PB-225 801

NITROGEN FERTILIZATION AND MANAGEMENT IN TROPICAL RICE

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North Carolina Agricultural Experiment Station

Prepared for:

Agency for International Development

November 1972

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BIBLIOGRAPHIC DATA SHEET	1. Report No. 633.18-5211	PB 225 801
4. Title and Subtitle: Nitrogen Fertilization and Management in Tropical Rice		5. Report Date: November, 1972
		6.
7. Author(s): Pedro A. Sanchez		8. Performing Organization Rept. No.
9. Performing Organization Name and Address: North Carolina Agricultural Experiment Station, North Carolina State University at Raleigh, Raleigh, North Carolina 27607		10. Project/Task/Work Unit No. 931-17-124-525
		11. Contract/Grant No. AID/csd-2806
12. Sponsoring Organization Name and Address: Department of State, Agency for International Development, Washington, D. C. 20523		13. Type of Report & Period Covered: Technical Bulletin No. 213
		14.

15. Supplementary Notes

16. Abstracts

Rice is the main food crop in the tropics. It is the only important crop capable of growing in flooded soils because of its ability to oxide its rhizosphere. Rice responds almost universally to nitrogen fertilization. Nitrogen reactions are markedly affected by oxidation-reduction status of the soil, which largely depends on water management and soil physical conditions. Temporary flooding in most tropical areas causes loss of native or applied nitrogen. The responses of rice to nitrogen are minimal when tall varieties are used. In contrast, the responses are large and economical when higher rates are applied to short-statured varieties. Nitrogen recommendations for flooded rice are based on soil properties, plant type, solar energy, temperature, water management, and spacing. The most effective nitrogen sources are ammonium sulphate and urea. The efficiency of nitrogen utilization in rice is lower than in other crops, and much lower under intermittent flooding than under constant flooding. The potential for improvements for tropical rice are great.

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 633

18. Availability Statement	Reproduced by NATIONAL TECHNICAL INFORMATION SERVICE, U S Department of Commerce, Springfield VA 22151	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 33
		20. Security Class (This Page) UNCLASSIFIED	22. Price $3.75

FORM NTIS-35 (10-70) USCOMM-DC 14952-P72

November, 1972 Tech. Bul. No. 213

Nitrogen Fertilization and Management In Tropical Rice

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NITROGEN FERTILIZATION AND MANAGEMENT IN TROPICAL RICE [1]

INTRODUCTION

Rice is the most important food crop produced in the tropics. It accounts for the bulk of the caloric intake of the Asian people and for a large portion of the diets in tropical America and Africa. Rice is the only important food crop capable of growing in flooded soils because of its ability to oxidize its rhizosphere. Flooding brings about a series of physical, chemical and biological changes which result in a number of soil-plant relationships completely different from those taking place in other crops. Rice responds almost universally to nitrogen fertilization and with less frequency to other elements. The magnitude of these responses is of great practical importance. The purpose of this bulletin is to summarize the present knowledge about the theory and practice of nitrogen fertilization in rice in relation to prevailing water management and cultural practices common in Tropical Latin America.

NITROGEN DYNAMICS IN RICE SOILS

Nitrogen reactions are markedly affected by the oxidation-reduction status of the soil, which depends to a large extent on water management and soil physical conditions.

Effects of constant flooding

When a dry soil is suddenly and thoroughly flooded, the structural aggregates become saturated with water and the pressures generated by air entrapped in soil pores cause many soil aggregates to crumble (Yoder, 1936). The magnitude of this phenomenon depends upon the soil's aggregate stability and the speed and thoroughness of the wetting operation. Soil pores remain saturated with water and 2:1 type clays expand. Percolation through the soil decreases, reaching levels of 20 to 33 percent of the original in rice fields cultivated for several years (Mikklesen and Patrick, 1968).

The availability of oxygen decreases to zero in less than a day after flooding. The rate of diffusion of atmospheric oxygen through water is 10,000 times slower than in the absence of water. Aerobic microorganisms rapidly consume the remaining oxygen, become latent or die. Anaerobic microorganisms multiply rapidly and take over the decomposition of soil organic matter using, instead of oxygen, oxidized soil components as electron acceptors. These products are reduced in the following thermodynamic sequence: nitrates, manganic oxides, ferric oxides and

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[1]Paper presented at the Second Soils Colloquium on Nitrogen Use in the Tropics, sponsored by the Colombian Society of Soil Science, Palmira, Colombia, August 31, 1971. The preparation of this report was supported by funds from the U. S. Agency for International Development, Contract AID/csd 2806.

hydroxides, several intermediate products of organic matter decomposition, sulphates, CO_2, and possibly phosphate (Ponnamperuma, 1965). The reduction process is intensified by the presence of easily decomposable organic matter, the substrate of the microorganisms, and high soil temperatures. Oxidation-reduction potentials drop sharply in two to four weeks after flooding and then decrease gradually (Ponnamperuma, 1965).

The process of soil reduction induces a series of chemical changes. Whatever the original soil pH, flooded soils reach and maintain an equilibrium pH value between 6.5 and 7.0 within approximately three weeks after flooding (Fig. 1). The pH increases in acid soils due to the reduction of ferric hyroxides and manganic oxides into ferrous and manganous forms, releasing OH^- ions. The pH decreases in alkaline soils due to increases in the partial pressure of CO_2.

The nitrates present in the soil are reduced to N_2 and N_2O gases which escape to the atmosphere. The mineralization of organic nitrogen stops at the ammonification stage. The NH_4^+ ion is stable under reduced conditions and tends to accumulate in flooded soils (Fig. 2). The concentration of other elements such as P, Fe and Mn in the soil solution increases with flooding, reaches maximum values during the first month or so and then gradually decreases. Although these changes are in general beneficial to the rice plant, excessive production of Fe^{++}, Mn^{++} and certain organic acids may reach toxic levels. High concentrations of these cations release non-reducible exchangeable cations such as K^+, Ca^{++}, Mg^{++}, and Na^+ into the soil solution. The conductivity in non-saline soils increases to values of 2 to 4 mmho/cm. The partial pressure

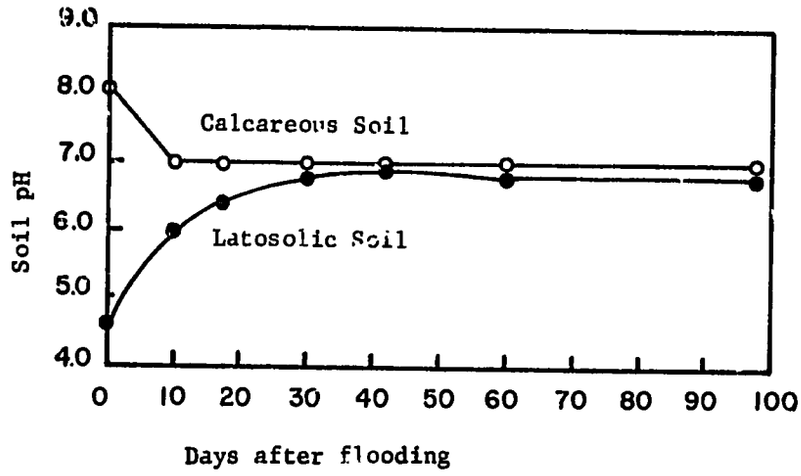

Fig. 1. pH changes in two soils under constant flooding (Sanchez and Delgado, 1969).

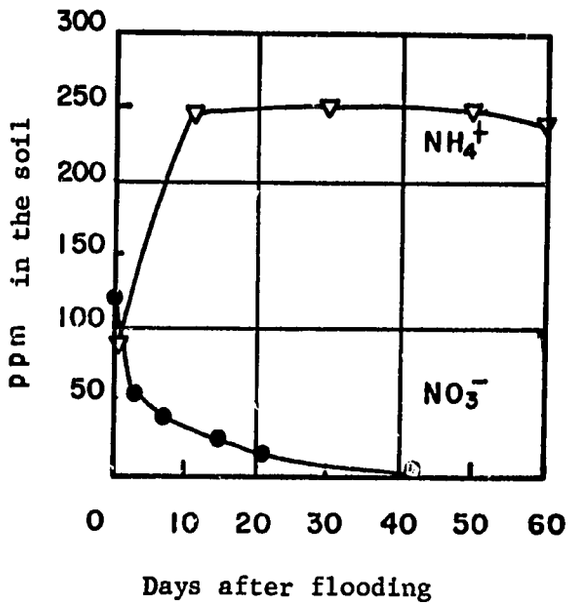

Fig. 2. Constant flooding effects on the concentration of ammonium and nitrate ions (Sanchez and Delgado, 1969).

of CO_2 also increases, reaches levels of 0.2 to 0.8 atmospheres in two to four weeks after flooding and decreases gradually. These generalizations have been taken from a summary by Sanchez (1968). Ponnamperuma (1955, 1965), Redman and Patrick (1965), and Mikklesen and Evatt (1966) discuss the effects of soil reduction in more detail.

