Increasing Fertilizer Nitrogen Efficiency by Minimizing Losses in Tropical Wetland Rice Soils

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Numerous experiments have shown that the normal recovery of fertilizer nitrogen applied to the wetland rice crop is seldom more than 30 - 40%. Even with the best agronomic practices and strictly controlled conditions, recovery of fertilizar nitrogen by the rice crop seldom exceeds 60-68% (De Datta *et al* 1968, Prasad *et al* 1970, Prasad and De Datta 1979). Balance of most of the nitrogen is lost in the soil, or to the atmosphere by nitrification and denitrification, ammonia volatilization, immobilization, leaching, and ammonium fixation.

The energy shortage and costs of fertilizer processing have generated serious interest in the efficient use of plant nutrients for rice production in the developing world It is apparent that fossil fuels needed for the manufacture of nitrogen fertilizer are not unlimited. Research results during the era of abundant fertilizer supply and low cost must be reexamined to conserve energy, minimize farmers' costs of production, maximize his profits, and in some instances minimize pollution hazards. While learning to maximise grain yields at a high but profitable fertilizer rate, the maximization of yields at a low fertiliser rate should not be ignored if the results are to be meant for developing world in tropical Asia. Savings in fertilizer use, and hence, costs, could help millions of small rice farmers obtain a higher yield with less fertilizer. The low fertility of rice soils and the limited supply of inorganic fertilizers are serious constraints in increasing rice yields in South and Southeast Asia In the International Rice Research Institute (IRRI), for example, field studies suggest that insufficient fertilizer level or inefficient management of nitrogen fertilizers, particularly improper timing of nitrogen application, accounts for atleast 1 t/ha gap between farmers' actual yield and potential rice yields during the dry season. Even in the wet season when response to nitrogen fertilizer is lower, fertilizer's contribution to the yield gap is high (Fig 1). It appears that one-third to one-half the yield gap could be closed if all farmers applied high rates of fertilizers. This situation exists in most rice-growing countries in South and Southeast Asia Some farmers who use high fertilizer rates suffer low yields because of improper timing or method of nitrogen

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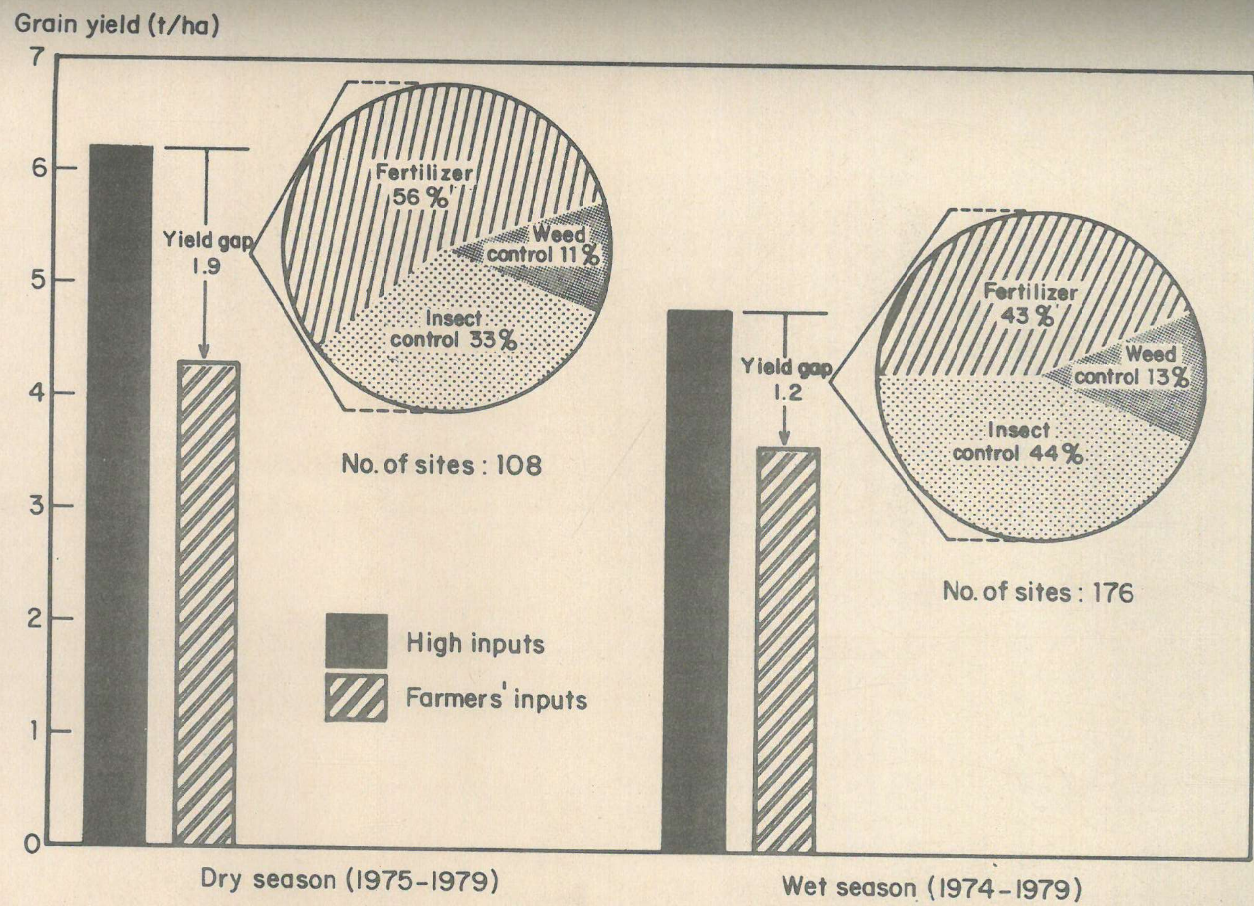

