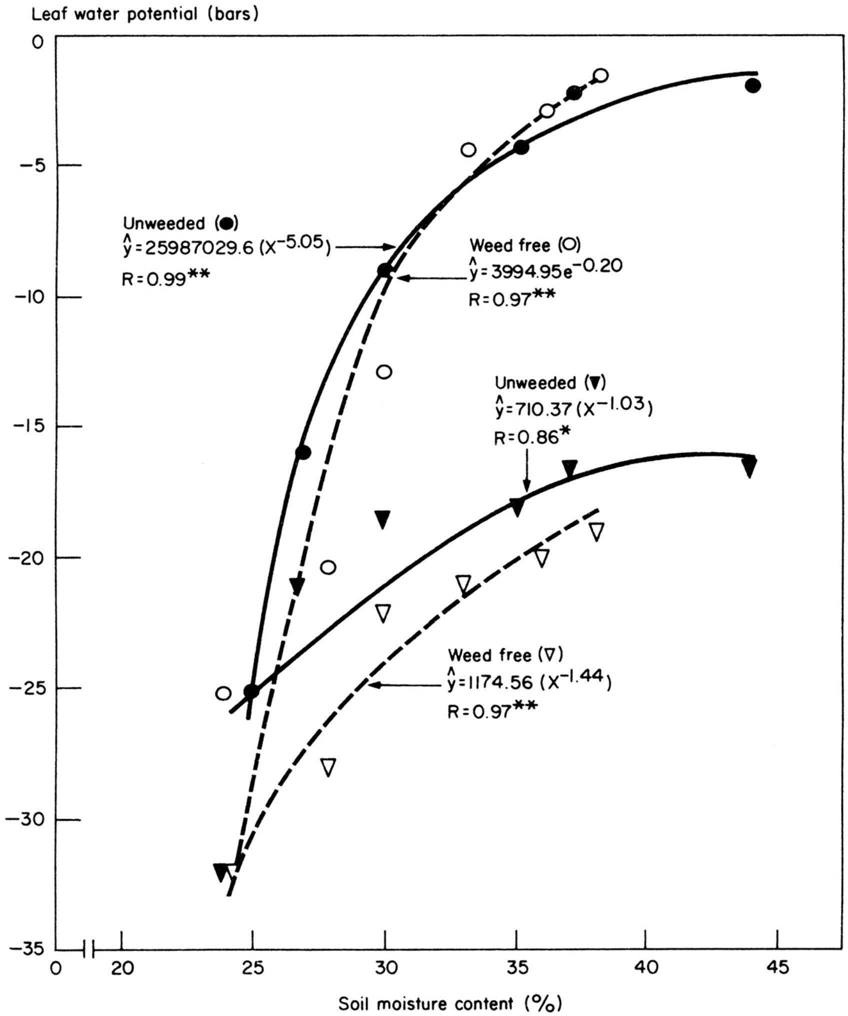
In another experiment, the leaf water potential of rice at 60 DE in both weed-free and unweeded plots was higher at dawn than at midday at all moisture regimes (Fig. 2). Similar observations were reported by Hsiao et a1 (11) and Cruz et al (4). At dawn, the leaf water potential of rice was less than −5 bars at soil moisture contents equal to or greater than 32% in both the presence and absence of weeds. When the soil moisture content was less than 32%, a drastic decline in leaf water potential occurred. There was less than 1 bar difference in leaf water potential between rice in weed-free plots and rice in unweeded plots at soil moisture content equal to or greater than 28%. Greater differences were observed at lower soil moisture contents.

At midday, the leaf water potential of rice was greater than −15 bars in both weed-free and unweeded plots at all moisture regimes. The leaf water potential of rice in unweeded plots was higher than in weed-free plots. The higher leaf water potential of rice in the unweeded plots could be due to a micro-environment that favors water conservation (29) during peak radiation load (22).

E. indica and *R. cochinchinensis,* the two dominant weed species, had higher leaf water potentials than rice at both sampling times (Fig. 3). Reduction in leaf water potential due to water stress was greater in rice than in the weeds. Cruz et a1 (4) also reported that weeds had higher leaf water potentials than rice.



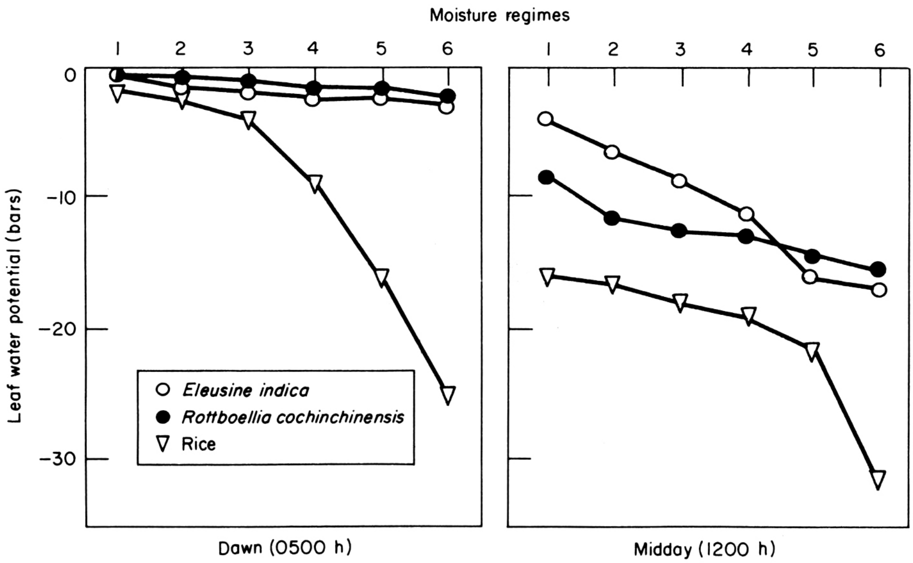
1. Weed flora composition 30 d after rice emergence as affected by amount of water applied and weed control treatment (av of 4 replications).



2. Relationship between soil moisture content and leaf water potential at 60 dafter emergence.

Iwata and Takayanagi (13,14) found that upland weeds had a higher adaptability to low soil moisture content than the associated rice crops.

The higher leaf water potential of weeds in the moisture-stressed plots could be due to deeper root penetration which enabled them to exploit moisture that rice roots were unable to explore. The leaf water potentials of the weeds at midday were higher than those of rice, indicating that the weeds were capable of drawing more water from the soil to maintain higher leaf water status during periods of high water demand. The ability of weeds to maintain a high midday water potential may be due to lower plant resistance to liquid phase water flow (4).



3. Leaf water potential of rice and weeds in unweeded plots at dawn and midday as affected by moisture regime.

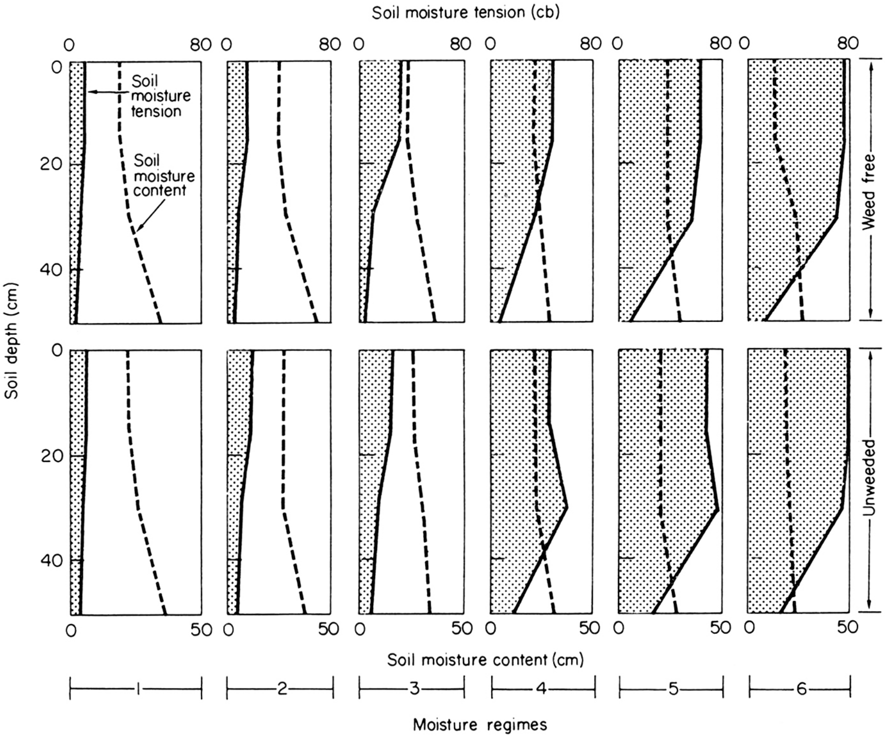
The soil moisture content increased with depth while soil moisture tension decreased with depth in both weeded and unweeded plots (Fig. 4). Soil moisture tension was highest at 15 cm soil depth, regardless of the water regime and the weeding regime. Thus, soil moisture depletion was greatest at this depth.

Soil moisture tension was higher in unweeded than in weed-free plots (Fig. 4). Okafor and De Datta (21) reported similar results. Greater moisture depletion occurred when the total soil moisture content was below field capacity (32% soil moisture content). Cruz et al (3) reported that moisture depletion in ricefields was greater when the soil moisture content was low.

In weed-free plots, soil moisture tension at 50 cm soil depth was lower than in unweeded plots. The greatest water extraction occurred within the top 30 cm of soil. This suggests that most rice roots were confined in this zone. Rose and Stern (24) reported that the maximum water uptake by roots was between the soil surface and 25 cm below the surface and that the rate of withdrawal was relatively low below 30 cm.

In unweeded plots, soil moisture tensions at the 30 and 50 cm soil depths were higher than those in weed-free plots at all moisture regimes. The increase in soil moisture tension at 50 cm soil depth could be due to deeper root penetration by weeds than by rice. Thus, moisture depletion at this depth was greater than in plots kept weed-free. Moisture depletion in unweeded plots was greatest in the top 30 cm, suggesting that competition for moisture was greatest in this zone.

Grain yield of rice when 505 mm water was applied was significantly increased by 1 hand weeding; no further increase in yield was observed by



4. Soil moisture content (- - - -) and soil moisture tension (__) at different soil depths in weed-free and unweeded plots at 60 d after emergence.

Table 1. Effect of weed control method and moisture regime on rice grain yield, IRRI, 1983.[a]

Weed control method	Grain yield (t/ha) at moisture regimes					
	1	2	3	4	5	6
Unweeded check	0.7 b	0.4 b	0.4 a	0.6 a	0.4 a	0.1 a
Weeded once (14 DAE)	1.5 a	0.8 ab	0.8 a	0.4 a	0.5 a	0.1 a
Weeded twice (14 end 35 DAE)	1.7 a	1.3 a	0.8 a	0.7 a	0.6 a	0.2 a
Weed free	1.8 a	1.4 a	1.1 a	1.1 a	0.8 a	0.2 a

[a]Av of 4 replications. In a column, means followed by the same letter are not significantly different at the 5% level. DAE = days after emergence.

additional hand weeding (Table 1). When 456 mm water was applied, 2 hand weedings were needed to significantly increase rice yield. At the other moisture regimes, rice yields were unaffected by weed control. Rice yield decreased, spikelet sterility increased, and 1,000-grain weight decreased with a decrease in soil moisture content in both weed-free and unweeded plots. This suggests that even with good weed control, high yields cannot be obtained without adequate soil moisture. Janiya and Moody (15) and Sankaran and De Datta (27) reported similar results.

Herbicide Performance

It is remarkable that weed control with herbicides is so frequently successful if we consider the great difference in weather conditions under which they are applied (2). Temperature and moisture before, during, and after application have a great deal to do with the success or failure of a herbicide treatment.

With postemergence herbicide applications, weed control is best when soil moistures and temperatures before spraying have favored uniform germination and rapid growth. At the time of spraying, temperature is important in determining the plant response: high temperatures favor more rapid movement of the herbicide into the plant and increase its activity. When the humidity is high at the time of herbicide application and for some days after application, more herbicide penetrates the leaves and more weeds are killed. However, heavy rainfall shortly after herbicide application may wash the chemical off the leaves before it can be taken up, reducing its efficiency.

Rainfall is essential for satisfactory weed control with most soil-applied herbicides. Application on moist or wet soil and adequate moisture through timely rains or irrigation during the first 3-4 wk after application are the conditions that seem to effectively activate preemergence herbicides, giving prolonged weed control with little crop damage (20). Herbicide applications without follow-up rains can result in deactivation and volatilization and complete loss of herbicide effectiveness (18).

Schiller and Indhaphun (28) reported that the efficacy of butachlor applied preemergence depended on soil moisture conditions after application. When the herbicide was applied to dry soil or when dry conditions occurred immediately after application, or both, the effectiveness of the herbicide was markedly reduced. Jikihara and Kimura (16) found that thiobencarb gave excellent herbicidal activity when rain fell soon after application. Herbicidal activity decreased as rainfall was delayed and as soil moisture decreased following application. Janiya and Moody (15) and Sankaran and De Datta (27) also reported that the activity of butachlor and pendimethalin decreased as soil moisture decreased.

Roots will not explore dry soil. The uptake of herbicides active through the root system is encouraged by adequate soil moisture (5). Herbicides are adsorbed more tightly by dry soil and are less available for absorption by weeds (15). Under saturated conditions, water displaces herbicide molecules in the soil solution, resulting in the availability of high herbicide concentrations for plant uptake. When soil moisture is low, the herbicide molecules compete favorably for adsorption sites on the soil colloids, resulting in lower availability to the plant (1). The amount of herbicide actually in solution is much greater in a wet soil than in a relatively dry soil (5).

Sahu (25) reported that the downward movement of butachlor increased with an increase in soil moisture content. While this ensures effective control of susceptible weed species to a greater soil depth, it also increases the susceptibility of emerging crop seedlings to the herbicide (26). Sankaran and De Datta (27) reported that a soil water content above 35% was critical for increased solubility and movement of herbicides.

Hurle and Walker (12) stated that, because adequate water and temperature are essential for most biological and nonbiological processes, rates of herbicide degradation should increase with increasing temperature or moisture or both. Mabbayad et a1 (17) found that the higher the temperature, the faster the dissipation of butachlor in soils maintained at 90% of field capacity. In a loam soil, at 25 °C initial butachlor concentration was reduced to half in 42 d after treatment (DAT), at 35 °C, in 28 DAT, and at 45 °C, in 21 DAT. At an incubation temperature of 35 °C, dissipation of butachlor was fastest when soil moisture was maintained at 90% of field capacity. In a loam soil, the higher the soil moisture content, the faster the dissipation of butachlor.

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Cropping systems

Effect of climatic factors on rice cropping patterns in Bangladesh

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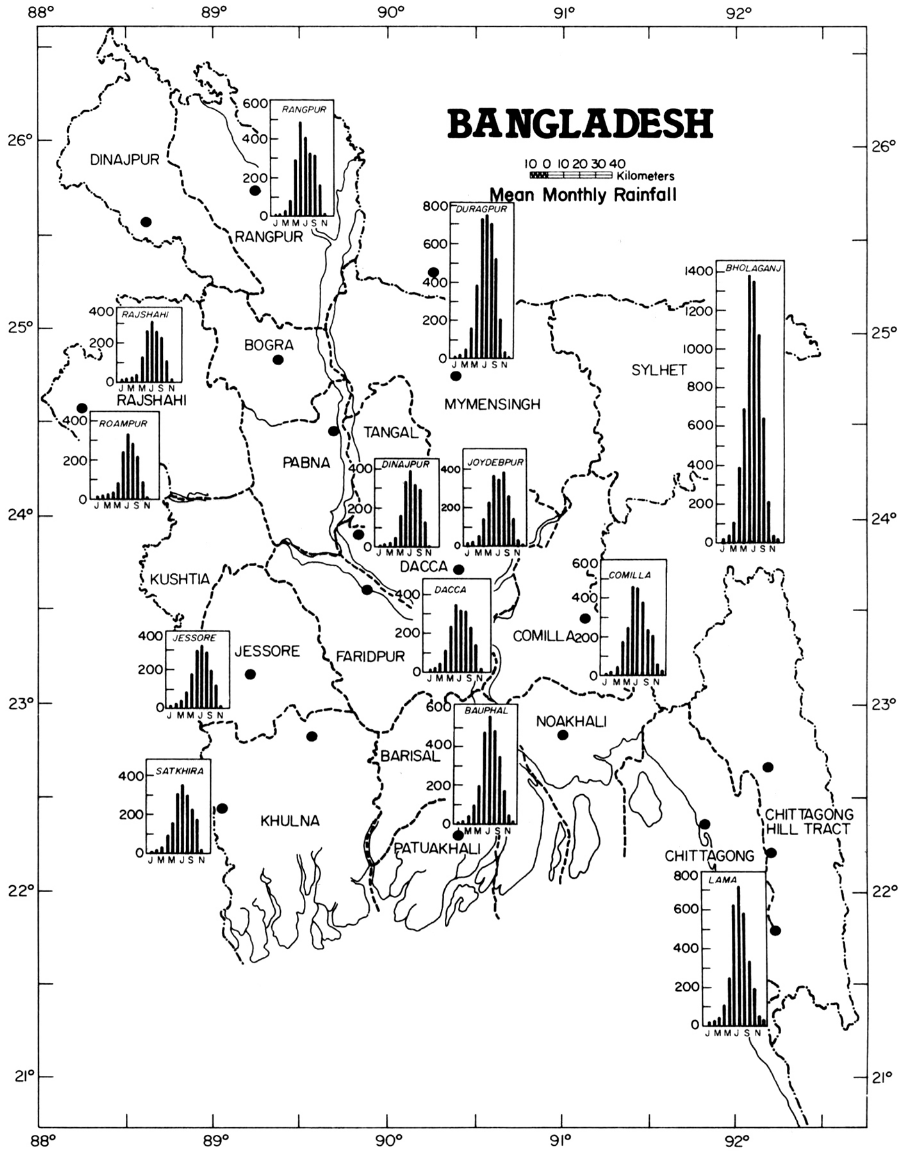
ABSTRACT

Bisected by the Tropic of Cancer, Bangladesh has distinct seasons with fluctuation of temperatures, daylength, and solar radiation. Large river systems cause flooding during the monsoon. Annual rainfall during a single monsoon season ranges from 1,200 to 6,000 mm, winter is dry and cool. Under rainfed conditions, one or two rice crops, and under irrigated conditions, three crops can be grown in a year in the same field. Nonrice crops are grown in combination with rice in sequence or as mixed crops. The result is a large number of cropping patterns. Aus is seeded directly after premonsoon rainfall; transplanted aman follows the aus harvest. Aus suffers from drought and low solar radiation; late planted t. aman suffers from low-temperature damage. Deep water rice (DWR) is seeded in dry fields March-April, inundated May-July, and harvested water-free in November-December. DWR also is transplanted following boro harvest. Boro, mostly grown with irrigation, has a long vegetative phase because of low temperatures, but late planting affects grain yield because of high temperatures. Improved aus-t. aman cropping patterns perform better with higher annual rainfall. Agroclimatic and agroecological zone definitions would help in developing improved technology for rice-based cropping systems.

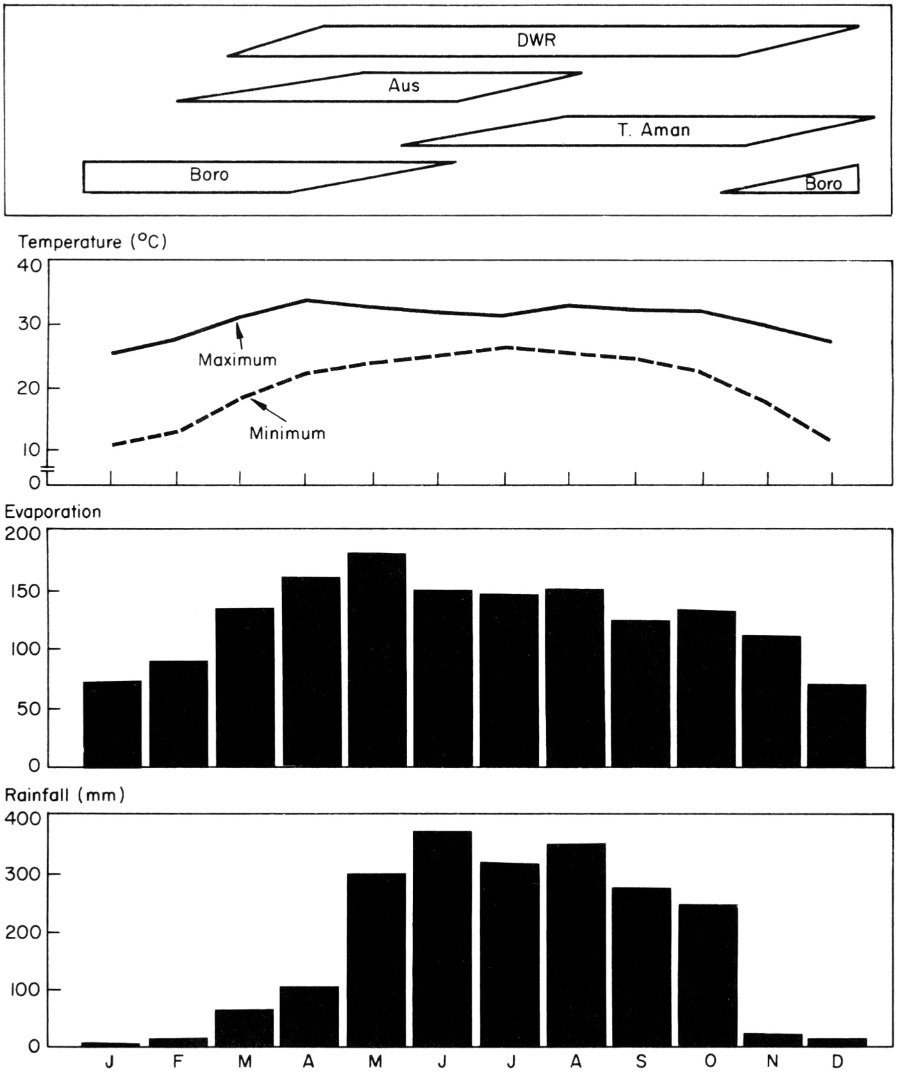
Bangladesh is located within 21.5°N to 26.8°N latitude and 88°E to 92.5°E longitude. Bisected by the Tropic of Cancer, Bangladesh has distinct seasons with wide fluctuations of temperature, daylength, and solar radiation. It has extensive flat alluvial plains with scattered lakes and depressions, hilly areas in the north and eastern part of the country, and a long coast line in the south with variable soils and flooding. The large river systems of the Ganges, the Brahmaputra, the Meghna, and the Teesta, with their innumerable tributaries, cause flooding in adjoining low-lying lands during the monsoon.

Annual rainfall in Bangladesh ranges from about 1,200 mm in the west to more than 6,000 mm in the northeast (Fig. 1). It falls in a single monsoon season from April to October, with 4-7 wet months (> 200 mm/mo). Northeasterly winds bring cool temperatures during November-February, when the weather is mostly dry. Daylength varies from 10.5 h in December to 13.5 h in June (7).



1. Mean monthly rainfall in different regions of Bangladesh (5).

The cropping pattern is mostly rice-based (Fig. 2), except in the northwest where rice is grown alternately with sugarcane in a 2-yr rotation. Rice can be grown throughout the year if irrigation is provided, except when seeded in August-September; then, temperatures from November to early February are cool enough to interrupt reproductive growth (Fig. 3).

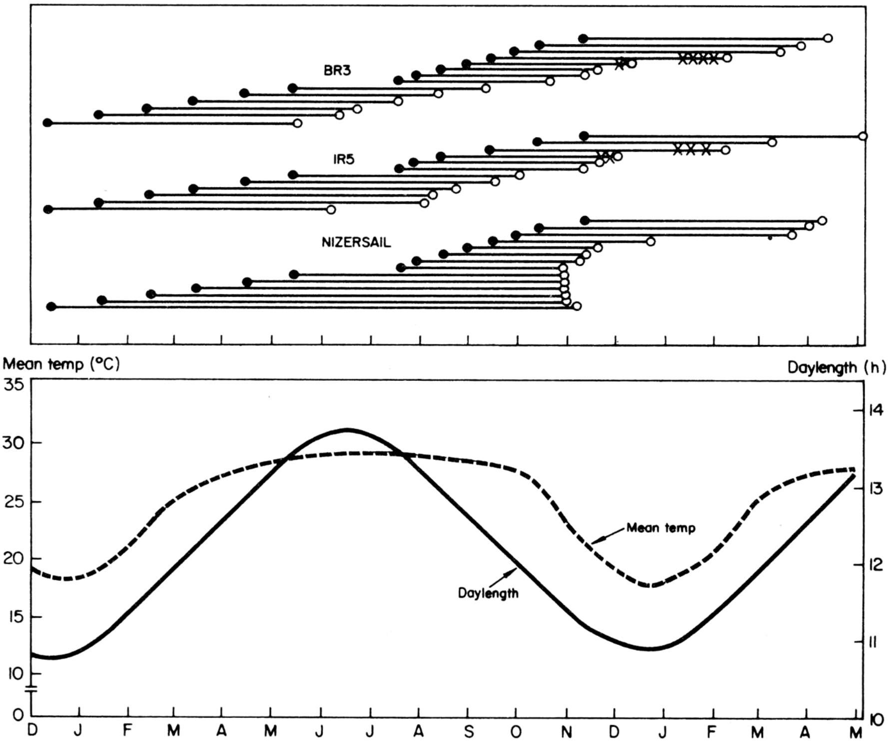


2. Rainfall, evaporation, and maximum and minimum temperature (1975-84 mean) at Joydebpur, and rice cropping pattern in Bangladesh (3).

Major Rice Crops of Bangladesh

Aus rice

Aus rice is grown on 3.0 million ha, mostly as an upland crop direct-seeded March-May with the onset of premonsoon rainfall. Seeding starts earlier in the east than in the west. The crop is harvested from June to September. Traditional varieties are short duration, photoperiod insensitive, and drought tolerant. In

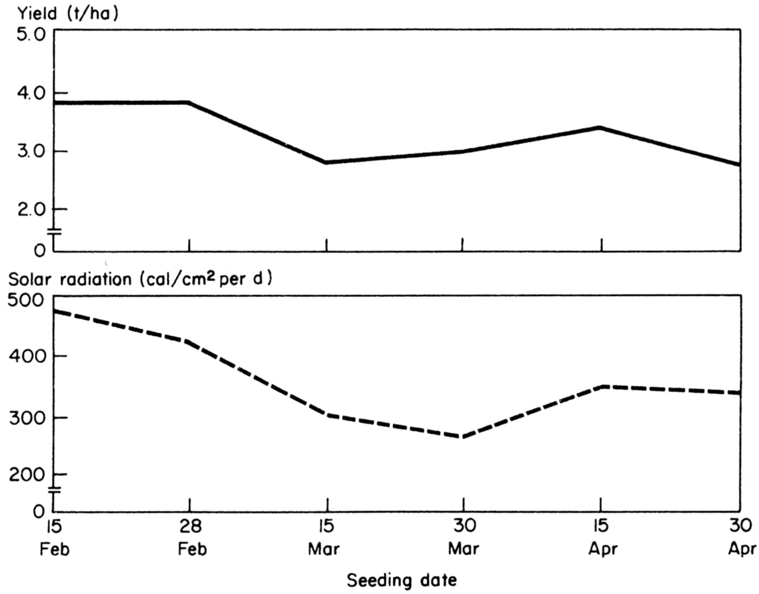


3. Duration from seeding to flowering of three rice varieties grown in Joydebpur (30-d-old transplanted seedlings) (11).

some areas, aus rice is transplanted when late rainfall does not permit timely direct seeding. The entire growth period has high temperatures and the crop suffers from drought at early growing stages and low solar radiation at later growth stages (Fig. 4). The crop also can suffer submergence at ripening due to heavy rainfall (10). Aus rice competes with jute. It also is grown as a mixed crop with deep water rice (DWR) or sesame and chili. Grain yields vary from 1 to 2 t/ha.

Deep water rice

Deep water rice, also called broadcast aman, occupies about 1.8 million ha. Seeding starts in dry fields in March/April. The crop is inundated sometime in May-July, depending on the topography and flooding patterns of a region. The rice plant grows with the rise of the flood, which reaches 2-5 m in August. Floodwater starts to recede in September and the crop is harvested November-December under almost water-free conditions. In many areas, DWR is transplanted after boro harvest. Grain yield of DWR is 1.5-2.5 t/ha.



4. Relationship between solar radiation during flowering (10 d mean) and grain yield at Rajshahi during aus season (6).

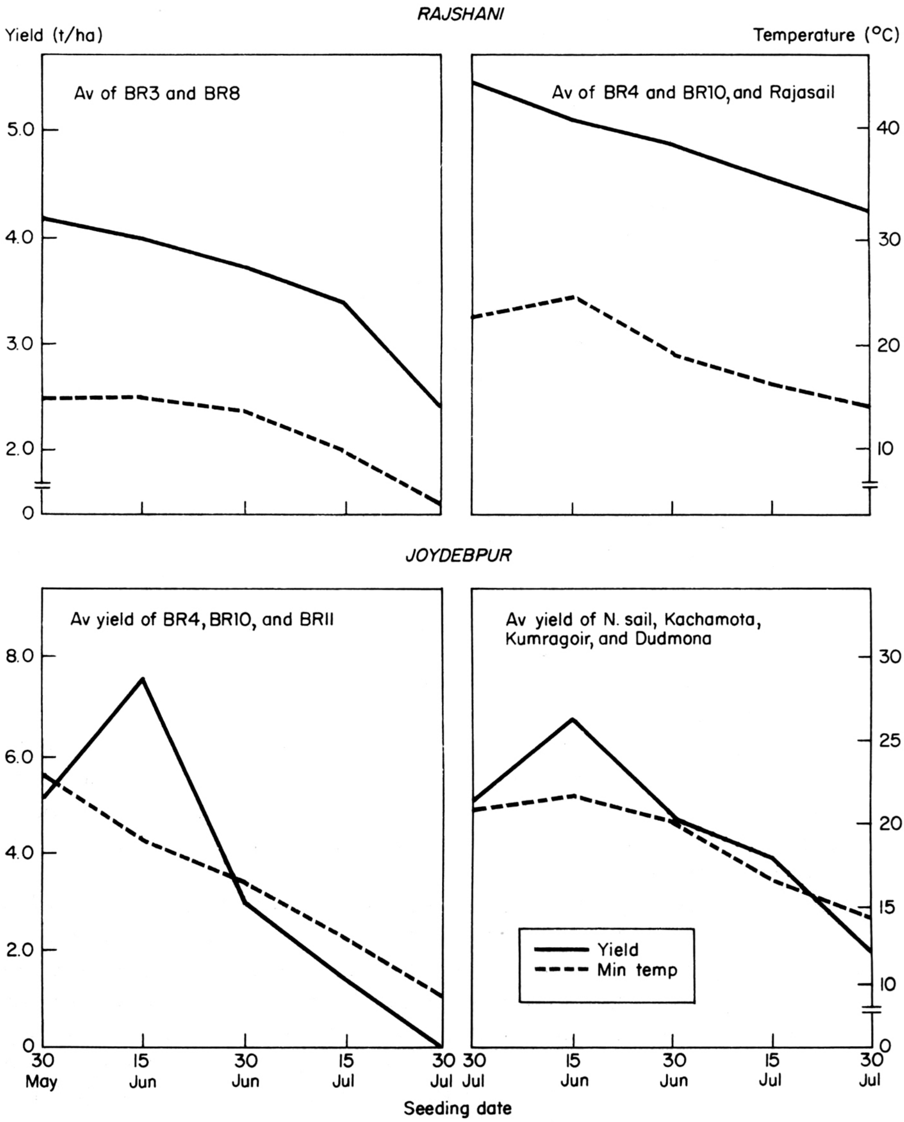
Transplanted aman

T. aman occupies the largest area, 4 million ha. Seeding is in wet seedbeds June-July and transplanting is in July-September. About 25% of the area, where timely planting is assured, is planted to modern varieties (MVs). T. aman is also called lowland rice, because a large area is inundated with about 1 m water; traditional tall varieties are grown there.

In coastal low-lying areas, the crop is inundated by tide once or twice a day during the monsoon. The crop also suffers from flash flood submergence following transplanting. About 40% is transplanted late, resulting in low grain yield (Fig. 5). Under such conditions, traditional photoperiod-sensitive varieties are grown, because they can escape low-temperature damage by timely flowering (Fig. 3). The crop may suffer from drought at later growth stages when October rainfall is insufficient. In the west, the probability of at least 100 mm rainfall in October is only about 50% (8).

Boro rice

Boro, occupying about 1.5 million ha, is grown primarily with irrigation, except for about 15% grown in canal beds, in marshy lands, and along the river slopes. Tall local varieties are transplanted there. The entire irrigated area is covered by high-yielding modern varieties and Pajam. Seeding starts in wet seedbeds in November-December, with transplanting in January-February. It is a long-duration crop with a long vegetative phase because of low temperatures. The crop is harvested April-June. Boro grain yields decrease as seeding time shifts from November to January (Fig. 6), with a gradual decrease in growth duration.

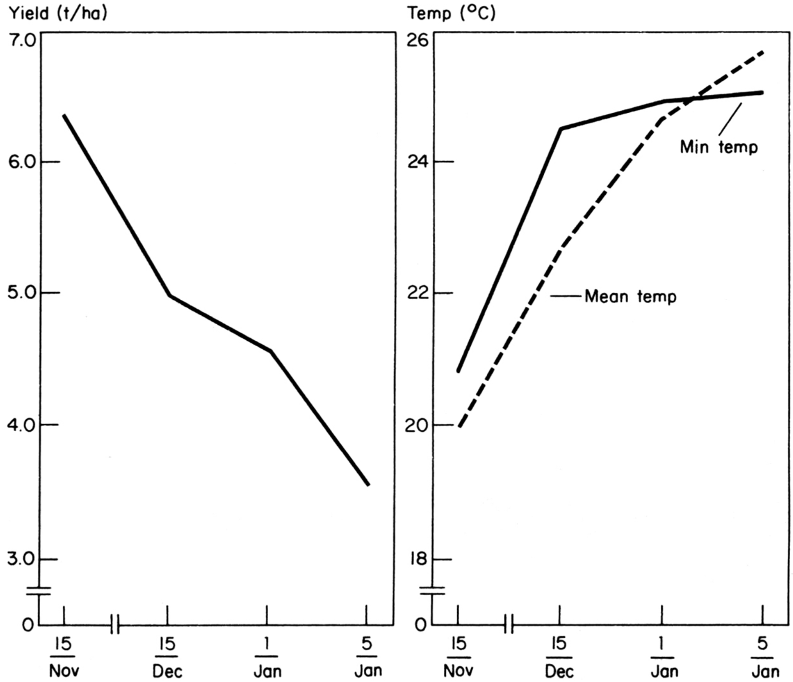


5. Relationship between minimum temperature and grain yeld of t. aman rice (2).

Major Agroclimatic Factors and Rice Cropping Patterns

Aus rice patterns

Rice-based cropping patterns can include one, two, or three rice crops a year. In addition, various other crops can be grown in combination with rice, either in sequence, mixed, or intercropped. The result is a large number of complex and variable cropping patterns (Table 1). However, of 12.5 million ha, 10.2 million ha are occupied by rice.



6. Relationship between mean temperature at vegetative stage, minimum temperature at ripening stage, and grain yield of boro rice (1).

In rainfed areas, direct-seeded aus and DWR cultivation begins with the onset of premonsoon rainfall, March in the northeast to May in the west.

The rice growing season is determined by temperature, daylength, rainfall patterns and associated soil characteristics (moisture-holding capacity), and irrigation. The end of a season is determined partly by cessation of rainfall and partly by the fall of temperature to a critical level (when minimum temperature falls below 20 °C, flowering is seriously affected).

In some areas, soil and hydrological conditions modify the climatically determined length of growing patterns:

- Some Teesta flat plain soils retain moisture throughout the dry season, partly because of a high water table and partly because of unusually high moisture-holding capacities (7). This permits aus seeding before premonsoon rains. Seeding is delayed in soils with low moisture-holding capacity, including the light-textured flooded plain ridge soils and the permeable red-brown terrace soils of Madhupur and Barind, where seeding of aus may not be safe before the end of May.
- The puddled silty or clay topsoils of the gray terrace soils of Barind in the northwest do not have enough moisture-holding capacity for aus to be safely seeded with premonsoon rainfall. On these soils, a single t. aman crop is planted June-July. Within the same rainfall zone, soils and hydrological conditions may prevent rice from being grown at all.

Table 1. Major cropping patterns in regions of Bangladesh (3).[a]

Irrigated			Rainfed		
Boro/Rabi	Aus	T. aman	Boro/Rabi	Aus	T. aman
	Rangpur			*Rangpur*	
Wheat	MV	Pajam	Fallow	LV/Jute	LV
Potato	MV	Local/Pajam	Fallow	LV	MV/Pajam
Wheat/Potato	Jute/MV	LV	Tobacco/ Potato	LV	Pajam
			Sugarcane	-	-
	Thakurgaon (Dinajpur)			*Jamalpur*	
Fallow	MV	MV	Pulse/ Fallow	MV	Pajam/LV
Wheat	Fallow	MV			
MV	Fallow	MV		*Mymensingh*	
Sugarcane	-	-	Fallow	LV	LV/Pajam
	Faridpur		Fallow	LV	MV
MV	Fallow	MV			
Sugarcane	-	-		*Sylhet*	
	Comilla		Fallow	Fallow	LV
MV	Fallow	MV	MV	Fallow	LV
Wheat	MV	MV	Pulse	LV	MV
	Kishorganj			*Gazipur*	
MV	Fallow	MV/Pajam	Fallow	LV	LV/MV
Fallow	Jute	Pajam	Fallow	MV	LV/Pajam
MV	LV	MV	Fallow/Rabi	LV	LV/Pajam
	G. K. Project (Kushtia)			*Chandpur*	
Fallow	MV	MV	Wheat	LV	Pajam
Rabi	MV	MV	Fallow	MV/LV	LV/MV
	Barisal			*Chittagong*	
MV	Fallow	MV	Fallow	LV/MV	LV/Pajam

[a]MV = modern rice varieties, LV = local rice varieties.

Table 2. Yields (t/ha) of photoperiod-sensitive variety/breeding lines under late planting (5).

Variety/breeding line	24 Aug planting		21 Sep planting	
	Flowering data	Yield	Flowering date	Yield
BR534-5-2-1-2-1	12 Nov	4.2	15 Nov	3.6
BR539-17-4-3-3-1	8 Nov	4.8	12 Nov	3.8
BR554-156-1-1-3-1	10 Nov	4.6	17 Nov	3.5
BR555-778-1-1-5-5-1	10 Nov	4.4	18 Nov	3.4
BR716-7-2-1-1	6 Nov	4.9	16 Nov	3.9
BR1141-2B-37	15 Nov	4.9	19 Nov	3.6
BR1196-2B-87	12 Nov	4.2	19 Nov	3.1
BR11(CK)[a]	8 Nov	3.7	25 Nov	0.7
Nizersall (CK)[b]	3 Nov	3.2	10 Nov	2.8

[a]Photoperiod-inrensitive modern t. aman variety. [b]Strongly photoperiod-sensitive t. aman variety.

T. aman patterns

Optimum transplanting is from July in the west to August in the east. Often, timely planting is not possible:

- When the aus harvest is late, t. aman planting is delayed.
- In areas that remain inundated by floodwater after aus or jute harvest, t. aman planting is possible only after floodwaters subside in September.
- A long turnaround time after aus harvest delays planting of t. aman.

Planting time has the maximum impact on t. aman yields. Grain yields decrease abruptly as planting time is shifted from July-August to September; this is caused by low minimum temperatures at the reproductive stage. For timely planting of t. aman, varieties with taller seedling height and reduced turnaround time or technology with zero tillage need to be developed. Yield loss due to late planting can be reduced by using photoperiod-sensitive MVs (Table 2).

