Efficiency of Nitrogen Fertilizers for Rice

Proceedings of the Meeting of the
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The responsibility for this publication rests with the International Rice Research Institute.

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COUNTRY REPORTS

Foreword

Since its inception in 1960, the International Rice Research Institute has supported work on management of the rice crop, a major part of which has been management of nitrogen fertilizers. In 1976, IRRI invited several countries and the International Fertilizer Development Center (IFDC) to work with it in the International Network on Fertilizer Evaluation for Rice (INFER), later renamed the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) when it was decided that both organic and inorganic fertilizers should be considered and long-term fertility trends should be monitored. Some 19 countries currently participate in INSFFER activities, which include common trials on fertilizer efficiency for rice and on organic manures and soil fertility maintenance, monitoring visits to observe field trials in cooperating countries and discuss common problems, and sharing of research results relating to fertilizer efficiency for rice. Training programs are also organized for staff of participating organizations.

In 1984, INSFFER cooperators decided to accept an invitation to visit Australia, where much relevant research on fertilizer efficiency for rice was being conducted, and where advanced rice production methods could be seen in the field. With support from the Australian Centre for International Agricultural Research (ACIAR), the New South Wales Department of Agriculture, and the Commonwealth Scientific and Industrial Research Organization (CSIRO), visits to the major Australian rice production region in the Murrumbidgee Irrigation Area and to Australian research organizations were arranged. A meeting to present papers on Australian rice farming and recent research results related to fertilizer efficiency in rice production and future INSFFER activities was also held. Funding for the meeting came from the Australian and Swiss Governments.

This volume contains the papers given at the meeting, which was held 10-16 April 1985 at the CSIRO Division of Irrigation Research, Griffith, New South Wales.

J.R. Freney, R. Wetselaar, A.C.F. Trevitt, and J.R. Simpson of the CSIRO Division of Plant Industry, Canberra, made the arrangements in Australia and were the technical editors of this volume. C.P. Mamaril, INSFFER coordinator, and S.K. De Datta, IRRI agronomist, helped co-ordinate preparations for the meeting. S.J. Banta of IRRI edited the volume and supervised its production.

M.S. Swaminathan
Director General
IRRI

Recommendations

In addition to the presentation and discussion of the papers, the annual INSFFER planning meeting was held, at which the following decisions were taken:

More attention will be given to green manuring. To enable a range of green manures to be studied, seeds of the stem-nodulated *Sesbania rostrata* and other legumes will be distributed to collaborators. Long-term fertility trials will be continued. More in-depth analysis arid interpretation of results of INSFFER experiments are needed. This can be promoted by

- distribution of INSFFER reports several months ahead of the planning meetings;
- assignment of participants to working groups, to consider results of experiments well in advance of a meeting and to report to the meeting on their analysis of the results;
- consideration and recommendation by the working groups of action on important related activities such as the establishment of new experiments, including a broader integrated nutrient management experiment; long-term fertility trials on rice; site characterization, and adoption and modification of the Fertilizer Capability Classification of Buol and Sanchez for ricelands; training; and interaction with extension services, machinery development groups, and others; and
- giving the annual planning meeting more time so that the reports of the working groups can be fully discussed and future action decided, if necessary following proposals formulated in working group meetings.

It was also agreed that a general theme might be associated with each monitoring tour and planning meeting. It was suggested that the next monitoring tour should be related to the theme of integrated nutrient management, and that it might appropriately be held in China, in September 1986. The subsequent meeting should be associated with the theme "maintenance of soil fertility (soil health)."

It was further agreed that conferences on specific topics are needed from time to time. An in-depth conference on nitrogen and rice would be timely within the next two years, at which recent advances in nitrogen research related to fertilizer use and the nutrition of the rice plant, and the implications of the research in terms of rice production, could be fully reviewed. Such conferences could be best held at IRRI.

These recommendations could be implemented by activating the Advisory Committee. Country representatives had been appointed at an earlier meeting and could be the convenors (chairpersons) of the working groups.

The training course should be continued. The Philippines and Thailand were interested in their azolla trainees having an opportunity to complete training at the Chinese National Azolla Research Center.

Trends in Production, Trade, and Use of Fertilizers: a Global Perspective

P.J. Stangel and G.T. Harris

Shortages in foreign exchange have produced unexpected declines in fertilizer consumption trends. Many countries were forced to reduce fertilizer imports or expansion plans. Many farmers had to decrease their P and K inputs to offset production expenses, and some governments had to reduce fertilizer subsidies. World N consumption was least affected, with an increase in total use of 5.6%/yr, compared with 10.1% for Asia. In 1983, world consumption was 66.8 million t with an expected increase to 70.2 million t in 1985, and 83.7 million t in 1990. P and K fertilizer consumption grew only at 2.8% and 2.2% annually, respectively, between 1973 and 1983. Although the use of these fertilizers in the developing countries doubled over that period, this growth was less than needed for sufficient food production. In 1973, the USA and Western Europe used about half of the total P fertilizer produced, but in 1983 they used less than one third, because of increased use of P in Asia and the USSR. In the last ten years, Latin America, the USSR, and Asia have increased their share of world K fertilizer consumption. For the 1982-90 period, the projected growth rates for P and K fertilizers are 3.8% and 4.3% a year, respectively. It is imperative that farmers receive the necessary incentives to use fertilizers, as this is the most effective way to increase food production.

The world fertilizer sector has been shaken by a series of events over the past decade that have altered the course of its development and will continue to be influential for many years to come. The purpose of this paper is to review the effects of these events on production, consumption, and trade of N, P, and K fertilizers for the period 1973-83; to look at the changes in the forms in which fertilizer is consumed; and to examine the future, including projections of consumption, of these three fertilizer nutrients through 1990.

The events and activities that have had a major impact on the fertilizer sector during the past decade have been both political and economic in nature. The most significant are the following:

- the oil embargo of 1973-74;
- the food and fertilizer crises of 1973-74;
- the Lima Declaration of 1975, in which a commitment was made to strengthen the fertilizer sector of developing nations;
- the rapid escalation in energy prices, particularly during 1979 and 1980;
- the economic recession that gripped the world during the early 1980s and which in some countries has not yet abated; and
- record crop production and low commodity prices since 1981.

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After the food and fertilizer crises of 1974, governments and the private sector conceived and implemented a number of strategies. In the developed countries, major strategies were designed to stimulate the agricultural and fertilizer sectors to produce fertilizer and food to feed a starving world. Programs were designed to plant "fence row to fence row" as part of an effort to achieve full production. This quickly led to large increases in food production and caused governments to try to reduce surpluses through programs such as the payment-in-kind effort in the USA. In the developing countries, on the other hand, strategies were based on the recognition that the solution to the food and foreign exchange problem lies with increased domestic production of food. Many countries launched programs to achieve self-sufficiency in basic commodities such as rice, wheat, and maize. They established fertilizer as the centerpiece in carrying out this strategy and adopted policies to stimulate its domestic production and consumption. These strategies were implemented through policies that included the use of fertilizer subsidies, government ownership of major production facilities, and government control of fertilizer prices and profits.

The impact that political and economic events and changes have had on the fertilizer sector during the past decade is reflected in the patterns of production, consumption, and use of N, P, and K fertilizers on a global and regional basis. Asia and Western Europe, in particular, have been affected by these events.

In this paper, the "fertilizer year" and regional delineations follow the Food and Agricultural Organization (FAO) convention. The latest fertilizer statistics available for individual countries are for 1982. Therefore, comparisons for individual countries were between 1972 and 1982. Projections for 1990 were interpolated from the 1988-89 and 1992-93 forecasts.

CONSUMPTION

Prior to 1974, annual world fertilizer consumption had increased each successive year since 1945. Since 1974, total fertilizer consumption has declined from the previous year in three of the past nine years (1974, 1981, and 1982) (5, FAO unpublished statistics). Of the three major nutrients, K has declined in consumption five times, P three times, and N twice from the previous year.

World consumption of N fertilizer benefited most by the events of the past decade. Total annual consumption, which in 1973 was 38.9 million t of N, grew rapidly throughout the decade; although it stagnated temporarily in 198 1 at 60.3 million t of N because of the world recession, it made a strong recovery and closed at 66.8 million t of N in 1983. Average annual compound growth was 5.6% for the IO-year period (Table 1). Neither fertilizer P nor K enjoyed such strong growth over the entire period.

World P fertilizer consumption, which in 1973 was 10.6 million t of P, grew at a rather unsteady rate during the decade before reaching 14 million t in 1983. Phosphate consumption grew at an average annual compound growth rate of 2.8% for the 10-year period (Table 1) in spite of actual drops in consumption over the previous year in 1974, 1981, and 1982.

Table 1. World fertilizer consumption by region, 1973 and 1983 (4.5, FAO unpublished data).

	Nitrogen				Phosphorus				Potassium			
Area	Quantity (10^6 t N) 1983	World share (%) 1973	World share (%) 1983	10-year annual growth rate (%)	Quantity (10^6 t P) 1983	World share (%) 1973	World share (%) 1983	10-year annual growth rate (%)	Quantity (10^6 t K) 1983	World share (%) 1973	World share (%) 1983	10-year annual growth rate (%)
North America	11.3	22.6	16.9	2.5	2.3	21.1	16.4	0.1	4.6	23.4	22.0	1.6
Latin America	2.7	4.4	4.0	4.8	0.8	5.7	5.6	2.8	1.0	4.4	4.7	3.3
Western Europe	9.8	19.1	14.8	2.9	2.2	24.8	16.0	−1.6	4.4	26.3	20.9	−0.2
Eastern Europe	5.3	9.8	7.9	3.4	1.5	11.6	10.3	1.9	2.8	16.1	13.4	0.1
USSR	10.3	15.9	15.4	5.2	2.5	11.2	17.9	7.6	5.1	17.6	24.4	5.6
Asia	25.3	24.9	37.9	10.1	3.7	16.1	26.6	8.0	2.5	9.2	11.8	4.9
Africa	1.8	2.8	2.7	5.2	0.5	2.9	3.4	5.1	0.3	1.5	1.6	3.0
Oceania	0.3	0.5	0.4	3.7	0.5	6.6	3.8	−3.3	0.2	1.5	1.2	−0.3
World Total	66.8	100.0	100.0	5.6	14.0	100.0	100.0	2.8	21.1	100.0	100.0	2.2

Growth in K fertilizer use over the 10-year period was even more sluggish. Starting from a base of 17 million t, K use peaked at 20.3 million t in 1978 and then steadily declined through 1982 to 18.9 million t before recovering sharply in 1983, when 21.1 million t was consumed (Table 1). The average annual compound growth rate was 2.2% for the 10-year period.

Regional trends

Growth rates have varied not only among nutrients but also among regions for a given nutrient. As a result, there have been marked changes over the past decade in each region's share of the world total of N, P, and K consumed.

Nitrogen. Asia consumed 38% of the world's fertilizer N in 1983. Other leading regions in 1983 were North America (17%), Western Europe (15%), and USSR (15%). Collectively they accounted for 85% of the N consumed in 1983 (Table 1).

Asia is not only the largest but also the fastest growing N market in the world. Starting from a base of 9.7 million t of N in 1973, average annual consumption in Asia grew at a steady rate of 10.1%, well above the world average of 5.6%, and reached 25.3 million t in 1983. As a result, Asia's share of the world N market rose 13% from 1973 to 1983. China, India, Pakistan, and Indonesia - where consumption bases were already large and annual growth rates of use were in excess of 14% for most of the decade - were responsible for the rapid growth in the Asian market. In contrast, N use rose at a much slower rate in North America (2.5%), Western Europe (2.9%), and Eastern Europe (3.4%). This caused a drop of 6%, 4%, and 2%, respectively, in their share of the world total. Growth rates of N use in most of the other regions approximated the world growth rate. Therefore their share of the world total changed little between 1973 and 1983.

Intensity of N use varied sharply by region (Table 2). Developed countries averaged 51 kg/ha, whereas developing countries used only 33 kg/ ha. European farmers used N fertilizer most intensively, averaging 105 kg/ ha in 1982, up more than 30 kg from 1972. Asia was second in intensity of use (50 kg/ ha), followed by North America (40 kg/ha), the USSR (39 kg/ha), Latin America (16 kg/ha), Africa (10 kg/ ha), and Oceania (6 kg/ ha).

Phosphorus. Phosphorus fertilizer consumption (excluding ground phosphate rock for direct application) has grown at markedly different rates in various parts of the world. For example, Western Europe and North America have been replaced by Asia and the USSR as the leading consumers of P fertilizer. This shift has been due to an absolute decline in P use in Western Europe, near stagnant demand in North America, and a sharp increase in use in the USSR and Asia (Table 1). Annual P use for the IO-year period dropped 0.9 million t for Western Europe (-1.6%) and rose only 0.1 million t for North America. On the other hand, annual use rose 3.0 million t in the USSR and 4.6 million t in Asia. As a result, Asia accounted for 27% and the USSR for 18% of the world total consumed in 1983. In contrast, Western Europe and North America each accounted for 16% of the world's total consumption in 1983, down markedly from the collective total of 46% achieved by these two regions in 1973.

Table 2. Fertilizer use for world, major geographic regions, and economic regions (4, 5).[a]

Region	N (kg/ha)		P (kg/ha)		K (kg/ha)	
	1972	1982	1972	1982	1972	1982
Eastern Europe (excl. USSR)	74	105	26	26	46	50
Western Europe	75	107	28	25	45	47
North America	34	40	10	8	16	17
USSR	24	39	7	11	12	18
Latin America	12	16	4	5	5	7
Asia (incl. China and Japan)	19	50	4	7	3	5
Oceania	4	6	12	10	5	4
Africa	2	10	1	3	1	2
Developed countries	38	51	12	14	21	23
Developing countries	14	33	3	5	2	3
World	25	41	7	9	11	13

[a] Arable land plus land in permanent crops.

Lesser shifts in P use were noted in other regions during the period. Consumption in Eastern Europe increased at 1.9% annually, slightly below the world average, and its share of the world total changed from 12% recorded in 1973 to 10% in 1983. Phosphorus fertilizer use in Latin America rose 2.8% (0.18 million t of P). Its share of the world total remained near the 5.7% established in 1973. Africa posted a 5.1% annual increase, but because of its low use base, accounted for only 3.4% of the world total in 1983. Oceania (mainly Australia and New Zealand) recorded a significant annual drop (-3.3%) in P use, and its share in world consumption also declined (Table 1).

Levels of P fertilizer use varied significantly by region (Table 2). Developed countries used P at the rate of 12 kg/ ha in 1972 and 14 kg/ ha in 1982. Although developing countries doubled their P use per ha from 1972, the average use of 5 kg/ ha in 1982 was less than half that of developed countries. Europe led all regions in intensity of P use, nearly 26 kg, ha in 1982. This level of use had changed little over the decade. On the other hand, levels of P use doubled in Asia and tripled in Africa. However, the levels of 7.5 kg/ ha (Asia), 5.2 kg/ ha (Latin America), and 2.6 kg/ ha (Africa) were still far below the rates used in Europe.

Potassium. Developed countries account for the major portion of K consumed in the world. In 1973 they were responsible for an astounding 90% of all K consumed (Table I). By 1983 the share had dropped only 6 percentage points to 84%. This was in spite of the fact that K use in developing countries grew at the rate of 7.5%/yr, whereas use in developed countries rose at only 1.4%/yr. There are many reasons why K use has not grown more rapidly in developing countries (10, 11, 12), the main ones being 1) lack of long-term research trials showing the importance of K in a high yield system fertilized mostly with N and P, 2) government policies that favor use of N and P over K, 3) limited credit, and 4) failure to promote K use by extension and industry agronomists.

Western Europe, the USSR, and North America consumed almost equal quantities of K in 1983 and collectively accounted for slightly more than two thirds (67%) of world K use. Eastern Europe accounted for 13%, Asia 12%, Latin America 5%, Africa 2%, and Oceania just over 1% of the 1983 world total (Table 1). The major growth market was the USSR, where K use increased at a 10-year annual average of 5.6%. Substantial growth was also recorded for Asia (4.9%), Latin America (3.3%), and Africa (3.0%). Potassium use remained the same in Oceania.

Intensity of K use varied (Table 2). Europe maintained very high levels over the 10-year period, averaging between 45 and 50 kg/ ha. Average K use in other regions was much lower: the USSR 18 kg/ha, North America 17 kg/ha, Latin America 6.6 kg/ ha, Asia 5 kg/ ha, Oceania 4 kg/ ha, and Africa only 1.7 kg/ ha (1982).

Key countries

A few countries account for a major share of the N, P, and K use in the world. Trends in these countries indicate the types of shifts occurring in different regions..

Nitrogen. China, USSR, USA, and India led the world in N consumption in 1972 and again in 1982 (Table 3). Together they accounted for over a half (55%) of world N fertilizer use in 1982. The next ten consumers of N, ranked in order for 1982, were France, United Kingdom (UK), Federal Republic of

Table 3. World top nitrogen fertilizer producers, consumers, and traders 1982 (5, modified from FAO) data).

Country	N ('000 t)			
	Production	Consumption	Imports	Exports
USSR	11 481	9 038	44	1 643
China	10 219	11 969	1 750	0
United States	8 715	8 342	2 409	1 848
India	3 430	4 043	425	0
Romania	2 008	880	0	1 037
Canada	1 897	1018	145	995
France	1 530	2 196	883	217
Netherlands	1 505	457	166	1 262
United Kingdom	1 399	1 560	289	110
Poland	1 298	1 239	57	8
Federal Republic of Germany	985	1 465	816	454
Mexico	1 067	1 255	190	3
Iran	22	493	473	0
Denmark	161	391	273	41
Brazil	397	642	247	1
Belgium/Luxembourg	755	197	243	809
Norway	458	109	0	350
Japan	1 126	687	73	332
Qatar	305	1	0	285
Total	48 758	45 982	8 483	9 395
Other countries	14 592	15 124	4 285	2 755
World total	63 350	61 106	12 768	12 150

Germany (FRG), Mexico, Poland, and Canada. The leading consumers ten years earlier were, in order, USA, USSR, China, India, France, FRG, Poland, UK, Japan, and Italy.

The countries leading in intensity of use were from developing as well as developed regions (Table 4). The leading countries were, in order, Netherlands (530 kg N/ha), Ireland (305), Egypt (271), Democratic People's Republic of Korea (DPRK)(261), Belgium/Luxembourg (237), UK (223), FRG (196), German Democratic Republic (GDR) (149), Denmark (148), and Switzerland (147). The Republic of Korea (RK)(142) and Japan (142) ranked eleventh in 1982. Ten years earlier RK was third and Japan fifth.

The top countries in Asia, Africa, and Latin America in intensity of use in 1982 are shown in Table 5. The top countries in Asia were DPRK, Japan, RK, China, Israel, Lebanon, Saudi Arabia, Indonesia,. Pakistan, and Vietnam. Several Asian countries recorded substantial increases from 1972 to 1982. The very large increases in Saudi Arabia, China, Iran, DPRK, Indonesia, Pakistan, and Turkey caused Asia to be the region with the largest increase. The leading countries in Latin America were Cuba, Costa Rica, El Salvador, Mexico, and Guatemala; and in Africa they were Egypt, Mauritius, South Africa, Zimbabwe, and Libya.

Phosphorus. USSR, USA, China, and France led in P consumption in 1972 and 1982, accounting for 43% of world use in 1982 (Table 6). These were followed, in 1982 ranking, by Brazil, India, Poland, FRG, Japan, and Australia. The order ten years earlier was USA, USSR, France, China, FRG, Australia, Poland, Japan, Brazil, and Italy.

The leading countries, measured by intensity of use, were all from developed regions (Table 7). The top six, in 1982 order, were Iceland, New Zealand, Ireland, Japan, Belgium/ Luxembourg, and Switzerland. They were the same in 1972 though in different order. Apart from Iceland and New Zealand with very high rates (495 kg/ ha and 309 kg/ ha), P use ranged from 27 to 66 kg/ ha (Table 7). This was substantially more than the P use per ha of even those developing countries which consumed more than 20 000 t of fertilizer nutrients

Table 4. World top countries in use of nitrogen in 1982 (4, 5).

Country	N (kg/ha)
Netherlands	530
Ireland	305
Egypt	271
Democratic People's Republic of Korea	261
Belgium/Luxembourg	237
United Kingdom	223
Federal Republic of Germany	196
German Democratic Republic	149
Denmark	148
Switzerland	147
Republic of Korea	142
Japan	142

Table 5. Use of nitrogen, phosphorus, and potassium fertilizer (kg/ha) for Africa, Asia, and Latin American countries consuming 20 000 t or more of plant nutrients 1982 (4.5, modified from FAO data).

Fertilizer use (kg/ha)											
	Africa				Asia				Latin America		
	N	P	K		N	P	K		N	P	K
Egypt	271	27	3	Japan	142	66	100	Cuba	86	11	51
South Africa	35	16	9	Republic of Korea	142	30	60	Uruguay	11	11	1
Mauritius	92	13	98	Dem. P.'s R. of Korea	261	25	17	Mexico	54	9	3
Libya	17	9	1	Lebanon	58	20	38	Costa Rica	77	9	13
Zimbabwe	26	7	9	Israel	93	17	39	El Salvador	61	8	4
Kenya	14	6	1	China	121	14	4	Brazil	16	7	10
Algeria	7	4	4	Saudi Arabia	52	13	2	Colombia	27	7	10
Morocco	11	4	4	Iran	36	13	0.3	Venezuela	19	6	8
Tunisia	9	4	1	Malaysia	32	11	37	Panama	24	5	10
Mozambique	7	2	2	Turkey	32	9	1	Guatemala	33	4	6
Zambia	13	2	1	Indonesia	50	8	6	Chile	9	4	2
Malawi	10	1	1	Sri Lanka	37	6	17	Ecuador	13	3	7
Ghana	5	1	3	Philippines	20	2	4	Nicaragua	11	2	2
Nigeria	3	1	1	Pakistan	47	-	-	Dominican Republic	21	2	8
Ivory Coast	2	1	4	Vietnam	41	-	-				
Senegal	1	1	1								
Ethiopia	1	1	-								
Sudan	4	-	-								

Table 6. World top phosphorus fertilizer producers, consumers, and traders 1982[a] (5, modified from FAO data).