Fig. 1. Relative contribution of three inputs (fertilizer, weed control, and insect control) to the improvement of rice yields in farmers' fields in four Philippine provinces, 1974-1979. (S.K. De Datta and F.V. Garcia 1980, unpublished)

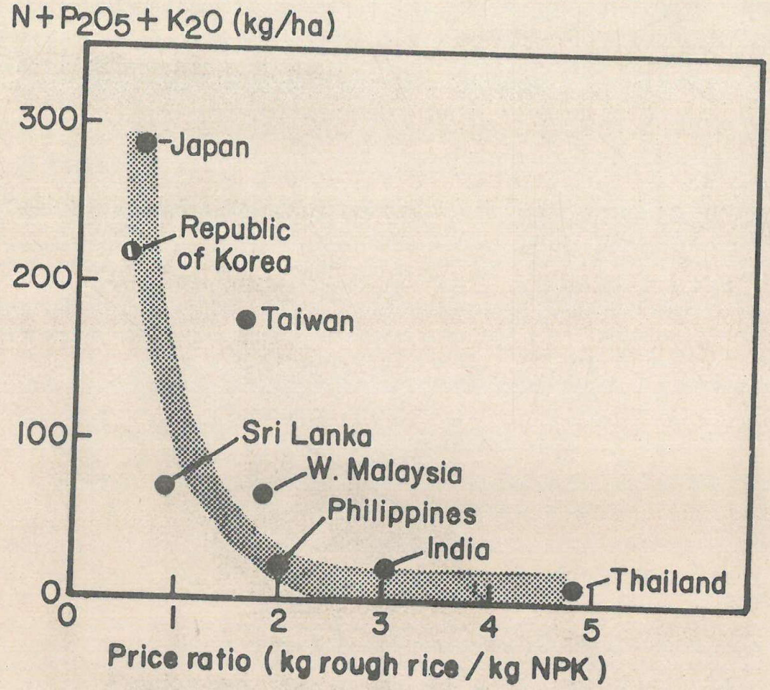

Fig. 2. NPK rates applied to rice and rice price-fertilizer price ratio (1972). (From Kemmler 1980)

application. The efficient use of fertilizer in rice is vital to increasing grain yields further than the levels attained by most farmers in tropical Asia.

Because of the importance of inorganic fertilizers for increasing rice production, there is a rapid expansion in the capacity for nitrogen fertilizer production in many South and Southeast Asian countries. As a result of increased fertilizer use, the world's grain production inventories in 1979-80 were at record levels, 20% higher than in the previous year and equal to about 17% of the world's grain consumption (Stangel 1980). Most of this improvement in food supply in general and rice supply in particular is due to increased use of fertilizers together with higher use of other production inputs such as water and improved seeds. An outstanding example of success story happened in India recently. In 1977, there was a great concern about an overriding shortage of food grains in India currently enjoys 18 million tons of food grains as a buffer stock (USDA 1979, Carlson and Aggarwal 1979). The favourable weather, increased supplies of credit, intensive promotion program, improved irrigation, and use of modern varieties in greater areas, all contributed to this sizable surplus However, the heavy use of fertilizers, brought about by improved fertilizer polices that increased availability and enhanced profitability for use by the farmers, was the most important single factor for the substantial food surplus in such a short time (Stangel, 1980). Another factor that must be favorable for increased rice production is the rice price fertilizer price ratio This ratio has been highly favourable in Japan, Republic of Korea, and Taiwan but unfavourable in India and Thailand (Fig. 2). These favorable price ratios between rice and fertilizer on a continuous basis provide incentives to farmers to increase rice yields through greater use of fertilizers. National average grain yield has been particularly high in east Asian countries (Japan, Korea, and Taiwan) due to favorable rice price-fertilizer price ratios, irrigation facilities, use of modern varieties, and high levels of inputs. Furthermore, unless high losses and low efficiency of nitrogen fertilizers are corrected, most of the potential benefits to increased use of fertilizer nitrogen may not be realized.

The paper deals with some basic and applied studies relevant to increased fertilizer nitrogen efficiency in wetland rice soils.

Basic Studies on nitrogen Losses

The magnitude of nitrogen loss and mechanisms of nitrogen losses should be clearly identified to develop suitable management practices for maximum efficiency in a given soil, climate, and water regime.