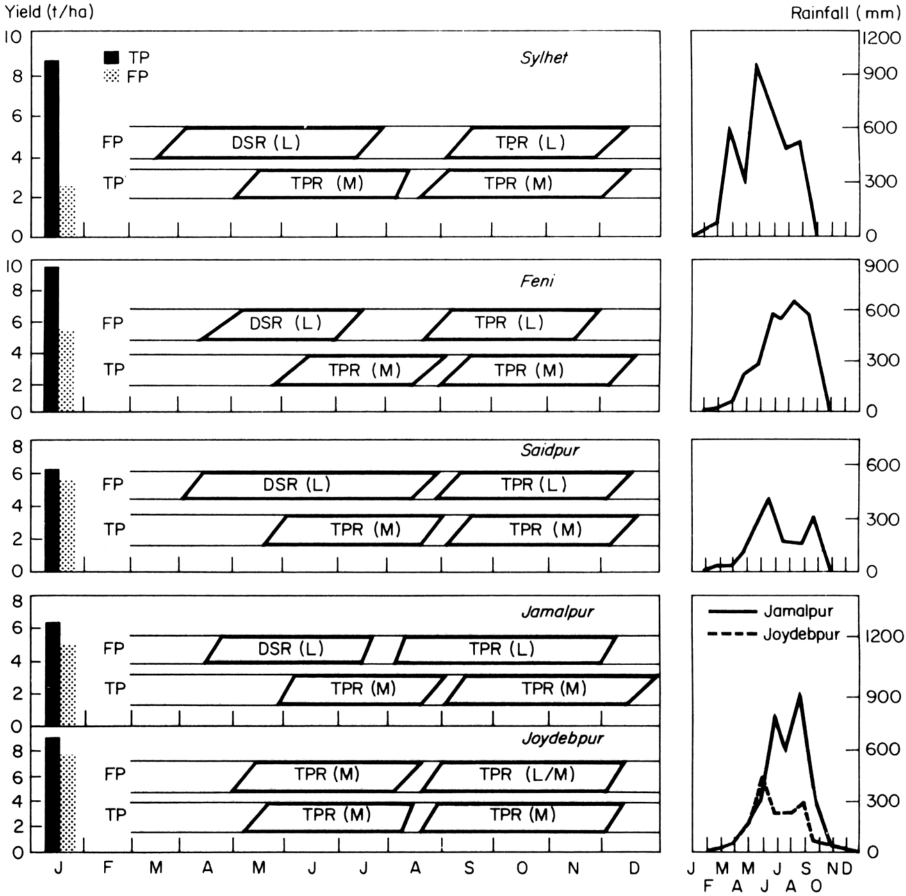
Boro/aman patterns

Under irrigation, a boro - fallow - t. aman cropping pattern is often followed. But in the G.K. project area (Kushtia), a fallow - t. aus - t. aman pattern is mostly followed. In deep water areas, either a single boro or a single DWR or boro followed by transplanted DWR is practiced. Boro yields decrease progressively as seeding time is shifted from November to January. This is caused by high mean temperatures at the vegetative stage and high minimum temperatures at

Table 3. Yield (t/ha) performance of tested cropping patterns compared to farmers' patterns in Bangladesh regions, 1982 (4).

Location	Cropping pattern[a]		Yield	Yield increase over farmers' pattern (%)
Sylhet	TP	BR1-BR4	8.6	260
	TP	BR1-BR10	8.0	235
	TP	BR1-BR11	9.4	295
	FP	Local (DSR)-Local (TPR)	2.4	-
Saidpur	TP	BR1-BR4	6.3	20
	TP	BR1-BR10	6.6	27
	TP	BR1-BR11	6.8	30
	TP	BR1-Nizersail	5.9	13
	FP	Local (DSR)-Local (TPR)	5.2	-
Jamalpur	TP	BR1-BR4	7.3	42
	TP	BR1-BR10	7.6	46
	TP	BR1-Nizersail	7.8	50
	FP	Local (DSR)-Local (TDR)	5.1	-
Joydebpur	TP	BR1-BR4	9.1	40
	TP	BR1-BR10	9.3	41
	TP	BR1-BR11	9.6	46
	TP	BR1-Nizersail	8.4	28
	FP	BR1/BR3-Local	6.6	-
	FP	BR1/BR3-BR4	9.8	-
Feni	TP	BR1-BR4	10.3	89
	TP	BR1-BR10	9.6	80
	TP	BR1-BR11	9.9	81
	TP	BR1-Nizersail	8.2	50
	FP	Local (DSR)-Local (TPR)	5.4	-

[a]TP = rested pattern, FP = farmers' pattern, DSR = direct seeded rice, TPR = transplanted rice.



7. Performance of tested and farmers' rice cropping patterns in regions with variable rainfall (3). TP = tested patterns, FP = farmers' pattern, DSR = direct seeded rice, TPR = transplanted rice.

the ripening stage. Nevertheless, many farmers seed/ transplant late to reduce the amount of irrigation water required.

Performance of improved patterns

Under rainfed conditions, the traditional farmers' pattern is mostly direct seeded aus followed by t. aman, both of local varieties. Modified and improved cropping patterns have been successfully established that replace local varieties with MVs in transplanted aus (Table 3). The improved patterns tested gave average yield increases over farmers' patterns of 22% in Saidpur, 36% in Joydebpur, 44% in Jamalpur, 75% in Feni, and 263% in Sylhet. Improved cropping patterns performed progressively better with higher rainfall (Fig. 7).

Conclusion

In Bangladesh, about 15% of the rice hectarage is under irrigation; any further increase will be rather slow. Improved cropping patterns under rainfed conditions are being emphasized. For this development, agroclimatic zones and agroecological zones related to soils and hydrological regime need to be defined. At the same time, large-scale testing of improved rice cropping patterns in each agroecological zone should be emphasized.

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Characterizing rainfall distributions at IRRI cropping systems research sites in the Philippines

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ABSTRACT

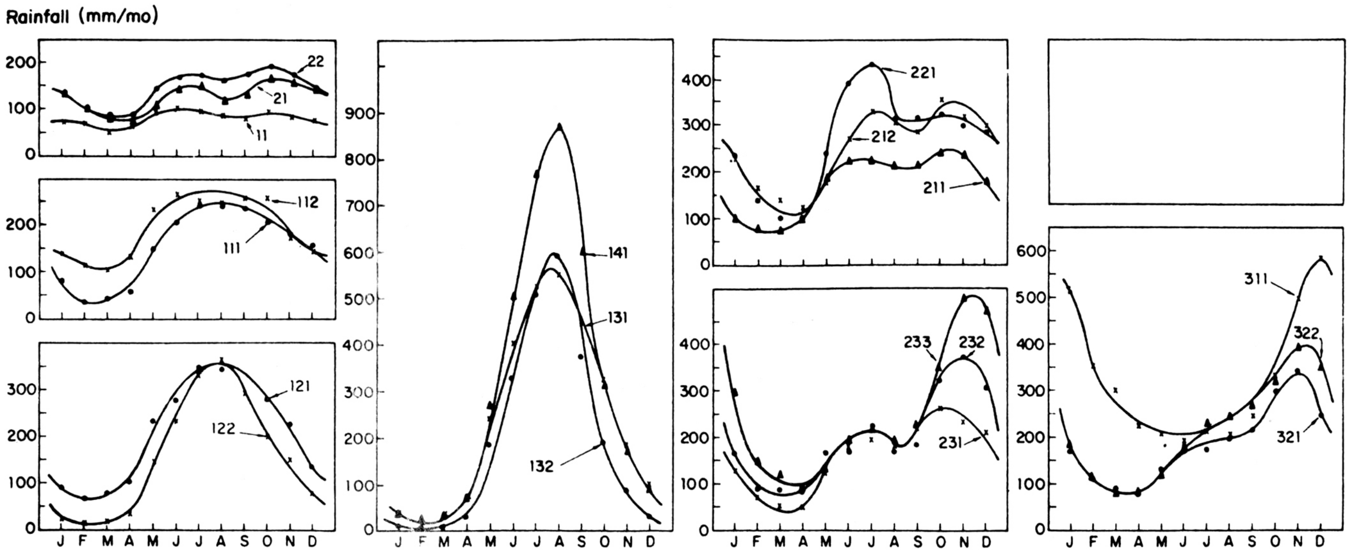
Rainfall, as the sole source of transpiration in rainfed agriculture, also has a profound effect on the suitability of soil conditions for such important field operations as tillage, planting, weed control, and harvesting. Cropping systems scientists at IRRI, during 10 yr experience with rainfed agriculture at 5 research sites in the Philippines, have used several analytical methods to characterize and interpret seasonal distribution, stability, special similarities, and field-suitable conditions for important cultural operations. Monthly rainfall is used in the most widely adopted classification. Evapotranspiration modeling, return period analysis pentad diagrams, and mathematical clusterings have also been used to analyze and characterize rainfall distributions. Although emphasis has been on analytical methods that can be used by scientists in national programs who have limited agrometeorological expertise and who lack access to computers, there is a need to develop more quantitative methods for determining yield stability over years, estimating probabilities of field-suitable conditions, and defining the boundaries of target environments with respect to rainfall and soil terrain features.

Approximately one-fourth of the research in IRRI's Cropping Systems (CS) Program is conducted on-farm, in environments representing extensive rice-growing areas. The CS Program is also linked to national programs through the Asian Rice Farming Systems Network.

Soon after the CS Program was established in 1972, a workshop was convened to develop an agroclimatic classification for evaluating cropping systems potentials in Southeast Asia rice-growing regions (5). The classification system considered rainfall distributions, soils, and terrain. We describe here IRRI's experiences with the rainfall component in five rainfed environments in the Philippines.

Background

Figure 1 shows idealized annual rainfall patterns from a classification of Philippine rainfall patterns (14). Class limits were established with the aid of a



0. Low rainfall, less than 3 mo > 200 mm.
   - 01 (1). Less than 6 mo > 100 mm.
   - 02. 6 or more mo > 100 mm.
     - 021. Less than 6 mo > 150 mm.
     - 022. 6 or more mo > 150 mm.

1. High rainfall, 3 or more months > 200 mm. May-Sep unimodality.
   - 11. 2 or more consecutive months > 200 mm and 0 or 1 > 300 mm.
     - 111. 2 or more months in the dry period (Jan-Apr) < 50 mm.

2. High rainfall, 3 or more months > 200 mm, May-Sep and Oct-Feb bimodality.[a]
   - 21. May-Sep maximum about equal to Oct-Feb maximum.[b]
     - 211. Less than 4 mo > 300 mm.
     - 212.4 or more months > 300 mm.
   - 22 (1). May-Sep maximum greater than Oct-Feb maximum.
   - 23. May-Sep maximum less than Oct-Feb maximum.
     - 231. Weak maximum, less than 3 mo > 300 mm, none > 500 mm.
     - 232. Moderate maximum, 3 or 4 mo > 300 mm, none > 500 mm.

112. 0 or 1 mo in the dry period < 50 mm.
12. 2 or more consecutive months > 300 mm and 0 or 1 > 400 mm.
121. Robust, 6 or more months > 200 mm.
122. Peaked, less than 6 mo > 200 mm.
13. 2 or more consecutive months > 400 mm and 0 or 1 > 650 mm.
131. Robust, 6 or more months > 200 mm.
132. Peaked, less than 6 mo > 200 mm.
14 (1). Two or more consecutive months > 650 mm

233. Strong maximum, 4 or more months > 300 and 1 or more > 500 mm.
3. High rainfall, 3 or more months > 200 mm, Oct-Feb unimodality.
31 (1). 2 or more consecutive months > 400 mm.
32. Less than 2 consecutive months > 400 mm.
321.5 or less months > 200 mm.
322. More than 5 rno > 200 mm.

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[a] A pattern is regarded as bimodal if there are differences of at least 25 mm between both months of maximum monthly rainfall in the May-Sep and Oct-Feb peaks and the lowest rainfall of any intervening month and at least 2 mo between the months of maximum rainfall in the peaks.
[b] A Pattern is regarded as equal if the months of maximum rainfall in the peaks differ by less than 50 mm.

1. Mean monthly rainfall from 19 rainfall classes (data points) and idealized rainfall patterns (curves) corresponding to those data points. Class criteria are below the figures (14).

clustering algorithm applied to the data from 100 stations which had records for 20 or more years. The classes in Figure 1 differ in annual totals, seasonal totals, wet season onset and termination, wet season length, dry season length, and transition rates between seasons. The variation in these rainfall patterns illustrates the agricultural diversity in the Philippines and shows why agricultural scientists are interested in the analysis of rainfall distributions.

Scientists in the CS Program rarely used mathematical clustering and other complex methods to characterize rainfall. Simpler classification methods were adopted because those who would use them would not be trained in agrometeorology, would probably not be quantitatively oriented, and would not have easy access to computers.

The most commonly used classification system simply classifies rainfall patterns on the basis of wet and dry season durations (number of consecutive months with rainfall > 200 mm, number of consecutive months with rainfall < 100 mm). Secondary limits separate out patterns with high wet season rainfall (rainfall in at least 1 mo > 500 mm) and patterns with abrupt wet season onsets (0-1 mo between dry and wet seasons). This is essentially the system developed at the 1974 workshop, based to a large degree on a rainfall classification of Java and Madura by Oldeman (16). All CS research sites have been classified (Table 1). Although these characterizations are inadequate for some purposes, they are useful starting points from which to develop a research plan.

Most crop-weather research (including that used to support crop simulation model development) is aimed at questions related to crop water status, transpiration, and net photosynthesis of fully autotrophic plants. It assumes that a farmer would not plant a crop if its chances of establishment were not high (this implies research in a stable cropping system, not where attempts to change the system are being made). Models that simulate transpiration and growth of autotrophic plants are rather insensitive to a few days of extreme weather, faulty parameter estimation, and erroneous initiation of starting states. Models that simulate evaporation or O_2 depletion from the surface 10 cm are sensitive to small changes in these factors.

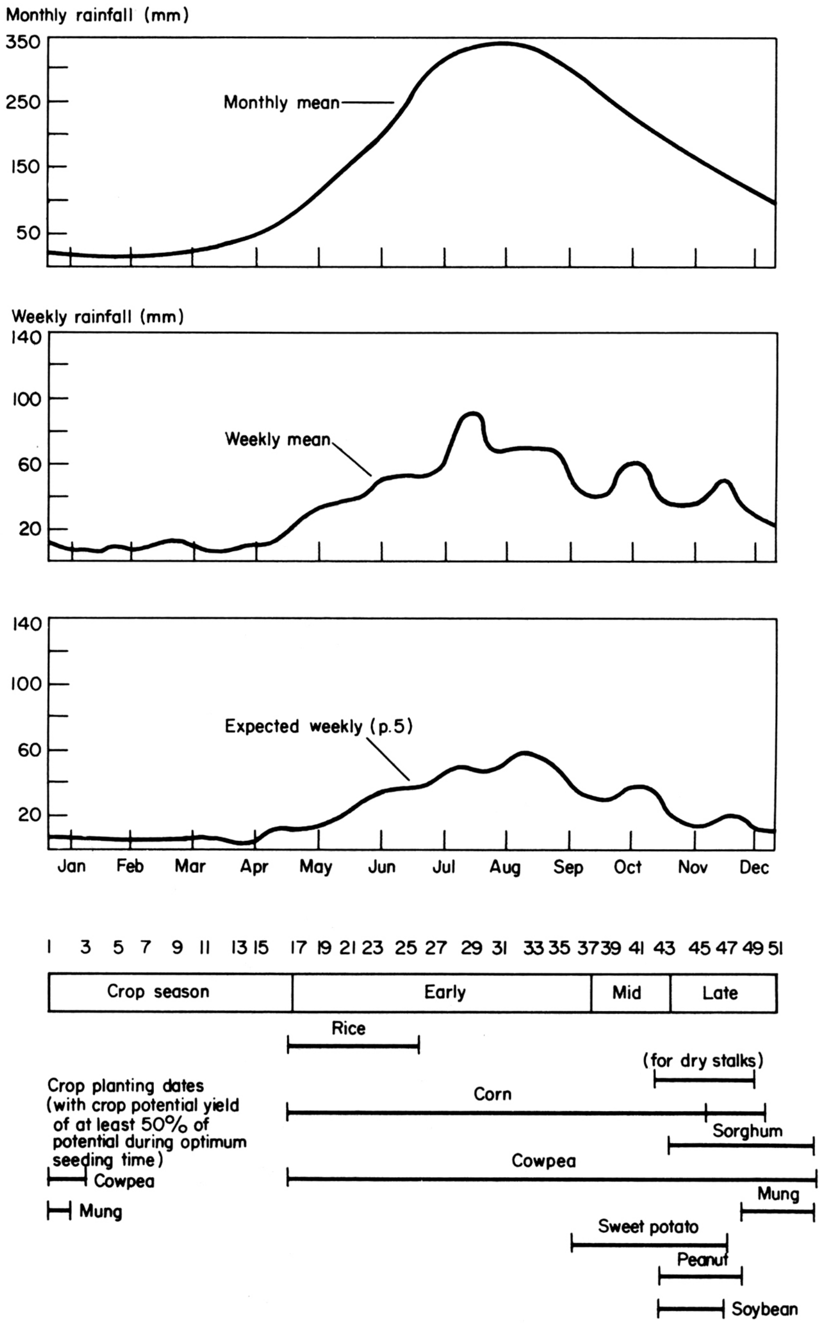
Rainfall does not determine field-suitable conditions directly, but through interactions with soil physical properties and terrain features. Interactions with physical properties of the plow layer determine conditions suitable for field operations (primary and secondary tillage, interrow cultivation, herbicide application). Those interactions also affect crop establishment before roots are sufficiently well developed to draw water from below the plow layer. The lack of methods to characterize field-suitable conditions for key field operations forces research projects to be replicated for several years before scientists can predict the likelihood of conditions suitable for important operations.

The influence of rainfall on field-suitable conditions is a neglected research area and one in which advances will probably not come quickly. Our experiences have shown that examining rainfall during short key intervals, while it provides some insight, has not been satisfactory.

Table 1. Years of research site operation, rainfall patterns, terrain, and traditional rice cultural types in five rainfed environments,

	Tanauan, Batangas	Oton-Tigbauan, Iloilo	Manaoag, Pangasinan	Solana, Cagayan	Claveria, Misamis Oriental
Years of full operation[a]	1973-76	1975-79	1975-79	1980-83	1985-88
Rainfall[b]	5 wet/4 dry	6 wet/4 dry	5 wet/6 dry	5 wet/5 dry	6 wet/2 dry
Terrain	Gentle volcanic slopes	Broad flat marine plains and alluvial-colluvial interhill plains	Broad flat alluvial plains	Alluvial terraces	Gentle to steep volcanic slopes
Traditional rice cultural type	Upland[c]	Favorable rainfed lowland[d]	Favorable rainfed lowland	Drought- and submergence-prone lowland[e]	Upland

[a]Staff from one or more disciplines frequently are retained to continue investigations on topics such as control of specific diseases, comparisons of social organization among farmers operating in different hydroecological strata, or profiles of human nutrition. [b]A wet month is when the long-term mean rainfall total exceeds 200 mm; a dry month is when the total is less than 100 mm. [c]Rice is cultivated on unpuddled and unbunded fields. Rainfall is the only water source. [d]In most years, rainfall is sufficient to cultivate rice without yield being significantly reduced by drought stress. [e]Rainfall patterns and terrain characteristics combine to create an environment in which drought stress is frequent but, on occasion, rainfall is sufficiently intense to submerge the rice crop canopy for more than 4 or 5 d.



2. Water availability and field crop patterns for upland rice farms of eastern Batangas, Philippines (6).

Table 2. Potential yields of field crops using the best available crop technology for upland rice farms in eastern Batangas, Philippines. Estimated from the highest recorded yields of research trials and farmer-managed trials, 1974-75 (6).

	Yield (t/ha)		
	Potential		Actual
	Research-managed	Farmer-managed	Farmer-managed
Upland rice	4.6	4.0	1.9
Maize	4.1	3.7	2.8
Sorghum	4.2	4.2	3.1
Mungbean	1.5	1.0	0.5
Sweet potato	15.0	12.0	9.3
Peanut	1.0	0.9	0.9
Soybean	1.1	1.1	0.6

Batangas

The Batangas research site was selected because it is in an upland area where IRRI researchers believed that traditional rices could be replaced by improved rices and because the location is not far from Los Baños. Because Batangas was IRRl's first full scale on-farm CS research site, frequent visits to the site to refine on-farm research methods were anticipated. As is generally the case in upland areas, soils were well drained, friable, and could be worked within 1 or 2 d after a heavy rain. Also, the moisture range for tillage was wider than for clayey lowland soils. The main interest in rainfall was as a source of transpiration water.

In Batangas, seasonal rainfall rises abruptly, peaks in July or August, and tapers off as the wet season terminates. Weekly medians were used for many planning purposes (Fig. 2).

In 1974-75, a typical farmer's rice yield with traditional technology was 1.9 t/ha, maize yield was 2.8 t/ha, and mungbean yield was 0.5 t/ha (Table 2). There was scope for yield increases.

Rainfall simulations and crop water balance modeling were used to determine the number of stress weeks per season (19). A rainfall simulator, based on an incomplete gamma distribution, generated weekly rainfall predictions. The number of stress weeks, computed from a water balance model, was used to estimate grain production. Table 3 shows estimated yields of upland rice and four legumes for simulated unfavorable conditions (random rainfall, zero inputs) and favorable conditions (average rainfall, high inputs). This and other analyses suggest that yields would be much higher if average rainfall were assumed and high inputs were used, but that yields would decline substantially when unfavorable weather occurred.

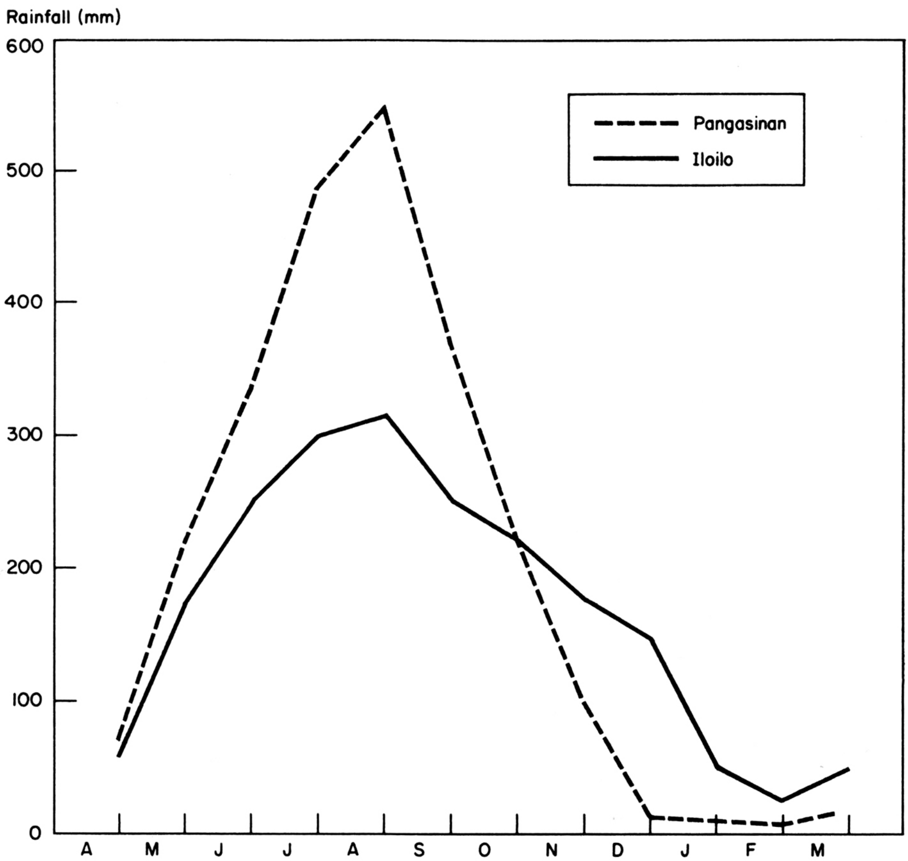
Pangasinan and Iloilo

Research at Pangasinan and Iloilo sites started in 1975. The Pangasinan rainfall pattern is representative of the major rice growing areas of northern Central

Table 3. Simulated yields, favorable vs unfavorable conditions (t/ha) (19).

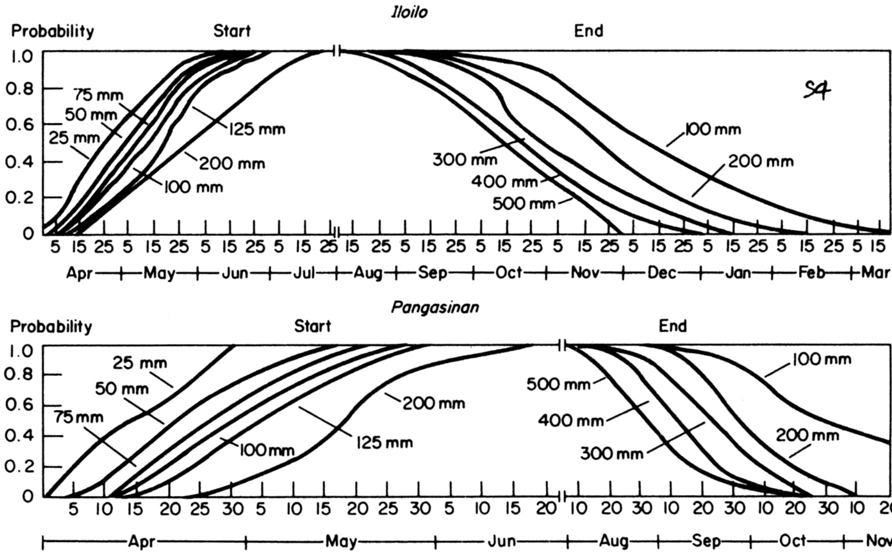
Crop	Yield (t/ha)	
	Unfavorable[a]	Favorable[b]
Upland rice	1.53	4.23
Mungbean	0.66	1.44
Cowpea	0.88	1.92
Peanut	0.99	3.33
Soybean	1.07	2.42

[a]Random rainfall, zero inputs. [b]Average rainfall, high Inputs.



3. Long-term mean monthly rainfall for Dagupan, Pangasinan, and Tigbauan, Iloilo.

Luzon: rains start rather abruptly in May or June, peak in July or August (with a monthly total exceeding 500 mm in at least 1 mo), and terminate rather abruptly in October or November. The Iloilo rainfall pattern is representative of the major rice-growing areas of south central Panay: rains start in May or June, peak in July or August (but rainfall does not normally exceed 500 mm in any



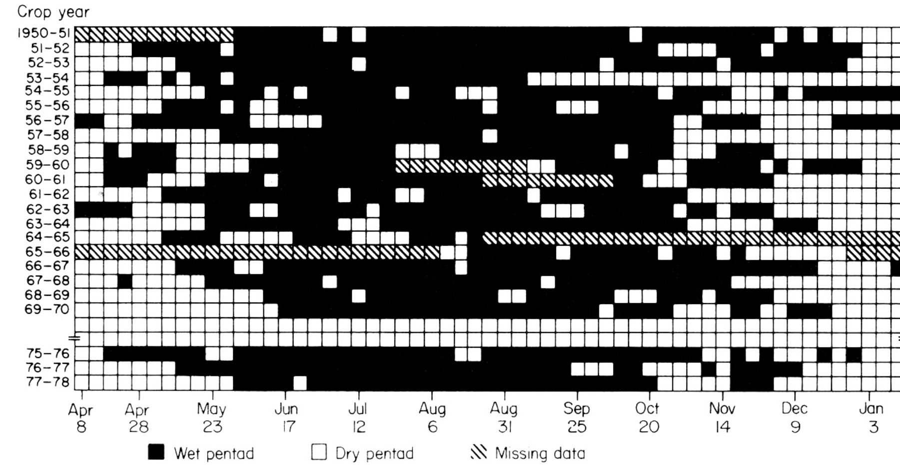
4. Cumulative probabilities of having received a given amount of rain on a certain date (start) and of still receiving a certain amount of rain after a given date (end) for the Iloilo and Pangasinan rainy seasons (Tigbauan, Iloilo, rainfall records 1950-70; Dagupan, Pangasinan, rainfall records 1949-70) (15).

Table 4. Total days available for first and second rainfed rice crops (15).

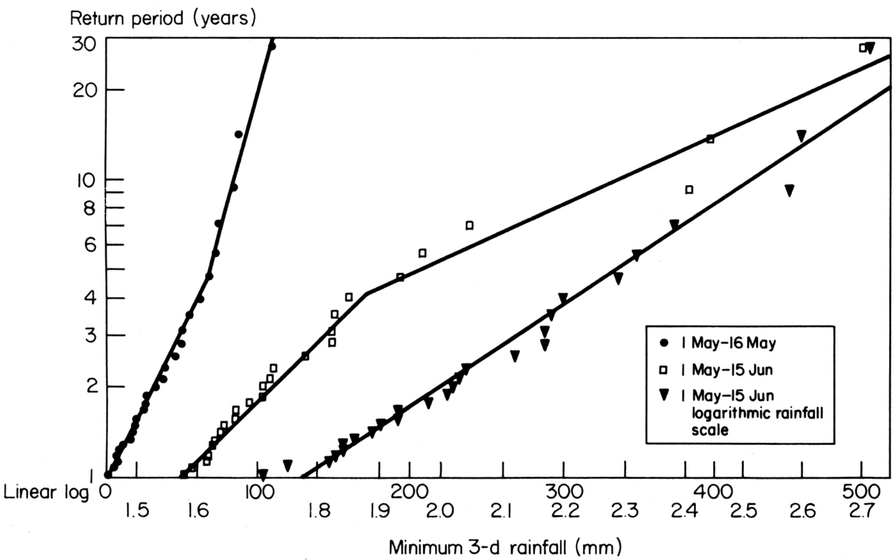
Location	Probability	Expected date of 75 mm accumulation	Expected date of 100 mm remaining rainfail	Days (no.) available for two crops
Pangasinan	0.8	11 May	4 Oct	146
Pangasinan	0.5	27 Apr	28 Oct	184
Iloilo	0.8	25 May	12 Nov	171
Iloilo	0.5	9 May	10 Dec	205

month), and terminate gradually between October and January (Fig. 3). These rainfall patterns served as the starting points for field research.

As scientists attempted to increase cropping intensity by starting crops earlier in the wet season and extending them later in the dry season, questions arose about rainfall reliability, especially at the start and end of the wet season. At both research sites, early wet season rainfall was an important consideration because rice crops were to be planted as early as possible so that time remained for a second rice crop or an upland crop. To obtain a clearer picture of wet season starting and ending probabilities, cumulative rainfall distributions were plotted (Fig. 4). Probabilities for having received a selected amount (start) and of still receiving a selected amount (end) of rainfall on a given date were determined. These probabilities also permitted estimating the number of days available for sequential rice crops (Table 4).

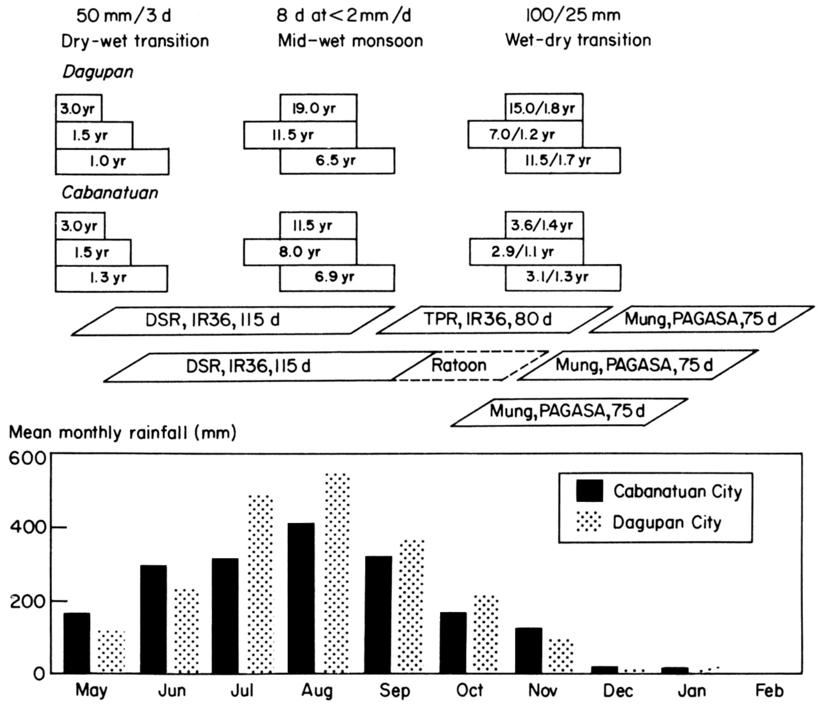


5. Wet and dry pentads (5-d periods) for crop years 1950-51 to 1969-70 and 1975-76 to 1977-78, Tigbauan, Iloilo, Philippines (7).



6. Return periods for maximum 3-d rainfall totals from 1 May to 16 May and from 1 May to 15 Jun. A logarithmic transformation was applied to 1 May to 15 Jun rainfall. Dagupan, Philippines (13).

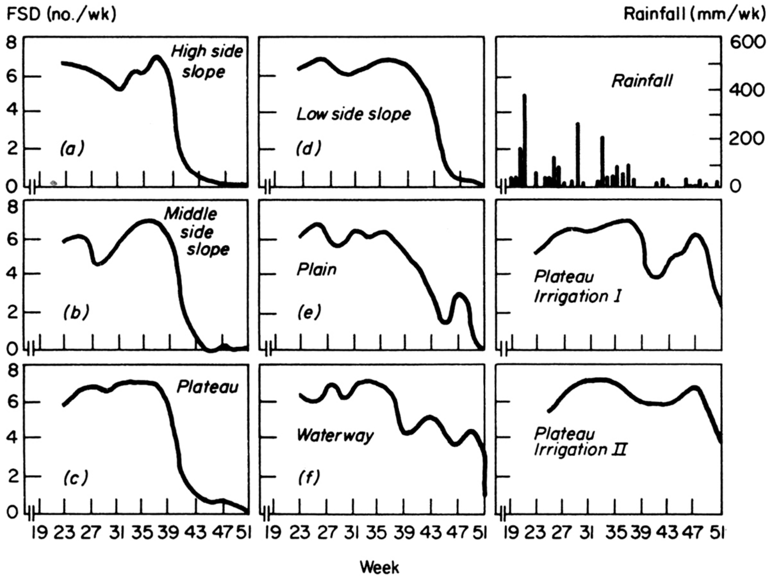
Pentad (5 d) diagrams are another way to examine the reliability of rainfall patterns (Fig. 5). These diagrams reveal starting and ending variability as well as midseason reliability. A pentad diagram is sensitive to criteria used to classify a 5d period as wet or dry. To interpret the diagrams, an understanding of the implications of pentad criteria is necessary and field experience is helpful.



7. Crop varieties and field durations, dry-wet and wet-dry monsoon transition rainfall criteria and return periods, mid-wet monsoon consecutive dry day criteria and return periods, and mean monthly rainfall for Dagupan and Cabanatuan, Philippines (13).

As an additional analytical tool for the Pangasinan project, return period diagrams were constructed. Pangasinan has an abrupt wet season start, making timing of crop establishment critical. Better quantification of significant rainfall events during the wet season onset (dry-wet transition) and termination (wet-dry transition) was sought. Figure 6 is a return period diagram of 3d rainfall totals for selected early wet season intervals. Figure 7 shows cropping periods and return periods for dry-wet and wet-dry monsoon transition criteria. The 50 mm/ 3 d criterion during the wet-dry transition was regarded as an indicator of when field operations could be performed (sufficient water in the plow layer for tillage and planting). The 100 mm/3 d criterion was regarded as an indicator of temporary waterlogging damage to recently planted grain legumes.

It became evident that terrain features in Pangasinan and Iloilo greatly modified the water available for transpiration and field-suitable conditions. Figure 8 illustrates the effect of terrain on mean number of flooded days per week during 1976. Statistical analyses showed that late in the wet season, terrain and soil texture were the most important factors influencing differences among fields (12). Early in the season, before sufficient rainfall accumulated to recharge the profiles of medium-textured soils at the Iloilo site, soil texture was important. Depth to water table was important in Pangasinan. In the middle of



8. Weekly total rainfall and estimated flooded status day (FSD = days with measurable standing water) regimes for eight heavy-textured rainfed and irrigated Iloilo land units, weeks 19-51, 1976 (15).

Table 5. Average yields of single- and double-cropped rainfed rice, Pangasinan and Iloilo cropping systems sites, crop year 1977-78 (15).

Crop year	Yield (t/ha)			
	Pangasinan		Iloilo	
	Single	Double	Single	Double
1976-77	3.3	4.7 + 2.8	5.3	5.3 + 3.4
1977-78	3.7	5.1 + 1.9	4.8	5.9 + 1.6

the season, rainfall was sufficient to cancel any effects terrain or soils had on run-on, runoff, or percolation.

Table 5 compares rice yields for 2 yr in Pangasinan and Iloilo. In Iloilo, the 1977-78 season was short, well below the expected duration (Table 6). The shortness of the season accounted for the lower percentage of double-cropped fields and the lower yields of those that were double-cropped. Table 7 illustrates the effect of terrain on frequency of double-cropping and on second crop grain yields. First crop yields were only slightly affected.

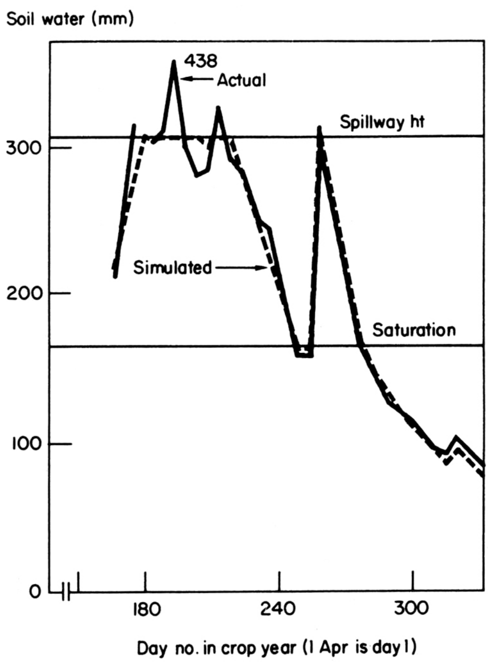
Rainfall reliability for the second rice crop in Iloilo was examined by crop simulation (1,2). The two major terrains on which rice was grown were considered. The model used 1977-79 crop growth and soil water data. Figure 9 shows actual and simulated available water (including standing water) for a

Table 6. Growing season duration for Pangasinan and Iloilo (75 mm rain for onset and 100 mm rain for termination) crop years 1976-77 and 1977-78 (15).

Crop year	Duration (d)	
	Pangasinan	Iloilo
1976-77	173	225
1977-78	171	151
Expected (median)	160	185

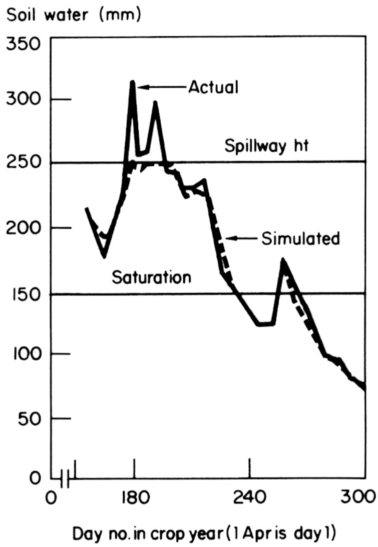
Table 7. Average yields of single- and double-cropped rice for Iloilo, by landscape position crop years 1976-77 and 1977-78 (15).

Crop year	Yield (t/ha)					
	Side slope		Plateau		Plain and waterways	
	Single	Double	Single	Double	Single	Double
1976-77	5.1	5.0 + 1.7	5.2	5.3 + 2.3	4.4	5.5 + 3.4
1977-78	4.6	6.9 + 1.0	5.2	5.8 + 0	4.5	5.8 + 1.8



9. Actual and simulated soil water balance for the plain position from 10 Sep 1978 to 9 Feb 1979, Iloilo, Philippines (8).

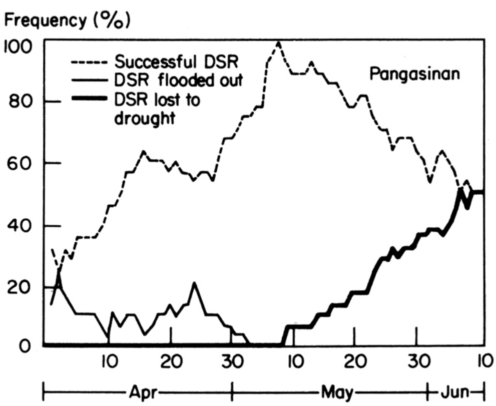
second crop on a plain. Figure 10 shows the corresponding results for a plateau. The model was used to predict second rice crop yields for two earlier years (Table 8). The model also was used to establish the dates by which the second crop should have been planted to obtain target yields with selected probabilities.



10. Actual and simulated soil water balance for the plateau position from 4 Sep 1978 to 31 Jan 1979, Iloilo, Philippines (8).

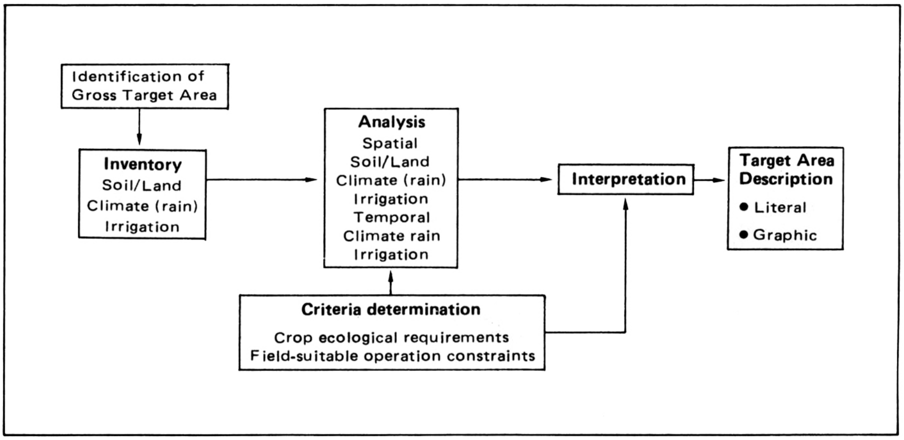
Table 8. Simulated and actual yields of the second rainfed rice crop at Oton-Tigbauan, Iloilo, Philippines, 1975 and 1976 (8).

