THE MINERAL NUTRITION OF THE RICE PLANT

Proceedings of a Symposium at
The International Rice Research Institute
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Foreword

The Symposium on the Mineral Nutrition of the Rice Plant was the fourth in a series of technical meetings convened by The International Rice Research Institute to discuss specific areas of rice research.

It brought together at the Institute in Los Baños, Laguna, Philippines, more than seventy-five scientists from eighteen countries to facilitate the exchange, discussion, pooling, and utilization of available knowledge about the mineral nutrition of the rice plant. Twenty-five of these world authorities were participants from Japan, Taiwan, the Philippines, the United States, France, the Food and Agricultural Organization of the United Nations, and the Institute; while about fifty were invited observers from Australia, Ceylon, Taiwan, France, India, Japan, Korea, Malaysia, the Netherlands, Okinawa, Pakistan, Thailand, the United States, Vietnam, West Africa, Italy, and the FAO.

A total of twenty-six technical papers reporting years of studies on various aspects of the mineral nutrition of rice were presented and discussed in the five-day conference. A review of the symposium papers also was presented at the concluding session.

Dr. Akira Tanaka, Institute plant physiologist, acted as co-ordinator, while Dr. F. N. Ponnamperuma, Institute soil chemist, served as moderator during the symposium. Dr. Ponnamperuma was assisted by Dr. H. T. Chang, Department of Agriculture and Forestry, Taiwan; Dr. Richard Bradfield, consultant to The Rockefeller Foundation, New York; and Dr. Robert F. Chandler, Jr., director of the Institute. Drs. Tanaka and Ponnamperuma, Dr. H. R. von Uexkull, Taiwan Potash Research Foundation, Hong Kong, and Dr. R. P. Humbert, Foundation for International Potash Research, United States, served as technical editors of the symposium papers.

The Ford Foundation, the Foundation for International Potash Research, and the International Potash Institute provided financial support for the symposium.

Editorial work and publications arrangements for the symposium proceedings were handled by the Institute's Office of Communication.

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INTRODUCTION

Problems Peculiar to Rice Production in the Tropics

1

The Environment of Tropical Rice Production

JAMES C. MOOMAW *and* BENITO S. VERGARA[1]

Rice is cultivated as far north as 49° in Czechoslovakia (Kratochvil, 1956) and as far south as 35° in Australia. Evidence indicates that although rice is primarily a tropical and subtropical crop, the best grain yields are obtained in temperate areas, such as the Po Valley, Italy (45°45′ N), northern Honshu, Japan (38°), or New South Wales, Australia.

This paper describes the environmental regime operating during the growing season of the tropical rice plant in contrast to that in temperate areas and discusses the effects of these differences on the growth pattern and yield of the rice plant. Climatic differences must be carefully considered in comparing the performance of the rice plant or a rice variety grown at different places.

RAINFALL

Water is frequently stated to be the most important single factor in rice production (Grist, 1959), and water control of both irrigation and drainage requires continued attention. As rice yields are generally higher in dry sunny seasons than in rainy seasons, irrigation of a dry-season crop in areas where none is now grown may more than double the total annual production in such areas. This may be the simplest and most direct way to increase rice production in many cases.

Ramiah (1954) and others point out that there is no relationship between the amount of rainfall and rice yield. Although irrigation is being developed in many places in the major rice-producing countries, such as Burma and Thailand, where storage capacity is available, only 10 per cent of the area (Grist, 1959) can be classified as irrigated. Temperate countries, such as Italy, Spain, Egypt, the United States, and Japan, produce irrigated rice almost entirely, but the aggregate area is small relative to world production.

The timing of irrigation and the total amount of water used to grow rice depend on variety, soil, and environmental characteristics. These include amount of filtration and deep percolation, clay type, organic-matter content, levee construction and condition, seasonal differences, plant spacing, duration, and other factors. The timing of irrigation and drainage may be important in some areas, but water-control practices vary from frequent and prolonged drainage to continuous deep submergence with little movement of water.