The profile of a flooded soil is not completely reduced. Several oxidized zones exist in which the above described processes do not occur (Fig. 3). A superficial layer less than 1 cm deep, remains oxidized since it is in equilibrium with the oxygen dissolved in the water layer. The rest of the plowed layer is reduced except for the rhizosphere of active rice roots which is oxidized. This can be visually recognized by the presence of yellowish red root coatings caused by precipitation of ferric components. The subsoil may be reduced but with less intensity than the above layer, due to lower organic matter contents. It can be oxidized when the plowed layer is puddled and the water table is deep. Fig. 3 shows the need to use ammoniacal sources of nitrogen incorporated in the reduced layer since the application of nitrates or ammonium to the superficial oxidized layer may cause serious denitrification losses.

Effects of intermittent flooding

The majority of tropical rice soils undergo alternate oxidation and reduction caused by flooding and drying periods because of a poor dis-

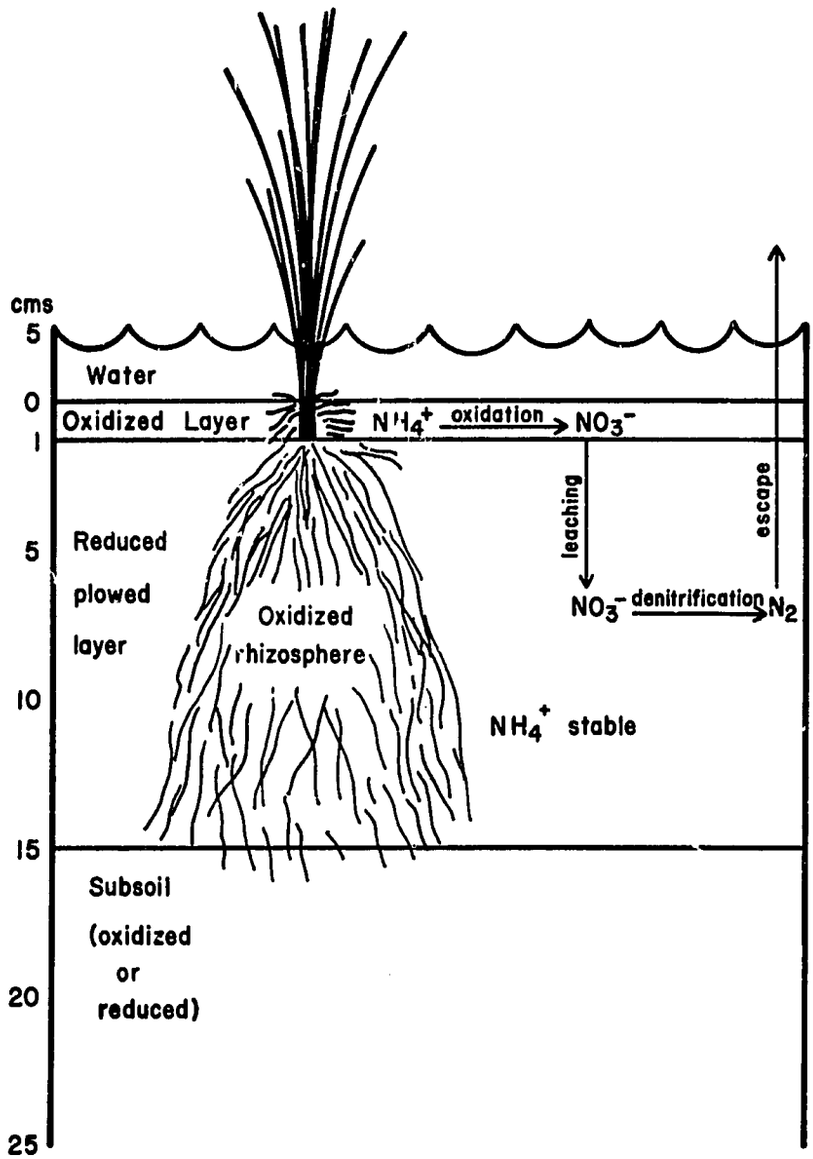

Fig. 3. Redox profile and nitrogen dynamics in a constantly flooded soil.

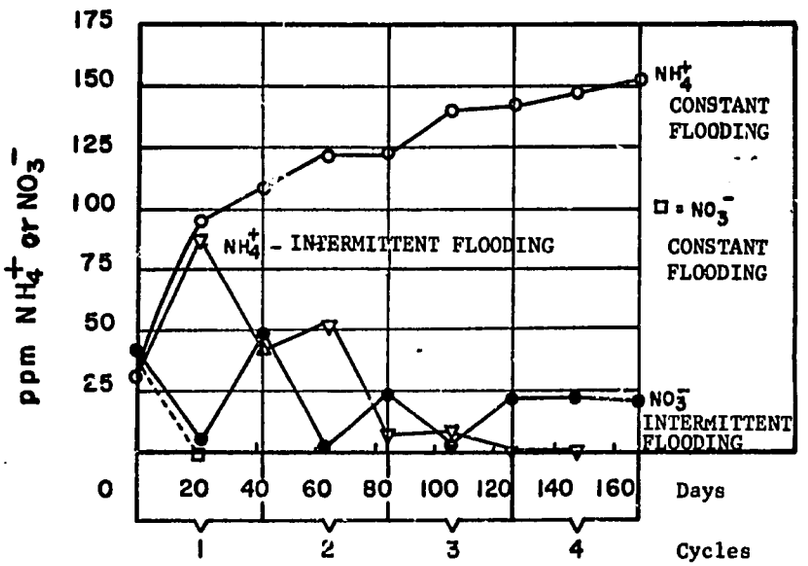

Fig. 4. Effects of constant and intermittent flooding in NH_4^+ and NO_3^- production under laboratory conditions. Flooding every 42 days. (adapted from data of Patrick and Wyatt, 1964).

tribution of irrigation water, or more frequently because of the absence of irrigation and large variability in rainfall. More than two thirds of the transplanted rice area in Asia does not have controlled irrigation and therefore lacks constant flooding. The upland (direct seeded, rainfed) cropping system, which predominates in Latin America and Africa, often presents alternate oxidation-reduction conditions caused by temporary flooding due to heavy rains followed by drought periods. Nitrogen losses under these conditions are great (Fig. 4).

A cycle appears in which all the nitrates present before flooding are lost in less than ten days after flooding (Patrick and Wyatt, 1964) The concentration of ammonium increases while the soil is reduced, but NH_4^+ ions are transformed into nitrates when the soil dries and becomes oxidized. These nitrates are then denitrified during the next flood. Losses are great during the first cycle but tend to decrease afterwards, as shown in Fig. 4. Since rice utilizes either NH_4^+ or NO_3^- ions indiscriminately (Tanaka, *et al.*, 1964), the limiting factor is the availability of the forms under alternate redox conditions.

Effects of puddling

Almost all flooded soils suffer certain degrees of puddling (i.e., the transformation of the soil structure into a uniform mud with the clay

particles oriented in parallel and the soil pores saturated with water). In Asia, puddling is performed intentionally during land preparation and unintentionally with the worker's feet during transplanting, weeding and other cultural practices. The principal effect of puddling is to decrease the movement of water through the soil. Percolation decreases by several orders or magnitude (Sanchez, 1968) and evaporation losses also decrease sharply (Buehrer and Aldrich, 1946). The soil dries out very slowly, and in some instances reduced conditions can be maintained for several weeks without flooding (Breazeale and McGeorge, 1937; Aomine and Shiga, 1959). Puddling, therefore, has a significant influence on nitrogen behavior in the soil. The puddling process does not increase nitrogen uptake or availability but significantly increases the efficiency of applied nitrogen due to lower leaching losses (Sanchez, 1968). Puddling may decrease the detrimental effects of intermittent irrigation by maintaining the soil in the reduced state for longer periods of time.