Landscape position	Planting date	Planting method	Yield (t/ha)	
			Simulated	Actual
Plateau	15 Oct 1975	Wet seeded	0.3	0.5
Plateau	13 Sep 1976	Transplanted	3.3	3.4
Plateau	21 Sep 1976	Wet seeded	1.2	1.9
Plain	15 Sep 1976	Wet seeded	2.9	3.2



11. Frequency of success, loss to drought, and loss to flooding of dry-seeded rice (DSR) for seeding dates from 1 Apr to 9 Jun in Pangasinan, Philippines, based on simulation of DSR germination, emergence, and early survival over 28 yr (20).

The crop simulation model also was used in the Pangasinan project to assess the reliability of rainfall for early direct seeded rice (DSR). Figure 11 shows that the probability of a DSR crop being successfully grown will be greatest if it is sown in early May.



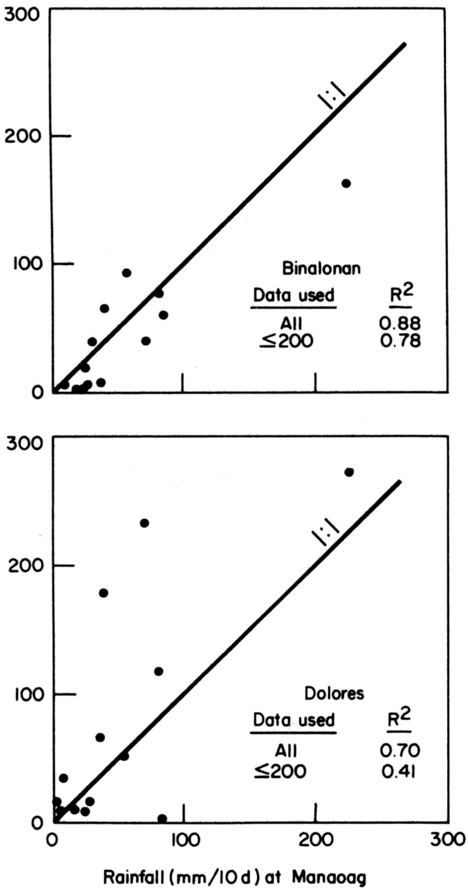
12. A routine for defining target areas for cropping systems projects (11).

The Pangasinan and Iloilo research sites represent the important rainfall patterns for areas of Southeast Asia where rice is a common crop. They also were selected because they represent two large rice-growing regions of the Philippines. Secondary data were analyzed to determine how far from the research sites similar rainfall patterns, soils, and terrain features occurred. The sequence of steps followed is outlined in Figure 12.

To determine spatial similarities in rainfall patterns, data from other stations in the target area were regressed on rainfall at the research sites for as many years as records existed. Regressions were limited to sequences of 10-d spans during the transition periods. The essential similarities being sought were those of wet season onset and termination, the implicit assumption being that mesolevel factors such as proximity to mountain ranges and the sea have a more significant influence on the variable rainfall prevalent during transition periods than on the heavier rainfall during the main wet and dry seasons. Locations were regarded as similar or dissimilar to the reference site according to closeness of fit (R^2) and magnitude (b).

Binalonan (10 km from the Pangasinan research site) and Dolores (110 km from the site) are examples from Central Luzon (Fig. 13). Paired analyses for 18 stations were used to draw Figure 14. Wet season termination similarities extended over a smaller area than wet season onset similarities, apparently because high mountains to the northeast of Pangasinan influence the moisture content of November winds.

Although these methods provide useful information about rainfall distributions, they must be regarded as only stop-gap methods until weather records are more complete over a longer time span, until better methods are developed, and until the capabilities of Farming Systems Research staff in national programs are strengthened. Sparse data (incomplete and short records, low numbers of observation stations) and data of questionable accuracy are constraints to objective, quantitative assessment of rainfall pattern similarities.



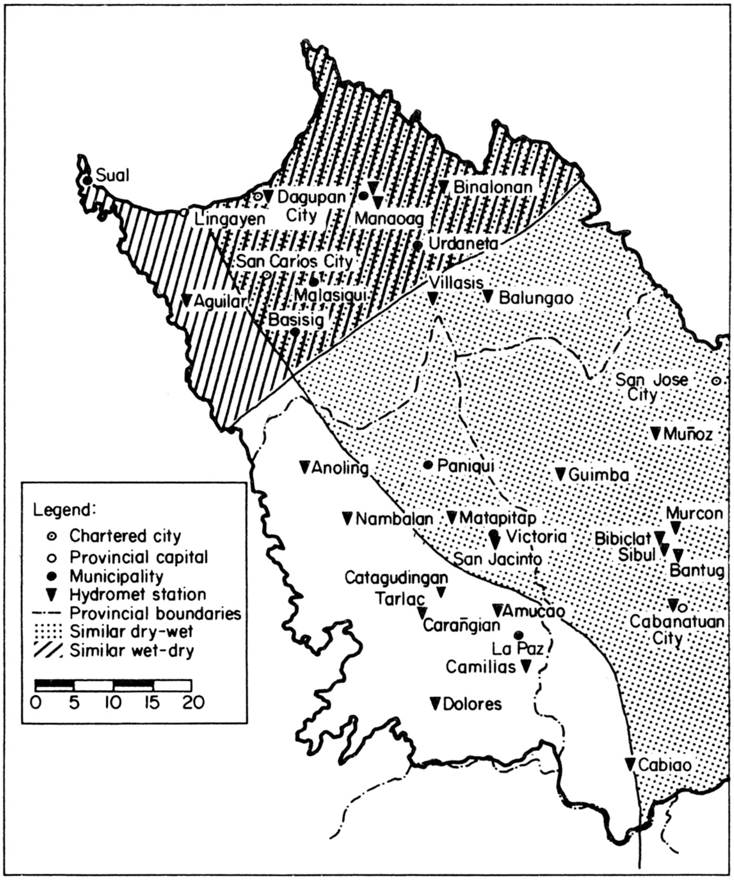
13. Scatter diagrams of wet-dry transition period rainfall at Manaoag and two contrasting stations, and R^2 for Y = bX . . using deleted and undeleted rainfall data (13).

Cagayan

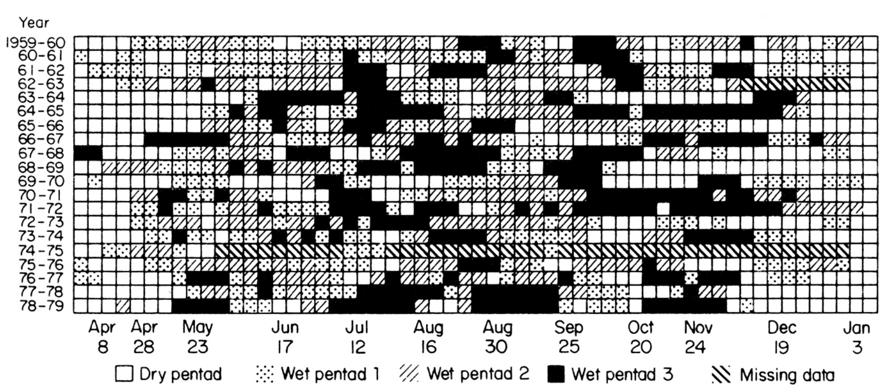
The Cagayan project was initiated in 1980 to test technology where field hydrologies are adverse. In the Cagayan environment, terrain and rainfall distributions combine to create high probabilities of drought and flooding (temporary submergence above canopy level). First, available rainfall and river flood stage data were sought. Flood stage data were examined for recurring periods of peak flooding. Pentad diagrams were constructed from rainfall data using three levels of wet pentads (Fig. 15). The four levels in the diagram correspond roughly to rainfall that:

- is well below the ET requirement of a typical annual crop = Dry
- meets about 1/2 the ET requirement = Wet 1
- meets about 3/4 the ET requirement = Wet 2
- exceeds the ET requirement = Wet 3

In two-thirds of the years, sequences of three or more Dry and/or Wet 1 pentads occurred between 31 Aug and 29 Nov (the late vegetative - early reproductive stages of most traditional rices), suggesting that midseason



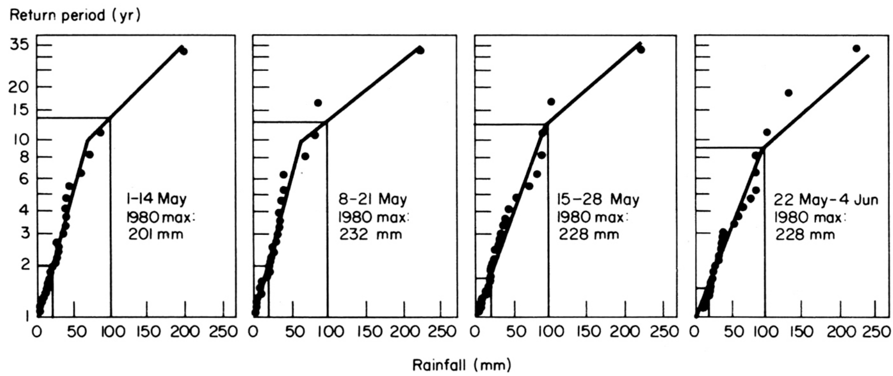
14. Areas similar to and different from Manaoag during the dry-wet and wet-dry transition, determined by cluster analysis (13).



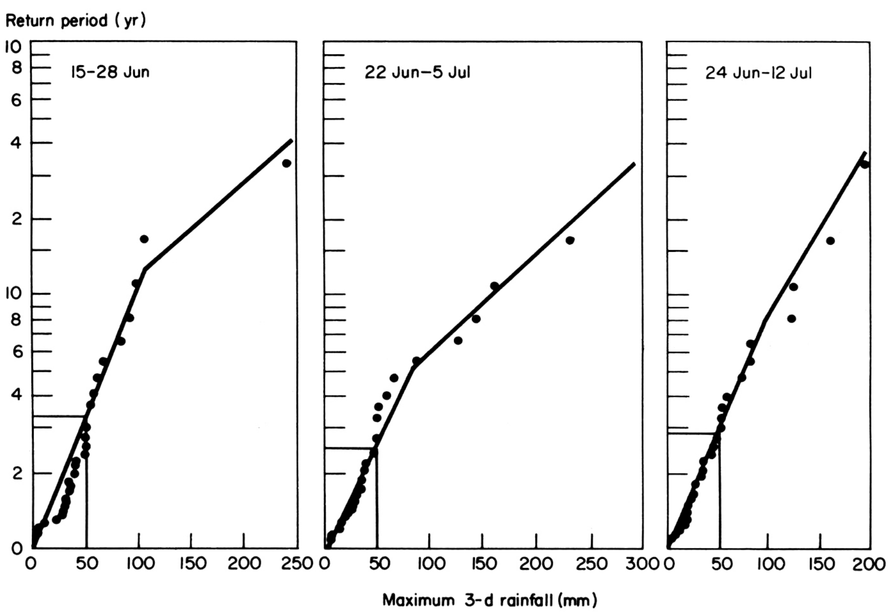
15. Pentad 5-d period diagram showing seasonal variability in rainfall for 1959-79 in Tuguegarao, Cagayan, Philippines (9).

drought is common. Experiences in 1980-85 suggest that drought depresses crop yields and delays field operations more frequently than flooding, but that flooding causes more complete crop failures.

To examine rainfall patterns at times when key field operations must be performed and crops are in growth stages most vulnerable to drought or flood, return period analysis was applied to selected periods of the year. Three periods were regarded as important: May to early June (for establishing a mungbean crop), mid-June to mid-July (for establishing a DSR crop), and October to



16. Return periods for maximum rainfall per 3-d period, 1 May-4 Jun 1980, Solana, Cagayan, Philippines (9).



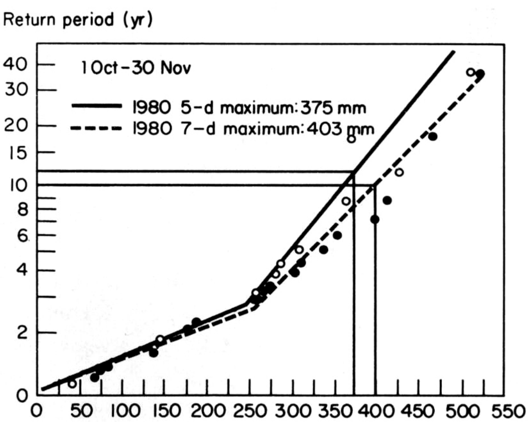
17. Return periods for maximum rainfall per 3-d period for 3 seeding times of direct-seeded rice. Solana, Cagayan, Philippines, 1980 (9).

November (when the main or second rice crops would be booting or flowering). Return period diagrams for these three periods are shown in Figures 16, 17, and 18.

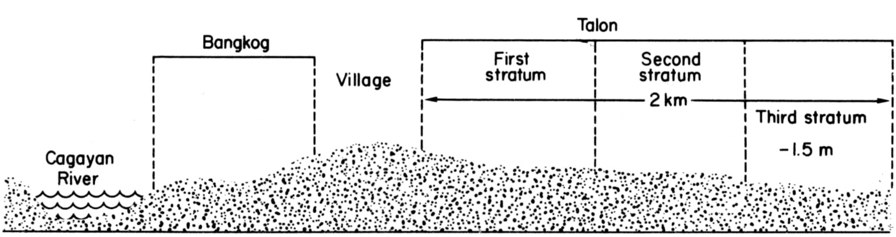
As in Pangasinan and Iloilo, terrain interacted with rainfall to create different field water regimes. In Cagayan, terrain differences were gradual and boundaries between terrain classes were diffuse. Figure 19 is a schematic cross-section of the terrain. Figures 20 and 21 show field water status in two contrasting years.

In the dry year (1983-84), terrain had little influence on the field water regime; in the wet year (1981-82), flooding was deeper and standing water remained longer on the third stratum. However, except for the first year (1980-81), flooding has not been a major hazard. Even in the third strata, the level of flooding experienced in 1980 has not recurred, although flooding in that stratum is a continuing threat to rice. Drought has proved to be a greater problem, especially for proposed early rice crops.

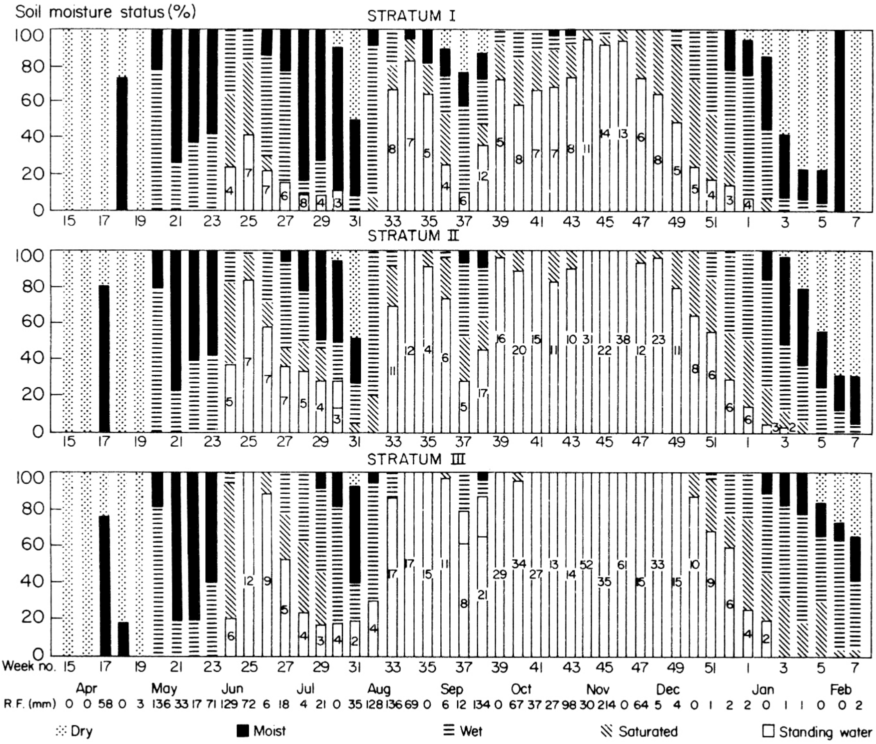
In addition to causing drought stress to transplanted crops, prolonged dry periods also delay transplanting. When drought forces holding seedlings of modern rices in the seedbed for more than 35 d, yields decline. For traditional varieties, delayed transplanting is of no consequence.



18. Return periods for maximum rainfall per 5- and 7-d periods, 1 Oct to 30 Nov, Tuguegarao, Cagayan, Philippines, 1980 (9).



19. Schematic cross-section of the landscape at the cropping systems research site, Solana, Cagayan (4).



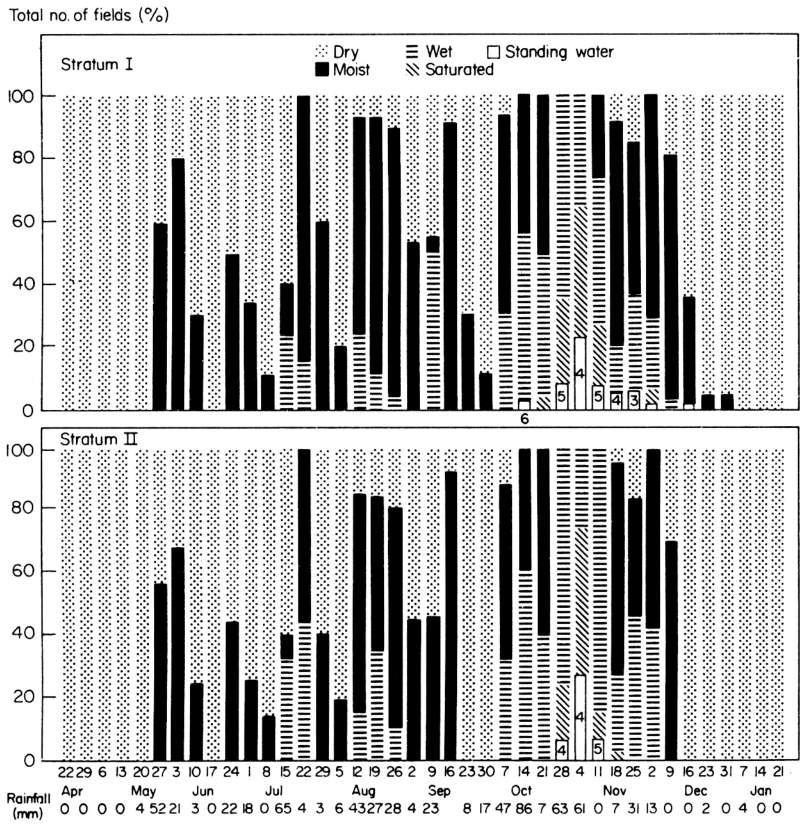
20. Soil moisture status of cropping pattern fields by stratum, Solana, Cagayan, Philippines, 1983-84. Numbers in open bars indicate standing water in centimeters (10).

Table 9 shows mean yields by stratum for 4 yr. Except in 1981, a favorable year, yields were low regardless of stratum, although the third stratum was at an advantage. Figure 22 suggests that farmers in the second and third strata approach land preparation and transplanting more leisurely than do farmers in the first stratum. In Stratum I, 65% of the farmers finished transplanting within 8 d of the first land preparation activity.

Claveria

The Claveria research site represents an upland area with a long wet season and soils of low productivity. In terms of rainfall pattern analysis, the research site presented a problem. Whereas previous sites were located near established rain gauges and long-term rainfall records representative of the research site existed, such records did not exist for Claveria. The site is at the foot of a mountain range on a small plateau 600 m above sea level, but only 15 km from the sea. Mesoclimatic influences are strong.

Rainfall patterns from a number of stations in northern Mindanao were examined. Using those data, physiographic features, and knowledge of seasonal



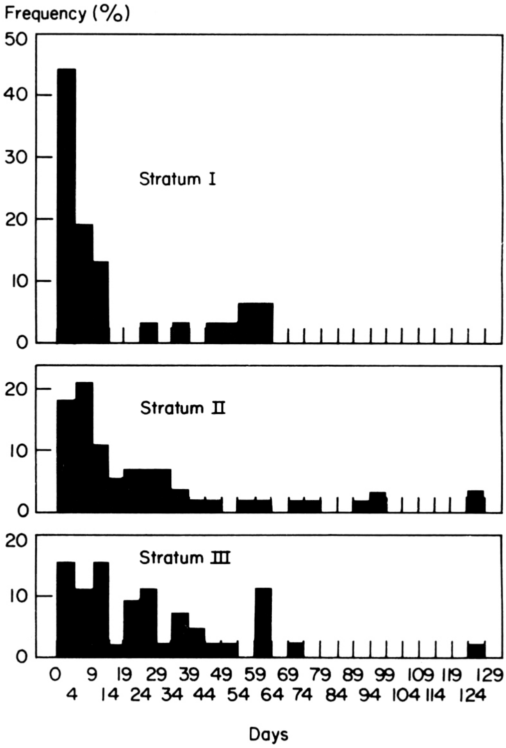
21. Soil moisture status of cropping pattern fields by stratum, Solana, Cagayan, crop year 1981-82 (10).

Table 9. Mean yields (t/ha) of all planted rice crops (with unharvested crops entered as 0). Solana, Cagayan, Philippines, 1980-83 (4).

Year	Stratum I	Stratum II	Stratum III	Mean
1980	0.9	0.9	1.5	1.1
1981	3.1	2.4	2.7	2.7
1982	1.2	1.6	1.6	1.5
1983	0.7	0.8	- [a]	0.7

[a] In 1983, testing was not conducted in stratum III.

winds, rainfall patterns in northern Mindanao were mapped (17). This mapping placed the research site in a rainfall class with 5-6 mo at >200 mm/mo and 2-3 mo at <l00 mm/mo (Fig. 23). On the basis of discussions with farmers, we think that the actual distribution is at the wetter end of this range, or just over the class limit, with 7 wet months.

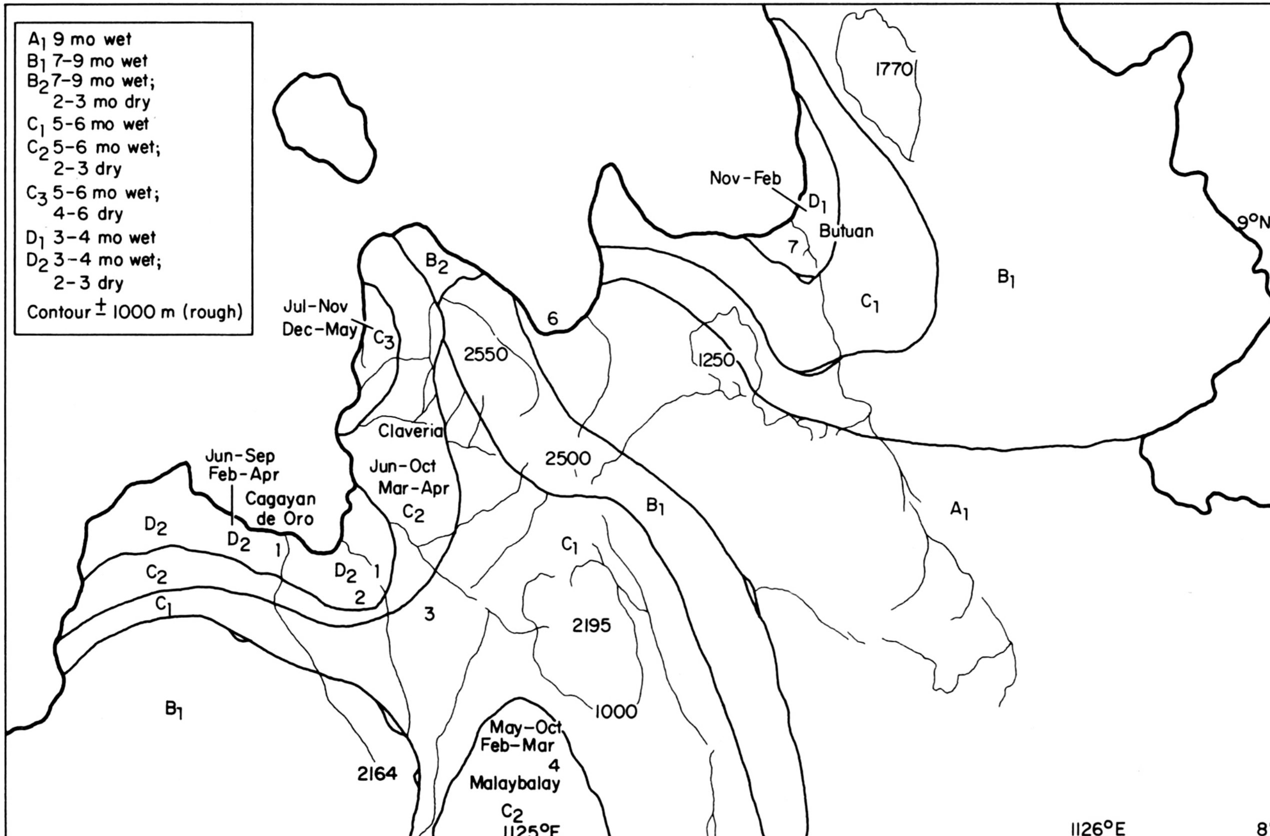


22. Frequency of time gap (d) between first plowing and transplanting in cropping pattern fields, by stratum. Solana, Cagayan, Philippines. 1980-82 (4).

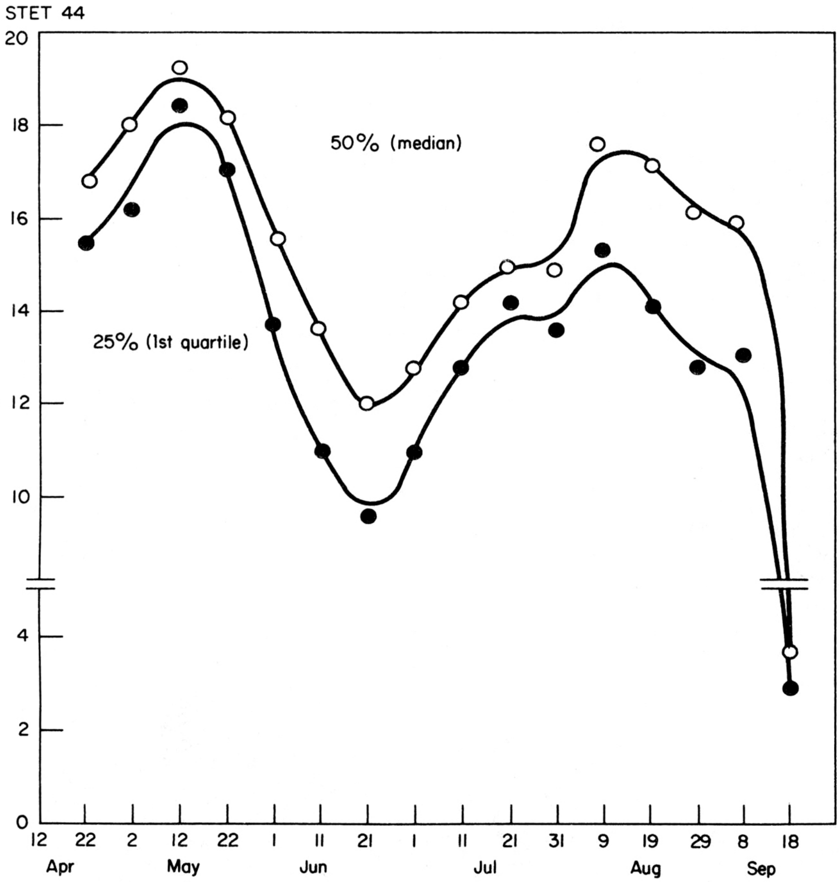
Unlike in puddled lowland environments, field-suitable conditions are not a significant concern in the Claveria project. The contribution of rainfall to evaporative demand is of overriding importance. Once again we turned to water balance modeling to help evaluate cropping potentials in terms of evapotranspiration. Using a simulation procedure developed by Geng et al (3) to estimate parameters from mean monthly rainfall and the number of rain days per month, daily rainfall was generated for 20 wet seasons. To estimate the required parameters, rainfall data were taken from Manolo Fortich, located across a valley 35 km south of Claveria.

The 20-yr generated rainfall data were used in a simple water balance model to predict evapotranspiration during the last 44 d of crop growth. Sixteen simulations were run at 10-d intervals, starting with 22 Apr and ending with 18 Sep. Figure 24 shows median and first quartile predicted ET for these dates.

The analysis suggests that upland rice plantings between 1 and 20 May are preferred and that plantings between 1 Jun and 15 Jul are to be avoided. The dip in Figure 24 is associated with a period of low rainfall which normally occurs from late August to early September. In respect to estimated STET 44 (actual ET for the last 44 d), the values in Figure 24 are likely to be conservative because Manolo Fortich is in a slightly drier environment than Claveria. However, the seasonality should be correct.



23. Agroclimatic map of Claveria, Misamis Oriental. Region X (18).



24. Median and quartile model-derived STET44 (actual ET) values for planting between 12 Apr and 18 Sep. Rainfall was generated using simulation-model parameters estimated from long-term Manalo Fortich data.

Conclusions

In rainfed agriculture, rainfall is the water source for crop transpiration. Rainfall also influences soil properties which determine a field's suitability for tillage and other field operations and for seed emergence. Agriculturalists have keen interests in seasonal and spatial distributions of rainfall.

Several analytical methods have been used by CS scientists to examine rainfall variability over time and to identify regions exhibiting similarities in rainfall distributions. Simplicity has been emphasized in most analytical methods. Those methods have helped scientists gain insights into the likelihood of rainfall meeting crop water requirements and of field conditions being suitable during periods when key field operations must be performed. While the methods used in the examples have proven useful to varying degrees, they are, for the most part, dependent on user judgment.

Better methods are needed:

(1) to determine yield stability with respect to meeting crop water requirements throughout a season,

(2) to estimate probabilities of field-suitable conditions, and

(3) to define the boundaries of target environments.

Models are available which can be adapted for determining yield stability and defining environmental boundaries. Models which can be easily applied to estimating field-suitable conditions are not available. Because terrain features and soil properties influence field water regime, and because it is the field water regime that ultimately must be predicted if cropping schedules are to be tailored to fit the limitations imposed by rainfall, methods that incorporate both land and climatic components are needed.

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Climatic analyses and cropping systems in the semiarid tropics

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ABSTRACT

Interyear and intraseason weather variability is large in the semiarid tropics. Total annual rainfall has a coefficient of variation of 20-30% and risks to dependable crop production are high. Agroclimatic analysis to quantify the length and variability of growing season and the dependability of the onset of the rainy season for establishing crops and to assess weather damage at harvest greatly assists the development of new and improved cropping systems. Intercropping has been found to be more efficient in such environments. Agroclimatic analyses could help define the recommendation domain for transferring technology from the research center to farmers' fields.

Climate and agriculture are intimately related. Both long-term meteorological factors (the climate) and short-term meteorological events (the weather) affect crop growth, development, and production. Studies of climate help us understand crop production and other land use patterns that have evolved over a long period of time and assist us in introducing new and more productive farming systems. At ICRISAT, we are studying the relevance of climatic environment to the development of improved cropping systems for semiarid tropical areas.

The Agroclimatic Setting

Semiarid tropical (SAT) areas are defined as those regions that have a mean annual temperature exceeding 18 °C and mean monthly rainfall exceeding mean monthly potential evapotranspiration for 24.5 consecutive months in the dry SAT and 4.5-7 mo in the wet/dry SAT. Much of ICRISAT's work has been confined to the dry SAT. In this region, total annual rainfall varies from 500 to

1200 mm; 80-90% of it is received during a short rainy season. Precipitation is characterized by annual and seasonal variability. The coefficient of variation for annual rainfall is 20-30%. Even within the rainy season, droughts of varying durations are common.

Traditional Land Use and Cropping Systems

Traditionally, the SAT areas have had agropastoral, silvipastoral, and agroforestry production patterns. Cultivation had been mainly restricted to dryland crops, with a crop or two of rice in the lowlands or where irrigation water is available. With large population increases in recent years, most of the land is now sown to crops; the area under forests and grasslands is rapidly decreasing. Soil erosion has increased tremendously and surface water storage systems have lost much of their effective storage capacity. Crop production is much more variable in both drylands and irrigated areas. Average crop production from the drylands does not exceed 0.7 t/ha a year in most of the SAT.

To cope with the variable climate, farmers tend to grow a mixture of crops. They usually include long-duration crops in their cropping systems.

Increasing Crop Productivity

The major climatic constraint to crops in the tropics is lack of adequate water. Against a continuing evaporative demand, the supply is discontinuous and variable, particularly in the drylands.

Avenues to improve crop production in the SAT include:

- Adopting cropping systems which make maximum use of available water. In practice, this means that adequate amounts of soil moisture would be available to each crop across its growth.
- Increasing the length of the growing season by advancing planting dates.
- Adopting cropping systems which avoid mid- or end-season droughts.
- Adopting improved agronomic practices, such as crop rotation and moderate inputs.

Role of Agroclimatic Analysis

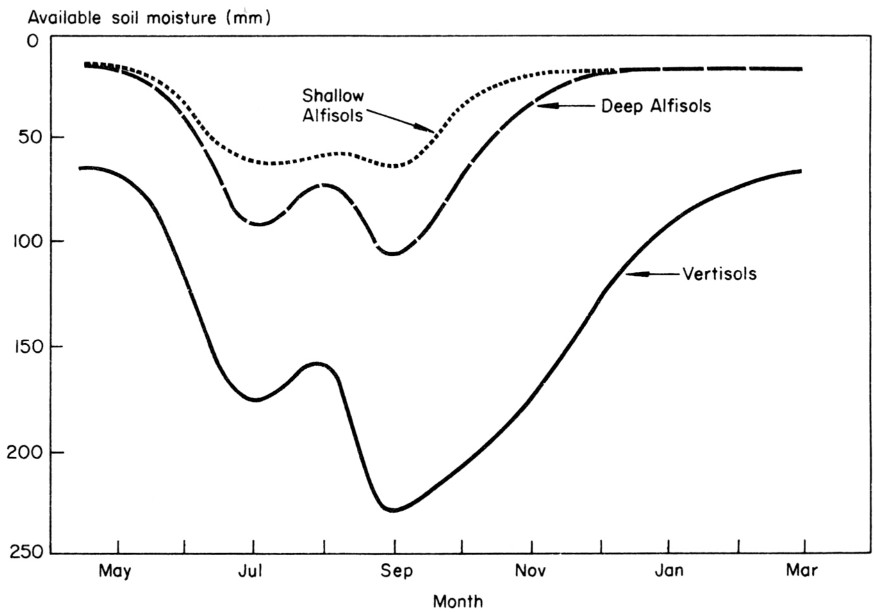
Characteristics of growing season

The length of a crop growing season can be defined by a water balance model. If the climatic record is fairly long (230 yr), a stochastic model could be used. Average lengths of the growing season at Hyderabad for Alfisols (average water-holding capacity [AWC] = 100 mm) and Vertisols (AWC = 250 mm) at different probability levels are shown in Table 1.

Those predictions show that a 90-d crop could be grown successfully in Alfisols and a 120-d crop could be successful in 8 of 10 yr in Vertisols. A long-duration crop, 130 d in Alfisols and 170 d in Vertisols, would be successful at least 50% of the time.

Table 1. Length of growing season at Hyderabad (1901 to 1970).

Probability (%)	Growing season (d)	
	Alfisols	Vertisols
80	85	126
Mean	130	170
20	140	210



1. Climatic water balance of Alfisols and Vertisols (1901-70)

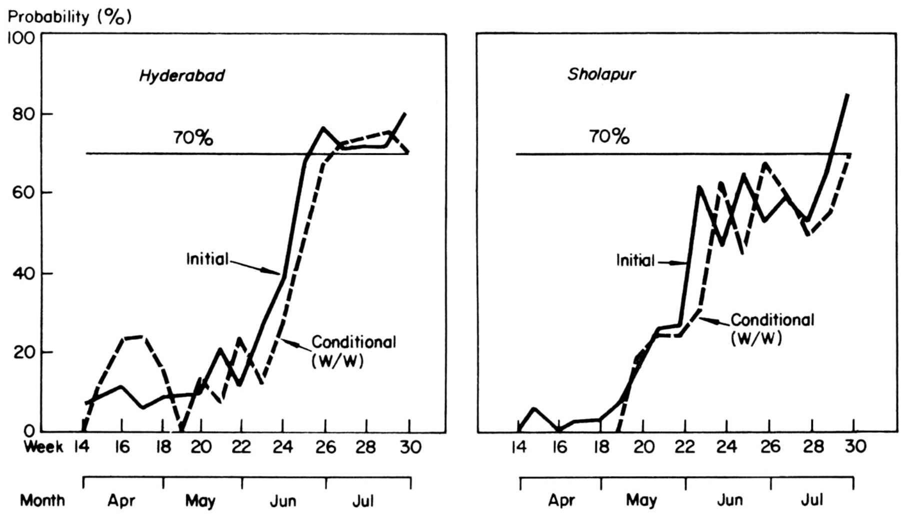
Relative availability of moisture would be a good guide to crop selection. In shallow Alfisols, soil moisture stored in the soil profile does not exceed 75 mm at any time during the growing season; in Vertisols, it exceeds 200 mm in September (Fig. 1). While short-term droughts could lead to crop moisture stress in Alfisols, the likelihood of a crop being affected by drought is considerably less in Vertisols.

In Alfisols in Hyderabad, the prospects for success of a 90- to 100-d crop (pearl millet or sorghum) are much higher than for 120- to 130-d crops; in Vertisols, even a drought-sensitive crop like maize would be successful most years. In long-duration crops, castor bean is more drought hardy than pigeonpeas. For Alfisols, a good combination would be a pearl millet - groundnut intercrop and castor bean; for Vertisols, a suitable cropping system would be maize - sorghum and pigeonpea.

Our cropping systems experiments confirm these predictions (Table 2).

Table 2. Yield of some cropping systems in two soils at Hyderabad (t/ha).

Cropping system	Vertisols Fertilizer Low	Vertisols Fertilizer Medium	Cropping system	Aifisols Fertilizer Low	Aifisols Fertilizer Medium
Maize - pigeonpea	0.7	1.7	Millet - castor	1.0	2.0
	1.2	1.3		0.08	0.3
Sorghum - pigeonpea	1.1	2.0	Millet - groundnut	0.7	0.1
	1.0	1.3		1.0	1.1



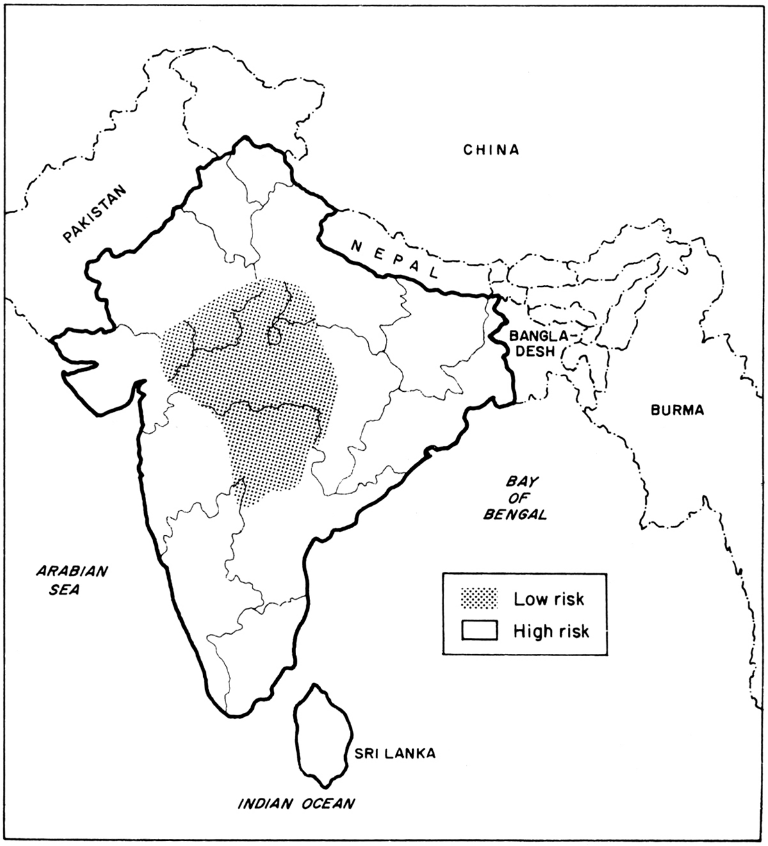
2. Initial and conditional rainfall probabilities at two semiarid Indian locations.

Rainy season onset and crop establishment

We have found that preparing the seedbed ahead of the rainy season and seeding just before the rains start gain 2-3 wk of growing season. This is particularly important for sequential cropping or intercropping. Clearing the field 2 wk before planting the second crop gives it a head start. In intercropping, competition from a short-duration crop is removed and all the resources are available to the intercrop.

Estimating initial and conditional probabilities of rainfall around planting time is useful in evaluating the suitability of an area for dry planting. The probability of rainfall for Hyderabad and Sholapur, typical locations in semiarid India, are shown in Figure 2.

Onset of rainfall at Hyderabad is abrupt. Once the rainy season sets in (initial probability $\geq$ 70%), rain is likely to continue (conditional probabilities of rainfall exceed 70%). A dry-planted crop has a reasonable chance of being established at the onset of the rainy season. But at Sholapur, the chance of failure of a dry-seeded crop is almost 50%.



3. Possibilities of dry seeding on Vertisols in India.

Such an analysis of rainfall probabilities could be used to screen sites for dry seeding (Fig. 3).