In a rain-fed rice culture, the usual pattern involves a shallow flood early in the season followed by a slow rise in water level and an equally gentle decline late in the crop season. The in-field water level varies from 2 to 5

[1] The International Rice Research Institute, Los Baños, Laguna, Philippines.

meters in the floating rice paddies of central Thailand to little more than saturation in areas of pervious soils and steep slopes. Deep submergence of normal tropical varieties from the time of panicle initiation until the crop is fully headed seems to be particularly damaging (Matsushima, 1962), and water stress at the same stage is also most injurious. Considerable latitude in water management is possible at earlier and later stages.

The total water requirement for tropical rice production has been measured in a number of places, and results vary widely, depending on the environmental, management, and soil conditions of the test (Aglibut, 1957; Kung, 1960; IRRI, 1963). Estimates of minimum water use are generally about 1,000 mm per crop, though evaporation and transpiration alone account for 600 to 700 mm, depending on crop duration, season, and other factors.

Most of tropical Southeast Asia receives abundant rainfall above the 2,000-mm annual isohyet. This is especially true in the major parts of Burma, Thailand, Indonesia, Cambodia, the Philippines, and South Vietnam. Even in the places where convergence or orographic patterns limit rainfall to 1,200 to 1,500 mm annually, if the rainfall is concentrated in the monsoon season (as is usual), this amount is probably adequate for at least a single rain-fed crop. Large areas of the mainland of China, India, and West Pakistan fall below this level. The characteristic high variability of tropical rain limits rice production in areas other than the great deltas and basins of the Mekong, Irrawaddy, Chao Phraya, Brahmaputra, Ganges, and Indus rivers where the major problem is drainage.

The environmental factor that determines the timing of rice planting for most of Southeast Asia is the start of the monsoon rains. The all-important water supply for rice production comes directly from rainfall for about 80 per cent of the rice in the world, and for the irrigated portion the water is obtained from monsoon-fed rivers in which the water either is impounded or flows directly to the fields.

Soils that become cemented, dry, and infriable during the dry season can only be plowed with available implements after being rain-soaked. The onset of the monsoon determines the planting time and thus the day length and radiation available during the growing period. The cloudy weather accompanying the monsoon reduces temperatures and light intensity, compared to cloudless seasons. Relative humidity, which may fall to low levels in the dry season, remains continuously high when the daily rains begin. Wind movement, relatively slight at low latitudes, may be accelerated by typhoons in the monsoon season.

The monsoon results from the shrinkage of the polar air mass in summer over the Asian continent (Trewartha, 1961). The intertropical front moves north until it is positioned north of the Himalayas and across Central Asia, and the tropical easterly winds then cross the equator and are deflected to the right (north) by the earth's rotation (Coriolis effect), becoming the general southeast monsoon (southwest over India). Wind movements are of low velocity, but as they cross the vast areas of the Pacific and Indian oceans they function as "sea breezes" and carry high humidity and constant cloud cover. Although rainfall is not necessarily high, it usually becomes so because the monsoon is accompanied by a constant succession of tropical cyclones (typhoons, hurricanes) which bring unusually low pressures and frequently high winds. Table 1–1 illustrates the position of Southeast Asia in the world typhoon record.

Two generalizations can be made about

TABLE 1–1: Average Frequency of Tropical Cyclones (Gentilli, 1958)

Area	Number per year
East Asian waters	21
Bay of Bengal	10
Madagascar	7
Southwest Pacific to Queensland	6
Arabian Sea	2
California waters	1

rainfall variability: (*a*) for tropical and temperate areas of equal rainfall amount, the coefficient of variability is generally higher in the tropics; and (*b*) where rainfall is low, variability is high regardless of latitude (Riehl, 1954). These two facts have several implications for the rice-growing areas of the tropics. Even where rainfall is adequate for rice growing, the variability may be so high that little of the water can be considered *effective rainfall*. Table 1–2 shows some of the record high-intensity rainfall occurrences at tropical stations and illustrates the hazards of uneven rainfall distribution.