Minimizing ammonia volatilization losses from nitrogen fertilizer application

Agronomic factors such as N source, rate, and method of application have a profound effect on ammonium-N behavior in the soil (Mikkelsen and Finfrock 1957, Mikkelsen and De Datta 1979). Ammonia volatilization losses are difficult to measure directly in natural field conditions. Recent field studies (Mikkelsen *et al* 1978) evaluated the effect of fertilizer N source and placement on ammonia volatilization losses newely transplanted rice, where variable portions of either ammonium fertilizers or urea were broadcast or placed in the soil. The broadcast treatments were made into 5-8 cm of standing water and fertilizers were placed at 10-12 cm deep into the soil in the alternate hills of rice.

The neutral Madras clay soil (Aquic Tropudalf) contributed to the largest volatilization losses because diurnal fluctuations of the water pH ranged from 7.2 to 10.0. Nitrogen losses from top-dressed fertilizer applied 10 days after transplanting were about 20% with most of the ammonia lost in the first 3 days after application (Fig 3). Deep placement of fertilizer nitrogen virtually eliminated nitrogen losses and ammonia. Futhermore, losses were lower from acid Luisiana clay than from neutral Maahas clay (Mikkelsen *et al* 1978, Mikkelsen and De Datta, 1979).

Recent research on losses involved modified urea fertilizers such as slow-release sulfur-coated urea (SCU), deep-placed urea supergranules, and sulfur-coated supergranules. Figure 4 shows nitrogen loss through ammonia volatilization from the ordinary prilled urea and modified urea fertilizers developed by the Tennessee Valley Administration (TVA) and the International Fertilizer Development Center (IFDC) in the United States. Results show-that slow release and deep-placed nitrgen fertizers dramatically reduce ammonia loss.

Some estimate of the potential for ammonia loss can be obtained by simply measuring the concentration of urea and ammonium nitrogen in the floodwater after fertilizer application. Results of our recent outdoor drum experiment suggest that the pH values of floodwater after fertilizer application were higher with surface application of urea than with broadcast and incroporated SCU. pH values were 8.5 on the first day after surface application of urea, 9.0 on the fourth day, and peaked to 9.3 - 9.7 on the eighth day. With slow-release SCU, the pH started at 7.7 on the first day, then rose to 8.5 with the peak of <9.0 (Fig. 5). The average N content of floodwater was very high (180 μg N / ml) on the second day after urea application and dropped to lower values (40 μg N/ml) on the fourth day and to very low values onwards. The N content of floodwater after incorporation of SCU was very low (10 μg N / ml).

Results further suggest that modified urea products (SCU and supergranules) minimize ammonia volatilization loss in clayey soil with high CEC. In coarser-textured soils with low CEC, a slow-release nitrogen fertilizers is better than deep supergranules for minimizing nitrogen lossess as ammonia.

Movement and distribution of ammonium nitrogen

Recently, Savant and De Datta (1980) reported on the movement and distribution of NH_4^+ - N after deep placement of different forms of urea in a wetland rice soil. Results suggest that a distinct concentration gradient of NH_4^+ - N after deep placement of urea will probably exist for 4 weeks or more. Two advantages may be accrued from this situation. During the first 2 - 3 weeks after transplanting when the N requirement of the rice plant is low, it will be adequately met from the native N - pool or from the outer diffused zone of soil-urea reaction having low NH_4^+