NITROGEN RESPONSE AND FACTORS AFFECTING IT

Orders of magnitude

A summary of several thousand rice fertilization experiments compiled by Doyle (1966), shows that this crop responds almost universally to nitrogen applications, but in many cases the response is negative at high rates. The linear correlation obtained (Fig. 5) shows a world

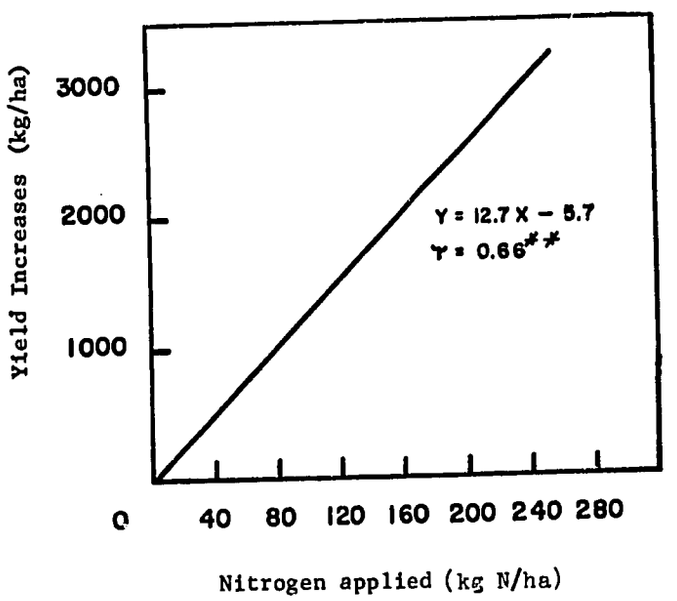

Fig. 5. World correlation between yield responses and nitrogen application rates in rice, based on 385 responses in 20 countries (Doyle, 1966).

average response of 12.7 kg of rough rice per kg of applied nitrogen. The variability in both axes of the response curve is large and it is affected by the following factors: plant type, solar radiation, water management, cultural practices and soil type. Representative responses of rice in different countries with traditional plant types (Fig. 6) illustrate how variable the response curves are. These curves can be grouped in two categories. The principal rice producing countries such as China, India, Indonesia, Thailand, Brazil and others show moderate responses at low levels of yield and applied nitrogen, with maximum yields obtained between 30 and 50 kg N/ha. In many cases, higher nitrogen rates resulted in negative responses. The second group, represented by rice-growing regions located outside the humid tropics (Australia, Egypt, Mali, United States and Peru), show sharp yield increments and optimal nitrogen rates higher than the previous group.

Countries with low responses are characterized by the use of tall varieties and poor water management. In Australia and the United States, as well as in Japan and Taiwan, the high responses obtained are associated with the use of varieties with moderate resistance to lodging, excellent water management and cultural practices. In countries like Mali and Peru where the varieties, cultural practices and water management are not so advanced, high responses are probably associated with very favorable climatic conditions. This situation indicated that the potential of nitrogen fertilization in rice in the humid tropics could not be so high as in other areas. The introduction of a new plant type for the tropics by the International Rice Research Institute in 1966 completely changed this concept.

Plant type

The IR8 variety is the prototype of the new tropical rice plant. It is characterized by its short stature, high tillering capacity, erect stems and leaves, high grain:straw ratio and resistance to lodging. The traditional plant types have vigorous growth, tall stature, low tillering capacity, weak stems and leaves and low grain:straw ratios. These traditional varieties respond to nitrogen by increasing their height, which causes lodging and subsequent yield losses at high rates of nitrogen (Tanaka, 1965; DeDatta, Moomaw and Dayrit, 1966). Figures 7, 8, and 9 illustrate the differences in responses between short-statured plant types (IR varieties) and traditional varieties under three different environments. The negative responses of traditional varieties at high nitrogen rates are largely the result of lodging.

Plant type differences in terms of several growth characteristics are shown in Fig. 10 to 14. These figures compare the performance of IR8 and the traditional variety Minabir 2 in Peru at several nitrogen levels (Sánchez, Ramírez and Calderón, 1970). Fig. 10 shows that the increase in height with N applications is much greater with the tall Minabir variety than with IR8. A close negative correlation between plant height and yield response has been reported by DeDatta, Tauro and Balaoing (1968). In spite of the high nitrogen rates used, neither plant type shows significant changes in its growth duration (Fig. 10). Nitrogen uptake at harvest was essentially identical (Fig. 11). Among the three yield components, the number of panicles per unit area is more

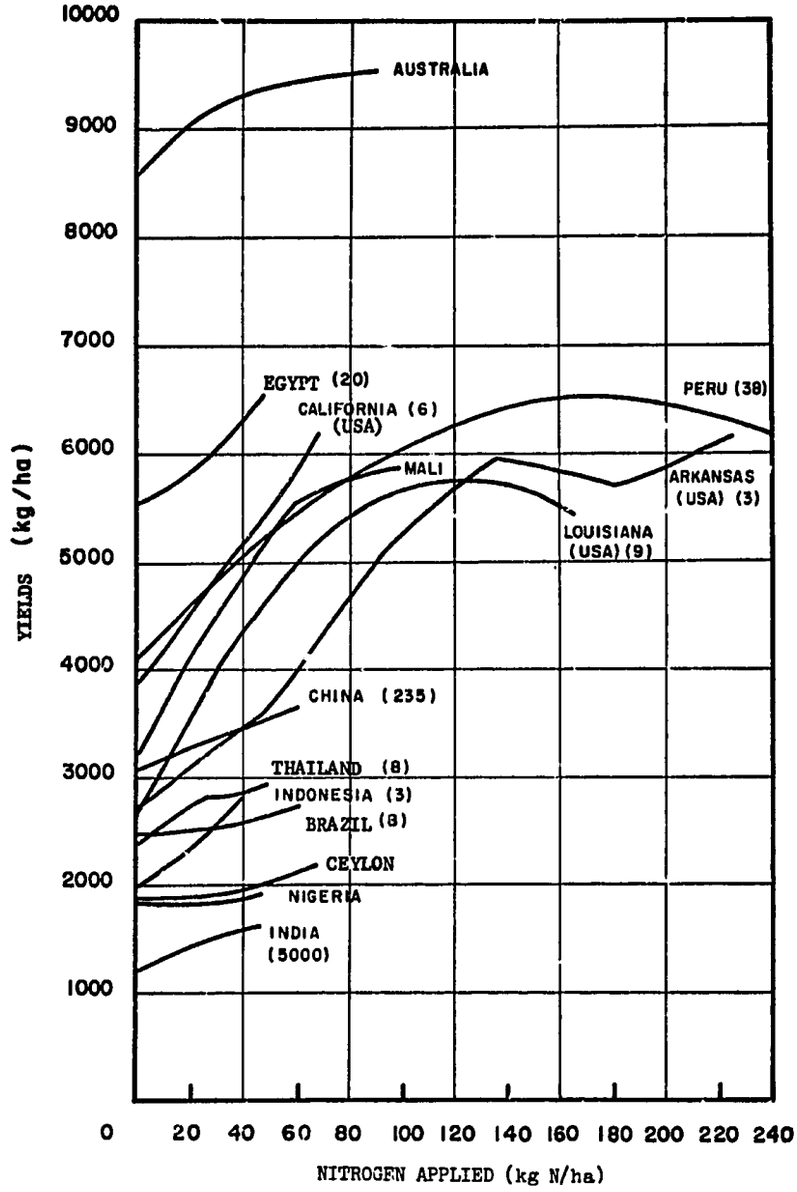

Fig. 6. Representative N responses to rice in different countries. Number of experiments in parenthesis when specified in the literature. Sources: Doyle (1966), Oliveira et al (1965, 1966), Mikklesen and Patrick (1966) and Carmen (1966).

