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NITROGEN AVAILABILITY INDEXES FOR SUBMERGED RICE SOILS

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I. INTRODUCTION

Rice culture occurs on soils that differ considerably in their characteristics, including their nitrogen-supplying capacity. According to Moormann (1978), rice is grown on all the 10 soil orders given in the soil classification system of

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Table I

Major Soil Classifications According to Soil Taxonomy Used for Rice Growing[a]

	Suborders of soils used for rice culture		
Order	Major importance	Local importance	Minor importance
Alfisols	Aqalfs, Ustalfs	Udalfs	Xeraffs
Aridisols		—	Orthids, Argids
Entisols	Aquents	Fluvents	Orthents, Psamments
Histosols	—	—	Hemists, Saprists, Andepts
Inceptisols	Aquepts, Ochrepts, Tropepts	—	—
Mollisols	—	Aquolls	Udolls
Oxisols	—	—	Orthox, Ustox
Spodosols	—	—	Aquods
Ultisols	Aquult, Udults	Humults	Usfults
Vertisols	—	Uderts Usterts	Torrerts Xererts

[a]From Moormann (1978).

soil taxonomy. The relative importance of the various soil suborders is shown in Table I.

The mineralizable nitrogen (N) pool in soils plays a dominant role in nitrogen nutrition of wetland rice. Studies using ^{15}N-labeled fertilizers have shown that approximately one-half to two-thirds of the total N utilized by a rice crop, even in well-fertilized rice paddies, comes from the soil-mineralizable N pool (Broadbent, 1978; IAEA, 1978; Reddy and Patrick, 1980; Koyama, 1981). The current shortage of fertilizers coupled with soaring prices resulting from energy costs involved in their manufacture warrant the most judicious and efficient use of fertilizer N, for which it is essential to know the nitrogen-supplying capacity of soils. Thus, development of laboratory indexes for predicting soil nitrogen availability to rice forms an important component of research for efficient use of fertilizer nitrogen.

Numerous biological and chemical laboratory methods have been proposed for predicting soil N availability to various crops, including rice, and these have been reviewed by Bremner (1965), Gasser (1969), Robinson (1975), and Chang (1978). However, there is no comprehensive review available on the nitrogen availability indexes for submerged soils, although rice yields more than those of any other crop depend on soil nitrogen availability. This article will review the recent literature on methods proposed for assaying the nitrogen-supplying capacity of wetland rice soils and recommend those methods which have potential for predicting soil N availability, thus making possible the judicious and efficient use of fertilizer nitrogen for rice production. No attempt will be made to discuss the literature covered in earlier reviews (Bremner, 1965; Patrick and Mahapatra, 1968; Gasser, 1969; Robinson, 1975; Chang, 1978; Sahrawat, 1982d). However, the mineralization process, which is basic to soil nitrogen availability to wetland rice, will be discussed in some detail.

II. FACTORS AFFECTING MINERALIZATION OF ORGANIC NITROGEN

Mineralization of organic nitrogen, which does not proceed past ammonium production in wetland rice soils, is the most important biological process that is involved in the availability of soil N to rice grown under submerged conditions. The term *mineralizable N* will be used to signify $NH_4{}^+$ production, because in a flooded paddy soil nitrification is at a low ebb because of the lack of oxygen. The process of mineralization in submerged soils is adequately described by Ponnamperuma (1972), Broadbent (1979), and Sahrawat (1983b), and only the literature pertinent to the factors affecting the mineralization and availability of soil N will be discussed here.

A. TEMPERATURE

Among the several factors which affect soil N mineralization, temperature and moisture regime are perhaps the most important. Studies at the International Rice Research Institute (IRRI) in the Philippines demonstrated that the release of water-soluble NH_4^+ in eight soils was least at 15°C and increased progressively with increases in temperature from 15 to 45°C through 25 and 35°C increments (IRRI, 1967). The amount of water-soluble NH_4^+ released was twice as much at a temperature regime of 38–35°C as at 20°C in a silt loam (Cho and Ponnamperuma, 1971). In another study, it was found that ammonium production in four soils under anaerobic incubation increased with an increase in temperature from 15 to 45°C (IRRI, 1974; Table II). Similarly, Myers (1975) reported that the ammonification of organic N in a tropical soil increased with an increase in temperature from 20 to 50°C, was maximum at 50°C, and then decreased slightly with further increases in temperature. The ammonification rate was highest during the first week. These results are consistent with the conclusion drawn by Ponnamperuma (1972) that most of the organic N in a soil is mineralized within 2 weeks after submergence if the temperature is optimum.

Numerous studies made in Japan (Kai *et al.*, 1969; Onikura *et al.*, 1975; Yoshino and Dei, 1977) and elsewhere (see reviews by Ponnamperuma, 1972; Broadbent, 1979) emphasize the importance of temperature to N mineralization

Table II

Effect of Temperature on NH_4^+ Release in Four Soils Incubated Anaerobically for 2 Weeks[a]

Soil	NH_4^+ released (ppm) in dry soil (°C)			
	15	25	35	40
Keelung silt loam	65	140	165	200
Casiguran clay loam	205	250	325	340
Pila clay loam	125	150	195	240
Luisiana clay	50	115	200	130

[a]From IRRI (1974).

in submerged soils. These studies suggest that the differences in rice yields obtained in cooler and warmer regions could be explained by the effects of temperature on mineralization–immobilization and the availability of soil N during the growing season, especially in the later stages of growth (see Yanagisawa and Takahashi, 1964; Yamane, 1967; Gotoh and Onikura, 1971).

B. Moisture Regime and Soil Drying

Similarly, the moisture regime of a soil is critical for mineralization of organic N. It has been found that soil drying prior to flooding changes the pattern of soil mineral N release. The pioneering work of Shioiri and co-workers (Shioiri *et al.*, 1941; Shioiri, 1948) in Japan showed that soil drying enhances mineralization of soil organic N. Subsequent studies by Ventura and Watanabe (1978) and Sahrawat (1980a, 1981a) have also shown that soil drying enhances soil N mineralization and thus its availability to rice. The soil-drying effect was very marked in four permanently waterlogged Philippine Histosols. There was a virtual absence of mineralization in these permanently waterlogged soils, but airdrying the soils prior to flooding caused a surge in release of NH_4^+ (Sahrawat, 1981a; Fig. 1). These results suggest that careful water management is necessary to avoid either nitrogen deficiency or excessive loss of organic matter accompanying rapid mineralization when the Histosols are used for wetland rice culture.

Sahrawat (1981b) performed greenhouse pot and field studies to examine the effects of soil drying versus flood fallowing on the availability of soil and fertilizer N; he found that the N availability of unfertilized soils was not affected by continuous flooding or soil drying and flooding one or more times during the growing season, as judged by crop growth and N uptake. Perhaps soil drying compensated for the small N losses that occurred because of nitrification–denitrification by enhanced mineralization.

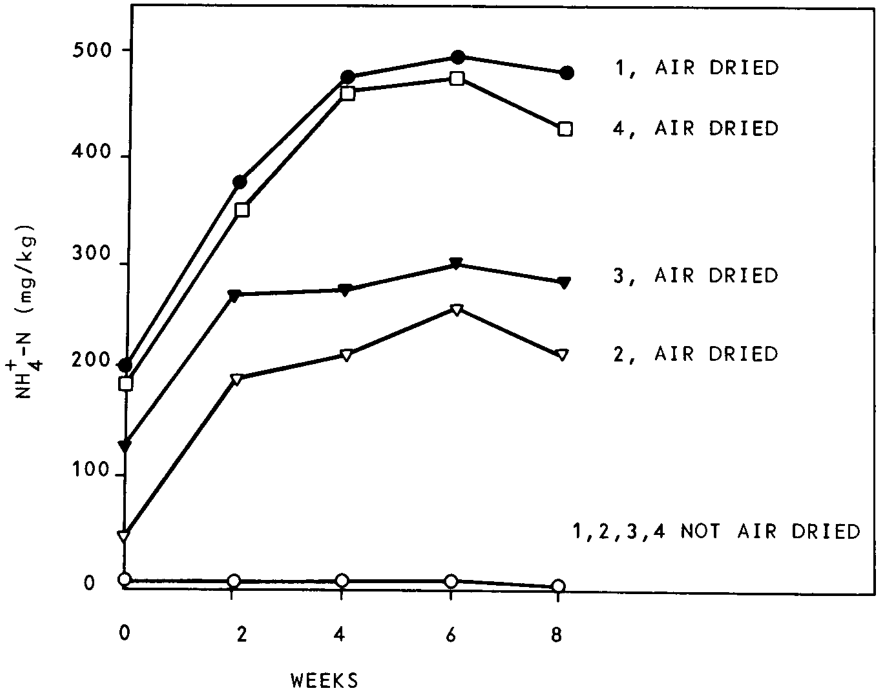

FIG. 1. Effect of air-drying on ammonification of soil organic N in four Philippine lowland Histosols incubated anaerobically at 30°C (Sahrawat, 1981a).