Assessing weather damage at harvest

In the tropics, a major weather-related problem is excessive humidity or rainfall, leading to development of seed molds and germination of mature seeds. The probability of rainfall at crop maturity could help quantify risk. An example for sorghum and millet crops at Hyderabad is shown in Table 3.

At Hyderabad, short-duration sorghums grown during the rainy season are likely to be exposed to weather deterioration due to the high humidity in most years; medium-duration sorghums are likely to be damaged 1 out of 3 yr. The millet crop is likely to be exposed to the risk of deterioration 6 out of 10 yr. Predictions such as these have led ICRISAT Crop Improvement Program researchers to develop sorghum cultivars resistant to grain mold and millet cultivars with seed dormancy.

Table 3. Amount of rainfall expected at sorghum and pearl millet crop maturities at Hyderabad.

Crop	Maturity (d)	Expected rainfall (mm) at a given probability			
		80%	60%	50%	30%
Sorghum	Medium (130-150 d)	1	6	13	50
	Short (90-110 d)	42	98	125	195
Millet	65-70 d	17	36	48	79

Recommendation domain

An efficient cropping system for a locale is determined largely by climatic, edaphic, and management factors. A more complete quantification of the temporal and spatial distributions of natural resources is a key factor in assessing the agricultural production potential of a region. Mapping the agroclimate of an area in relation to its resources could give the recommendation parameters for improved cropping systems or farming systems technology.

During the past decade, ICRISAT has worked intensively to increase production on Vertisols. We found that improved technology could be transferred to areas with Vertisol soils at least 70 cm deep; more than 250 mm water storage in the root profile; more than 750 mm total, dependable rainfall during the main rainy season; and minimum winter temperatures above 8-10 °C. A map of semiarid India showing the suitability of areas for the adoption of improved Vertisols technology has been prepared.

Impact of climatic factors on irrigated and partially irrigated rice cultures

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ABSTRACT

Rainfall is usually the dominant climatic factor, not only in partially irrigated environments but also in fully irrigated environments. Rainfall determines water availability at the irrigation source, irrigation requirements of the crops grown, and cropping calendars.

The rice plant's utilization of available nutrients may be affected by solar radiation, especially when yields higher than 5-6 t/ha are sought. In most South and Southeast Asian rice areas with low yield levels, the relatively low solar radiation in the wet season is not a major limitation to raising rice yields by planting better varieties and by using more efficient crop-soil-water management practices.

Temperature is another constraint. Low temperatures limit plant growth and growing season, high temperatures (in excess of 35 °C, especially during anthesis) can cause spikelet sterility. Such cultural practices as adjusting cropping calendar, using older seedlings, and water management can be used to circumvent those problems. Maintaining ponded water in the field (during cold days, groundwater temperature is usually higher than air temperature) may help increase plant body temperature. High plant body temperature may be reduced by allowing cool irrigation water to flow through the ricefields (water temperatures in large reservoirs are often lower than air temperatures in summer). However, flowing irrigation is inefficient water use.

Climate plays a dominant role in agricultural production systems; it tends to define the bounds within which the physiological growth of crops occurs. Consequently, cultural practices are influenced extensively by climatic factors. The physiological effects of climatic factors on crops such as rice may not vary significantly between irrigated and rainfed environments, but cultural aspects of rice production can differ greatly, depending on the hydrologic environment in which the crop is grown.

Table 1. Selected rice cultural practices and related activities within irrigation systems linked to major climatic factors.

Rice cultural practices or related activities within irrigation systems	Climatic factors		
	Rainfall	Solar radiation	Temperature
Cropping calendar	•	•	•
Cropping intensity	•		•
Land preparation and crop establishment	•		•
Field water management	•	•	•
Fertilizer use and management	•	•	
Crop management	•	•	•
Harvesting and crop processing	•	•	
Available water at irrigation system source	•		
Irrigation service area	•	•	•
Irrigation water delivery schedule	•	•	•

Among the climatic factors that affect rice culture, rainfall is the most dominant (Table 1). Sastry (13) emphasized that the success or failure of crops in both rainfed and irrigated agriculture is closely linked to rainfall patterns. The development of irrigation facilities for a certain area does not render that area totally independent of rainfall. At both the water source (catchment of reservoir or river diversion) and the water service area, actual seasonal or preseasonal rainfall patterns often affect rice culture. This effect is more pronounced in partially irrigated areas where the irrigation supply during one or both seasons of the year is not fully adequate for rice culture. Other climatic factors which influence rice culture in irrigated or partially irrigated environments are solar radiation and temperature.

Here we assess the impact of selected climatic factors — rainfall, solar radiation, and temperature — on rice culture in irrigated and partially irrigated environments. Emphasis is on the climates and rice growing environments of Asia, where more than 90% of the world's rice is produced (7). The term rice culture is used in the context of rice production practices and related decision-making processes. Where possible, specific examples from research findings support relevant impact points.

Rainfall and Irrigated Rice Culture

Rainfall and rainfall patterns influence rice cultural practices in irrigated environments through their effects on the availability of water at the irrigation source, the irrigation requirements in the crop field, and the optimum cropping calendars for farmers.

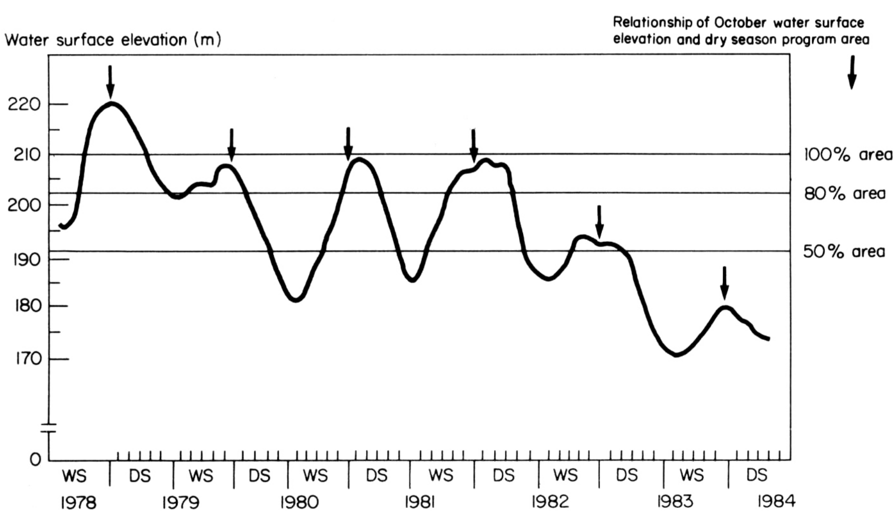
Water availability at irrigation source

In any irrigation system, the amount of water available for irrigation during a season is determined by the amount of precipitation in its catchment area. This may be true even for irrigation systems using groundwater; local rainfall can be the primary water source for the annual recharging of a groundwater aquifer. The rice area that can be supported by irrigation depends on the amount of water available during the most water-demanding period of the season, which is dependent on rainfall in the catchment. An irrigation system's design addresses this uncertainty by considering a supply value which long-term records predict has a reasonable probability of being available.

Unexpected reductions in the amount of water available at an irrigation system's source, such as those caused by drastic reductions in rainfall in the catchment, have been known to cause major cutbacks in the serviceable area of the system as well as severe drought stress in areas that could be only partly supplied with irrigation water. A notable example of such a problem was found recently in the Pantabangan reservoir of the Upper Pampanga River Integrated Irrigation System (UPRIIS) in the Philippines.

That system was designed to irrigate more than 100,000 ha in the wet season and is expected to serve more than 80,000 ha in the dry season. Figure 1 shows water levels in the reservoir during the last 7 yr. Low wet season rainfall in 1982 and 1983 caused October water levels in the reservoir to remain well below the expected 210 m elevation, which reduced the irrigated hectarage in the subsequent dry seasons to about 83% of a normal year's coverage in 1982 and to 40% in 1983 (5). Also, many farms within the program area for irrigation could be only partially served (Table 2). in the absence of any significant rainfall, substantial yield reductions due to severe drought stress occurred.

Such incidents are common in irrigation systems. When they happen, many farmers find themselves coping with the difficult problem of the change of their farms from fully irrigated to partially irrigated or rainfed.

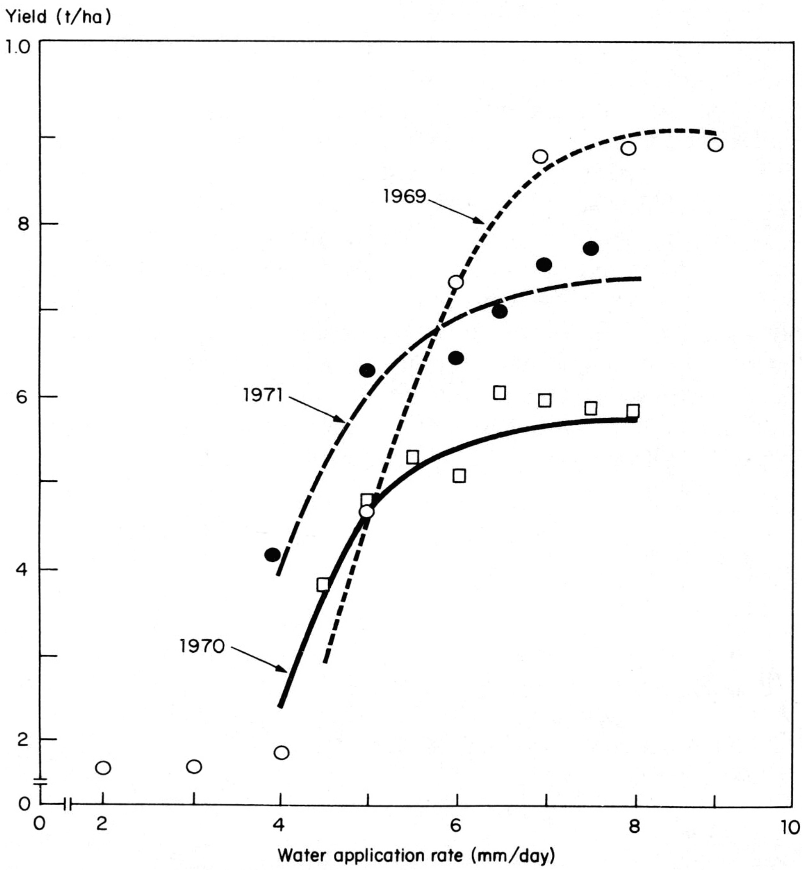


1. Water surface elevation at Pantabangan reservoir, UPRIIS, 1978-84. Arrows indicate October elevation, the basis for programming DS area.

Table 2. Areas (hectares) suffering severe crop damage due to water stress; farms exempted from irrigation fee payment[a] in four districts of UPRIIS, 1983 and 1984 dry seasons.

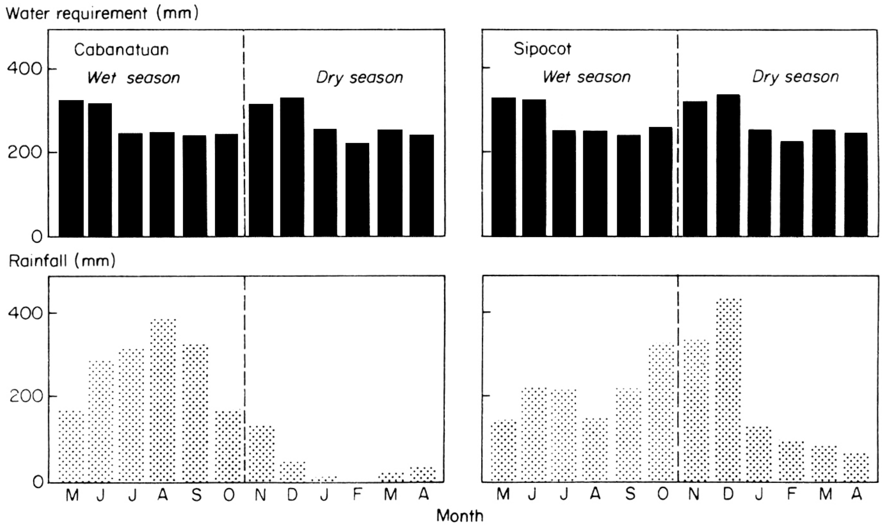
District	1983 DS	1984 DS
I	491	-
II	858	161
III	951	3,958
IV	255	2,296
UPRIIS	2,556	6,416

[a] Exemption given those farms that produced less than 2.0 t rough rice/ha.



2. Relationship between rice yield and water application rates for IR8 variety with 100 kg N/ha. IRRI, 1969, 1970, 1971 dry seasons (8).

A similar example makes the point for pump-based irrigation systems. In the 3,900-ha Libmanan-Cabusao Pump Irrigation System (LCPIS) in Camarines Sur, Philippines, a vital consideration in determining the number of pumps (of a total of four) that can be operated simultaneously is the river level.



3. Rainfall pattern and water requirement for rice in Cabanatuan, Nueva Ecija Province, and Sipocot, Camarines Sur Province, Philippines. Rainfall data period: 1949-83 for Cabanatuan, 1969-81 for Sipocot.

When the water level in the river is less than 30 cm above the top of the pump intake pipe, a maximum of 2 pumps can be operated simultaneously without drastic reduction in pumping efficiency. Late in the 1983 dry season, low rainfall at the river catchment brought the river water level at the pump intake below 30 cm for about 3 wk, forcing the system manager to reduce the number of operating pumps to 2 until the early part of the 1983 wet season, when the water level in the river rose to normal. This problem contributed significantly to a reduction in the hectares prepared for rice cultivation during the wet season (6).

Irrigation requirement of crops

Meeting the evapotranspiration demand of the rice plant is essential to attaining potential grain yield. Water stress occurring at any growth stage adversely affects plant growth and reduces yield. Water stress is most damaging when it occurs at the reproductive stage (12), because water deficits from the reduction division stage to heading can cause a high percentage of sterility (18). Studies at IRRI show that yields are greatly reduced when water application rates fall below a certain level. That level is close to the field water requirement (the sum of the potential evapotranspiration rate of the crop and the seepage and percolation rate in the field). Water supply in excess of that rate does not increase grain yield (Fig. 2) (8).

The irrigation needed to meet the crop evapotranspiration demand is determined by rainfall and such climatic factors as temperature, relative humidity, and wind speed. Figure 3 shows the rainfall patterns of two different locations in the Philippines and the corresponding water requirements for rice culture. Cabanatuan City, Nueva Ecija Province, has a much more distinct dry

Table 3. Monthly water deficits to be met from irrigation source; energy required to pump the irrigation water. Cabanatuan City, Nueva Ecija, and Sipocot, Camarines Sur, Philippines.

	Cabanatuan		Sipocot	
	Water deficit[a] (mm)	Energy required (kWh/ha)	Water deficit (mm)	Energy required (kWh/ha)
May	161	62	186	72
Jun	34	13	101	39
Jul	0	0	37	14
Aug	0	0	104	40
Sep	0	0	25	10
Oct	83	32	0	0
Nov	185	71	0	0
Dec	282	108	0	0
Jan	241	93	123	47
Feb	221	85	132	51
Mar	233	90	171	66
Apr	213	82	178	68
Total (annual)	1653	636	1057	407

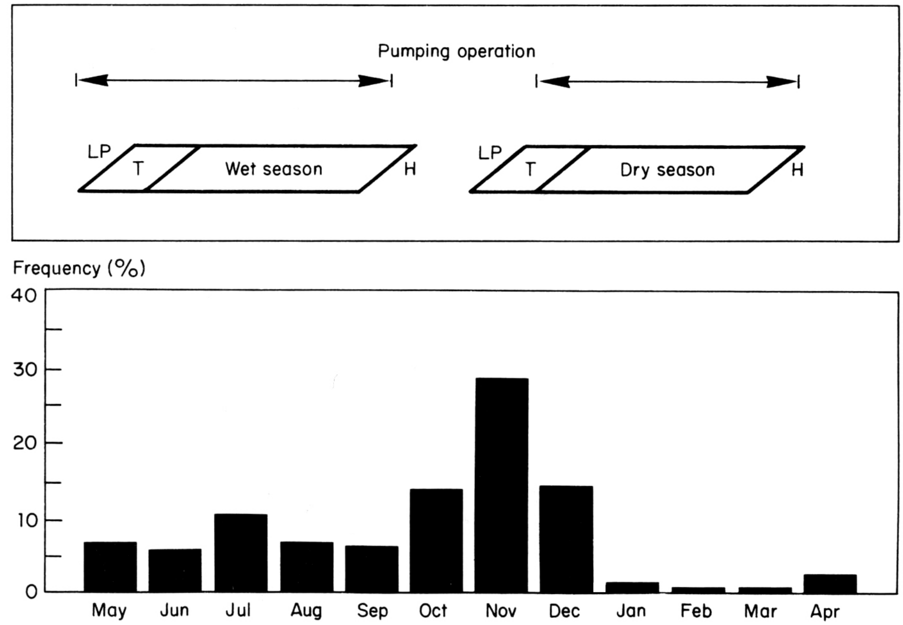
[a]In estimating deficits, it is assumed that all rainfall up to total water requirement is effective for both sites.

season than Sipocot, Camarines Sur Province. As such, the energy required to pump water to meet water deficits are different in the two locations (Table 3). Cabanatuan would require about 636 kWh of energy to irrigate each hectare of rice annually, 56% more than the energy requirement at Sipocot (assuming that both locations use a pumping system similar to that of LCPIS) (Table 3).

Optimum cropping calendar

An optimum cropping calendar is largely dictated by climatic factors. Cropping calendars are usually developed to make the best use of the climate favorable for crop production. The specific objectives often considered include: (1) to maximize use of rainfall (and minimize irrigation requirement); (2) to optimize use of solar radiation; (3) to avoid crop damage due to extreme temperatures, typhoons, or floods; and (4) to optimize cropping intensity. In reality, a trade-off between some of these objectives may become unavoidable. For example, for a given location, maximizing rainfall use and optimizing solar radiation use may not be fully compatible. Compromises are required.

In LCPIS, the dry season starts during late November, when most of the major typhoons have passed and water in the field is still abundant. Irrigation required for land preparation is minimal. The dry season ends in April, when rainfall is very low. That condition is ideal for postharvest operations (abundant solar radiation). The wet season starts in May, but the problem then is a high irrigation requirement to start land preparation. Some areas within the system have difficulty receiving irrigation water for timely land preparation and crop establishment. But delayed planting increases the risk of crop damage because of



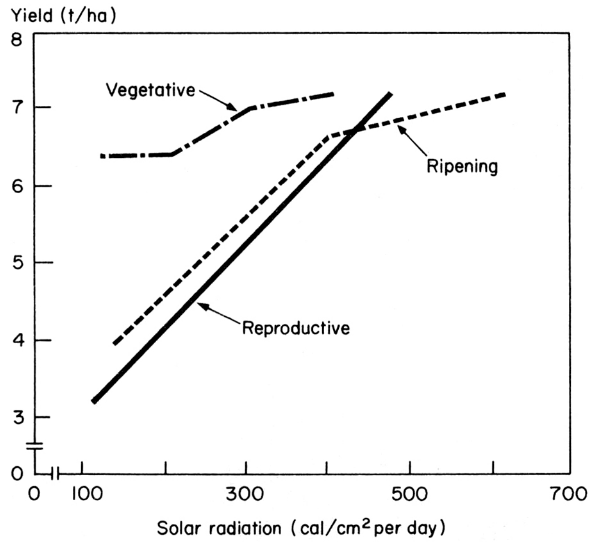
4. Typhoon frequency, cropping calendar, and pumping operation schedule, Libmanan-Cabusao Pump Irrigation System, Camarines Sur, Philippines (15, 16).

typhoons, which are frequent in October and November (Fig. 4). The interrelated problems can be resolved only with improved management of the irrigation system.

An interesting example of climatic factors influencing a cropping calendar was identified recently at Guimba, Nueva Ecija Province. Farmers there are unwilling to advance their dry season rice planting from February to the previous October or November, although such an advanced planting date would enable them to achieve several benefits. They could use the greater discharge capacity of the deep well, which begins to decline in December. An additional upland crop, such as mungbean, could be grown between dry and wet season rice crops. The farmers' reason for not wanting to advance the dry season rice schedule is the low yield associated with earlier planting (confirmed through field research in 1985). Research is continuing to determine whether the yield decline is due to strong wind at flowering (the farmers' perception), low night temperatures, or other climatic factors (Morris, pers. comm.)

Solar Radiation

High solar radiation, particularly during the reproductive and ripening stages, is considered necessary for high rice yields. Solar radiation in the tropics is generally less in the wet season than in the dry season. However, extensive cloud cover during the wet season is not considered a significant limiting factor in



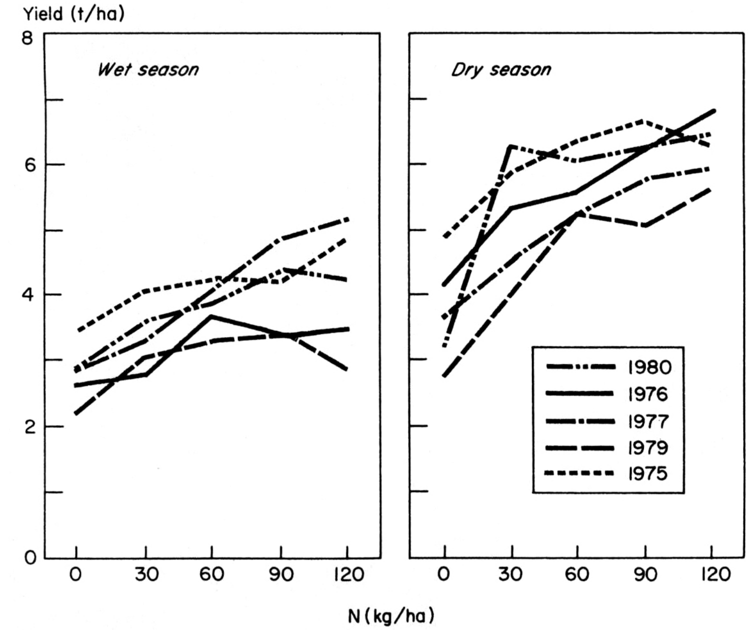
5. Effect of solar radiation at different growth stages on grain yield of IR74782-6 (18).

obtaining grain yields of 5-6 t/ha (18). The limitation reportedly applies when yields higher than 5-6 t/ ha are sought. That would require a solar radiation of more than 300 cal/cm^2 per d during the reproductive stage (Fig. 5). Considering the low average yields achieved in most South and Southeast Asia rice areas, the relatively low solar radiation in the wet season should not limit raising average rice yields in many irrigated or partially irrigated rice areas. Yoshida (18) emphasized that adapted varieties and good soil-water-crop management practices should be the strategies to achieve higher production in those areas.

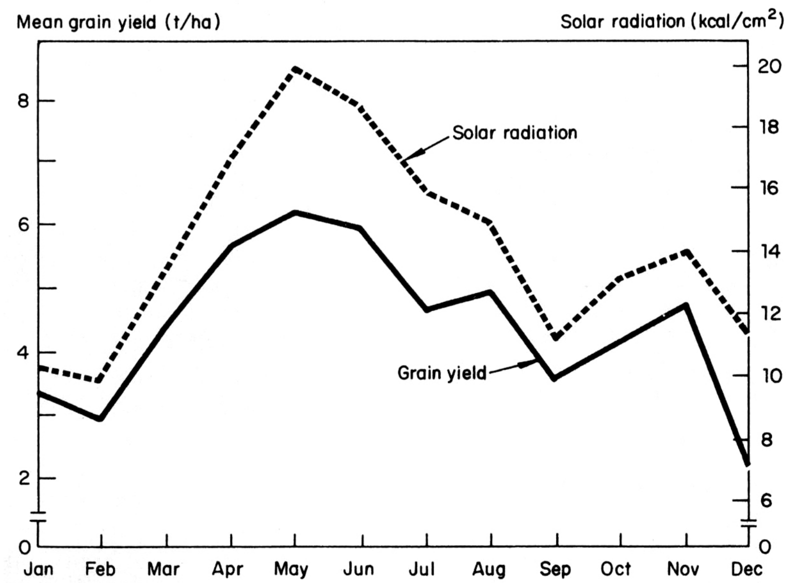
It is evident from numerous research results that the yield response of irrigated rice to N is significantly higher in the dry season than in the wet. Experiments at IRRI in fully irrigated fields demonstrated that, for the same amount of N applied, a much higher yield could be expected in the dry season (Fig. 6). For example, at 90 kg N/ha, the 1979 dry season yield was about 55% higher than the wet season yield. In 1976, the difference was even higher. For irrigated rice, the major external difference between the two seasons is solar radiation. De Datta and Zarate (4) found that grain yields of irrigated rice closely follow the pattern of solar radiation during the 45 days before harvest (Fig. 7).

We can conclude that, under full irrigation, the rice plants' ability to utilize available nutrients for grain production is higher with higher solar radiation. Therefore, it becomes relatively easier to achieve a higher yield in the dry season than in the wet season. But low solar radiation (less than 300 cal/cm^2 per d) can become a yield-limiting factor, even with abundant water, fertilizers, pest control, etc., when yields of more than 5-6 t/ha are the goal.

In the dry season, crop evapotranspiration (ET) is mostly met from irrigation water. To obtain high yields, the rice crop must be allowed to use water

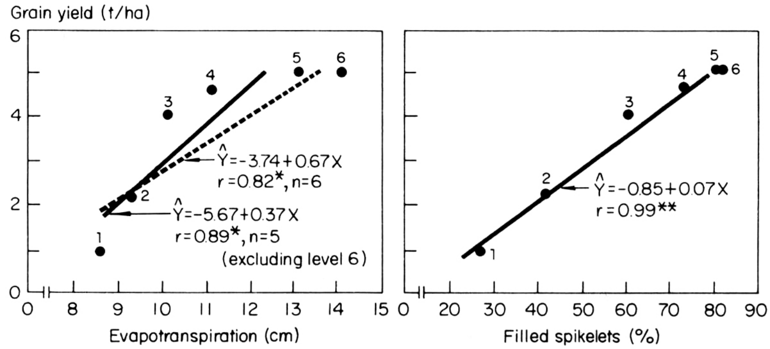


6. Response of IR36 to nitrogen, IRRI, 1975-80 (1).

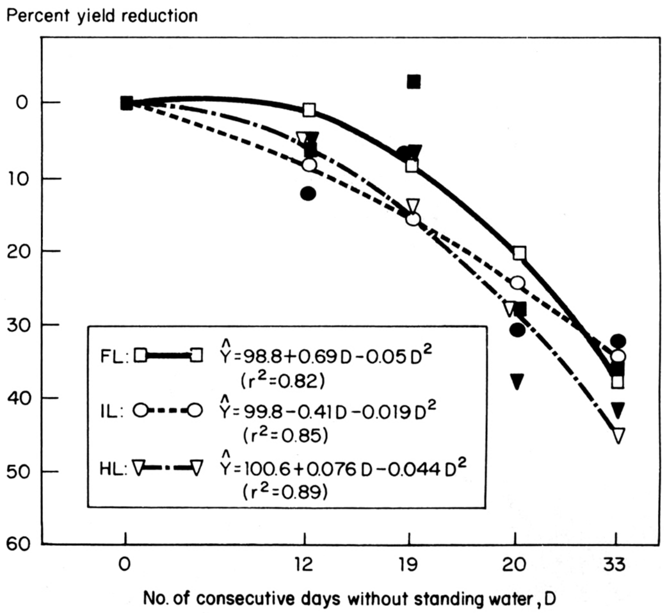


7. Mean grain yield of IR8 with 3 levels of N (0, 30, 90 kg/ha) and 3 spacings (15 × 15, 25 × 25, 35 × 35 cm) plotted against solar radiation 45 d before harvest (DBH) (4).

at its potential ET rate or yields will be reduced due to increased spikelet sterility (Fig. 8) (9). In irrigated environments, farmers usually take advantage of higher solar radiation in the dry season and use more fertilizers, especially N, than they



8. Relationship between grain yield and evapotranspiration (15 d cumulative) and gram yield and spikelet sterility of IR36, IRRI, 1980 (10)



9. Yield reduction of IR36 due to water stress during reproductive stage for three input management levels. FL = farmer level, IL = Intermediate level, HL = high level (2).

use in the wet season. But higher solar radiation also induces a higher ET demand in the crop, increasing irrigation requirements. Irrigation system operational planning and management must be more efficient in the dry season to avoid the effects of water stress on grain yields. Water stress at the reproductive stage of a crop with higher levels of fertilizer inputs can be even more damaging to yield (Fig. 9). When the water supply in a system is lower than demand, the water allocation decision should consider giving priority to areas where the crop is in the critical reproductive stage.

Temperature

Temperature influences both growth duration and growth pattern of the rice plant. The temperature extremes found in many Asian countries create major problems in irrigated rice culture. Critical low and high temperatures for different growth stages of the rice plant have been identified (17). Depending on growth stage, injury to the rice plant may occur when the mean daily temperature drops below 20 °C (18).

Low temperatures also limit the rice growing season. For example, although all rice in Japan is irrigated, cold temperature limits the rice-growing season to between May and October. The plants complete their early growth stages in a rising temperature regime and their postflowering stages in a declining temperature regime (3). Only one crop can be grown a year and even for that, seedlings must be grown under cover to protect them against very low temperatures. Similar practices are used in Korea and parts of China.

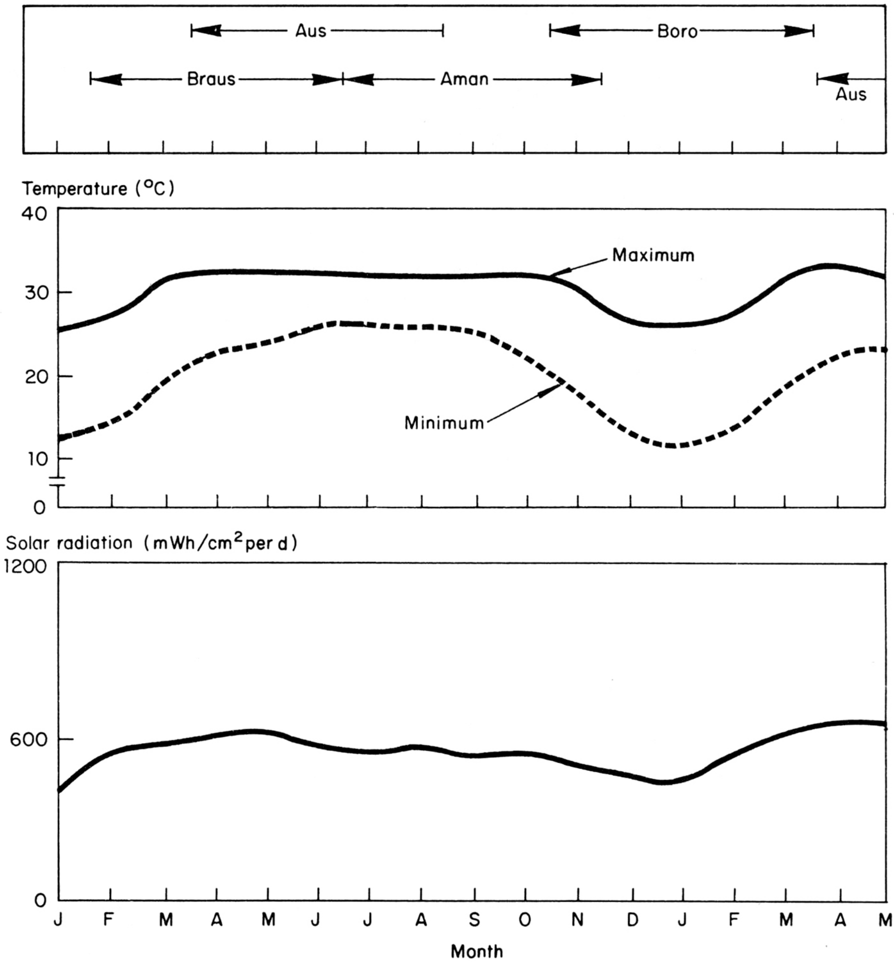
Low-temperature injury to rice plants has been reported by a number of Asian rice-growing countries, including Bangladesh, China, India, Indonesia, Iran, Japan, Korea, Nepal, Pakistan, and Sri Lanka (18). In Bangladesh, low night temperatures during December and January have popularized a delayed boro season (braus) that starts in February and ends in June, overlapping the aus season (Fig. 10). This practice reduces the use of costly irrigation water (supplied mostly by mechanized pumping or manual lifting). Water use is less in braus rice than in boro. The boro crop does not grow much during December and January because of low temperatures. Vegetative growth is prolonged, requiring more irrigation water.

If irrigation water temperature is higher than air temperature, ponding water in the field will help maintain a higher temperature in the plant body. Because water has a high heat retention capacity, ponded water can buffer low night temperatures. With higher ponded water depths, greater thermal insulation is provided the plant.

At early growth stages, higher field water temperatures affect yield by influencing panicle numbers per plant, spikelet numbers per panicle, and percentage of ripened grains (18). At later stages, air temperatures affect percentages of unfertilized spikelets and percentages of ripened grains. Nishiyama et a1 (11) concluded that increasing the water depth 15-20 cm when air temperature falls below the critical level at the reduction division stage is an efficient method of protecting the rice plant against sterility.

At the other extreme, high temperatures are a critical factor in rice production because they induce spikelet sterility. One hour or more of temperatures exceeding 35 °C at anthesis can cause a high percentage of spikelet sterility (18). Such problems have been reported for Cambodia, Thailand, India, Pakistan, Iran, and tropical African countries.

During a hot summer, the water temperature in a large reservoir is generally cooler than the air temperature. Frequent applications of irrigation water to the field help lower plant body temperatures; a slow but continuous flow maintained



10. Long-term maximum and minimum temperatures and solar radiation. Joydebpur, Bangladesh (14).

in the field can help prevent plant injury due to high temperature. However, such a continuous flow is usually expensive because much of the water ends up in drainage channels and is wasted. In many parts of South and Southeast Asia, rice farmers practice continuous-flow irrigation, although that choice is often unrelated to plant injury. On the other hand, rice irrigation systems are designed and operated on the assumption that water will be drained from the field only at the end of the irrigation season.

Conclusion

Irrigated rice culture is affected by climatic factors in many ways. Rainfall is a major determinant of rice production, not only in a partially irrigated environment but also in an irrigated environment, because of its direct influence on both water availability at the irrigation source and water status in the field. Rainfall patterns affect cropping calendars, cropping intensity, and such cultural practices as land preparation, crop establishment, and crop management. The stochastic nature of rainfall introduces a degree of uncertainty into the production system that challenges irrigation system managers and farmers with water shortages for which they may not be prepared. Scientific planning and designing of irrigation systems and the use of efficient management techniques at both the system and farm levels can help overcome these difficulties.

Apart from rainfall, solar radiation and temperature affect irrigated rice culture significantly. Although apparently these are unalterable factors, manipulations in cultural practices to avoid the deleterious effects of extremes can significantly improve the rice production environment. Research plays a critical role in the choice of such manipulations.

While management improvements are desirable to make the best use of given climatic conditions, development of rice varieties that can perform better within climatic limitations is vital. The combination of improved management and better-performing varieties seems to have the best chance of contributing significantly to increasing rice production.

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Deterministic models

Weather simulation models based on summaries of long-term data

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ABSTRACT

Weather simulation models can be used in connection with crop or disease models to evaluate weather impacts on crop production or agricultural systems. But most available weather simulators require historical dally weather data to specify model parameters. This prevents applying these models to areas where documented historical daily data are unavailable. We propose a new approach in which weather simulation models are constructed from information in monthly summaries. The data simulated by this new approach have compared favorably to data collected by the traditional method and agree closely with the actual data from three locations: Los Baños, Philippines; Davis, California, and Wageningen, The Netherlands.

The growth and development of a plant at any given time can be described as the net result of the interactions of the biochemical and physiological processes of the plant with the environment in which it lives. Inevitably, in modeling plant growth and development, weather conditions or climatological variables must be included to induce plant responses. Detailed models of plant photosynthesis and light (33, transpiration and temperature (6), and crop canopy structure and micrometeorology (9,18) developed in the last 20 yr have laid the foundation for approaches to crop simulation.

The impact of weather on crop yields and on planning decisions in agriculture has been studied for many years by many researchers (1,10,16,17). Successful applications of crop models for agricultural systems evaluation and analysis can be seen in de Wit and Penning de Vries (4). The approach is well documented and described in Penning de Vries and Van Laar (14).

To further advance simulation technology for crop models and its applicability in cultural practice and field management, in evaluating weather impacts on crop production, and in forecasting crop performance, weather models must be fully developed in conjunction with crop models.

Several weather simulation models have been developed in the last several years (2,11,13,15).These models provide useful tools for analyzing the impact of weather on agriculture and on the risks associated with alternative management decisions. However, to use these models, many years of daily weather records for a particular location are needed to generate the necessary estimates of a model's parameters. This requirement imposes a serious restriction and greatly limits applications of the technique in areas where long historical weather records do not exist or are not accessible.

Recently, Geng et al (8) proposed a method in which only data from monthly summaries are needed to deduce model parameters for rainfall simulation. That method takes advantage of certain empirical relationships that exist between model parameters across environments and simplifies the method of estimation. The objectives of this paper are:

- To extend the idea presented by Geng et a1 by constructing weather models for maximum temperature, minimum temperature, and solar radiation, that is, to construct weather simulation models based on data from monthly summaries, and
- To use the proposed weather model to evaluate variation in rice production.

Method and Analysis

Geng et al (7), in their review of several weather simulation models, found the models of Larsen and Pense (11) and Richardson and Wright (15) the most comprehensive and thoroughly tested. But in application, each has advantages and disadvantages. Richardson and Wright's model (RWM) requires the fewest parameters and is the simplest to apply. And, it is capable of producing representative data for a large number of locations. For these reasons, we adapted RWM as the long method model against which we developed short method models based on monthly summaries.

Long method

Richardson and Wright's model can generate samples of daily precipitation, maximum temperature, minimum temperature, and solar radiation. Precipitation was assumed to follow a Markov chain-gamma distribution; the other variables were considered to follow the Fourier series models conditioned on the rainfall status of the day. Daily fluctuations of temperature and radiation were generated from a trivariate normal distribution.

Let X_{ij} represent the ith daily observed value of the jth meteorological variable (j = 1 represents maximum temperature, j = 2 represents the minimum temperature, j = 3 represents solar radiation). Then,

$$X_{ij} = \bar{X}_{ij} (1 + d_{ij} C_{ij}) \quad (1)$$

where $\overline{X}$ is the estimated mean and C_{ij} is the estimated coefficient of variation (CV) of the jth variable at the ith day. d_{ij} is a noise factor associated with X_{ij}. Both $\overline{X}_{ij}$ and C_{ij} are assumed to follow the simple Fourier model,

$$Y_{ij} = a_{oj} + a_{lj} \text{ COS } [2 (i-q)/365] \qquad (2)$$

where Y_{ij} is either X_{ij} or $C_{ij} \cdot a_{oj}$, a_{lj} and q are coefficients of the cosine model estimated from historical data. Note that a_{oj} is the annual mean, a_{lj} is the amplitude of the cosine curve, and q is the Julian date at which the peak of the curve occurred. The noise factor, d_{ij}, is assumed to follow a weakly stationary generating process,

$$d_i = B_o\, d_{i-1} + B_l e_i \qquad (3)$$

where d_l represents the vector of d_{il}, d_{i2}, and d_{i3}, and

$$B_o = R_l RO^{-1},\ B_l B_l' = R_o - R_l RO^{-1} R_{l-}'$$

R_O is the cross correlation matrix between X_{ij}'s for j = 1,2, and 3. R_l is the serial correlation matrix with lag-1 day between the 3 variables. e_i is normally distributed with a zero mean vector and variances and zero covariances.

After testing at 31 locations in the United States, Richardson and Wright were able to replace a number of model parameters by estimated constants and to combine several models into fewer representations. RWM was used to generate data on rainfall, maximum temperature, minimum temperature, and solar radiation for Los Baños, Davis, and Wageningen. Model parameters were estimated for 25 yr of data for Los Baños, 18 for Davis, and 10 for Wageningen.

Short method

The short method of constructing simulation models is based on the assumption that only monthly summary data are available for a location and that all model parameters must be estimated from that monthly information. Theoretically, if a simple Fourier model is adequate to describe the mean distribution of a weather variable, then the model can be estimated by monthly means as well as by daily means. This model depends on only three parameters (equation 2), which can be estimated adequately by 12 data points around the curve.

One problem in using monthly summaries is that indirect methods must be used to separate the overall mean into means for dry days and means for wet days. This problem is particularly important for maximum temperature and solar radiation, since previous work (11,15) has demonstrated that these means depend on rainfall status. Several combinations of meteorological and geographical variables were made to characterize the mean difference between dry and wet days and certain meaningful expressions were found.

Another difficulty in using monthly data is that they provide no information on yearly variation by day or month. Our approach was to express the model parameters of the CV's curve as functions of the model parameters of the mean curve. The functional relationship of the two sets of parameters was established from locations where both sets of parameter estimates were calculated by Richardson and Wright.

Mean difference. Because the mean difference in minimum temperature for dry and wet days was shown to be not significant by Richardson and Wright, the following procedure to separate means is recommended for maximum temperature only. As the first attempt to simplify the problem, we assumed that the difference between dry and wet means is a constant across years, and that it depends on the number of rain days. Fitting the data of 31 locations from Richardson and Wright's reports with Los Baños, Davis, and Wageningen data establishes this regression equation,

$$d_t = 10\,(1\text{-}2\,f) \tag{4}$$

where d_t is the temperature difference (°F) between dry and wet days and f is the fraction of number of rain days in a year for a location. This equation should be used cautiously, only for f values approaching 0.1 or 0.5, and should not be used for f values greater than 0.5.