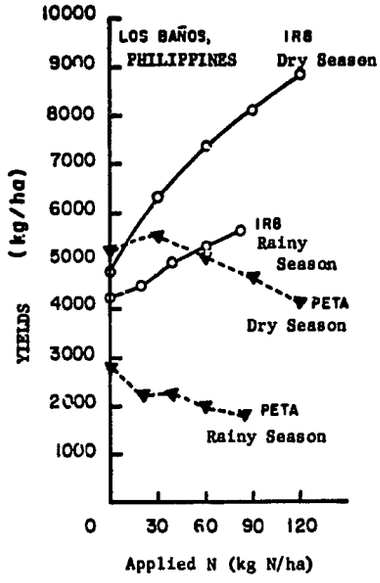

Fig. 7. Response of two plant types during seasons of different solar radiation in Los Baños, Philippines. Transplanting system under constant flooding. Three-year average (De-Datta, 1970).

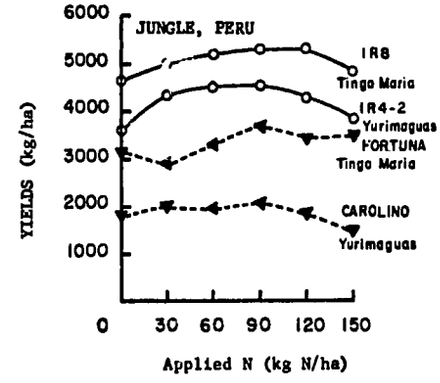

Fig. 8. Response of two plant types under upland conditions in two localities of the Peruvian Jungle (Kawano, et al. 1971b).

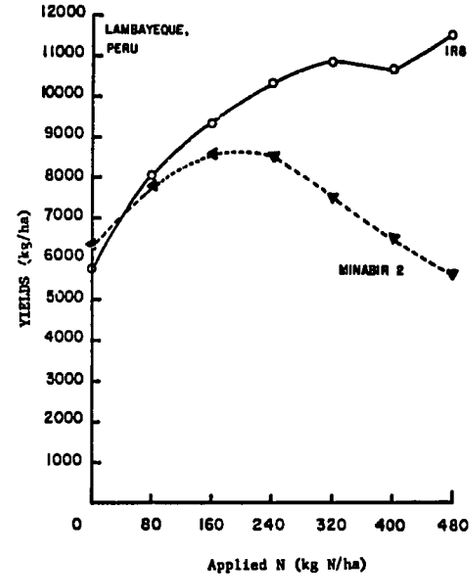

Fig. 9. Nitrogen response of two plant types under high solar radiation conditions in Lambayeque, Peru. Average of 10 experiments 1968-1971.

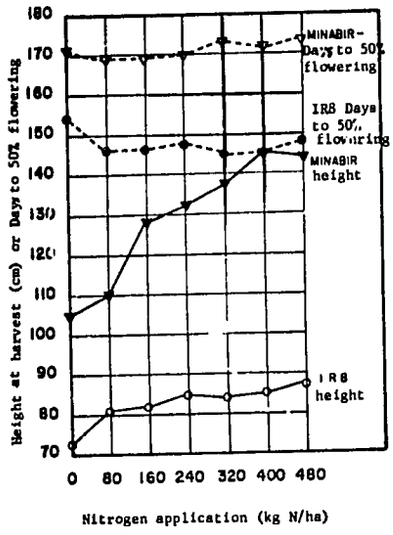

Fig. 10. Effects of N applications on plant height and growth duration at Lambayeque, Peru (Sanchez, Ramirez and Calderón, 1970).

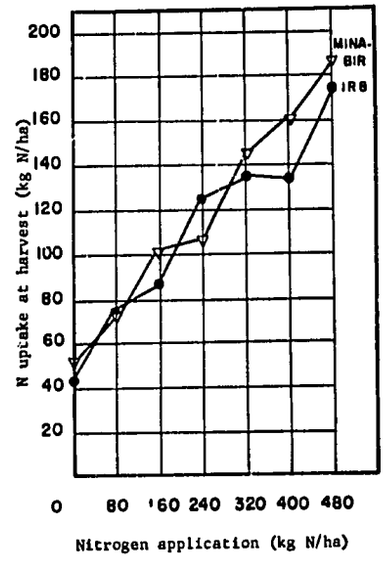

Fig. 11. N uptake by two contrasting plant types at Lambayeque, Peru (Sanchez, Ramirez and Calderón, 1970).

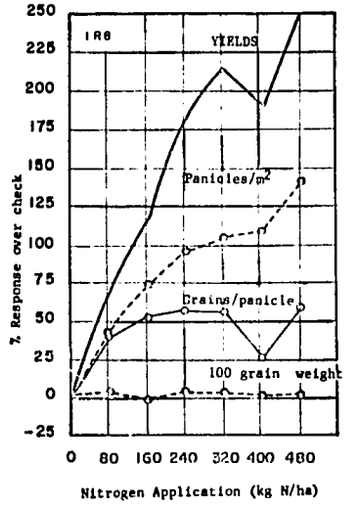

Fig. 12. Relative yield and yield component responses to N in IR8 at Lambayeque, Peru (Sanchez, Ramirez and Calderón, 1970).

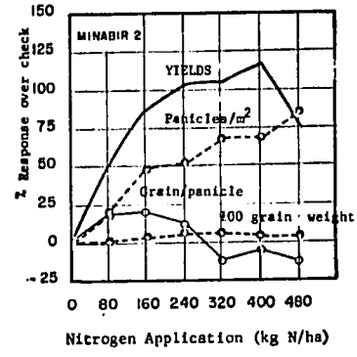

Fig. 13. Relative yield and yield component responses to N in Minabir 2 at Lambayeque, Peru (Sanchez, Ramirez and Calderón, 1970).

closely related to yield increases in IR8 than the number of filled grains per panicle or the individual grain's weight (Fig. 12). For Minabir 2, yield responses are related to both panicles per unit area and filled grains per panicle (Fig. 13). These results suggest that the new varieties respond mainly by increasing their tiller number while traditional varieties also respond in terms of panicle size. Tillering in rice is intimately associated with the nitrogen status of the plant (Tanaka *et al*, 1964). The overall differences between the two plant types are summarized in Fig. 14, which shows the proportion of grain to straw produced as a function of nitrogen applied. The new varieties have the ability to convert more nitrogen and photosynthates into grain, using a smaller straw base to produce it than the tall traditional varieties.

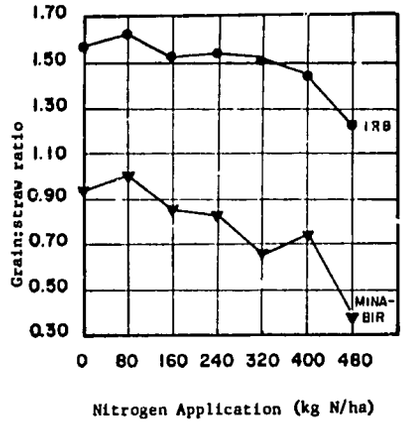

Fig. 14. Grain:straw ratio as a function of N rates in two plant types at Lambayeque, Peru (Sanchez, Ramirez and Calderón, 1970).

Solar radiation

When rice is grown in constantly flooded soils, the differences in its nitrogen responses between rainy and dry seasons are mainly associated with differences in solar radiation, since the fluctuation of other climatic and agronomic factors is small (DeDatta, 1970). The greater solar radiation during dry seasons provides more photosynthetic energy and allows larger nitrogen responses and yields in both plant types than during the rainy season. Nitrogen responses are higher in short plant types (Fig. 7). The rainy season with its high degree of cloudiness provides less solar radiation and consequently lower yields and nitrogen responses. During the reproductive period, yields and solar radiation are highly correlated (DeDatta and Zarate, 1970). Nitrogen response in the Peruvian jungle (Fig. 8) is similar to that observed during the rainy season in the Philippines, due to similar levels of solar radiation. The high responses obtained in the Peruvian coast result partly from solar radiation levels higher than those during the dry season in the Philippines, allowing high yields and optimum responses at 160 kgN/ha with the traditional variety (Sánchez, 1969b). The intermittent flooding typical of this area explains in part the high rates used. The dominating influence of solar radiation on nitrogen response is evident in Fig. 15,