Soil	pH (1:2 H_2O)	Organic matter (%)	Total N (%)
1	6.2	36.7	1.48
2	5.6	22.0	0.56
3	6.1	39.0	1.20
4	5.9	42.0	1.40

C. SOIL CHARACTERISTICS

It is also recognized that soil nitrogen availability and rice growth improve on acid soils with liming (Ponnamperuma, 1958; Borthakur and Mazumdar, 1968). These effects may perhaps be attributable at least partially to the alleviation of toxicity from elements such as iron as well as to a general improvement in the availability of other nutrients with liming (Ponnamperuma, 1958). Sahrawat (1980b) reported that ammonification of organic N proceeded well in two acid

Table III

Correlations between Ammonium Produced by Anaerobic Incubation and Organic Matter, and Total Nitrogen Content of Philippine Soils

		Correlation coefficient (r)		
Number of samples	NH_4^+ released as % of total N	NH_4^+ versus organic matter	NH_4^+ versus total N	Reference
9	2.2–12.3	0.897[b]	0.912[b]	Sahrawat (1982a)
31	NR[a]	0.81[b]	NR[a]	IRRI (1964)
39	1.9–10.7	0.91[b]	0.94[b]	Sahrawat (1983b)
43	2.6–15.0	0.86[b]	0.85[b]	Gaballo (1973)
280	3.5–26.0	NR[a]	0.79[b]	IRRI (1978)
483	1.8–14.2	0.72[b]	0.79[b]	IRRI (1973)

[a]Not reported.
[b]Significant at $p = .01$.

sulfate soils from the Philippines that had pH values of 3.4 and 3.7, respectively. These results suggest that ammonification in soils is perhaps adapted even in extremely acidic soil conditions, although nitrification may not operate under such conditions (Sahrawat, 1980a,b, Sahrawat 1982b).

Studies made at the IRRI with a large number of Philippine soils have shown that ammonium produced by anaerobic incubation is highly significantly correlated with organic matter and total N; total N recovered as ammonium varied from 1.8 to 26.0% (Table III). In a detailed study of 39 diverse Philippine rice soils, Sahrawat (1983b) found that ammonification of soil organic nitrogen under waterlogged conditions was highly positively correlated with organic carbon ($r = .91^{**}$) and total N ($r = .94^{**}$) and highly negatively correlated with the C/N ratio ($r = -.46^{**}$) of the soils. Other soil properties, such as pH, clay content, and cation-exchange capability (CEC) were not significantly correlated with ammonium production. Multiple regression analyses showed that organic matter content, measured by organic C and total N, accounted for most of the variation in mineralizable N in these soils. The soils tested differed greatly in mineralizable N contents (17–428 ppm $NH_4{}^+$-N), suggesting that they would need different amounts of fertilizer N to obtain a given yield level.

D. Organic Amendments

In addition to soil and environmental factors, the incorporation of organic residues also greatly influences the mineralization of soil N and its availability to rice (for reviews see Broadbent, 1979; Sahrawat, 1979, 1980d). Pioneering work by Acharya (1935) clearly established that although the decomposition of crop residues was slower under anaerobic conditions, the net immobilization and nitrogen factors were much lower for the anaerobic decomposition than for the aerobic decomposition of the plant materials.

The important factors that govern the effect of organic residues on the mineralization and availability of soil nitrogen are soil nitrogen status, nitrogen content and C/N ratio of the residues added, temperature, and moisture regime.

E. Land Preparation and Tillage Practices

Similarly, tillage and land preparation operations also influence soil N mineralization and its availability to rice crops (see DeDatta and Barker, 1978). Puddling, a common practice for lowland rice culture in Asia, has been found to have beneficial effects on rice growth. However, with the present state of knowledge, it is rather difficult to attribute the beneficial effects of soil puddling entirely to enhanced mineralization and availability of soil N because puddling affects rice growth in many ways other than by increasing the supply of soil N (see Sanchez, 1973a,b; DeDatta and Kerim, 1974). Japanese scientists, however, have claimed that cultivation and puddling of soils enchances mineralization of soil organic nitrogen (Harada *et al.*, 1964; Sakanoue and Matsubara, 1967).

It is evident that the time of soil sampling is most critical, particularly with regard to the season and cultural practices that are followed for land preparation for rice culture before and after taking the soil samples for assessing the N-supplying capacity in the laboratory.

III. BIOLOGICAL INDEXES

The techniques involving estimation of mineral N formed during brief incubation periods have been suggested as the most satisfactory means of assessing the nitrogen-supplying capacities of soils. The various incubation techniques that have been used for estimation of potentially mineralizable N in soils are discussed by Bremner (1965), and most of the earlier references on the subject can be found in this review. However, it is evident that the methods have been tested more extensively for the upland soils, with less emphasis on submerged rice soils (Patrick and Mahapatra, 1968; Chang, 1978; Sahrawat, 1982d). This section discusses the incubation methods employed for measuring mineralizable N particularly for submerged soils and its availability to rice crops as evaluated by greenhouse and field studies (see Table IV).

Table IV

Incubation Methods Used for Predicting Soil Nitrogen Availability to Rice in Greenhouse and Field Studies

Method	Reference
Anaerobic incubation (under waterlogged conditions) at 30, 35, or 40°C for 6–14 days and in some cases for as much as 12 weeks	Lopez and Galvez (1958); Subbiah and Bajaj (1962); Ponnamperuma (1965, 1978); Sims and Blackmon (1967); Sims *et al.* (1967); Bajaj *et al.* (1967); Kawaguchi and Kyuma (1969); Koyama (1971); Lin *et al.* (1973); Yoshino and Dei (1974, 1977); Onikura *et al.* (1975); Shiga and Ventura (1976); Singh and Pasricha (1977); Bajaj and Hasan (1978); Ponnamperuma and Sahrawat (1978); Bajaj and Singh (1980); Dolmat *et al.* (1980); Sahrawat (1980c, 1982d)
Aerobic incubation at 30°C for 1–2 weeks	Bajaj *et al.* (1967); Bajaj and Hasan (1978); Bajaj and Singh (1980); Dolmat *et al.* (1980)

A. Anaerobic Incubation Methods

Ponnamperuma (1965) has discussed the implications of ammonia release in wetland soils for rice culture and reported that ammonia production in submerged soils followed approximately an asymptotic course described by the following equation, which could be used for predicting NH_4^+ production in wetland soils:

$$\log(A-Y) = \log A - ct \qquad (1)$$

where A is the mean maximum NH_4^+ nitrogen concentration, Y is the actual concentration t days after flooding, and c is a parameter of the soil. A is a characteristic for a soil under a given temperature regime that is related to the organic matter content of paddy soils (Ponnamperuma, 1972).

Work done at the IRRI in the Philippines has indicated that almost all the mineralizable nitrogen in a flooded soil is converted into ammonium within 2 weeks of submergence provided the temperature is favorable and the soil is neither strongly acid nor greatly deficient in available phosphorus (Ponnamperuma, 1972). Working with tropical rice soils, Lopez and Galvez (1958) and Ponnamperuma (1965) suggested that the amount of ammonia released by anaerobic incubation is a good measure of available nitrogen in flooded soils. Lopez and Galvez (1958) reported that rice grain yields correlated significantly with the mineralized N released within 2 weeks under waterlogged conditions in greenhouse experiments but not in field conditions. Subbiah and Bajaj (1962) found that in 18 Indian soils under waterlogged conditions the ammonium nitrogen released at 35°C within 1 week was a good index of nitrogen availability to rice.

It was further noted that the NH_4^+ released under waterlogged conditions within 1 week was significantly correlated with crop response ($r = -.783$**), but NH_4^+ released after 2 and 3 weeks was not significantly correlated with crop response. On the other hand, Waring and Bremner (1964a) suggested that the ammonium produced in soils after 2 weeks of incubation under waterlogged conditions at 30°C was a good index of N availability to upland crops. This conclusion was based on their results which showed that mineralization of organic N under aerobic conditions was highly correlated with NH_4^+-N released under anaerobic incubation. Anaerobic incubation tests, because they are simple and involve only the measurement of NH_4^+-N, are more adaptable than aerobic incubation tests. Similarly, studies by Japanese scientists have shown that the ammonia produced during 2 weeks of anaerobic incubation is a good index of available nitrogen in paddy soils (Kawaguchi and Kyuma, 1969; Koyama, 1971, 1981; Yoshino and Dei, 1974).

Lin *et al.* (1973) evaluated nine nitrogen availability indexes for predicting N availability in 20 Taiwanese soils in a pot experiment, reporting that the amount of NH_4^+ released after 1 week of anaerobic incubation at 40°C was highly correlated with N uptake or percentage yield of rice grain. These authors proposed that ammonia production after 1 week of waterlogged incubation at 40°C can be employed for predicting the N-supplying capacity of rice soils. Similarly, in the United States, Sims *et al.* (1967) and Sims and Blackmon (1967) assessed the nitrogen-supplying capacity of 61 soils from Arkansas (in a pot study) and concluded that a single determination of NH_4^+ after 6 days of waterlogged incubation at 40°C provided one of the better indexes of N availability to rice. Soluble plus extractable NH_4^+-N after 6 days of incubation accounted for 91% of the variation in yield on the 19 clay soils, but it accounted for only 18% variation on the 42 silt loams, which suggests that similar incubation tests may not be equally effective in predicting the nitrogen-supplying capacity of diverse types of soils. Dolmat *et al.* (1980) found that the amounts of ammonium released in surface soils from Louisiana during anaerobic incubation (30°C, 2 weeks) was the best of the eight nitrogen availability indexes tested for predicting the yield of rice grain in field experiments conducted at 34 locations (Table V). These results indicated the usefulness of the anaerobic incubation method for predicting the availability of soil N to rice under field conditions.