Country	('000 t)			
	Production	Consumption	Import	Exports
United States	3 367	1 661	53	1 563
USSR	2 545	2 351	43	110
China	1116	1 380	264	0
France	528	690	242	46
Brazil	501	532	33	1
India	433	521	28	0
Poland	382	363	22	0
Romania	330	240	0	90
Australia	323	317	26	0
Italy	279	289	141	26
Federal Republic of Germany	248	326	141	60
Japan	275	317	70	31
Iran	3	176	173	0
Pakistan	33	117	109	0
Mexico	111	214	104	1
Hungary	99	172	81	11
Bulgaria	105	159	72	0
Canada	256	287	72	42
Tunisia	212	18	0	194
Belgium/Luxembourg	202	41	20	194
Netherlands	152	34	23	148
Republic of Korea	192	66	0	125
Morocco	130	36	0	90
Yugoslavia	166	103	18	56
Total	11 990	10411	1 733	2 701
Other countries	2 139	2 737	868	388
World total	14 129	13 148	2 601	3089

[a] Does not include ground phosphate rock for direct application.

Table 7. World top countries in use of phosphorus and potassium in 1982 (4.5).

Country	Fertilizer use (kg/ha)	
	P	K
Iceland	495	715
New Zealand	309	166
Ireland	66	158
Japan	66	100
Belgium/Luxembourg	50	141
Switzerland	47	134
Federal Republic of Germany	44	116
Czechoslovakia	41	99
Netherlands	40	98
France	39	78
German Democratic Republic	27	82
Norway	33	87

NOTE. Expressing Intensity of fertilizer use as kg/ha of arable land and permanent crops can be misleading in countries where most of the fertilizer is applied to grasslands rather than arable land.

per year (Table 5). For example, among the leaders in Asia, excluding Japan, in 1982 (RK, DPRK, Lebanon, Israel, China, and Saudi Arabia), average annual use ranged from 13 to 30 kg P/ha. Even lower levels were recorded for the leaders in Africa and Latin America (Table 5). P use ranged from 27 to 4 kg/ ha in the leading countries of Africa, excluding South Africa (Egypt, Mauritius, Libya, Zimbabwe, Kenya, and Algeria), and from 11 to 7 kg/ha in Latin America (Cuba, Uruguay, Mexico, Costa Rica, El Salvador, and Brazil).

Potassium. The top five consumers of K in 1982 (USSR, USA, France, Poland, and FRG) accounted for nearly 60% of world use (Table 8). They were followed by Brazil, India, Czechoslovakia, Japan, and UK. Compared with 1972, India had replaced GDR, which dropped from eighth to eleventh place.

The leading countries on the basis of intensity of K use were all developed countries (Table 7). As with P, Iceland was well in the lead, averaging 715 kg K/ha in 1982. It was followed by New Zealand, Ireland, Belgium/ Luxembourg, Switzerland, FRG, Japan, Czechoslovakia, Netherlands, and Norway. Since 1972, Norway replaced GDR. Average use, excluding Iceland, ranged from 166 to 87 kg K/ha.

With few exceptions the level of K use per ha for the developing countries was only a small fraction of that attained by the leading users (Table 5). Japan posted 100 kg/ ha in 1982, but the remaining nine leaders in Asia ranged from 60 kg/ ha (China) to 4 kg/ ha (Philippines). Similarly, in Latin America, the leading ten ranged from 51 kg/ha (Cuba) to 4 kg/ ha (El Salvador). In Africa, apart from Mauritius (98 kg K/ha), the nine leading countries ranged from 9 kg K/ ha (South Africa) to I kg K/ ha (Kenya).

PRODUCTION

World production of fertilizer N increased from 40.9 million t in 1973 to 67.6 million t in 1983. This represents an annual compound growth rate of 5.2%.

Global production of P fertilizer was 15 million t in 1983. This had increased from 11 million t in 1973, which represents an annual growth rate of 3.1%. Potassium fertilizer production also increased. climbing from 18.2 million t in 1973 to 23.2 million t in 1983, an annual growth rate of 2.4% (Table 9).

Regional trends

The quantities of N, P, and K produced and the rates of production growth differed among regions.

Nitrogen. The events of the past decade have propelled the Asian region into the position of world leader in N production. From 8.4 million t of N in 1973 (20% of the world market), N production rose steadily over the decade at an annual compound rate of 9.8% (Table 9). As a result, N production for the region reached 21.6 million t in 1983, 32% of world production. Consequently the proportion of world production coming from North America and Western Europe, which increased production by only 1.6% and 1.3% over the same period, declined sharply - from 47% in 1973 to 33% ten years later. The rate of growth of N production was also substantial in Africa (12.5%/yr) and Latin

Table 8. World top potassium producers, consumers, and traders in 1982 (5, modified from FAO data).

Country	K ('000 t)			
	Production	Consumption	Imports	Exports
USSR	6 706	4 143	14	2 058
Canada	4 465	287	17	3 867
German Democratic Republic	2 850	413	0	2 352
Federal Republic of Germany	1 848	865	247	1 098
United States	1 395	3 654	3 264	470
France	1 329	1 448	395	508
Israel	749	17	0	720
Spain	564	219	3	368
United Kingdom	217	432	288	90
Italy	111	315	321	71
Poland	0	912	1 031	0
Brazil	0	727	727	0
India	0	516	530	0
Czechoslovakia	0	512	540	0
Japan	0	483	507	0
Hungary	0	407	395	0
China	21	326	305	0
Total	20 254	15 675	8 586	11 602
Other countries	12	3 286	3919	15
World total	20 966	18 961	12 505	11 617

America (9.7%/yr), but their shares of world production, being small, increased only slightly, to 2.2% from Africa and 3.2% from Latin America in 1983. The production increases in Eastern Europe and the USSR were in line with global rates of increase, so that their shares of world production (10% and 19%) changed little from 1973. Nitrogen production in Oceania, already small, dropped over the decade to 0.3%.

Phosphorus. Developed countries produced 76% of the world's P fertilizer in 1983, as against 86% ten years earlier. Furthermore, P production grew at 8.9%/yr in developing countries but at only 1.7%/yr in developed countries. Phosphorus production actually declined in Western Europe and Oceania (Table 9), particularly the former, whose annual rate of production fell by 0.6 million t, and whose share of world production fell from 26 to 15%. Annual growth of production was above the world average (3.1%) in Asia (8.4%), Africa (8.1%), USSR (7.4%), and Latin America (6.2%). Growth also occurred in North America (2.9%) and Eastern Europe (2.2%), but the levels were below the world average. Phosphorus fertilizer production in Oceania actually declined by 0.26 million t; hence its share of world production dropped from 6.4% in 1973 to 2.9% in 1983.

Potassium. Nearly all the world's K fertilizer is produced by developed countries. North America, Europe, and USSR combined produced about 96% of the world total in 1983 (Table 9). This was not greatly different from their share of world production in 1973. Production growth in Western Europe was

Table 9. World fertilizer production by region, 1973 and 1983 (4, 5, FAO unpublished data).

	Nitrogen				Phosphorus				Potassium			
Area	Quantity 1983 (10^6 t N)	World share (%) 1973	World share (%) 1983	10-year annual growth rate (%)	Quantity 1983 (10^6 t P)	World share (%) 1973	World share (%) 1983	10-year annual growth rate (%)	Quantity 1983 (10^6 t K)	World share (%) 1973	World share (%) 1983	10-year annual growth rate (%)
North America	11.6	24.5	17.2	1.6	4.0	27.6	27.0	2.9	7.1	33.8	30.8	1.5
Latin America	2.2	2.2	3.2	9.7	0.6	2.8	3.8	6.2	-	-	-	-6.4
Western Europe	10.7	22.7	15.8	1.3	2.2	25.6	14.7	-2.4	4.4	23.7	19.0	0.2
Eastern Europe	7.1	10.8	10.5	4.9	1.4	10.0	9.1	2.2	2.8	11.9	12.2	3.0
USSR	12.7	17.6	18.8	5.8	2.7	12.0	17.9	7.4	7.8	26.9	33.7	4.6
Asia	21.6	20.5	32.0	9.8	2.9	12.0	19.6	8.4	1.0	2.3	4.3	8.2
Africa	1.5	1.2	2.2	12.5	0.7	3.6	5.0	8.1	-	1.4	-	-28.0
Oceania	0.2	0.5	0.3	2.1	0.4	6.4	2.9	-4.1	-	-	-	0.0
World total	67.6	100.0	100.0	5.2	14.9	100.0	100.0	3.1	23.1	100.0	100.0	2.4

particularly sluggish in the decade, averaging only 0.2%/yr. In North America, growth was only slightly greater. As a result, the world share of K fertilizer dropped from 24% in 1973 to 19% in 1983 for Western Europe, and from 34% to 3 1% for North America. On the other hand, both Eastern Europe (3.0%) and the USSR (4.6%) raised K fertilizer production to rates slightly above the world average (2.4%) and thereby increased their share of world production to 12.2% and 33.796, respectively.

Key countries

During the decade 1972-82, major shifts occurred in N and P fertilizer production in key countries, although little change was noted for the top K-producing countries (Tables 3, 6, and 8).

Nitrogen. USSR, China, and USA are the leading producers of N fertilizer (Table 3). In 1982 these three countries accounted for 48% of N fertilizer produced in the world. Other top producing countries, in 1982 order, were India, Romania, Canada, France, Netherlands, UK, and Poland. This list is substantially different from 1972.

Phosphorus. USA, USSR, China, and France were the top producers of P fertilizer in 1982 (Table 6). Together they accounted for over half (53%) of the world total. These countries were also the top four in 1972. They were followed in 1982 by Brazil, India, Poland, Romania, Australia, and Italy. Of these, only Australia and Poland were included among the top ten 10 years earlier.

Potassium. The top producers of K fertilizer were, in 1982 order, USSR, Canada, GDR, FRG, USA, France, Israel, Spain, UK, and Italy (Table 8). The ranking had changed very little from 1972. USSR and Canada were by far the leading producers of K fertilizer. Together they accounted for 11.1 million t of K, or over half of world production.

WORLD TRADE IN FERTILIZERS

The world trade in fertilizer is of major importance to the fertilizer sector. In 1982 about 27 million t of N, P, and K moved in international trade (Tables 3,6, and 8).

Key exporting countries

USA, USSR, Netherlands, and Romania are the leading exporters of N. In 1982 these countries accounted for 40% of the 12.1 million t of N exported. They were followed by Canada, Belgium/Luxembourg, FRG, Norway, .Japan, and Qatar. Ten years earlier Japan was the top exporter and USSR twelfth; Qatar was not among the top ten.

The USA accounts for over half of world exports of P fertilizer, followed by Tunisia, Belgium/ Luxembourg, Netherlands, and RK. These five countries exported 72% of the P fertilizers in 1982, compared with 62% in 1972. The USA ranked first in both years. Tunisia and the RK became more important during the decade, Canada less.

Canada is the largest exporter of K fertilizer in the world, followed by USSR, GDR, FRG, and Israel. These five countries accounted for 87% of world exports of K in 1982, compared with 83% in 1972. The ranking of countries changed little during the decade.

Key importing countries

The USA has become the world's leading importer of N. accounting for nearly 20% of all imports of N in 1982. China ranks second. accounting for 14%. Since China does not export N, it is the world's leading net importer. Other leading importers of N in 1982 were France, FRG, Iran. India. UK, Denmark, Brazil, and Belgium/ Luxembourg.

China and France were by far the largest P importers in 1982, followed by Iran, FRG, and Italy. These five countries accounted for only 37% of world imports of P. China and Iran were not important importers 10 years earlier.

The USA is the largest importer of K, accounting for slightly over one fourth of the world total. Poland, Brazil, Czechoslovakia. and India follow. These five countries account for about one half of world imports of K. During 1972-82 India and Brazil became more important. whereas the rankings of UK and Japan declined.

CHANGES IN FERTILIZER FORM

The form (type) of fertilizer produced at a given location and time is strongly influenced by the technology that is available, the crops that are to receive the fertilizer, and the magnitude of geographical demand for a particular form of fertilizer. Each new facility represents a slightly different picture of the state of the art and reflects change in the system. The world fertilizer sector has been changing almost constantly since 1945 and particularly since the 1960s; thus it is not surprising that there have been great changes in the form of fertilizers made and consumed over the past 20 years.

Global trends

Statistics are incomplete for any given year and are not always compiled in a manner that would allow comparisons of change in form over time. Three approaches, all of which represent only partial solutions to the problem, have been used to estimate changes; they are based on shifts in installed capacity, production, and consumption.

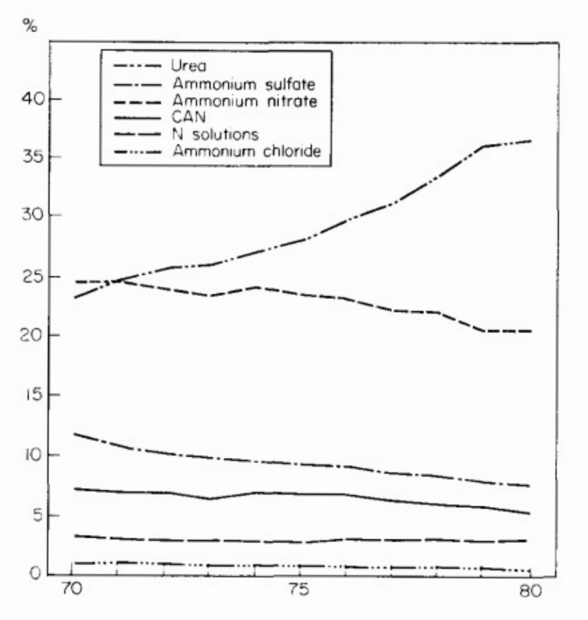
Nitrogen. Urea is now the leading form of N consumed, accounting for 30% of the world total in 1982 (Table 10). Other important forms in 1982 were nitrate (22%), compounds (19%), and ammonium sulfate (5%). The large proportion (24%) classified as "other" consists mainly of N solutions. anhydrous ammonia, calcium ammonium nitrate (CAN), ammonium chloride, and calcium cyanamide. In the late 1950s, ammonium nitrate replaced ammonium sulfate as the dominant N source used in the world and it remained in that position until 1970. The share of ammonium sulfate, after declining for many years, has started to stabilize at about 10% of the world total. This is partly because it is a by-product

Table 10. Total nitrogen consumption and percentage by form: global and regional 1981 (1).

Region	Total N consumption ('000 t)	% of total N as				
		Ammonium sulfate	Ammonium nitrate	Urea	Other straights	Compounds
Western Europe	10 045	4	47	10	8	31
Eastern Europe	5 180	8	46	26	2	19
USSR	8 383	4	42	22	13	19
Africa	1 936	6	34	33	2	26
North America	11 002	1	9	11	58	22
Central America	1 397	28	5	36	17	14
South America	1 191	17	11	47	2	24
Oceania	295	22	8	39	14	16
Asia (excl. China)	10 000	6	4	69	1	20
China	11 285	2	7	38	52	2
World	60 714	5	22	30	24	19

of several industries including caprolactam, steel, and nonferrous extractions. Another factor is its importance as a source of S. Capacity for producing CAN, N solutions. and ammonium chloride has remained constant since 1970; it has lingered at 75%, 4%, and 2% (Fig. 1). On the other hand, urea has increased in importance markedly over the decade, accounting for over 35% of the world total in 1984 (Stangel, unpublished data).

Phosphates. The vast majority of P consumed by world agriculture is in the form of compounds (60%) (Table 11). Single superphosphate (SSP) and double superphosphate combined are a distant second (20%), followed by triple



1. Percentage share of world nitrogen fertilizer production capacity by major product. 1970-80 (9).

Table 11. Total phosphorusconsumption and percentage by form: global and regional 1981 (1).

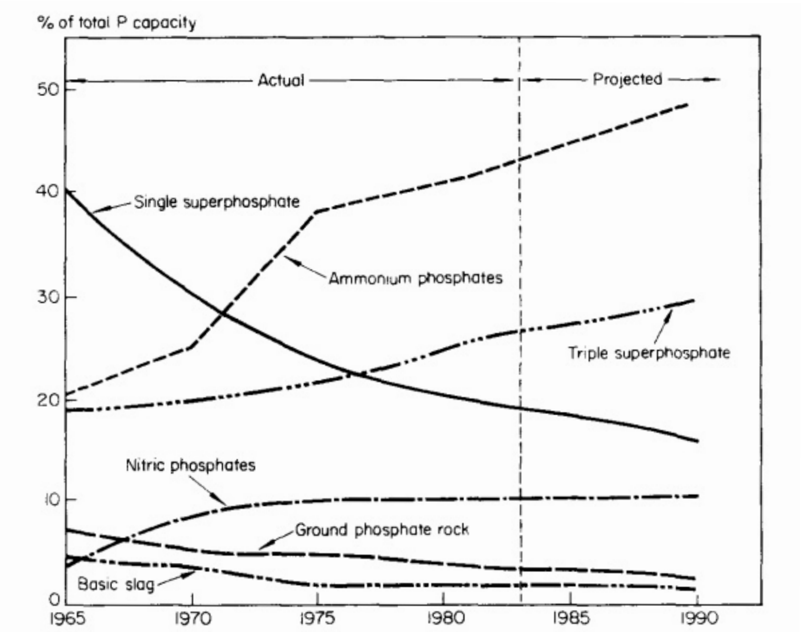
Region	Total P consumption ('000 t)	% of total P as				
		Superphosphates		Basic slag	Other straights	Compounds
		Single/double	Triple			
Western Europe	2 428	6	7	6	2	79
Eastern Europe	1 477	30	25	0	5	40
USSR	2 587	18	13	1	13	55
Africa	552	20	13	-	1	66
North America	2 165	<1	7	<1	1	91
Central America	209	15	20	-	2	63
South America	702	17	32	1	7	45
Oceania	521	65	2	-	<1	33
Asia (excl. China)	1 679	11	15	-	8	66
China	1 265	62	5	-	24	9
World	13 585	20	12	1	7	60

superphosphate (TSP) (12%), other straights (7%), and basic slag (1%). This is somewhat different from 30 years ago. In the late 1950s, SSP (normal) was the dominant form of P fertilizer produced and accounted for over 60% of the world total. Basic slag, concentrated superphosphate, ammoniated phosphates, and complex fertilizers each made up between 10% and 15% of the total produced at the time. This distribution had changed dramatically by the early 1970s when SSP made up only 20% of world production, and ammoniated phosphates (diammonium phosphate [DAP] and monoammonium phosphate [MAP]) and NPK fertilizers had taken the lead. At that time, DAP, MAP, and NPK fertilizers accounted for nearly 50% of the world total, This trend has continued, and today ammoniated phosphates and compounds are the dominant forms produced and consumed (Fig. 2). The consumption of basic slag has continued to decline; in 1983 it was less than 2% of the world total. On the other hand, TSP has remained relatively constant over the years, accounting for 15% to 20% of the world total.

Potassium. Most (54%) of the world's K fertilizer (Table 12) is applied directly as potassium chloride and as compounds (40%). Relatively small quantities are applied directly as potassium sulfate (2%), double salts of potassium and magnesium (1%), or as other forms (3%). This distribution is quite different from that 20 years ago, when nearly 75% of the K was applied directly as potassium chloride and about 22% as compounds. Undoubtedly, a major reason for this shift has been the rapid acceptance of bulk blending, particularly in the USA and Brazil, and to a lesser extent in Japan and Western Europe.

Trends in Asia and Oceania

Twenty years ago the centers of fertilizer production and consumption were in Western Europe, North America, and to a lesser extent Japan. Neither Western Europe nor Japan had indigenous raw materials necessary to produce P or N



2. Trend in world phosphate capacity by specific product (1965-90) (TVA, unpublished statistics).

fertilizers; most, if not all, of the raw materials had to be imported. On the other hand, North America, particularly the USA, had abundant supplies of the raw materials needed to build a strong fertilizer sector. Twenty years ago many of the developing countries were not aware of the extent of their indigenous fertilizer raw materials. There was no need to do the necessary exploration, because the demand for fertilizer in most of these countries was minimal. As a result, most of

Table 12. Total potassium consumption and percentage by form: global and regional 1981 (1).

Region	Total K consumption ('000 t)	% of total K as				
		Potassium chloride	Potassium sulfate	Potassium magnesium sulfate	Other straights	Compounds
Western Europe	4 125	18	2	1	2	77
Eastern Europe	3 172	69	1	<1	4	25
USSR	4 071	79	<1	3	9	8
Africa	339	12	13	-	-	74
North America	4 515	54	1	1	1	43
Central America	330	73	7	0	-	30
South America	749	73	3	0	-	24
Oceania	212	24	2	-	-	74
Asia (excl. China)	1812	48	3	-	-	49
China	477	84	7	-	-	9
World	19 802	54	2	1	3	40

the fertilizers were imported. Events of the past decade, particularly the food, fertilizer, and energy crises, have made these countries more aware of their resources, stimulated their development, prompted construction of new capacity, and changed the forms in which fertilizers are being consumed.

Asia. There are vast differences within Asia in the form in which fertilizers are consumed. Also, the percentage of the total supplied in each form has changed markedly over the past 20 years.

In 1982 urea was the dominant form of N used in Asia (excluding China); it accounted for 69% of the total consumed (Table 10). Lesser quantities of N were supplied in the form of compounds (20%), ammonium sulfate (6%), and ammonium nitrate (4%). This is in direct contrast to 20 years previously, when N was supplied primarily as ammonium sulfate and compounds. This major shift can be explained by the large N capacity that has been newly built in much of Asia, primarily to produce urea; the poor handling qualities of ammonium nitrate in the tropics and its hazards as an explosive; and the relatively low analysis of ammonium sulfate.

Japan is one exception to this general trend in Asia. It is ironic that Japan, historically a major exporter of urea fertilizer, should supply very little straight urea to its domestic agricultural market. However, Japan produces substantial quantities of by-product ammonium sulfate and ammonium chloride. It also has significant quantities of surplus sulfuric acid. To use these by-products effectively, Japan makes large quantities of compound fertilizer that may also contain urea. This explains why nearly 80% of the N used by Japanese farmers is supplied as compound (3).

Another exception is China where ammonium bicarbonate is the dominant form of N, although urea now comprises 38% of the total N because of openings of new urea plants in the late 1970s. The trend towards greater dominance of urea is likely to continue in China, but urea is not likely to increase in other parts of Asia, as the countries in the region achieve self-sufficiency in rice and their planners redirect programs towards increasing the production of upland crops.

Phosphorus is supplied primarily in the form of compounds in most countries of Asia (Table 11). The two exceptions are Indonesia, where most is supplied as TSP, and China, where nearly 62% was supplied as SSP and double superphosphate in 1982. The trend towards high-analysis NPK will continue in Asia as countries strive towards a more balanced and efficient fertilization program.

Most of the K used in Asia is consumed directly as potassium chloride or as NPK compounds. China consumes most (84%) of its K as directly applied potassium chloride. The other countries of Asia use K primarily in the form of compounds (Table 12).