About 71% of the total variation at these locations can be explained by this representation. This simple relationship permits an objective way to estimate means for dry and wet days from the overall mean ($\bar{X}_t$),

$$\bar{X}_t\,(\text{dry day}) = \bar{X}_t + d_t f$$

and

$$\bar{X}_t\,(\text{wet day}) = \bar{X}_t - d_t\,(1\text{-}f)$$

These means can then be used to adjust the coefficient a_{o1} in the Fourier Series model (equation 2), which can then be applied to generating daily maximum temperatures for a given rain status of a day.

For solar radiation, the following equation is useful:

$$d_s = \text{ABS}\,[410 - 3.12\,(\text{latitude}) - 0.35\,(\bar{X}_s)] \tag{5}$$

where $\bar{X}_s$ is the overall average of solar radiation (langley). The R^2 of this equation is only 0.36, but all coefficients are significantly different from zero ($p < 0.01$). The coefficient a_{o2} in equation 2 can be adjusted accordingly for dry days and wet days,

$$\bar{X}_s\,(\text{dry day}) = \bar{X}_s + d_s f$$

and

$$\bar{X}_s\,(\text{wet day}) = \bar{X}_s - d_s\,(1\text{-}f)$$

where f is the fraction of wet days in a year.

Coefficient and variation. The CV curves for maximum and minimum temperatures need to be estimated for any location where weather simulation is applied. The coefficients in equation 2 for solar radiation are assumed constant, as in the long method (15).

From the 34 locations observed (used to establish equation 4), Fourier curves of the CV appear to be the inverse images of the Fourier curves of means, ignoring the units. The parameters of the two types of curves tend to correlate negatively. Let V_{ij} be the mean value of CV for the jth variable (j = 1 is the maximum temperature, j = 2 is the minimum temperature) of the ith day. Then, for the maximum temperature,

$$V_{i1} = (0.536 - 0.00573\, a_{01}) - \text{Exp}\,(-4.63 + 0.0952\, a_{11}) \qquad \text{COS}\,[2\,(i-q)/365] \quad (6)$$

where a_{01}, a_{11}, and q are the mean, amplitude, and days to peak of the mean curve of the maximum temperature. Thus, all parameters of the CV-curve are expressed in terms of the parameter of the mean curves.

Similarly, the CV-curve of the minimum temperature is approximated as

$$V_{i2} = \text{Exp}\,(-0.0466\, a_{02}) - \text{Exp}\,(-4.64 + 0.146\, a_{12}) \qquad \text{COS}\,[2(i-q)/365]$$

where a_{02}, a_{12}, and q are the mean, amplitude, and days to peak for the mean curve of the minimum temperature. V_{i2} is the mean CV of minimum temperature for the ith day.

With the empirical equations 4, 5, 6, and 7, all parameters of RWM can be estimated from monthly summary data. The short method described can be considered an approximation of the RWM.

Comparison and Results

Fortran computer simulation programs for the short method were developed on the minicomputer (DEC LSI 11/73) at the Department of Agronomy and Range Science, University of California at Davis. Programs for the long method were taken from Richardson and Wright (15) and adapted to our computer system. Simulations were performed as many times as the years of available data: 25 yr for Los Baños, 18 yr for Davis, and 10 yr for Wageningen. The actual data and simulation are summarized and presented in Tables 1, 2, and 3. Standard deviations between years were also calculated.

In all cases, the monthly means generated by both long and short methods closely resemble the actual data. The seasonal patterns of the means are well preserved by the simulation for all three meteorological variables and at all locations. The maximal difference between the monthly means of actual and data simulated by the short method for maximum temperature are less than 2.3 °F for Los Baños, 4.5 °F for Davis, and 5.9 °F for Wageningen; for minimum temperature, they are less than 3.1 °F for Los Baños, 0.2 °F for Davis, and 3.9 °F for Wageningen. On a yearly basis, in no case was the difference more than 3% of the actual mean. The averages of simulated data are in close agreement with averages of actual data. The difference between the long and short simulation methods is negligible for all three variables evaluated at all three locations.

The monthly extremes of the actual data and the simulated data over the years are plotted with the monthly means in Figure 1 for maximum temperature,

Table 1. Monthly mean and standard deviation (SD) of maximum and minimum temperatures and solar radiation at Los Baños.

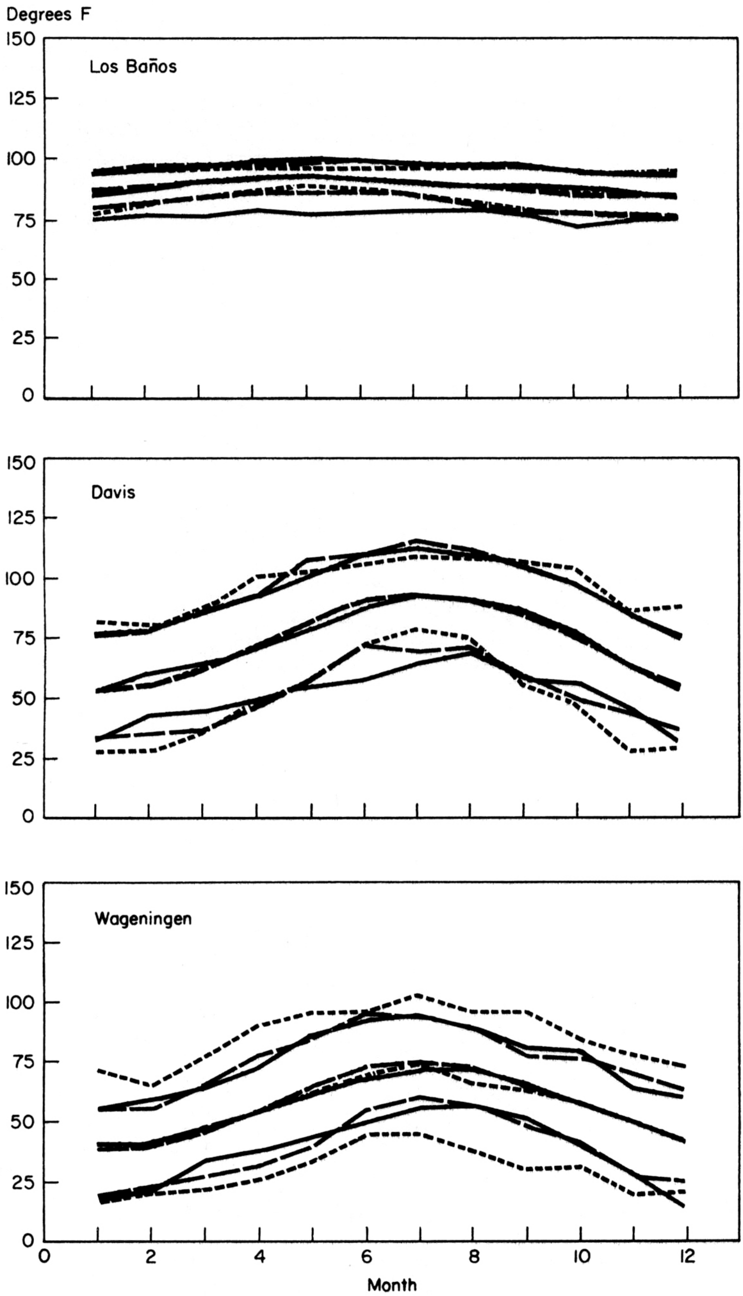
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Av
						High temperature (°F) (real data)							
Mean	84.20	86.30	89.30	92.80	93.40	91.30	89.30	88.80	88.80	87.90	86.30	84.50	88.58
SD	3.38	3.93	3.56	2.74	3.59	3.34	3.08	3.22	2.98	3.07	3.03	3.32	3.27
						(simulation - long method)							
Mean	36.80	89.00	90.60	91.90	92.10	91.60	90.10	88.20	86.10	85.30	84.40	85.20	88.44
SD	2.96	3.88	2.45	2.20	2.26	2.30	2.42	2.71	2.98	2.99	3.03	3.1 6	2.70
						(simulation - short method)							
Mean	86.50	88.30	90.10	91.50	92.30	91.80	90.50	88.70	87.10	85.70	85.00	85.10	88.55
SD	3.13	2.41	1.93	1.53	1.21	1.43	1.85	2.28	2.96	3.17	3.42	3.26	2.38
						Low temperature (°F) (real data)							
Mean	69.40	69.20	70.60	73.00	74.60	74.40	74.00	73.80	73.70	73.20	72.60	71.40	72.49
SD	2.36	2.79	2.34	1.92	1.69	1.69	1.81	1.75	1.83	1.73	1.88	2.25	2.00
						(simulation - long method)							
Mean	71.30	72.30	73.30	74.10	74.60	74.50	73.80	72.50	71.30	70.60	70.30	70.80	72.45
SD	2.13	2.07	1.81	1.54	1.42	1.49	1.70	1.91	2.20	2.24	2.31	2.37	1.93
						(simulation - short method)							
Mean	71.00	72.30	73.50	74.30	74.90	74.70	73.70	72.60	71.70	70.30	70.40	70.20	72.47
so	2.82	2.34	1.90	1.61	1.33	1.50	1.79	2.19	2.87	2.98	3.10	2.95	2.28
						Solar radiation (Langley) (real data)							
Mean	340.30	415.80	488.50	542.70	495.20	437.90	405.50	390.10	384.00	371.20	325.70	298.20	407.93
SD	108.18	115.42	120.58	113.22	136.83	132.86	146.31	148.55	135.33	135.14	127.07	109.00	127.37
						(simulation - long method)							
Mean	416.10	475.40	410.30	521.00	493.80	451.20	396.50	365.70	318.00	305.10	309.70	349.50	409.36
SD	127.85	116.15	111.28	113.99	123.81	147.21	152.38	155.69	143.98	144.96	144.80	139.81	135.16
						(simulation-short method)							
Mean	411.20	495.40	528.20	553.10	506.00	423.70	368.30	349.30	284.40	306.40	284.60	337.80	404.03
SD	139.51	136.22	132.99	128.06	148.54	165.13	167.33	165.32	158.67	154.66	153.15	150.44	150.00

Table 2. Monthly mean and standard deviation (SD) of maximum and minimum temperatures and solar radiation at Davis.

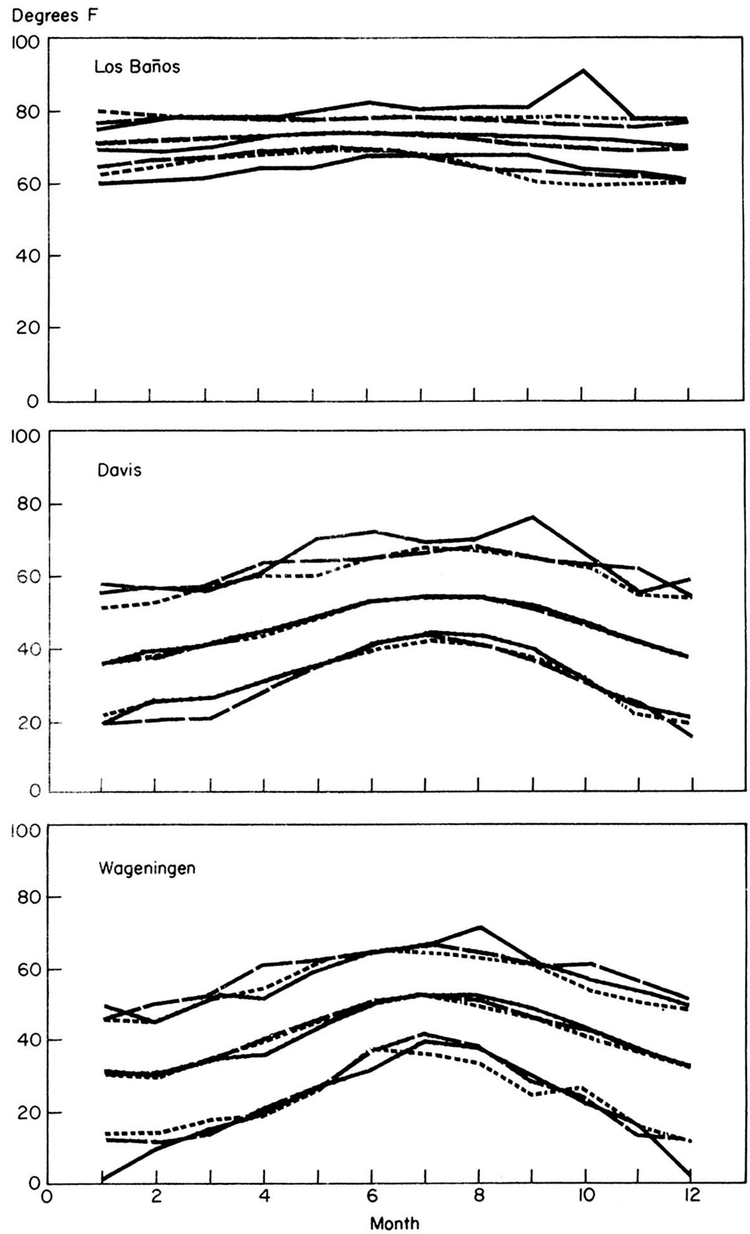
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Av
						High temperature (°F) (real data)							
Mean	52.90	60.20	64.50	70.60	79.80	87.60	92.50	91.30	86.80	77.40	62.80	52.60	73.25
SD	6.83	6.12	7.34	8.87	9.46	9.14	6.88	7.15	7.54	8.79	7.53	6.83	7.71
						(simulation - long method)							
Mean	53.20	54.80	62.00	71.50	82.10	90.70	93.80	92.20	84.70	74.40	63.50	55.00	73.16
SD	7.20	7.54	8.63	7.81	8.37	7.09	6.76	7.06	7.89	8.15	7.50	7.16	7.60
						(simulation - short method)							
Mean	52.50	55.70	63.40	72.40	82.50	91.00	93.50	91.60	85.30	74.80	63.90	54.30	73.41
SD	9.52	9.02	9.70	9.04	7.57	5.47	5.11	5.47	7.69	9.48	9.32	9.66	8.09
						Low temperature (°F) (real data)							
Mean	36.10	39.90	41.00	43.50	48.60	53.90	54.60	54.90	52.50	47.70	41.70	37.00	45.97
SD?	7.26	5.87	5.70	5.63	5.50	5.24	4.06	4.25	4.97	5.12	6.45	7.35	5.62
						(simulation - long method)							
Mean	37.50	37.40	41.60	45.40	50.00	54.10	55.30	55.20	61.30	46.70	41.90	38.00	46.20
SD	6.26	6.14	6.38	6.05	5.41	4.13	4.17	4.47	5.20	6.08	6.17	6.48	5.58
						(simulation - short method)							
Mean	36.20	38.20	41.60	45.40	49.80	54.20	55.40	54.60	51.40	46.50	41.80	37.40	46.04
SD	5.21	5.1 2	5.52	5.42	4.79	4.21	4.61	4.31	4.93	5.45	5.21	5.53	5.03
						Solar radiation (Langley) (real data)							
Mean	181.60	281.20	409.50	548.30	651.40	700.20	711.10	632.90	513.50	363.80	221.80	160.00	447.94
SD	89.54	113.58	139.20	147.01	123.79	106.49	63.27	77.20	84.63	90.52	88.94	79.08	100.60
						(simulation - long method)							
Mean±	179.00	277.90	400.80	541.90	663.30	697.40	680.30	596.30	466.70	325.70	209.90	154.00	432.77
SD	84.33	99.63	122.34	121.60	99.42	102.13	93.94	96.08	108.63	96.41	84.62	75.85	98.75
						(simulation - short method)							
Mean	183.10	271.10	397.80	540.00	667.50	708.20	687.90	612.90	468.60	335.10	208.90	147.10	435.68
SD	81.40	107.88	121.11	126.43	98.53	95.32	88.47	90.84	109.65	94.14	84.93	78.27	98.08

Table 3. Monthly mean and standard deviation (SD) of maximum and minimum temperatures and solar radiation at Wageningen.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Av
						High temperature (°F) (real data)							
Mean	40.80	41.30	48.00	54.10	62.20	67.90	71.20	71.70	65.70	57.00	48.20	41.60	55.81
SD	7.64	7.30	5.62	7.50	8.41	8.05	7.86	6.75	5.15	6.09	6.89	7.27	7.05
						(sirnulation - long method)							
Mean	38.10	39.40	45.70	55.20	64.60	72.50	74.80	72.50	64.30	58.30	48.20	41.40	56.25
SD	6.71	6.05	7.87	7.81	8.11	6.15	6.19	6.44	6.57	7.72	7.88	7.03	7.04
						(simulation - short method)							
Mean	41.10	39.10	48.90	53.70	72.80	69.20	74.1 0	65.80	62.90	56.80	49.90	43.30	55.63
SD	9.12	8.96	10.46	11.73	12.08	11.21	1 1.59	10.74	12.33	10.46	11.31	9.41	10.78
						Low temperature (°F) (real data)							
Mean	31.70	30.70	34.90	35.80	43.40	49.80	53.10	52.60	48.90	43.50	37.70	32.50	41.22
SD	8.77	6.99	6.47	6.39	6.41	5.71	5.21	5.54	5.98	6.91	7.55	8.04	6.66
						(simulation - long method)							
Mean	30.40	31.50	35.20	40.70	46.40	51.00	52.90	51.10	46.30	42.90	36.60	32.90	41.49
SD	6.59	5.92	7.07	7.21	6.10	4.73	4.45	4.97	5.55	6.66	7.46	7.19	6.16
						(simulation - short method)							
Mean	30.00	29.40	35.40	39.70	45.60	50.00	53.00	49.40	45.90	41.00	36.10	32.20	40.64
SD±	5.47	5.96	6.07	6.40	6.18	4.71	4.68	4.88	5.73	5.67	6.22	5.62	5.63
						Solar radiation (Langley) (real data)							
Mean	52.60	109.90	178.40	311.40	387.00	403.40	387.00	345.60	234.80	133.20	65.90	41.80	220.92
SD	34.12	64.60	94.89	133.84	161.63	154.19	146.56	115.19	95.81	65.21	36.49	25.46	94.00
						(simulation - long method)							
Mean	27.20	100.50	196.20	311.90	408.40	446.00	430.00	345.50	246.10	124.70	42.40	19.20	224.84
SD	32.36	57.47	85.55	99.37	113.04	118.61	99.59	106.40	85.09	68.06	39.47	18.29	76.94
						(simulation - short method)							
Mean	51.20	115.80	200.80	300.40	377.10	420.10	413.50	346.50	248.70	138.70	58.90	50.00	226.81
SD	61.19	91.51	103.23	123.93	123.75	124.96	125.47	115.93	110.12	94.43	68.25	50.87	99.47

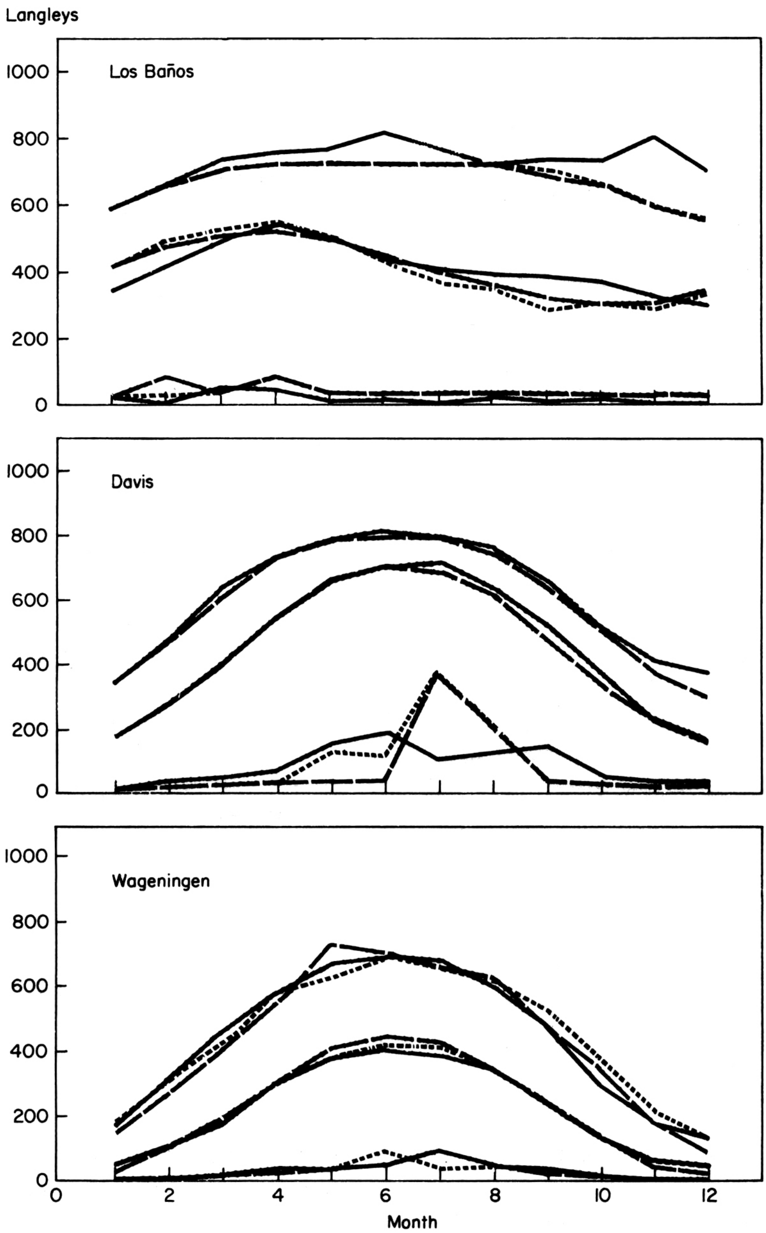


1. Average and extreme maximum temperatures for actual data (_____), simulation by long method (– – –), and simulation by short method (----).



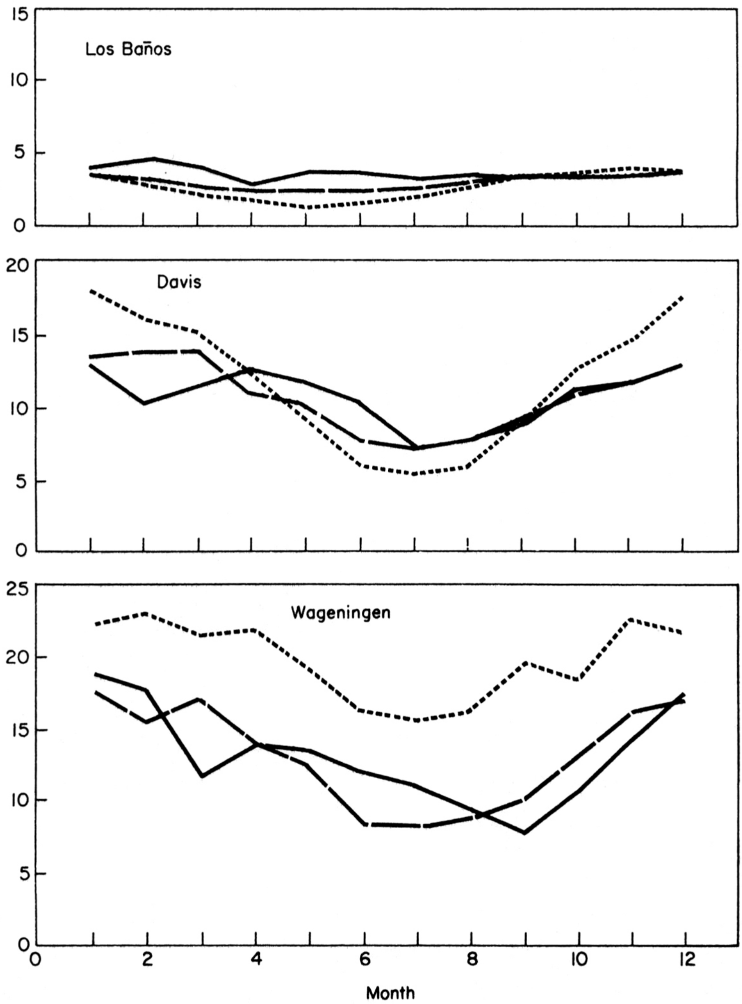
2. Average and extreme minimum temperatures for actual data (____), simulation by long method (– – –), and simulation by short method (----).

in Figure 2 for minimum temperature, and in Figure 3 for solar radiation. The simulated means follow the actual means closely. The extreme values show that the simulation slightly underestimated the potential extreme variation between



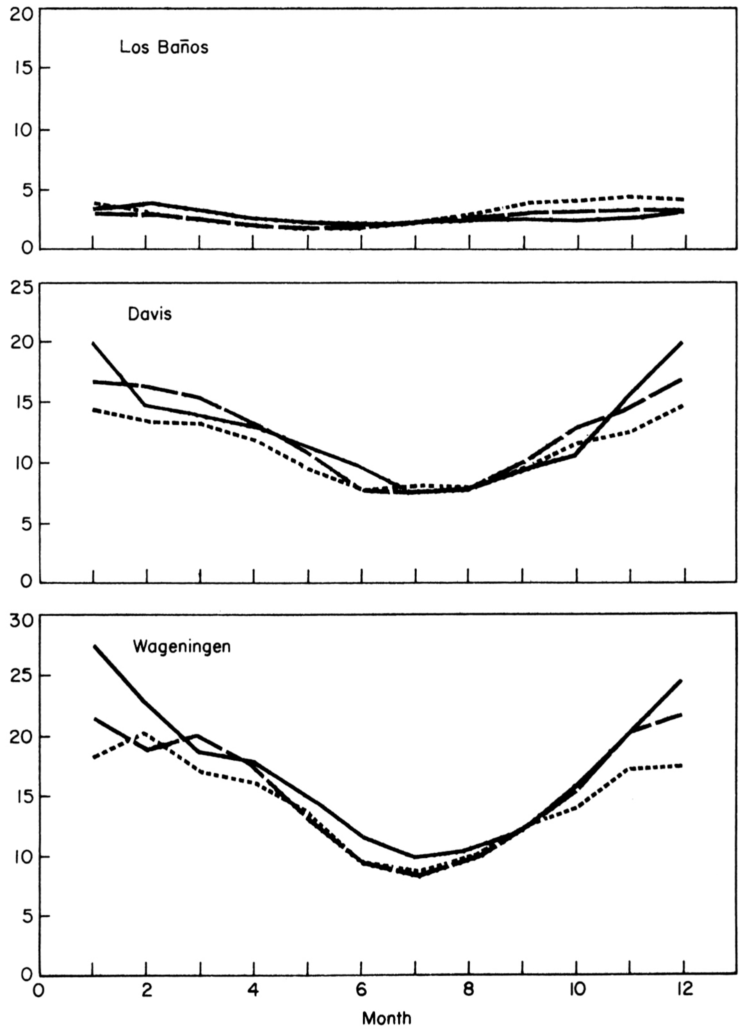
3. Average and extreme solar radiations for actual data (_____), simulation by long method (– – –), and simulation by short method (----).

years for both maximum temperature and minimum temperature at Los Baños. Also, the short method somewhat overestimated the yearly extremes of maximum temperature at Wageningen.



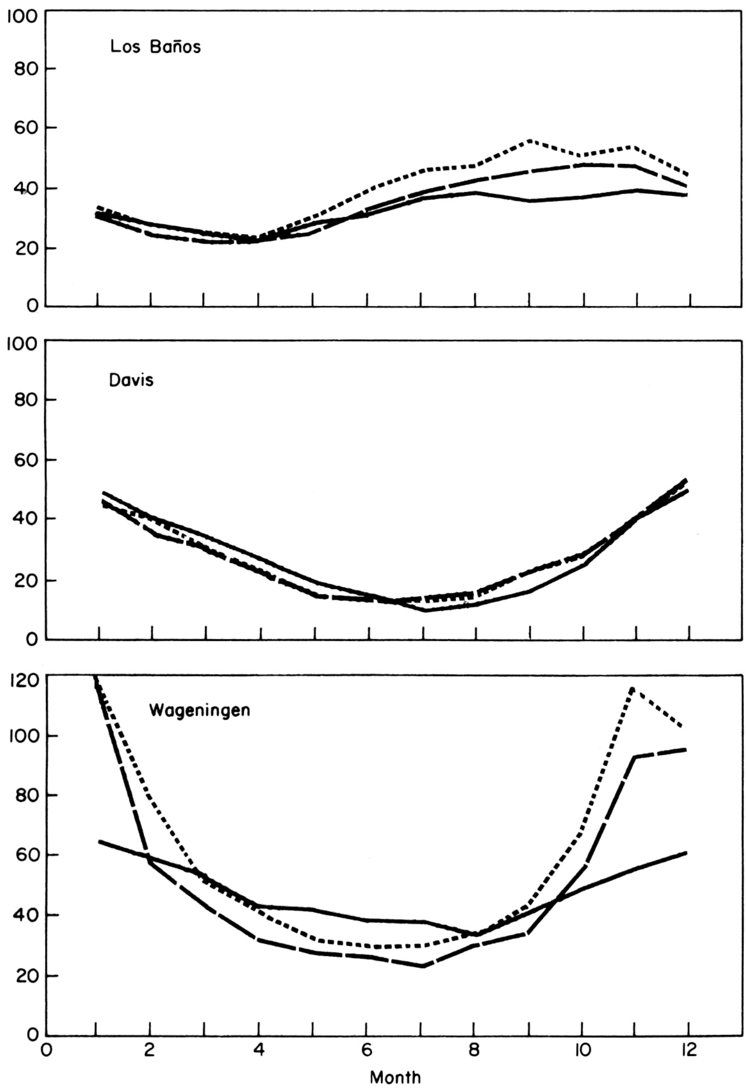
4. Coefficient of variation of the maximum temperature for actual data (—), simulation by long method (— — —), and simulation by short method (- - -).

The standard deviations calculated between years were divided by the means and converted to CV's for the maximum temperature (Fig. 4), minimum temperature (Fig. 5), and solar radiation (Fig. 6). The only notable discrepancy is that the short method produced consistently greater CV's than the actual data and the long method for maximum temperature in Wageningen. Otherwise, the CV curves of simulation data are in reasonable agreement with the CV curves of the actual data. These results are very important, because the capability of a simulation model to generate comparable yearly variation is necessary if the model is to be applied to study weather impact.



5. Coefficient of variation of minimum temperature for actual data (—), simulation by long method (— — —), and simulation by short method (- - -).

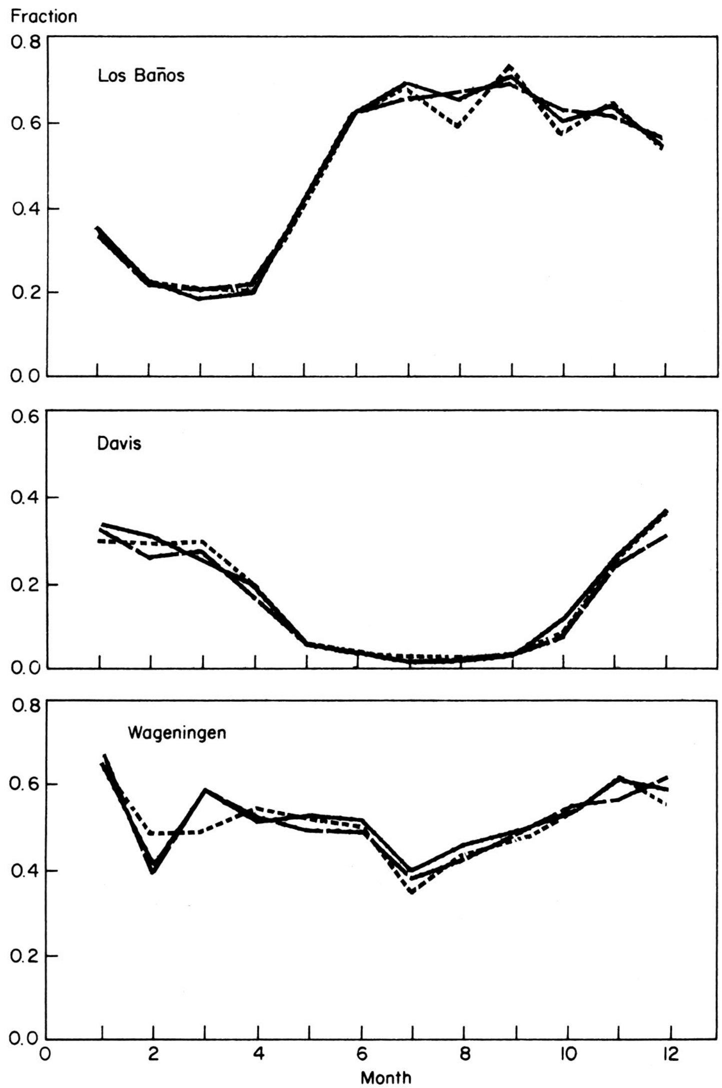
It should be noted that the temperature and solar radiation data were generated conditionally on the status of rainfall of a given day. Therefore, simulated rainfall data need to be compared with actual data. Figure 7 shows the means for monthly fractional wet days in the actual data and the simulated data of the three locations. Figure 8 shows the monthly means of the amount of rain (mm) per wet day. Obviously, rainfall means simulated by both long and short methods are in good agreement with the actual means. Again, there is no difference between the long and short methods, as was documented by Geng et al (8).



6. Coefficient of variation of solar radiation for actual data (___), simulation by long method (– – –), and simulation by short method (- - -).

Discussion and Conclusion

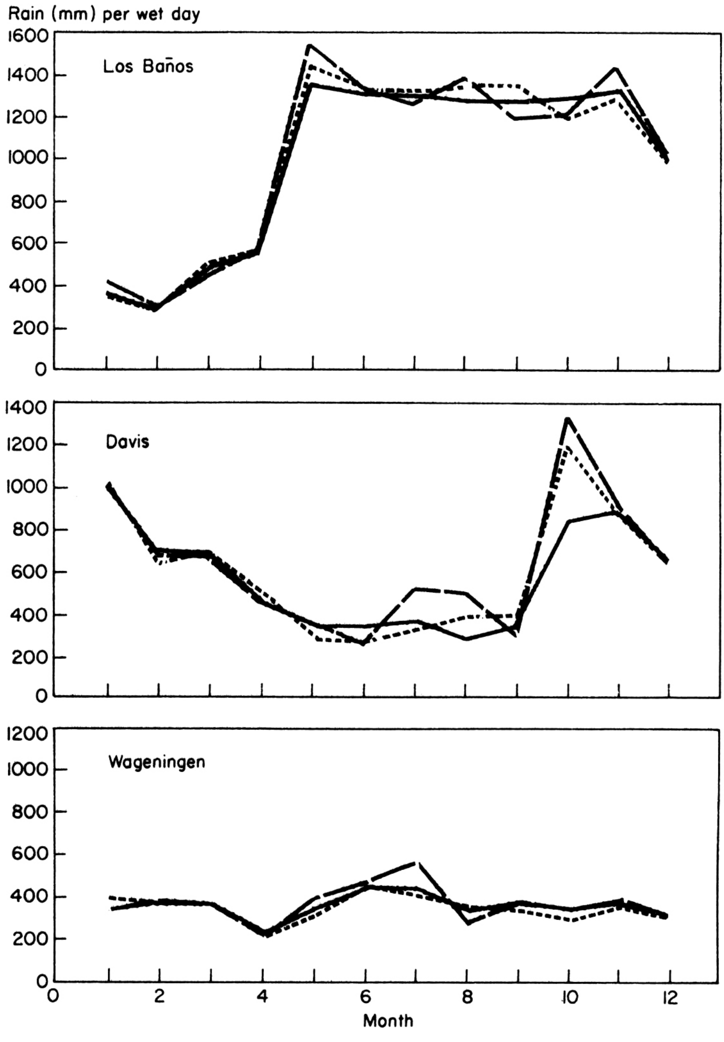
The short method of constructing weather simulation models represents a crude approach to an extremely complex problem. No doubt the models can be further modified for various applications and for emphases on characteristics of the weather variables that must be preserved in the simulation. Further



7. Fraction of wet days for actual data (__), simulation by long method (— — —), and simulation by short method (- - -).

improvement is likely to be achieved by broadening the range of locations over which the short method's relationships are based. In particular, including more weather data from tropical stations would strengthen the applicability of the method to those environments.

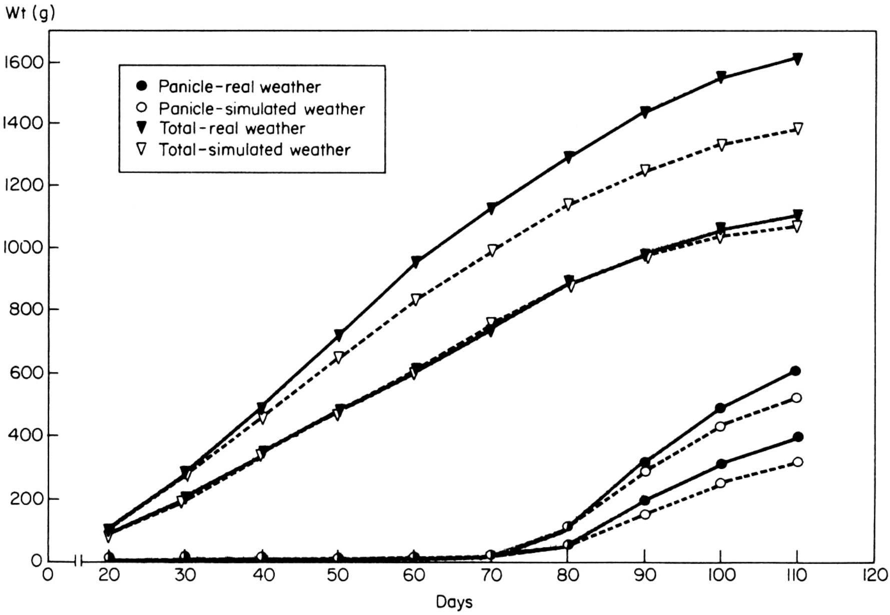
However, the idea that weather simulation models can be constructed from long-term monthly summary records is clearly demonstrated. The fact that, even



8. Amount of rain per wet day for actual data (__), simulation by long method (— — —), and simulation by short method (- - -).

with only limited monthly information, simulation models can be developed that not only can generate expected daily weather values of rainfall, maximum temperature, minimum temperature, and solar radiation, but also can, to a large extent, produce similar yearly variations to those observed in nature is truly remarkable.

The approach that we have taken provides a useful tool for analyzing and simulating weather impacts on agriculture for locations where historical daily weather data are unavailable. It also provides a convenient vehicle for interfacing with crop models for production evaluation.



9. Total weight and panicle weight of rice plants generated by RICEMOD interfaced with actual weather data and weather data simulated by short method. The growth curves are approximately the 95% confidence limits of the mean growth curves based on 25 yr data.

To illustrate the interface, we used a rice model — RICEMOD (12) — to evaluate the possible weather impact on rice production. Actual weather data and short-method simulated data were used for the simulation. Twenty-five growth simulations were performed for each set of weather data (true evapotranspiration data were used for both cases). The means, plus and minus two standard deviations, were plotted for panicle weight and total weight (Fig. 9). It can be seen that the approximate 95% confidence limits of panicle weight produced by the simulated data are slightly less than those produced by the actual data. The 95% confidence limits from the simulated data are within the limits generated from the real data. These results are to be expected, since the simulated weather data were in some ways less variable than the actual data at Los Baños (Figs. 1-3). The lower panicle weight with the simulated weather data is probably due to the underestimated solar radiation in August, September, and October in Los Baños.

This discrepancy may or may not be important, depending on application objectives. It points out, however, that further effort devoted to developing simulation models with better performance in producing yearly variations may be worthwhile.

Acknowledgment

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Crop modeling: applications in directing and optimizing rainfed rice research

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ABSTRACT

The critical role of weather-dependent soil water status in rainfed rice cultural systems is well documented. A systems analysis approach is needed to direct and focus research on the major complex interactions spawned by variable soil-water statuses in drought-prone rainfed rice areas. IRRI's interdisciplinary rainfed rice research program is used as an example. Crop modeling automatically results in a critical analysis of our state of knowledge, exposing deficiencies in quantitative documentation. In model building, the review and evaluation of knowledge phase leads intuitively to research priorities. In addition, the systems approach creates awareness among administrators and scientists alike of the economic and intellectual benefits of interdisciplinary research. Using crop simulation models to pretest new genetic and agronomic technology has long been considered desirable. The conceptual plant type model used to develop a hypothetical intermediate plant type adapted to the drought-prone region of north India was simulated using a crop model sensitive to numerous genetically controlled morphological and physiological traits. The simulation model could differentiate between modern high yield (HYV), traditional (TRD), and new intermediate (INT) plant types. Through simulation, the 3 plant types were tested using 20-yr data of varying weather and soil physical properties characteristic of the target environment. The simulations supported the conceptualization that the new INT plant type would have higher potential yields than the current TRD type and greater year-to-year stability of yield than the HW type. In addition, the simulations illustrated that, given the unfavorable nature of this rainfed rice environment, potential yields would be lower than the conceptual model goal. The drought-resistant traits conferred on the new INT plant type were shown to exhibit spatial variability due to the limited root system development associated with varying soil bulk densities in the target area. Crop modeling is seen as a sound tool for research direction and as a way to test new genetic technology before undertaking the resource-intensive, long-term activities of breeding and selection. The model building process and simulation capability may contribute significantly to agricultural research efficiency, especially where highly variable rainfall distributions decrease the effectiveness of standard research techniques.

