AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

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1. SUBJECT CLASSIFICATION	A. PRIMARY: Agriculture
	B. SECONDARY: Soils and Fertilizers

2. TITLE AND SUBTITLE
A Summary of Research to Increase The Efficiency of Chemical Fertilizers

3. AUTHOR(S)
Brady, N.C.; Yoshida, Tomio; and De Datta, S.K.

4. DOCUMENT DATE	5. NUMBER OF PAGES	6. ARC NUMBER
July 1974	23p.	ARC 633.18072-B812

7. REFERENCE ORGANIZATION NAME AND ADDRESS
The International Rice Research Institute
Los Banos
Laguna, The Philippines

8. SUPPLEMENTARY NOTES (*Sponsoring Organization, Publishers, Availability*)

9. ABSTRACT

The development and dissemination of fertilizer-responsive varieties of wheat, rice and other cereals has encouraged steady increases in the use of fertilizer in the developing world. Fertilizer-responsiveness is a key factor in differentiating among the traditional rices and the new high-yielding varieties. Only where at least modest levels of fertility are present, do yield differences between the new and the old become significant. Without fertilizer, the new varieties yield a little better than the old. But with fertilizer, their yield potential is often double or even triple that of the traditional varieties (Figure 1). This fact has encouraged fertilizer usage up to rates of 100 or 150 kg/ha by some of the more progressive rice growers, including some small farmers.

Current high prices and low supplies of fertilizers will likely limit, for at least the next two years, the quantity of fertilizers, and especially nitrogen, needed to increase rice yields. This has led to increased interest in methods of maximizing yields using low rates of fertilizer.

10. CONTROL NUMBER	11. PRICE OF DOCUMENT
PN-AAB-106	

12. DESCRIPTORS	
Rice, Wheat, Other Cereals, High Yielding Varieties, High Prices, Low Supplies, Nitrogen	13. PROJECT NUMBER: 931-17-130-443
	14. CONTRACT NUMBER: AID/CSD-2541
	15. TYPE OF DOCUMENT: Research Study

AID 590-1 (4-74)

A SUMMARY OF RESEARCH TO INCREASE THE EFFICIENCY OF CHEMICAL FERTILIZERS[1]

The development and dissemination of fertilizer-responsive varieties of wheat, rice and other cereals has encouraged steady increases in the use of fertilizer in the developing world. Fertilizer responsiveness is a key factor in differentiating among the traditional rices and the new high-yielding varieties. Only where at least modest levels of fertility are present, do yield differences between the new and the old become significant. Without fertilizer, the new varieties yield a little better than the old. But with fertilizer, their yield potential is often double or even triple that of the traditional varieties (Figure 1). This fact has encouraged fertilizer usage up to rates of 100 or 150 Kg/ha by some of the more progressive rice growers, including some small farmers.

Current high prices and low supplies of fertilizers will likely limit, for at least the next two years, the quantity of fertilizers, and especially nitrogen, needed to increase rice yields. This has led to increased interest in methods of maximizing yields using low rates of fertilizer.

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[1] Prepared by N. C. Brady, Tomio Yoshida and S. K. De Datta, The International Rice Research Institute, to provide information on fertilizer efficiency for the Technical Advisory Committee of the Consultative Group for International Agricultural Research, July 10, 1974

Studies at The International Rice Research Institute (IRRI) since its beginning have dealt with the response of rice to fertilizer. During the past two years, these efforts have been focused on techniques of increasing rice yields using low fertilizer rates. Work at IRRI and elsewhere has identified some practices which, if followed, will increase markedly the efficiency of applied fertilizer.

Modern versus traditional varieties

Contrary to popular belief, the high-yielding tropical varieties developed at IRRI and elsewhere are not wholly dependent upon fertilizers. These semi-dwarf, erect, high-tillering varieties generally yield more than the traditional tall tropical rices even when no fertilizers are applied. In one set of experiments in the Philippines performed at four locations for a period of 5 years, two new varieties out-yielded an old by an average of at least 0.6 tons per hectare (see Table 1). While this difference widened as the fertilizer rate was increased, even with low fertilizer applications, the advantage of the new varieties has been demonstrated (Figure 1).

Response to nitrogen, phosphorus and potassium

Under paddy conditions in the tropics, rice yields are more commonly limited by a lack of nitrogen than by that of any other element (see Table 2) However, where the crop removal is high under intensive cropping with high-yielding varieties or where the available soil nutrient levels are very low, there is generally some response to phosphorus and potassium (Table 3). Likewise, deficiencies of other elements such as zinc may limit yields even where NPK fertilizers are applied. Large areas of of zinc-deficient soils have been identified in the Philippines and India and are likely present elsewhere.

Fate of fertilizer nitrogen applied to rice soils

Much of the fertilizer nitrogen applied for a rice crop is not taken up by plants. Depending upon the type of soil and the method and time of fertilizer application, 20 to 60 percent of fertilizer nitrogen utilization by the crop during a given growing season will vary from 20 to 60 percent of the nitrogen added. Some of the remainder is combined by soil microorganisms with organic forms in the soils and may be releaed later for crop uptake. Some is lost to the atmosphere by the biological process of denitrification. In figure 2 is shown the fate of fertilizer nitrogen under flooded and upland conditions in IRRI experiments in the Philippines. Obviously, the challenge is to reduce to a minimum the losses of fertilizer nitrogen and to increase the efficiency of fertilizer nitrogen usage by the rice crop.