TABLE 1–2: Maximum Rainfall Intensity in 24 Hours Reported from Several Tropical Stations (after Watts, 1955)

Station	Rainfall (mm)
Baguio, Philippines	1,168
Cherrapunji, India	1,036
Funkiko, Taiwan	1,034
Honomu, Hawaii	810
Los Baños, Philippines	305

When 30 to 50 per cent of the annual rainfall can occur in a single storm in 24 hours, control and utilization of this water is difficult. Hence, rice farmers in the nonirrigated 80 per cent of the rice-growing world are reluctant to drain their fields, once rain water is impounded within their bunds, even in places where drainage is possible.

In general, we can say that while rainfall amount is not likely to be limiting in a single-crop rice culture in Southeast Asia, the timing and variability of the monsoon rains are major problems in the field management of Asian rice.

RADIANT ENERGY

Light is the energy source for the production of all plant life and is particularly important for producing man's harvest of some crops. Evidence is accumulating that it plays an unusually important role in rice growing in the tropics. The photosynthesis reaction takes most of its energy from the visible spectrum lying between 0.4 and 0.74 μ, but there is also a long-wave component (Trickett, Moulsley, and Edwards, 1957).

Light values can be measured in a number of ways for correlation with rice yields, but unfortunately they are rarely recorded in any form at the ordinary meteorological stations in Southeast Asia. Light values are measured most simply as number of rainy days, cloudiness indexes, or number of sunshine hours. More precise measures are made as visible light (lux), total radiation (langleys), or net radiation.

Several workers have studied correlation of rice-crop yields with environmental factors (Sato, 1955, 1956; Matsuda, 1960), but most studies have been in Japan or other temperate areas (Shaw and Durost, 1962) where low temperatures are particularly important. For instance, three of the great famines in Japan (Arakawa, 1957) have been caused by low rice yields in years of unusually low temperature.

The comprehensive work of Daigo (Nagai, 1958) showed Japanese yields to be highest in years with above-normal temperatures in summer and with below-normal rainfall. The years of high rainfall were presumably times of high amounts of cloudy weather.

In tropical areas, few major studies of this kind have been made, but data have been accumulated from which inferences can be drawn. It is not unreasonable to assume that the production limit of a crop that is well fertilized and grown under a flood of water would be determined by the available light level or the level of damage by pests.

Total radiation is lower at low latitudes during the growing season than at higher latitudes (Table 1–3), and, by any measure, available light is of low abundance in the rainy season (Fig. 1–1).

Nuttonson (1957a) reported improved yields from sections of Burma where the monsoon ends early in most seasons. At The International Rice Research Institute, much higher

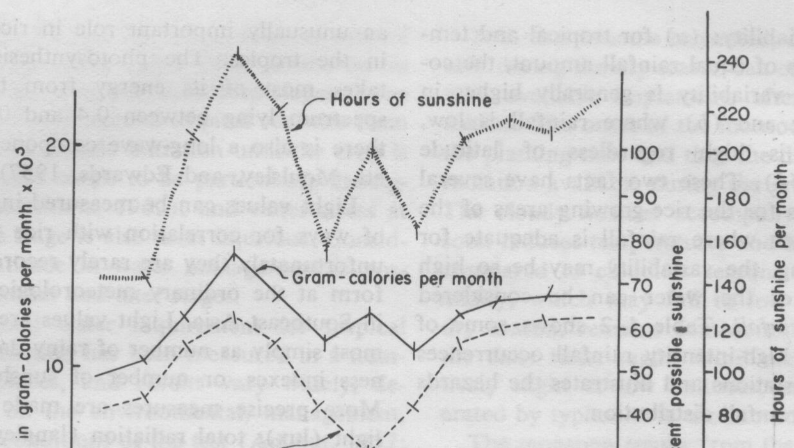

FIG. 1–1: Energy and light relationships for the Los Baños climate (14°N), 1961.