Sahrawat (1980c) studied the N-supplying capacity of eight Philippine rice soils by growing six crops of rice under flooded conditions in a greenhouse experiment, and found that the dry matter yield and N uptake were highly significantly correlated with the amounts of ammonium released in these soils under waterlogged conditions within 2 weeks at 30°C. In a more detailed study with 39 diverse rice soils it was further confirmed that the mineralizable N (NH_4^+) released during anaerobic incubation of soils either at 30°C for 2 weeks or at 40°C for 1 week was a very good index of soil N availability to rice grown

Table V

Linear Correlation Coefficients (r) between Soil N Availability Indexes and Rough Rice Yields at 34 Locations in Louisiana without Application of Fertilizer N[a]

N availability index	Correlation coefficient (r)[b]
Total N	0.363
Alkaline permanganate[c]	0.273
Anaerobic incubation[d]	0.560
Aerobic incubation[e]	0.433
Autoclaving in 0.01 M $CaCl_2$[f]	0.352
Boiling in 0.01 M $CaCl_2$[g]	0.315
Boiling in 0.5 N sodium pyrophosphate[g]	0.323
Acid hydrolysis[h]	0.289

[a]Adapted from Dolmat *et al.* (1980). Experimental plots received P (24.6 kg/ha) and K (46.5 kg/ha) fertilizers.
[b]Significant at $p = .01$.
[c]Subbiah and Asija (1956).
[d]Waring and Bremner (1964a).
[e]Keeney and Bremner (1965).
[f]Stanford and DeMar (1969).
[g]Stanford (1968).
[h]Purvis and Leo (1961).

Table VI

Correlations between Values of Available Soil Nitrogen by Different Methods with Dry Matter Yield and Nitrogen Uptake of Rice in a Greenhouse Pot Study[a]

	Correlation coefficient (r)	
Available N method	Dry matter weight	N uptake
Organic C	0.45[b]	0.82[b]
Total N	0.46[b]	0.84[b]
Anaerobic incubation, 30°C (2 weeks)	0.40[c]	0.84[b]
Anaerobic incubation, 40°C (1 week)	0.46[b]	0.82[b]
Alkaline $KMnO_4$	0.40[c]	0.81[b]
Acid $KMnO_4$	0.39[c]	0.75[b]
Acid $K_2Cr_2O_7$	0.39[c]	0.74[b]
H_2O_2	0.46[b]	0.82[b]
H_2SO_4 (0.5 M)	0.10[d]	0.42[b]

[a]$n = 39$; from Sahrawat (1982d).
[b]Significant at $p = .01$.
[c]Significant at $p = .05$.
[d]Not significant at $p = .05$.

under flooded conditions on these soils in greenhouse pots (Sahrawat, 1982d; Table VI). Ponnamperuma and Sahrawat (1978) found that the nitrogen-supplying capacity of 506 diverse Philippine wetland rice soils measured by anaerobic incubation ranged from 13 to 637 μg/g of airdried soil and was highly correlated with the soil organic carbon content. It was further shown in field tests that soils with a nitrogen-supplying capacity exceeding 150 μg/g, measured by anaerobic incubation, gave yields of 4.5–7.0 tons/ha without nitrogen fertilizer.

It is clear from the preceding discussion that ammonium released in soils under waterlogged conditions is a useful index for predicting soil N availability to wetland rice. Many more examples emphasizing the capability of anaerobic incubation tests for predicting N availability to rice can be found in an earlier paper by Sahrawat (1982d).

B. Factors Affecting Results of Laboratory Incubation Tests

It should be emphasized here that the methods of preparing soil samples before incubation affect the mineralization of soil organic N. For example, Shiga and Ventura (1976) found that the pattern of NH_4^+ release in a clay soil was influenced by whether the soil was incubated in moist field conditions or after airdrying. It has been shown that soil drying prior to flooding enhances mineralization of organic N (Shioiri *et al.*, 1941; Shioiri, 1948; Ventura and Watanabe, 1978; Sahrawat, 1980a). Sahrawat (1981a) found that airdrying produced a very quick release of NH_4^+ in four Philippine organic soils, although there was a virtual absence of ammonification in the continuously wet Histosols (Fig. 1).

Soil mesh size also has a profound effect on soil N mineralization. It has been observed that grinding of soil samples results in increased respiration and mineralization of nitrogen under aerobic and anaerobic conditions (Waring and Bremner, 1964b; Chalk and Waring, 1970; Craswell and Waring, 1972a,b; Hiura *et al.*, 1976; Powlson, 1980). Rovira and Greacen (1957) showed that the enhanced respiration in soil samples following compression and shearing resulted from exposure of the organic matter which had been inaccessible to soil microorganisms, rather than from enhanced aeration. Grinding and disruption of soils increases the mineralization of soil N more in clay soils where clay had protected organic matter from microbial attack (Rovira and Greacen, 1957; Craswell and Waring, 1972a). Powlson (1980) found that the grinding of two soil samples destroyed about one-fourth of the biomass in each sample, which resulted in increased mineralization of soil N. These examples stress the need for careful preparation of soil samples for studying them for potentially mineralizable N in laboratory incubation tests.

In a study of 19 diverse Philippine rice soils, Sahrawat (1982c) showed that either the addition of a nitrification inhibitor (Nitrapyrin) or the exclusion of air increased the amounts of NH_4^+ released in soils under waterlogged conditions within 2 weeks with near-neutral or alkaline pH soils, probably by halting losses from nitrification–denitrification. These results suggest that the exclusion of air is essential for anaerobic incubation tests used for determining mineralizable N to avoid losses resulting from nitrification and denitrification. The addition of nitrification inhibitors to the soil–water system could also help halt these losses.

Another important point which should be considered while measuring NH_4^+ released following waterlogged incubation of soils is that the soil samples should not be directly distilled with MgO; instead, filtered extracts of the samples should be used. This conclusion is based on the findings of Sahrawat and Ponnamperuma (1978), who found that direct distillation of soil samples gave inflated NH_4^+ values because of hydrolysis of organic matter at high pH (9.9–10.7) caused by the boiling MgO suspensions.

Recent work has also suggested that carbon dioxide evolved during direct distillation with MgO of anaerobic soils causes a negative error in ammonium determination compared to distillation of the soil extracts using the steam distillation–titration methods (Sahrawat, 1982g). Earlier work indicated that direct distillation of soils resulted in inflated values for NH_4^+ nitrogen, presumably as a result of hydrolysis of organic matter at the high pH attained by soil–MgO suspension (Sahrawat and Ponnamperuma, 1978). In fact, these studies emphasize the complex interaction that occurs between positive error caused by organic matter hydrolysis and negative error caused by carbon dioxide evolved during direct distillation of anaerobic soils with MgO for estimation of ammonium. The final result obtained will thus be the resultant of the positive and negative errors, especially in anaerobic soils following their incubation underwaterlogged conditions (Sahrawat, 1982g). A recent report by Clausen *et al.* (1981) has also indicated that the carbonates interfere with the determination of mineral nitrogen in soils using the direct steam distillation method.

Smith *et al.* (1980) found that the aerobic leaching incubation procedure used for estimating soil nitrogen mineralization potentials in three mineral soils employing the first-order model resulted in the leaching of significant amounts (13–163% of total mineralized N in 11 weeks) of organic N when 0.01 *M* $CaCl_2$ was used. These authors concluded that organic N extracted with inorganic N should be considered to avoid serious errors in the determination of N mineralization potentials and mineralization rate constants for soils using the aerobic incubation technique with successive subsequent leachings.

While studying the mineralization of organic N in four wetland Histosols from the Philippines, Sahrawat (1983a) found that 2 *M* KCl extracts of these soils in aerobic and anaerobic states contained significant amounts of organic N, but that the amounts were higher in anaerobic samples following 4 weeks of incubation under waterlogged conditions. These results suggest that ignoring the amounts of organic N extracted by salt solutions used for measuring mineral N may cause serious errors in the estimation of potentially mineralizable N in organic soils. However, no data are available for mineral wetland rice soils to show whether any organic N will be extracted by the salt solutions commonly used for the determination of NH_4^+ following anaerobic incubation. Results with organic soils also indicated that the amounts of organic N extracted by 2 *M* KCl increased in these soils following submergence. Because low-molecular-weight N compounds are synthesized in submerged soils (Ponnamperuma, 1972), and because whether these are extracted by salt solutions in soils will affect the estimation of potentially mineralizable N in wetland rice soils, this aspect needs further investigation.

Thus, it is suggested that the methods of soil preparation, and the procedures used for anaerobic incubation and extraction of NH_4^+ following anaerobic incubation, should be clearly defined because all these steps affect the results obtained for potentially mineralizable N in submerged soils. It is recommended that the soil samples should be incubated anerobically (by excluding air) under moist field conditions with a 2–3 cm layer of standing water. Filtered extracts of the incubated soil samples, rather than the soil–KCl suspensions, should be used for the estimation of ammonium.

C. Ammonium Content in Soil Solution

When a soil is kept submerged, a considerable portion of ammonia (NH_3 + NH_4OH + NH_4^+) may be found in the soil solution phase, especially in coarse-textured soils with a fair content of organic matter. This highly mobile form of ammonia is the direct source of nitrogen for the rice plant (Ponnamperuma, 1965, 1972). Studies made at the IRRI in the Philippines have shown that as with ammonium production in soils, the ammonia in soil solution also followed widely different asymptotic courses that were related to the rate of ammonium production and cation-exchange reactions. For example, a sandy loam rich in organic matter had a concentration of 70 ppm water-soluble (soil solution) ammonia during 75 days of submergence; on the other hand, a neutral clay loam, low in organic matter, accumulated only 5 ppm ammonia in the same period (IRRI, 1964). The soil solution of submerged soils is a dynamic phase and its composition relative to plant nutrients can be a useful tool for fertility evaluation (Ponnamperuma, 1965; Cho and Ponnamperuma, 1971).