Timing and placement of fertilizer nitrogen

There are two stages in the growth of transplanted rice at which the efficiency of fertilizer nitrogen utilization appears to be highest. One is soon after transplanting to encourage maximum tillering. The second is at panicle initiation to encourage a maximum number of panicles and grain numbers per panicle. The efficiency of nitrogen utilization applied at four stages of growth of three IRRI lines is shown in figure 3. The two most critical stages for nitrogen utilization are illustrated. For the two lines with medium maturity requirements (124 and 127 days), fertilizer nitrogen supplied just before panicle initiation gave highest efficiency of use. The shorter seasoned line showed highest efficiency after basal application but responded well to the treatment applied just before panicle initiation.

When properly timed, split applications of nitrogen fertilizer have given higher yields than where all the fertilizer is applied as a basal treatment. In one experiment at the IRRI farm during the 1973 dry season, split applications of urea yielded 1.4 t/ha more rice than did a single basal treatment applied at the same rate. An increase of 0.5 t/ha was obtained from split applications at a comparable experiment at the Maligaya station in Central Luzon.

The efficiency of fertilizer nitrogen use by two IRRI medium maturity varieties was greater for split applications than for a single basal application (Figure 4). A shorter-seasoned variety showed an advantage for the single basal treatment.

The effect of timing of application on the uptake of nitrogen by rice plants is shown in table 4. A higher proportion of the added nitrogen was absorbed by the plant at latter stages of plant growth. However, yield differences did not always correlate with differences in nitrogen uptake.

Placement of the basal nitrogen treatment for paddy rice greatly affects its efficiency. Experiments at IRRI as early as 1966 showed a recovery of fertilizer nitrogen of 68 percent when the fertilizer was placed at a 10 cm depth. This compares to a 28 percent recovery when the fertilizer was broadcast and incorporated by harrowing. These results are in accord with those of other rice researchers who have found losses to be as high as 60 percent of the fertilizer applied (see Table 5).

Deep-placed nitrogen fertilizer is apparently protected from microbiological oxidation. The urea and ammonium forms of nitrogen which are commonly used for rice are changed to nitrate in the upper layer of soil in the paddy (Figure 5). Nitrates are in turn subject to leaching and move downward in the soil to a reduced zone where microorganisms utilize the combined oxygen in the nitrate ion and release the nitrogen in the gaseous form. In table 6 are data showing the loss of nitrates even at depths of 2 centimeters below the soil surface. The denitrification was more pronounced where the soil had not been presubmerged in water before the nitrate was added. This process of denitrification accounts for most of the loss of nitrogen from rice soils.

Under rainfed paddy conditions, this loss of nitrogen is commonly more serious than in irrigated fields. Rainfed areas are often not under continuous flooding during the growing season, but rather suffer alternate flooded and unflooded conditions. If the soil is allowed to even partially dry out, the ammonium or urea forms of nitrogen are changed to nitrates. When the soil is resubmerged, reducing conditions prevail except in the top centimeter or so of soil. This results in denitrification and a consequent loss of nitrogen to the atmosphere. This loss is higher under conditions of alternate flooding and drying than where continuous flooding or continuous upland conditions prevail (see Table 7).

There appears to be considerable advantage in keeping the nitrogen fertilizer concentrated rather than dispersing it throughout the soil. In one experiment just completed, nitrogen was concentrated in "mudballs" (see Figure 2) to ascertain the extent of this advantage. When so concentrated, a 60 kg/ha treatment gave a higher yield than a 100 kg/ha treatment applied by broadcasting and then mixing with the soil (see Table 8). Greater efficiency from this mudball deep placement may be due to the fact that the nitrogen is better protected from microbiological changes including those which bind the nitrogen to soil organic matter. Experiments are being initiated to compare banded nitrogen fertilizer placement with broadcast applications.

Sources of nitrogen

For paddy rice, a large number of experiments have shown both urea and ammonium fertilizers to be satisfactory sources of nitrogen. Inhibitors of nitrification such as N serve /2-chloro-6-(trichloromethyl) pepidine/ and ST and AM (Japanese products), while effective in the laboratory, have generally not been effective in reducing the field loss of nitrogen from submerged rice soils. Sulfur-coated urea has been used in a number of trials and, in some cases, has proved to be superior to ordinary urea. Experiments at two locations in 1973 showed sulfur-coated urea to be equal or superior to ordinary urea when both were supplied as a basal treatment (Table 9). When split dosages were used, however, ordinary urea was as effective as sulfur-coated urea.

During the 1974 dry season, the effects of lower rates of nitrogen (60 and 100 kg/ha) applied as urea or sulfur-coated urea were determined for two disease and insect resistant rices (Table 10). The sulfur-coated urea was superior in both cases. The comparisons are for basal treatments of each chemical.