Weather factors impact the rice crop, influence agroclimate zoning and land-use planning, and affect the determination of rice-based cropping systems. Indirectly, weather exerts its influence on many of the biotic stresses that determine rice growth and yield. In addition, abiotic physical-chemical environmental factors react with the crop directly (solar radiation) or indirectly (rainfall through soil moisture).

Rice cultural systems are most readily classified by the hydrological background in which they function. Irrigated rice is buffered against many weather-related chemical and physical constraints to growth. Rainfall is the most important weather parameter affecting nonirrigated crop areas; the greatest constraints to rainfed rice yields worldwide are water deficits and excesses.

We consider only drought-prone rainfed rice here. It is a significant (approximately 35 million ha) component of the world's rice area (10, 17). Year-to-year rainfed rice production is intimately related to weather dynamics.

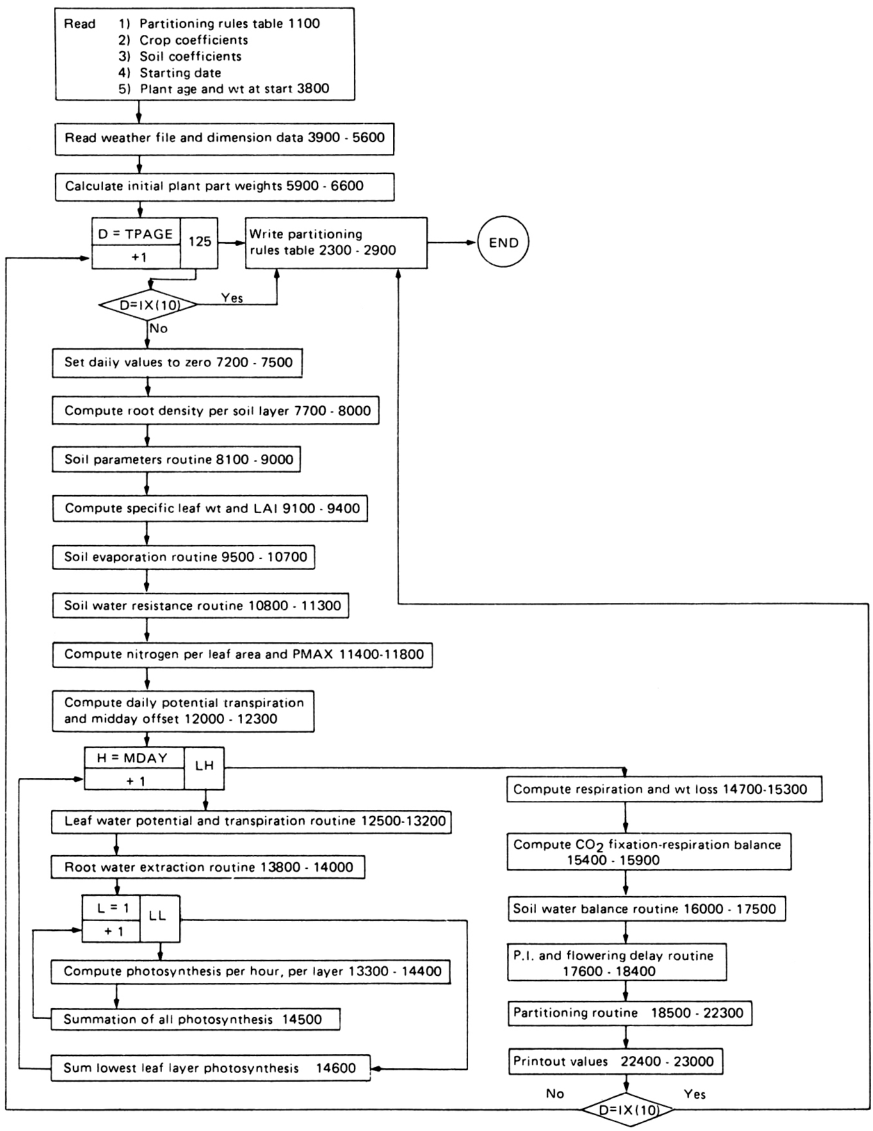
The growth and yield of rainfed rice can be impacted by a host of environmental factors. In the drought-prone rainfed rice sector, water deficit plays a pivotal role, interacting with physiographic, edaphic, climatic, hydrologic, biotic, and agronomic factors to determine yields. The complexity and variability of these interactions were summarized by O'Toole and Chang (16). It is obvious that, to gain a comprehensive understanding of weather's impact on rainfed rice growth and yield, a systems analysis approach is needed.

Individual researchers who have long experience in a particular rainfed rice area can provide an empirically based, short-term prediction of yield for that locale. But a simulation model is necessary to expand those particular predictions to include all salient parameters, to take into account their secondary and tertiary interactions, and to predict growth and yield at diverse locations and over diverse weather patterns covering 20-40 yr periods. Models currently being developed can generate particular environmental parameters, such as weather, when long-term historical data are insufficient. Crop modeling has the potential to direct and to optimize rainfed rice research.

Research Directions

Determining knowledge status and setting priorities

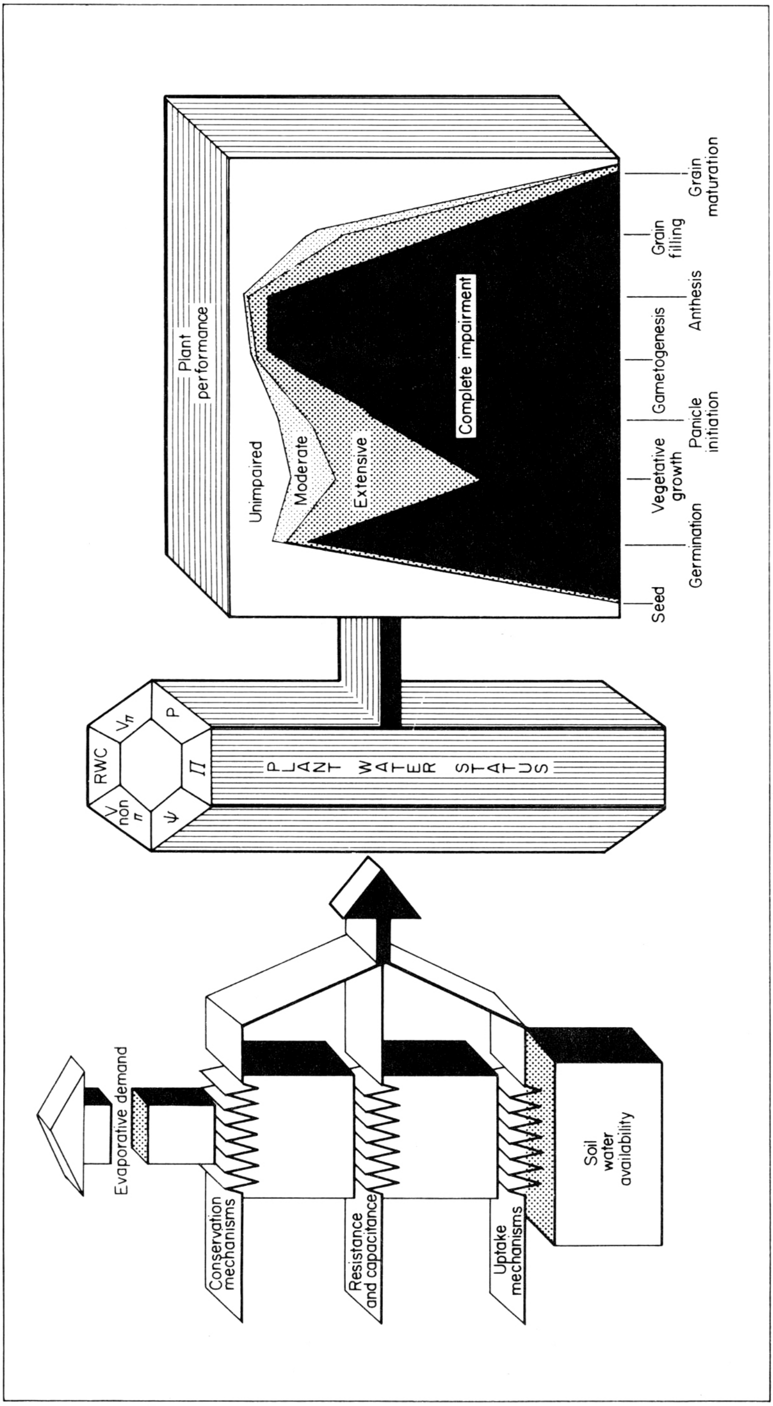
By its very nature, crop modeling is an exercise in assessing what is known and, more importantly, what is not known, poorly understood, or lacking in quantitative documentation. Crop modeling usually requires a systems analysis approach which, because of the complexity of interacting components and number of required iterations, demands computer assistance. The framework or skeleton of a model is the flow chart which illustrates the basic components and, to some degree, their linkages. Figure 1 illustrates how RICEMOD (14) attempted to link crop physiology with the physical environment — primarily



1. Flowchart for RICEMOD 300. The model illustrates how rainfall affects (indirectly, through soil moisture dynamics) soil physical and crop physiological components. Line numbers refer to program listing (14).

climatic information, from which a soil water balance was derived. The flow chart symbolizes an attempt to organize and structure knowledge.

Much less complex conceptual models or thought processes also lead to the organization and evaluation of information that is basic to a systems analysis approach. Figure 2 illustrates a conceptual model of IRRI's research into how



2. A conceptual model illustrating the interaction of water movement through the soil-plant-atmosphere continuum, plant water status, and crop growth stage sensitivity to water stress (20).

the soil-plant atmosphere continuum determines plant water status (itself a complex mixture of measurable units) and how water status is transduced to plant performance, depending on growth stage sensitivity.

Crop modeling can be conceptual or computer based. The common goal is the important point. Both approaches seek to organize and to structure the biochemical and biophysical processes at work in a growing rice crop from a more integrated and dynamic perspective than is associated with discipline-oriented research.

How is a systems approach useful in directing research? The model building process not only demands evaluation of knowledge on particular components of a system, but also requires knowledge of the interactions between components. The interactions may be poorly researched if crossovers between strict disciplines or hierarchial organization levels are required.

Model building is based on quantitative documentation. It is surprising how many of the "understood" relationships in a growing rice crop lack quantitative expression. Attempts at crop modeling automatically result in a critical analysis of our state of knowledge and expose deficiences in quantitative documentation. After evaluating knowledge, assessing salient interactions, and testing quantitative documentation, it is relatively easy to assign priorities and to design new research projects appropriate to overall program goals and resource bases.

In the following section, we demonstrate how crop modeling can generate new research initiatives and modify research priorities. The example is our attempt to model water stress effects on rainfed rice growth and yield.

Feedback from modeling exercise

In 1979, J.A. McMennamy, working at IRRI, began to build a simulation model for irrigated rice with luxuriant water and nutrient availability. The initial model performed well for Los Baños, Philippines, conditions (13). Because water is the most limiting environmental factor in rainfed rice production, a decision was made to incorporate crop response to water stress into the model. Table 1 identifies the major areas where lack of understanding or insufficient data did not allow quantitative expression. Attempts to simulate the soil water balance and belowground processes in general were hindered by that lack of information. Major interactions, such as that of water-nitrogen, could not be documented.

During the model-building process, the deficiences enumerated immediately became high-priority research goals within IRRI's interdisciplinary rainfed rice program. IRRI annual reports (5,6,7,8,9,11) and scientific publications too numerous to cite here demonstrate tangible feedback from modeling to research. In addition, there was a noticeable shift toward interdisciplinary research, bringing soil and plant water relations, soil and water N transformations, and canopy level studies of photosynthesis and dry matter production together for the first time. The systems approach dramatically affected research planning and implementation because of the increased economic and intellectual benefits of coordinated data acquisition and interpretation.

Table 1. High priority research subjects identified during evolution of RICEMOD. Entries represent areas of the rice crop system about which little or no information was available (≅ 1979) on which to base quantitative relationships. Comments refer to availability of information unique to rice, about interactions due to water status in lowland/wetland hydrological conditions (estimation from literature on other cereal species not possible).

	Available information	
	Interaction with drought stress	Hydrological conditions
Soil physical/chemical parameters		
Soil physical or mechanical impedance; its effect on root growth	None	None
Nitrogen-transformations-cycling, etc.	None	Little
Water holding and transmission properties of soil (role of perched water table)	Little	None
Crop parameters		
Canopy level photosynthesis and respiration rates	None	None
Root growth and development/function (location, root length density, radial/ axial resistance)	None	None
Crop level growth stage sensitivity to environmental stresses (drought, flood, salinity, etc.)	None	Little

Optimizing Research

Merging conceptual and simulation models to evaluate new genetic technology

Conceptual model development. In this section, we demonstrate the utility of a rice simulation model in evaluating and testing new genetic technology. The target area is the drought-prone rainfed rice belt across the Indian states of Bihar, Uttar Pradesh, and Madhya Pradesh. In this region, significant rainfall is distributed only from the onset of the southwest monsoon (10-15 Jun) to its withdrawal (about 1 Oct). The monomodal pattern usually brings rainfall totals to 900-1,400 mm during the crop season. Rainfall distribution exhibits high variability, especially from 1 Aug to 15 Sep (19), when increased probability of drought stress coincides with the sensitive reproductive stages of the rice crop.

Over the past two decades, plant breeders and agronomists have studied the regions' innate climatic variation, along with soil water dynamics and genotypic variation in response to drought. From their observations, a conceptual plant type model has evolved. It includes the best traits from the poorly adapted, but high-yielding modern plant type (HYV) and the well-adapted but agronomically inferior traditional plant type (TRD).

During a 1978 International Rice Testing Program monitoring tour in north and eastern India (4), participants from India and other countries with similar problems worked on a plant breeding strategy for the region. During the next 5 yr, as breeders met frequently at Faizabad in eastern Uttar Pradesh, they

Table 2. Attributes of available plant types which lead to conceptual model of an "intermediate plant type" for drought-prone rainfed rice culture.

Attribute [a]	Plant type		
	Traditional	High yield	Intermediate
Yield potential	Low (1.0-2.0 t/ha)	High (4-6 t/ha)	Intermediate (2-4 t/ha)
Yield stability	High	Erratic	Intermediate
Maturity class [b]	105 d	105 d	105 d
Plant height	Tall (1.3 m+)	Short (<.7 m)	Intermediate (1 m)
Leaf area index	Low (<2.5 $m^2 m^{-2}$)	High (6+$m^2 m^{-2}$)	Intermediate (4.0 $m^2 m^{-2}$)
Tiller number/plant	Low (3-8)	High (20-30)	Intermediate (12-20)
Rooting depth	Deep (–1 m)	Shallow (>–.7m)	Deep (–1m)

[a]These attributes were evaluated based on their relevance to rainfed rice production in north central India and on their ability to be manipulated genetically. [b]Rainfall distribution in eastern Uttar Pradesh places a 105-d limit on crop duration.

determined the desirable attributes of a new rice plant type adapted to problematic seasonal rainfall distribution. Through field tests of exotic germplasm and individual conceptual modeling, they resolved the practical questions related to genetic sources and heritability of the desired traits. A large number of crosses to combine these desirable qualities were accomplished at IRRI and at Indian locations. Table 2 lists the most important traits of the hypothetical new cultivar and their relative "intermediate"degree of expression. The hybridization-selection process is still in progress. The creation and testing of new cultivars can take 7-10 yr or longer where high year-to-year climatic variability decreases the repeatability of results.

A great deal of effort and resources are being committed to testing the conceptual model of a new rice plant type. If a simulation model programmed with sensitivities to the genetic differences in HYV and TRD were available, the conceptual model could be evaluated quickly to confirm that indeed, combining these traits would give the desired results.

Simulation model development. To develop and test such a model, we modified the generic crop growth and yield model ALMANAC, which is a submodel of the Erosion-Productivity Impact Calculator (EPIC) (21). We validated the rice model's ability to simulate rainfed rice yield using data from experiments conducted at IRRI on vegetative stage water stress (1) and on the more difficult problem of reproductive stage water stress (2).

Table 3 gives the genetic coefficients which allow ALMANAC to simulate the three plant types — HYV, INT, and TRD. Briefly, GK accounts for differences among the plant types in harvest index or the fraction of total biomass which becomes the economic product. DMLA is the maximum leaf area. HMX and RDMX represent the limit of crop height and rooting depth. In ALMANAC, potential crop growth is a linear function of intercepted photosynthetically active radiation (PAR) during a day. The model converts PAR to kg dry matter increase/ ha. Water stress, as well as other stresses, reduces the conversion efficiency.

Table 3. ALMANAC model parameters used to simulate genetically controlled characteristics of modern semidwarf high yield variety, plant type (HYV), intermediate plant type (INT), and traditional or land race plant type (TRD).

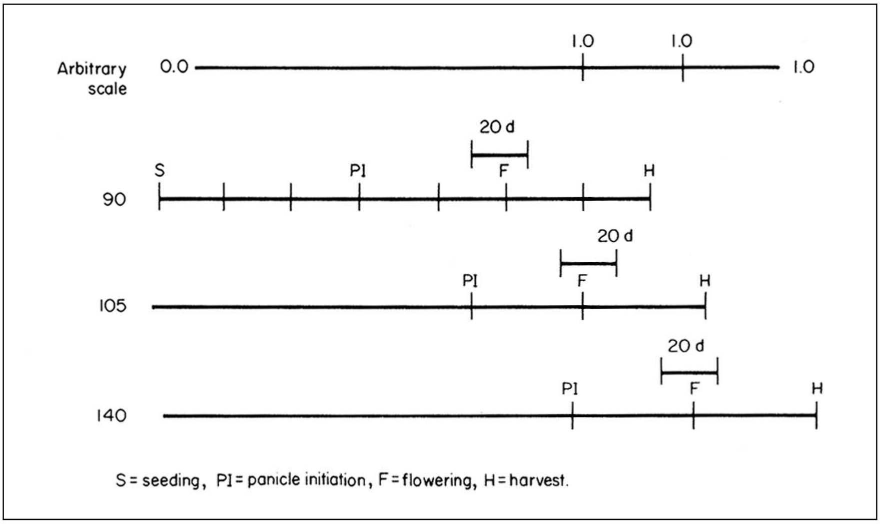
Parameter	Descriptor	Value		
		HYV	INT	TRD
GK	Total biomass (including roots) = economic yield	2.40	2.67	3.40
	(conventional harvest index)	(0.42)	(0.37)	(0.29)
DM LA	Maximum leaf area index ($m^2 m^{-2}$)	7.5	5.0	4.0
HMX	Maximum crop height	0.75 m	1.0 m	1.5 m
RDMX	Maximum root depth	0.7 m	1.0 m	1.5 m
GEX	Water stress effect on efficiency of radiation conversion to biomass	2.0	1.5	1.5
WSX	Harvest index sensitivity to water stress	2.0	1.5	1.5
HIS	Minimum limit of harvest index reduction	0.99	0.99	0.99

Because the HYV is more susceptible to water stress than the TRD, the exponential variable GEX is higher for the HYV. Research suggests that the harvest index of TRD cultivars is less sensitive to drought stress near flowering than that of HYV cultivars. This difference is reflected in the exponential variable WSX, which is 2.0 for HYV and 1.5 for TRD cultivars. The variable HIS is the maximum effect of water stress on harvest index. In rice, unlike in most other field crops, the harvest index can be reduced to near zero by catastrophic drought at flowering. Therefore, HIS is set to 0.99, allowing up to 99% reduction in harvest index. It should be noted that the HYV are considered more sensitive to water stress than the TRD, because of their shallower root system and the greater relative stress reduction of the harvest index accounted for in WSX.

The INT plant type attempts to capture the desirable adaptive traits exhibited in the TDR. These drought resistance traits and an intermediate level of GK (harvest index) represent characteristics which should increase yield potential above that of the TRD while maintaining yield stability.

Growth duration in the new INT was assumed to be limited to less than 105 d because of regional rainfall patterns. We chose to simulate 3 maturities — 90, 105, and 140 d. The genetic coefficients in ALMANAC which control crop development and phenology are shown in Figure 3. Nonstressed leaf area index development increases sigmoidally with increasing heat units to a maximum that is dependent on plant type (Table 3, DMLA). LAP2 and DLAI control leaf area development and senescence. PHU are the potential heat units for each maturity group. CSYP1 and CSYP2 delineate the critical period of extreme sensitivity to drought stress. This period brackets the flowering stage (+10 d) for each maturity group. For short-season (90 d) cultivars, CSYPl is 0.55 and CSYP2 is 0.78 on a scale of 0-1.0 from seeding to harvest.

The EPIC model has a unique weather-generating feature (18). We utilized weather information from Hargreaves (3) and Sreenivasan (19) and from



Parameter	Descriptor	Value
LAP2	Phenological stage (0-1.0) when crop reaches 0.5 of leaf area index (i.e., 50 d/90 d = 0.55).	90 d = 0.55 105 d = 0.60 140 d = 0.71
DLAI	Phenological stage (0-1.0) when crop begins postanthesis senescence of leaves (i.e., 90-30 d from flowering = 60/90 = .67).	90 d = 0.67 105 d = 0.71 140 d = 0.78
PHU	Potential heat units above a base of 10° C. determining the potential nonstressed crop growth period.	90 d = 1850 105 d = 2150 140 d = 2850
CSYP1	Beginning of the 20 d critical period for water stress interaction with reproductive growth stages (i.e., 90-40 d = 50/90 = 0.55).	90 d = 0.55 105 d = 0.60 140 d = 0.71
CSYP2	End of 20-d critical period for water stress interaction with reproductive growth stage (i.e., 90-20 d = 70/90 = 0.78).	90 d = 0.78 105 d = 0.81 140 d = 0.86

3. Schematic representation of model parameters used to simulate genetically controlled characteristics of rice plant types differing in days to maturity. Examples are 90, 105, and 140 d to maturity.

Faizabad, U.P. (D.M. Maurya, pers. comm.) to generate daily temperature, rainfall, and solar radiation input values for a 20-yr test period. Soil input parameters were obtained for two soils (15) — Basiaran and Itwa series — characteristic of the target environment. Unless otherwise specified, all simulations were on the Basiaran soil series with split application of 40 kg N/ha basal incorporated and 15 kg N/ha at panicle initiation.

The ALMANAC rice model genetic coefficients in Table 3 and Figure 3 are the quantitative equivalent of the plant breeder's conceptual model parameters in Table 2. These coefficients and weather generation capabilities allow testing the conceptual plant type model over time and space via the simulation model.

The potential for optimizing scarce research resources and feeding relevant information back to the plant breeders involved is an obvious benefit of such a challenging exercise.

Results of 20-yr simulations. The initial question was: "Given nonstressed conditions, will the three plant types being modeled perform as expected?" Figure 4A illustrates the 20-yr cumulative yield probabilities when irrigation is used to eliminate soil water stress (auto irrigation feature of EPIC) and the 105 d maturity constraint imposed by the weather is relaxed to 140 d maturity. The mean optimum yield levels of the simulation appear to agree with the conceptual model (Table 2), given that the 140 d maturity raises the potential yield level of all plant types.

Figure 4B demonstrates the yield that might be expected when the growing season is restricted to 105 d, as is the case for our target environment. The relatively low (3.2 t/ ha) nonwater-stressed yield potential demonstrates that the target area is not a favorable rice growing region. It also cautions against unrealistically high expectations from the INT plant type proposed.

The 20-yr model simulations also were run for the 3 plant types and 3 maturity groups in a rainfed environment. Table 4 shows the mean yields for all nine plant type and maturity group combinations. It can be compared with the nonstressed yield levels in Figure 4. The low and highly variable 20-yr means for 140-d varieties of all plant types illustrate why most of the new rice germplasm tested in the region over the last 15-20 yr has been rejected in favor of very early (<l05 d) local varieties.

Within the practical limit of 105 d maturity, the INT plant type has a relatively small (0.2 t/ha) advantage over the HYV type. However, the 1.0 t/ha standard deviation of the HYV agrees with the empirically established disadvantages of HYVs in this environment. The INT plant type maintained a mean yield closer to the HYV level, coupled with a standard deviation nearer that of the stable TRD plant type.

The 20-yr cumulative probabilities of yield for the 9 plant type by maturity groups are shown in Figure 5. The simulation model allows us to create comparisons that could not be done through conventional breeding, selection, and field testing. In the two practical cases, 90 and 105 d to maturity, the low but stable yield characteristic of the TRD type are illustrated by the flat slope and mean yields of 1-1.5 t/ha. In contrast, the HYV shows its potential ability to

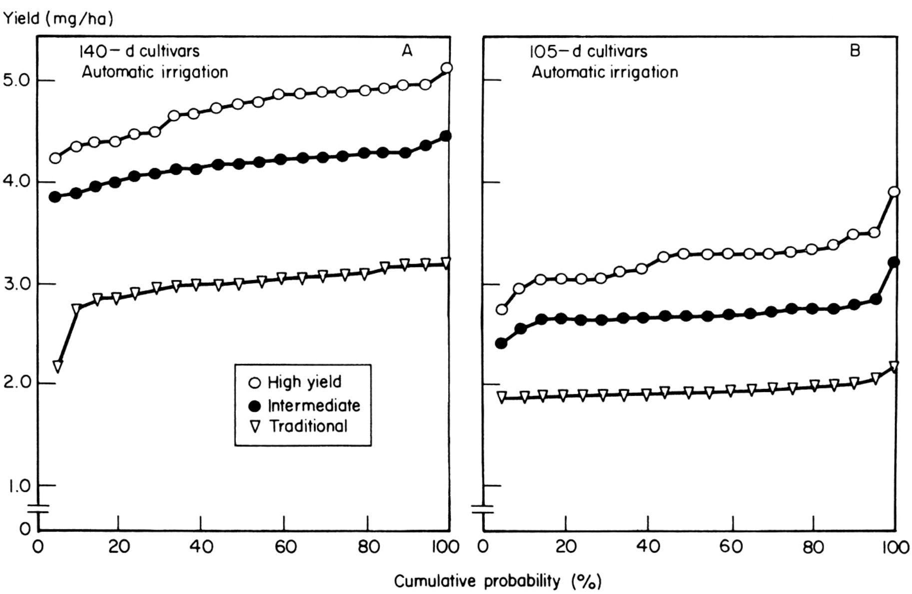
Table 4. Average yields (t/ha ± standard deviation) from 20-yr simulations of 9 combinations of plant type and maturity group.

Plant type	Av yield (t/ha ± SD)		
	90 d	105 d	140 d
High yield	1.98 ± 0.60	2.02 ± 0.99	1.32 ± 1.15
Intermedlate	1.82 ± 0.22	2.19 ± 0.56	1.50 ± 1.21
Traditional	1.26 ± 0.08	1.69 ± 0.38	1.22 ± 0.98

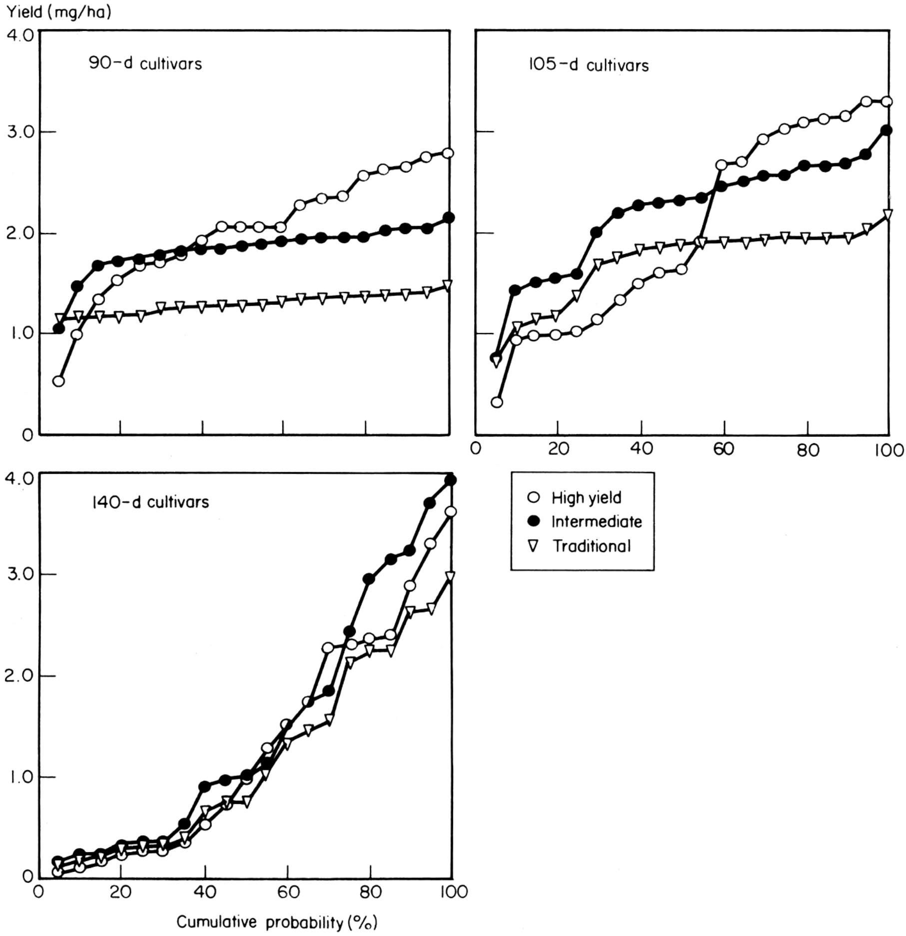
respond to favorable years with 105 d to maturity yields approaching 3 t/ha. However, its erratic, water stress-sensitive nature is also demonstrated in that 50% of the 20-yr means are below 1.6 t/ha. The response of the proposed INT plant type graphically demonstrates its ability to respond to favorable years while maintaining the desired level of yield stability over the 20-yr period. The conceptual and simulation model parameters appear to agree well with the desired trait expression.

In this case, the simulation model allowed the evaluation of proposed genetic solutions prior to or concurrent with actual long-term hybridization and selection efforts. This exercise confirms the validity of the empirically derived intermediate plant type model and provides additional support for directing resources into breeding the new rainfed rice plant type.

As the conceptual model was being built, concern was expressed that the new INT plant type be responsive to increasing use of fertilizer. Agronomic practices throughout India demonstrate a trend toward moderately increased use of N fertilizer. Traditional varieties characteristically do not exhibit increased yield responses to applied N fertilizer. The simulation model allows pretesting the INT plant type for ability to respond to additional N fertilizer. Figure 6 shows responsiveness of the INT type and the traditional variety to increased N. Although ALMANAC is not sensitive to the possibility of the traditional tall variety lodging when N fertility is increased to high levels, it does show a basic difference in the plant type's ability to respond to higher levels of agronomic technology. It is interesting to see increased N response in the INT type during years with unfavorable rainfall (<25%).



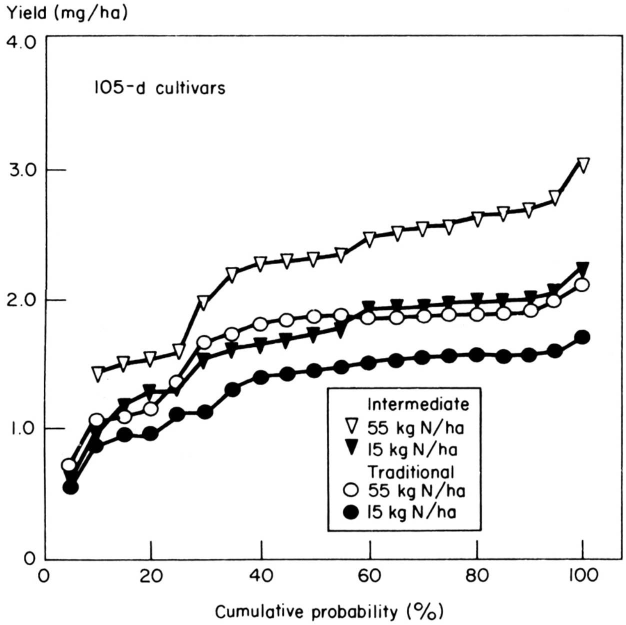
4. Simulated 20 yr cumulative probability of yield when water deficits were eliminated through irrigation. A = crop season was lengthened to 140 d, B = 105 d maturity limit.



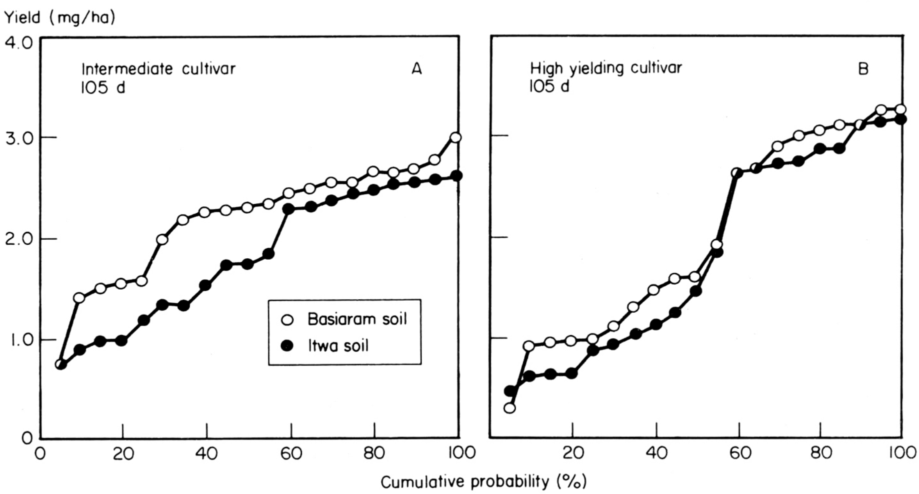
5. Simulated 20 yr cumulative probability of yield for all combinations of 3 plant types and 3 maturity groups.

In this example, we concentrated on rainfall as the major constraint to rice plant types reaching their potential yields. The ability to access additional soil water was the primary drought resistance adaptation conferred on the INT plant type. In addition to incorporating architectural changes in the proposed INT plant type shoot, we specified increased rooting depth. However, soils within the target area often exhibit increased bulk density, which impedes deep root growth. To test the response of the INT type on these soils, we ran the 20-yr simulation using the Itwa soils series instead of the Basiaran series. The Itwa soils are characterized by bulk densities ranging from 1.4 to 1.65 g/cc in the 8-95 cm root zone. The Basiaran soil bulk densities range from 1.2 to 1.3 g/cc over the same depths.

Figure 7 shows the cumulative probabilities of yield for the HYV and INT plant types grown on the Basiaran and Itwa soil series. The HYV yield drops



6. Simulated 20 yr cumulative probability of yield for traditional and intermediate plant types at low (15 kg N/ha) and moderately high (55 kg N/ha) fertility levels.



7. Relationship between yield and cumulative probability of high intermediate plant type (A) and high yield type (B) on two soils differing in bulk density within the profile.

only slightly in the drier years on the Itwa soil; the INT type shows a much greater yield reduction. Presumably, the high bulk density of the Itwa soil caused truncation of rooting depth in both plant types (12). The detrimental effects were more significant in the INT plant type because its adaptive advantage was primarily due to greater rooting depth.

This example illustrates another use of the simulation model, that of evaluating and pretesting conceptual plant type models not only across varying climatic zones, but also in varying edaphic conditions.

Conclusion

Future weather — soil water balance related research directed toward the rainfed rice sector can benefit from a systems analysis approach. The interactions of such major environmental factors as water and N include numerous researchable components which can only be appreciated by a crop simulation model and/or a sufficiently complex conceptual model. Model building itself can be viewed as a review and organization process which yields benefits in setting research priorities, fostering interdisciplinary research, and — not the least important — increasing research efficiency.

Using crop simulation models in conjunction with conceptual model development provides complimentary processes, especially in the realm of plant breeding programs involving long-term commitment of resources. We encourage the use of crop modeling in assessing new genetic and agronomic technology.

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IBSNAT and the CERES-Rice model

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ABSTRACT

The goal of the International Benchmark Sites for Agrotechnology Transfer (IBSNAT) project is to bridge the information and technology gap between rich and poor nations, primarily through the use of a decision support system. One component of this system is the use of computer simulation models. CERES-Rice is a computer model being developed for IBSNAT. Details are given for model parameters, inputs, structure, and outputs. A simple, user-friendly model, CERES-Rice estimates yields for rainfed and irrigated rice. It can predict the growth of different rice varieties under all agroclimatic conditions. Preliminary testing shows that the model behaves satisfactorily; it should be a useful tool for management decision making.

The International Benchmark Sites for Agrotechnology Transfer (IBSNAT) project arose out of the realization that the gap in agricultural and information technologies between rich and poor nations was increasing. The discrepancy was due mainly to the poorer nations being unable to afford both high-cost technological tools and the research and support personnel needed to maintain and operate them. Nations that have access to information and that can utilize the tremendous amount of new knowledge about rapidly changing technologies have the best chance of controlling their own destinies. Without some concerted effort to bridge the technology and information gap, poorer nations could become more and more dependent on other nations for their food and fiber needs.

The IBSNAT project was developed to alleviate this problem and to solve another—that of research redundancy and incompatibility between nations.

The project's principal aim is to reduce costly trial-and-error research through increased use of systems analysis and simulation techniques.

The objectives of IBSNAT are to accelerate the flow of agrotechnology on a scientific basis from its site of origin to new sites with similar agroenvironments and to increase the success rate of technology transfer from agricultural research centers to farmers' fields. The overall goal of IBSNAT is to accelerate the rate of technology transfer to and between developing countries on a cost-effective and scientific basis, to improve the understanding of cropping systems and to provide decision makers with the means for predicting crop yields using crop simulation models, and to use crop models to develop management strategies at all levels.

The IBSNAT project, begun in 1982, is funded through the United States Agency for International Development (USAID). The University of Hawaii provides the organization, leadership, and support for IBSNAT activities; 16 national, 3 regional, and 3 international agricultural research centers in South, Central, and North America, Africa, the Middle East, the Caribbean, the Indian Subcontinent, Southeast Asia, and the Pacific participate.

IBSNAT's strategy is to network these national, regional, and international research institutions, all of which conduct research in dominant agroecological zones composed of major tropic and subtropic soil types. The network allows a ready exchange of information and technology through a central data base management system housed at the IBSNAT headquarters at the University of Hawaii. The data base system is the primary reference source and centralized storage of the data sets submitted by and accessible to all collaborators.

Most of the research done through the project is site specific. Thus, a major activity of IBSNAT is transforming the site-specific information into data usable by all project members. Standardized guidelines for designing and conducting experiments help facilitate this information transfer. From the data, crop simulation models (for maize, rice, sorghum, wheat, beans, groundnuts, soybeans, aroids, cassava, and potato) will be developed, tested, and validated. These models will predict the performances of the various crops under different soil and climatic conditions, thus helping countries make better decisions on the best crops to plant, and where.

IBSNAT uses an integrated computer system, referred to as a decision support system for agrotechnology transfer (DSSAT). In the DSSAT are crop models and site, soil, and weather data, in addition to programs for entering and retrieving data, for linking the models with data, and for analyzing real and simulated data. With the system, crop simulation models that are adapted or developed can be evaluated for their utility in providing soil and crop management alternatives. Model predictions are compared with actual experimental observations. The model validations give users confidence that the information from the simulation models is accurate for specific crop, soil, and weather conditions. Some model predictions are standardized, so that collaborators can interpret the results from different models, facilitating additional analysis of the results.

The CERES-Rice Model

CERES-Rice, a computer model designed at Michigan State University, is one of the models being developed through the IBSNAT project. The model ultimately will estimate yields for rainfed and irrigated rice. It is a relatively simple, user-oriented, yet comprehensive, rice model that will be able to predict the growth of different varieties under all agroclimatic conditions. Programmed in FORTRAN 77 and designed to run interactively in a microcomputer, the model represents a transformation of such input materials as seed, water, and fertilizer into grain and straw through the use of land, energy (solar, chemical and biological), and management practices, subject to such environmental factors as solar radiation, maximum and minimum air temperatures, precipitation, daylength variation, soil properties, and soil water conditions. It has the flexibility to run with irrigation and with N fertilization.

Consistent with the IBSNAT project goals and other CERES models, the model has been developed for

- assisting in farm decision making,
- analyzing for strategic planning,
- making production management decisions,
- analyzing policies, and
- defining research needs.

The model primarily handles

- phasic development or duration of growth stages as influenced by plant genetics, weather, and other environmental factors;
- biomass production and partitioning;
- root system dynamics; and
- effect of soil water deficit and N deficiency on photosynthesis and photosynthate partitioning in the plant system.

Other limiting factors (such as weeds, diseases, and insects) which are important in the crop production process are not considered limiting factors in the model. Their random nature, great number, and variability by species prevent them from being easily represented. Also, they can usually be controlled through good management. Leaving them out of the model does not minimize their importance nor does it imply that they are too complex to model. A particular pest could be modeled and incorporated into the crop model by using feedback between the two models.

The general process diagram of the CERES-Rice model is presented in Table 1.

Model Inputs

The CERES-Rice model requires these inputs:

- daily weather, at least for the duration of the cropping season, including solar radiation, maximum and minimum air temperatures, and precipitation;

Table 1. General process diagram for CERES-Rice.