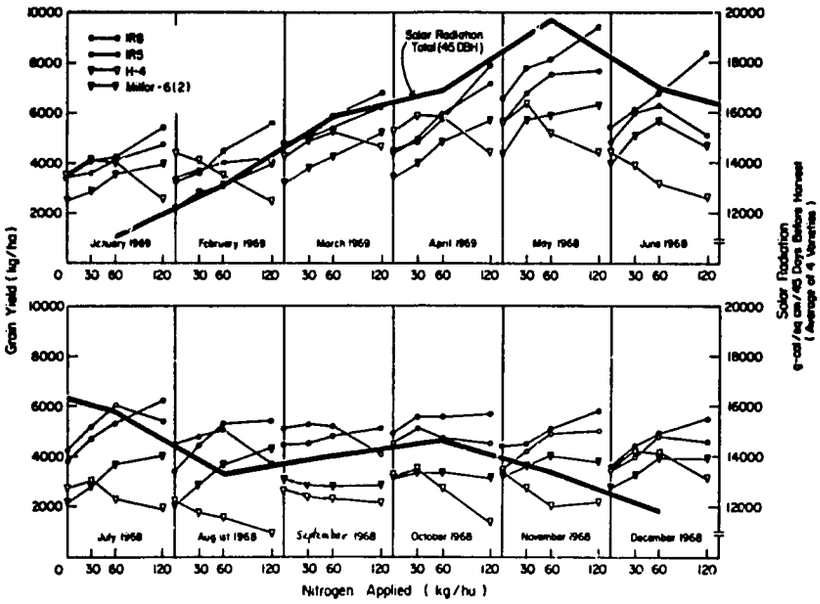

Fig. 15. Nitrogen response of four indica rice varieties by their month of harvest plotted with the solar radiation total for 45 days before harvest (DBH). Transplanted, constant flooding, Los Baños, Philippines (DeDatta and Zarate, 1970).

which illustrates the variety-nitrogen interactions as a function of planting dates.

Growth duration and temperature

In the tropics, the average growth duration for traditional varieties and cultural practices is about 120 to 140 days from seeding to harvest (Tanaka and Vergara, 1967). This range excludes extremes in photosensitivity which are usually associated with low yields. The variability in growth duration of varieties slightly photoperiod-sensitive, is small and does not affect their nitrogen response except for varieties very susceptible to lodging. In such cases prolonging growth duration increases plant height and thus lodging susceptibility (DeDatta and Zarate, 1970). Large rice-producing areas exist in the tropics where low temperatures are a limiting factor during part or all of the growing season, due to elevation or other climatic conditions (Arraudeau, 1970; Battacharyya and DeDatta, 1971 and Sanchez, 1969b). Mean monthly temperatures lower than 21 degrees C are considered limiting to rice (Sanchez, 1969a). Low temperatures normally extend the growth duration. Maximum yields are associated with growth durations between 160 and 180 days on the coast of Peru (Kawano, Arriola and Velazquez, 1971a) These authors observed that varieties of shorter growth duration did not produce sufficient dry matter to achieve high yields, while those which required more than 180 days to mature showed a low grain: straw

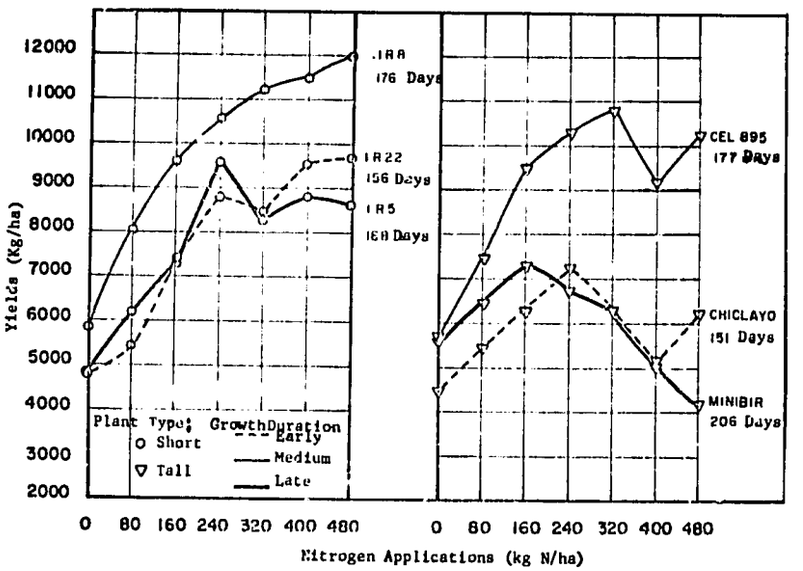

Fig. 16. Influence of plant type and growth duration on nitrogen response under conditions of low temperatures, high solar radiation and intermittent flooding in transplanted systems. Lambayeque, Peru (Ramirez and Sanchez, 1971b).

ratio associated with high spiklet sterility induced by low temperatures. Nitrogen response under limiting temperature varies widely with growth duration and date of seeding (Fig. 16). Varieties with optimum growth duration respond positively to nitrogen applications regardless of plant type up to levels of 320 kg N/ha. At higher nitrogen rates, the yield of a tall plant type CEL895 decreased while IR8 continued to increase. Varieties with shorter or longer growth durations than the optimum established by Kawano, Arriola and Velazquez (1971a) responded with less intensity, showing a clear effect of plant type. When dates of seeding are delayed (Fig. 17), the possibility of low temperature induced sterility at the flowering stage increases. Both plant types show progressively lower responses to nitrogen, reaching complete sterility in the last planting of this example.

Water Management

Due to the large nitrogen losses caused by alternate flooding and drying, nitrogen responses under these conditions are lower than under constant flooding. Studies conducted in the United States (Patrick, *et al*, 1967) and in India (Fig. 18) show that nitrogen response curves under intermittent flooding were lower and parallel to those obtained under constant flooding. This suggests that the optimal nitrogen levels are the same, but due to the large nitrogen losses the yield potential is lower under intermittent flooding. A preliminary test in Peru (Fig. 19)

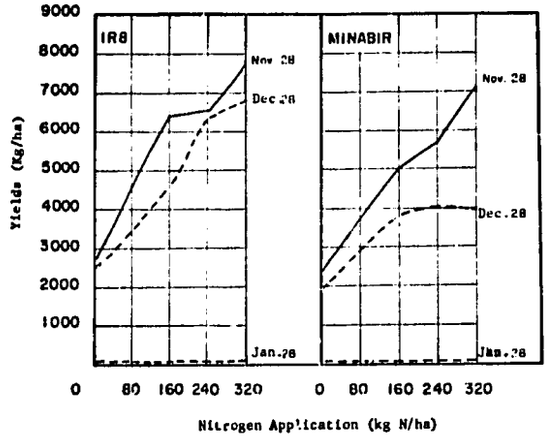

Fig. 17. Effects of date of seeding on the nitrogen response of varieties with different plant type and growth duration in Lambayeque, Peru (Ramirez and Sanchez, 1970).

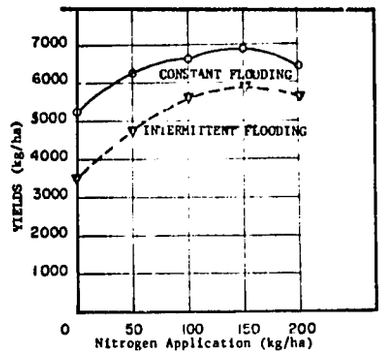

Fig. 18. Water management effects on nitrogen response of Padma variety, New Delhi, India. (Adapted from AICRIP, 1969).

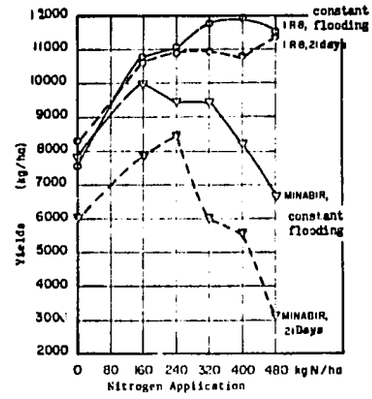

Fig. 19. Effects of constant flooding vs flooding every 21 days on nitrogen responses of two varieties in Lambayeque, Peru (Ramirez and Sanchez, 1971b).

suggested the existence of considerable varietal differences. In this experiment, the variety IR 8 was less affected by intermittent irrigation than the traditional variety Minabir 2. The latter variety was heavily attacked by *Pyricularia oryzae*, a disease which is often severe under limited water supply. Recently Nicou, Seguy and Haddad (1970) have indicated that the variety IR8 has more root ramifications than other varieties under upland conditions in Africa. These indications of varietal differences merit further study in order to quantify these crucial variety-nitrogen-water interactions.