Nitrogen fixation

Under some tropical conditions, rice has been grown for centuries with little or no obvious means of supplying nutrients for the rice crop, the yields of which tended to remain fairly constant. Sources of nitrogen for these sustained rice yields were a mystery until the discovery was made that blue-green algae "fix" considerable quantities of nitrogen from the atmosphere, and release it to the water or soil for crop assimilation. Scientists have discovered recently a second important source of nitrogen for lowland rice -- fixation by micro-organisms growing in the rhizosphere of the rice plant.

Much research is yet to be done before there is a full understanding of the process of nitrogen fixation in rice paddies. Research already completed at IRRI and elsewhere, however, confirms that this process is an important one and of considerable practical importance. As much as 63 kg of nitrogen per hectare per cropping season may be fixed by this process under flooded conditions (see Table 11). The process is enhanced by the presence of the rice plant, much more nitrogen being fixed in planted as compared to unplanted soil. Nitrogen fixation under upland rice culture is much less important although it does occur to a limited extent.

Scientists are investigating this newly discovered nitrogen addition to soils and are attempting to better understand the process and means of encouraging it. Research has shown that nitrogen gas can move down the rice plant into the rhizosphere. The nitrogen gas content of rice soils is higher when planted to rice than when unplanted (Table 12). Apparently, root exudates of organic compounds encourage the growth of microorganisms near the root surfaces. This may account for the fact that fixation is much higher in the daytime than at night. Nitrogen gas transported down the rice plant is utilized by some of these micro-organisms which fix the nitrogen into combined forms which can be assimilated by the rice plant. Root zone nitrogen fixation is most rapid during the reproductive phases of plant growth (see Table 13). Thus, most of the nitrogen is fixed during a critical period of plant nutrition. Field response to phosphorus and potassium without nitrogen on plots do not show this P & K response when nitrogen is applied suggests that P & K may be important for the rhizosphere nitrogen fixing process.

From our research at IRRI, it would appear that five major factors affect rhizosphere nitrogen fixation:

1. the presence of N_2 fixing organisms,
2. an anaerobic environment,
3. a supply of carbon compounds,
4. a supply of nitrogen gas, and
5. an adequate supply of soil nutrients.

Research is under way to identify varietal differences in nitrogen fixation. Also, IRRI scientists are trying to determine the effects of soil and other environmental factors on this important process.

Weed control and fertilizer response

The response of rice to nitrogen fertilizers is markedly influenced by the adequacy of weed control. In farmer surveys in the Philippines and Thailand, there was a definite interaction between the on-farm control of weeds and profit from fertilizer use (see Table 14). Where weeds were not controlled, their competition with the rice for the fertilizer limited the economic response to fertilize; only where fields were controlled was there a highly profitable response from fertilizer.

These data emphasize the interaction among fertilizer response and good agronomic practices. Without the control of weeds, insects and diseases, little response from nitrogen can be expected. Likewise, factors such as variety selection, water management and seedbed management will influence yield responses to fertilizer.

Significance to small farmers

The wide range of soil and climatic conditions under which rice is grown makes it difficult to generalize on practices that will improve the efficiency of nitrogen use. However, under most environmental conditions, farmers can increase the efficiency of limited quantities of nitrogen fertilizers by doing the following:

1. Use a modern insect and disease resistant high yielding variety. Contrary to popular belief, these fertilizer responsive varieties generally yield more than traditional varieties even without fertilizer.

2. Keep the fields free from weeds so as to minimize competition for the added fertilizer. Surveys of farm operations show little response to nitrogen unless weed competition is removed.

3. For lowland rice, prevent the paddies from drying out once fertilizer has been applied. Alternate flooding and drying result in excessive losses of fertilizer nitrogen to the atmosphere.

4. Apply the fertilizer at critical growth stages of the rice plant. The most important times appear to be at transplanting and at panicle initiation. Split applications applied at these growth stages are generally most efficient.

5. <u>Basal nitrogen treatments for lowland rice should be applied in a band or mixed with the soil, not as a surface dressing</u>. Nitrogen losses to the atmosphere are high when surface dressings are made before rapid plant growth is occurring.

It is obvious that even small farmers can increase the effectiveness of nitrogen fertilizers. The few practices cited are simple and require inexpensive and easily applied management practices.

Table 1. Yield of a traditional variety (Peta) compared with two semi-dwarf improved varieties without nitrogen fertilizers at four locations (Data from S.K. De Datta).

Year	Rice yields (t/ha) (Average 4 locations)		
	Peta	IR-8	IR-20
1968	3.6	4.0	3.8
1969	3.6	4.8	4.7
1970	2.3	3.5	3.7
1971	3.0	3.3	3.4
1972	3.3	3.6	3.7
Average	3.2	3.8	3.9

Table 2. Effects of NPK fertilization on the grain yield of rice (avg of 3 varieties[a]) in the first crop and the 20th crop. IRRI, 1964 wet season and 1974 dry season. (Data from S.K. De Datta.)