Input	Process	output
Controllable		
Variety	Plant growth	Yield
Plant spacing	Phasic development	Yield components
Date of sowing	Morphological development	Aboveground biomass
Sowing depth	Soil water balance	Dates of phasic development changes
Date and amount of irrigation	Soil N balance	Optional output at user-selected frequency
Date and amount of N fertilization	Plant N balance	Soil water balance components
Type of fertilizer		Soil N balance components
Genetic coefficients		Root densities
		Indices of N and water stress
Noncontrollable		
Daily weather data		
Latitude		
Soil properties and initial conditions		

- soil properties, including single values of drainage, runoff, evaporation, and radiation reflection coefficients; values at several depth increments of rooting preference factors; soil water contents at the drained upper limit, lower limit, and saturation; N and organic matter details;
- initial conditions of soil water content, NO_3. and NH_4 at several depth increments;
- management practices, such as variety, plant density, sowing depth, planting date, irrigation (frequency and amount), and N fertilization (frequency, type, and amount);
- latitude of the production area to evaluate daylength during the cropping season; and
- genetic coefficients: thermal time required for the plant to develop from after emergence to end of juvenile stage (P1), rate of photoinduction (P2R), optimum photoperiod (P2O), thermal time for grain filling (P5), conversion efficiency from sunlight to assimilates (G1), tillering rate (TR), and grain size (G2).

Growth and Development

Phasic development

Phasic development in the CERES-Rice model is concerned with the duration of growth stages. The growth stages are numbered 1 through 9: 1 through 5 represent the active aboveground growing stages, 6 through 9 describe other events in the crop cycle. Growth stages and their corresponding descriptions are summarized in Table 2.

Table 2. Phenological stages of CERES-Rice.

Stage no.	Event	Plant parts growing
7	Fallow or presowing	
8	Sowing to germination	
9	Germination to emergence	Roots, coleoptile
1	Juvenile	Roots, leaves
2	Floral induction	Roots, leaves, stems
3	End of leaf growth and heading	Roots, leaves, stems, panicle
4	Anthesis or flowering	Roots, stems, panicle
5	Grain filling	Grain
6	Physiological maturity to harvest	

The CERES-Rice model assumes that development rates are directly proportionate to temperatures between 8 and 32 °C. When minimum and maximum daily air temperatures are within this range, thermal time is calculated as the average between the minimum and maximum temperatures, with a base temperature of 8 °C. That is,

$$\text{daily thermal time (DDT)} + \frac{(\text{max temp} + \text{min temp})}{2} - 8$$

If the maximum and minimum temperatures are outside the given range, thermal time is calculated using a different set of relationships.

Thermal time requirements for each growth stage vary with stage and variety. Photosensitivity of a variety directly affects the thermal time requirement during the induction stage (stage 2). A photoperiod-sensitive variety has a longer thermal time requirement when daylength is longer than the optimum photoperiod. The coefficients associated with the thermal time (P1, P2R, and P2O) have been calculated from our own phytotron studies on some cultivars and from photoperiod studies for a large number of cultivars (13). P1 is the approximate thermal time equivalent of the basic vegetative phase (BVP); P2R can be calculated from the different photoperiod lengths; P2O, the optimum photoperiod, when induction occurs, follows the definition used by Vergara and Chang (13). Our phytotron studies on a diversity of rice genotypes are similar to the maize studies of Kiniry et al (4,5).

Biomass production and partitioning

Germination. The germination factor used in the model was derived from the 90% germination curve proposed by Livingston and Haasis (6). Using a base temperature of 8 °C, seed germination requires 45 degree days.

Leaf area and dry matter production. The total leaf area of a rice population is closely related to grain production; physiologically active leaves contribute to the photosynthesis of the plant. As in many models of photosynthesis, the CERES-Rice model adapts Beer's Law to quantify light absorption by the plant community (15):

$$I/I_o = \exp(-K*LAI)$$

where:

I/I_o = light transmission ratio,
LAI = average cumulative total green leaf area per unit of ground area, and
K = foliar absorption coefficient or extinction coefficient (dimensionless).

The photosynthetic rate is expressed as a function of the photosynthetically active radiation (PAR), following that of models CERES-Maize (3) and CERES-Wheat (11). The percentage of incoming PAR intercepted by the canopy then becomes an exponential function of the leaf area index (LAI). The value of PAR above the canopy is assumed to be equal to 50% of the incoming solar radiation. Photosynthesis is expressed mathematically in the model as:

PCARB = G1*PAR*(l-exp (-K*LAI))

where:

PCARB = potential dry matter production in g/m^2 per day:
PAR = photosynthetically active solar radiation in MJ/m^2 per day; and
G1 = conversion factor of PAR to dry matter in grams per MJ of intercepted PAR.

The actual rate of dry matter production (CARBO) is usually less than the potential rate because of the environmental effects of nonoptimal temperature, water stress, or N deficiency. That is,

CARBO = PCARB*PRFT*AMINI (SWDF1,NDEFl)

where:

PRFT = 0-1 stress value calculated from minimum and maximum daily air temperatures, with optimum value at 26 °C.

SWDFl = 0-1 stress value due to water deficit, derived from a ratio of the total potential daily root water uptake and transpiration; and

NDEFl = 0-1 stress value due to N deficiency, which is a function of the critical, actual, and minimum N concentration of the stover (nongrain shoot).

Dry matter partitioning. Assimilate partitioning follows the general principle used in RICEMOD (7), where the assimilates are proportionately partitioned among the growing parts at each stage. However, in the CERES-Rice model, when water stress or N deficiency occurs, partitioning to the top decreases in favor of the roots.

Root system dynamics

Biomass is partitioned into shoots and roots. The proportion partitioned to roots affects root density and thus the ability of the root system to supply water and nutrients to the shoot. The fraction of assimilates partitioned to the roots depends primarily on the growth stage of the crop, declining as the plant matures. However, at all growth stages except stage 5, the fraction partitioned to the roots increases with water deficits or N deficiency.

Total root growth in a day is determined by the amount of biomass partitioned to the roots. To determine the distribution of roots in the soil, a rooting preference factor that decreases with depth is input for each soil layer. The preference factor of a layer is reduced when the soil water content is below a threshold value. Thus, when a particular soil layer becomes dry, root growth in that layer decreases. Compensatory root growth occurs elsewhere in the profile, where the water status is favorable.

The potential rate of downward root growth is assumed to be proportionate to the rate of plant development, which is influenced by temperature. The water content of each depth is used to determine the distribution of root growth in the profile. The mass of assimilate partitioned to the roots is converted to a root length, assuming a constant proportionality between root mass and length, to provide estimates of root length density. A small reduction in root length in each depth accounts for root sloughing.

Grain Yield

According to Yoshida (15), the 1,000-grain weight of field crops is a very stable varietal character. Individual grain weights vary to some extent, but the mean value is constant. In the CERES-Rice model, grain weight is the product of grain growth rate times duration of filling. A genetic coefficient (G2) determines the grain growth rate under optimum conditions. Grain growth rate varies among varieties according to three main classifications: long, medium, and short.

In this model, grain yield is directly proportionate to panicle weight. The model does not set any maximum yield potential. Rate and duration of panicle growth, as influenced by the environment and plant size, control yield.

Soil Water Balance

The soil water balance is calculated to evaluate possible yield reduction caused by soil and plant water deficits. However, if the soil water balance is assumed to be nonlimiting, it can be bypassed. This part of the model includes user-selected soil depth increments where water balance calculations are made.

Water content in any layer can increase in response to infiltration of rain, irrigation water, or flow from an adjacent layer. Water content can decrease because of soil evaporation, root absorption, or flow to an adjacent layer. The limits to which water content can increase or decrease for each layer are input as the lower limit of plant water availability, the field-drained upper limit, and the field-saturated water content.

Infiltration is calculated as the difference between daily precipitation and runoff. Runoff is estimated by a Soil Conservation Service Curve Number technique as modified for layered soil by Williams et al (14). When irrigation inputs are encountered in the model, the runoff estimation is bypassed, allowing all irrigation to infiltrate.

Drainage is calculated as a function of water content above the drained upper limit (DUL). Evapotranspiration (ET) is calculated using procedures presented by Ritchie (9). Potential ET is calculated using an equilibrium evaporation concept as modified by Priestly and Taylor (8).

Root water uptake is calculated using an empirical evaluation of the maximum possible single root water uptake rates. From the estimates of root length density and soil water, the maximum possible uptake per unit root length in each soil layer is converted to the maximum uptake for the entire root system. If this maximum uptake value exceeds the calculated potential transpiration, then transpiration is assumed to occur at the potential rate. If the maximum uptake for the entire root zone is less than potential transpiration, then the actual uptake becomes the maximum uptake and transpiration is reduced to that value. This reduction in transpiration, expressed as fraction of the potential, is used to reduce photosynthesis, leaf expansion, and assimilate partitioning in the growth subroutine. More details of the soil water balance subroutines were discussed for CERES-Wheat by Ritchie (10).

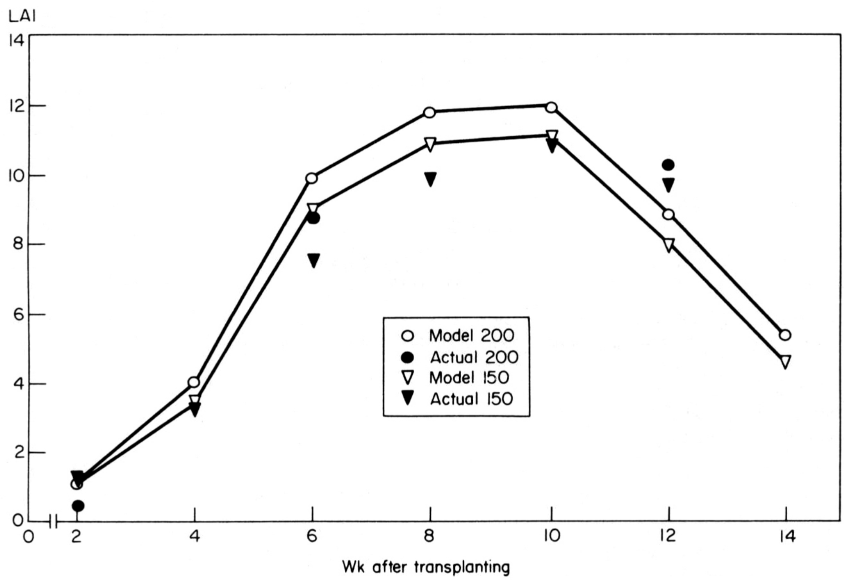
Nitrogen Component

As with the soil water balance, the N component in the CERES-Rice model can be bypassed when N fertilization is considered nonlimiting. Included in the N subroutine are the initial of soil N conditions and fertilizer management, as well as the transformation processes of humus, organic N, soil nitrate, and soil ammonium into N forms usable by the plant system. The process involves the mineralization of organic N and the immobilization of mineral N from organic matter decomposition (based on the mineralization immobilization routine in PAPRAN [12]) and the nitrification of ammonium in each soil layer (or denitrification whenever soil water in the layer is greater than the drained upper limit and the NO_3-N concentration is greater than 1.0 g N/mg soil).

This component of the model calculates the demand for N by the crop, the supply of N available to the crop, and the N uptake by the crop. A N stress is developed when the actual N concentration of the stover (nongrain shoot) is less than the critical N requirement; a severe stress occurs when the actual concentration is equal to the minimum allowable value. N stress affects leaf expansion, photosynthesis, and grain N concentration in the growth subroutine. More details of the N subroutines used for CERES-Maize are available in Jones et a1 (3).

Model Performance

The CERES-Rice model is in its early stages of development. It has not been tested with a complete data set because of the unavailability of the data. However, from the incomplete data we have, the model behaves satisfactorily. Testing against 1969 wet season data published on IR8 (2), the model output on LAI at 200 and 150 kg N/ha closely approximated actual output (Fig. 1).



1. LAI in model output and actual data, IR8, 200 and 150 kg N/ha. 1969 wet season, IRRI, Los Baños, Philippines

Table 3. Comparison of actual data and model output on several plant characters of IR8 at 150 kg N/ha, (1969 wet season, Los Baños, Philippines).[a]

Plant characters	Actual values	Model output
Maximum LAI (at heading)	10.9	11.1
LAI at flowering	10.4	11.0
LAI at harvest	4.7	4.6
Biomass at flowering (g per m^2)	1132	1152
Biomass at harvest (g per m^2)	1448	1554
Panicles per m^2	341	353
Panicle/straw ratio	0.97	1.13
Grain yield (t/ha)	7.1	6.8

[a] Because 1969 weather data were unavailable, 1983 weather data were used for the model run.

Although the weather data used in the model run were for 1983, we assumed that under average conditions, the weather pattern for the area varies little from year to year. The sowing date was assumed to be 8 Jul.

Table 3 compares actual data and the model on some plant characters of IR8 at 150 kg N/ha. Runs were also made to evaluate the model's ability to predict the phenological stages of the rice crop. Unpublished data provided by O'Toole (IRRI, pers. comm.) for 1983-84 under upland conditions at IRRI were used (Table 4). The phasic development calculations usually were within 1-2 d of the measured phenological events.

Table 4. Comparison of actual data and model output on date of changes in phenological development (Block UV, IRRI 1983-84).

	Phenological stage								
	7	8	9	1	2	3	4	5	6
1. IR43									
Planting No. 1	20 Jun	-	24 Jun	-	24 Aug	25 Sep	-	-	25 Oct
Model	20 Jun	23 Jun	24 Jun	30 Jul	24 Aug	25 Sep	4 Oct	24 Oct	26 Oct
Planting No. 2	8 Jul	-	12 Jul	-	10 Sep	15 Oct	-	-	12 Nov
Model	8 Jul	11 Jul	12 Jul	18 Aug	10 Sep	13 Oct	22 Oct	11 Nov	13 Nov
Planting No. 3	28 Aug	-	1 Sep	-	4 Nov	6 Dec	-	-	2 Jan
Model	28 Aug	31 Aug	1 Sep	7 Oct	27 Oct	30 Nov	9 Dec	31 Dec	2 Jan
2. UPL-R15									
Planting No, 1	20 Jun	-	24 Jun	-	24 Aug	23 Sep	-	-	17 Oct
Model	20 Jun	23 Jun	24 Jun	2 Aug	25 Aug	26 Sep	5 Oct	18 Oct	19 Oct
Planting No. 2	8 Jul	-	12 Jul	-	6 Sep	11 Oct	-	-	5 Nov
Model	8 Jul	11 Jul	12 Jul	21 Aug	10 Sep	13 Oct	22 Oct	3 Nov	5 Nov
Planting No. 3	28 Aug	-	1 Sep	-	4 Nov	29 Nov	-	-	22 Dec
Model	28 Aug	31 Aug	1 Sep	10 Oct	26 Oct	29 Nov	8 Dec	22 Dec	23 Dec

Conclusion

A great deal of time is still needed to refine some of the model parameters with available empirical data sets. A major constraint is the unavailability of weather and soil information in published research reports. We are optimistic, however, that the CERES-Rice model will become a useful management decision tool for predicting yields of different varieties under many agroclimatic conditions, accelerating the rate of technology transfer to and between rice-based developing countries.

The present rice model is primarily an adaptation of parts of the CERES-Maize and CERES-Wheat model structures. We recognize that rice growth in a wetland environment is different from maize and wheat growth. Therefore, we are continuing to further develop the model, especially in reference to the unique root growth dynamics of rice and its N transformation. The Angus and Zandstra (1) model called IRRIMOD should provide useful details on the water balance components that are unique to wetlands, especially on hillsides. We believe that, with several groups collecting IBSNAT data sets on rice, a general model for use in decision making for many purposes is forthcoming.

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Using a simulation model to evaluate weather effects

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ABSTRACT

Simulation of crop growth and production using existing knowledge about the basic processes is compared to statistical analysis of field data, with summaries of advantages and disadvantages of each method. The structure of the simulation model is discussed briefly and examples of its use to predict and analyze the rice crop's response to weather variables are given. Simulation results and a regression equation derived from data from the International Rice Testing Program describing the relationship of minimum temperature and radiation level to final yield are compared. Potentials of the simulation approach to more fully use available weather data are given.

Scientists try to describe the relationship between crop growth and environmental factors for many reasons: to estimate the yield in a region, to perform risks analysis, to optimize the efficiency of treatments such as fertilization, and to predict the production potential of new varieties.

Weather has been widely studied as one of the major environmental factors influencing rice production (4). But in many rice-growing areas of the world, no long-term weather data are available. Recently, the rice weather program has introduced standardized data collection procedures (6). Local weather data, combined with crop data obtained at the same site, can be used to quantify environmental effects on growth. Two basically different methods can be used: a statistical or correlation approach or an analytical or simulation approach.

The first approach uses empirical data and statistical methods to quantify the observed relationship between environmental and crop variables. The second approach uses knowledge about underlying physical, chemical, and physiological processes to predict the effect of the environment on growth and production.

Statistical Methods and Simulation Models

The widely used correlation method yields reliable statistical relationships (or models) between yield and one or more weather variables (1,2,5,9). These correlations differ with the number of variables and the type of weather data used. The time of year for which weather data must be available also varies. In some models, this is dependent on the developmental stage of the crop (normally after anthesis). Yields can be estimated for any sowing date. In other models, weather data gathered on fixed dates must be used. Then calculation of production is possible only for specific sowing or transplanting dates.

Statistical methods can provide reasonable estimates of yield and require no biological knowledge. They also can establish confidence intervals for the predicted variables. However, they have several limitations:

- The use of a statistical model is rather restricted, often to only a part of the year (2) or to a specific region (1).
- The model is often rigid. New input variables cannot be introduced without changing the whole model. Also, a model will yield only one output (usually final yield); it is not possible to calculate estimates for variables other than those for which the model was originally designed.
- Constructing statistical models requires a large body of empirical data. Normally, no more than two or three yields can be obtained per year in the field. It takes some years after a new variety is introduced before a new relationship can be established.
- Only outcome of crop growth is quantified, not the growth processes themselves. Such a model is not very useful in research on the effects of environmental or biological factors monitored in the field, such as weeds, on crop growth.
- Statistical models do not increase our understanding of processes; they are directly based on information from past experiments without further analysis of the mechanisms that regulate growth and production.

Several of these disadvantages can be overcome using simulation models:

- Physiological processes in the plant are basically the same at all times everywhere in the world; an explanatory description of the effects of environmental factors on these processes can be used universally.
- When a good description of a process has been established, other environmental influences, such as the effect of temperature on leaf photosynthesis, can be introduced without changing the basis of the model.
- Description of the processes still must be based upon experimental data and the outcome of a model simulating combined processes must be evaluated against other experimental data. However, fewer expensive field experiments are required than for constructing statistical models. The production potential of new crop varieties can be calculated quickly when certain physiological and morphological differences from the old varieties are known.

- A dynamic model can be used to calculate crop growth during the growing season. The effects of diseases and insect pests at different stages of the crop cycle can be introduced relatively easily.
- During construction of a simulation model, the types of data that are lacking and which processes are not yet sufficiently understood or quantified become clear. This makes it easier to define goals for further research.

The simulation method also has disadvantages:

- When working with simulation models, the purpose for which they will be used should be clear. When data for quantifying basic processes are lacking, the outcome of the model can be unreliable and/ or inaccurate. In such a case, the model may be useful in research, but should not be used for prediction. Models that serve educational purposes also are often useless for research.
- For statistical calculations, computer or pocket calculator packages are often available which enable users to select and perform the type of calculation they want. No such packages are available for simulation models.
- Many simulation models are not easily understood by those not involved in their construction: first, because models often are poorly described, second, because the equations are complex, and third, because many of the computer languages used are inaccessible.
- Even when a model is understood, it is not possible to work with it if hardware (the computer) or software (the simulation language used) are unavailable.

A Simulation Model for Rice Growth

The Centre for Agrobiological Research (CABO) and the Department of Theoretical Production Ecology (TPE, Agricultural University) in Wageningen, The Netherlands, have acquired considerable experience in developing and using simulation models (3,7,8,10,11). With this experience in simulation, and with data on rice provided by IRRI, a simulation model was developed for rice and used in the course Implementation of Systems Analysis and Simulation in Rice Production (Wageningen, February-March 1986).

Short outline of the model

The rice model is a summary model derived from more detailed simulation models (BACROS; 3) for the various processes that together determine crop growth. Four levels of production are distinguished (7):

1. optimal, production limited only by crop characteristics and weather;
2. water limited, yield also influenced by availability of soil water;
3. N limited, yield also influenced by availability of N;
4. P limited, yield also influenced by availability of P.

In all these situations, yield can be affected by biological constraints, weeds, insect pests, and/or diseases.

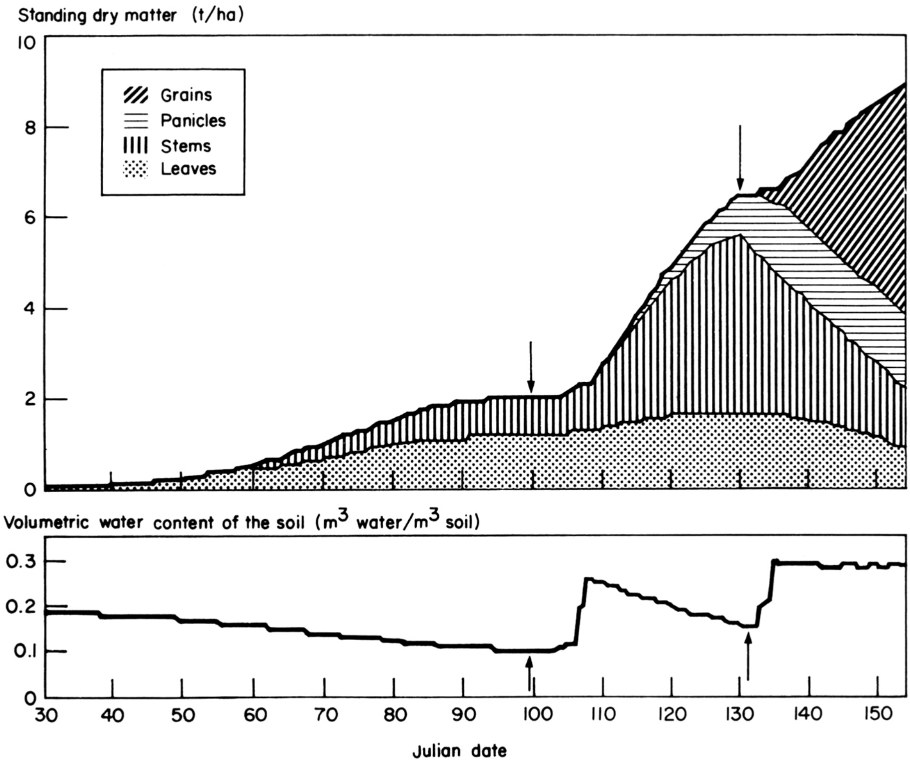
The processes that determine crop growth under production level 1 form the basis of the model: photosynthesis, partitioning of carbohydrate over the various plant parts, maintenance respiration, growth respiration, and morphological and physiological development (12).

When production level 2 is simulated, three processes are added to the model: transpiration by the crop, evaporation, and soil water movement.

The model takes no account of the nutrient supply (production levels 3 and 4), mainly because simulation of the processes determining the fate of N or other nutrients in the soil is not yet very accurate. Therefore, the model should only be used for situations where nutrient supply is ample.

The model is written in the computer language CSMP specifically developed for simulation modeling. The rates of all ongoing processes are calculated for each day of the growing season; the new values for the crop characteristics are calculated by numerical integration of these rates.

The core of the model is formed by a set of equations calculating potential photosynthesis of the crop as a function of daily weather data (temperature and



1. Standing dry matter and volumetric water content during the growing season for upland rice, predicted by the simulation model using weather data from Los Baños Lowland Station, 1979.

radiation) and the present status of the crop, with leaf area and photosynthetic capacity as the main characteristics. Maintenance respiration, depending on temperature and biomass, uses part of the carbohydrates provided by photosynthesis. The remaining carbohydrates are partitioned over the various plant parts using a distribution function dependent on the physiological age of the crop. The carbohydrates are converted into plant biomass, during which the amount of growth respiration that occurs is dependent on the chemical composition of the different organs.

In the present model version, physiological development of the crop is dependent only on temperature. Morphological development (tiller and panicle development, grain formation, leaf area production) is dependent both on physiological development and current photosynthetic rate.

The model for production level 2 (upland rice) also keeps track of the soil water content, determined primarily by daily rainfall, evaporation from the soil surface, and transpiration by the crop. A new soil water status is calculated each day. If water availability is too low, transpiration and photosynthesis, and therefore crop growth for that day, are lowered accordingly. This results in a feedback between crop growth and soil water balance throughout the season. An example of results from this model is shown in Figure 1; arrows indicate the occurrence of water shortage to the crop.

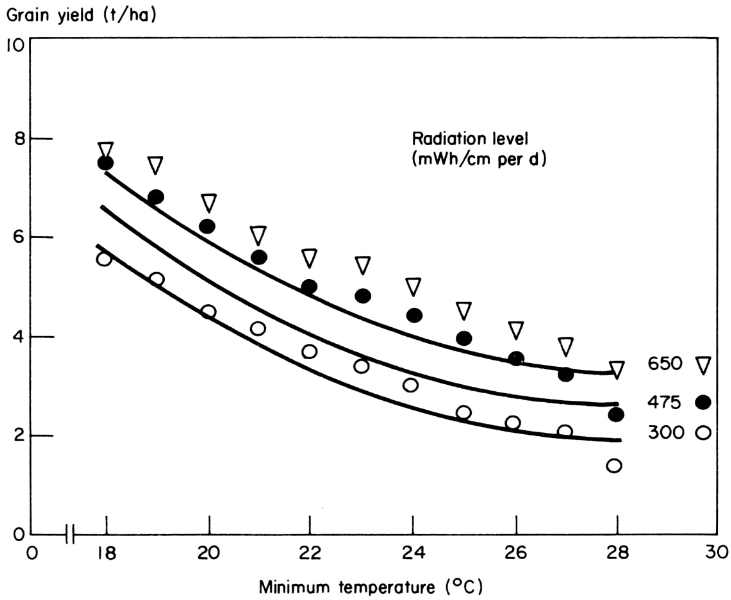
The model (with or without water balance) is easily extended to account for weeds, insect pests, or diseases. Lack of basic information on the biology of these yield-reducing factors, and on the relationship between occurrence and damage, makes the extended model more suitable for use as a research tool, rather than to predict yields.

Influences of radiation and temperature

To compare the use of statistical and simulation models, results with varying values for radiation and temperature are presented. The influence of these factors on final yield is considered for early-maturing rice crops which have ample water throughout the growth period.

For this purpose, the simulation model was run a number of times, using different radiation levels and temperatures. Radiation levels varied from 300 to 650 mWh/cm^2 per d and minimum temperatures from 18 to 28°C. This range includes most of the weather conditions under which rice is grown worldwide. Radiation level influences crop growth directly and simply: high radiation levels favor crop growth. Temperature influences crop growth through such processes as photosynthesis, maintenance respiration, and the rate of phenological development.

Seshu and Cady (9) carried out a statistical analysis of weather data and yield measurements from IRRI's International Rice Testing Program nurseries. They used the results of 40 field experiments conducted over several years at various localities in Africa, Asia, Latin America, and Oceania. With these data, they developed a regression equation for the relationship between rice yield and radiation and temperature.



2. Yield of lowland rice predicted by the simulation model (triangles, circles, and squares) and by the regression equation developed by Seshu and Cady (10; solid lines). For the simulation, temperature and radiation were kept constant during the entire growing season; maximum temperature equal minimum temperature plus 10 degrees Celsius.

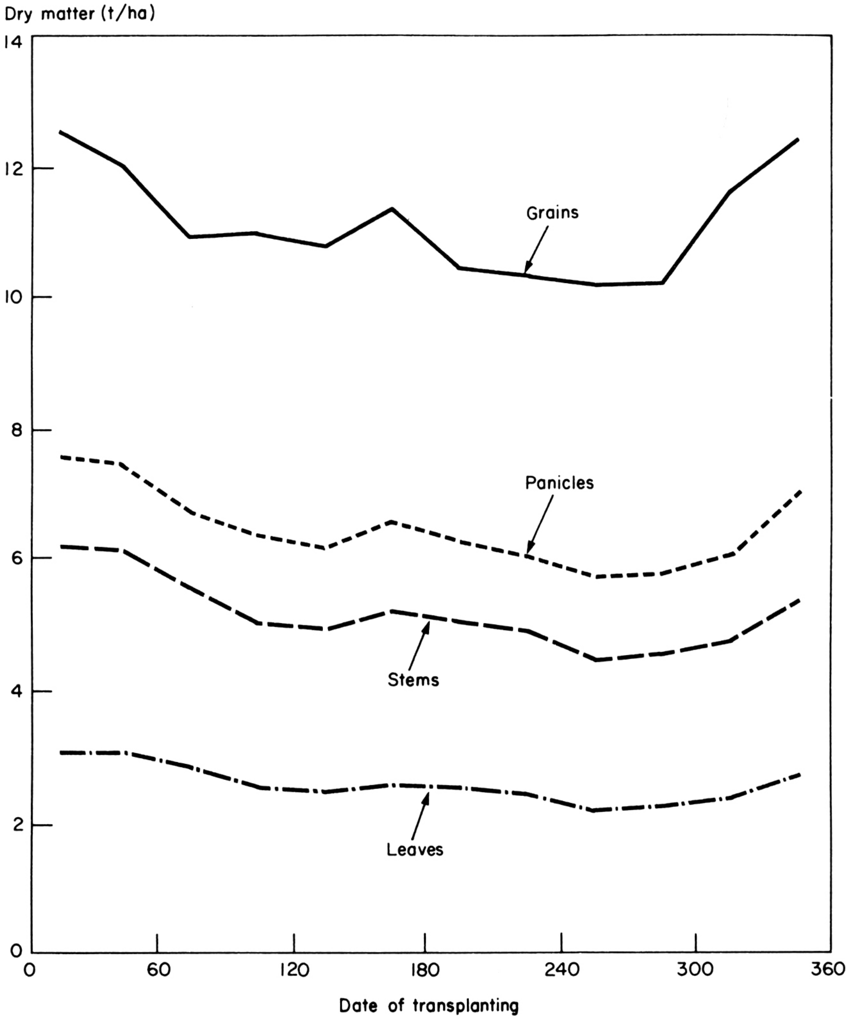
Figure 2 presents the results of the simulation runs compared with those obtained by Seshu and Cady. The statistical regression suggests a curvilinear dependence of yield on minimum temperature, which corresponds to the outcome of the simulation model.

Although there is a general similarity in the outcomes of the two methods, there are also some clear differences. Instead of a linear relationship between yield and radiation, the simulation model predicts a curvilinear relationship. In general, the simulation model also predicts a higher yield.

Apart from these differences in results, there are other major consequences of the different approaches. With data from field experiments, one cannot be certain that yield differences are caused only by differences in temperature and radiation level and not also by other differences between localities or years (9). Using a simulation model, the effects of various factors can be investigated without considering this problem. The simulation model also has a wide applicability. Determining a relationship like that shown in Figure 2 for late-maturing varieties or for varieties with lower maintenance respiration requires only hours of simulation work by one person, instead of years of experimental research by teams.

Some applications

Weather fluctuations may have considerable effect on rice. An example of predicting the effect of transplanting date on yield is shown in Figure 3. It gives a



3. Yield of lowland rice as a function of date of transplanting, predicted by the simulation model using weather data from Los Baños Upland Station, 1983.

fairly detailed picture of expected seed and straw productions for alternative transplanting dates in a particular year.

Repeating this procedure using weather data from a number of years enables us to determine the planting date that gives the highest average yield and an acceptable variation in yield over the years. Such a simulation could speed up testing the yield stability of a new cultivar.

Simulation also can be useful in quantitatively analyzing the performance of a rice crop under untested conditions. One can examine the effect of high altitude on yield or the advantage of irrigation for a specific locality without field data.

Conclusion

When combined with weather data and data from field experiments, simulation models can contribute to a better understanding of the factors that influence the performance of a rice crop under varying conditions. The advantages of the simulation approach, apart from speed and low costs, are its ability to provide scientifically sound and easily interpretable extrapolations and to perform separate analyses of the effects of factors otherwise difficult to disentangle.

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Some opportunities for using crop models in rice

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ABSTRACT

Opportunities for applying crop growth simulation models to rice production lie particularly in potential crop production and crop production with temporal water shortage but ample nutrients. Opportunities for application include yield prediction, extrapolation and interpolation of crop performance over country-size regions, and simplification and combination with other models to link with other sciences. Such applications can lead to more effective use of existing knowledge for extension, agronomic, and cropping systems research and for breeding; to more efficient experimentation, and to further integration of the scientific disciplines involved in crop production. Providing training and stimulating international cooperation among persons involved in modeling in rice-growing countries could help realize more applications.

Simulation is a technique that can be applied in many agricultural sciences. Achievable applications are possible in the next 3-5 yr.

The simulation of carbon and water balance processes in plant physiology, soil physics, and agrometeorology has advanced far enough to provide appropriate models that can be applied in such related disciplines as agronomy, cropping systems, breeding, and agricultural planning. Modest adaptations are still required for more concrete applications. Determination of the value of several parameters specific to a cultivar or soil type is still needed. Data from old experiments are usable, some new experiments need to be done. Although the data collected in the Rice Weather Program so far are useful, more weather data are needed to extend the areas in which crop models can be fully used.

O'Toole and Jones (13) present clear examples of how building and testing a model can help to guide, improve, and integrate research activities. Other examples are given elsewhere (15).

The advantages of using models for training are implicit, as is illustrated in some recent textbooks for international postgraduate courses (16,17,23). Several examples of model application used here are taken from case studies formulated during a course on simulation in rice crops.

The term model refers to explanatory models that simulate a real-world system in which all processes proceed continuously, although at changing rates; *explanatory* implies that the behavior of a modeled system (such as the growth rate of the crop) is computed, and hence explainable, day to day, on the basis of such physiological processes as photosynthesis (3). Such models are more complex than statistical models, but their generalizability and applicability in new situations are also much larger. Bakema and Jansen (1) demonstrate this.

Simulation models can be used to accelerate research in the scientific field of the model itself, to apply knowledge to other fields, and to train students on the behavior of the system modeled and the causes of that behavior. Preliminary, comprehensive, and summary models have different potentials and restrictions (14). The slowly emerging summary models are particularly suited to application in other areas and for training.

A Simulation Course

Eight case studies for modeling rice crops were developed during a recent simulation training program. The immediate goal of the modeling course was to teach participants to understand and use modeling and simulation techniques to increase the breadth and depth of their work on rice production and to increase the applicability of modeling within their home institutes.

The course, held in Wageningen February-March 1986, was attended by eight teams of four researchers each. Most of the participants had no previous training in simulation. The teams were from different countries in Asia: India (Pant University of Agricultural and Technology, Pantnagar, and the Central Rice Research Institute, Cuttack), Indonesia (Sukarami Research Institute for Food Crops, Institute, Padang), Malaysia (Universiti Pertanian Malaysia, Kuala Lumpur), Philippines (University of the Philippines at Los Baños and IRRI), Thailand (Khon Kaen University, Khon Kaen), and Sri Lanka (Regional Agricultural Research Centre, Bombuela). Team members were from the same national organization but from different scientific disciplines. The teams are now elaborating their case studies at their home institutes.

Those case studies involve using crop growth models to examine one or two problems related to rice production. Each study also contains a field trial to evaluate results and other small experiments to establish values for certain parameters. Each team was provided with a personal computer with which to practice simulation.

A final workshop at IRRI in 1987 will refresh participants on some course elements, evaluate the project, and plan future cooperation.

The implementation of systems analysis and simulation for rice production project, created to conduct this course, is financially supported by the Dutch

Ministry of International Cooperation and executed jointly by the Centre for Agrobiological Research and the Department of Theoretical Production Ecology of the Agricultural University, Wageningen, and the Multiple Cropping Department, IRRI. The actual form of the course was based on experiences with international postgraduate courses in developed and developing countries. Those courses were well received (2), but did not fulfill their potential because they were short, directed at individuals, and could not provide participants with back-up or simulation tools.

Some Opportunities for Applying Crop Growth Models

Two domains of simulation application are potential production and water-limited production. Potential production is defined as a situation in which only weather and crop characteristics determine crop growth; water-limited production is the same situation, but with water shortages (3). Both situations refer to intensively managed, arable fields.

The consequences of nutrient shortages or important biological constraints have not been well-simulated. In practice, dynamic models cannot yet be applied to situations where those are important. Model applications to yield prediction, interpolating and extrapolating data from only a few key trials to country-size regions, summarizing or simplifying use of models for other fields of science or extension, and combining models from other disciplines are explained here.

Growth and Yield in Fully Irrigated, Intensively Managed Fields

Crop growth models have been used first to determine growth rate and potential production in conditions with ample nutrients and water, without insect pests, diseases, and weeds. Growth rate and yield are then a function of weather (radiation and temperature), physiological characteristics of the cultivar, and certain agronomic measures (planting date and density, etc.).

Prediction

Simulation of potential crop yields quantifies obtainable ceiling yields, highlighting the scope for yield improvement or the extent of current yield losses. With sensitivity analyses, simulation also can estimate the impact of potential breeding or new agronomic practices. Examples of such applications can be found in van Keulen (20) for rice, De Wit et al (4) for several agricultural crops, van Keulen and De Milliano (22) for wheat in Zambia, and Versteeg (25) for several crops in Peru. Among the case studies are the effect of planting density and planting date on rice yield and harvest index (Malaysia) and the impact of breeding for certain physiological or morphological characteristics in short-, medium-, and long-duration rice varieties (Pantnagar).

A heavy and continuous cloud cover, with a consequent low light level, during anthesis of rice is probably the prime cause of low grain numbers and grain yields in eastern India; the Cuttack team is investigating this hypothesis

(11) and the potential advantages of shifting the date of transplanting or of changing the variety.

Interpolation and extrapolation

Simulation of potential yields of several rice varieties at the 23 sites of the Rice Weather Programme (12) is one theme of the IRRI case study. Once it is confirmed that simulated yields are comparable with those of field trials, future experimentation with new varieties or new sites can be more effective; conclusions, such as those about yield potential of varieties and breeding lines in IRRI-IRTP trials, could be drawn faster and with less experimental effort. Using weather data of a sequence of years at any location, simulation could support experimentation in such a way that year-to-year yield variability could be established much faster than by experimentation alone. Either real weather data or carefully generated weather data (7) can be used.

The Sri Lanka case study involves simulating potential rice production in the low, southeastern part of the island; only a few trials are planned for evaluation.

To support planning for development of national agriculture, crop growth models have been used to simulate potential production of several alternative crops in specific circumstances (23).

Model simplification

Simplified access to models is needed to allow widespread use by nonspecialists. This may be achieved two ways: by simplifying the model itself or by adding an interface. An interface could ask a novice user for the most crucial inputs and suggest defaults for all others. Because of technical limitations in simulation techniques, most model simplifications so far are of the first group. However, the new powerful, yet inexpensive, computers that provide interfaces between end-user and very well-evaluated models may be a way to go. The CERES model (18) is a beginning (E. Alocilja, Michigan State Univ., pers. comm.).

Versteeg and van Keulen (26) demonstrate that a model to compute potential production of annual crops in the tropics can be considerably simplified, provided the model is limited to this one purpose. Such simplification results in models with only a few lines, clear and easy to grasp. Venkataraman (24) advocates their use.

Model combinations

Combining a crop growth model with a model for a related biological or physical system with a similar time constant can yield a very powerful way to investigate interactions. Good examples are combinations with insect pest, disease, and weed models (17). Strong interactions between crop growth and disease or insect pest development make this combination potentially interesting for interactive crop management. A combination model could be used for advice about timing fungicide sprays, thereby avoiding unnecessary applications.

The epidemiology of diseases and insect pests on rice is still too little developed to provide fully dynamic combination models. Because many of the teams in the simulation course deal directly with diseases or insect pests in their research, a compromise was found for their case studies: a certain level of intensity and duration of one insect pest or disease is imposed on the crop model. The damage is investigated by varying level and duration (IRRI and Thailand case studies: damage due to stem borer and leaffolder; Pantnagar and Cuttack: damage due to bacterial leaf blight; Indonesia: damage due to leaf blast). As soon as disease or insect pest development can be simulated sufficiently, such a model should replace the rigid level and duration of a biological constraint used in current models.

Growth and Yield in Rainfed, Intensively Managed Fields

An almost infinite number of soil type, weather, and agricultural practice combinations are possible in rainfed fields. In addition, fluctuations in weather (particularly rain) are more important in rainfed crops than they are in irrigated crops. Experimentation in all of the important situations goes far beyond field research capacities; it is necessary to involve modeling to consider the agronomic potentials of combinations. This topic has received attention from several groups of agroclimatologists, soil scientists, and agronomists for many years. Two cases can be distinguished, based on the presence or absence of upward movement of water in the soil. Models for the first case are simpler and yield better results than those for the second case.

Prediction models

Growth rate and yield are directly related to weather and available soil moisture; nutrient shortages and biological constraints are not considered. These crop growth models include a soil water balance section and can be used to simulate yield, crop water use, and moisture remaining in the soil after a crop is harvested. The area of rainfed lowland and upland crops to which such models could be applied is huge.