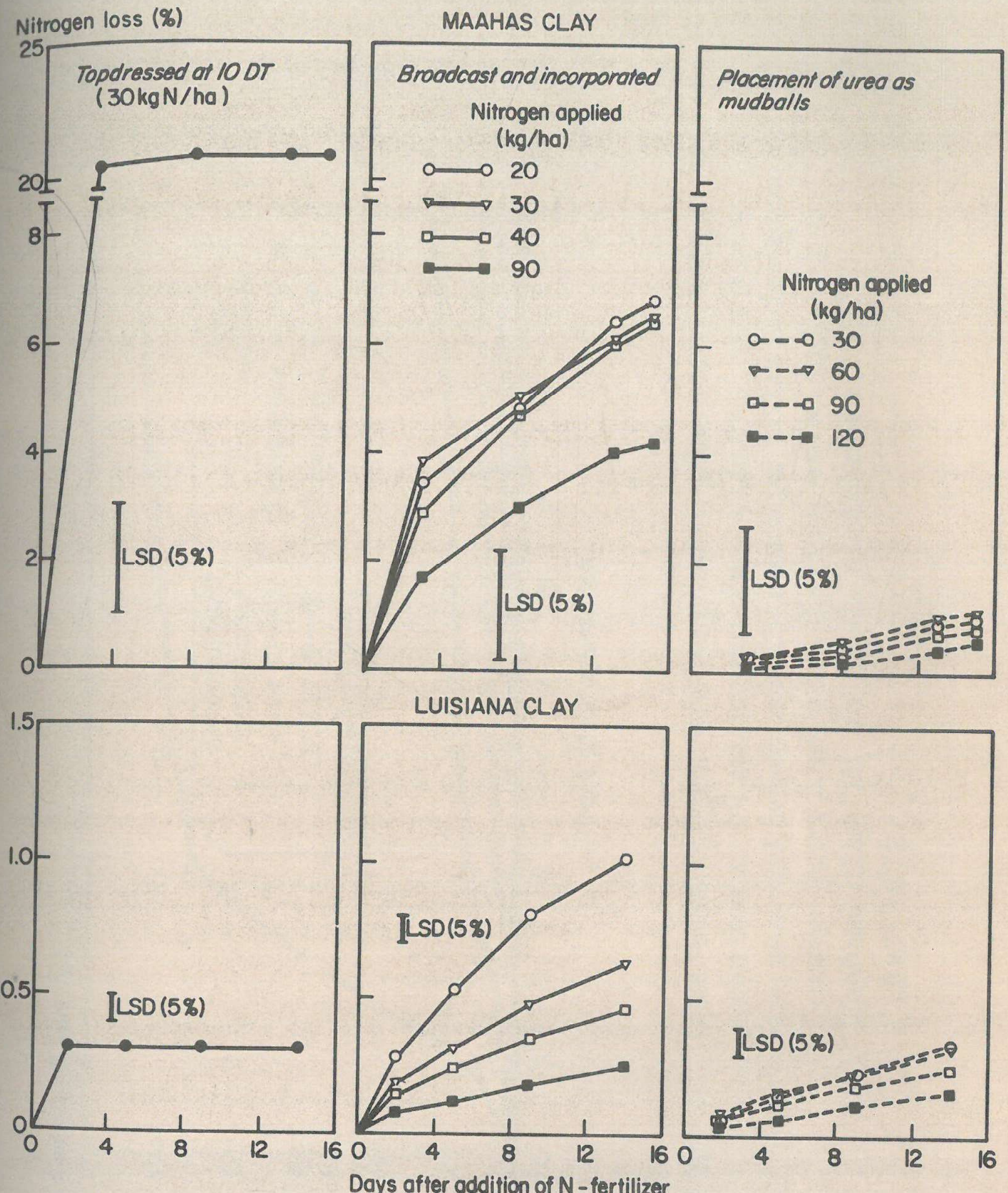

Fig. 3. Effect of time and method of N application on ammonia volatilization loss as percentage of total N application on Maahas and Luisiana clay. Field experiments. IRRI, 1977 dry season. (Adapted from Mikkelsen and De Datta 1979) DT = days after transplanting.

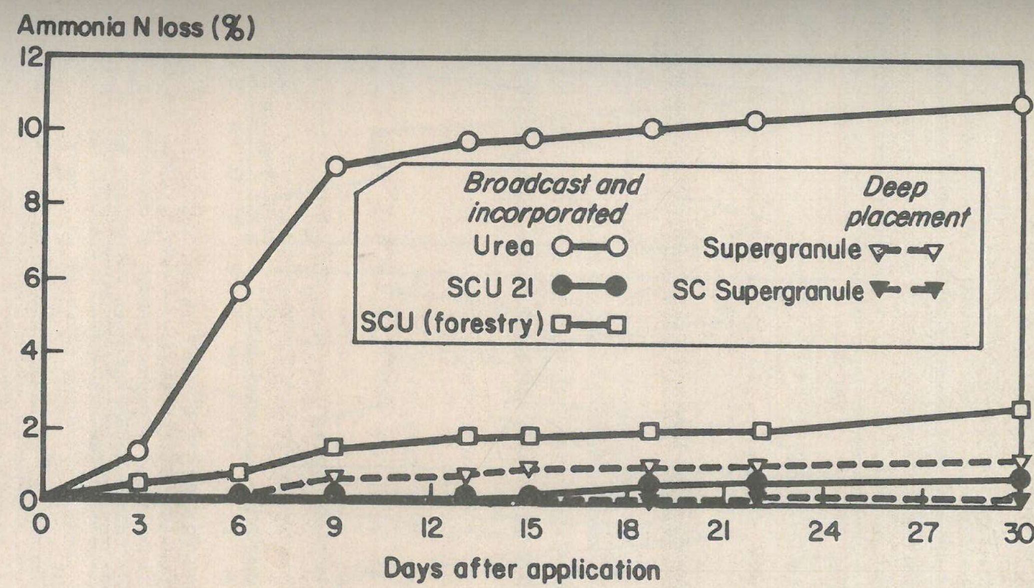

Fig. 4. The advantages of deep soil placement or treatment of nitrogen fertilizers are seen in the differences in ammonia volatilization losses from the urea fertilizers applied to Maahas clay in an IRRI greenhouse, 1978. (IRRI 1979)