Fertilizer treatment (kg/ha)			Yield (t/ha)	
			1964	1974
N	P_2O_5	K_2O	Wet season	Dry season
0	0	0	3.0	3.4
0	30	0	3.4	3.9
0	0	30	3.2	3.7
140[b]	0	0	3.7	7.2
140[b]	30	0	3.6	7.3
140[b]	0	30	3.5	7.2
140[b]	30	30	3.9	7.2
140[b]	30	30	3.2	7.1
LSD (5%)			0.9	0.4

[a]1964 wet season: Chianung 242, Milfor 6(2), and BPI-76. 1974 dry season: IR8, IR20, and IR26.
[b]Wet season N rate = 60 kg/ha.

Table 3. Mean effects of NPK fertilization on grain yields of flooded rice grown for 10 successive seasons at three Philippine experiment stations. IRRI-BPI cooperative long-term fertility experiments, 1968-72. (From S.K. De Datta)

Fertilizer (kg/ha)			Yield[a] (t/ha)						
			Maligaya		Bicol		Visayas		
N[b]	P_2O_5	K_2O	Dry	Wet	Dry	Wet	Dry	Wet	Avg
0	0	0	3.4	3.1	3.5	3.3	2.6	2.2	3.0
140/70	0	0	5.6	4.4	4.6	4.0	5.2	3.4	4.5
140/70	60	0	6.2	4.7	5.2	4.8	5.9	4.1	5.2
140/70	0	60	5.6	4.4	5.7	4.6	5.0	3.3	4.8
140/70	60	60	6.6	5.2	6.9	5.4	6.0	4.3	5.8
140/70	60	30+30[c]	6.7	5.1	7.1	5.6	6.4	4.3	5.9
Average			5.7	4.5	5.5	4.6	5.2	3.6	

[a]Average over 5-crop years (1968-1972) each with three varieties replicated three times.
[b]140 kg/ha N in the dry season; 70 kg/ha N in the wet season.
[c]Applied in split doses: basal + panicle initiation.

Table 4. Recovery of tagged fertilizer nitrogen applied at different growth stages of the rice crop (%). IRRI dry season, IR20. 1973.

Time of application	Plant	Soil	Lost
Basal (broadcast)	15.2	44.8	40.0
Basal (incorporated)	32.4	51.6	16.0
Maximum tillering (broadcast)	32.6	35.8	31.6
Panicle initiation (broadcast)	41.6	38.2	20.2
Booting (broadcast)	51.6	33.2	15.2
Flowering (broadcast)	50.2	34.0	15.8

Table 5. Losses from surface applied ammonium nitrogen as compared with deep placement of the fertilizer (From T. Yoshida, 1972).

Researcher	Percentage Loss
Mitsui, Japan (1956)	30-50
Abichandai and Patnaik, India (1959)	20-40
Mikkelsen and Finfrock, USA (1957)	25-35
Freid, FAO/IAE (1966)	10-60
Simsiman et. al., Philippines (1967)	56

Table 6. Effects of soil depth on the denitrification under submerged soil conditions (From T. Yoshida, 1972).

Soil Condition	Change in nitrate level after 12 days incubation (MgN/flask)		
	0.5 cm. depth	2.0 cm. depth	4.0 cm. depth
Presubmerged soil	+3.2	-7.6	-8.8
Soil not presubmerged	+0.8	-16.9	-42.6

Table 7. The influence of water management and crop residues on the gaseous loss of tagged fertilizer Nitrogen IRRI (From T. Yoshida, 1971).

Water management	Percent of added nitrogen lost	
	No rice straw	Rice straw added
Continuous submerged	18.2	12.5
Continuous upland	27.0	25.7
Alternate submerged/upland	39.0	33.8

Table 8. Grain yields of two insect and disease resistant rices, IR26 and IR2061-464-1, as affected by method and rate of urea application. IRRI, 1974 dry season (From S.K. De Datta).

Fertilizer rate (kg/ha)	Yield[1] (t/ha)			
	IR2061-464-1		IR26	
	Placed as mudball[2]	Broadcast & harrowed in	Placed as mudball[2]	Broadcast & harrowed in
Control	4.6 e		4.9 e	
60 kg/ha	7.8 abc	6.4 d	8.1 ab	7.1 cd
100 kg/ha	8.2 ab	7.3 bc	8.7 a	7.6 bc

[1]Means followed by a common letter are not significantly different at the 5% level. [2]Placed at the 10-12 cm soil depth.

Table 9. The yield of rice at 2 locations as affected by urea and sulfur-coated urea applied at the rate of 150 kg N/ha as basal and split applications, dry season 1973 (From S.K. De Datta).

Location and method of application	Rice yields[1] (t/ha)	
	Urea	Sulfur-coated urea[2]
(IRRI farm)		
Basal application	6.5 b	7.8 a
Split application[3]	7.9 a	7.9 a
(Farmer's field (Maligaya))		
Basal application	9.1 a	9.9 a
Split application	9.6 a	8.3 a

[1]At each location, means followed by a common letter are not significantly different at the 5% level.
[2]Seventeen percent dissolution rate in 2 weeks.
[3]Three doses: at last harrowing, 30 days after transplanting and at panicle initiation.