TABLE 1–3: Radiant Energy Received in Tropical Latitudes, Sea Level, 10 per cent Albedo, Clear Sky (cal/cm²/day) (after Gentilli, 1958)

Latitude	Maximum (June)	Minimum (December)
0°N	678	596
10°N	683	540
20°N	713	436
30°N	733	332

yields and greater response to nitrogen have been obtained in the dry season than in the wet season. Yields that are double the average wet-season production are possible using close spacing and varieties not sensitive to photoperiod. This requires that the crop be planted to permit harvest in March and April, when the maximum sunlight is available during the ripening period. In the Philippines, planting for dry-season harvest is generally practiced if irrigation water is available, but full advantage is seldom taken of closer spacing and higher rates of nitrogen in this season.

Sato (1955, 1956) studied the effects of temperature on yield during midseason (July and August) and of light intensity during the ripening of rice in southern Japan. From a series of correlation analyses, he concluded that highest yields were associated with mean air temperatures of 27 C in July and August (t) and 400 hours of sunshine in September and October (s) according to the relationship:

$$\text{Yield } (\%) = 9.0 + 0.2s \times 25.4e^{-4.32(t-27.2)^2}$$

With further refinements and simplification of the method, sunshine duration in mid-July and mid-September were both shown to be important (Matsuda, 1960).

The accumulation of more than 14,000 cal/cm² or 200 hours of sunshine during the 30 days before harvest, combined with a dry-season harvest, appears to be important (Aspiras, 1964). In addition, the lower temperatures in December and January appear to favor high net assimilation and contribute to maximum yields. These are general impressions, and detailed data to confirm them are still being accumulated.

DAY LENGTH

Rice cultivation in the higher latitudes is limited to a great extent by temperature, while rainfall variability and low light intensity limit cultivation in the lower latitudes. Under field conditions, total solar (and net) radiation and temperature are closely related to day length; however, day length (or photoperiod) has specific effects on plant growth. Day length, per se, is not a limiting factor if nonphotosensitive varieties are used; however, most varieties grown in the tropics are photosensitive, and day length is a major factor in tropical rice cultivation.

Over the centuries, photosensitive rice varieties have probably been selected in tropical areas because they could be planted whenever the monsoon rains began, yet they would always mature at a fixed date after the rains had stopped and the floodwaters had receded. Such varieties make use of the increased sunlight at late stages of growth, which has a beneficial effect on yield, and the lower water levels permit easier harvest. Although lodging and pest damage may be more serious with the longer crop duration, damage from typhoons at late stages of growth is minimized. This and other factors have probably given increased reliability of the harvest if not actual quantitative increases in yield.

The changes in day length during the growing season of the rice crop differ from one latitude to another. At various locations at the same latitude, because of different rainfall patterns, dates of planting may differ markedly, so that the day lengths received by the rice crops may be quite different.

Figure 1–2 shows the day-length patterns in various rice-growing areas during the "main" cropping season. In the tropics, double-cropping is practiced in some areas, so the day length shown in Figure 1–2 applies to the wet-season crop.

At the northern latitudes (Sapporo, 43°N; and Konosu, 36°N) day length increases and then decreases during the growing season. At lower latitudes (Taipei, 25°N; Chiengmai, 19°N; Bangkhen, 14°N; and Los Baños, 14°N) the day length decreases during the main growing season.

The rate of change in day length increases with distance from the equator.

Near the equator (Bukit Merah, 5°N), there is little change in day length. Remarkably, this small difference (35 minutes) is sufficient to control the flowering of some varieties. These differences in day length during the planting season may account for the wide range of response to photoperiod of rice varieties.

Whether continuously decreasing day length during the crop cycle contributes more to increased grain yield than a regime in which day length increases and then decreases (as in Sapporo and Konosu) is not known.