Oceania. Australia and New Zealand contrast sharply with Asia in the predominant forms of fertilizer used in their respective markets. While urea is the leading form of N applied (39%), it is by no means dominant. Significant quantities of N as ammonium sulfate (22%), ammonium nitrate (8%), other straights (14%), and compounds (1 6%) are also used by farmers to satisfy the N needs of the crop (Table 10). An even greater deviation from the Asian pattern prevails in the forms of P and K used by farmers in Oceania (Tables 11 and 12). For example, 65% of the P is supplied as SSP or double superphosphate, and 33% as compounds. This is undoubtedly due to the high S requirement by Australian and New Zealand agriculture. Nearly all (98%) of the K used in Oceania is supplied as muriate of potash (KCl), either as compounds or as straight (24%) material.

PRICES AND PROFITABILITY OF FERTILIZER USE

The rapid increase in the price of energy since 1973 and the resultant spiral in cost of many essential items, coupled with the constant threat of food and fertilizer shortages, particularly during the mid and late 1970s. triggered imposition of a wide range of government policies that have had a decided impact on the fertilizer sector. The objective of these policies was to reduce the countries' dependency on offshore supplies of food by increasing domestic production of food through increased use of fertilizer. Most of these policies were aimed at accomplishing this by strictly regulating the prices of both input (fertilizer) and output, and thereby improving the profitability of using fertilizer. Countries varied markedly in their efforts and success in achieving this goal.

Prices of fertilizer

Prices of fertilizer have been greatly affected by world events since 1973. Prices in the international market have fluctuated widely. Some countries have made no effort to protect farmers and have allowed the fluctuations to be felt directly at the farm gate. However, the majority of the developing countries have instituted subsidy policies designed to insulate the farmer from variations in the international market. This move, currently in effect in most developing countries, is proving increasingly difficult to maintain financially.

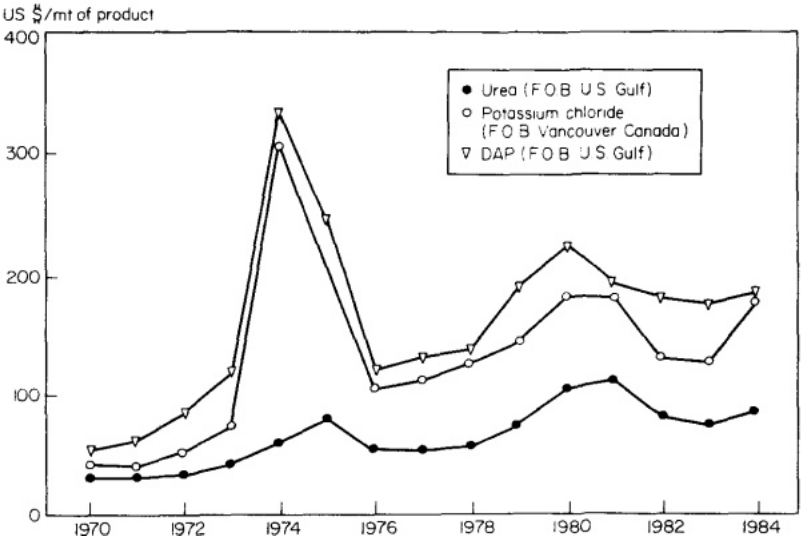
International prices. The period 1973-75 was marked by skyrocketing prices of finished fertilizers and to some extent fertilizer raw materials (Table 13, Fig. 3). For example, urea and DAP prices soared from below $100/ t in 1972 to a high of $500-$550/ t in a span of 24 months before plummeting to $100-$120 in 1976. Since then, the prices of urea and DAP have increased but are nowhere near the 1975 levels and show no indication of approaching those levels in the near future.

Fertilizer raw materials have also been affected by the events in the past decade, but in a somewhat different manner. The prices of raw materials in real terms are well above their pre-1973 levels and have increased substantially more than the prices for finished fertilizers. Prices of phosphate rock increased sixfold between 1973 and 1974. Although they have come down somewhat since that time, they remain substantially above the pre-1973 levels in real terms. The price of S, a major raw material used in the manufacture of phosphoric acid and TSP, has increased tenfold since 1973 and is now at the highest level on record. Similarly, the prices of phosphoric acid, ammonia. and potash fertilizers have remained well above their pre-1973 levels. This disparity between the price of raw materials and finished fertilizers has placed great financial pressure on

Table 13. Export price indications for key fertilizer raw materials and intermediates, 1971-84 (2, 7, 8).

Year	Export price (US$/t)					
	Sulfur[a]	Sulfuric acid[b]	Phosphate rock[c]	Phosphoric acid[d]	Ammonia[e]	Potash[f]
1971	14-1 7	11-14	10-12	90-100	38-4 1	33
1972	14-16	10-14	10-11	100-120	3445	33-34
1973	14-25	11-20	12-42	110-280	44-180	35-55
1974	30-50	15-35	42-68	200-500	140-400	40-80
1975	50-60	3-35	55-68	250470	90-400	60-95
1976	37-40	8-25	38-48	155-280	95-125	45-75
1977	30-40	14-25	32-38	175-195	95-145	45-55
1978	37-45	18-30	31-39	185-220	90-120	52-68
1979	40-60	20-50	32-50	215-365	110-165	65-100
1980	75-110	35-60	45-55	365-395	150-170	110-125
1981	105-120	30-50	48-53	300-375	165-195	105-120
1982	110-113	25-35	45-53	270-315	145-180	67-110
1983	84-110	na[g]	31-48	260-300	145-230	71-85
1984	105-137	na	32-40	310-315	190-300	83-90

[a] Brimstone fob Vancouver. [b] fob Northwest Europe. [c] fas Casablanca (70% bone phosphate of lime [BPL]). [d] fob US Gulf (per t P_2O_5). [e] c&f Western Europe. [f] Potassium chloride fob Vancouver, [g] na = not available.



3. Export price trends (bulk) for some major fertilizer materials (current prices) (Y. H. Chung, personal communication, 7).

countries whose production capacity is based on imported raw materials and who sell products to the farmer at subsidized prices.

Farm-gate prices. Farm-gate prices for wheat, rice, and maize, as well as various kinds of fertilizers, vary widely from country to country. Japan, RK, and Zambia buy maize, wheat, and rice from farmers at prices three to five times the world market price (Table 14). On the other hand, Mexico, Thailand, and Pakistan set farm-gate prices of rice at levels somewhat below prevailing world market prices. Others do the same for wheat and maize. Similar variations in price prevail for fertilizer. Using phosphate sources of TSP, DAP, SSP, and phosphate rock as examples, Zambia sells TSP to the farmer at five times the world market price, Japan and RK at more than twice that price, and Indonesia at only 75% of the price (Table 15). Additionally, several countries price their locally produced fertilizers on the cost of indigenous raw materials (Brazil and Sri Lanka for phosphate rock) at levels less than those of domestically produced material based on imported raw materials, intermediates, or imported finished fertilizers.

Table 14. Typical 1984 farm-gate prices for food crops in selected countries (Y. H. Chuang. personal communication).

Country	Farmgate price (US$/t)		
	Wheat	Rice	Maize
Japan	744	964	
Zambia	522	1 000	610
Republic of Korea	414	801	544
South Africa	374		293
India	190		149
Bangladesh	166	222	
Sri Lanka		118	
Indonesia		250	
Pakistan		105	
Brazil		196	101
Philippines		158	128
Thailand		142	135
Mexico	144	121	147

Table 15. Some typical 1984 farm-gate prices for phosphorus fertilizers in selected countries (Y. H. Chuang, personal communication).

Country	Farm-gate price (US$/t)[a]			
	TSP	DAP	SSP	PR
Japan	395	337		
Zambia	1 094			
Republic of Korea	395			
South Africa	257	447		
India		293		
Bangladesh	151	162		
Sri Lanka	110	406		44
Indonesia	91	91		
Pakistan		192	53	
Brazil	338	431		55
Philippines	175	358		
Thailand	351			
Mexico	126	173		

[a] TSP = triple superphosphate, DAP = diammonium phosphate, SSP = single superphosphate, PR = phosphate rock.

Profitability of fertilizer use

The key determinant of increased fertilizer use is its profitability to the farmer. This is true regardless of the cost of fertilizer or the price the farmer receives for his output. Two simple approaches are used as measures of profitability to the farmer. These are crop-to-fertilizer price ratio and value-to-cost ratio. The limitations of each are recognized. Each measure is used for illustration purposes and for showing how government policies are being used to stimulate fertilizer use.

Crop-to-fertilizer price ratio. The crop-to-fertilizer price ratio represents the number of units of fertilizer (in this example TSP equivalent) that can be purchased with a unit of a specific crop. These ratios vary among countries and among major crops within countries (Table 16). The higher the ratio the more profitable it is for the farmer to use fertilizer. Conversely, if ratios are very low, farmers are less likely to use fertilizer; if they do, it is likely to be at relatively low rates. Table 16 shows the crop-to- fertilizer price ratios in 13 countries for rice, in 7 countries for maize, and in 6 countries for wheat. For example P use appears to be more profitable on rice than on maize or wheat except in Mexico. In general, Sri Lanka, Japan, Indonesia, Brazil, and RK have very high ratios for rice, indicating that use of P fertilizer should be very favorable on that crop. On the other hand, the low ratios for rice (less than 1) for Mexico, Zambia, Philippines, Pakistan, and particularly Thailand suggest that it is much less profitable to use P fertilizer on that crop in these countries.

Value-to-cost ratio. A rather simple extension of the crop-to-fertilizer price ratio, used in this paper as a measure of profitability, is the value-to-cost ratio. For example, if 1 t of rice sells for $300 at the farm gate and the price of TSP at that point is $150, the crop-to-fertilizer phosphate price ratio is 2. The practical application of this number comes from the following assumptions: one unit of

Table 16. Cropto-fertilizer price ratios at farm for key food crops and phosphorus fertilizers in selected countries (Y. H. Chuang, personal communication).

Country	Rice	Maize	Wheat
Sri Lanka	2.69[b]		
Japan	2.44		1.88
Indonesia	2.38		
Brazil	2.21[b]	1.15[b]	
Republic of Korea	2.02	1.38	1.05
Bangladesh	1.90[c]		1.42[c]
India	1.26c	0.71[c]	0.90[c]
South Africa	1.14		1.46
Mexico	0.96	1.16	1.14
Zambia	0.91	0.51	
Philippines	0.90	0.73[c]	
Pakistan	0.85[d]		
Thailand	0.40	0.38	

[a] All comparisons made on TSP equivalency basis and prices used are for TSP unless otherwise stated. [b]Phosphate rock, [c]Diammonium phosphate. [d]Single superphosphate.

rice will buy two units of TSP, and one kg of TSP will, on P-responsive soils, increase rice yields an average of 5 kg. Since the value of the rice produced is twice the cost of the TSP, the value-to-cost ratio is 10. On the basis of this simple calculation, the following general statements can be made about the profitability of using P fertilizer in many developing countries. The addition of P is profitable on rice, maize, or wheat in the RK (Table 17). However, this profitability has declined since 1980 and, because of heavy financial pressure, apparently reflects a major shift in policy by the government to reduce the cost of the subsidy. Phosphate use is very profitable on rice grown in Sri Lanka. However, government policy favors the use of indigenous phosphate rock and discourages the use of imported DAP (Table 18). A similar policy appears to be in place in Brazil where use of phosphate rock on maize or rice appears to be much more profitable to the farmer than either TSP or DAP (Table 19).

Table 17. Cropto-fertilizer (TSP) price[a] and value-to-cod ratios for the Republic of Korea 198084 (Y. H. Chuang, personal communication).

Year	Rice	Maize	Wheat
1980	6.46	2.99	1.83
	(32.3)	(15.0)	(9.1)
1981	3.79	2.23	1.93
	(18.9)	(11.1)	(9.6)
1982	5.41	2.59	3.14
	(27.0)	(13.0)	(15.7)
1983	2.95	1.85	1.53
	(14.7)	(9.2)	(7.6)
1984	2.02	1.38	1.05
	(10.0)	(6.9)	(5.2)

[a] Based on actual farm-gate prices for October of given year. [b]Figures in parentheses are value-to-cost ratios.

Table 18. Rice-to-fertilizer price[a] and value-to-cost[b] ratios for Sri Lanka 198-84 (Y. H. Chuang, personal communication).

Year	TSP	DAP	PR
1980	1.49	1.38	1.85
	(7.4)	(6.9)	(9.2)
1981	0.96	0.59	1.58
	(4.8)	(2.9)	(7.9)
1982	1.05	0.64	1.73
	(5.2)	(3.2)	(8.6)
1983	1.07	0.67	1.86
	(6.3)	(3.3)	(9.3)
1984	1.07	0.4 1	2.69
	(5.3)	(2.0)	(10.3)

[a] Based on actual farm-gate prices for October of given year. [b]Figures in parentheses are value-to-cost ratios.

Table 19. Crop-to-fertilizer price[a] and value-to-cost[b] ratios for Brazil 1980-84 (Y. H. Chuang, personal communication).

Year	Maize			Rice		
	PR[c]	TSp[d]	DAP[e]	PR[c]	TSp[d]	DAP[e]
1980	0.68	0.39	0.41	1.18	0.67	0.71
	(3.4)	(1.9)	(2.0)	(5.9)	(3.3)	(3.5)
1981	0.48	0.30	0.30	0.84	0.53	053
	(2.4)	(1.5)	(1.5)	(4.2)	(2.6)	(2.6)
1982	0.53	0.23	0.24	1.44	0.62	0.64
	(2.5)	(1.1)	(1.2)	(7.2)	(3.1)	(3.2)
1983	1.11	0.39	0.42	1.55	0.84	0.90
	(5.5)	(1.4)	(2.1)	(7.71	(4.2)	(4.5)
1984	1.15	0.30	0.33	2.23	0.58	0.63
	(5.7)	(1.5)	(1.6)	(10.11	(2.9)	(3.1)

[a] Based on actual ferm-gate prices for October of given year. [b] Figures In parentheses are value-to-cost ratios. [c] Phosphate rock. Price based on 30% P_2O_5. PR adjusted to 46%to be comparable to TSP. [d] Tripie superphosphate. [e] Diammonium phosphate. DAP price adjusted. Remove N component in price by multiplying by 0.72.

OUTLOOK

The events of the past decade have placed the fertilizer sector on a permanent new course. No longer are Western Europe and North America the only primary centers of fertilizer production and use. Major centers of production and use now exist in Eastern Europe, USSR, and Latin America. Most noteworthy has been the emergence of Asia as the leading producer and consumer of fertilizer, particularly N.

A note of optimism

The benefits of increased production and use of fertilizer are clear. No longer do most countries of Latin America and Asia face an insoluble food problem. As a matter of fact, several countries, including China, India, Brazil, and Pakistan, have emerged as exporters of rice, wheat, maize, or soybean. Several other countries appear to be at or near self-sufficiency in one or more of these crops. Leaders in developing countries seem committed to following through on these new strategies with fertilizer as the centerpiece, for successes of the past decade would seem to indicate that such a move is most prudent. Although this may prove to be the correct and only real option over the long run, it may be difficult to maintain such an effort.

A word of caution

Many countries must overcome a number of short-term obstacles if the current momentum in food production is to be maintained. The most notable of these are the following:

- The heavy external debt incurred by many countries in achieving self-sufficiency of food through increased production and use of fertilizer. This is limiting the funds available to finance new ventures.
- The current shortage of local currency in many countries. This makes it difficult to finance the huge subsidies needed to retain the profitability required to produce and use fertilizer.
- The need to improve a nation's diet by redirecting government efforts towards stimulating the production of pulses, edible oils, and vegetables, but without losing the momentum generated in increasing the production of cereals, particularly rice and wheat.

These constraints all point to the difficulty several countries in Asia and Latin America face in maintaining the achievements of the past decade. Compounding this problem is the dilemma that farmers now face in North America, particularly in the USA.

The USA, traditionally the world's major exporter of food, finds its agriculture in deep financial trouble. Selling its agricultural products abroad has become extremely difficult for several reasons: the strong dollar, embargoes on grain to the USSR, world surpluses of wheat, maize, and rice, and stiff competition not only from traditional supply sources like Canada, Australia, France, and Argentina, but also from new exporters like China (maize and wheat), India (wheat), and Brazil (soybean). These difficulties, coupled with high interest rates in the USA, have placed US agriculture in its most tenuous position since the 1930s depression. This uncertainty and economic duress have had a decided impact on fertilizer use, particularly P and K, in the USA and in a number of countries in Western Europe. This impact is compounded further during times of economic crisis, since farmers in these countries are now taking advantage of the high levels of residual P and K in many of the soils, built up over years of heavy fertilization. This residual fertility serves as a hidden reserve already paid for by the farmers and used to economic advantage when crop-to-fertilizer price ratios are unfavorable.

Failure to solve these problems can have a major impact on the rate as well as the location at which increases in fertilizer production and use will occur. These uncertainties make it extremely difficult to forecast future demand for fertilizer.

Fertilizer use forecasts

Political turmoil or an economic crisis in one or more of the leading fertilizer-producing or -consuming countries could cause a major change in growth rates and render meaningless any forecasts made before the disturbance. As uncertain as forecasts are, however, they do serve as a guide for policymakers, marketing executives, and investors in developing plans for fertilizer development. Although several researchers have estimated fertilizer demand for various stages in the future, most have relied on the projections developed by the FAO/UNIDO/World Bank Working Group (6). Therefore, only forecasts from this group will be discussed here.

Nitrogen consumption. The Working Group estimated world N consumption to be 70.2 million t by 1985 and 83.7 million t in 1990. Demand in North America was expected to reach 11.7 million t in 1985 and 13.7 million t in 1990. In contrast, N use in Asia was expected to grow substantially but at a slightly lower rate, climbing to 27.0 million t in 1985 and 31.2 million t in 1990.

Phosphate consumption. The Working Group included ground phosphate rock used for direct application in their P projections, although their earlier discussions did not include this. Worldwide P fertilizer use (including rock) is expected to increase from 13.5 million t in 1982 to 18.3 million t in 1990. This would be a growth of 3.8% annually. The largest regional increase in use will occur in Asia, where a growth of 1.5 million t of P is expected between 1982 and 1990. In relative terms, Latin America and Africa are expected to be the fastest growing regions during the period, their projected annual growth rates are 5.8% and 5.3%. Very little growth in use is expected in Europe, USSR, and Oceania.

Potassium consumption. Worldwide K consumption is projected to increase from 18.9 million t in 1982 to 26.4 million t in 1990. This represents an annual growth rate of 4.3%, The largest regional increase will be in North America where a growth of 2 million t is expected between 1982 and 1990. Latin America and Asia are expected to be the fastest growing regions, each with an annual growth rate of 6.3%. Very little growth is projected for Western Europe.

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Advances in Soil Fertility Research and Nitrogen Fertilizer Management for Lowland Rice

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S.K. De Datta

Basic studies to quantify the fate of the urea N not absorbed by the rice crop under different management practices should complement other research on management and provide a rational basis for developing improved N fertilizers, When urea is surface-applied shortly after transplanting irrigated rice, losses by ammonia volatilization can be large. Results suggest that N recovery efficiency from different fertilizers is inversely related to the concentration of ammoniacal N in the floodwater after fertilizer application. The strategies designed to increase N use efficiency include proper timing of N application, good water management, deep placement of urea fertilizers, use of controlled release or slow release fertilizers, and use of urease and nitrification inhibitors.

There have been many attempts to determine if rice production in Asia will meet future demands, and such studies generally highlight the need for action to increase rice production. Herdt et al (20) reported that cereal production in South and Southeast Asia may increase by 2.2 to 2.8% annually, thereby keeping up with per capita consumption, but demand may well grow by 2.5 to 3.0% each year if income effects are considered.

The same authors (20) contend that increases in rice production will result from a combination of improved water management, varietal improvement, increased fertilizer and pesticide use, increased productivity from nonirrigated areas, and appropriate government policies.

Introducing modern varieties such as Taichung (Native) 1, IR8, and Jaya in the mid to late 1960s encouraged greater use of inorganic fertilizers in Asian rice growing countries. Total fertilizer consumption in Asia is almost five times that in the 1960s (5). The rapid spread of fertilizer-responsive rice and wheat varieties, and the sharp increase in fertilizer prices in 1973 and 1981, caused concern and encouraged scientists to identify the causes of low efficiency and to develop management practices to increase fertilizer efficiency in lowland rice. Some of the factors which cause low farm yields are inadequate N application rates, improper timing of fertilizer application, and faulty application methods (11), but the reasons for the variable efficiencies at different sites are still not known.

The main N fertilizer used for rice in Asia is urea but it is not used efficiently, and the rice crop only recovers about 30 to 40% of the applied N (12).

Therefore, the broad aim of the International Rice Research Institute's (IRRI) soil fertility and fertilizer management research is to generate the

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knowledge and technology to maximize N use efficiency in lowland rice. This paper reviews our progress in identifying the causes of the poor efficiency of urea fertilizer, and in identifying improved fertilizer sources and management practices.

EFFICIENCY OF NITROGEN FERTILIZER

Nitrogen recovery by rice

Most Asian farmers broadcast urea directly into the floodwater two to four weeks after transplanting rice (13). Research by Craswell et al (7) showed that broadcasting urea into floodwater resulted in an average 30% recovery of fertilizer N by the rice crop in dry and wet seasons. Applying two thirds of the urea by broadcasting and incorporating before transplanting, and the remainder at panicle initiation - called best split - increased recovery to 40%.

Using ^{15}N-labeled fertilizer, Savant et al (25) found that rice grown on Maahas clay (Andaqueptic Haplaquoll) recovered 25 to 34% of split-applied urea. Recent experiments on the same soil have confirmed this result, with 33% of the applied N being recovered in the grain and straw at harvest in the dry season and 32% in the wet season (3).