Examples of applications are given by van Keulen (21) and Bakema and Jansen (1); many others are in the literature. For upland rice crops, Morris (10) shows such applications as choosing planting date to avoid drought stress at critical periods (establishment, panicle initiation) for minimal variability in yield. Virmani (27) used a model to predict the suitability of dry seeding sorghum for specific areas of the semiarid tropics. O'Toole and Jones (13) predict effects of breeding for desirable new traits in rice.

With multiple-year weather data, estimates of weather-related variability in yield and water use can be generated. The technique for generating long series of daily precipitation values from historic records only a few years long (6) will probably be helpful (10).

Interpolation and extrapolation

Potential production and water use on soils with a deep water table can be simulated well (23). Grashoff (CABO, pers. comm.) simulated yield variability of faba bean in relation to summer droughts in western Europe. Virmani (29) provides examples from the semiarid tropics.

Summary models for crops on soils with a water table in or near the root zone still need thorough evaluation at several locations, as has been started with the IRRI case study. Then, as with the Rice Weather Program, it will be possible to extrapolate results from relatively few field trials to other rainfed and upland rice areas. This could reduce the size and number of trials required in a possible IRRI Upland Rice Program.

Another example is Thailand's case study, in which the amount of water left after the rainy season and main rice crop is estimated. After evaluation, the model will be used to predict more quickly and accurately the growing season durations that can be expected for second crops in unexploited land areas.

Still another kind of extrapolation is the simulation of the effects of the increasing ambient CO_2 concentration on rice yield, harvest index, and water use. That simulation could help breeders. An example of such a simulation exercise is given by Goudriaan et al (8).

Model simplification

Experience and trials over many years have evolved simple rules of thumb for crop husbandry in traditional situations. In relatively new situations or conditions, new rules of thumb would be helpful. An example is the development of a drought stress index for rice (Ingram and Garrity, IRRI, pers. comm.) to quantify when rice really starts to suffer from drought, or to estimate the number of days without rain before irrigation would be required for new varieties in specific areas in India (9).

Fagi and Las (5) emphasize the importance of food security. Improving agricultural zoning by using models (suggested here in several contributions) could be one way to achieve this. The resulting maps and recommendations are another form of summarizing knowledge.

The Philippine team plans to establish the frequency of droughts during the rainy season in their upland ricefields, then derive the optimal weeding period. The Thailand case study, dealing with an undulating landscape and a long dry season, will attempt to indicate where and when the water table depth on slopes should be registered, and how this value can be translated into the expected growing season for the second crop.

Model combinations

Wosten and Bouma (28) published a simulation model to compute trafficability of a soil surface as a function of the soil water content. It is meant to calculate how many times the surface can be worked. Combining their model with other models, such as the one by Bakema and Jansen (1), could support studies of the minimum period required for land preparation between successive crops.

Rosegrant (19) developed a model for optimizing water distribution in three specific irrigation systems in the Philippines. His crop growth module is a simple, statistical description of afield experiment on how rice responds to water and fertilizer. His module could be replaced by a dynamic crop growth model, perhaps further condensed, to make the entire model more applicable to locations inside and outside the Philippines (Rosegrant, IFPRI, pers. comm.). A simple form of the effect of soil fertility and fertilization still has to be included (23).

Realization

There appear to be many opportunities for applying crop growth models to improve extension and to speed research. There are several potential subjects, most of them for several countries and regions. But many of these possibilities probably will not be realized within the next few years because of serious bottlenecks: lack of trained personnel, lack of equipment and methods, and lack of knowledge.

There are still obvious and serious restrictions to modeling. But topics based on the current state of knowledge can be chosen. A range of models exists, but their development should be pursued. This could be undertaken most effectively at existing modeling centers. Among the important topics are the N economy of the soil, crop response to adverse soil conditions, and crop protection.

Lack of equipment is no longer a serious constraint; reasonable software and hardware is or could be available to almost every research organization.

The lack of trained modelers for rice production simulation is evident. Courses could be taught for small groups and on-the-job training could be provided to individuals at centers where skills have been acquired. Because modeling is not only a technique, but also a whole approach to dealing with crops, full adoption and adaptation of models for research and extension in their own environments takes new groups several years. Those using models should be given the opportunity to cooperate nationally and internationally.

Most modeling groups are still rather young and small; all could benefit from mutual support and inspiration. International cooperation would be effective because it allows researchers from many countries to more rapidly make use of conclusions.

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Photothermal models of rice growth duration for three varietal types in China

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ABSTRACT

Multiple regression was used to establish photothermal models of rice growth duration from sowing to heading for three major varietal types (early, medium, and late). The models are based on crop data for 12 representative varieties grown at different locations throughout China and on meteorological data from the same locations during the same periods. The modeling method reduced error over the traditional temperature summation method by about 3 d for early varieties, 6-9 d for medium varieties, and 18-20 d for late varieties.

Rice growth duration depends primarily on varietal characteristics and environment. The influence of climate on rice growth duration is significant in adjusting crop and varietal disposition, choosing optimum cropping systems, selecting suitable sowing dates, forecasting seasonal operations, and making management decisions.

It is well known that rice growth and development are influenced by temperature. However, efforts to develop a temperature summation function for rice growth duration have not been successful. One major reason is that in the traditional method, temperature has been considered as a single factor. But in fact, light, in addition to furnishing energy, also serves an important function in regulating flowering and maturation of the rice plant.

In China, Gao (4) analyzed the influence of daylength on temperature summation and developed a photothermal coefficient. Nan (8) extended the concept “sum of dark period” to describe the relationship between length of photosensitive stage and environmental conditions. Gao et al (5) developed photothermal models of rice growth duration for five local varieties in the Naning area. The models presented here can be applied to all of China’s rice-producing areas.

Methodology

Basic considerations

1. Regression analyses describe the effect of one or more predictor variables on a single response variable by expressing response as a function of predictor (6). Rice growth duration from sowing to heading was hypothesized as a function of environmental conditions and their interactions.
2. The success of a modeling project depends upon the choice of the predictor variable, which should explain the significant physical and/or physiological factors influencing the response variable.
3. For rice varieties, the ripening phase (heading to maturity) is relatively constant in duration. But duration from sowing to heading varies greatly and largely determines the entire growth duration (3,5,13). Growth duration was taken as equal to the number of days from sowing to heading, plus 40 d for japonica varieties and 30 d for indica varieties.
4. The optimum temperature for all rice varieties is 25 °C (9). The 30°N latitude line across Central China bisects its rice-growing regions. For most rice regions, local sowing dates are after 1 Apr. Standard duration was defined as duration under standard conditions (T = 25 °C, f = 30°N, and S = 1 Apr).
5. These models are application oriented. emphasizing convenience combined with precision.

Choice of factors

The temperature summation method does not reflect the effect of daylength on growth duration. Yet daylength has a strong influence on rice growth duration (1,11,14,15). The extent of its influence differs with photoperiod sensitivity. According to Gao (5) and Holmes and Robertson (7), the average daylength experienced by a rice crop is determined by local sowing date and latitude. These two factors and their interaction were selected, instead of average daylength alone, as factors in the models. In addition, they are easy to measure.

Temperature regime greatly affects growth duration (3,5,12,15). Thermosensitivity is one of the most important varietal characteristics which determine the stability of growth duration (2). Although the temperature summation method may be effective in describing the total heat requirement of a rice crop, it often fails to indicate thermosensitivity. Both the linear and quadratic terms of temperature from sowing to heading were included in the models. The response of the growth curve to temperature, including minimum, optimum, and maximum temperatures, can be easily expressed (10).

Regression approach

The growth duration models for different varietal types followed the general form

$$\hat{D} = D' + b_1\Delta T + b_2\Delta\phi + b_3\Delta S + b_4(\Delta T)^2 + b_5\Delta\phi \cdot \Delta S \qquad (1)$$

where:

$\hat{D}$ = growth duration, in days, from sowing to heading;

D' = standard duration (T = 25 °C, ϕ = 30°N, and S = 1 Apr);

ΔT = temperature difference, in °C, between local mean temperature from sowing to heading and standard temperature of 25 °C;

$\Delta\phi$ = latitude difference, in degrees, between local latitude and the standard latitude of 30°N. $\Delta\phi$ is negative when latitude is $\leq$30°N and positive when $>$30°N;

ΔS = difference in days between local sowing date and standard sowing date of 1 Apr. ΔS is considered negative when sowing date is before 1 Apr and positive when after 1 Apr;

$\Delta\phi \cdot \Delta S$ = interaction term between $\Delta\phi$ and ΔS; and

b_i = partial regression coefficients. (i = 1,2, . . .).

Selecting the best regression models

Eight representative rice varieties differing in varietal type and duration were chosen. Regression equations using various combinations of factors were obtained for each variety. Estimated standard errors (S_D) and coefficients of determination (R^2) were computed. The significance of each multiple regression model was tested. For each variety, the regression equation which was significant at the 1% level and which had the smallest error and the largest R^2 was selected as the best rice growth duration model for that variety.

To compare the regression models with the temperature summation method, errors (converted into days) in effective temperature summation during the period studied were computed. The threshold temperatures for effective temperature summation were assumed to be 10 °C for japonica and 12 °C for indica (5).

Data Used

Crop data (sowing date, heading date, and number of days between sowing and heading) were collected, partially from the national rice ecological experiment conducted at 8 locations (Yan County, N18°21'; Guangzhou, N23°08'; Kunning, N25°12'; Changsa, N28°13'; Nanjing, N32°00'; Tianjin, N39°02'; Qongzhuling, N43°3l', and Miguan, N44°07') over 2 yr (1962-63) under Ding (Coordinating Group of Rice Ecological Research, 1978), and partially from the Jiangsu Academy of Agricultural Sciences experiments conducted in different counties of Jiangsu Province 1979-80.

To fit the environment-crop relationship, working data also included latitude, mean daily temperature, etc., taken from the meteorological stations at the same locations during the same periods.

Results

Determining growth duration models for three major rice varietal types

Early rice or medium rice with weak photoperiod sensitivity. Table 1 sum-

Table 1. Errors (in days) in determining early and medium rice growth duration models.

Variety	Factor chosen	S_D	R^2	Error of temperature summation	Sample size
Weiguo	ΔT, $\Delta\phi$, ΔT^2	24.93	0.91		
(early japonica)	ΔT, $\Delta\phi$, ΔS, ΔT^2	±5.02	0.91	±8.03	30
	ΔT, $\Delta\phi$, ΔS	±7.10	0.82		
	ΔT, ΔS, ΔT^2	±7.23	0.81		
Nantehao	ΔT, $\Delta\phi$, ΔT^2	±5.87	0.81		
(early indica)	ΔT, $\Delta\phi$, ΔS, ΔT^2	±6.39	0.78	±8.87	30
	ΔT, $\Delta\phi$, ΔS	±10.33	0.41		
	ΔT, ΔS, ΔT^2	±7.70	0.67		
Dayaomahuang	ΔT, $\Delta\phi$, ΔT^2	±5.77	0.91		
(medium indica	ΔT, $\Delta\phi$, ΔS, ΔT^2	25.79	0.92	±8.65	30
	ΔT, $\Delta\phi$, ΔS	27.70	0.85		

S_D= estimated standard error (model error).

Table 2. Errors (in days) of two rice growth duration models and temperature summation methods.

Variety	Error of models (S_D)	Error of temperature summation	R^2	Sample size
Wuyuhuang (early indica)	25.35	±7.89	0.87	30
Miquanheimeng (early japonica)	25.63	±8.90	0.89	30

marizes different combinations of the factors chosen. The estimated standard error (S_D) indicates the precision (in days) of fit through the regression equations. R^2 indicates the proportion of duration variability from sowing to heading explained by the factors chosen. Error (converted into days) of effective temperature summation are given for comparison.

For this varietal type, the regression model involving the three factors DT, Df, and DT^2 is best, with the smallest S_D and the largest R^2, significant at the 1% level. The growth duration model for this varietal type was determined as

$$\hat{D} = D' + b_1\Delta T + b_2\Delta\phi + b_3(\Delta T)^2$$

Using equation 2, two more early rice varieties were evaluated with the model and errors compared to those using the temperature summation method (Table 2). Compared with the temperature summation method, the rice growth duration model reduced error by about 3 d for this varietal type.

Medium rice with medium photoperiod sensitivity. Table 3 shows the results using combinations of factors for medium varietal type Huangkezao 20.

Table 3. Errors (in days) in model determination of rice growth duration for medium varietal type, represented by Huangkezao 20.

Variety	Factors chosen[a]	S_D	R^2	Error of temperature summation	Sample size
Huangkezao 20 (medium japonica)	ΔT, $\Delta\phi$, ΔT^2	±9.89	0.84	±15.64	26
	ΔT, $\Delta\phi$, ΔS	±10.25	0.83		
	ΔT, $\Delta\phi$, ΔS, ΔT^2	±11.01	0.82		
	ΔT, $\Delta\phi$, $\Delta S'$	±3.77	0.98		
	ΔT, $\Delta\phi$, $\Delta S'$, ΔT^2	±3.63	0.98		

[a]S' = no effect of sowing date (S) considered below 25°N latitude ($\phi \leqslant 25$°N).

Table 4. Errors (in days) of model for determination of rice growth duration for late varietal types.

Variety	Factor chosen	S_D	R^2	Error of temperature summation	Sample size
Zhechang 9 (late indica)	ΔT, $\Delta\phi$, ΔS, ΔT^2, $\Delta S \cdot \Delta\phi$	±3.96	0.97	±22.17	26
	ΔT, $\Delta\phi$, ΔS, ΔT^2	±9.40	0.92		
	ΔT, $\Delta\phi$, ΔS	±9.39	0.91		
	ΔT	±24.75	0.35		
Zhumaozu (late japonica)	ΔT, $\Delta\phi$, ΔS, ΔT^2, $\Delta S \cdot \Delta\phi$	±5.82	0.97	±25.97	24
	ΔT, $\Delta\phi$, ΔS, ΔT^2	±5.90	0.97		
	ΔT, $\Delta\phi$, ΔS	±6.38	0.96		
	ΔT	±23.04	0.40		

For this varietal type, the combinations (ΔT, $\Delta\phi$, ΔT^2), (ΔT, $\Delta\phi$, ΔS), and (ΔT, $\Delta\phi$, ΔS, ΔT^2) did not reduce error. However, the combinations (ΔT, $\Delta\phi$, $\Delta S'$) and (ΔT, $\Delta\phi$, $\Delta S'$, ΔT^2) greatly improved precision. AS' means that the effect of sowing date on growth duration was not considered in the low latitude regions ($\phi \leq 25$°N) but was considered in the middle and/or high latitude regions. In low latitude regions, daylength is always short enough to satisfy the requirement for this varietal type. The combination of (ΔT, $\Delta\phi$, $\Delta S'$, ΔT^2) is much more complex to compute than (ΔT, $\Delta\phi$, $\Delta S'$), but errors (in days) are almost the same. Therefore, the current model for this varietal type was established as

$$\hat{D} = D' + b_1\Delta T + b_2\Delta\phi + b_3\Delta S' \quad (3)$$

Comparison with temperature summation shows that the model reduced error by about 12 d.

Late rice with strong photoperiod sensitivity. Table 4 summarizes combinations of factors for late varietal types Zhechang 9 and Zhumaozu.

For these two varieties, using the temperature summation method to estimate late growth duration from sowing to heading resulted in a large error of

22-26 d. Single linear regression with a single temperature factor did not reduce the error. Using the factors DT, Dϕ, and DS greatly improved precision. The multiple regression model with five factors chosen is best; error can be reduced by 18-20 d. For late rice varietal types, the growth duration models established are:

for indica

$$\hat{D} = D' + b_1\Delta T + b_2\Delta\phi + b_3\Delta S + b_4(\Delta T)^2 + b_5\Delta S \cdot \Delta\phi \quad (4)$$

for japonica

$$\hat{D} = D' + b_1\Delta T + b_2\Delta\phi + b_3\Delta S \quad (5)$$

Summary

Rice growth duration models can be grouped according to varietal type (Table 5). The modeling method effectively reduces error over the temperature summation method by about 3 d for early or medium types with weak photoperiod sensitivity, 6-12 d for medium types with medium photoperiod sensitivity, and 18-20 d for late types with strong photoperiod sensitivity. The statistical tests showed that error can be reduced to ±3-6 d in all of China's rice producing region and to ±2-4 d within an area in a province.

The rice growth duration models for 12 representative rice varieties differing in varietal type and maturity are given in Table 6.

Table 5. Three major forms of rice growth duration models by varietal type.

Varietal type	Factors chosen in models		
Early or medium rice with weak photoperiod sensitivity	ΔT, $\Delta\phi$, ΔT^2	or	ΔT, $\Delta\phi$, $\Delta S'$
Medium rice with medium photoperiod sensitivity	ΔT, $\Delta\phi$, $\Delta S'$	or	ΔT, $\Delta\phi$, ΔS, ΔT^2
Late rice with strong photoperiod sensitivity	ΔT, $\Delta\phi$, ΔS, ΔT^2, $\Delta\phi \cdot \Delta S$	or	ΔT, $\Delta\phi$, ΔS

Table 6. Rice growth duration models (RD_M) for rice varieties differing in type and maturity in China.

Variety	Varietal type	Maturity	Rice growth duration model	Sample size	Error of model	F-test[a]	R^2
Miquanheimeng	Early japonica	Medium	$\hat{D} = 61.97 - 3.39\Delta T + 0.31\ (\Delta T)^2 + 0.89\Delta\phi$	30	±5.63	**	0.89
Weiguo	Early japonica	Late	$\hat{D} = 80.32 - 3.93\Delta T - 0.05\ (\Delta T)^2 + 0.74\Delta\phi$	30	±4.93	**	0.91
Wuyuhuang	Early Indica	Medium	$\hat{D} = 69.32 - 3.50\Delta T + 0.22\ (\Delta T)^2 + 0.70\Delta\phi$	30	±5.35	**	0.87
Nantehao	Early Indica	Medium	$\hat{D} = 74.94 - 3.11\Delta T + 0.07\ (\Delta T)^2 + 0.63\Delta\phi$	30	±5.87	**	0.81
Shenglixuan	Medium indica	Early	$\hat{D} = 83.25 - 3.92\Delta T + 0.49\ (\Delta T)^2 + 0.55\Delta\phi$	30	±4.56	**	0.86
Dayaomahuang	Medium indica	Early	$\hat{D} = 90.90 - 4.73\Delta T + 0.58\ (\Delta T)^2 + 0.58\Delta\phi$	30	±5.77	**	0.91
Aizizhen	Medium indica	Medium	$\hat{D} = 97.85 - 4.54\Delta T + 0.55\ (\Delta T)^2 + 0.75\Delta\phi$	30	±5.57	**	0.82
Shuiyan 300	Medium japonica	Early	$\hat{D} = 77.33 - 2.99\Delta T + 0.74\Delta\phi - 0.05\Delta S'$	30	±5.84	**	0.85
Taizhong 65	Medium japonica	Medium	$\hat{D} = 98.84 - 3.63\Delta T + 0.94\Delta\phi - 0.03\Delta S'$	30	±3.84	**	0.92
Huangkezao 20	Medium japonica	Late	$\hat{D} = 111.41 - 3.83\Delta T + 0.98\Delta\phi - 0.35\Delta S'$	26	±3.77	**	0.98
Zhumaozu	Late japonica	Late	$\hat{D} = 159.76 - 2.34\Delta T + 0.99\Delta\phi - 0.72\Delta S$	26	±6.38	**	0.97
Zhechang 9	Late Indica	Medium	$\hat{D} = 155.35 - 0.69\Delta T + 5.95\Delta\phi - 0.96\Delta S + 0.84(\Delta T)^2 - 0.07\Delta\phi\cdot\Delta S$	24	±3.96	**	0.99

[a]**Sianlficant at 1% level. Source: Ding's experiment.

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Influence of planting density on assimilate partitioning and yield: a simulation model for Malaysia

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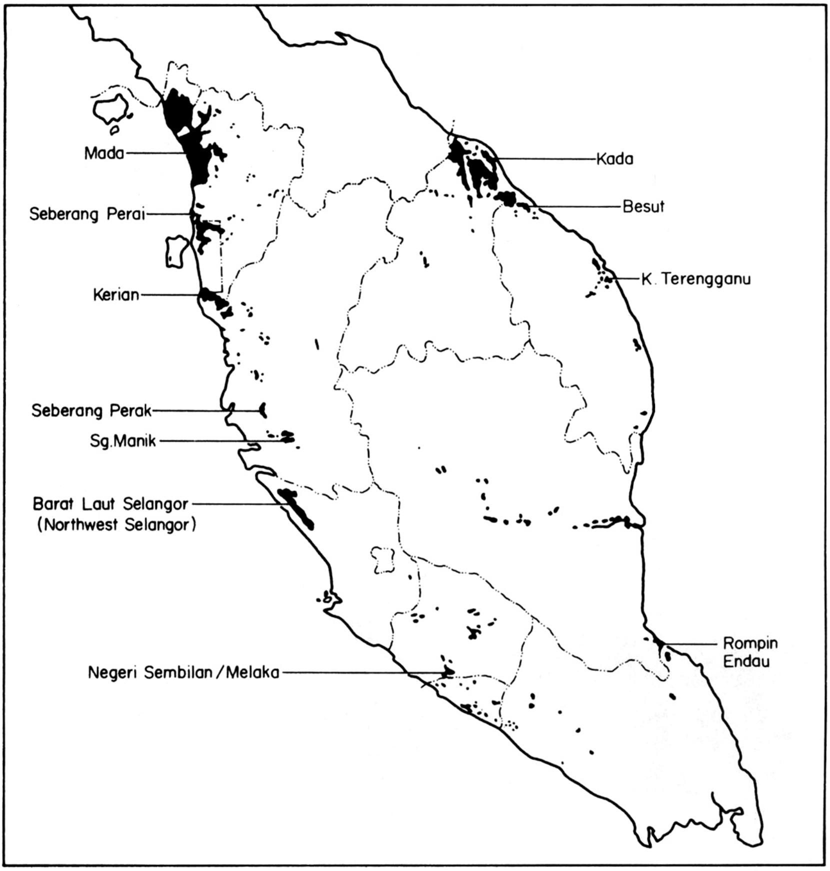
ABSTRACT

The long-term objectives of the rice modeling research at Universiti Pertanian Malaysia (UPM) were used to propose a case study in connection with the CABO-TPE-IRRI course Implementation of Systems Analysis and Simulation for Rice Production. The basic LORICE simulation model gave a lower potential yield than expected, approximately 6 t/ha. Adjusting the rate of tiller formation, assimilate partitioning, and other parameters increased potential yield to 7.5 t/ha. Lack of reliable information on growth, development, and assimilate partitioning at different planting densities, as well as the rather low planting density practiced in Malaysia, led to the case study proposal. The long-term modeling program and detailed methodology for the case study are described.

Most rice production systems in Malaysia are classified as irrigated wetland (Fig. 1). Average yields range from 3.1 t ha in the northeast region (KADA) to 3.5 t/ha in the central region (Northwest Selangor), with a high of 4.4 t/ha in the northwest region (MADA) (5). A yield of more than 8 t/ha has been attained from experimental plots.

Yield variations have been attributed to soil type, water, and fertilizer management and, to a lesser extent, meteorological conditions. In particular, soils of the MADA and Northwest Selangor areas, mainly marine alluvium with 2:1 clays, are more fertile and better water retainers than the predominantly riverine alluvium of KADA, mainly 1:1 kaolinitic clays (3). Further yield reductions may also occur because of inadequate control of weeds (*Echinochloa* spp.), insect pests (stem borer and brown planthopper), and diseases (blast and penyakit merah).

Many of the processes that lead to growth and development of rice have been quantified. That information has been integrated into simulation models for insights into crop response to environmental factors, for research, and for



1. Rice-growing areas of Peninsular Malaysia (5).

yield predictions (1,2). With these simulation models, quantitative estimates of the effects of the more limiting factors, as well as the reducing factors, could be obtained and weighted. But such models need to be modified for application to specific conditions.

Long-Term Objectives

The long-term objectives of rice modeling research at UPM are:

- To evaluate the production potentials of some of the major rice growing areas in Malaysia;
- To identify means of narrowing the gap between current yields and potential yields, specifically cultural techniques, soil and water management, and control of weeds, insect pests, and diseases; and
- To develop simulation models for soil and water management and weed, insect, and disease control at the area level.

Initially, the rice crop growth simulation model will be adapted for use at production level 1, with optimum water and nutrients but growth rate determined by weather conditions. The most important elements are radiation and temperature (4). The model then will be used to estimate potential yields of the major rice growing areas of the country. This, in turn, will help establish priorities on which management decisions could be made to improve efficiency and productivity in each area. Area specific (e.g., soil, water) and problem-specific (e.g., pests) information will be used to develop appropriate management simulation models.

The Case Study

A case study to investigate the influence of planting density on assimilate partitioning and yield of two rice cultivars, assuming optimum water and nutrient availability with adequate insect and disease control, will be conducted April-December 1986.

Justification

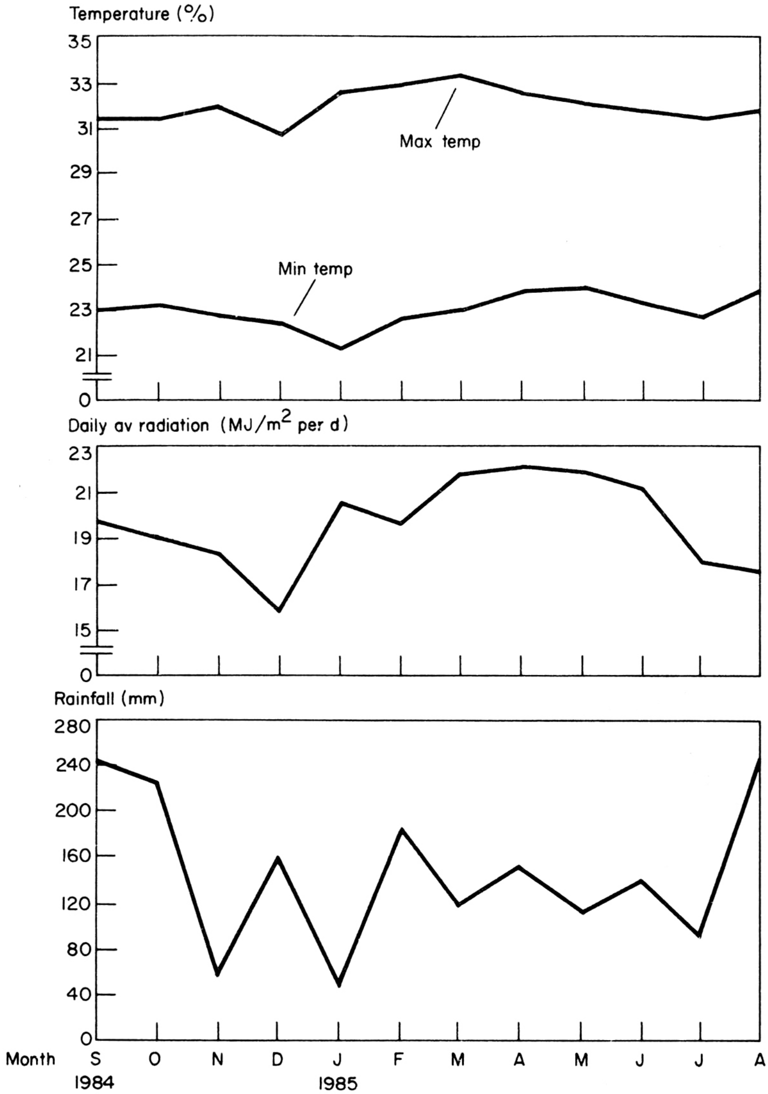
The case study is related to the first long-term objective. Although it is unrealistic to expect the model to predict the absolute potential yield, we do want it to give reasonably acceptable values for potential yield.

Simulation runs of LORICE model (1) using weather data from MADA area gave potential yields of less than 6 t/ha, far below expectation. Experimental yields of more than 8 t/ha have been recorded. When rate of tiller formation, grain weight, and assimilate partitioning ratio were modified and the appropriate developmental stages adjusted, the model gave higher predictions.

Results of the simulation runs for various planting dates and planting densities are given in Table 1. Figure 2 summarizes the monthly weather data used. Rainfall data were not used in the simulation, but are included here for completeness. For the same assimilate partitioning ratio, grain yield is observed

Table 1. Predicted yield at Telok Chengai, MADA, from simulation runs at different planting densities and dates.

Planting date	Yield (t/ha)		
	20 × 20 cm	30 × 30 cm	40 × 40 cm
25 Feb	7.9	6.5	4.8
25 Mar	8.0	6.5	4.6
25 Apr	7.9	6.4	4.8
25 May	7.8	6.8	5.1
25 Jul	8.0	6.3	5.7
25 Aug	7.3	6.0	4.6
25 Sep	7.2	6.1	4.5
26 Oct	6.3	5.6	4.2



2. Average daily radiation, maximum and minimum temperatures, and monthly rainfall for MADA area (Sep 1984-Aug 1985).

to increase with higher planting density. Because of small variations in daily radiation and maximum and minimum temperatures, potential yields for different planting dates do not differ substantially.

An exception is considerably depressed yields from the October planting, due mainly to the lower radiation in December when panicle initiation and reduction division stages occur. March (off-season) and August (main season) planting dates result in the expected highest yields.

The planting density commonly practiced now is 30 × 30 cm. Experimental evidence has shown that higher planting densities could result in improved yields. This is borne out by the simulation results. But reliable data on assimilate partitioning, especially for Malaysian varieties, are lacking. We propose to study the effect of planting density on growth, assimilate partitioning, and yield of two varieties commonly grown in Malaysia.

Implicit in the case study are assumptions about optimum water and nutrient availability and adequate pest and disease control under Production Level 1. Increasing density up to an optimum level should result in an increase in total plant biomass. If the assimilate partitioning ratio is not adversely affected, yield would be expected to increase with density.

Methodology

Field experimentation

A field trial will be conducted in Tanjung Karang during the off-season (April-September) 1986 using a split-plot design. Two varieties commonly grown in Tanjung Karang areas — MR77 and MR10 — will be used. Three planting distances - 40 × 40 cm, 30 × 30 cm, and 20 × 20 cm - will be tested. A uniform rate of N, P_2O_5, and K_2O (90:60:60)/ha will be applied. N will be applied in 3 equal splits, just before transplanting, at panicle initiation, and at 50% flowering. P and K will be applied as basal dressing.

Treatments will be replicated 4 times, for a total of 24 experimental units. Each experimental unit measures 9.6 × 9.6 m. Three applications of Furadan 3G will be made against lepidopterous stem borers. For other pests, appropriate pesticides will be applied as needed. Two rounds of hand weeding will be done.

Measurements and analysis

Soil samples will be taken to determine texture, bulk density, soil water characteristics, depth of plow pan, water table, pH, soil OM, CEC, total N, available P, exchangeable K, Ca, and Mg, and Al saturation. Daily radiation, maximum and minimum temperatures, relative humidity, and rainfall weather data will be recorded.

Weekly tiller counts will be taken from 2 wk after transplanting to heading. Plant samples taken at transplanting, weekly to 2 wk after 50% flowering, and at harvest will be analyzed for growth (dry matter, leaf area, and assimilate partitioning) and chemical profile (N, P, and K). Plant height, panicle number, yield components, chemical profile of tissues and grain, and maximum rooting depth will be recorded at harvest. Stem borer population and blast will be monitored regularly.

From the center rows in each plot, 3 × 3 m will be retained for yield determination; 4 border rows will be retained as buffer; the remaining rows will be used for plant sampling. Each sample will be 3 × 4 hills from each experimental unit.

Modeling aspects

The model will be calibrated for tiller formation and tiller death, spikelet and grain development, and assimilate partitioning using the data available on several local varieties. The case study will be used to validate the model, leading to further improvement.

Additional Activities

Parallel to the case study, a review of literature on pest control, the influence of soil types and soil physical properties, and agronomic aspects of assimilate partitioning will be done to use as bases for subsequent modeling in these problem areas.

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Recommendations

Weather and biological stresses

The extent to which information on the prevalence of rice pests under different cultural types and climatic conditions is quantitative or qualitative needs to be reviewed.

Information on the current status of major pests in different rice-growing environments should be collected in a central data bank. A survey of IRTP collaborating scientists to identify annual and seasonal shifts in pest status is recommended.

Pest monitoring should be incorporated into studies on rice-weather relationships, including data on both research plots and adjacent farmers'fields. Consideration should be given to expanding instrumentation at certain sites to study the dispersal stages of insects and pathogens in relation to natural weather parameters.

Provision for measuring or calculating leaf wetness, an important parameter in disease epidemiology, should be added to the basic data set. Continuous temperature and humidity records are desirable.

Short-term disease and insect forecasting systems based on empirical relationships between site-specific weather parameters (such as temperature, humidity, and rainfall) and the progression of outbreaks should be tested in new locations. The development and use of simulation models should be encouraged to promote wide applicability, evaluate weather as an effective predictor of a range of pest outbreaks, and assist in focusing research needs.

Pest incidence forecasting, particularly of migrant insects, should be studied using synoptic weather data and closely integrated with more site-specific studies. Patterns of wind-borne organism dispersal have high regional significance and international collaboration is critically important. An International Pest Management Working Group should be constituted to collaborate with rice-weather programs.

Weather and rainfed rice

We agreed to use the term *environment* instead of *weather* to take into account aerial, edaphic, and topographic features. The term *upland rice* is taken to be synonymous with dryland rice raised with no bunding and no access to any water table. The constraints to upland rice production can be grouped as environmental, environment-dependent, and site-specific.

Because rainfed lowland rice occupies a large area and offers considerable scope for increased yields, it was decided to take up work on shallow rainfed lowland rice along with upland rice. Considering the socioeconomic problems in regions of rainfed rice farming, the complexity of stabilizing rainfed rice yields at satisfactorily high levels, and the benefits, experience, and results of IRTP trials, the time seems ripe to mount a cooperative. coordinated program on rainfed rice.

Constraints. The constraints to rainfed rice production include:

- Climate: rainfall amount and variability, solar radiation, and temperature.
- Technology: insect pests and diseases, weeds, and rats and birds; land preparation; planting methods; soil nutrient management; soil erosion and other physical problems; cropping patterns; and water conservation.
- Genotype: seed dormancy and vigor, rooting characteristics, insect and disease resistance, resistance to temperature extremes, drought resistance, and crop duration.
- Socioeconomic: production incentives, labor, markets, infrastructure, and credit.

Most of these constraints can be related directly or indirectly to climatic factors or site characteristics.

Research methodology. Water balance is the best tool for determining soil water availability or deficiency throughout the crop season. Two levels of water balance study were identified:

1. Site classification and climate-soil resource inventories, based on a simple water balance. Simple water balance models developed by CSIRO and FAO require only rainfall, soil water-holding capacity, and potential evapotranspiration as weekly or monthly inputs.
2. Detailed water balance studies in conjunction with agronomic experiments. Computing a detailed water balance in upland and rainfed lowland experiments would require similar minimum data sets.

For rainfed lowland rice, only two additional measurements — depth of standing water and depth of water table when no standing water is seen —would need to be made (see table).

Specific recommendations. Because of the socioeconomic problems in rainfed rice regions and the complexities of environmental constraints on rainfed rice, international collaboration of the type exemplified by IRTP and ARFSN is the only avenue with the potential to contribute significantly to increased and stabilized production. It is recommended that:

1. a coordinated series of experiments be conducted at a few sites to collect minimum data sets on three varieties — short-duration, medium-duration where appropriate, and locally adapted — with more than one sowing date.

Minimum data set for detailed water balance description:[a]

I. Meteorological	*II. Soil and landform*	*III. Crop*
A. Rainfall (M)	A. Texture (I)	A. Seeding-transplanting date (1)
B. Max-min temp (M)	B. Hydraulic conductivity	B. Seedling age if transplanted (1-L)
C. Solar radiation (M)	C. Water retention (I)	C. Planting density and spacing (I)
D. Wind (M)	D. Water infiltration (I)	D. Tillering (I)
E. Minimum relative humidity or vapor pressure deficit (M)	E. Slope or runoff (1)	E. Flowering date (I)
F. Pan evaporation (M)	F. Chemical properties (I)	F. Plant height (I)
	G. Rootable depth (I)	G. Periodic harvest biomass accumulation
	H. Moisture profile (M)	H. Nutrient analysis (M)
	I. Site description (I)	
	J. Water depth or water table depth when there is no standing water (M-L)	

[a]M = monitored through crop season, I = measured during initial site characterization or once during crop season, L = rainfed lowland only.

2. trials be conducted at sites representative of upland and rainfed lowland rice regions which encompass the full range of climate and soil variations. The number of sites should be limited to ensure that they can be adequately maintained and monitored.
3. cooperative centers be selected after prospective collaborators provide details of site characteristics and facilities related to infrastructure.
4. ancillary agronomic work relating to crop establishment and management, intercropping and sequence-cropping, water conservation, nutrient dynamics, and coping with early and midseason weather vagaries be undertaken or intensified.

The proposed studies should be useful in interpreting IRTP and ARFSN trials and should complement crop modeling efforts. Rice-weather programs in irrigated rice also should be strengthened to complement efforts in rainfed rice.

Rice modeling

Given the recommendations of the Symposium on Agrometeorology of the Rice Crop (1980) and of the Rice Crop Modeling Workshop (1983), we arrived at these conclusions:

1. Although much effort has gone into establishing standard instrumentation for weather data measurements in the rice-weather network, the potential for using these data in simulation modeling has not been fully realized. Most, if not all, of the existing rice simulation models require the same type of data. Weather and crop data along the lines of the recently completed rice-weather project should continue to be collected.

   While network cooperators will benefit from reports of data use, the rice modeling teams also are encouraged to contact leaders of national rice-weather projects. Such interaction could lead to greater utilization of the data as well as greater modeling capability.

Collecting crop data on other rice cultivars, including japonicas, and other management practices should be considered.

2. Several different rice crop simulation programs are being used. The models have similar objectives (integration of scientific knowledge, application to agronomic decisions, and other purposes) but use, at least partially, different approaches. Each major model is superior to all others in at least one aspect. Each model could be improved by direct exposition to the others, at the same time lessening confusion among potential model-users.

   We recommend that a small workshop be organized to compare the 3-5 major rice growth models, such as the CERES-rice, ORYSIM, and CABO models. Comparing by simulation a few well-documented trials (such as from the IRRI Agronomy Department, the Rice Weather Programme, or UC) would enable evaluation on accuracy in different environments, ease in use and understanding, and extent of documentation and evaluation. The workshop could well be part of the final session of the CABO-TPE-IRRI course on rice crop simulation.

3. In partially irrigated and rainfed lowland rice, and in other crops grown in association with rice, field puddling and hardpan complicate soil-water relationships, plant water uptake, hydraulic properties, and water economy. When water stress in partially irrigated rice occurs, it may be treated in the same manner as water stress in rainfed lowland rice. The same soil water balance component will be the major constraint to extending the model to rainfed upland situations. On shrinking and swelling soils, by-pass flow of water may be important. Current soil water balance models do not deal adequately with that.

   In collaboration with national programs, IRRI should further develop suitable methodologies and instrumentation to describe soil-water relationships as well as root growth under puddled conditions and hardpan. The newly developed technique for estimating water infiltration with by-pass flow should be followed up. This program requires one fairly representative site for each lowland and upland condition.

   Experimentation supported by modeling should lead to more simple procedures and methods that yield basically the same information. These trials should be replicated for many soil type-climatic combinations for several years, as was done in the rice-weather program. Existing models can help assess the relevance of by-pass flow for rice cropping.

4. Most rice crops suffer from N shortage during at least one growth stage. In rice-based cropping systems, N must be used with maximum efficiency. A better understanding of soil and crop nitrogen balance processes is needed to speed up research on fertilization. Modeling needs to be encouraged here.

A new technique promises to become a means of generating daily weather data from only a fraction of the basic data required so far. This technique can be important in reducing the number of weather parameters to be recorded (processed, stored) per site and to expanding the use of short data sets. This technique should be developed for lowland and upland situations. It also can improve our capacity for mapping climatic data.

Diseases, insect pests, and weeds cause important yield losses in most rice-growing areas. Efficient control will become even more important when intensive rice production systems are widely adopted. To prepare for this situation, more studies are needed on the population dynamics of major biological constraints and on the damage they cause. Modeling needs to be encouraged here, too. Because such research requires highly specialized skills, experiments, and/ or facilities, we recommend that such studies be done at specialized institutes and that IRRI associate itself with those studies by organizing and attending relevant meetings and by participating in ongoing experiments.

5. Modeling rice crop growth and other crops associated with it is considered to have great potential for strengthening research and for improving the application of that research to practical recommendations by national and international institutes. Currently, there are very few institutes with modeling capability and with scientists trained in modeling. IRRI should take the lead in maintaining contacts among rice modelers and others by organizing regular meetings and providing adequate training in rice crop modeling. This would give national programs the opportunity to expand their use of systems analysis and modeling in rice research at their national institutes.

General recommendation

Because of the importance of the impact of weather on the rice crop, the major importance of the crop, and the success of the UNDP-funded Rice-Weather Project in initiating the collection of essential basic information on weather and rice crop yields, and noting that the project has already established a basis for prediction models for rice yield and shows potential for developing forecasting models for pest outbreaks, the workshop unanimously recommends that appropriate donor agencies make funds available to IRRI to continue the rice-weather project, encompassing as far as possible the recommendations of the working groups.

WORKSHOP ON IMPACT OF WEATHER PARAMETERS ON THE GROWTH AND YIELD OF RICE
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