A wide variation is reported in the effects of short-day and long-day treatments on tillering, leaf formation and development, yield and yield components, elongation of internodes, sterility, and production of dry matter (Oñata and Espino, 1948; Misra, 1955, 1962). Possibly some of the effects reported are the result of increased growth duration and not day length per se.

Change in the growth duration of the rice plant is one of the major effects of photoperiod. For a particular photosensitive variety, the longer the day length, the longer the growth duration. Unfavorable day lengths may cause very early or delayed flowering as well as irregularity in flowering, resulting in uneven maturity. Nonphotosensitive varieties, of course, do not show any marked response to day length.

Very early flowering or delayed flowering often results in low grain yields. Short growth-duration plants usually do not have time to produce enough tillers or leaf area. On the other hand, plants having a long growth period become tall and leafy and then suffer from low light transmission to the lower leaves and low nutrient availability. An opti-

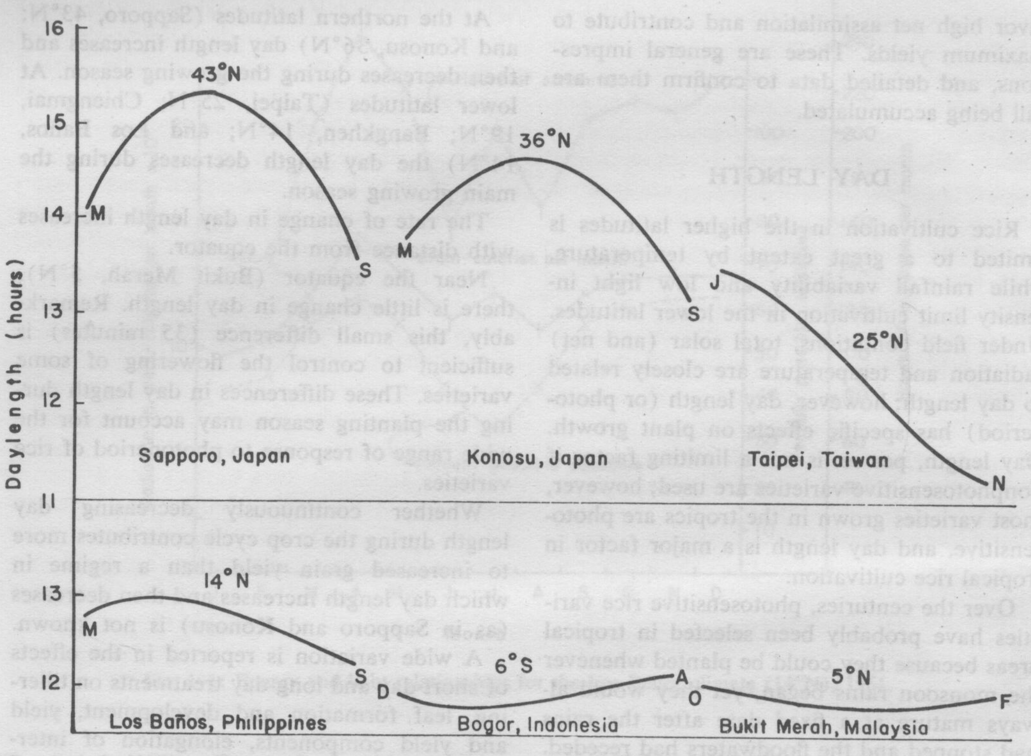

FIG. 1-2: Day-length patterns during the main rice crop season at six locations in Asia.

mum growth duration, in which the tiller number, leaf area, light-transmission rate, and nutrient availability are balanced, is necessary for the production of high grain yields.

In the tropics, rice can be grown throughout the year in places where irrigation is practiced. Although photosensitive varieties can be planted in these areas at any time of the year, their actual planting season is restricted to the onset of the rainy season. Obtaining the optimum growth duration with photosensitive varieties thus requires delayed planting in locations where the monsoon starts early.