Mangaraja *et al.* (1976) tested several modifications of the Waring and Bremner (1964a) waterlogged incubation test for predicting the nitrogen-supplying capacity of 16 soils from Orissa (India) to rice grown under submerged conditions in greenhouse. It was found that the anaerobic incubation method involving incubation of the soil samples with 75 or 100 ppm N (as ammonium sulfate) for 7 days and measuring the ammonium nitrogen present in the supernatant solution gave the best correlations with the relative yield or N uptake of rice.

D. Soil Biomass Nitrogen

Jenkinson and Powlson (1976) developed a method for measuring microbial biomass N and mineralization of soil N that involves fumigation of soil samples with chloroform. This results in the release of mineral N (which is then measured) from the killed microorganisms. Ayanaba *et al.* (1976) suggested that the mineral nitrogen released following chloroform fumigation of soils was related to their nitrogen-supplying capacity. The fumigation technique suggested by Jenkinson and Powlson is very sensitive and has been extensively used to assess the effects of agricultural practices on the size of microbial biomass (see Powlson and Jenkinson, 1981; Lynch and Panting, 1982). However, the method has not been evaluated for assessing the nitrogen-supplying capacity of soils as assessed by plant performance in greenhouse or field experiments. Also, this technique has not been used to evaluate the nitrogen-supplying capacity of wetland rice soils. It will be useful to evaluate this technique for determining the nitrogen-supplying capacity of submerged soils, because these differ from upland soils in that their microbial populations are predominantly bacterial and thus less diversified than those of their upland counterparts.

IV. CHEMICAL INDEXES

Numerous chemical methods have been proposed for assessing soil nitrogen availability to crops, including rice. Earlier work on this subject is reviewed by Bremner (1965), Robinson (1975), and Chang (1978). More recent references on chemical methods used for predicting soil N availability to wetland rice in greenhouse and field studies are listed in Table VII.

A. Organic Carbon and Total Nitrogen Content of Soils

The chemical indexes proposed for availability of soil nitrogen to rice include simple methods such as measurement of organic C and total N contents of soils (Bajaj *etal.*, 1967; Sims *et al.*, 1967; Ghosh and Hasan, 1980; Sahrawat, 1980c, 1982d). The logic behind using organic C or total N as an index of soil N availability is that the available N pool in soils ultimately comes from organic matter through the mineralization process. Soil-testing laboratories in India use

Table VII

Chemical Methods Used for Predicting Soil Nitrogen Availability to Rice in Greenhouse and Field Studies

Method	Reference
Organic C (organic matter)	Bonner (1946); Sims *et al.* (1967); Bajaj *et al.* (1967); Singh and Tripathi (1970); Singh and Pasricha (1977); Bajaj and Hasan (1978); Ponnamperuma (1978); Ponnamperuma and Sahrawat (1978); Bajaj and Singh (1980); Sahrawat (1980c, 1982d)
Total N	Sims *et al.* (1967); Ponnamperuma and Sahrawat (1978); Dolmat *et al.* (1980); Sahrawat (1980c, 1982d)
Mineral N	Sims and Blackmon (1967); Sims *et al.* (1967); Singh and Pasricha (1977); Bajaj and Hasan (1978); Bajaj and Singh (1980)
Alkaline permanganate digestion	Subbiah and Asija (1956); Tamhane and Subbiah (1960); Bajaj *et al.* (1967); Singh and Tripathi (1970); Rajamannar *et al.* (1970); Ranganathan *et al.* (1972); Ramanathan and Krishnamoorthy (1973); Gopalswamy *et al.* (1973); Singh and Pasricha (1977); Bajaj and Hasan (1978); Ponnamperuma and Sahrawat (1978); Velayutham (1979); Bajaj and Singh (1980); Dolmat *et al.* (1980); Sahrawat (1980c, 1982d)
Acid permanganate extraction	Sahrawat (1978, 1982d)
Acid dichromate extraction	Sahrawat (1982d)
Hydrogen peroxide oxidation	Sahrawat (1980c, 1982d)
Extraction with dilute H_2SO_4	Dolmat *et al.* (1980); Sahrawat (1982d)
Autoclaving in $CaCl_2$ (0.01 *M*)	Dolmat *et al.* (1980)
Boiling $CaCl_2$ (0.01 *M*) extraction	Dolmat *et al.* (1980)
Sodium pyrophosphate (0.5 *N*) extraction	Dolmat *et al.* (1980)
Alkali hydrolysis with $Ca(OH)_2$ or NaOH	Chu (1962); Bajaj and Hasan (1978); Bajaj and Singh (1980)

organic C content as the index of nitrogen availability to rice (see Patnaik, 1970; Ghosh and Hasan, 1980; Sahrawat, 1980c, 1982d). In a study of 39 diverse Philippine rice soils, Sahrawat (1982d) found that organic C and total N contents of soils were good indexes of soil N availability to rice grown in pots under flooded conditions. Further studies indicated that potentially mineralizable N released under waterlogged conditions was highly significantly related to organic C and total N (Sahrawat, 1983b). These results, together with earlier evidence (for review see Robinson, 1975; Chang, 1978), suggest that simple tests like organic C and total N contents of soils could be used for predicting soil N availability to rice. However, there are reports in literature in which organic C or total N contents of soils have been found to be poor indexes of nitrogen availability to crops, including rice (see Bremner, 1965; Sims *et al.*, 1967; Chang, 1978). In a field evaluation of several indexes of nitrogen availability at 34 locations in Louisiana, Dolmat *et al.* (1980) found that the rough yields of rice were correlated with total N content of soils, but the prediction was poor (Table V). Based on this discussion, it is concluded that organic C and total N contents of soils merit evaluation as possible indexes for N availability to rice.

B. Alkaline Permanganate Method

Alkaline permanganate oxidation was first developed for determining the easily mineralizable N in organic manures (Assoc. Official Agricultural Chemists, 1930). Later Truog (1954) used the release of NH_4^+ from soil by the action of permanganate and Na_2CO_3 for predicting the potentially mineralizable N pool in soils. In his method, the soil samples were boiled with $KMnO_4$ and Na_2CO_3 for 5 min to release easily mineralizable N, mainly NH_4^+ nitrogen. This method has been greatly modified (see Stanford, 1978; Sahrawat and Burford, 1982). The alkaline permanganate digestion method has been widely used for assessing the potentially mineralizable N pool in soils, especially in India for paddy rice (Subbiah and Asija, 1956; Tamhane and Subbiah, 1960; Bajaj *et al.*, 1967; Patnaik, 1970; Rajamannar *et al.*, 1970; Singh and Tripathi, 1970; Ramamoorthy *et al.*, 1971; Dolmat *et al.*, 1980; Ghosh and Hasan, 1980; Sahrawat, 1982d; also see Table VII). Stanford (1978) has summarized previous work pertaining to the use of the alkaline permanganate method as an index of soil N availability to upland crops.

Although the chemistry of the method is not clearly understood (Bremner, 1965), it is evident that alkaline permanganate releases nitrogen from soil organic matter by both oxidative and hydrolytic action (Stanford, 1978). Sahrawat and Burford (1982) found that the alkaline permanganate method could assess the availability of soil N, included nitrogen from amino acid and NH_4^+ but not nitrogen from urea, NO_2^-—, or NO_3^-— in the available N pool (Table VIII). Based on the results obtained with upland soils, which accumulate nitrate nitrogen, these authors suggested that the noninclusion of nitrate nitrogen in the available N pool might be the reason for the poorer predictability obtained by this method for upland crops than for paddy rice; nitrate formed in wetland soils may be lost because of denitrification.

Boswell *et al.* (1962) found a good correlation between the values of available N obtained by the Truog method and the nitrifying capacity of 30 soils. In a study

Table VIII

Recovery of Different Forms of N on Treating Pure Solutions of Specified Compounds with the Alkaline Permanganate Digestion and Distillation Method[a]

Form of N	Compound added	Recovery[b] (%)
Amino acid	L-Aspartic acid	93
	DL-Leucine	94
	L-Glutamic acid	95
	L-Lysine monohydrochloride	80
	Mean	91
Urea	Urea	2
Ammonium	$(NH_4)_2SO_4$	95
Nitrite	$NaNO_2$	1
Nitrate	KNO_3	1

[a]From Sahrawat and Burford (1982).
[b]Based on the addition of 2500 μg N in solution as specified compounds.

of 17 Indian soils, Srivastava (1975) found that the available N in soils determined by the alkaline permanganate method was correlated with organic matter, total N, amino sugar-N, hydrolyzable ammonium + amino sugar-N, hydrolyzable NH_4^+-N, and amino acid-N contents of soils. The NH_4^+ released by this method correlated with the potentially mineralizable N in soils, but the correlation coefficients were poor (Stanford, 1978).