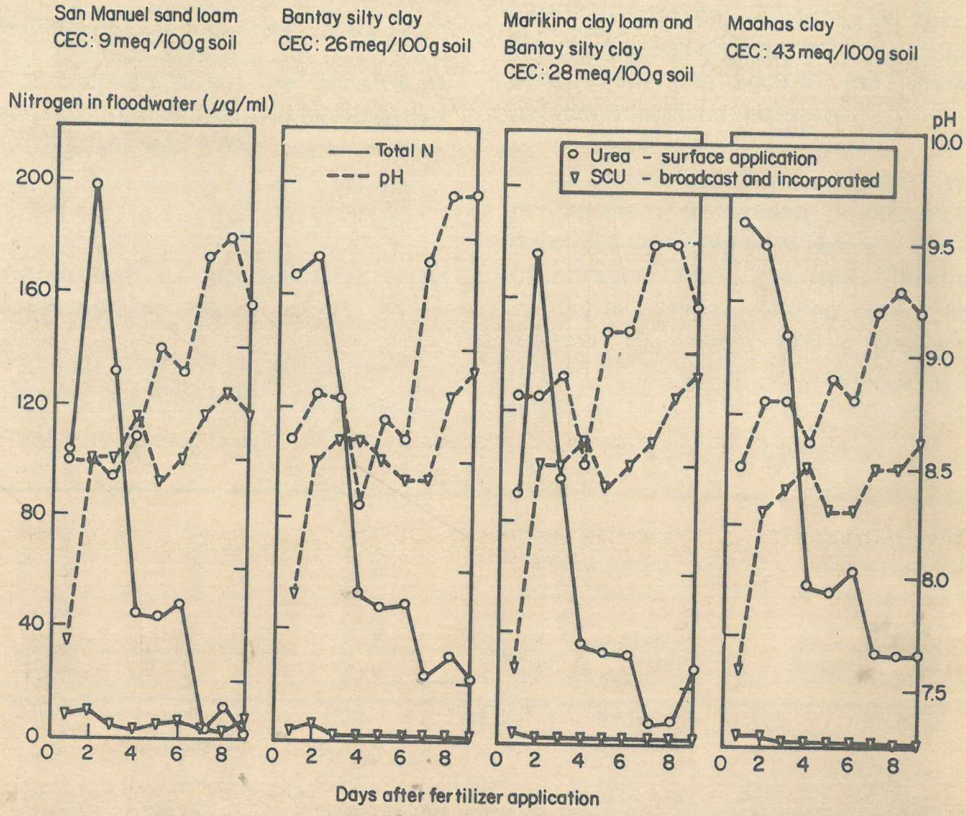

Fig. 5. Changes in urea-nitrogen + ammonium nitrogen concentration and pH of floodwater as affected by cation exchange capacity and texture of the soil. Large-drum experiment, IRRI, 1979 late dry season. (From S.K. De Datta and W.N. Obcemea, IRRI 1979, unpublished)

concentration, or from both. This is because the rice roots generally avoid proliferation through the soil-urea reaction zone of high NH_4^+ concentration gradient. However, with time, as a consequence of movement of NH_4^+, when the concentration gradient decreases, the plant roots may gradually begin to proliferate through the soil-urea reaction zone.

It is apparent that the benefits of deep placement of urea will be observed only when the NH_4^+ distribution pattern is undisturbed during the early period of growth (Savant and De Detta, 1980).

Management of nitrogen fertility of lowland rice soils

Almost 100% of the N absorbed by a rice crop in nonfertilized fields and up to 70% of the N in fertilized fields come from the soil. It appears then that organic nitrogen plays a major role as a sink for supplying nitrogen for the nutrition and grain production of wetland rice. Even with increased fertilizer nitrogen application the amount of soil nitrogen recovered in the harvested crop is often higher than in the absence of fertilizer nitrogen. This may be due to the priming effect suggested by Broadbent (1965) or as result of root growth by added fertilizer nitrogen.

To maintain high nitrogen fertility it is important to develop management practices that replenish heavy remov a of nitrogen from the soil - fertilizer system by a high - yielding crop. Table 1 shows that about 125 kg N/ha is removed by an IR8 crop producing 6.9 t grains and 6.2 t straw per hectare. This

TABLE 1. Nutrient removel of IR 8 yielding 6.9 t rough rice/ha [a], IRRI experimental farm, Los Banos, Philippines, 1979 dry season.

Nutrient element	Mineral content in straw (%)	Mineral content in grain (%)	Amount of mineral removed by the crop at harvest (kg/ha)		Amount of mineral removed per ton of rice production (kg)	
			Straw	Grain	Straw	Grain
N	0.62	1.26	38.2	86.9	6.2	12.6
P	0.07	0.18	4.3	12.4	0.70	1.8
K	2.28	0.27	140.4	18.6	22.8	2.7
Mg	0.18	0.10	11.1	6.9	1.8	1.0
Ca	0.33	0.05	20.33	3.4	3.3	0.49
Fe	0.02	0.0051	1.23	0.35	0.2	0.05
Mn	0.013	0.00262	0.80	0.18	0.13	0.03
Zn	0.001	0.00119	0.06	0.08	0.01	0.01
Cu	0.000237	0.000265	0.01460	0.0183	0.0024	0.00265
B	0.00459	0.001775	0.28	0.12	0.046	0.017
Si	8.10	1.18	499.0	81.4	81.01	11.80
Cl	0.20	0.16	12.32	11.04	2.0	1.60
S	0.0805	0.1122	4.96	7.74	0.805	1.12

a/Straw yield=6.2 t/ha.

amount of nutrient removal is the highest except for removal of silicon among all the nutrients removed by a modern variety with high yield. Replenishment of the nitrogen through fertilizer application, management of soil nitrogen by proper straw and water management practices and providing phosphorus in floodwater for proper growth of azolla and other nitrogen-fixing organisms will help obtain high yields on a sustained basis with limited quantity of inorganic fertilizer.

Management practices for high fertilizer nitrogen efficiency

There has been much attention to evaluating various nitrogen fertilizers for lowland rice in tropical Asia. It is apparent that urea is the main nitrogen fertilizer for rice and will remain so in tropical Asia. Ammoniated phosphate and urea will be the two major fertilizers for continental Asia with Japan using heavy amount of ammoniated phosphate.