Magnitude of nitrogen loss

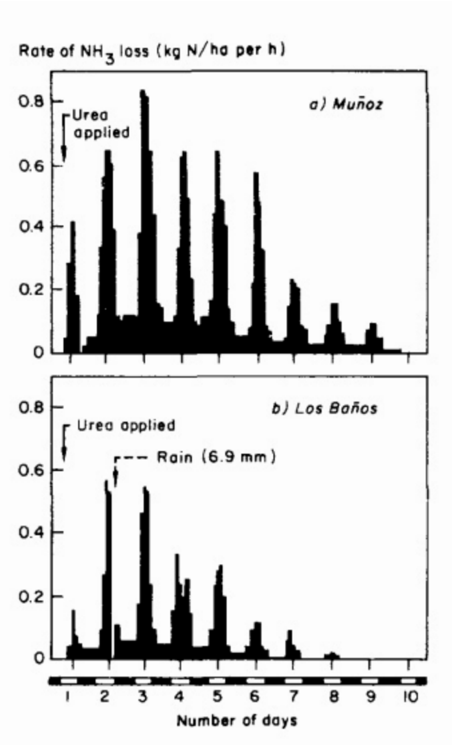
Until recently, the major cause of fertilizer N inefficiency was thought to be nitrification-denitrification in the aerobic/ anaerobic layers of lowland rice soils. This view has been challenged recently, and IRRI and International Fertilizer Development Center research teams have sought to determine the fate of the urea N not absorbed by the rice plant.

Ammonia volatilization. Bouldin and Alimagno (1) revived interest in ammonia volatilization from lowland soils when they reported that up to 60% of the broadcast fertilizer N was lost through ammonia volatilization.

Subsequent intensive field and greenhouse research (23) suggested that ammonia loss from surface-applied urea was about 20% of the applied N. Vlek and Craswell (26) showed that ammonia loss under controlled conditions was directly related to the aqueous ammonia concentration in the floodwater. Other factors known to affect ammonia volatilization are pH and temperature of the floodwater, algal and aquatic weed growth, crop growth, windspeed, and soil properties (8,24,27).

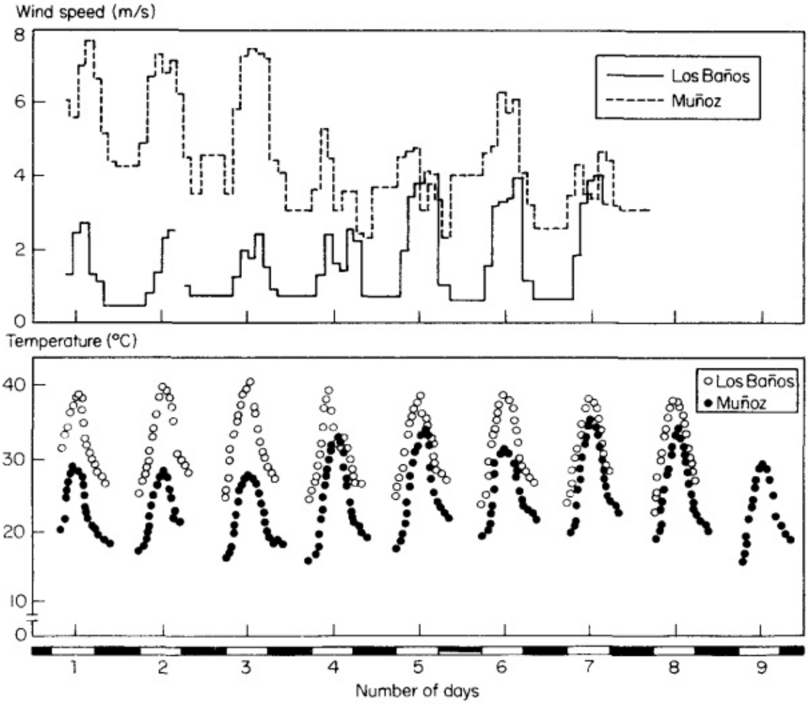
Because environmental conditions influence NH_3 losses, Freney et al (18) advocated that losses be quantitatively assessed under a range of field conditions and with a nondisturbing technique. Fillery et al (15) quantified NH3 loss after urea application to flooded rice using a representative range of fertilizer management treatments and a nondisturbing technique (14) at the Maligaya Rice Research and Training Center in Nueva Ecija, Philippines, and at the IRRI farm in Los Baños. When fertilizer was applied 14 or 2 1 days after transplanting, NH_3 loss accounted for 47% of the N applied at Maligaya and 27% at Los Baños (Fig. 1).

1. Ammonia fluxes following urea application to floodwater, 14 DT and 21 DT at Muñoz: and Los Baños. Reproduced with permission from Soil Science Society of America, Inc. (15).



Research is under way in the Philippines to evaluate simple non-disturbing field techniques to measure ammonia loss (19) by monitoring wind velocity, NH_3 concentration, pH, and temperature of the floodwater (IRRI-Commonwealth Scientific and Industrial Research Organization collaborative project).

Alternative loss mechanism. Until recently, the major cause of N fertilizer inefficiency was thought to be nitrification-denitrification. However, Craswell and Vlek (6) pointed out that much of the supporting evidence for this theory was circumstantial because the gases that are lost - N_2 and nitrous oxide gases - have not been measured directly. To resolve the contribution of NH_3 volatilization to the total N loss after applying urea to flooded fields, experiments were conducted at two locations in the Philippines (17). Total N loss was determined by ^{15}N balance in microplots within fields where NH_3 loss was measured concurrently by a direct, nondisturbing technique. The results suggest that ammonia volatilization accounted for all the loss at Maligaya, but for only 45% of the loss at IRRI. Thus denitrification did not seem to be important at Maligaya but was as important as ammonia volatilization at IRRI. Differences in windspeed and temperature (Fig. 2) and, possibly, soil properties may have accounted for the relative contribution of these alternative loss mechanisms at the two sites.

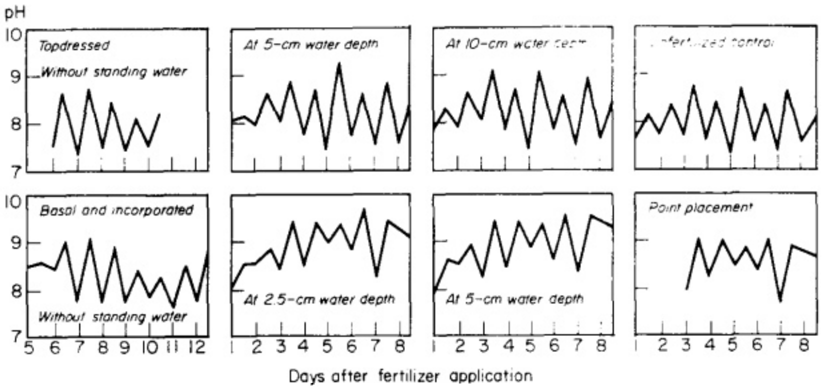


2. Diurnal fluctuations in windspeed and floodwater temperature during field studies after transplanting at Muñoz and Los Baños. Reproduced with permission from Martinus Nijhoff Publishers, Dordrecht (17).

Fate of urea in floodwater. Research at IRRI (7) showed that the efficiency of recovery by rice of various N fertilizers was inversely related to the ammoniacal N concentration in the floodwater immediately after fertilizer application. It also established that urea produced much higher concentrations of floodwater N than ammonium sulfate, presumably because urea is only weakly absorbed by clay colloids.

The effect of water depth and method of fertilizer application on floodwater N concentration, pH, and NH_3 volatilization was evaluated in the 1984 dry season in a farmer's field near San Jose City, Nueva Ecija, Philippines. The highest floodwater pH value (9.6) was obtained in the 2.5 cm deep flooded field with basal application and incorporation of the N fertilizer. In other N treatments, the maximum floodwater pH was 9.0 to 9.5 (Fig. 3). The diurnal changes in pH were pronounced in the treatments without standing water, three to four days after the plots were irrigated (9).

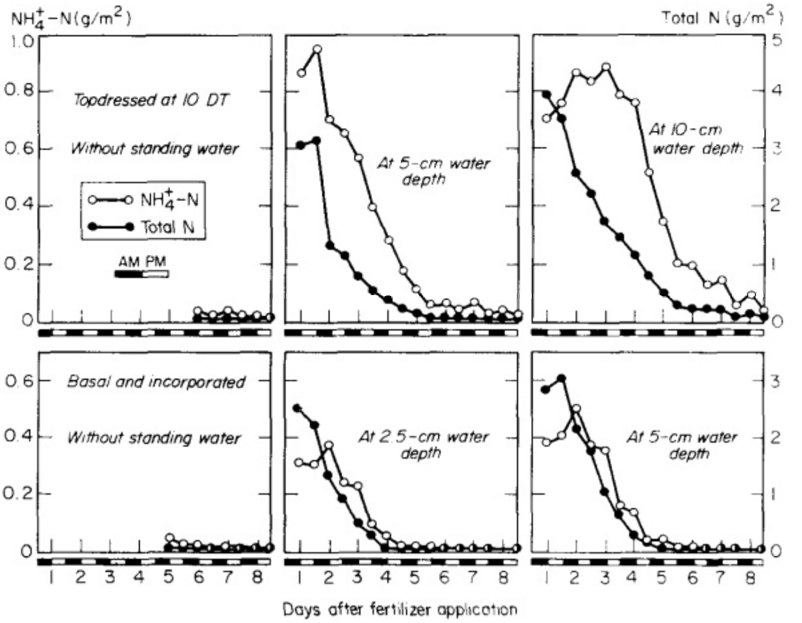
When N fertilizer was applied and incorporated without standing water, NH_4^+-N concentrations were negligible one day after flooding the plot (Fig. 4). With the same treatment and 2.5 cm standing water, NH_4^+-N in the floodwater was 0.3 g N/m^2 on the first and second day, rose to about 0.4 g N/m^2 on the third, and dropped to almost zero on the fifth day. The trend was similar when N fertilizer was incorporated with 5 cm standing water. When fertilizer was



3. Changes in floodwater pH as affected by water depth and fertilizer application method. San Jose City, Nueva Ecija, Philippines, 1984 dry season (9).

topdressed onto the plot without standing water 10 days after transplanting, NH$_4^+$-N in the floodwater was low one day after flooding the plot (Fig. 4).

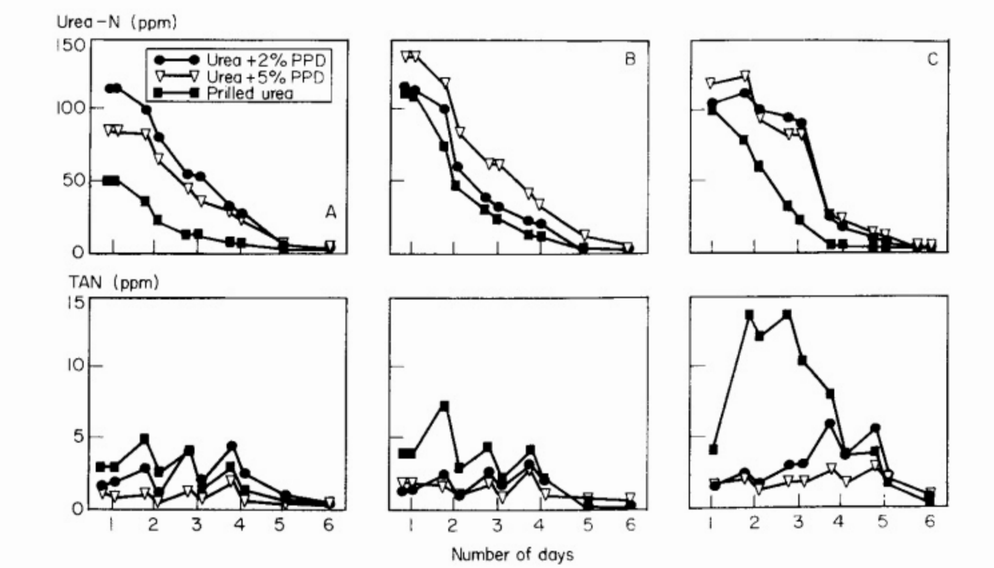
These results show that NHa$_4^+$-N buildup in the floodwater during early crop development can be controlled by the use of suitable management practices.



4. Total N and NH$^+_4$-N concentration changes in floodwater as affected by water depth and method of application. San Jose City, Nueva Ecija, Philippines, 1984 dry season (S.K. De Datta, W.N. Obcemea. and Chen Rong-Ye. unpublished data).

Urea hydrolysis and urease inhibitors. It is impossible to modify windspeed and temperature to restrict NH_3 volatilization in rice fields but it is possible to minimize the buildup of ammoniacal N in floodwater, after urea application, by deep placement (3,23) or the use of modified urea products (7) such as sulfur-coated urea (SCU). The use of SCU and deep placement of urea supergranules (USG) has been evaluated widely throughout Asia with the aid of the International Network on Soil Fertility and Fertilizer Evaluation for Rice (10), but the use of urease inhibitors to limit ammonia volatilization in the field has not been widely examined.

The transformation of urea into ammonium bicarbonate within two or three days of fertilizer application is catalyzed by the enzyme urease. Hydrolysis occurs at the soil-water interface, although the suspended colloids and biomass in the floodwater also show some urease activity (28). Fillery et al (16) studied the effect of phenyl phosphorodiamidate (PPD) on floodwater properties, N uptake, ^{15}N recovery, and grain yield of lowland rice at Maligaya and IRRI. The results suggest that the addition of PPD retarded urea hydrolysis by one to three days, depending on the time and method of urea application. PPD most effectively reduced floodwater ammoniacal N concentrations when applied with urea between 18 and 26 days after transplanting (DT). For example, in the 1982 dry season the maximum ammoniacal N concentration in the floodwater declined from about 14 to about 3 ppm when PPD (5% wt/wt) and urea were applied to the floodwater at 20 DT (Fig. 5). PPD is most likely to reduce potential NH_3 loss when applied with urea two to four weeks after transplanting when ammoniacal N concentrations in floodwater would normally be high (16).



5. Urea and total ammoniacal-N (TAN) floodwater concentrations after applying urea and PPD-amended urea. Los Baños, 1982 dry season. A) Fertilizer sources applied and incorporated before transplanting. B) Fertilizer sources applied immediately after transplanting; no incorporation. C) Fertilizer sources applied 20 DT; no incorporation. Reproduced with permission from Martinus Nijhoff Publishers, Dordrecht (16).

Plant N uptake and grain yield were not significantly affected by adding PPD with urea in three of the four experiments conducted, even though PPD substantially reduced ammoniacal N concentrations in the floodwater (11,16).

Ammonium fixation and release. It is important to quantify the amount of NH_4^+ in nonexchangeable form because it may contribute substantially to the nutrition of the rice plant. The amount of nonexchangeable ammonium released from three lowland rice soils in the Philippines was studied under field conditions using ^{15}N tracers (22). The net release of nonexchangeable NH_4^+ during the growing season was highest for Maligaya silty clay loam and lowest for Guadalupe clay (Table 1). The results show that even though the Santa Rita clay had about three times more nonexchangeable NH_4^+ than the Maligaya soil, it released less nonexchangeable NH_4^+ than the Maligaya clay loam. Fertilizer N rates did not affect the net release of nonexchangeable NH_4^+ (22).

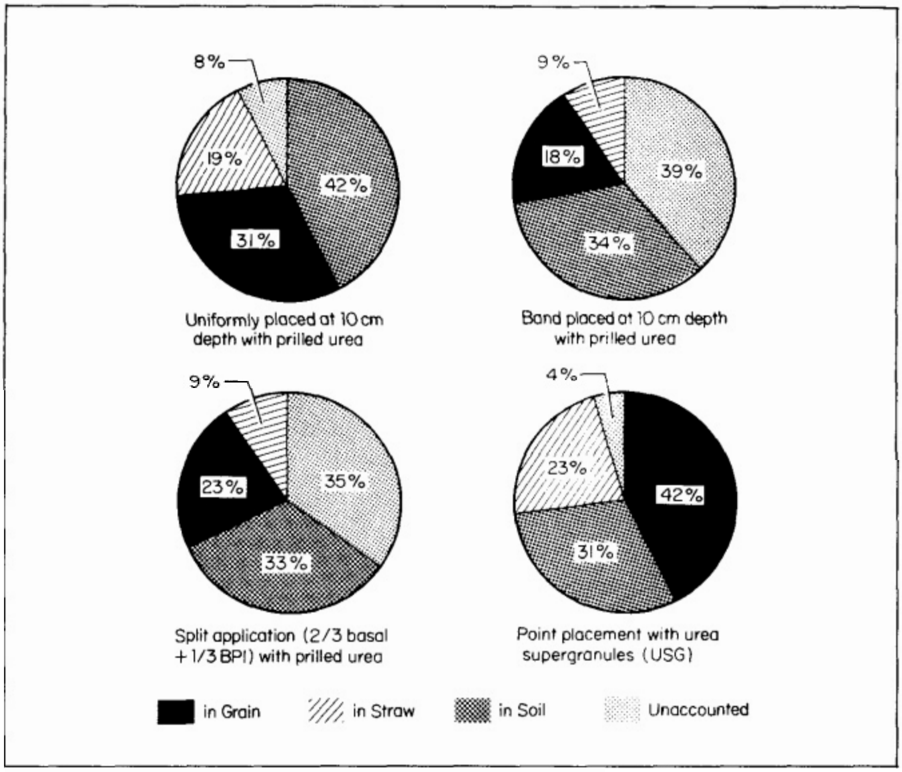
^{15}N balance. Until recently, few ^{15}N balance studies had been conducted in lowland soils. Cao et a1 (3,4) studied the effect of fertilizer placement techniques on the recovery of ^{15}N-labeled fertilizer in plants and soil. They found that the overall ^{15}N recovery was 79-87% with deep placed USG (Fig. 6). The increased N recovery with USG deep placement was due to markedly lower floodwater urea and ammoniacal N concentrations (3). Even in a calcareous soil, urea deep point placement resulted in minimum N loss (5% unaccounted for) and maximum N use efficiency (Fig. 7).

In an IRRI-Justus Liebig University collaborative study, the distribution of labeled N between a number of soil fractions was studied after application of ^{15}N-labeled fertilizer to a Maligaya silty clay loam (Entic Pellustert) (Fig. 8). About 10% of the labeled N was incorporated into the hydrolyzable organic N fraction and about 20% was incorporated into the nonexchangeable N fraction. The total recovery was 60% of the applied N (Fig. 8).

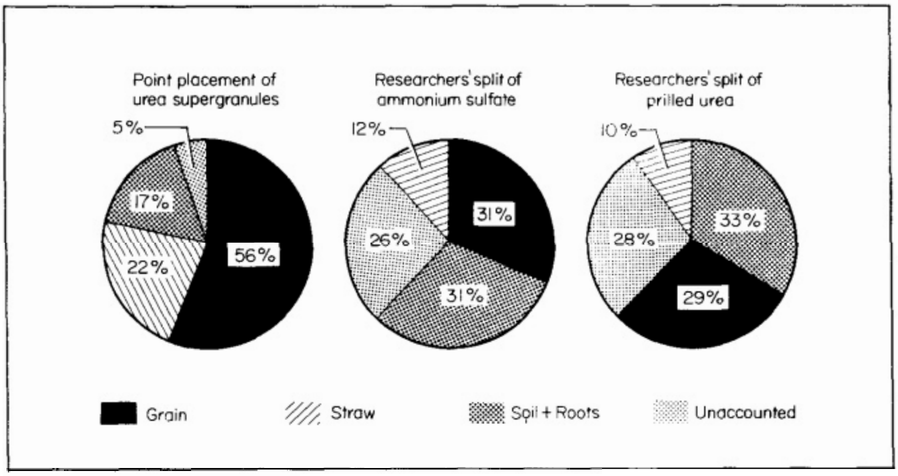
Table 1. Nonexchangeable NH_4^+ content of incubated soils at the beginning and end of the experiment (22).

soil	Nitrogen applied (kg N/ha)	NH_4^+ in oven-dry soli		A
		Beginning (mmol/kg)	End (mmol/kg)	
Maligaya silty clay loam	0	10.3	6.9***	–3.4
	60		7.0***	–3.3
	120		7.5***	–2.8
Guadalupe clay	0	5.3	4.5***	–0.8
	80		4.6**	-0.7
	120		4.5***	-0.8
Santa Rita clay	0	17.5	19.0 ns	+1.5
	60		16.0**	–1.5
	120		15.7**	–1.8

*Significant difference at the 5% level. I *Significant difference at the 1% level. ***Significant difference at the 0.1% level. ns = not significant.

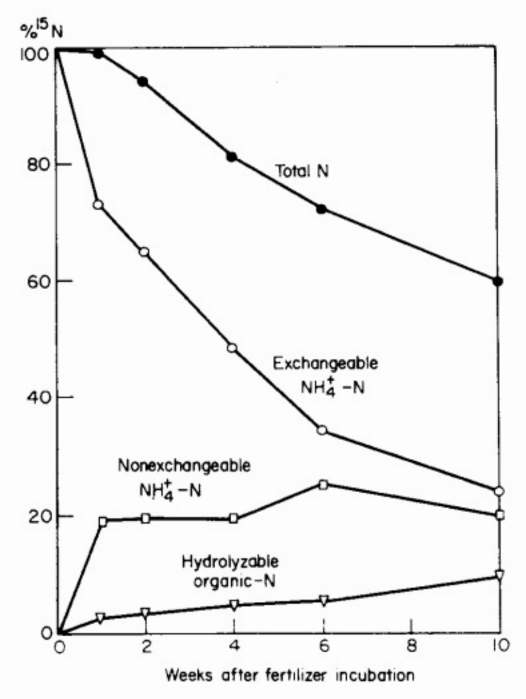


6. Balance of ^{15}N-labeled urea at harvest withvarious placement methods. IRRI, 1981 wet season(3). BPI = before panicle initiation.



7. Balance of ^{15}N-labeled fertilizer at harvest with various application methods in a calcareous soil. Pangasinan, Philippines, 1983 dry season (S.K. De Datta, I.R.P. Fillery, and W.N. Obcemea, unpublished data).

8. Recovery of ^{15}N-fertilizer at various sampling times on Maligaya silty clay loam. Laboratory experiment (H.F. Schnier, K. Mengel, and S.K. De Datta, IRRI-Justus Liebig University cooperative project).



INCREASING NITROGEN USE EFFICIENCY IN LOWLAND RICE

Low soil fertility, and particularly a deficiency of N, is an important constraint on grain yield in rice growing countries. The steadily increasing cost of fertilizer has encouraged the study of methods for improving N fertilizer efficiency in lowland (irrigated and rainfed) rice. One way to increase fertilizer efficiency is to apply the fertilizer when it will be used most effectively for the metabolism or growth of the rice plant. Other ways of increasing fertilizer efficiency are to select the rice variety which makes the most efficient use of soil and fertilizer N, place the fertilizer below the soil surface, use controlled release fertilizer formulations, and use nitrification and urease inhibitors.

Improved timing of nitrogen application

Nitrogen management should maximize N uptake at critical growth stages and ensure that N absorbed by. the plant is used for grain production (absorption efficiency).