Sahrawat (1982e) found that the amounts of available N in Philippine rice soils determined by the alkaline permanganate method (alkaline $KMnO_4$-N) were significantly correlated with the organic C, total N, and potentially mineralizable N contents determined by the anaerobic incubation methods (Table IX). It was also found that alkaline $KMnO_4$-N was highly significantly correlated with N uptake or the dry matter weight of rice grown under flooded conditions in pots with 39 diverse soils (Table VI). These results and evidence obtained by other researchers (Tamhane and Subbiah, 1960; Bajaj *et al.*, 1967; Chang, 1978), suggest that this method can be useful in predicting the availability of soil N to wetland rice. However, in a field study of 31 soils at 34 locations in Louisiana, Dolmat *et al.* (1980) found that the alkaline permanganate method was a poor predictor of rice yields (Table V). Bajaj and Singh (1980) evaluated several nitrogen availability indexes for rice in two field experiments and found that the available N determined by the alkaline permanganate method and ammonium released during 1 week of waterlogged incubation were significantly correlated with the yields of rice, but these correlation coefficients (r) were also low (0.40 and 0.25, respectively).

Table IX

Correlations between Chemical Indexes of Available N and Organic C, Total N, and Mineralizable N released during Anaerobic Incubation of 39 Philippine Wetland Rice Soils[a]

Chemical index compared	Correlation coefficient $(r)^b$			
	Organic C	Total N	Mineralizable N[c]	Mineralizable N[d]
Alkaline $KMnO_4$-N	0.855	0.882	0.859	0.812
Acid $KMnO_4$-N	0.839	0.845	0.800	0.788
H_2SO_4-N	0.440	0.461	0.541	0.457
Acid $K_2Cr_2O_7$-N	0.830	0.855	0.858	0.828
H_2O_2-N	0.814	0.840	0.855	0.795

[a]From Sahrawat (1982e).
[b]Significant at $p = .01$.
[c]Mineralizable N produced in soils under waterlogged incubation at 30°C for 2 weeks.
[d]Mineralizable N produced in soils under waterlogged incubation at 40°C for 1 week.

C. Acid Permanganate Method

Stanford and Smith (1978) found that the ammonium extracted by an acid permanganate solution (0.02 *M* $KMnO_4$ in 0.5 *M* H_2SO_4) was a good index of potentially mineralizable nitrogen in diverse soil samples collected from many scattered locations in the United States. Based on the comparative evaluation of the acid permanganate and alkaline permanganate methods, they suggested that the release of ammonium from soil organic nitrogen by the oxidative action of acid permanganate was a better index of potentially mineralizable N than the alkaline permanganate method (Stanford, 1978; Stanford and Smith, 1978). Sahrawat (1982d) showed that the ammonium released by acid permanganate (acid $KMnO_4$-N) was highly correlated with N uptake or dry matter yield of rice grown under submerged conditions in pots (Table VI). As observed with alkaline $KMnO_4$-N, acid $KMnO_4$-N correlated highly significantly with organic C, total N, and potentially mineralizable N produced under waterlogged conditions (Sahrawat, 1982e; Table IX).

D. Other Chemical Methods

In addition to the chemical indexes previously described, a few other chemical methods have been proposed for predicting soil N availability to rice. Sahrawat (1980c, 1982d) found that the ammonium released from the soil organic N pool by hydrogen peroxide oxidation (H_2O_2-N) correlated highly with the N uptake or dry matter yield of rice grown under submerged conditions in pot experiments

(Table VI). Additionally, it was indicated that H_2O_2-N was highly correlated with organic C, total N, and potentially mineralizable N released under flooded conditions in 39 diverse rice soils from the Philippines (Sahrawat, 1982e; Table IX). The results of this study also showed that NH_4^+ extracted with 0.5 *M* H_2SO_4 (H_2SO_4-N) was correlated with organic C, total N, and NH_4^+-N released under flooded conditions, although the correlations were poor (Table IX). Also, H_2SO_4-N was found to be a poor predictor of the soil N availability to rice grown in submerged soils in a greenhouse study (Table VI). Evaluations of alkali-hydrolyzable N as an index for soil N availability to rice have met with limited success, as did methods employing dilute acid solutions for hydrolysis of soil organic N (Chu, 1962; Bajaj and Hasan, 1978; Dolmat *et al.*, 1980; Bajaj and Singh, 1980).

In a study with a large number of diverse surface soil samples collected from the different rice-growing areas of the Philippines, Sahrawat (1982e) found that the ammonium extracted with a 0.02 *M* $K_2Cr_2O_7$ (in 0.5 *M* H_2SO_4) solution was highly significantly correlated with the organic C and total N contents, as well as with the amounts of ammonium released under waterlogged conditions at 30°C within 2 weeks or at 40°C within 1 week (Table IX). In a greenhouse pot experiment, when rice was grown under flooded conditions on these soils the ammonium extracted with acid dichromate ($K_2Cr_2O_7$-N) was found to be a good index of soil nitrogen availability to rice; the acid $K_2Cr_2O_7$-N was highly positively correlated with the dry matter and N uptake of the rice (Sahrawat, 1982d; Table VI).

Sahrawat (1982f) then developed a method which can be used for the simultaneous determination of organic C and acid dichromate-oxidizable N in soils. The method is based on a simple modification of the Walkley–Black method used for determination of organic C. The amount of ammonium released by the oxidative action of acid dichromate during organic C determination is measured by distilling an aliquot after titration of excess chromate with ferrous sulfate [rather than ferrous ammonium sulfate (to avoid ammonium contamination)] with alkali. This method will provide opportunities for testing organic C and acid dichromate-N alone or in combination as indexes for soil N availability. Initial results obtained with 15 soils from the Philippines showed that acid dichromate-N was highly positively correlated with the amounts of $NH_4{}^+$ released during anaerobic incubation tests of these soils (Sahrawat, 1982f).

Several other methods have been proposed for measuring the pool of soil available N but have not been evaluated for predicting soil N availability to wetland rice. Based on their chemistry and evaluation for upland crops, these techniques have potential for predicting soil N availability to rice crops.

Jenkinson (1968) suggested that the glucose extracted by shaking soil samples with 0.05 *M* $Ba(OH)_2$ was a good index of potentially mineralizable N in British soils. His studies and investigations by Whitehead *et al.* (1981) and Whitehead

(1981) have shown that this method provides a good index for soil N availability to grasses in greenhouse and field studies. However, this method has been found to be less suitable for routine use (Whitehead, 1981).

Stanford *et al.* have developed several laboratory techniques for measuring potentially mineralizable N (Stanford, 1977). For example, the method based on the extraction of NH_4^+ by autoclaving soil samples with $CaCl_2$ has been widely tested and found to be useful in predicting potentially mineralizable N in soils and its availability to upland crops (Stanford and Smith, 1972, 1976; Stanford, 1977; Whitehead *et al.*, 1981; Jones *et al.*, 1982). Jones *et al.* (1982) have evaluated this technique to estimate potentially mineralizable N and rate constants for mineralization under field conditions with 90 samples representing eight soil orders; the prediction was greatly improved when chemical and taxonomic criteria were considered simultaneously. These authors developed regression equations for the estimation of potentially mineralizable N based on the use of a multiple regression of soil pH, organic C, total N, and soil taxonomy, which accounted for 83% of the variation of potentially mineralizable N in 90 samples from 67 soils representing eight soils orders.

Mac Lean (1964) suggested a chemical method based on the extraction of soil samples with a dilute (0.01 *M*) $NaHCO_3$ solution and the measurement, by digestion, of the organic N extracted by the reagent. In subsequent studies of the method, Fox and Piekielek (1978a) developed a method which measures the organic N content in the bicarbonate extract by measuring the optical absorbance of the extract at 260 nm, which is more adaptable than the Kjeldahl procedure used by Mac Lean (1964). Michrina *et al.* (1981) evaluated this method in greenhouse and field studied for predicting soil N availability to corn; the availability of N was significantly correlated with N uptake in the greenhouse, but the correlation was not significant in the field study with 10 soils common to greenhouse and field experiments. It was also observed that the organic matter of soils accounted for 72% of the variation in greenhouse relative N uptake but for only 23% of the field relative uptake variation. Based on extensive evaluation of several chemical indexes in laboratory, greenhouse, and field studies, Fox and Piekielek (1978b) and Michrina *et al.* (1981) concluded that field experiments are necessary for evaluating laboratory indexes for available N, and that greenhouse testings are no substitute for field evaluation of the nitrogen availability indexes because of entirely divergent results obtained under the two situations with a given set of soils.

Michrina *et al.* (1982) found that the chemical indexes based on extraction of N by 0.01 *M* $NaHCO_3$ (Mac Lean, 1964) and boiling 0.01 *M* $CaCl_2$ (Stanford, 1968) extracted specific fractions of the soil organic N which differed significantly in their chemical composition. They found that 43–92% of the N extracted by $NaHCO_3$ was in protein form and 8–30% was detectable as ninhydrin. In the case of the boiling $CaCl_2$ extract, about 25–30% of the N was detectable as ninhydrin. For the 10 soils studied, ninhydrin-detectable N values in $CaCl_2$ extracts were closely correlated to greenhouse and field relative N uptake values, whereas the ninhydrin-detectable N values in $NaHCO_3$ extracts were unrelated to both greenhouse and field relative N uptake by corn. However, the protein N and protein N plus ninhydrin-detectable N values of the $NaHCO_3$ extract were closely correlated to the relative N uptake values in the greenhouse study. This study indicates the usefulness of chemical characterization of the extracts obtained by chemical indexes for understanding which fractions of organic N contribute to the soil available N pool for different crops. More such studies may be needed to determine the applicability of different chemical indexes to different crops.

Some of the extraction methods employing heating and boiling (such as the $CaCl_2$ method) evidently result in a greater organic nitrogen fraction than those employing extraction at room temperature (e.g., see Greenland, 1965). Jenkinson (1968) also pointed out that the amounts of polysaccharides extracted from soils increased markedly with boiling extraction methods. In addition, boiling causes the molecular hydrolysis of organic N compounds and the destruction of soil aggregates which may facilitate the extraction of increased amounts of organic N (Michrina *et al.*, 1982).