The upland system (defined as direct seeding of rice on land without dikes to trap water and depending exclusively upon rainfall for its water supply) is used in more than 75 percent of the rice areas in Latin America (Brown, 1969). It predominates in Africa and is used in vast areas of Asia. Recent studies have shown that the same relationships among plant type and solar radiation developed under irrigated conditions are applicable to upland conditions, and that the yields obtained, as well as the nitrogen responses, are also affected by the duration of drought periods (DeDatta and Beachell, 1971). Jana and DeDatta (1971) found that upland rice suffers from moisture stress at soil moisture tensions lower than the range considered as adequate for other crops (between 0.3 and 15 atmospheres). The optimum range for rice appears to be between field capacity and saturation (DeDatta and Beachell, 1971). It is not necessary to keep a water layer to obtain high yields; saturation is sufficient.

In an experiment conducted in the Philippines, Jana and DeDatta (1971) illustrated the influence of water stress and solar radiation on nitrogen response (Fig. 20). The July 6 seeding did not suffer from lack of water and nitrogen response was normal. For the July 21 seeding, the lower response was associated with water stress during the reproductive stage. The August 14 seeding was seriously affected by lack of water during flowering. The August 22 seeding suffered serious water

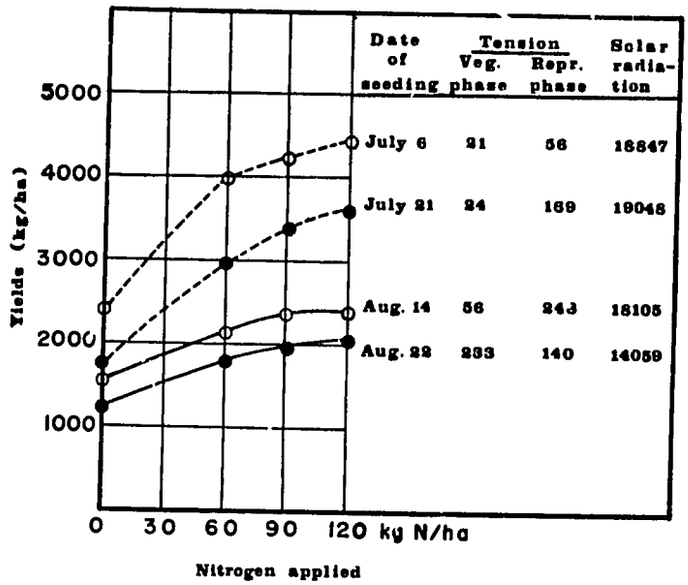

Fig. 20. Influence of soil moisture tensions at 20 cm depth (mm Hg) during the vegetative and reproductive growth phases and solar radiation (g-cal/cm^2) during the reproductive phase, on nitrogen response by upland rice in Los Baños, Philippines. (Adapted from Jana and DeDatta, 1971). Field capacity: 250 mm Hg.

stresses during the vegetative stage but not in its reproductive stage. In the last two cases the responses were very low. The differences among the first three seedings are exclusively related to different degrees of water stress since the solar radiation levels were similar. The August 22 seeding reflects the effects of lower solar radiation. Several studies suggest that in areas with annual rainfall of over 2000 mm water stress at any stage of growth is the most critical factor affecting upland rice production (DeDatta and Beachell, 1971).

Cultural practices

Since nitrogen response and tillering capacity in the tropics are closely related (Tanaka *et al*, 1964), tiller production depends principally on nitrogen application rates. Tillering is also affected by plant type and solar radiation levels. Based on extensive experimental results, Villegas and Feuer (1970) recommended plant spacings designed for obtaining optimum nitrogen responses in the Philippines (Table 1). Tall varieties

Table 1. Spacings between hills recommended in the Philippines to obtain maximum response to N. From Villegas and Feuer, 1970.

	Spacing (cm)	
Plant Type	Low solar radiation	High solar radiation
Short	25 x 25	20 x 20
Tall	35 x 35	30 x 30

require wide spacing to reduce the detrimental effects of mutual shading and lodging. Short plant types do not have the tendency to lodge and can use solar energy to the maximum with close spacing because of their erect leaf habit. In climatic conditions with high solar radiation, both plant types can be seeded more densely because the greater leaf area is able to intercept the higher amounts of solar energy available. In Latin America, most of the rice farms visited by this writer show evidence of excessive spacing for obtaining optimal nitrogen responses.

Other cultural practices which affect nitrogen responses are pest and weed control. In studies with three different types of herbicides and insecticides (IRRI, 1966), it was noticed that the shape of the nitrogen response curve was similar, but the magnitude of the response was related to the degree of pest and weed control.

Soil properties

Rice is generally grown on soils with high water retention capacity resulting from their texture, structure, or the presence of slowly permeable layers in the subsoil. Cation exchange capacity and available soil nitrogen seem to be the most important soil parameters affecting

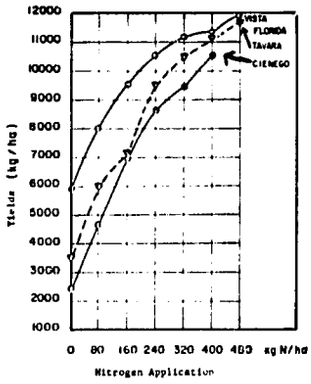

Fig. 21. Nitrogen response in three experimental fields in the Lambayeque Valley, Peru, 1970 and 1971. IR8 variety. (Data of Ramirez and Sanchez, 1971b and Gavidia, 1971).

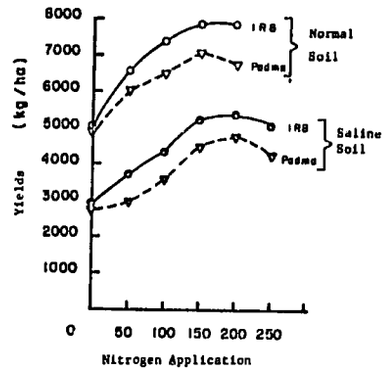

Fig. 22. Varietal response in saline and normal soils in New Delhi, India. Transplanted system, rainy season. (AICRIP, 1969).

nitrogen response. The higher the exchange capacity, the larger will be the capacity of the soil to supply and retain NH_4^+ (DeDatta, 1970; Villegas and Feuer, 1970). Soil nitrogen alone can produce between 1 and 9 ton/ha of rice. In some cases under similar climatic conditions, varieties and cultural practices, great differences in native fertility tend to decrease as nitrogen rates increase (Fig. 21). Nitrogen response curves are affected by deficiencies or toxicities of other nutrients and physiological disturbances. High levels of soil salinity in India (Fig. 22) caused a parallel decrease of the response curve relative to non-saline soils.

Formulating nitrogen recommendations to farmers

From the previous discussion it is obvious that the development of realistic economic recommendations for nitrogen use in rice is a problem different from that of other crops. Routine soil analysis mainly for organic matter or total nitrogen content are of poor predictive value (Ponnamperuma, 1965; Peterson, *et al*, 1971). Countries such as Japan and the United States base their recommendations upon field experiments conducted on the principal rice soils and upon the experience of farmers and research workers. The most realistic recommendations are divided according to plant types, rainy and dry seasons and principal soil types (Villegas and Feuer, 1970). It is interesting to note that recommendations determined in this manner in India and the Philippines (Kanwar, 1971; Villegas and Feuer, 1970) included higher rates (80 and 192 kg N/ha) for the new varieties. These rates were previously considered not economical for tropical rice. Recently, Sims, Wells and Tackett (1967a) have shown that the measurement of NH_4^+-N production after

six days of anaerobic incubation has some potential for evaluating nitrogen availability of rice soils. So far, this technique has not been applied in soil testing laboratories.

FACTORS WHICH AFFECT THE EFFICIENCY OF NITROGEN USE

Nitrogen sources for constant flooding

The nitrogen dynamics in flooded soils illustrated in Fig. 3 indicate that ammoniacal sources are superior to nitric ones. A recent review of the literature on this subject (DeDatta and Magnaye, 1969), as well as a series of field experiments with N^{15} conducted by the International Atomic Energy Agency in 15 countries (IAEA, 1970), confirms the general absence of differences between ammonium sulphate and urea in constantly flooded soils (Table 2). For soils deficient in sulfur,

Table 2. Relative performance of three nitrogen sources on constantly flooded soils. Mean of 15 experiments in 13 countries. (Calculated from data of IAEA, 1970).