TEMPERATURE

As stated before, low temperature is one of the limiting factors in rice cultivation in temperate climates. It greatly influences not only the growth duration but also the growth pattern of the rice plant. During the growing season, the mean temperature, the temperature sum, the range, the distribution pattern, diurnal changes, or combinations of these may be highly correlated with grain yields.

Optimum temperatures for germination, tillering, inflorescence initiation and development, dehiscence, and ripening have been determined by a number of workers. It is probably not desirable to have the optimum temperature for certain growth phases of the rice plant in order to obtain high grain yields, particularly since optimum values are usually determined on the basis of maximum vegetative growth rather than on the basis of direct relevance to yield.

In northern latitudes, rice plants are sown at a low temperature, complete the early growth stages in a rising temperature cycle, and, after flowering, complete their growth in a regime of declining mean temperatures (Fig. 1–3). For tillering, the optimum temperature reported in Japan is 32 to 34 C (Matsuo, 1959). This optimum temperature is never attained in the northern areas.

Areas in the lower latitudes have a high temperature at sowing time and slowly declining temperature until maturity, while near the equator little change in temperature occurs. These areas have the optimum temperature for tillering. For any variety, one would then expect more active tillering near the equator.

The range of diurnal change for any location will depend upon elevation and proximity to a large body of water. During the crop season, areas in the northern latitudes and at high elevations have greater diurnal change than low-latitude stations (Fig. 1–3).

In northern Japan, a rather low night temperature (16 to 21 C), except during tillering and late ripening, favors grain production (Matsushima and Tsunoda, 1958).

It has been shown that water temperature can affect the number of panicles per plant, height (Matsushima and Tsunoda, 1958), root and shoot growth (Nagai and Matsushita, 1963), and sterility (Kondo, 1952). In northern Japan, low-temperature irrigation water is often a serious problem. In the tropics, high-temperature irrigation water can be a problem (IRRI, 1963).

Temperature summation (sum of daily mean temperatures) for the 6-month growing season shows a marked increase with decrease in latitude (Table 1–4). It is reported (Nagai, 1958) that in Japan rice plants need a temperature sum of 3,300 to 4,490 C. At Sapporo, the temperature summation for 6 months is only 2,900 C, which is the lowest figure for a major rice-growing area. The rice crop at this latitude is grown for less than 5 months, but the seedlings are artificially heated. Since grain yield at Sapporo is relatively high, accumulated temperature above 3,000 C per crop seems unnecessary. In much