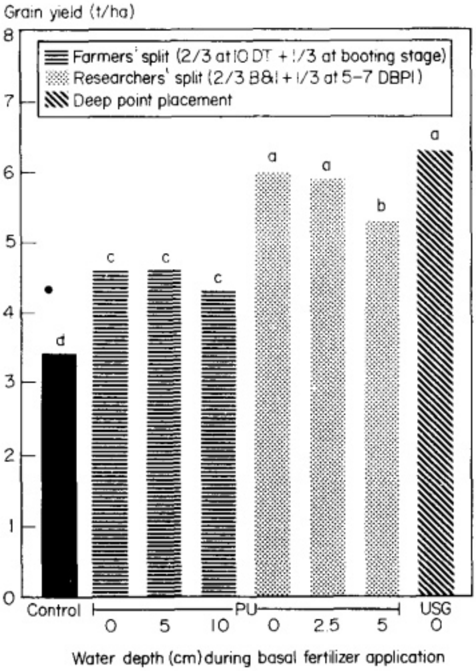
The common farmers' practice of broadcasting fertilizer into the standing water at 10-15 DT causes high N losses. In IRRI studies, fertilizer application and incorporation in the mud without standing water resulted in only 13% of the applied N being detected in the subsequently applied floodwater, compared with the normal farmers' practice where 59% of the N was found in the floodwater. Similarly, yields from plots where N was applied to the soil without standing water were significantly higher (0.9 t/ha in the dry season and 0.5 t/ha in the wet

Table 2. Effect of water depth, application method, and urea source on grain yield of IR58[a] (IRRI, 1984 dry and wet seasons).

Urea source[b]	Application method	N applied (kg/ha)		Water depth (cm) during basal fertilizer application	Grain yield[c] (t/ha)	
		Dry season	Wet season		Dry season	Wet season
-	No fertilizer N	0	-	-	2.9 c	2.7 c
PU	Researchers' split	87	58	0	6.4 a	4.4 a
PU	Researchers' split	87	58	5	5.5 b	3.9 b
PU	Farmers' split	87	58	0	5.4 b	4.1 b
PU	Farmers' split	87	58	5	5.2 b	3.8 b
USG	All basal, hand point placement	87	58	5	6.6 a	4.5 a

[a] Average of four replications. [b]PU = prilled urea, USG = urea supergranule. [c]In a column, means followed by a common letter are not significantly different at the 5% level by Duncan's multiple range test.

season) than yields after application of the fertilizer into standing water (Table 2). New fertilizer management practices based on these findings are now part of the 16-step recommendations of the Philippine Masagana-99 Program. With improved water control at the time of fertilizer N application, the difference between researchers' split and deep point placement is narrower (Fig. 9).



9. IR58 grain yield as affected by water depth and method of application of N fertilizer (X7 kg ha) (San Jose City, Nueva Ecija. Philippines, 1984 dry season). Bars with a common letter are not significantly different at the 5% level (S.K. De Datta, W.Z. Obcemea, and Chen Rong-Ye, IRRI Agron. Dep., unpublished data).

Efficient utilization of soil nitrogen

Eight years of experiments at four Philippine experiment stations have clearly demonstrated varietal differences in the ability of rice to utilize soil and fertilizer N. By exploiting those differences, management practices can be developed to increase fertilizer use efficiency. IR42 utilizes soil and fertilizer N more efficiently than IR36 or IR8, which is also susceptible to insect pests and diseases (Fig. 10).

Data further suggest that there is no need for farmers to revert to traditional tall rices if there is limited money to purchase fertilizers. For example, even without fertilizer N, traditional Peta produced less than the modern varieties IR36 and IR42. With a small increment of fertilizer (30 kg Na), IR36 and IR42 outyielded Peta (Fig. 10).

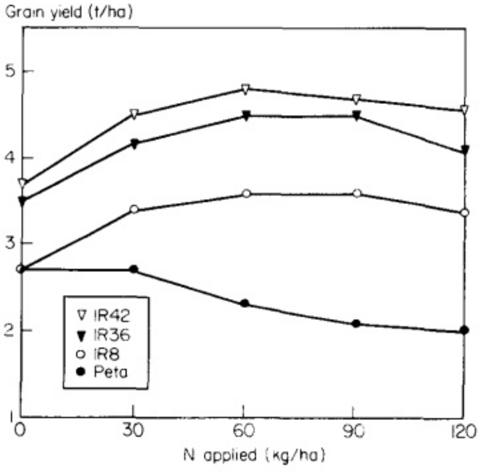
Studies with ^{15}N-depleted ammonium sulfate (IRRI-University of California Cooperative Project) suggest that some varieties depend primarily on soil N while others use fertilizer N more efficiently (2).

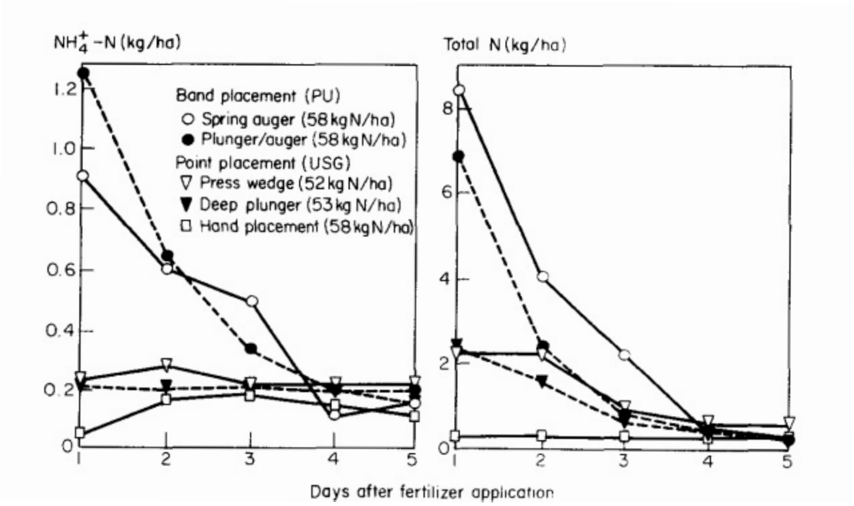
Deep placement of nitrogen fertilizer

Deep placement of urea by machine and by hand was evaluated in 1984 dry season trials in Maligaya silty clay loam, and it was found that the yields obtained with machine point placement were similar to those obtained with hand point placement. Similar promising results were obtained from band placement of urea with a spring auger machine, or point placement with a press wedge. In Maahas clay, machine placement was not as good as hand point placement,

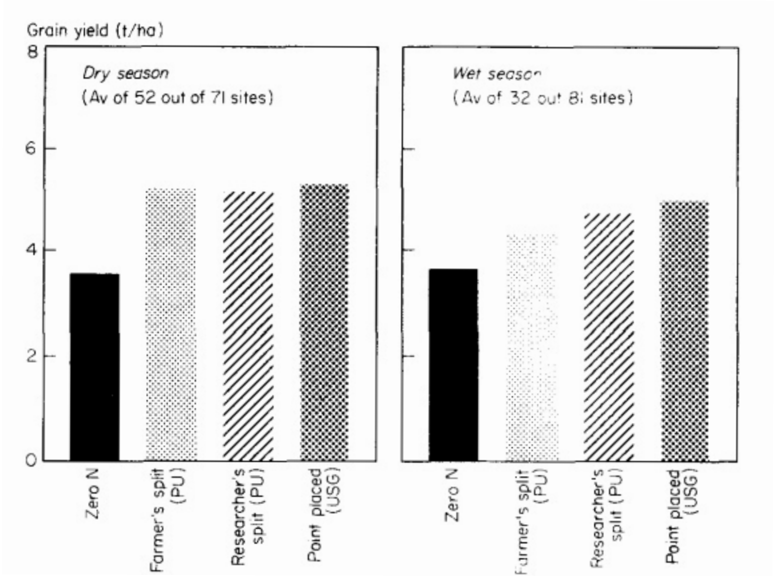
As discussed above, recovery by rice of fertilizer N is inversely related to the ammoniacal N concentration in the floodwater immediately after fertilizer application. Hand and machine deep placement of USG resulted in very low floodwater ammoniacal N concentrations (Fig. 11) and increased yields of rice grain (Fig. 12).

10. Grain yield response of 4 rices to level of N. Data are average for IRRI and 3 experiment stations of the Philippine Bureau of Plant Industry (Maligaya, Bicol, and Visayas). 1976-84 wet seasons (S.K. De Datta, J.P. Descalsota, and B.S. Cia, IRRI Agron. Dep., unpublished data).





11. Floodwater NH_4^+-N and total N (urea + NH_4^+) at 1300-1400 hours as affected by machine- and hand-placed fertilizer. IRRI, 1984 wet season (S.K. De Datta and J.P. Descalsota, IRRI Agron Dep., unpublished data).



12. Yields with deep-placed USG compared with yields with farmers' and researchers' split-applied PU on farms with significant response to deep-placed N. Yield constraints experiments in Nueva Ecija, Tarlac, Bulacan, and Camarines Sur, Philippines, 1982-84. Data are summarized for 52 and 32 trials where significant N response was recorded (S.K. De Datta. F.V. Garcia. W.P. Abilay, Jr., and J. Alcantara, IRRI Agron. Dep., unpublished data).

Controlled release nitrogen fertilizer

SCU is a controlled-release fertilizer that has been widely tested on rice. In most trials, applying SCU produced grain yields similar to those obtained with deep point placed USG. In general, SCU was more effective than PU (Table 3).

Table 3. Number of trials in which rice responded positively to SCU and USG when compared separately with PU (Fifth International Trial on N Fertilizer Efficiency in Wetland Rice 1981-1983) (21).

Country	Total	No. of trials		
		SCU>PU	USG>PU	No response
Bangladesh	4	2	2	0
Burma	5	0	0	3
Cameroon	1	0	0	0
China	6	3	4	0
India	35	18	19	1
Indonesia	26	2	5	3
Nepal	4	0	0	2
Philippines	22	8	6	4
Thailand	1	0	1	0
Vietnam	5	1	1	1
Total	109	34 (36)[a]	38 (40)	14

[a] Values in parentheses are percentages of the 95 trials where a positive response to N was obtained.

Use of nitrification and urease inhibitors

The potential of nitrification and urease inhibitors for increasing N fertilizer efficiency was evaluated over a three-year period. The use of dicyandiamide, a nitrification inhibitor, did not increase grain yield. IRRI field trials with PPD showed that it retarded urea hydrolysis and delayed the appearance of aqueous ammonia in the floodwater. Its use, however, did not increase grain yield or total N uptake when compared with the control without urease inhibitor.

COOPERATIVE FARM LEVEL NITROGEN RESEARCH

Fertilizer management practices such as deep placement and optimum timing of fertilizer applications were evaluated in farmers' fields in a cooperative program involving Thailand, Indonesia, Bangladesh, and the Philippines. Through the

Table 4, Nutrient removal by an IR36 crop with and without fertilizer N in a farmer's field (Calauan, Laguna, Philippines, 1983 dry season).

Nutrient element	Nutrient removed by crop at harvest (kg)					
	Without fertilizer			With 174 kg N/ha		
	Straw	Grain	Total	Straw	Grain	Total
N	18	34	52	75	143	218
P	2	10	12	5	26	31
K	59	10	69	232	26	258
S	0.8	1.0	1.8	3.3	4.9	8.2
	Yield (t/ha)					
Grain		3.4			9.8	
Straw		2.8			8.2	

INSFFER program and farm-level testing of the technology developed at IRRI, research results are fine-tuned to assure rapid adoption by national programs.

Research on integrated N management aims to determine the long-term effects of complementary use of inorganic and organic N sources such as green manures, *Azolla,* rice straw, and straw compost on soil fertility and productivity. Monitoring fertility changes under intensive cropping is vital for maintaining stable soil fertility and high yields in resource scarce situations.

Modern rice varieties such as IR36 would remove less N, P, K, S, and Zn, and produce lower yields without fertilizer N than with high levels of fertilizer N (Table 4). Nevertheless, fertilizer technology that will produce relatively high grain yields with low rates of fertilizer N is now available for use by farmers in South and Southeast Asia.

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The Photosynthetic Aquatic Biomass in Wetland Rice Fields and Its Effect on Nitrogen Dynamics

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I. Watanabe

The photosynthetic biomass that develops in the floodwater of wetland rice fields affects nitrogen dynamics in the ecosystem. This review summarizes available data on the nature, productivity, and composition of the photosynthetic aquatic biomass, and its major activities regarding the nitrogen cycle, i.e., nitrogen fixation by free living blue-green algae and *Azolla,* nitrogen trapping, nitrogen accumulation at the soil surface, its effect on nitrogen losses by ammonia volatilization. nitrogen recycling, and the supply of nitrogen to the rice crop.

Transformation of nitrogen (N) has been a major topic of edaphological studies of flooded rice fields, but attention has concentrated on the soil. Recent studies of N losses by volatilization of ammonia provide some information on transformation of N in the floodwater. However, investigations on the ecological aspects of N dynamics in floodwater including exchange of nutrients between the reduced soil and the oxic-photic zone are very limited (87).

After flooding and transplanting, five major subsystems can be distinguished in a wetland rice field: the floodwater, the surface oxidized layer, the reduced puddled layer, the subsoil, and the rice plant. Floodwater and the oxidized layer are oxic-photic environments where a photosynthetic biomass of algae and aquatic macrophytes develops in addition to rice. Because of a similar oxic-photic status and the movements of algae and invertebrates between the two, the floodwater and oxidized layer are usually considered a continuous ecosystem where four major mechanisms are operating in relation to soil fertility: 1) biological nitrogen fixation (BNF), 2) N losses by volatilization of ammonia (partly due to the photosynthetic activity of the submerged biomass) and by the nitrification-denitrification process, 3) trapping and recycling by the photosynthetic biomass of C, N, and mineral salts released from soil and fertilizers, resulting in N and C accumulation at soil surface, and 4) transport of nutrients from the soil to the water by the primary consumers. The intensity of these activities is directly related to the properties of the floodwater and the activity of the biomass present in land.

The chemical status of standing water depends primarily on that of the irrigation water and the soil. However, large variations in composition occur during the crop cycle and within a field plot in relation to: 1) fertilizer

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application, 2) mechanical disturbances of the soil causing dispersion of soil particles in the water, 3) the nature and the biomass of the aquatic communities, 4) dilution by rain and irrigation water, 5) absorption by surface soils, and 6) rice growth. Diurnal variations are mainly regulated by the activity of the photosynthetic biomass which causes large variations in dissolved O_2 and CO_2, and in pH. As the crop grows, diurnal variations become less marked due to shading by the rice canopy.

Major components of the biomass in the standing water and at the soil-water interface are phytoplankton, aquatic macrophytes (mainly submerged and floating plants), bacteria, zooplankton, and aquatic macro-invertebrates. Among these, the photosynthetic aquatic biomass composed of primary producers is quantitatively the most important.

This paper summarizes the current knowledge of the photosynthetic biomass and its effects on N dynamics in wetland rice fields.

MAJOR CHARACTERISTICS OF THE PHOTOSYNTHETIC AQUATIC BIOMASS

Nature of the components

The submerged photosynthetic aquatic biomass is composed of photosynthetic bacteria, algae, and vascular macrophytes.

Algae are primitive plants devoid of true leaves or seeds. They reproduce by vegetative, asexual, and sexual means. Morphologically, algae present in rice fields can be categorized into three groups.

- Planktonic algae, some of which give rise to blooms, including unicellular, colonial, and simple filamentous forms.
- Filamentous green algae such as *Cladophora* (cotton mat type), Spirogyra (slimy and green type), *Hydrodictyon* (water net type), etc., which frequently form a scum.
- Macroalgae such as *Chara* and *Nitella* which, though nonvascular, resemble vascular plants, possess stems and branches, and grow as anchored plants.

Physiologically algae can be classified into N_2-fixing and non-N_2-fixing forms.

- Nitrogen-fixing algae belong exclusively to the blue-green algae (BGA) which are procaryotic. Their growth adds N to the ecosystem.
- Non-N2-fixing algae consist of some BGA and all eucaryotic algae.

Aquatic vascular macrophytes are usually divided into three groups.

- Submerged forms growing beneath the water surface and rooted to the soil.
- Surface or free-floating forms having a majority of their leaves and flowers near the surface of the water. Both rooted and free-floating species occur in this group. They possess special parenchymatous tissues for buoyancy.
- Emersed or marginal forms growing in shallow water or on wet soils.

In this review we restrict the discussion to algae, and submerged and floating macrophytes.

Quantitative variations during the crop cycle

Phytoplankton and filamentous algae. Information on the biomass variations of algae during the rice crop cycle has been summarized by Roger and Kulasooriya (60). Dense algal blooms observed just after transplanting (66) may be due to fertilizer application or plowing or both and to high light availability. In rice fields in Japan, the maximal algal biomass was observed in about two weeks (41) or one month (30) after transplanting and the subsequent decrease of the biomass was related to consumption by grazers and deficient light under the rice canopy. In the Ukraine, maximum algal growth was observed just before tillering (56). In rice fields in Senegal the maximum biomass developed between tillering and panicle initiation (62). In upland rice fields in India a similar algal evolution was observed, while in lowland fields the maximal biomass was observed slightly later (26). In the Philippines during the dry season, algal density was highest just after heading stage of the rice crop, while during the wet season development was at a maximum after harvesting (86), probably because of an increase in light availability. Roger and Kulasooriya (60) concluded that maximal algal biomass could develop at any time in the rice crop cycle and is mainly related to fertilizer application and micro-environmental conditions, especially light availability as affected by the season and the rice canopy.

Macrophytes. Little information is available on the variation of the macroalgal and vascular macrophyte biomass in wetland rice fields. In a recent study, Vaquer (75) reported the evolution of *Chara* spp. and *Najas* minor biomasses in rice fields of the Camargue (France). After a slow growing phase of about 2 weeks following spore germination, Chara grew exponentially to a maximal biomass (1 5 to 65 g DW/m^2) 2 to 3 weeks later. Biomass then decreased gradually through the crop cycle. The sigmoid growth curve reported by Westlake (90) proved to be a good model for Chara growth. After the exponential phase, growth decreased because of self-shading and the increasing density of the rice canopy. Vaquer also reported that grazing of Chara by chironomid larvae is a reason for the decline of the standing crop.

Biomass and productivity

Phytoplankton and filamentous algae. Probably because of methodological difficulties in estimating algal abundance, quantitative evaluation of algal biomass in kg/ ha is scarce. From the available data it appears that total algal biomass evaluations range from a few kg/ha to 24 tons FW or 500 kg DW/ha (60 and Table 1). Reported N_2-fixing algal biomass evaluations also range within the Same limits. However, these data are of little value without information on water and/or ash contents, which vary within very large limits; extrapolation to kg N/ha is hazardous.

Blooms from six strains of N_2-fixing BGA growing for 2 to 3 weeks in soil trays with ample available P and in the absence of predators (Table 2) produced standing biomasses equivalent to 170 to 270 kg DW/ ha, on an ash free basis, and corresponding to 10 to 20 kg N/ha (34). In microplots with five soils from the Philippines flooded for two months, standing algal biomass ranged from 213 to

Tabla 1. Biomaas of planktonic algae in rice fields (60, 64).

Location	Dry weight (kg/ha)	Fresh weight (kg/ha)	Remarks
China		7 500	After inoculation
India	3-300	60-6 000	Green algae dominant
	32	600	N-fixing BGA dominant
USSR		16 000	Total algal biomass
Senegal		2-6 000	Total algal biomass
		2-2 300	N-fixing algal biomass
Philippines	2-114		
India	480	9 000	*Aulosira* bloom
India		100-2 100	
Philippines	177	24 000	*Gloeotrichia* bloom

Table 2. Composition and productivity of monospecific soil based inocula of nitrogen fixing blue-green algae (Roger et al, unpublished data).

Strain	Soil-algal mat				BGA (calculated on ash free basis)		
	Dry wt (kg/ha)	N (%)	C (%)	Ash (%)	Dry wt (kg/ha)	Algal N (kg/ha)	N (%)
Soil before inoculation	-	0.150	1.33	84.4	-	-	-
Anabaena variabilis	313	0.509	3.78	78.5	176.0	15.94	6.32
Aulosira fertilissima	470	0.545	3.92	79.0	278.6	13.24	7.03
Fischerella sp.	273	0.758	4.73	78.4	212.5	13.29	5.88
Nostoc sp.	377	0.563	4.25	79.3	252.1	11.50	6.53
Scytonema sp.	430	0.444	3.24	81.3	188.3	18.98	6.81
Tolypothrix tenuis	356	0.514	3.92	79.8	226.2	16.91	7.96

Table 3. Standing crops and productivity of some submerged aquatic macrophytes (64).

Species	Standing crop		Productivity (t DW)	Location
	Fresh wt (t/ha)	Dry wt (t/ha)		
Chara sp.	9-15			Rice fields, India
Chara and *Nitella*	5-10			Rice fields, India
Ceratophyllum *demersum*		6.8	9.0	Temperate lake, USA
Hydrilla verticillata			2.5	Florida, USA
Najas guadalupensis		1.1		USA
Najas and *Chara*		0.4		Rice fields, Philippines
Nymphoides aquaticum		1.8		USA
Sagittaria subulata			23.2	Florida, USA
Sagittaria eatonii			27	Subtropical spring
Thalassia testudinum			33.5	Puerto Rico
Total submerged vegetation	1-3			Rice fields, Philippines
Total submerged vegetation	7.5			Fallow rice fields
Total submerged vegetation	25-30			Weedy canal

540 kg DW/ha when grazer populations were controlled with pesticides of plant origin, whereas it ranged from 67 to 257 kg DW/ha when grazers were not controlled.

Macrophytes. The productivity of aquatic macrophytes in rice fields (Table 3) seems to be higher than that of algae (Table 1). The biomass of submerged weeds (mainly *Chara* and *Najas*) was studied in 44 plots at the IRRI farm (40). It was found that the population of submerged weeds under a rice crop at the end of tillering had a mean biomass of about 1 t/ha (range, 0.4 to 3 t FW/ha) and that it increased at maturity to a mean of 3 t/ha (range, 0.2 to 4.5 t/ha). The highest values, which ranged from 2.7 to 12 t/ha, with a mean of 7.5 t/ha, were recorded in fallow plots. Twenty measurements of floating and emersed weeds in planted fields at the tillering stage gave a mean value of 1.7 and a maximum value of 4.1 t FW/ha. Measurements conducted by the IRRI Agronomy Department over 9 crops in 3 years (De Datta, personal communication) gave similar variations, ranging from 70 to 2 400 kg DW and averaging about 500 kg DW/ha.