Nitrogen Sources	Yield (ton/ha)		% Recovery of applied N in the grain	
	Incorp. in 0-5 cm layer	Broadcast prior to pan. init.	Incorp.	Broadcast
Ammonium sulfate	5.1	5.0	18.8	23.1
Urea	5.1	4.9	18.4	23.1
Sodium nitrate	4.1	4.5	3.0	10.9

ammonium sulfate is sometimes superior to urea, but the reverse is true in extremely acid soils with low Fe contents where H_2S toxicity may occur. Urea hydrolysis into ammonium carbonate requires the same time in flooded soils as in well-aerated ones (Delaune and Patrick, 1970). Before hydrolysis, urea cannot be fixed by the clay particles; therefore, it can move as fast as nitrates. This greater mobility plus possible volatilization losses when applied to the soil surface are the most frequent explanations given in cases where urea is inferior to ammonium sulfate (DeDatta and Magnaye, 1969).

The inefficiency of sodium nitrate in constantly flooded soils can be observed in Table 2. Nitrate utilization increases when it is applied to the surface at the time when the rice plant has developed a superficial mat of roots capable of absorbing nitrates before they are leached to the reduced zone. Even in these cases, its efficiency is inferior to that of ammoniacal sources. Nitrification inhibitors used as additives have failed at the field level (DeDatta and Magnaye, 1969; IAEA, 1970). Anhydrous ammonia is an excellent nitrogen source for flooded rice, but mechanization difficulties and possible volatilization losses at the time

of incorporation have prevented large scale use. Organic manures of plant or animal origin have been used for centuries in Asia. Although organic matter generally decomposes more slowly under flooded conditions, the responsible microorganisms function at higher C/N ratios than under aerobic conditions (DeDatta and Magnaye, 1969). With the nitrogen levels now recommended, the actual potential of organic fertilizers is limited. They can be used only as possible supplements to inorganic sources.

Nitrogen sources for intermittent flooding

Comparisons between nitrogen sources are very limited under intermittent flooding. Studies in Peru (Fig. 23) indicate that when nitrogen is applied in split applications there are no differences between urea and ammonium sulfate, in spite of the fact that the soil had an aerobic pH of 8.2. $NaNO_3$ applications at panicle initiation were extremely inef-

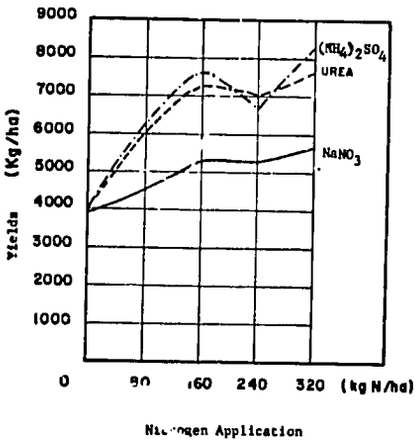

Fig. 23. Effects of three N sources on N response under intermittent flooding in Lambayeque, Peru. IR5 variety. (Ramirez and Sanchez, 1971a).

ficient, since rice under alternate flooding and drying conditions does not develop a significant quantity of superficial roots able to absorb NO_3^- before it can be leached down to the reduced layer (Ramirez and Sanchez, 1971a). Recently, several slow-release sources of nitrogen such as sulfur-coated urea have been studied in various countries. Experiments with sulfur-coated urea supplied by the Tennessee Valley Authority have indicated that this source behaves similarly to conventional urea under flooded conditions and low percolation rates (IRRI, 1969; Patrick *et al*, 1969). However, under intermittent flooding (Table 3) sulfur-coated urea incorporated before transplanting seems superior to conventional sources applied in the same manner and in some instances is superior to split applications of regular urea. The potential of slow-release fertilizers for upland systems is being evaluated in several countries.

Table 3. Effects of sulfur-coated urea (SCU) and placement methods at transplanting on IR8 yields at Rajendanagar, India. N rate = 120 kg N/ha. (Adapted from data by Ten Have, 1971).

Nitrogen Source	Grain yields (ton/ha)		
	Broadcast on surface	Incorporated at 5 cm	Incorporated at 10 cm
Urea	4.5	5.5	6.1
Urea & Sulfur	4.3	5.4	6.0
SCU—type I	6.5	7.3	8.2
SCU—type II	6.1	6.9	7.8
Urea split in 3 applications		6.0	
No nitrogen		2.3	

Methods of nitrogen placement

Nitrogen is normally applied in two ways: either incorporated in the soil before seeding or transplanting, or broadcast at different stages of growth. The need to incorporate ammoniacal sources into the reduced layer in systems with constant flooding is well known (Mikklesen and Finfrock, 1957; DeDatta, 1970). Incorporations 5 cm. deep are sufficient for constant flooding conditions (Fig. 24) but without constant flooding a deeper application may be beneficial as the data in Table 3 indicate. The N^{15} studies conducted by the International Atomic Energy Agency (IAEA, 1970) have provided additional information (Table 4). The

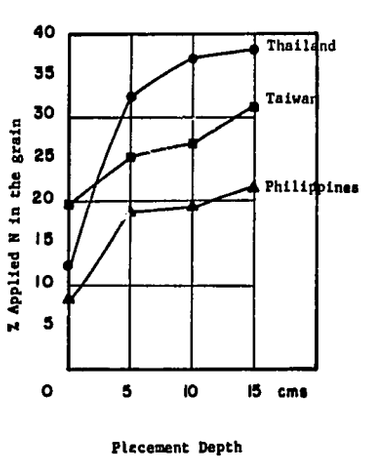

Fig. 24. Influence of placement depth of basal applications of ammonium sulfate on the efficiency of N in three localities. (Adapted from IAEA, 1970).

Table 4. Efficiency of utilization of ammonium sulphate as affected by placement depth under constant flooding in several countries. (Adapted from IAEA, 1970).

Location	Aerobic pH	% Applied Nitrogen in the Grain	
		Surface application	Incorporated at 5 cm.
Thailand	4.7	23.0	23.3
Bangladesh	5.3	10.0	17.0
Philippines	6.1	17.7	23.3
Ceylon	7.3	12.3	18.6
Pakistan	8.1	25.7	28.0
Egypt	8.2	23.7	23.0

benefits of incorporation at 5 cm were not observed in soils with aerobic pH of 4.7 or 8.1. This effect has been attributed to the inhibition of nitrification of ammoniacal sources applied to the superficial layer where the pH does not change. At these pH extremes, nitrification is minimal.

Under alternate redox conditions in Peru, incorporation at transplanting was inferior to broadcast applications at advanced stages of growth (Fig. 25). Ramirez and Sanchez (1971a) have attributed this effect to great N losses caused by frequent and pronounced flooding and drought cycles during the initial periods of growth.

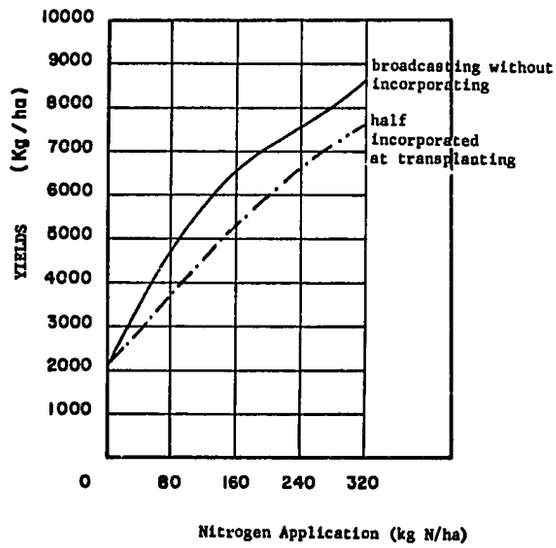

Fig. 25. Influence of two methods of N application under intermittent flooding in Lambayeque, Peru (Ramirez and Sanchez, 1971a).