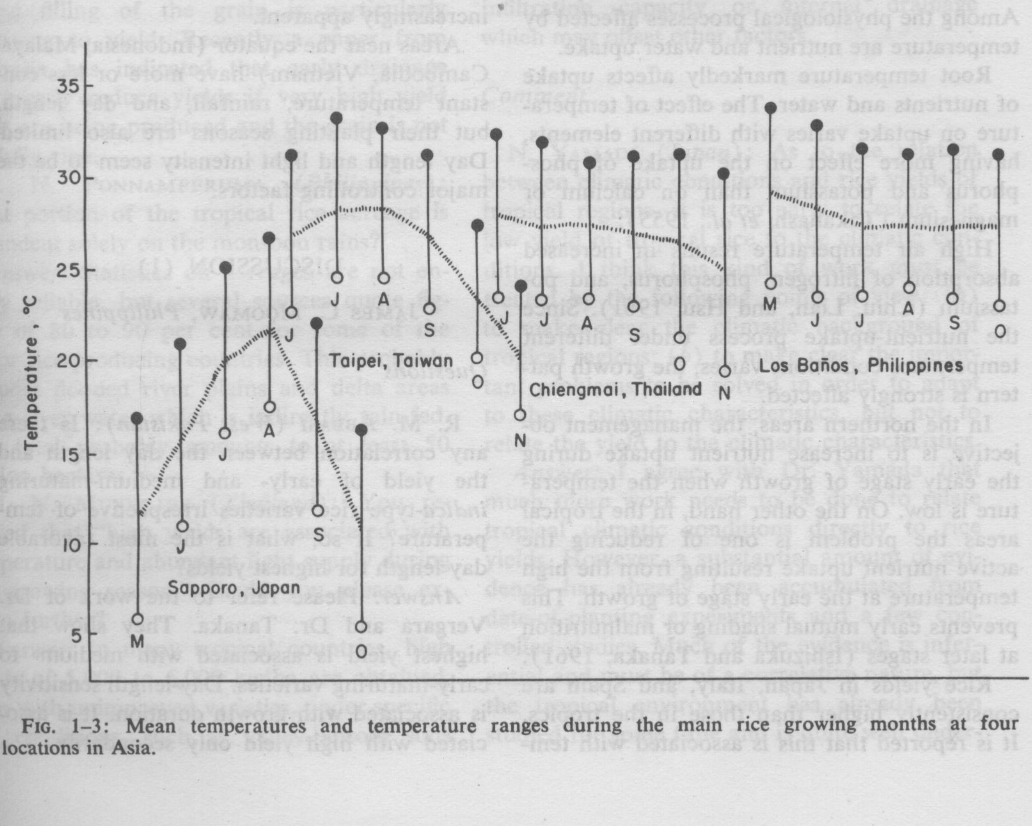

FIG. 1–3: Mean temperatures and temperature ranges during the main rice growing months at four locations in Asia.

TABLE 1–4: Temperature Summation during the Main Six-Month Rice-Growing Season at Seven Representative Locations in Asia

Locality	Latitude	Temperature summation per 6 months	
Sapporo	43°N	2,934 C	May–Oct.
Konosu	36°N	3,824 C	May–Oct.
Taipei	25°N	4,699 C	June–Nov.
Chiengmai	17°N	4,887 C	June–Nov.
Bangkhen	14°N	5,262 C	May–Oct.
Los Baños	14°N	5,057 C	May–Oct.
Djakarta	6°S	5,000 C	Dec.–June[a]

[a] Approximated from annual mean.

of the tropics, the temperature sum exceeds 5,000 day-degrees for 6 months, and the total for individual varieties is determined by their duration rather than by any temperature "requirement."

Apparently, the temperature range, the distribution pattern, and diurnal changes all can influence the growth process of the rice plant. Among the physiological processes affected by temperature are nutrient and water uptake.

Root temperature markedly affects uptake of nutrients and water. The effect of temperature on uptake varies with different elements, having more effect on the uptake of phosphorus and potassium than on calcium or magnesium (Takahashi *et al.*, 1955).

High air temperature results in increased absorption of nitrogen, phosphorus, and potassium (Chiu, Lian, and Hsu, 1961). Since the nutrient-uptake process under different temperature conditions varies, the growth pattern is strongly affected.

In the northern areas, the management objective is to increase nutrient uptake during the early stage of growth when the temperature is low. On the other hand, in the tropical areas the problem is one of reducing the active nutrient uptake resulting from the high temperature at the early stage of growth. This prevents early mutual shading or malnutrition at later stages (Ishizuka and Tanaka, 1961).

Rice yields in Japan, Italy, and Spain are consistently higher than those in the tropics. It is reported that this is associated with temperature and with the abundant light supply during the growing season (Nagai, 1958).

In rice, differences in temperature range, distribution pattern and diurnal changes, and day length result in different growth patterns. Since rice plants are grown in diverse environments, one should be cautious in comparing the effect of nutrient applications or nutrient uptake in separate areas, as the growth patterns of the varieties concerned may be quite different.

In relation to climate, rice workers at the northern latitudes (northern Japan) are more concerned with temperature and less with rainfall and day length. Temperatures at these areas during the growing season may fall to destructive or even lethal levels.

At lower latitudes (India, Burma, Philippines, and Thailand), rainfall is probably the major concern, as it determines or limits the planting season. Temperature, being more or less constant and within safe limits, is of little concern. The importance of light is becoming increasingly apparent.