Although the high analysis and price of urea make it the most popular fertilizer for rice, it is not an ideal fertilizer for the rice crop. Problems with urea include hygroscopicity, ready decomposition to ammonia and carbon dioxide, an increase in soil pH, and high losses. Recent advances in urea technology offer excellent opportunity to examine its effectiveness as a fertilizer for rice That technology includes granular urea, urea super-granules, slow- and controlled-release fertilizers, and use of nitrification inhibitors such as nitrapyrin and neem-coated nitrogen fertilizers.

No single urea fertilizer or urea fertilizer practice is now suited to all situations because of diverse climate and soil conditions. Widescale use of modified urea fertilizer or management practice will depend on agronomic research and further modification of the urea technology.

For efficient management of nitrogen fertilizers in wetland rice we are evaluating five concepts in our current research program:

1. Thorough broadcast and incorporation of nitrogen fertilizer during final land preparation and puddling operations;

2. Optimization of split application of nitrogen in relation to growth stages of rice;

3. Deep placement of nitrogen fertilizer in the reduced soil;

4. Use of slow-release or controlled release nitrogen fertilizer and

5. Combining the concepts of slow release and deep placement of nitrogen fertilizers.

Four of these concepts were evaluated in a single experiment during the 1980 dry season using the early-maturing variety IR 36 and intermediate maturing variety IR 46. Broadcast and incorporated prilled urea in Maahas clay soil (Alfisol) at 54 and 108 kg N/ha gave similar yields as split application of nitrogen with both IR 36 and IR 46 rices (Table 2). However, in all fertilizer treatments, IR 46 gave significantly higher grain yields than IR 36 rice. Broadcast and incorporated slow-release SCU at 27, 54, and 108 kg N/ha gave significantly higher yields than split application of prilled urea. The difference in yield between slow-release SCU and deep-placed urea supergranules were generally not significant except with IR 46 at 27 kg N/ha where SCU gave significantly higher yield than deep-placed urea supergranules (Table 2).

When the same three concepts (split application, slow release, and deep placement) were compared in another experiment at the IRRI farm using 10 early-maturing promising lines and 2-early maturing varieties (IR 36 and IR 50), the highest average productivity/ha per day (79 kg/ha) was obtained with IR 9729-67-3 and the least (33 kg/ha) with IR 8 which suffered from severe disease problems (Table 3). The differences in three concepts of nitrogen fertilizer application were negligible in all the rices tested. Most of the early-maturing rices suffered from lodging at different growth stages and no additional benefits were derived from 108 kg N/ha using SCU and deep placement of supergranules over split application of prilled urea. These results suggest that rates lower than 108 kg N/ha should be evaluated in a fertile Maahas clay if lodging of rice has to be minimized and show increased efficiency with better management of nitrogen fertilizers such as use of slow-release and deep-placed nitrogen fertilizers.

In the third experiment also at the IRRI farm, when new slow-release nitrogen fertilizers such as silica-polymer-coated urea (forestry grade) was

TABLE 2. Yields of IR 36 and IR 46 as affected by rates, forms of urea and methods of application. The Fourth International Trial on Nitrogen Fertilizer Efficiency in wetland Rice (INSFFER). IRRI, 1980 dry season.

Forms of urea	Nitrogen applied (kg/ha)	Method of application	Yield a/(t/ha)			
			IR 36	IR46	T-means	Difference
—	0	Unfertilized control	3.1g	3.6h	3.4	-0.4ns
Prilled	54	Broadcast and incorporated	4.5f	5.8de	5.2	-1.1**
Prilled	108	Broadcast and incorporated	5.6bcd	6.7b	6.1	-1.1**
Prilled	27	Split application	4.5f	4.7g	4.6	-0.3**
Prilled	54	Split application	4.8ef	5.4ef	5.1	-0.5**
Prilled	108	Split application	5.8bc	6.7b	6.2	-0.9**
Sulfur coated (SCU)	27	Broadcast and incorporated	5.2de	6.1cd	5.6	-0.9**
Sulfur coated (SCU)	54	Broadcast and incorporoted	5.6bcd	6.7b	6.2	-1.1**
Sulfur coated (SCU)	108	Broadcast and incorporated	6.3a	7.7a	7.0	-1.4**
Supergranule	27	Deep placement	4.8ef	5.3f	5.0	-0.5**
Supergranule	54	Deep placement	5.4cd	6.5bc	6.0	-1.0**
Supergranule	108	Deep placement	6.0ab	7.3a	6.6	-1.3**
		V-means	5.2	6.0	5.6	

a In a column, means followed by a common letter are not significantly different at the 5% level.
*Significant at 5% level; **Significant at 1% level; ns=not significant.

TABLE 3. Field duration and productivity of ten early meturing IR rices as affected by methods of nitrogen fertilizer application. IRRI, 1980 dry season. (From S.K. De Datta and J.C. Calabio, unpublished).