In some cases, submerged weeds develop a very high biomass. Mukherji and Ray (cited in 6) reported that the growth of Chara and Nitella is favored by high temperatures (27-35°C) and slightly alkaline water. According to them, clear days with most of the rainfall at night, which allow the muddy water to clear in the day and light to penetrate the water, helped in rapid and luxuriant growth of *Chara* and *Nitella* (5 to 10 t FW/ha) in very large areas (about 50 000 ha in India). The biomass produced by *Chara* was reported to be 9 to 15 t FW/ha (51). Charophyta is the most important component of the submerged vegetation of the rice fields of the Camargue, and biomass may reach 1 t DW/ ha after two months of submersion (75).

Productivity. Limited data are available on the photosynthetic productivity of the floodwater. In the Philippines, Saito and Watanabe (66) reported that net carbon production of the floodwater community was 50 to 60 g C/ m^2 in 90 days. The standing biomass of algae ranged from 2 to 114 kg FW/ha while the maximum standing biomass of submerged weeds (*Najas* and *Chara*) was 400 kg DW/ha. The total primary production of the floodwater community was equivalent to values in eutrophic lakes, and corresponded during the cropping period to 10% of that of the rice plants in a fertilized plot and to 15% of that in a nonfertilized plot. A similar value (71 g C/m^2 in 144 days) was reported elsewhere (93).

Chemical composition

The average composition of aquatic macrophytes is 8% dry matter, 2 to 3% N (DW basis), 0.2 to 0.3% P, and 2 to 3% K. Planktonic algae have higher N contents (3 to 5%). On a DW basis, this composition is very similar to that of many green manures except for K in macrophytes and N in planktonic algae, which are higher (64).

When considering the photosynthetic biomass and its role in the N cycle, although the most important component is obviously N, dry matter and ash contents are also of value in assessing the significance of biomasses recorded in terms of FW or DW/ha.

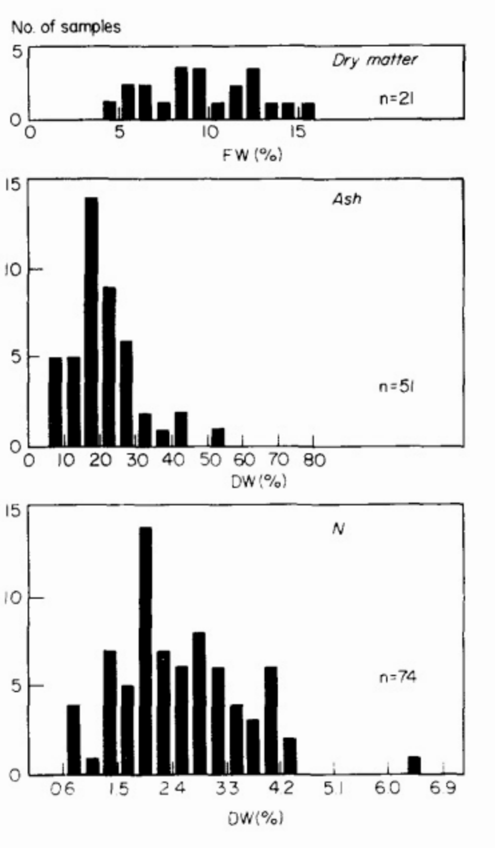
Phytoplankton and filamentous algae. Milner (50) pointed out the scarcity of information on the composition of freshwater algae; this is still true today. Table 4 gives the composition of natural samples of freshwater filamentous and microalgae, and shows how variable the composition can be. Dry matter content ranges from 1 to 15%, ash content from 12 to 59%, and nitrogen content (DW basis) from 1 to 6%. The relatively low N content, when compared with laboratory samples, is partly due to the higher ash content of the natural samples. From the analysis presented in Table 4 it appears that BGA have a low dry matter content, and their average N content might not be as high as previously thought (13). Mucilagenous BGA can develop very impressive blooms, but the corresponding N content may be low. A Nostoc biomass of 13 t FW/ha, which corresponds to an almost continuous layer of colonies 1 to 4 cm in diameter, frequently has a total N content of less than 5 kg/ha (Roger, unpublished). This is due to a low dry matter content and a very high ash content.

Macrophytes. Because of increasing interest in eutrophication of water bodies, more information is available on the composition of macroalgae and other aquatic weeds (Fig. 1). Little (43) summarized papers on tropical and temperate species and concluded that the ingredients of aquatic plants other than water are similar to those of terrestial plants.

Table 4. Dry matter, ash, and nitrogen content in natural samples of some planktonic and filamentous algae.

	DW (% FW)	Ash (% DW)	N (% DW)	P (%DW)	K (% DW)	Reference
Anabaena	4.2	13.3	5.73	0.35	0.42	a
Aphanizomenon	n.a.	n.a.	5.76	0.54	n.a.	(71)
Aphanothece	1.3	43.8	2.71	0.18	0.60	b
and *Gloetrichia*	n.a.	58.8	1.75	0.07	0.39	b
and *Nostoc*	1.5	58.5	2.22	0.12	0.33	b
Aulosira	7.6	25.6	5.43	0.33	0.36	a
Cladophora	n.a.	26.5	2.90	n.a.	n.a.	(89)
Cladophora	14.8	31.7	3.72	0.48	5.01	a
Cylindrospermum	8.4	34.4	3.82	0.35	0.17	a
Euglena	n.a.	19.5	5.37	n.a.	n.a.	(69)
Gloeotrichia	1.1	24.8	2.74	0.13	0.29	a
Hydrodictyon	3.9	11.9	3.66	n.a.	n.a.	(3)
Hydrodictyon	n.a.	24.4	2.52	n.a.	n.a.	(69)
Lyngbya	n.a.	17.2	5.02	n.a.	n.a.	(3)
Nodularia	n.a.	n.a.	2.8	0.18	n.a.	(27)
Nostoc	n.a.	47.4	2.75	0.14	0.28	b
Oedogonium	n.a.	12.7	2.54	n.a.	n.a.	(3)
Pithophora	14.9	27.4	2.68	n.a.	n.a.	(3)
Rhizoclonium	n.a.	19.8	3.45	n.a.	n.a.	(3)
Spirogyra	4.8	11.7	2.75	n.a.	n.a.	(3)
Spirogyra	n.a.	n.a.	1.00	0.10	n.a.	(27)
Spirogyra	n.a.	14.4	2.52	n.a.	n.a.	(69)

n.a. = not available. [a]P. M. Reddy and P. A. Roger, Unpublished data. [b]P. A. Roger et al, unpublished data.



1. Dry matter. ash, and N contents in freshwater submerged macrophytes. Genera analyzed (number of samples in parentheses) are: *Ceratophyllum* (4), *Chara* (5), *Egeria* (I), *Elodea* (10), *Hydrilla* (3), *Myriophyllum* (13), *Nitella* (1), *Nymphoides* (2), *Najas* (4), *Potumogeton* (17). and *Vallisneria* (5). Sources all cited in 43.

A high water content is certainly the overwhelming characteristic of aquatic plants; an average water content of 92% has been suggested (44). For comparison, terrestial forage plants contain 70 to 90% water.

A second characteristic of aquatic plants is the high content of ash, which varies with location and season (67). Sand, silt, and encrusted carbonates often account for much of the mineral content. Although silt is most frequently removed during analysis, in practice it represents part of the chemical composition of the harvest. Submerged macrophyte communities contain, on average, 21% ash on a DW basis, floating communities average 11.5%, and upland plants usually contain less than 10% (67).

A third characteristic of aquatic plants is the large variability in composition (as in algae), which is influenced by the composition of the water in which they grow. Lawrence and Mixon (42) have shown how aquatic plants growing in water containing ample quantities of P and K will exploit the situation by ‘luxury consumption’ of these elements, far in excess of the amount they need for healthy growth. An extensively quoted example is the K uptake by *Alternanthera philoxeroides* in which the consumption is 20 times more in fertilized pools compared to that in unfertilized pools (7.3% vs 0.36%).

NITROGEN FIXATION

Spontaneous N_2-fixation in rice fields

Photodependent N_2-fixing organisms in wetland rice fields consist of photosynthetic bacteria, free-living BGA, and symbiotic BGA in *Azolla.*

The presence of photosynthetic bacteria has been recorded in rice soils but their contribution in terms of kg N/ha is very low (65).

Free-living BGA are especially abundant and active in submerged soils, which partly explains why wetland rice can be grown on the same land year after year without N fertiizer and can produce low but consistent yields. Since De (7) first pointed out the role of BGA in the N fertility of rice soils, many studies have been conducted to elucidate this role. However, amounts of N fixed by BGA in flooded rice fields have not yet been satisfactorily estimated because of technical difficulties in the assessment. Reports of amounts of N_2 fixed in flooded rice soils were reviewed recently (60); the average of 38 evaluations was 27 kg N/ ha per crop and the highest was 80 kg N/ ha per crop. A value of 30 kg N/ ha fixed per crop seems to be a reasonable estimate of photodependent N2-fixation for the cases when BGA growth is visible. A full cover of BGA in the field contains from 5 to 20 kg N/ha depending on the BGA species (Roger et al, unpublished). Factors that lead to the development of a N_2-fixing algal bloom are still poorly understood and may include depletion of N in the floodwater, P availability, low CO_2 concentration due to alkaline reaction, low grazer populations or presence of algal populations resistant to grazing, and optimal temperature and light intensity.

Azolla is an aquatic fern which harbors the symbiotic N_2-fixing BGA Anabaena *azollae.* Spontaneous development of Azolla in rice fields is less frequent than that of BGA. Azolla needs to be inoculated and cultured before it can be used as green manure (81).

Agricultural practices to encourage free living N_2-fixing BGA growth

Until recently research on methods for using BGA in rice cultivation has emphasized algal inoculation (algalization) alone or together with agricultural practices favoring the growth of inoculated strains. This arose from the earlier belief that N_2-fixing strains were not normally present in many rice fields. Data on the occurrence of N_2-fixing BGA in rice fields are unreliable because unsuitable sampling and evaluation procedures probably resulted in some underestimated values. Reported percentages of soil samples exhibiting N2-fixing BGA vary widely: 5% in Asia and Africa (88), 33% in India (76), 71% in Japan (53), 95% in Senegal (59), 100% in Thailand (46), and 100% in the Philippines (Roger et al, unpublished data). N2-fixing strains are now known to be ubiquitous in rice fields. Therefore, equal importance should be given to algal inoculation and to agricultural practices that enhance the growth of indigenous BGA.

Algal inoculation. Since the agronomic potential of BGA was recognized in 1939 by De, many trials have been conducted in India, Japan, China, Egypt, Burma, and the Philippines to increase rice yield by algal inoculation.

Experiments have demonstrated that N_2-fixing BGA are a possible additional source of N for rice. However, biomass and N_2-fixation measurements, as well as results of inoculation experiments (60) indicate that BGA have a lower potential for increasing rice yield than legume green manures or *Azolla* (65).

Successful experiments on inoculation with free-living BGA have shown an average increase in yield of 14% (Table 5). Comparison with N fertilizer indicates an effect equivalent to the application of 30 kg N/ha (78). There are many uncertainties about algal inoculation. In successful field experiments, a similar yield increase was obtained with inoculation in the absence and in the presence of N fertilizer. Since N_2-fixation of free-living BGA in floodwater is depressed by mineral N, any yield increase attributed to inoculation in the presence of N fertilizer is difficult to understand simply in terms of N_2-fixation by BGA and may involve other effects. Therefore, the way in which BGA inoculation affects rice yield is still obscure.

In some algal inoculation trials, algal inoculum was spread several days after N fertilizer application. High loss of applied N, especially in alkaline soils, might have eliminated the negative effect of combined N on N_2-fixing ability of BGA. It must also be recognized that there might have been many nonpositive effects on yield which were not reported, because such data are seldom published. If such results are made available and considered, it may bring down the overall average yield increase in inoculation experiments. In most cases, quantitative analysis of BGA biomass, N_2-fixation rate, and the establishment of inoculum have not been reported. Reports on the area under algal inoculation

Table 5. Effect of algaliration on grain yield of rice (60).

Experimental	Grain yield in the control (kg/ha)	Variation in grain yield due to algalization	
		Relative (%)	Absolute (kg/ha)
Pot experiments			
Mean	-	42.0	-
Standard deviation	-	59.6	-
Number of data	-	64	-
Field experiments			
Mean	3 016	14.5	475
Standard deviation	803	8.9	274
Number of data	30	102	80
Field experiments without N fertilizer			
Mean	2 979	14.6	442
Standard deviation	789	10.4	267
Number of data	25	39	36
Field experiments with N fertilizer			
Mean	3 434	14.3	488
Standard deviation	867	11.8	269
Number of data	13	44	38

Location and number of experimental sites: India, 30; Japan, 5; China, 3; Egypt, 3; Philippines, 1; USSR, 1.

are unreliable; but even considering the most optimistic evaluations, use of algal inoculation seems to be restricted to a very limited area in a few Indian States (Tamil Nadu and Uttar Pradesh), Egypt, and Burma (65).

Current utilization of BGA is limited by lack of reliable technology. Quality of the inoculum and its establishment in the field are the two major factors. In the published methods of inoculum production, no test for assessing the composition and viability has been included. It has been shown that in many inocula the density of colony forming units of BGA varied from 10^3 to 10^7 per g of dry inoculum. In the so-called multistrain inocula only one or two species were dominant, and N_2-fixing strains were seldom dominant (34). Special attention must, therefore, be paid to the quality of inocula.

It seems more appropriate to consider that algal inoculation is at the stage of large field testing rather than ready for adoption by farmers. Before trying to disseminate ‘algalization’ in a wide range of environmental conditions, intensive research should be directed towards field problems to make it a more reliable technology rather than recommending it as a ‘blind’ technology developed on a ‘trial and error’ basis. To achieve this, attention has to be paid to the ecology of inoculated and indigenous algae, the development of high quality inoculum (high viable cell density of multiple species), the factors responsible for successful establishment of inoculum, and the effects of BGA on rice growth, other than N_2-fixation.

As indicated above, recent ecological studies showed that N_2-fixing BGA are widely distributed in rice fields. This indicates that in many rice soils adoption of agricultural practices favoring the growth of indigenous strains may be sufficient. Practices known to favor growth and N_2-fixation by BGA are summarized as follows.

Phosphorus and lime application. Soil properties that limit the growth of N_2-fixing BGA in rice fields are most commonly low pH and P deficiency. Application of P and lime has frequently increased growth of BGA, particularly in acidic soils (31,82). In the most responsive soils, the increase in N_2-fixation was estimated to be 0.7 to 1.2 g N/g P_2O_5 applied (31).

Nitrogen fertilizer deep placement. A study of different methods of N fertilizer application on the algal flora and photodependent N_2-fixation by Roger et al (61; Table 6) has shown that surface broadcast application of N fertilizer, which is widely practiced by farmers, not only inhibits photodependent

Table 6. Effects of fertilizer placement on the algal flora and nitrogen fixation in a field experiment 28 days after treatment (61).

Treatment	Control	Urea supergranule (deep placement)	Urea (broadcast)
ARA	70	48	0
mmol C_2H_4/m^2 per hour (% of the control)	100	69	0
Chlorophyll a (mg/cm^2)	12.4	12.3	21
Number of nitrogen-fixing blue-green algae/cm^2	2.0 x 10^5	1.7 x 10^5	7.0 x 10^4
Number of green algae/cm^2	104	5.0 x 10^5	1.0 x 10^7

N_2-fixation but also encourages the growth of green algae. A profuse growth of green algae increases the pH of the floodwater, encouraging fertilizer losses by ammonia volatilization. In contrast, deep placement of N fertilizer not only decreases the losses of N fertilizer by volatilization but also does not disturb the natural algal N_2-fixing system, thus providing extra input of N to the ecosystem.

Straw application. Beneficial effects of surface straw application on BGA growth and photodependent N_2-fixation have been reported (32,47,63). Decomposition of straw probably results in an increase of CO_2 and decrease of mineral N and O_2 concentrations in the floodwater, and the development of microaerobic microsites within the straw. Increased CO_2 availability and low N concentration favor the growth of N2-fixing BGA, and low O_2 concentration in the photic zone may increase their specific N_2-fixing activity.

Grazer control. Invertebrates like cladocerans, copepods, ostracods, mosquito larvae, snails, etc. are common grazers of algae in rice fields. The development of such populations prevents the establishment of algal inocula and causes the disappearance of algal blooms within one or two weeks (29,84). Recommended doses of some insecticides have been shown to enhance algal growth (57) and sometimes favor BGA growth over green algae and diatoms (60). Development of grazer population can be controlled by cheap pesticides of plant origin (20,24) and by drying the fields. In a greenhouse experiment in soil trays, we found that controlling grazers by the application of 10 g/m^2 of crushed neem (*Azadirachta indica*) seeds resulted in enhanced growth of BGA and N2-fixation ranging from 1.5 to 6.0 g N/ m^2 in two months, depending on the soil type.

Azolla. Because of its rapid growth and high N content, *Azolla* has been used as green manure in rice culture for centuries in northern Vietnam and southern China (45,81). The reported maximum standing crops of *Azolla* range from 0.8 to 5.2 t DW/ha and average 2.1 t DW/ha (38). Nitrogen contents ranged from 20 to 146 kg N/ ha and averaged 70 kg N/ ha. *Azolla* is grown in the rice field before and/or after transplanting and incorporated into the soil once or several times during the crop cycle. International field trials conducted for four consecutive years at 19 sites in nine countries have shown that incorporating one crop of *Azolla* grown before or after transplanting was equivalent to a split application of 30 kg fertilizer N (33). Incorporating two crops of *Azolla* grown before and after transplanting was equivalent to a split application of 50 to 60 kg fertilizer N.

Azolla has a similar N potential to that of legume green manures, is easier to incorporate, and can be grown with rice under flooded conditions. Environmental and technological problems limit the use of *Azolla* to about two million ha of rice fields. Problems related to inoculum conservation, multiplication, and transportation could be solved to a large extent if *Azolla* could be propagated through spores. Until recently, no method was known to induce sporulation and only vegetative multiplication was used for field propagation. Multiplication through sporocarps is now being studied in China. Temperature limitations and P requirements can be reduced by selecting cold- or heat-tolerant strains with improved P efficiency.

Labor costs may limit *Azolla* use, but not in many rice growing countries. Among green manures, *Azolla* is still utilized less than legumes but, unlike legumes, *Azolla* use is reported to be increasing and many countries are evaluating its possibilities.

NITROGEN TRAPPING AND NITROGEN ACCUMULATION AT THE SOIL SURFACE

The photosynthetic biomass assimilates part of the CO_2 (and CH_4 after being oxidized to CO_2) evolved from the soil and returns it as organic C in algal cells and aquatic weeds, thereby preventing organic matter losses in the form of CO_2 (28). The photosynthetic biomass may similarly reduce losses of NH_4^+-N and NH_4^+ dissolved in the floodwater, but this is poorly documented. In a pot experiment, Shioiri and Mitsui (69) recovered in the algal biomass 10 to 30% of N added as urea. In similar experiments Vlek and Craswell (79), using a gas-lysimeter and assuming that N_2-fixation by BGA was negligible because of the high level of ammoniacal N in the floodwater, concluded that urea fertilization stimulated algal growth and led to a net immobilization of 18 to 30% of N from fertilizer three weeks after application. Immobilization of ammonium sulfate N was much lower (0.4 to 6.3%).

Nitrogen fertilizer recovery in the photosynthetic biomass depends on the mode of application. When ammonium sulfate (60 kg N/ha) was mixed with the soil in concrete pots of 0.25 m^2, less than 5% of applied N was recovered in the photosynthetic biomass when the rice was harvested (K. Inubushi and I. Watanabe, unpublished data).

The positive effect of ‘algalization’ in the presence of high levels of N fertilizers has been sometimes interpreted as resulting from a temporary immobilization of added N, followed by a slow release through subsequent algal decomposition, permitting a more efficient utilization of N by the crop. Such an interpretation has yet to be experimentally demonstrated (60).

Under flooded conditions, N accumulates at the surface of the soil and this process is photodependent (1). Watanabe and Inubushi (83) applied the chloroform fumigation method to study the dynamics of available N (N in the microbiomass plus N released from nonfumigated soil) in a wetland rice soil. They observed that available N increased along the crop in the surface 0 to 1 cm layer and comprised 20% of available N in the 0.15 cm soil layer. This increase was also photodependent. Chlorophyll-like substances in soil and available N were positively correlated. Similarly, Wada et al (80) reported a close correlation between chlorophyll-like substances and N-supplying capacity of soils. We also found that if grazers are controlled, nitrogen accumulation in the surface 0.5 cm layer is increased by 1 to 3.5 times (Table 7), depending on the soil type and algae growing on it.

Nitrogen accumulated at the soil surface may come either from the atmosphere through N_2-fixation, from floodwater through trapping by the aquatic biomass, or from soil through absorption by rooted plants or ingested by invertebrates. Ono and Koga (54) measured the accumulation of 35 kg N/ha during a crop cycle of rice. When surface soil was isolated from deeper soil by

Table 7. Effects of controlling grazer populations with neem on nitrogen changer (kg/ha per two months) in the photosynthetic biomass and layers of submerged soils in microplots in a greenhouse (P. M. Reddy and P. A. Roger, unpublished data).

Soil	Layer	With neem[a]	Without neem
Maahas	biomass	+ 5.40	+ 2.92
	soil 04.5 cm	+25.08	+18.15
	soil 0.5-3.0 cm	+23.76	−21.78
	balance	+54.24	- 0.71
Luisiana	biomass	+ 8.02	+ 6.44
	soil 04.5 cm	+15.61	+ 4.62
	soil 0.5-3.0 cm	- 7.92	−25.74
	balance	+15.71	−14.68
Maligaya	biomass	+ 4.44	+ 3.10
	soil 0-0.5 cm	+27.72	+14.52
	soil 0.5-3.0 cm	+27.72	+11.88
	balance	+59.88	+29.50

[a] 100 kg/ha of crushed neem seeds were added to control grazer populations. Each value is the average of 4 replicates.

placing it in Petri dishes, N accumulation was 26 kg/ ha, indicating that N supply from lower soil layers was small. These results indicate that organic matter supplied by the photosynthetic aquatic biomass is an important component of the fertility of wetland soils.

NITROGEN LOSSES BY AMMONIA VOLATILIZATION

Recovery of fertilizer N by the rice plant is notoriously low, particularly if applied on the soil surface early in the growing season (8). The poor efficiency of utilization can be partly attributed to the susceptibility of N to loss mechanisms among which ammonia volatilization is recognized to be a major one in the tropics. Estimated losses by ammonia volatilization, as summarized by Fillery et al (12), range from 2 to 47% of the N applied.