V. SIMPLE MODELS OF NITROGEN-SUPPLYING CAPACITY BASED ON BIOLOGICAL AND CHEMICAL INDEXES

In this section, simple equations describing the relationships between the amounts of NH_4^+-N released under waterlogged conditions and environmental factors such as temperature and other soil characteristics are discussed. These relationships have been formulated from studies with diverse soils from a particular region and are limited in that they have not been widely tested. However, these simple models in this or modified form might help in making approximate predictions of mineralizable N in wetland rice soils. Studies at the International Rice Research Institute in the Philippines by Ponnamperuma and his associates have shown that soils rich in organic matter release ammonium rapidly, following a logarithmic increase with time which can be represented by the following equation (IRRI, 1965):

$$Y = a + b \log x \qquad (2)$$

where y is the total amount of NH_4^+-N released, a is the amount of NH_4^+-N content 1 day after flooding, b is the parameter highly correlated with the organic matter and total N contents of the soil, and x is weeks submerged.

Further studies using anaerobic incubation of wetland soils indicated that the soils low in organic matter released much smaller amounts of ammonium at comparatively slower rates; the increases in NH_4^+-N were not appreciable after 4 weeks, in contrast with soils rich in organic matter where concentrations of NH_4^+ continued to increase after 30 days. In soils low in organic matter, soil N mineralization followed an asymptotic course described by Eq. (1) or by the following equation (IRRI, 1964; Ponnamperuma, 1972):

$$(A-Y)/A = e^{-ct} \tag{3}$$

where A is the mean maximum amount of NH_4^+-N, Y is the actual amount of NH_4^+-N t days after submergence, and c is the parameter controlled by the soil.

Because temperature greatly influences the release of ammonium in submerged soils, Yoshino and Dei (1974) suggested the concept of *effective temperature* for predicting mineralizable nitrogen in incubation tests by correcting for the soil temperatures prevalent during the growing season (for a review see Dei and Yamasaki 1979). According to this concept, the potentially mineralizable nitrogen is calculated from the following equation:

$$Y = k[(T-15)D]^n \tag{4}$$

where Y is the amount of nitrogen mineralized, T is the mean temperature of the treatment or daily soil temperature in °C, D is the number of days, $(T-15)$ is the effective temperature (in °C), and k is the coefficient relating to the potentials of mineralized N. The exponent n is a constant relating to the pattern of N mineralization. In this model, 15°C is considered to be the threshold temperature for the occurrence of the mineralization process in submerged soils. It can be derived from Eq. (4); if the effective temperature is the same in two soils, the amount of N mineralized will be the same irrespective of the temperature regimes. In other words, the amount of N mineralized at 30°C during 20 days will be the same as that mineralized at 35°C during 15 days because the summation of effective temperature is same in the two cases. This also indicates that if the temperature during an anaerobic incubation test is higher, the incubation period can be reduced accordingly to obtain similar amounts of mineralizable N as released during longer incubation periods at lower temperatures.

Onikura *et al.* (1975), to calculate mineralizable N in submerged Japanese soils incubated for 70 days, developed a regression equation by considering the soil properties that affect the release of NH_4^+. According to these authors the best prediction of mineralizable N (N_{min}) was obtained by the following equation:

$$N_{min} = 1.70 + 17.57(\text{total N}) + 0.444(\text{CEC}) - 1.58(Fe_2O_3) - 0.233(\text{Ca}) \tag{5}$$

which accounted for 87% of the variability in mineralizable N for a large number of soils. It should be mentioned here that total N and CEC combined accounted for 62% of the variation observed in the mineralizable N values, and that a combination of total N, CEC, and free Fe_2O_3 accounted for 82% of the variation.

Sahrawat (1983b) developed regression equations to predict potentially mineralizable N as affected by soil properties using 39 diverse rice soils from the Philippines:

$$N_{min} = -59.96 + 85.15 \text{ (organic C)} \tag{6}$$

where $r^2 =$ 82.8%, and

$$N_{min} = -44.4 + 792.3 \text{ (total N)} \tag{7}$$

where $r^2 =$ 88.8%.

A combination of organic C and total N accounted for 89.4% variability in the mineralizable N by the following equation:

$$N_{min} = -29.9 + [1336.1 \text{ (total N)}] - 61.0 \text{ (organic C)} \tag{8}$$

The most variability ($r^2 = 91.8\%$) was found by the regression equation

$$N_{min} = -68.8 + [1969.6 \text{ (total N)}] - 128.8 \text{ (organic C)} + [9.9 \text{ (C/N)}] - 9.2 \text{ (pH)} + 0.88 \text{ (CEC)} - 0.75 \text{ (clay)} \tag{9}$$

It is clear from regression Eqs. (6)–(9) that in these soils organic matter, as measured by the organic C and total N contents of the soil, accounted for the most variations in mineralizable N. It also seems, from these equations, that organic matter may be used (or at least shows potential for use) for predicting mineralizable N in these soils under submerged conditions.

It has been suggested that the amount of soil N mineralized in time t is proportional to the square root of the period of incubation and can be expressed by the following equation (Stanford and Smith, 1972):

$$N_t = at^{\frac{1}{2}} \tag{10}$$

where a is the N mineralization rate and t is the time. However, this equation has the limitation that at infinite time it will give an infinite amount of mineralized N, which is incorrect (Houng, 1980).

Stanford and Smith (1972) suggested the following equation for calculating potentially mineralizable N:

$$1/N_t = 1/N_0 = b/t \tag{11}$$

where N_0 is the potentially mineralizable N, N_t is the amount of N mineralized in time t, and b is the constant related to soil properties. This equation was fitted into the first-order kinetic equation

$$\log(N_0 - N_t) = \log N_0 - b/2.303t \tag{12}$$

Lin *et al.* (1973) evaluated Eqs. (10)–(12) to calculate the potentially mineralizable N in 20 submerged Taiwanese soils and compared these values with the actual amounts of soil N mineralized during up to 12 weeks of anaerobic incuba-

Table X

Correlations Between *N* Uptake and Yield Index of Rice in a Greenhouse Study[a]

Parameter compared	Soil N mineralization rate[b]						N mineralization potential[c]	
	0–2	0–4	0–6	0–8	0–10	0–12		
N uptake from no N pots	0.834[d]	0.868[d]	0.877[d]	0.847[d]	0.846[d]	0.850[d]	0.7418[d]	0.7893[d]
Yield index $[(N_0/N_d) \times 100]$[e]	0.739[d]	0.729[d]	0.713[d]	0.694[d]	0.694[d]	0.704[d]	0.523[f]	0.596[f]

[a]Data of Lin *et al.* (1973) adapted from Houng (1980).
[b]Based on Eq. (10). Numbers represent weeks of incubation.
[c]Based on Eqs. (11) and (12), respectively, with 12 weeks of incubation.
[d]Statistically significant at $p = .01$.
[e]N_0 is the yield of no N pot; N_d is the yield of the N fertilizer pot, double application.
[f]Statistically significant at $p = .05$.

tion. They found, in a greenhouse pot study, that the actual amounts of NH_4^+-N released within a certain period of incubation, for example, during 2 or 4 weeks of submergence, were better correlated with the rice yield index or N uptake than with the values of potentially mineralizable N obtained (Houng, 1980; Table X).

Stanford and Smith (1976) estimated potentially mineralizable soil nitrogen (N_0) from the amounts of NH_4^+-N produced by hydrolysis of soil organic nitrogen during 16 hr of autoclaving (N_t) using 475 diverse soil samples from the United States representing 54 soil types; they developed the following regression equation:

$$N_0 = [(4.1 \pm 1.0)\ N_t] + 6.6 \tag{13}$$

where N_0 is the potentially mineralizable N and N_t is the amount of NH_4^+-N released during autoclaving.

Acid permanganate extraction has been proposed for the estimation of potentially mineralizable nitrogen in soils (Stanford and Smith, 1978) and of availability of soil N to wetland rice (Sahrawat, 1982d). The following regression equations were developed for the estimation of potentially mineralizable nitrogen (N_0) from values of NH_4^+-N released by the oxidative action of acid permanganate (0.02 M $KMnO_4$ in 0.5 M H_2SO_4) using 62 diverse soils from the United States (Stanford and Smith, 1978). For 43 noncalcareous soils

$$N_0 = 3.2\ (\text{acid } KMnO_4\text{-N}) - 19.8 \tag{14}$$

Using 19 calcareous soils,

$$N_0 = 3.0\ (\text{acid } KMnO_4\text{-N}) - 7.5 \tag{15}$$

For all the 62 soils,

$$N_0 = 3.1\ (\text{acid } KMnO_4\text{-N}) - 8.5 \tag{16}$$

The correlation coefficients (r) for these equations were 0.91, 0.86, and 0.89, respectively.

It is suggested, because results obtained in laboratory and greenhouse studies with some of these indexes have given encouraging results, that some of the simple models based on statistical relationships between potentially mineralizable soil nitrogen and other indexes of soil N availability should be evaluated for their ability to predict soil nitrogen availability to rice under field conditions (Stanford and Smith, 1976, 1978; Sahrawat, 1982,d,e,f).