		Grain yield (t/ha) a/						
		108 kg N/ha			150 kg N/ha			
Variety or line	ON	Split application	SCU B&I	Urea SG deep-placed	Split application	Av. yield (t/ha)	Field duration (days)	Av. daily yield (kg/ha)
IR 8	2.7f	3.5e	3.5d	3.6d	3.4f	3.3	101	33
IR 36	4.3bcd	5.8cd	5.8bc	6.0bc	6.0cde	5.6	84	66
IR 42	5.3a	6.7ab	5.8bc	6.5ab	6.9ab	6.2	108	58
IR 50	4.2bcde	6.4abc	6.2abc	6.4ab	6.6abcd	6.0	83	72
IR 9708-51-1-2	3.8cde	5.8cd	5.8bc	6.0bc	6.1bcde	5.5	76	72
IR 9729-67-3	4.6abc	6.9a	7.0a	7.1a	7.3a	6.6	83	79
IR 9752-71-3-2	3.7de	6 3abcd	6.6ab	6.6ab	6.7abc	6.0	81	74
IR 10179-2-3-1	3.5de	5.4d	5.5c	5.6c	5.6e	5.1	76	68
IR 13204-3-3-3-2	3.5de	5.8cd	5.8bc	6.1bc	6.1bcde	5.5	76	72
IR 19728-9-3-2	3.4ef	5.7cd	5.7c	5.8bc	5 9cde	5.3	77	69
IR 19743-25-2-2	4.8ab	6.0bcd	5.9bc	5.9bc	6.1bcde	5.8	77	75
IR 19746-28-2-2	3.8cde	5.6cd	6.2abc	6.1bc	6.4bcde	5.6	76	74
IR 19759-17-3-2	4.6abc	6.3abcd	6.0bc	6.5ab	6.4bcde	6.0	77	77
IR 19819-31-2-3	3.6de	5.5d	5.6c	6.0bc	5.8de	5.3	77	69

a/ Av. of four replications. In a column, means followed by a common letter are not significantly different at 5% level by DMRT: B&I=Broadcast and incorporated during final land preparation, SCU=Sulfur-coated urea broadcast and incorporated during final land preparation; Urea SG=Urea supergranules deep-placed.

TABLE 4. Effect of forms of urea and application methods on the grain yield of IR 50. IRRI, 1980 dry season. (From S. K. De Datta and J. C. Calabio 1980, unpublished)

Treatment	Grain yield** (t/ha)
No fertilizer nitrogen	4.2 c
87 kg N/ha	
Polymer-coated urea (forestry grade)*, broadcast and incorporated	6.9 a
Sulfer-coated urea (forestry grade)*, broadcast and incorporated	6.4 ab
Sulfur-coated urea supergranules*, placement at 10-12 cm deep	6.2 ab
Prilled urea, plowsole method	6.2 ab
Prilled urea, best split	5.8 b

** Av of four replications. In a column, mean followed by a common, means followed by a common letter are not significantly different at the 5% level by Duncan's Multiple Range Test.

* Provided by the International Fertilizcr Development Center, Muscle Shoals, Alabama, U.S.A.