Table 10. Yields of two IRRI rices receiving basal applications of urea and sulfur-coated ureat at 60 and 100 kg/ha. IRRI, 1974 dry season (From S.K. De Datta).

Variety/line	Rate of nitrogen application (kg/ha)	Rice yields[1/] (t/ha) Urea	Sulfur-coated urea
IR26	0	4.9 f	
IR26	60	7.1 de	8.0 abc
IR26	100	7.6 bcd	8.7 a
IR2061-464-1	0	4.6 f	
IR2061-464-1	60	6.4 e	7.5 bcd
IR2061-464-1	100	7.3 cd	8.4 ab

[1/]Means followed by a common letter are not significantly different at the 5% level.

Table 11. Summary of estimated amounts of nitrogen fixed per cropping season in flood rice fields, IRRI farm (kgN/ha) (From T. Yoshida and Roncal, 1972).

Season	Nitrogen fixed in Soil	Water	Roots	Total
Wet	51.7	3.1	1.9	56.7
Dry	63.3	13.7	2.8	79.8

Table 12. Volume of nitrogen gas in planted and unplanted field soil (cc/100 gm. dry soil) (From T. Yoshida et. al., 1974).

Days after transplanting	Volume of nitrogen in Planted soil	Volume of nitrogen in Unplanted soil
2	0.74	0.98
6	0.85	1.71
34	6.38*	1.42
48	3.75*	1.56
77	2.91	2.10

*Significantly higher than unplanted soil at the 5% level.

Table 13. Movement of ^{15}N-enriched N_2 through rice plants into the rhizosphere (From T. Yoshida, IRRI, unpublished data).

Time (hours)	Percent ^{15}N in atmosphere of roots	
	Bonnet-73 variety Tillering stage	CI-9940 variety Flowering stage
0	0.36	0.37
20	0.36	15.1
40	0.36	19.5
60	0.39	20.2

Table 14. The interaction between the effects of fertilizer use and weed control on net returns. From surveys of farms in the Philippines and Thailand (Data from R. Barker).

Fertilizer use	Weed control	Net return ($/ha)	
		Philippines	Thailand
Low	Low	128	78
Low	High	121	76
High	Low	137	87
High	High	171	127

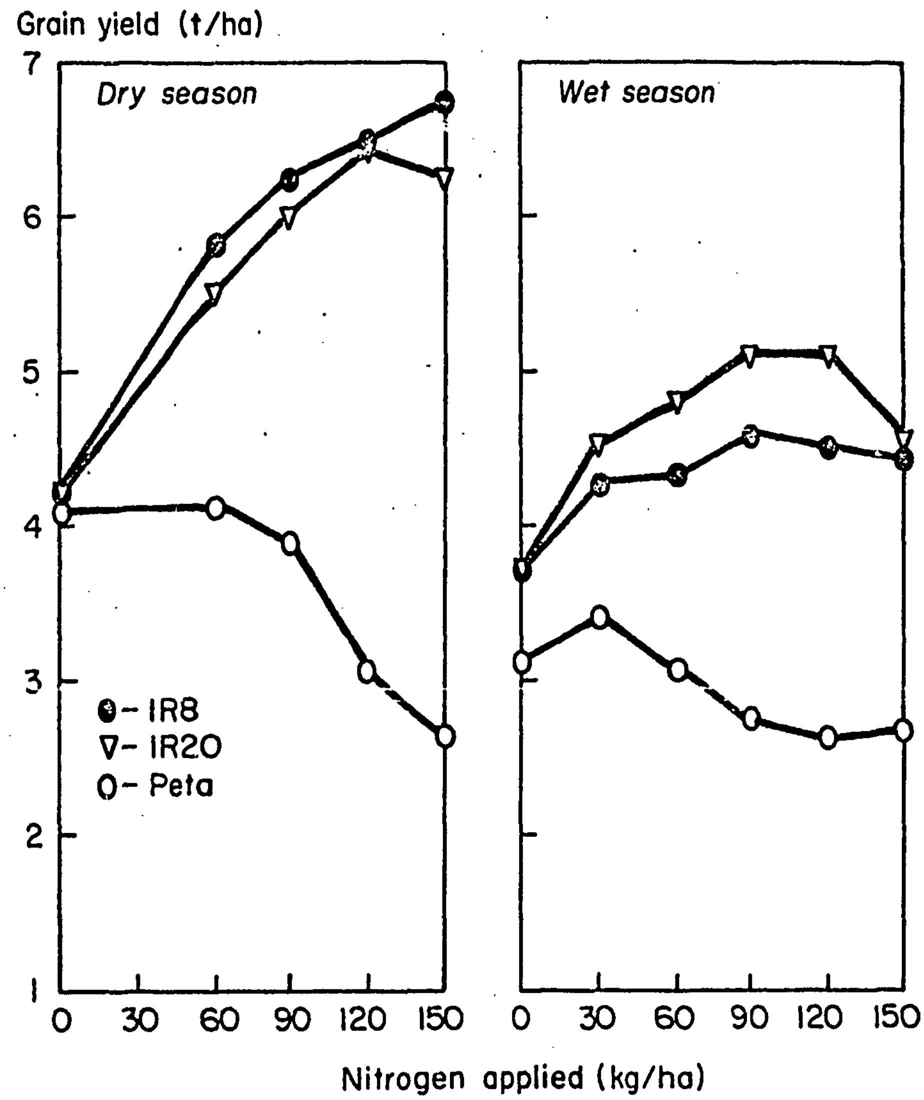

Fig. 1. Effect of levels of nitrogen on the grain yield of IR8, IR20, and Peta at four locations (IRRI, Maligaya, Bicol, and Visayas). Data are averages for 1968-73 cropping seasons. (From S.K. De Datta)