VI. *A* VALUES

In 1952, Fried and Dean suggested that the nitrogen-supplying capacity of soils could be determined by using ^{15}N-labeled fertilizers, which would make it possible to differentiate the contributions of soil and fertilizer N to plant uptake. The underlying principle of the *A*-value concept is that the amount of a given nutrient in the soil and the amount that is applied as fertilizer will have equal availability to plants. The main assumptions in using the *A*-value technique are that reactions between soils and fertilizer are minimal, and that if reactions do occur between fertilizer N and soils they must be similar for the soils under comparison (Rennie and Fried, 1971). Because rice is grown on diverse types of soils, these assumptions probably will not always be met in wetland rice culture. However, it is a useful concept which takes into consideration the effect on soil nitrogen contribution by cropping history. For example, based on the data obtained by the International Atomic Energy Agency (IAEA, 1970, reported by Broadbent, 1978), from field experiments in 13 countries, it was found that there was a linear relationship ($r = .851$) between the *A* value and the uptake of soil N by a rice crop (Fig. 2). The average *A* value from these experiments was 21% of the total N content of soils.

Based on the data obtained for nitrogen uptake for soil and fertilizer nitrogen sources, the *A*-value concept can be used to evaluate nitrogen available in the soil. The following equation is used to calculate *A* values:

$$A = [B\ (1-Y)]/Y \tag{17}$$

where *A* is the amount of nitrogen available in the soil, *B* is the amount of nitrogen in the standard, and *Y* is the proportion of nitrogen in the plant derived from the standard. In cases where ^{15}N-labeled fertilizer is used, *Y* is the percentage of the total nitrogen taken up by the plant from the fertilizer. The prospects and problems in the use of *A* values for characterizing available soil nitrogen pools have been critically discussed by several authors (Broadbent, 1970; Hauck and Bremner, 1976; Hauck, 1978, 1979). It is suggested that the use of *A* values as an index of soil nitrogen availability will require careful characterization of the conditions under which this estimate is made.

Studies indicate that *A* values in rice cultures are markedly affected by fertilizer N placement (Broadbent and Mikkelsen, 1968; Broadbent, 1970) and the time of fertilizer application (Koyama *et al.*, 1973). Studies conducted in Japan on 10 different soils showed *A* values ranging from 98 to 443 kg N/ha, and soil N contributed two-thirds of the total N taken by rice crops fertilized with varying rates of fertilizer N (Koyama, 1981). In pot study under flooded conditions with four Philippines rice soils it was found that the *A* values for these soils ranged from 13.5 to 30.5, with a mean value of 20.3. These *A* values are considerably higher than the reported average *A* values ranging from 4.3 to 8.7 for some upland soils (Hunter and Carter, 1965; Legg and Stanford, 1967; Herlihy and Sheehan, 1979). Broadbent and Keyes (1971) suggested that the difference in *A* values for wetland rice and upland soils could be partly because the available N pool in wetland rice culture is maintained mostly in the ammonium form, as compared to upland soils where it is maintained in both the ammonium and

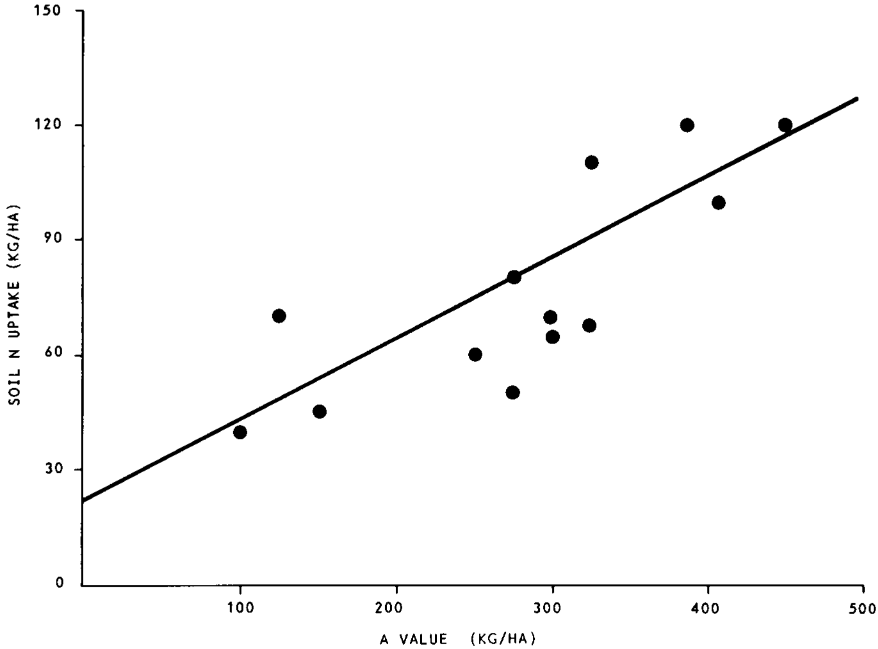

FIG. 2. Correlation of A values with uptake of soil nitrogen by rice plant in field. Y = 20.3 + 0.212X r = .851. (Broadbent, 1978.)

nitrate forms. Also, loss of fertilizer N is higher under flooded conditions of rice culture.

Broadbent (1978) has suggested that *A* values obtained from future field experiments should be measured more often under different soil cropping and environmental conditions so that a large body of data obtained under a set of defined conditions could improve the predictive value of this technique. With the availability of ^{15}N-depleted materials, field experimentation has become less expensive, and this should help in generating more field evaluations of the nitrogen-supplying capacity of wetland paddy soils under diverse soil and environmental conditions than are presently available. *A* values determined in a large number of field experiments in Japan between 1973 and 1983 have shown that *A* values vary greatly with the rate of fertilizer N, the type of fertilizer, and the method of application (Koyama, 1981).

VII. ELECTRO-ULTRAFILTRATION

The electro-ultrafiltration (EUF) technique is based on extracting different fractions of N from soils with varying voltages and temperatures. Electro-ultrafiltration thus offers a method to fractionate soil N into fractions which are instantaneously (intensity) available, released at 20°C and 200 V, as well as into those which represent potentially available N fractions or reserves (capacity), released at 80°C and 400 V (Nemeth, 1979). Using the EUF technique, NH_4^+ is discharged from soils at the cathode within 10–15 minutes. Dilute HCl is used to avoid the loss of ammonia through volatilization (Nemeth *et al.*, 1979). In addition to mineral N, the EUF technique also measures organically bound N in soils. For example, Nemeth *et al.* (1979) found that low-molecular-weight N compounds in the form of amino acids–nitrogen were present in the filtrates. Analysis by EUF using high voltage (400 V) and high temperature (80°C) have shown that soils rich in plant residues such as roots have a higher capacity to release reserve N. Studies made in Germany and Austria have indicated that the EUF technique gives a good prediction of potentially mineralizable N and soil N availability to upland crops (Nemeth, 1979; Wiklicky, 1982).

The EUF technique, as used for determining the nutrients (including N) available in soils, is discussed in detail by Nemeth (1979). It has been found, using EUF, that NH_4^+ can be measured precisely in soils rich in clay and low in K, whereas it is relatively difficult to measure NH_4^+ in soils high in K using this technique. Wanasuria *et al.* (1980) found that EUF-extractable NH_4^+ was related to the N uptake and grain yield of rice in Philippine wetland rice soils. Mengel (1982) has suggested that the intensity factor is important for assessing NH_4^+ availability in wetland rice soils which in this respect resembles K availability.

VIII. PLANT ANALYSES

Plant analysis is an accepted means of predicting fertilizer requirements and of diagnosing nutrient deficiencies based on critical nutrient values. Excellent reviews on the subject are available (Ulrich, 1952; Chapman, 1971; Jones and Steyn, 1973).

Studies made at the University of California have clearly demonstrated that the total N content of the most recent fully developed leaf, also referred to as the "Y leaf," of the rice plant at tillering is closely related to the grain yield of the rice (Reisenauer, 1978). It has also been indicated that the total N content of the leaf tissue is a better index than any nitrogen fraction. Tanaka and Yoshida (1970) made an extensive survey of rice fields in Asian countries and found that N deficiency was most notable in the rice plant. Their studies in the Philippines suggested that 2.5% was the critical concentration in the leaf blade of the rice plant at the tillering stage.

Wallihan and Moomaw (1967) monitored the concentration of total N in the last four leaves formed in three varieties of rice grown under submerged conditions in the field from the formation of flower primordia until flower emergence. They found that the concentration of total N changed with the leaf age and with the variety and growth stage of rice. Based on the stability of the nitrogen concentration and the sensitivity of the nitrogen supply, the blade of the next-to-last leaf (second leaf below the panicle), sampled at the time of flowering, was found to be suitable as the index leaf. No nitrate was detected in the leaf tissue. These observations corroborate earlier work done in Japan (Tanaka, 1961).

Thenabadu (1972) made greenhouse and field studies, arriving at critical values of 2.2–2.3% N in the first and second most recently matured leaf of the rice plant sampled 67 days after transplantation. Krishnamoorthy *et al.* (1971) made an extensive survey of rice fields, and based on the analyses of different leaf tissues of the rice plants they concluded that the third leaf from top was suitable as the index leaf. They found that the critical concentration of total N in the index (third) leaf sampled between 3 and 6 weeks after transplantation was 1.4%.

Hafez and Mikkelsen (1981) found that the Udy dye binding method (Udy, 1971), which is used for rapid estimation of protein in feeds, is also suitable for the analysis of rice plant leaf tissue for nitrogen content. Nitrogen content in leaf tissue determined by the dye binding method was highly correlated with the Kjeldahl nitrogen. This method, being simple and rapid, should aid in promoting plant tissue analyses for predicting nitrogen requirements of rice.