The parameters in floodwater which determine the rate and extent of ammonia volatilization are pH, temperature, and concentration of NH_4^+-N . Many studies (8) recognize that the higher the floodwater pH, the higher the potential for losses by ammonia volatilization. Up to about pH 8, ammonia concentration increases by a factor of 10 per unit increase of pH. In wetland rice fields, water pH undergoes diurnal changes, increasing to values as high as 10 in the middle of the day and decreasing by 2 to 3 pH units during the night (49). Many authors (2,5,12,49) have reported a diurnal pattern in floodwater pH which results mainly from the depletion of CO_2 in floodwater by the photosynthetic submerged aquatic biomass during the day and its replenishment through respiration at night. Comparing the diurnal changes in pH of floodwater on two soils receiving 60 kg N/ha as ammonium sulfate or urea, Mikkelsen et al (49) reported that diurnal variations were established earlier and they were larger in the soil where algal growth became noticeable earlier and was more profuse. With the addition of Cu^{++} to the floodwater, which inhibited algal growth, only small changes in dissolved CO_2 occurred in the floodwater. This suggested that the algal population was the major factor affecting the CO_2 equilibrium.

In a series of field experiments, Fillery et a1 (12) observed that the pH values in the floodwater of a fertilized area where an algal bloom was observed consistently exceeded those in background areas. An increase in diurnal fluctuations in pH was observed as algae grew. They concluded that aquatic photosynthetic organisms, especially algae, play a key role in the NH_3 volatilization process in flooded rice fields.

Distinct differences in algal growth and floodwater pH have been observed with different methods of fertilizer application (94). There was vigorous algal growth and an increase in pH in the floodwater where urea was basally broadcast and incorporated, and where urea was band applied. On the other hand, less algal growth was observed in the control as well as where urea was either point deep-placed or uniformly deep-placed. The effect of N fertilizer application on floodwater pH was more pronounced during the dry season when solar radiation was higher and floodwater depth generally lower than in the wet season. The authors concluded that such seasonal effects may reflect 1) the stimulatory effect of urea N and light on the biomass and photosynthetic activity of algae during the dry season, and 2) the reduced growth of algae and low photosynthetic activity because of lower incident light and frequent rainfall causing disturbance and turbidity of the water during the wet season.

In a recent study (11) the photosynthetic biomass was estimated in fields where N losses were evaluated. Observations seven days after fertilizer application showed a very limited growth of the photosynthetic aquatic biomass in the control as well as in N fertilized plots. Although algal colonies or clumps, aquatic weeds, and patches of oxygen bubbles at the soil/ water interface were observed (indicating photosynthetic activity), they were very sparse and had a very uneven distribution. Results of pH measurements at selected points showed very high variation related to the presence and the nature of photosynthetic organisms. In areas where neither growth nor indirect evidence of growth of photosynthetic organisms was observed, pH ranged from 7.2 to 7.8. It ranged from 8.0 to 9.3 where there were O_2 bubbles or floating soil crusts detached from the soil due to the production of O_2 bubbles. Highest pH values, reaching 10.5, were recorded where algal growth was visible to the naked eye. Enumerations indicated an algal abundance in the fertilized plots about twice that in the control, whereas N_2-fixing BGA were 5 to 20 times more abundant than in the control. A rough calculation of the algal biomass indicated a value of about 100 kg FW/ha in N treated plots. Despite the low value of the photosynthetic biomass, large fluctuations in pH in the floodwater had occurred, suggesting that large algal populations are not required to increase floodwater pH to levels which support rapid NH_3 losses.

Little information is available on the effect of aquatic macrophytes on the pH of the floodwater. Measurements conducted in the IRRI farm showed that submerged macrophytes such as *Chara* and *Najas* significantly increased the pH of the floodwater whereas pH was fairly stable under floating macrophytes such as *Azolla* or *Lemna.*

NITROGEN RECYCLING

Mechanism of release of nutrient

Living aquatic plants continuously excrete appreciable amounts of dissolved organic matter including soluble nutrients (39). Laboratory experiments have frequently shown that BGA liberate a part of their assimilated nitrogenous substances (60). Excretion of nutrients by aquatic plants is particularly pronounced during senescence, and the largest proportion of nutrients immobilized in plant tissue is released after death (39).

A laboratory study (9) illustrated two mechanisms by which algal populations decay under dark aerobic conditions: endogenous respiration by the algal cell themselves and decomposition by microorganisms. Active bacterial decomposition proved to be the most important mechanism by far. In the same study, the viability of bacteria-free algal cultures after 70 days in the dark, with no net P regeneration, was regarded as an indirect proof that bacteria not only can decompose algae but, under certain circumstances, can cause the termination of an algal bloom. However, whether the lytic bacteria act as pathogens and thus are the primary cause for decline, or act as saprophytes decomposing the dead algal material resulting from other primary processes, remains a question (10).

A major factor in the decline of phytoplankton populations and recycling of nutrients is grazing by invertebrate populations. Grazing of algal communities on rice fields was only scrutinized after zooplankton was identified as a cause of failure of algal inoculation, and the use of insecticides to control rice pests was seen to increase algal growth (see section on N_2-fixation). Recent studies (18,19,23,55,92) have shown that grazer populations play a major role in the ecology of the rice field ecosystem.

Decomposition

The decomposition rate of aquatic plants and algae depends on the species, the physiological state of the organism, and the environment. The susceptibility to microbial decomposition of 14 algal species was assessed in pond water with bacterial inocula from several environments (25). Some of the algae were destroyed in short periods, while others withstood microbial digestion for more than four weeks. The production of toxins did not account for the resistance of those algae not readily decomposed by microorganisms. The differing susceptibility to decomposition may be related to the relative biodegradabilities of specific components of the algal wall like polyaromatic compounds.

The decomposition, by the action of various soil bacteria, of four N_2-fixing BGA at two different physiological stages has been examined (85). Within 10 days of incubation with the most active strain (Bacillus subtilis), about 40% of the N from autolized cells and 50% of the N from fresh cells were converted to NH_4^+.

Regeneration of nutrients in floodwater. Most of the experiments concerning remineralization of nutrients from algae and aquatic plants in floodwater have been conducted either in the laboratory or in enclosures placed in situ and as such may not exactly represent the process occurring in the field. Foree et a1 (14) recognized three general stages of nutrient regeneration from algae placed in the dark: 1) the stage immediately after dark conditions commence (usually the first 24 h), during which either a release to or absorption from solution, or a release followed by an absorption of nutrients took place; 2) a stationary stage over a period of several days during which net nutrient release was zero; and 3) the stage in which net release nutrients into the solution occurred, lasting a few hundred days.

The N and P release from algae in dark aerobic (44 strains) and dark anaerobic (21 strains) conditions were studied (14) for periods ranging from 40 to 360 days; the extent of N regeneration under aerobic conditions ranged from 0 to nearly 100%, averaging 50% of the initial N.

De Pinto and Verhoff (9) studied the aerobic decomposition of unialgal cultures inoculated with a natural bacterial community in the dark and found that the conversion of particulate organic N to NH_4^- ranged from 51 to 94%. The incubation periods required for stabilization of the system varied from 29 to 55 days, about one third of which was bacterial lag time. All organic N regenerated appeared first as NH_4^+, which was later converted to NO_3^- by nitrification.

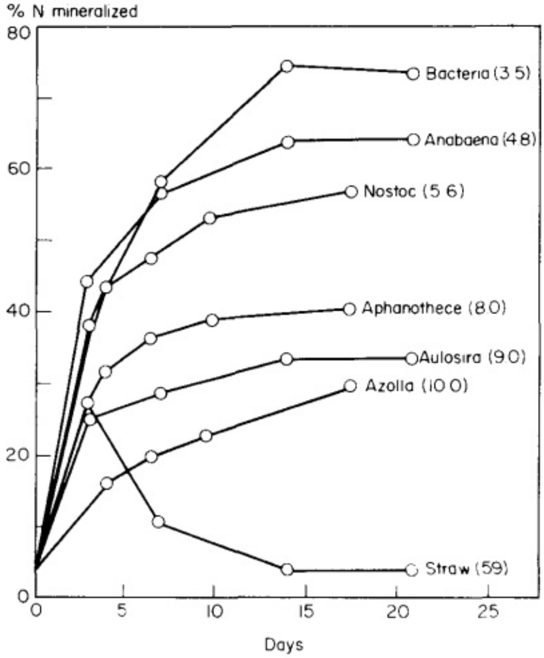
Mineralization in soil. Mineralization of some algae and weeds under flooded conditions was studied (52). Nitrogen contents of the plants varied from 2.2 to 6.6%, C contents from 39 to 44%, and C:N ratios from 6.6 to 20.1. The amounts of NH_4^+-N accumulated followed the same order as the C:N ratios, as long as the incubation period remained within 34 days. *Lemna* (floating weed, C:N = 6.6) accumulated the largest NH_4^+-N, whereas Spirogyra (filamentous green algae, C:N = 20.1) produced even less than the check.

Results of a mineralization study (Fig. 2) showed a clear correlation between the C:N ratio of the BGA material and the percentage of N mineralized in a given time. Depending on the C:N ratio of the strain. between 30 and 65% of the N of BGA was mineralized in three weeks.

Grazing

In limnology, grazing is a term used to describe the consumption of primary producers (photosynthetic biomass) by primary consumers (grazers and herbivores). Grazers are not always strict in their choice of energy source and may exist on sources from another trophic level, such as detritus or decaying organic matter. The outcome of grazing at either trophic level is mineralization of organic matter, assuming that assimilation of the ingested energy source occurs (some ingested material such as algal spores or straw residues may pass through the guts unchanged).

Nutrient recycling in rice fields is performed by microorganisms, protozoa, zooplankton, and the benthos, which include bottom-dwelling animals and certain invertebrate fauna such as oligochaetes and chironomid larvae (Diptera).



2. Nitrogen mineralization rates of blue-green algae compared with bacteria, Azolla, and straw. Figures in parentheses are C/N ratios.

The rice field fauna directly responsible for breakdown of photosynthetic biomass is frequently microcrustaceans and gastropods (Mollusca): These, together with the Protozoa and Rotifera, also recycle nutrients from decaying photosynthetic biomass, i.e. indirectly as secondary decomposers, where nutrients immobilized by primary decomposers (bacteria) are made available more quickly.

Nitrogenous excretion products of aquatic invertebrates are generally NH_4^+-N, amino acids, primary amines, and sometimes urea. Faeces also contain significant quantities of organic N. Recently, excretions of inorganic and organic forms of N have been measured in lake dwelling microcrustaceans (15,16,72), protozoa (68), tubificids and chironomids (17), and gastropods (4). Excretion rates of species present in rice fields are scarce and limited to rates obtained for Ostracoda (Crustacea) and Gastropoda.

Ostracods and gastropods readily consume certain green algae and BGA, but consumption of BGA has received more attention. Ostracod grazing rates on 5 species of BGA (18,19) showed that preferences by *Cyprinotus carolinensis* declined in the order *Tolypothrix* sp., *T. tenuis, Aulosira* sp., *Calothrix* sp., and Anabaena sp., and ranged from 1.0 to more than 100 mg DW alga/ ostracod per day for adult instars. The consumption of 26 BGA strains by *Heterocypris luzonensis,* a new species of ostracod dominant in parts of the Philippines, ranged from 8.2 to 61.4 with a mean of 38.5 ± 7.5 mg DW alga/ ostracod per day. The assimilation rates of N will no doubt vary with BGA species. Furthermore, laboratory estimates of N assimilation and excretion rates have usually utilized

BGA strains grown in culture, a measure which may overestimate field excretion rates owing to the higher N content of laboratory-cultured algae. Under such conditions, 1.10 mm (length) female *H. luzonensis* fed on *T. tenuis* (approximately 5% N DW) excreted 40 µg N/mg DW animal. With an average consumption of 38 µg DW alga/day, 1.10 mm long ostracods weighing 30 pg (DW) excreted about 63% of the N consumed. An unknown proportion of N excreted is derived from bacteria contaminating the BGA cultures, but as BGA *in situ* are not axenic, the bacterial contribution need not be considered separately.

The N assimilation efficiency of *H. luzonensis* fed on *T. tenuis* was in excess of 70% (underestimated, as a small proportion of the ^{15}N label is doubtless excreted during the feeding period of 1 h). Thus, 20 to 30% of the algal N is egested, most likely as organic N bound in gut bacteria. Efficiencies frequently increase when the food source is less plentiful.

Table 8 shows the calculated amounts of BGA consumed and NH_4^+-N excreted by a population of *H. luzonensis.* Laboratory determined ingestion rates of BGA converted to BGA consumed by a field population totaled 187 g N/ ha per day, of which 118 g was excreted as NH_3.

Excretion rates used to calculate N flux by the gastropod *Lymnaea viridis* were conservative and were similar to the rate of excretion measured from animals just after removal from the field. Because their feeding behavior has not been studied and food is sometimes limiting, an excretion rate measured at 24 h after food removal was used. The calculated amount of NH_4^+-N excreted by a field population was 123 g N/ha per day, while N contained in the faeces amounted to 296 g (total N)/ha per day. Moreover, until the population dynamics of grazers and their photosynthetic diets have been elucidated, accurate estimates of regeneration rates over a rice crop cycle cannot be made.

The fate of regenerated nitrogenous products released into the floodwater is only speculative and it is supposed that readily utilizable substrates are immediately taken up by primary producers and primary decomposers.

Breakdown of photosynthetic biomass by bacteria in the soil follows its incorporation by plowing, or passively at later stages of decomposition by burrowing tubificids (Oligochaeta) and some chironomid larvae (Diptera). Grazing of bacteria in soil by tubificids mineralizes N temporarily immobilized in the bacterial biomass. In Maahas clay (Philippines), soil N mineralization

Table 8. Nitrogen excretion by a field population of *H. luzonensis.*

Size (mm)	Ingestion rate (µg DW *T. tenuis* per animal per day)	Standing biomass (no./m^2)	BGA consumed[a] (g N/ha pwe day)	Excretion rate[b] (g NH_4 +-N/ha per day)
0.65	8.00	530	2	1.3
0.80	14.76	1 060	8	5.0
1.10	38.15	1 961	38	24.0
1.30	52.61	5 141	139	87.6
Total		8 692	187	117.9

[a] At 5% N, DW basis. [b] Excretion rates in the field will be affected by availability and N content of food, temperate, and season.

measured as NH_4^+-N production was doubled over 7 days by tubificid activities and algal mineralization was also increased (22).

Tubificid populations are large in soils rich in organic matter. Their burrowing activities mix and aerate the submerged soil, thereby changing the Eh and the behavior of mineralized N (21). Stimulation of organic matter decomposition in upper soil layers is evident from increased Fe^{++} concentrations. When the oxidized layer is disturbed, it releases NH_4^+-N, Fe^{++}, and $PO_4^=$into the floodwater. Furthermore, accumulations of total C and N in the upper soil, which occur in the presence of tubificids, presumably are derived from organic constituents of algae and weeds (37).

The increased production of labile N from readily mineralizable N (NH_4^+-N, amines, and easily hydrolyzable organic N) due to the presence of tubificids was 4.4 kg N/ ha per day. Release of NH_4^+-N by the tubificid *Limnodrilus* sp. was measured in vitro as 2.14 ng NH_4^+-N/animal per hour. With a population density of 10^4 tubificids/m^2, 500 mg N/ m^2 per day will be released into the soil as NH_4^+-N.

Translocation of photosynthetic biomass and its breakdown products from surface to deeper soil layers is expedited by tubificids (22). This action brings energy and minerals to N_2-fixing bacteria that are associated with the rice root and the coincident diffusion of 02 and N_2 downwards may create a microaerophilic environment which promotes heterotrophic N_2-fixation (21,37).

Availability of photosynthetic biomass nitrogen to rice

Apart from indirect evidence such as an increase in rice yield after algae or weeds were incorporated into the soil, information on quantities and ratios of nutrient release to the rice plant by the photosynthetic biomass has been obtained only from studies with BGA.

The transfer of algal N to higher plants other than rice has been demonstrated qualitatively in natural ecosystems (36,48,73) using ^{15}N tracer techniques. Tracer experiments aimed at determining the availability of algal N to wetland rice and its fate in soils have been qualitative (58,77) and quantitative (21,74, 91). In the quantitative studies, two treatments (surface applied and incorporated) were chosen to represent situations where a N_2-fixing algal bloom develops either early or late during the cultivation cycle.

If the algal bloom develops early in the cycle, decomposition by lytic microorganisms and grazing by aquatic fauna occurs during the same cycle, thereby making nitrogen available in the floodwater and soil. This situation may occur either with spontaneously growing BGA or when rice fields are inoculated with algae. It is somewhat similar to that in the treatments where dried BGA were surface applied. But unlike an algal bloom, the decomposition of surface applied BGA starts at the beginning of the growth cycle. Such a situation may lead to an overestimation of the availability of algal N to the current rice crop.

When the algal bloom develops later in the cycle, most of the algal material will dry on the surface of the soil after the harvest of the rice crop. It will decompose when incorporated by plowing at the beginning of the next rice growth cycle. This is similar to the situation where dried BGA were incorporated.

In a greenhouse experiment, Wilson et a1 (91) recovered in a rice crop 36% of the N from ^{15}N-labeled *Aulosira* sp. when spread on the soil, and 50% when incorporated into the soil. Uptake of ^{15}N from Nostoc sp. by rice was studied in pot and field experiments (74); the quantity of applied algal material was equivalent to that of a dense algal bloom and corresponded to 20 kg N/ha, 290 kg DW/ha, and 13 t FW/ha. Availability of ^{15}N from incorporated BGA was between 23 and 28% for the first crop of rice and between 27 and 36% for the first and second crops together. Surface application of the alga reduced ^{15}N availability to 14 to 23% for the first crop and 21 to 27% for the first and second crops together. Availability of algal N reported by Wilson et a1 (91) was almost twice as high as that measured under similar experimental conditions by Tirol et al (74). The reason for this discrepancy, according to Tirol et al, was related to the nature of the algal material, the method of its preparation, and the nature of the strain. Wilson et al used fresh algal material blended after resuspension in distilled water, while Tirol et a1 used dried material containing mainly vegetative cells in dormancy and akinetes, which was therefore much less susceptible to decomposition. This explanation was in agreement with the results of a preliminary pot experiment where Tirol et al (74) used the same Nostoc strain directly collected from the carboy culture. When this fresh material, composed mainly of vegetative cells, was incorporated, about 38% of the ^{15}N was recovered in the first crop instead of 28% when dried material was used.

The inconsistencies in recovery of algal N by rice were also interpreted by Grant and Seegers (21) as an effect of the benthic infauna. The upland soil used by Wilson et al (91) was dried and sieved prior to flooding, unlike lowland soil used by Tirol et a1 (74) which remained wet and would have contained an infauna. Grant and Seegers (21) showed that the uptake of algal N and total N by rice was affected by tubificids (Oligochaetes) in flooded soils. Tubificid activity reduced recoveries of algal N by rice by making soil N available through mineralization processes. Thus recovery of N from both surface and incorporated algae in Wilson's experiment was greater partly due to the lack of an invertebrate component which normally recycled soil organic matter N. In Grant and Seegers' experiment, recovery of algal ^{15}N by the first crop was 24 to 43%, and in the second it was 4 to 7%, recovery being affected by the method of algal application (surface versus buried) and the presence of tubificids which reduced the recovery of algal N by rice.

The pot experiment by Tirol et al (74) demonstrated that for the first crop, algal ^{15}N was less available than $(NH_4)_2SO_4$-^{15}N, but when considering two successive crops its availability was very similar. This indicates the slow-release nature of algal N. However, the low C:N ratio (5 to 8) of BGA gives it better N availability than that of organic fertilizers such as farmyard manure. After two crops, 57% of ^{15}N from BGA and 30 to 40% of ^{15}N from $(NH_4)_2SO_4$ remained in the soil, suggesting that algal N is less susceptible to losses than mineral N.

There is no information on the availability of N from submerged macrophytes to rice, but some data are available with regard to floating macrophytes. Shi et a1 (70) reported that 25% of the N from ^{15}N labeled water hyacinth was absorbed by the crop. Ito and Watanabe (35) observed that when

^{15}N labeled *Azolla* was placed at the surface of the soil (not floating), about two thirds of *Azolla* N was lost and 12 to 14% was recovered in the plant. When *Azolla* was incorporated, loss was significantly reduced and availability increased to 26%.

This result indicates that N that has been fixed or trapped in the photosynthetic aquatic biomass is more efficiently utilized by rice if it is incorporated into the soil.

CONCLUSIONS

The photosynthetic aquatic biomass that develops in wetland rice fields is comprised of planktonic, filamentous, and macro algae, and of vascular macrophytes. Its value is usually a few hundred kg DW/ ha and rarely exceeds 1 t DW/ha. Planktonic algae usually have a lower productivity than aquatic macrophytes. The development of the photosynthetic biomass depends on nutrient and light availability. Therefore, the largest biomasses are recorded in fertilized fields when the rice canopy has not become too dense, and in fallow plots. The average composition of aquatic macrophytes is about 8% dry matter, 2 to 3% N (DW basis), 0.2 to 0.3% P, and 2 to 3% K. Planktonic algae have higher N contents (3 to 5%). A common characteristic of the components of the photosynthetic aquatic biomass is low dry matter and high ash contents. From the available data on standing crops and composition of algae and aquatic macrophytes, it appears that 5 to 25 kg N/ ha is a reasonable estimate of the N content in the photosynthetic aquatic biomass. The productivity of the photosynthetic aquatic biomass in wetland rice fields corresponds to 10 to 15% of that of the rice crop and is equivalent to that in eutrophic lakes.

In rice fields, the photosynthetic biomass exhibits both beneficial and detrimental effects. When dominated by N_2-fixing BGA, it provides about 30 kg N/ ha per crop cycle. The growth of N_2-fixing BGA can be enhanced by cultural practices such as P application, liming, deep placement of N fertilizers, control of grazers, and by algal inoculation. When successful, algal inoculation increases rice yield by about 14%. However, the mechanisms of action and the limiting factors are still poorly understood, and algal inoculation is still in an experimental stage in most of the rice growing countries.