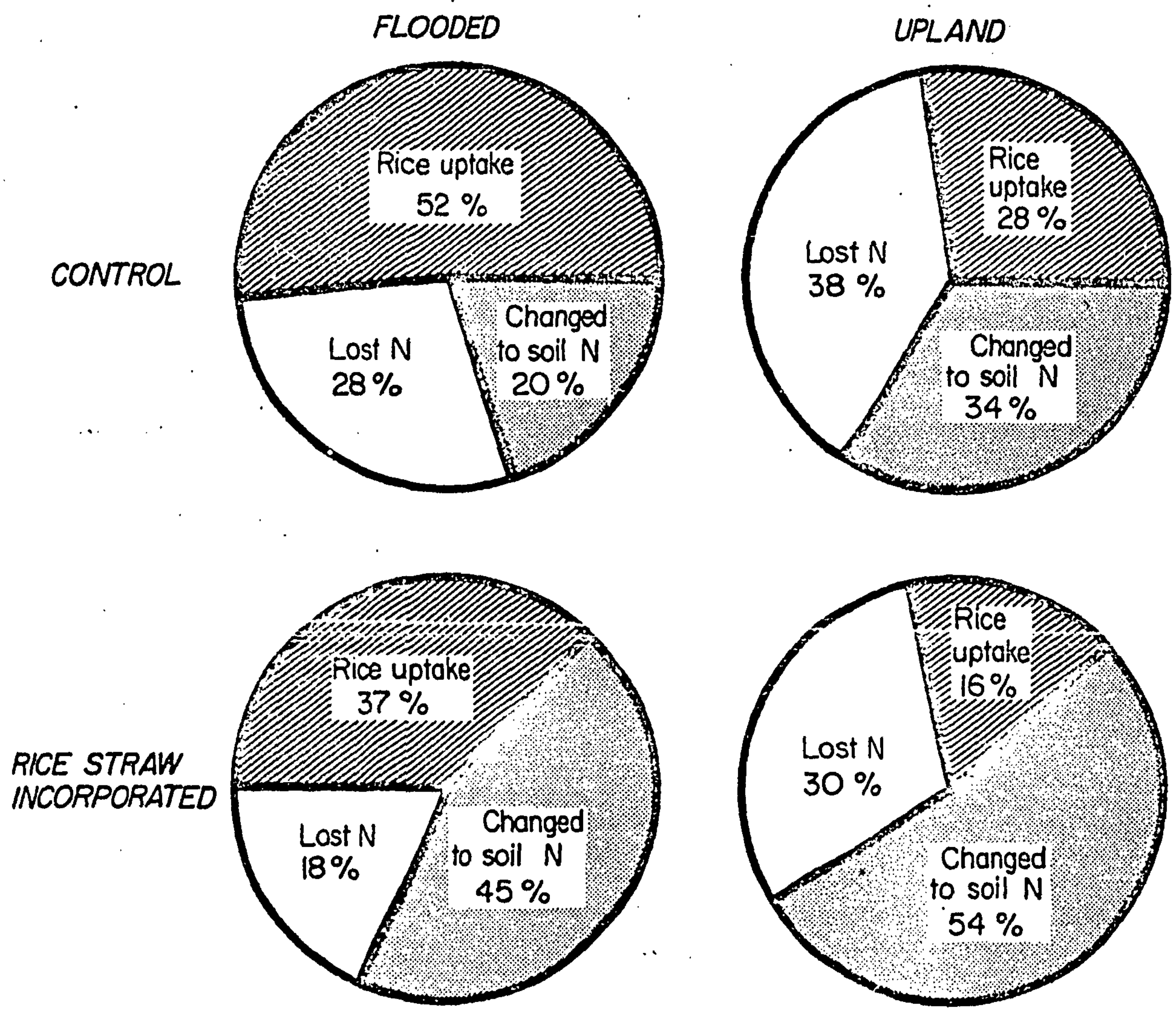

Fig. 2. Balance sheet of fertilizer N applied to rice soils. (From T. Yoshida)