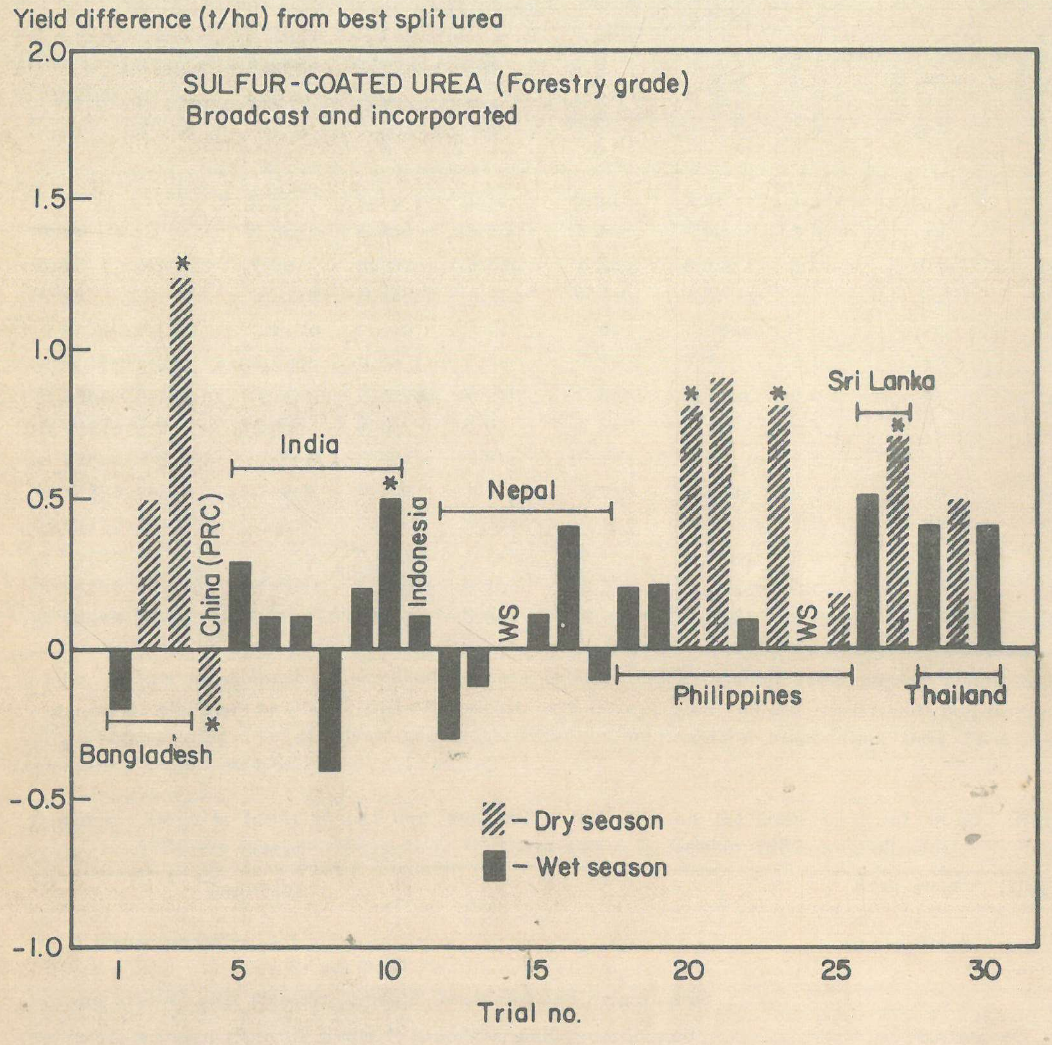

Fig. 6. Significant increase or decrease in grain yield in 30 trials with N (av of 2 rates) as SCU (forestry grade) broadcast and incorporated compared with urea applied in split doses at the same rate. The Third International Trial on Nitrogen Fertilizer Efficiency in Rice, INSFFER, 1978-1979. (IRRI 1980)

compared with forestry grade SCU, results appeared highly promising for an alternative source of coating other than sulfur. In fact, polymer and silica-polymer-coated forestry grade urea was the only treatment that gave significantly higher yield than prilled urea applied in split doses (Table 4) Deep-placed prilled urea using IRRI-designed plowsole applicator gave similar yield as slow-release nitrogen fertilizer

Multilocation trials

In multilocation trials during the dry season under the International Network on Soil Fertility and Fertilzer Evaluation for Rice (INSFFER), forestry grade SCU gave significantly higher yield in five cases (4 in the dry season and 1 in the wet season)and significantly lower grain yield (in the dry season) in one case than urea applied in split doses (Fig. 6). Results further suggest that supergranule urea placed at 10-12 cm soil depth gave in general similar results as SCU when compared with best-split urea (IRRI 1980).

A number of complementary practices have been proven to increase fertilizer nitrogen efficiency in wetland rice. For example, Roger *et al* (1980) recently showed that the placement of urea supergranules at 10 - 12 cm soil depth does not disturb the natural nitrogen-fixing algae flora. Nitrogen produced by the blue-green algae adds as a bonus associated with the use of urea supergranules, wheras broadcast application of urea increases the growth of green algae which is deleterious to the nitrogen economy of the rice soil-water system. Green algae do not contribute to the nitrogen economy of rice but raise the pH of floodwater thereby causing high loss of nitrogen as ammonia through volatilization.

In another study, the effects of plant density and plant geometry on grain yield of rice were evaluated. Results suggest that without fertilizer nitrogen and at low rates of fertilizer nitogen (> 60 kg N/ha) rice yields increased significantly with increased plant density. At the high level of applied nitrogen in the dry season (120 kg N/ha grain yield increased as the plant density was increased to a certain level beyond which the yield decreased with increased plant density because of excessive lodging and plant competition (Nguu and De Datta 1979). These results suggest that closer spacings are desirable in farm situation where soil fertility and fertilizer rates are often less than optimum.

Other cultural practices such as proper water management, and weeds and insect control emphasize the interaction between fertilizer nitrogen response and good agronomic practices and are adequately discussed in earlier papers (De Datta and Malabuyoc 1976, Prasad and De Datta 1979, and De Datta and Craswell 1980).

Rice straw and compost may serve as important sources of plant nutrients in addition to their other benefits. The benefits of rice straw in fertility management in rice soils are:

* it contains 0.6% N, 0.07% P, 2.28% K, and 8% Si (Table 1) in addition to other plant nutrients,

* straw incorporation may increase up to 57 kg N/ha per season when averaged for 14 cropping seasons (Ponnamperuma, 1980), and

* it adds organic matter, which encourages nitrogen fixation by bacteria and algae.

Straw compost increased the grain yield in 5 out of 13 croppings in 1 IRRI experiment (Castro *et al* 1980).

These results suggest that integrated nitrogen management practices for rice should be developed to maintain and, in some instances, increase nitrogen fertility of rice soils. (To increase the nitrogen fertility of rice soils) it is important to increase the efficiency of biological nitrogen fixation by the use of organic nitrogen sources such as composts and rice straw, the use of optimum organic practices such as proper water, weed, and other pest control, and the use of optimum plant spacing. Maximization of limited amount of inorganic fertilizer nitrogen would, never theless, still play the key role in increasing grain yields and production of wetland rice in tropical Asia.

In these total efforts in increasing nitrogen fertility of wetland rice soils and nitrogen fertilizer efficiency, research and development strategies that will involve massive undertaking by scientists from different organisations and countries have been proposed (De Datta and Craswell 1980).

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