Areas near the equator (Indonesia, Malaya, Cambodia, Vietnam) have more or less constant temperature, rainfall, and day length, but their planting seasons are also limited. Day length and light intensity seem to be the major controlling factors.

DISCUSSION (1)

JAMES C. MOOMAW, *Philippines*

Questions

R. M. ABBASI (*West Pakistan*): Is there any correlation between the day length and the yield of early- and medium-maturing *indica*-type rice varieties irrespective of temperature? If so, what is the most favorable day length for highest yields?

Answer: Please refer to the work of Dr. Vergara and Dr. Tanaka. They show that highest yield is associated with medium- to early-maturing varieties. Day-length sensitivity is associated with growth duration. It is associated with high yield only secondarily.

ABBASI: What is the maximum number of sunshine hours required for maximum production of medium- and early-maturing *indica*-type rice varieties?

Answer: The sunlight "requirement" foı rice production has never been properly measured in the tropics. The minimum amounts required for best yields in Japan have been estimated at 400 sunshine hours in the last two months of the crop. From our own data, I would say that a rough estimate of optimum light values might be 1,000 sunshine hours for a crop of 130 days' duration. The intensity should be higher in the later stages of the crop, and I would estimate minimum values at 220 to 240 hours (or 12,000 to 14,000 cal/cm^2) during the last 30 days.

ABBASI: What are the critical stages of the rice plant when lack of irrigation causes severe reduction in yield?

Answer: Please refer to Dr. Matsushima's work in Malaya, and others. They point out that water shortage at panicle initiation and during filling of the grain is particularly damaging to yield. Recently a paper from Australia has indicated that early drainage can greatly reduce yields if very high yield levels are being produced and the grain is not yet fully ripe.

F. N. PONNAMPERUMA (*Philippines*): What portion of the tropical rice acreage is dependent solely on the monsoon rains?

Answer: Statistics on acreages are not entirely reliable, but several sources quote figures of 80 to 90 per cent for some of the major rice-producing countries. This probably includes flooded river plains and delta areas using river water which is indirectly rain-fed. The total probably amounts to at least 50 million hectares.

H. N. MUKERJEE (*Thailand*): You reported that "high yields are associated with temperature and abundant light supply during the growing season." Could you please explain further?

Answer: In many tropical countries, high yields of 5,000 to 6,000 kg/ha are obtained, even with unimproved varieties, under specific soil conditions, such as valley-bottom soils where silt, bases, and organic matter in rapidly decomposable form accumulate.

MUKERJEE: Could you throw some light on any evidence with *indica* varieties which may define the soil and nutrient-supply conditions that may offset the adverse effects of the other factors mentioned?

Answer: These reports of high yield in tropical areas are of great interest, and we are investigating them whenever possible. Certainly the supply of nutrients must be available in these areas in the right amounts at the right time. This means 60 to 80 kg/ha of nitrogen per crop, with this continuing to be available late in the crop without the oversupply in the early stages that leads to lodging. It is difficult to generalize about phosphorus and potassium because so much depends on soil supplies and release rate. One other factor that is clearly worth mentioning is the importance of drainage. In addition to the adequate supply of water, many of these high-yielding fields seem to have a fairly high infiltration capacity or internal drainage which may offset other factors.

Comment

N. YAMADA (*Japan*): As to the relation between climatic conditions and rice yields of tropical regions, it is too early to relate the low yield of tropical rice to the climatic conditions. I think this kind of work must be treated by the following points of view: (*a*) to make clear the climatic background of tropical regions; (*b*) to make clear the important problems to be solved in order to adapt to these climatic characteristics, but not to relate the yield to the climatic characteristics.

Answer: I agree with Dr. Yamada that much more work needs to be done to relate tropical climatic conditions directly to rice yields. However, a substantial amount of evidence has already been accumulated from date-of-planting experiments and a few controlled studies. Much of the evidence is inferential and must be of a correlative nature, but the tropical environment has already been studied for some time and is quite well under-