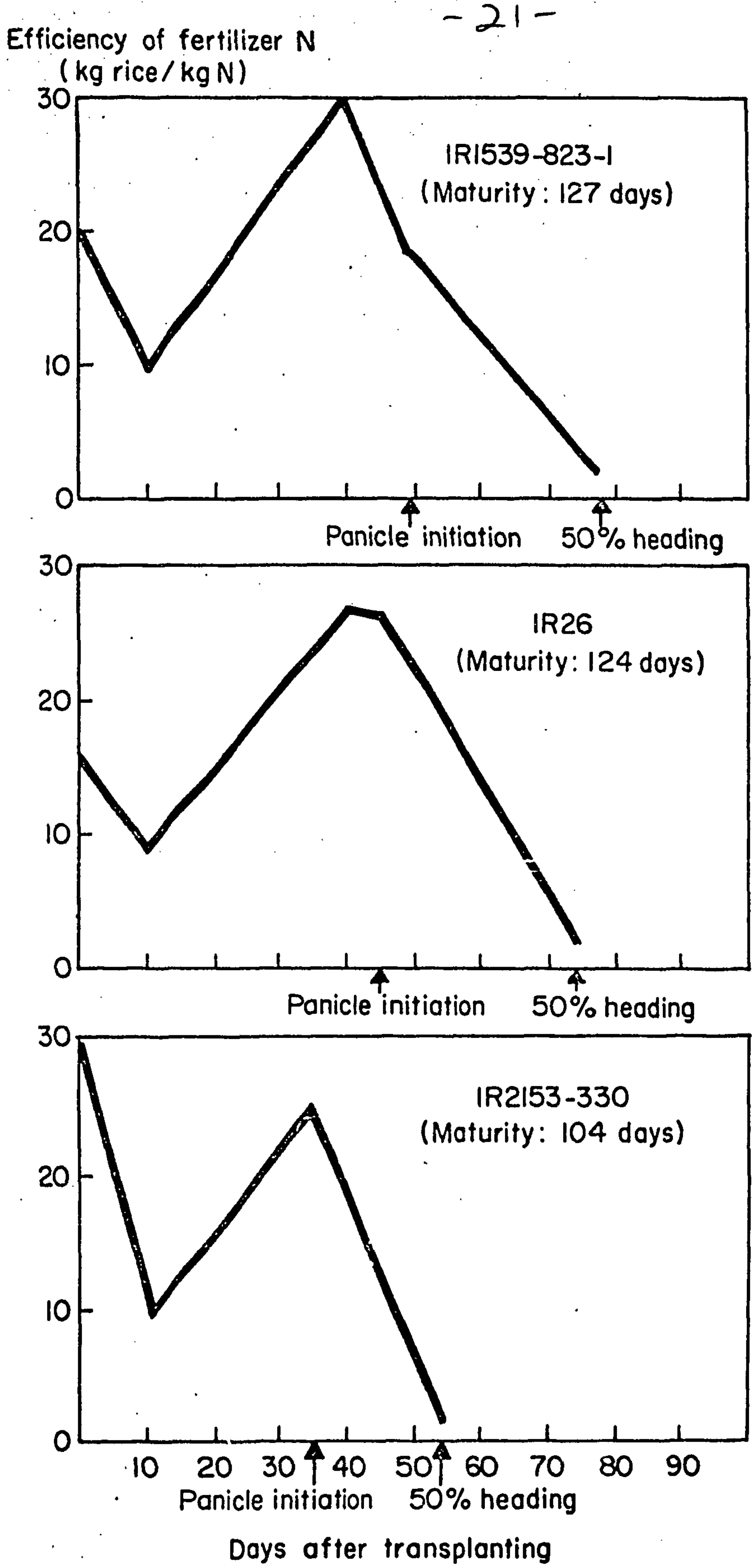

Fig. 3. Efficiency (kg rice/kg N) of 60 kg/ha N as urea applied in a single dose at different time to three rice varieties. IRRI, 1974 dry season. (From S. K. De Datta)