Broadcast applications at the tillering or panicle initiation stages are more efficient in the presence of a thin layer of standing water; it is not recommended that the soil be drained after nitrogen applications (AICRIP, 1969; DeDatta, 1970).

Timing of nitrogen applications under constant flooding

The rapid changes that nitrogen undergoes in rice soils during short periods causes the timing of nitrogen applications to be an extremely critical factor in this crop. Nitrogen uptake proceeds throughout the growth cycle of the rice plant, but its nitrogen supply during two physiological stages is critical under tropical conditions: the beginning of tillering during the vegetative phase and the panicle initiation stage (Matsushima, 1965). An adequate supply of available nitrogen during the beginning of tillering results in more tillers, which are closely correlated with yield in short-statured plant types. However, excessive supplies of available nitrogen after the maximum tillering stage and before panicle initiation may result in a large proportion of unproductive tillers and premature lodging of tall varieties. The nitrogen available between panicle initiation and flowering is closely correlated with the number of fertile grains per panicle. Excessive quantities after flowering may extend growth duration and increase the susceptibility to certain diseases. The purpose of timing nitrogen applications is to synchronize the plant's requirements with the availability of this element in the soil throughout the growing season. As expected, great variability of experimental results in different localities occur as well as in the same localities during different years (Evatt, 1965; DeDatta, 1970; Sanchez and Calderon, 1970).

Under constant flooding, a basal application entirely incorporated before seeding or transplanting is normally sufficient for soils with low percolation rates and with varieties resistant to lodging. In flooded soils with high percolation rates, splitting nitrogen applications in two is more efficient provided the second half is applied at the panicle initiation stage (Evatt, 1965; DeDatta, 1970). For varieties susceptible to lodging, applications at panicle initiation are advisable since they tend to reduce initial excessive growth (DeDatta, 1970) and may prevent lodging altogether (Sims, Hall and Johnston, 1967b).

Timing of nitrogen applications under intermittent flooding

When experiments are conducted on farmers' fields with inadequate water management, it is commonly found that the rates as well as the optimum timing of applications are completely different from experiment station results (IRRI, 1969; Sanchez and Calderon, 1971). Higher rates and splitting applications in two parts were necessary to obtain high yields with tall and short plant types and at several solar radiation levels. In cases of alternate flooding and drying, more than 90 percent of the nitrogen incorporated at transplanting may be lost, while when it is applied at the panicle initiation stage, yields increased (Fig. 26) and the efficiency of nitrogen utilization doubled (Sanchez and Calderon,

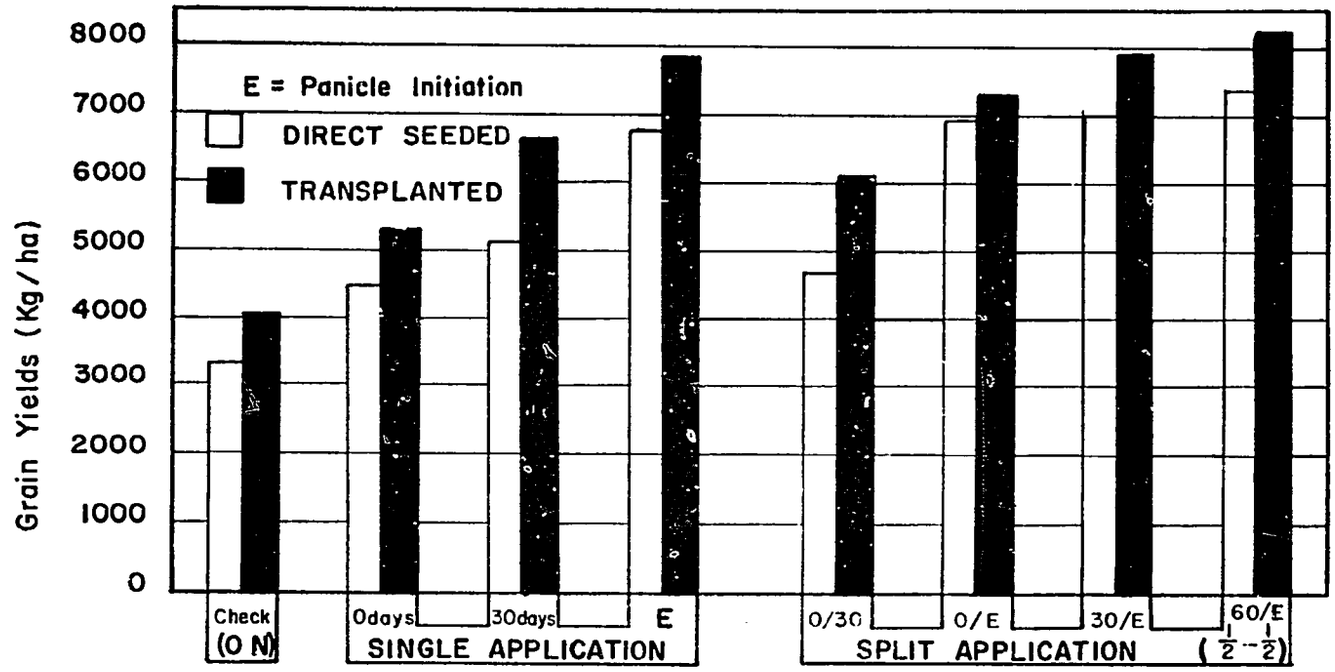

Fig. 26. Effects of timing of an application of 180 kg N/ha on rice performance under two planting systems and intermittent flooding (Sanchez and Calderon, 1971).

1971). In upland rice, splitting in two parts is definitively superior to a single application, especially during the reproductive phase. In general, few additional benefits are obtained with more than two applications.

Recovery of applied nitrogen

The efficiency of applied nitrogen utilization is somewhat lower in flooded rice than in other crops. In United States rice areas, Westfall (1969) estimated that the fertilizer recovery ranges from 33 to 53 percent with rates of 40 to 120 kg N/ha. Racho and DeDatta (1968) reported maximum efficiencies of 33 percent for applications of 30 kg N/ha in the rainy season and 57 percent with rates of 90 kg N/ha in the dry season in the Philippines. The different loss mechanisms have not been evaluated in detail, although it is assumed that denitrification and leaching are the most important processes involved.

Under alternate oxidation-reduction conditions, nitrogen losses increase. Apparent fertilizer recovery at harvest time fluctuated between 20 and 30 percent with the conventional management practices in Peru, but the efficiency can be increased substantially by the selection of sources, placement and timing practices most adequate for local situations (Sanchez and Calderon, 1971; Ramirez and Sanchez, 1971a).

SUMMARY AND CONCLUSIONS

The chemical reduction of the soil upon flooding results in a series of changes in nitrogen dynamics not found in other crops. Under alternate oxidation and reduction conditions due to temporary flooding in the majority of tropical areas, losses of native or applied nitrogen are great. Rice responses to nitrogen are minimal when tall traditional varieties susceptible to lodging are used, but responses are large and economical when higher rates are applied to short-statured varieties. Nitrogen recommendations for flooded rice cannot be based on soil analysis, since adequate methods have not been developed. In addition to soil properties, other factors such as plant type, solar energy, temperature, water management and spacing must be considered. The most effective nitrogen sources are the ammoniacal ones, especially ammonium sulfate and urea. Nitrate sources are unsatisfactory. New slow-release ureas may have a future for intermittent flooding conditions but apparently not for constant flooding. The best method of application is a basal dose incorporated in the soil before seeding or transplanting, followed by a second broadcast application during the panicle initiation stage, except in cases of constantly flooded soils with low percolation. Delaying the timing of applications to advanced stages of growth appears to be a more efficient practice in intermittently flooded and upland systems. The efficiency of nitrogen utilization in rice is lower than in other crops and much lower under intermittent flooding than under constant flooding. The potential for improving nitrogen management under inadequate water management conditions for tropical rice is large.

The basic concepts of nitrogen management in constantly flooded soils are well established. The necessary research in a new area essentially consists of establishing simple response curves for different ecological zones with variables such as plant types, solar radiation (through date of seeding trials) and manipulation of logical combinations of nitrogen sources, placement and timing of applications.

Under poor water management conditions, whether intermittent flooding or upland systems, it is necessary to quantify basic concepts and obtain more field data since this condition has not received much attention, in spite of the fact that the vast majority or rice areas in the tropics suffer from alternate redox conditions.

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