It is thus clear that plant analysis gives a good index of the nitrogen status of the rice plant, and can be a useful guide for top-dressing requirements for fertilizer nitrogen if the tissue analysis is made at the tillering stage (e.g., see Chang, 1978). It is also clear that much standardization work on plant analyses is required for different cultivars grown in different environments in order to obtain critical and sufficient range concentrations for N by selecting an index plant part. Perhaps a combination of soil and plant tissue testing might provide a better index for nitrogen requirements of rice culture where indexes based on soil analysis alone may not be sufficient because nitrogen losses are high. Plant analysis has not been widely employed because often it is too late to alleviate any nitrogen deficiency discovered. The concentration of nitrogen in plants is greatly affected by genotype, the growth stage of the rice, and environmental conditions, and it is difficult to make a general recommendation even for different regions in a large country such as India.

IX. NITROGEN-SUPPLYING CAPACITY AND FERTILIZER RECOMMENDATIONS

Soil tests have not been as successful for predicting the N-supplying capacities of soils and for making N fertilizer recommendations as they have been for other nutrients such as P and K. The main problems seem to stem from the fact that nitrogen availability to plants is governed by several environmental and soil factors which are not taken into account when empirical procedures for determining available N are used. However, tests for predicting the nitrogen-supplying capacities of soils are important for the efficient use of fertilizer N. It is always good to have a test which can provide a rough estimate of the pool of available N in soils so that fertilizer N can be applied to achieve a given yield of rice. This can be illustrated by an example taken from soil test crop-response project work in India (see Velayutham, 1979; Randhawa and Velayutham, 1982). The alkaline permanganate digestion method (Subbiah and Asija, 1956) was used for estimating the available N in soils for several crops, including rice (Ramamoorthy and Velayutham, 1976; Venkateswarlu, 1976). Based on the data obtained for rice grain, it was established that approximately 1.5–1.8 kg N/ha is needed for every 100 kg of grain in the alluvial soils of Delhi. From past experience it is known that about 26% of the available N (determined by the alkaline permanganate method) is taken up by the rice crop. For example, if the available N in a soil as measured by this method is 250 kg/ha, only about 65 kg of this pool will appear in the rice plants. Based on the yield target, the amount of fertilizer nitrogen (corrected for a use efficiency of 30–40%) required for wetland rice can be calculated. This test gives a rough guide for making fertilizer N recommendations which should result in the more efficient use of fertilizer than in cases where the nitrogen-supplying capacity of the soil is not taken into consideration.

Velayutham (1979) has summarized the Indian work on soil test crop response for rice. Briefly, the yield target and the required fertilizer nitrogen for achieving the yield target can be calculated from the following equations:

$$T = ns/(m-r) \tag{18}$$

and

$$F = rns/(m-r) \tag{19}$$

where T is the yield target in 100 kg/ha, n is the ratio of percentage contribution from soil and fertilizer N, r is the N requirement in kg/ha of grain production, m is the ratio of N requirement and contribution from fertilizer N, s is the soil test N value in kg/ha, and F is the fertilizer nutrient rate in kg/ha. This scheme seems to provide a fair degree of approximation for efficient use of fertilizer N considering the N-supplying capacities of soils.

Another example for fertilizer N recommendation based on the N-supplying capacity of rice soils is from the work done at the International Rice Research Institute in the Philippines by Ponnamperuma and his colleagues, who used the anaerobic incubation method to measure levels of available N. They sampled rice fields in 13 provinces in the Philippines and, based on the analysis of 483 soil samples, the available N in these soils ranged from 10 to 637 ppm. It was possible to separate low- and high-N-supplying capacities using the anaerobic incubation test (Ponnamperuma, 1978; Castro, 1979). Based on the results of potentially mineralizable N, Ponnamperuma (1978) formulated a rough guide for the fertilizer nitrogen requirements of a crop of 5 tons/ha for Philippine wetland rice soils.

1. Soils that needed no fertilizer nitrogen (available N > 150 ppm)
2. Soils that needed 50 kg N/ha at panicle primordia initiation (available N = 100–150 ppm)
3. Soils that needed about 50 kg N/ha at planting and about 50 kg N/ha again at panicle primordia initiation (available N=50–100 ppm)

It was further observed that at eight locations in a province, rice yields of 4.5–7 tons/ha were obtained on soils containing more than 155 ppm available N; zinc was applied but N was not (IRRI, 1974; Castro, 1979). These two examples illustrate the principle of basing the recommendation of fertilizer nitrogen needs of rice on the available N results, and it seems to be a step in the right direction. It is, however, recognized that these recommendations must be modified from time to time to reflect experience gained.

X. PERSPECTIVES

The high cost of fertilizer nitrogen combined with the need for increased yields of rice has stimulated research on methods of using soil and fertilizer nitrogen efficiently. For the judicious and efficient use of fertilizer, a measure of the nitrogen-supplying capacity of soils is prerequisite because rice soils vary widely in their capacity to release ammonium nitrogen when submerged. Our fertilizer recommendations will be only as precise as our methods for measuring the amounts of available soil nitrogen. Because of the fact that one-half to two-thirds of the nitrogen used by the rice plant, even in well-fertilized paddies, comes from soil nitrogen through mineralization, research on methods for measuring the nitrogen-supplying capacities of wetland rice soils assumes still greater importance.

For devising effective methods for measuring available nitrogen in soils, it is essential that the factors that affect mineralization and the availability of soil nitrogen to the rice plant be well understood. Soil and environmental factors that affect the mineralization of soil organic nitrogen are fairly well documented. However, with the present state of knowledge it is not possible to quantify (1) how the texture and the mineralogical makeup of a soil affect the release of nitrogen under submerged conditions, or (2) how the mineralization of soil organic nitrogen is affected by the presence of the rice plant. Attempts should be made in the future by using stepwise regression analyses to separate the effects of different soil characteristics on nitrogen mineralization in flooded soils for different regions with due consideration of taxonomic criteria. It is envisaged that a knowledge of the environmental (such as temperature and moisture) and soil factors that affect mineralization will be useful in developing improved anaerobic incubation tests and, eventually, in developing models for measuring soil nitrogen mineralization rates and hence nitrogen-supplying capacity under field conditions, No data are presently available on the measurement of soil nitrogen mineralization rates in the field or on the comparative evaluation of mineralization rates as measured in the laboratory and in the field. Anaerobic incubation tests have shown potential as indexes for soil nitrogen availability to rice in a large number of greenhouse pot experiments and a few field experiments. Improved incubation tests should be devised by considering the climatic conditions of a region, especially soil temperature. The anaerobic incubation method is quite versatile in that it is very responsive and amenable to ranges in temperature.

Research is also needed for the development of standardized methods for (1) determining the optimal time of soil sampling, (2) sampling soil (especially for submerged paddy fields after land-preparatory operations), (3) preparing soil samples for laboratory and greenhouse work, and finally (4) use in laboratory and greenhouse experiments. Recent work has revived interest in using organic matter (as measured by organic C and total N) as the index of soil nitrogen availability to wetland rice (Ponnamperuma, 1978; Ponnamperuma and Sahrawat, 1978; Sahrawat, 1980c, 1982d, 1983b). However, researchers usually have not obtained consistent results. It is known that both the quantity and the quality of organic matter affect the mineralization and availability of soil nitrogen. Little is known about the quality of organic matter (except for the C/N ratio) in wetland rice soils, which is indicated by our inability to answer simple questions even with our present knowledge about organic matter. For instance, (1) What are the criteria for characterizing the quality of organic matter in relation to its contribution to mineralizable nitrogen in submerged soils? and (2) How does the quality of organic matter affect mineralization and soil nitrogen availability to rice? More knowledge about the quality of organic matter, and especially about the fraction that contributes to soil mineralizable N pools, should improve our capability to use this simple index for predicting soil nitrogen availability to rice.

Considerable research efforts have been devoted to the development of chemical indexes for assessing available soil nitrogen in soils, but these indexes have not been tested extensively for rice soils. Ideally, chemical indexes that extract the soil organic nitrogen fraction, which is the source of mineralizable nitrogen through the biological process, should be satisfactory in assessing the nitorgen-supplying capacity of a soil. However, these conditions are usually not met and, in the case of many chemical indexes, their chemistry is not fully known. Alkaline permanganate digestion is the most extensively used chemical method, especially in India, for assessing the availability of soil nitrogen to rice. Recent knowledge about the chemistry of the method has shown that it exhibits a better potential for predicting soil nitrogen availability to wetland rice than to upland crops (Sahrawat and Burford, 1982). Simple models based on regression equations relating potentially mineralizable nitrogen (as measured by biological indexes) with chemical indexes and/or soil characteristics should be tested for their suitability to predict nitrogen availability to rice, since they have a sound basis (Stanford, 1977; Stanford and Smith, 1978; Sahrawat, 1983b).

In view of the diverse soil and climatic conditions (where rice is grown) that affect soil nitrogen availability, it is quite probable that a single index of nitrogen availability will not find universal acceptance. Research on nitrogen availability indexes for wetland rice soils compared to arable soils is still in infancy, and it is hoped that this article will stimulate research in this area which holds considerable promise for the efficient use of fertilizer nitrogen as well as for devising conservative soil management and cultural practices to regulate soil nitrogen release in connection with nitrogen uptake by the rice plant. International cooperation is desirable for extensive testing of the promising indexes of nitrogen availability.

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