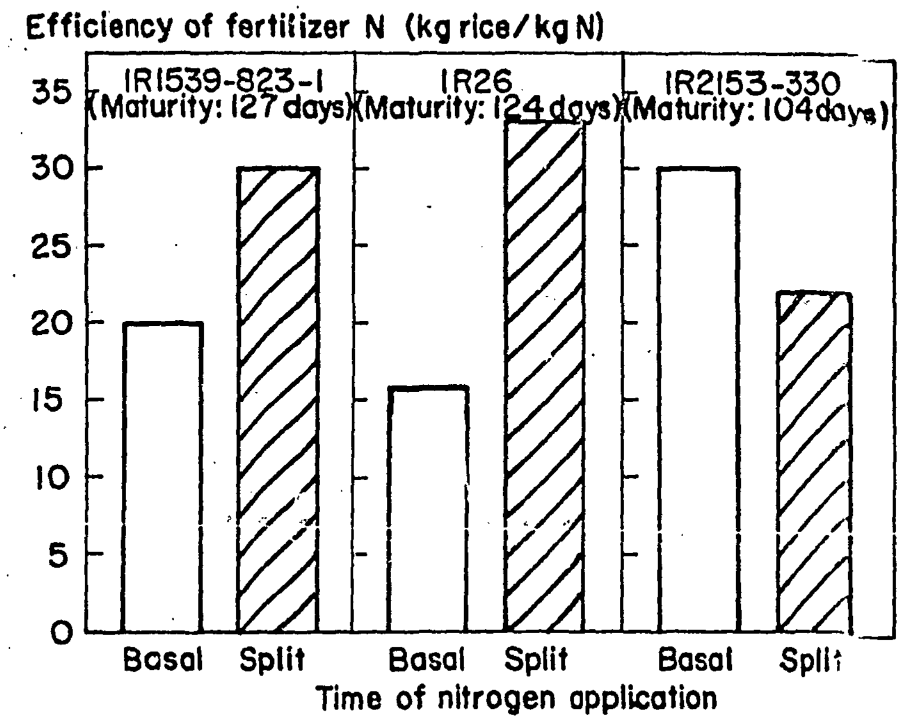

Fig. 4. Efficiency of 60 kg/ha N as urea as affected by basal and split application (basal = broadcast and incorporated; split application: for IR26 and IR1539-823-1 = 1/2 40 days after transplanting + 1/2 at panicle initiation; for IR2153-330 = 1/2 basal + 1/2 panicle initiation). IRRI, 1974 dry season. (From S. K. De Datta)

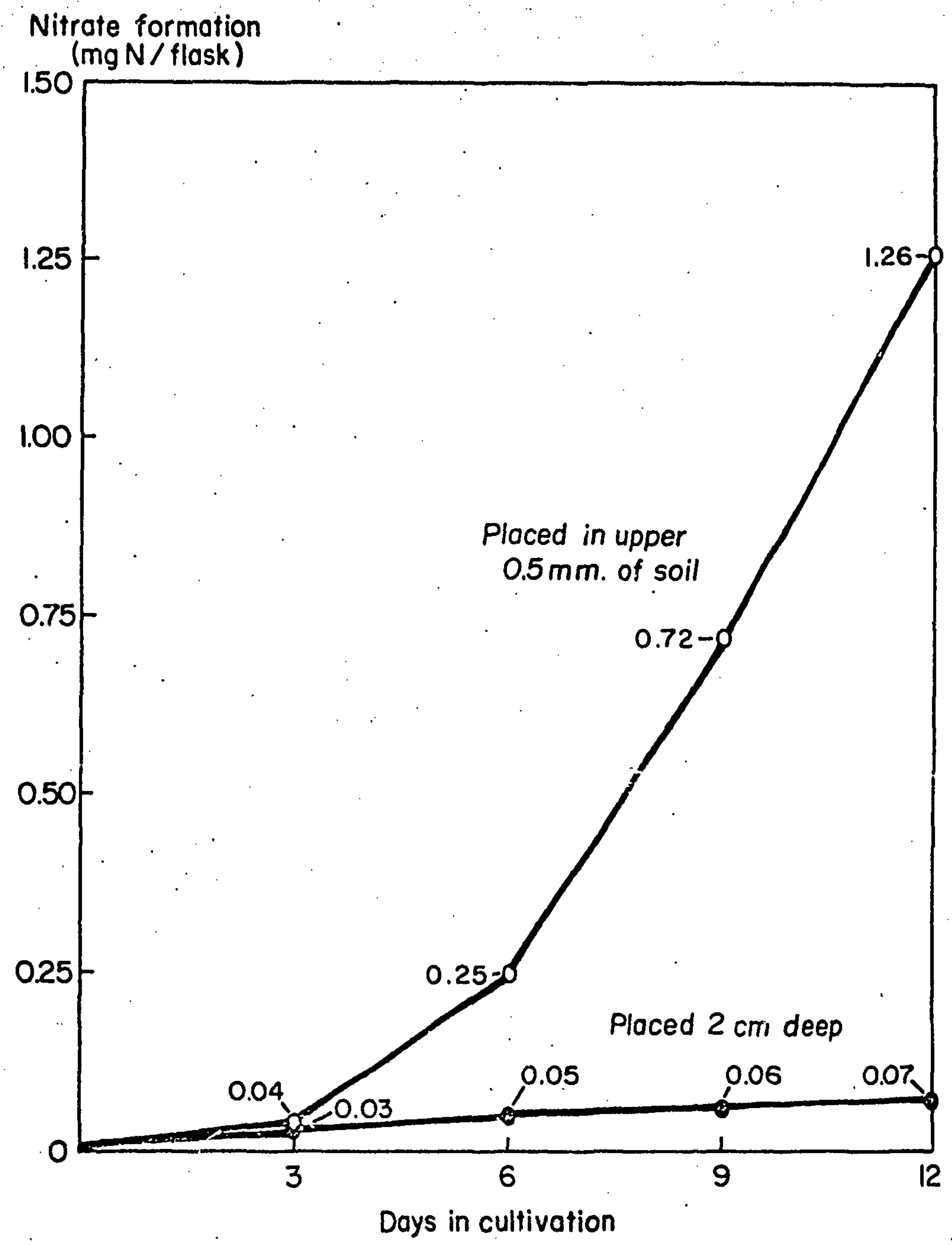

Fig. 5. Nitrates are formed rapidly when ammonium fertilizers are placed in the upper 0.5 mm. of soil but will form slowly only when the fertilizer is placed at 2 cm. and below (Data from T. Yoshida).