When inoculated, grown, and incorporated in wetland rice fields, *Azolla* has a N supplying potential similar to that of legume green manures. It is easier to incorporate than legumes and can be grown together with rice. Environmental, technological, and economical problems still limit the use of *Azolla.*

Non-N_2-fixing algae and macrophytes 1) compete with rice for space, light, and nutrients, 2) may have detrimental mechanical effects on the germinating seeds and the young plants, and 3) increase the pH of the floodwater causing N loss by volatilization. Recent studies of ammonia volatilization in wetland rice fields have shown a clear relationship between the development of the photosynthetic biomass and the increase in pH and the amplitude of its diurnal variations. At the beginning of the rice crop, even a small and heterogeneously distributed photosynthetic biomass may cause a marked increase in the floodwater pH and contribute to high rates of NH_3 loss.

Photoautotrophs assimilate CO_2 evolved from the soil and return it in the form of organic C in algal cells and aquatic weeds, thereby preventing C loss. A similar role by aquatic photosynthetic biomass in partly preventing NH_4+ loss is possible, but it is poorly documented.

In wetland soils, N accumulates at the soil surface. This process is photodependent. The fact that the amount of chlorophyll-like substances in rice soil and N-supplying ability of the soil are positively correlated suggests that the photosynthetic biomass contributes available N to the soil.

Nutrients accumulated in the photosynthetic biomass are released through exudation, autolysis, and decomposition. Grazing by invertebrate populations also permits recycling and maintains a supply of regenerated nutrients for primary producers (including rice), decomposers (bacteria), and N_2-fixing organisms. The effect of pesticide use on N recycling by invertebrate populations is still poorly understood.

About 15 to 30% of the N of the photosynthetic material is available to the rice crop depending on its nature, state, and location (surface applied or incorporated).

When considering the relationship between the photosynthetic biomass and N management, the most obvious possibility is to enhance biological N_2-fixation (BNF). However, BNF technologies currently adopted by farmers (green manuring with legumes or *Azolla*) are labor-intensive. Green manures are most often used under socioeconomic conditions where labor intensive practices are economically feasible. Utilization of N_2-fixing BGA is still limited by methodological problems and has lower potential than green manuring. In the future, it is unlikely that BNF could be an exclusive N source for producing high yields under economically feasible conditions (65). Most probably the future of utilization of BNF in rice cultivation lies in integrated management. A better knowledge of the microbiology and the ecology of rice fields will encourage high rice yields through a more efficient usage of chemical fertilizers and the simultaneous utilization of BNF. Deep placement of N fertilizers (8), which significantly decreases losses of N by volatilization and does not inhibit photodependent BNF by BGA, integrated with agricultural practices that enhance N_2-fixation by BGA (including inoculation if needed), is a good example of the kind of technology that must be developed.

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The Agronomy of Rice Production in the Riverina Region of Southeastern Austialia

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Rice growing in the Riverina region of New South Wales, Australia, has expanded since its inception in 1922 to an industry sowing up to 120 000 ha and producing average yields of 6 to 7 t/ ha with best yields exceeding 12.5 t/ ha. Only one rice crop can be grown each year. The growing season is characterized by long days and high solar radiation, with low temperatures at the beginning and end of the season. Rotations were once dominated by a long pasture phase, but rice is now grown more frequently. The emphasis on management is on sowing methods; fertilizer requirements are mainly restricted to N_2 and there is relative freedom from major pests or diseases. Weeds are normally controlled with appropriate herbicides. Aerial sowing of pre-germinated seed is the most popular method of establishment. A unique sowing method in the region is direct drilling or sod sowing either into pasture or rice stubble with no land preparation. Both medium and long grain varieties are grown to meet market needs. An increasing area is being sown with higher yielding semidwarf varieties. If the industry is to survive pressures from salinization, increased costs, and falling prices, innovative research will be required. Research will concentrate on the use of shorter rotations, reduced irrigation, earlier maturity, more reliable and higher yielding varieties, and the development of a reliable method for predicting N requirement.

In the Riverina region of southeastern Australia rice growing commenced in 1922 when the first 2.8 ha of experimental plantings of seed introduced from California were grown near Leeton, NSW (23). From that time, the area sown to rice has increased steadily so that by 1982 a record area of 121 872 ha was sown (Fig. 1).

The yields of unmilled rice also increased with time until 1974 when averages were depressed by increased sowings of lower yielding but higher priced long grain cultivars (Fig. 1). Overall average yield of the variety Calrose was 7.7 t/ ha in 1983 while Inga yielded only 6.5 t/ ha in the same year. Many crops exceed 10 t/ ha each year and whole crop yields of the variety M7 in excess of 13 t/ ha have been recorded.

Rice is grown in the Riverina region in an area bounded by latitudes 34 °S and 36 °S and longitudes 144 °E and 146.3 °E. The area is wholly contained within the State of New South Wales and is west of the Great Dividing Range. Rainfall in the rice area averages only 200 mm during the growing season and the crop is therefore grown almost entirely with water derived from catchments in the mountains to the east. Both the Murrumbidgee and Coleambally Irrigation

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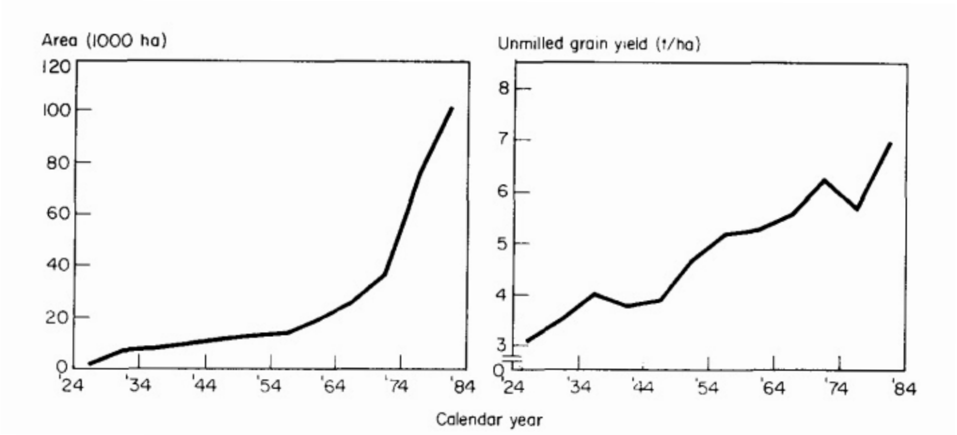
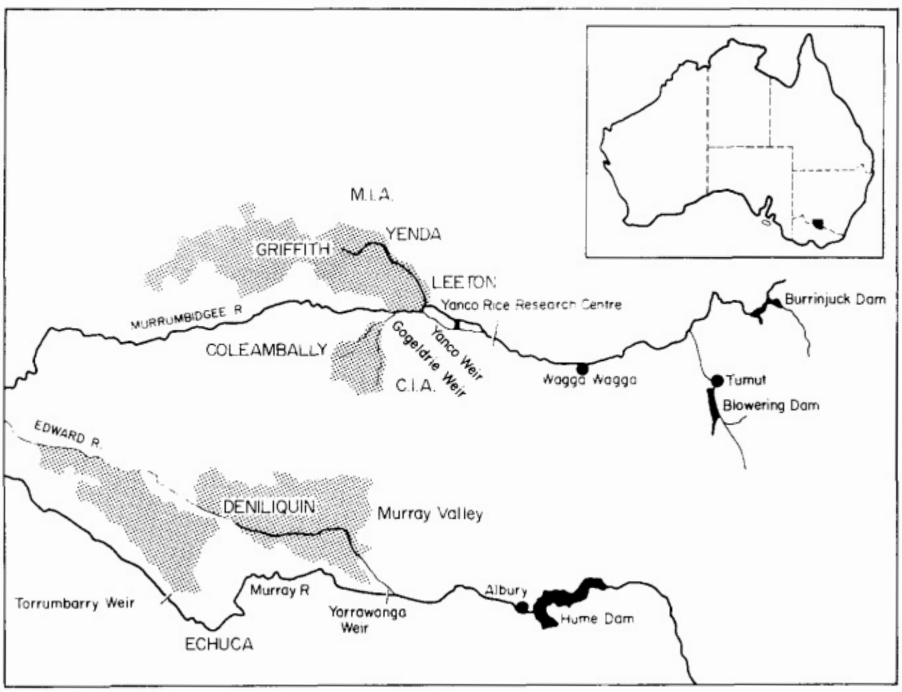


1. Mean area sown to rice and mean grain yield for 5-year periods since 1924.

Areas are watered from the Murrumbidgee river system, while the Murray river system feeds the southern Murray Irrigation Districts (Fig. 2). The Murray districts differ from those in the Murrumbidgee Valley in having a shorter growing season, less reliable water supply, larger farm size (although similar rice entitlements per farm), and generally heavier soil types.



2. Map of the rice-growing areas in the Riverina region of southeastern Australia (12).

Table 1. Summary of climatic data for Yanco Agricultural College and Research Centre, NSW (1941-1971).

Month	Temperature (°C)		Mean daily rainfall (mm)	Mean daily evaporation (mm)	Hours of sunshine (daily average)	Total global solar radiation [a]	Mean wind (km/d)
	max.	min.					
Jan	30.9	16.5	0.9	7.6	10.6	700	251
Feb	30.3	17.5	1.1	7.4	9.9	670	262
Mar	27.6	14.2	1.2	5.3	9.3	520	209
Apr	22.7	10.0	1.1	3.6	7.9	380	164
May	16.7	6.7	1.4	2.0	6.6	260	153
Jun	13.8	3.1	1.1	0.5	5.3	250	f37
Jul	12.8	0.4	1.2	1.3	5.4	240	119
Aug	14.8	3.1	1.1	1.8	6.6	340	174
Sep	17.7	5.6	1.2	2.8	8.1	460	193
Oct	21.9	8.9	1.4	4.3	8.6	560	212
Nov	26.7	11.3	1.2	6.4	9.7	720	236
Dec	28.9	14.2	1.1	7.4	9.7	710	243

[a] Cal/cm^2 per day. Data from Griffith (1932-71).

The region has distinct winter and summer seasons, with only one rice crop possible each year (Table 1). Summer days are long and hot with high levels of solar radiation, but with distinct variation between maximum and minimum temperatures. The growing season is characterized by low minimum temperatures during the October and November establishment period and the January and February reproductive period (Fig. 3). The influence of climate on rice growth in the Murrumbidgee Valley has been summarized by Boerema (5).

The long days and low temperatures during the spring and autumn force a long growing season with the sowing to maturity period ranging from 165 to 190 days for commercial varieties. The growth period is often extended by a long establishment period and a ripening phase which can vary from 40 to 70 days.

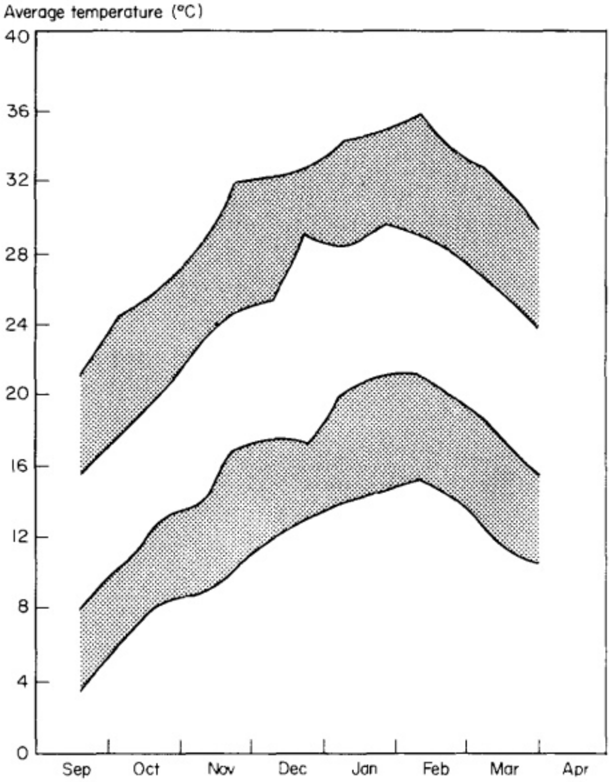
Many management decisions are influenced by the threat of low minimum temperatures during the reproductive period. Low temperatures during this time influence commercial yields (1), and complete crop failures have been observed following a period of cold nights and days.

Soils used for rice growing in the region range from clay loams to heavy, dispersing clays, and from red-brown earths to gray soils of heavy texture. Rice growing is generally only permitted where there is a heavy clay subsoil to minimize percolation losses. Parts of the region have underlying prior stream beds which may be saline, and these areas are avoided.

There is a greater proportion of heavy clay soils in the Murray Valley. The structure of these soils collapses with flood irrigation and this influences the decisions on sowing methods and rotations.

REGULATION OF RICE GROWING

Water is a limited and valuable resource in the Riverina region. Its supply is controlled by the New South Wales Government through the Water Resources



3. Maximum and minimum temperatures at Yanco Agricultural Institute in the Murrumbidgee Irrigation Area. Calculated from 15-day averages for the period 1959 to 1984 (80% confidence limit).

Commission (WRC). It is the task of the WRC to ensure that the supply system is maintained, that water is distributed fairly, and that the environment is protected.

The WRC, together with representatives of the rice industry, sets a maximum area of rice which can be grown on each farm. Each year, each grower must apply to the WRC for the right to grow rice on a particular portion of his farm. The maximum allowable area cannot be exceeded, and the grower should not vary the approved location. The area and location of each rice crop is strictly regulated by the WRC every year through aerial photography.

The regulatory system has been used to prevent two successive rice crops on the same area of land. This has now been relaxed to allow almost continuous cropping on the least permeable soils. The system is still used, however, to prevent rice growing on unsuitable areas.

For many years, rice growers in the Murray Valley have been restricted to a maximum water allocation each year and they must limit water use to the allocation. The actual allocation varies from year to year, depending on the total supply available. A similar system is soon to be introduced into the Murrumbidgee Valley, although the total allocation for this area is likely to be larger than that in the Murray Valley.

CULTIVATION METHODS

Rotation

Since rice can only be grown on 70 ha of a total irrigable area of 200 to 500 ha on each farm, it is necessary that rice be rotated with other enterprises.

It has been traditional for rice to be grown in rotation with legume-based pastures, with only one crop every 4 to 6 years. As outlined by McDonald (27), there are many advantages to this system. Soil fertility is improved by the pasture phase and additions of fertilizer to the rice are often unnecessary, weed control is simplified, and the risk of disease development greatly reduced. Rice crops grown after pasture are often high yielding and difficult to equal when using artificial fertilizer (28). Additionally, the cost of rice establishment is reduced by direct drilling into the pasture sward.

With the allowable area of rice per farm doubling in the past ten years and a relaxation of the ban on continuous cropping for impermeable soils, the pasture phase has become shorter or has been excluded completely. Rice is now grown in rotation with winter cereals and the sowing of rice into rice stubble is now a common practice.

No nutritional problems were observed after five continuous rice crops (25), but weed control became a problem in some situations. Phosphorus deficiency was observed in one crop after nine years of continuous cropping (22).

Irrigation layout

Rice is grown in bays surrounded by banks arranged on the contour. A vertical distance of 8 to 10 cm is allowed between contour banks which are built to retain 30 to 40 cm water. Bay size depends on the slope of the land but will range up to 8 ha.

There is now an increasing trend to landform rice to produce large, rectangular bays of even slope. Slopes vary from 1: 1 000 to 1:2 000 or flatter and are achieved using heavy machinery and laser leveling technology. Landforming promotes easier water management, increases the effective rice area, eliminates uneven water depths, and aids weed control. Landforming does carry the additional cost of reclaiming heavily ‘cut’ areas where the topsoil has been removed. Most cut areas can be reclaimed within three years using high N rates, phosphorus, and occasionally zinc applications on alkaline soils (18).

Land preparation

The degree of cultivation depends on the condition of the land and the sowing method to be used. No cultivation is necessary where the crop is to be direct drilled although the land should have been leveled prior to the previous crop or pasture. A finer seedbed is required for drill than for aerial seeding (3). Most preparation is achieved with scarifiers, disc harrows, and occasionally rotary hoes. The land is graded or planed following preparation.

The fallow period before sowing is generally as short as possible to prevent N losses from the organic matter pool (6).

Sowing and early management of the crop

Four methods are used to sow rice in the Riverina region. The choice of method depends on region, soil type, variety, and past history of the area to be sown.

Rice is drill seeded into a dry, relatively fine seedbed at the rate of 120 kg seed/ ha. The seed, usually treated with fungicide and insecticide, is drilled 1 to 3 cm deep in rows 15 to 17 cm apart. The first irrigation is applied immediately to promote germination. This water is removed after 24 hours. The crop may be similarly ‘flushed’ as necessary until the three-leaf stage when N fertilizer and herbicide application is followed by shallow permanent flood.

Directdrilling or sodseeding rice into pasture is gaining wider acceptance where rice is to be sown into pasture. Standing pasture is grazed heavily with sheep prior to sowing and may also be sprayed with a knockdown herbicide. The seed, usually treated, is directdrilled at 120 to 140 kg/ ha into rows 15 cm apart using triple disc seeders. Pasture regrowth is controlled between flushings by grazing, although this will not be necessary where pasture knockdown herbicides have been used. Permanent water is applied at the three-leaf stage following herbicide treatment and N application where required.

A modification of the directdrill method is used where rice is sown into rice stubble. The stubble is burned just prior to sowing, and rice direct-drilled at 120 kg/ ha. Early management is then as for drill seeding. However, care must be exercised when using herbicides with this method, as activated carbon in the ash may absorb herbicide (32).

Aerial sowing is more common in the Murray Valley where the growing season is shorter and the soils heavier and often sodic. The seedbed need not be as fine as for drill seeding. The final operation before flooding drills N fertilizer to a depth of 5 to 10 cm, which leaves ridges in the surface. Seed is pregerminated and dropped directly into the shallow, permanent floodwater (3).

The distribution of the sowing methods (Table 2) indicates the importance of aerial seeding for the Murray Valley, while direct drilling is gaining importance in the Murrumbidgee Valley.

Water management, drainage, and harvest

It is recommended that water depth be maintained at 5 to 10 cm until panicle initiation to promote tillering and early growth (3). After this stage the depth should be increased as far as the banks will allow, to protect the developing panicle from the effects of low minimum temperatures at the critical early microspore stage (19).

The time of drainage is a critical decision for rice growers. Early drainage results in lodging and reduced grain weight, while delayed drainage leads to wet harvest conditions and lower milling quality. It is recommended that, for most soil types, water be drained when the lower grains on the panicle are at the late dough stage. For heavier soils, which are able to supply water to the crop for a longer period, draining can be completed when there are some milky grains at the base of each panicle (7).

Rice is received below 22% moisture, and harvest should commence as soon as possible after this stage. All varieties are susceptible to checking (8), and

Table 2. Estimates of sowing methods used in the three rice growing areas of the Riverina region.

Method	Area (% of total)[a]		
	MIA	CIA	Murray Valley
Drill	20	30	10
Direct drill			
Posture	30	20	5
Stubble	35	30	-
Aerial	15	20	85

[a] MIA = Murrumbidgee Irrigation Area, CIA = Coleambally Irrigation Area.

moisture content at harvest is the most important determinant of milling quality (14).

Varieties

The rice industry of southeastern Australia was founded on japonica varieties introduced from California. This type of variety has dominated production since that time. Short-grain Caloro derivatives were replaced by medium-grain Calrose as the most important variety after 1967. Calrose is notable for its adaptability to the whole area, its potential to yield under adverse conditions, and its excellent milling quality.

Susceptibility to lodging reduces yield of Calrose, and semidwarf varieties were developed and tested to avoid this problem. Hartley and Milthorpe (15) showed that short-statured varieties, combined with high N availability, could improve yield potential. Semidwarf M7 (9) was introduced from California and released for commercial production in 1983. It quickly replaced Calrose as the most important variety in the Murrumbidgee Valley, but is not so well adapted to the shorter season in the Murray Valley.

The need for long-grain varieties was recognized in 1961, when Bluebonnet 50 was introduced from Texas and grown on a small scale (8). It was not well adapted to the region and could only be grown in the warm areas, even when seasonal conditions were very good for rice growing. It was followed by a succession of locally bred, relatively soft cooking long-grain varieties. Kulu was released in I967 and was important for its low-temperature tolerance (28). It was replaced by Inga in 1973, and this variety was grown commercially for more than ten years. Its vegetative response to N, combined with relative susceptibility to low temperatures, led to very low yields in the cold seasons. These were alleviated by later applications of N fertilizers (2,20). Neither Kulu nor Inga could be grown successfully in the Murray Valley. Pelde, released in 1982, has greater cold tolerance and higher yield potential than Inga, and has been grown in all rice growing areas.

The variety mix over the past ten years is illustrated in Table 3. Economic returns for long grain are set to encourage the correct mix of grain type for

Table 3. Production of the most important varieties since 1980.

Year	Variety (% of total production)					
	Caloro	Calrose	M7	Kulu	Inga	Pelde
1980	2.9	61.1	-	1.3	33.8	-
1981	1.9	65.8	-	0.5	31.7	-
1982	-	77.3	-	-	22.5	0.2
1983	-	69.1	0.6	-	26.2	4.1
1984	-	65.0	9.4	-	15.5	10.1
1985 (est.)		41.0	36.1		1.1	21.7

expected market requirements. This has resulted in an artificially high price for lower yielding Inga and Pelde to encourage production in competition with Calrose and M7.

The NSW Department of Agriculture and the Rice Marketing Board for the State of NSW jointly operate a pure seed scheme for the commercial varieties (13). Each grower purchases fresh supplies of the pure, high quality seed each year. This ensures that variety purity can be maintained and that the supply of each variety can be regulated to meet market requirements.

Fertilizer practices

Nitrogen fertilizer management and transformations will be discussed extensively in other papers, so we will only make brief mention of the practices now being used commercially in NSW. With rare exceptions, N is the only element required for rice production in the Riverina. The quantity required depends on the previous history of the area to be sown, and ranges from zero on fertile pasture soils to more than 200 kg N/ha on low fertility sites when using a semidwarf M7. Most N is applied as urea, although ammonium sulfate, anhydrous ammonia, and aqueous ammonia have been used at some time (27).

For most varieties the majority of the N is applied just prior to permanent flood (4). This represents the three-leaf stage for drilled and direct-drilled crops, and before sowing for aerial sown crops. There may be additional applications of N at the panicle differentiation stage. The proportion of N topdressed at the later stage varies with variety, field history, and total N to be applied (2, 20).

Weeds

The spectrum of important weeds varies with sowing method. Most weeds can be controlled chemically, but herbicides are expensive and impose a considerable cost burden on growers (30).

Echinochloa spp. is the most important weed of drilled and direct-drilled crops. Post-emergent applications of molinate, propanil, and thiobencarb are used to control this weed (11). A recent trend has been to apply the herbicides directly into the water when fields are flooded permanently. Control can be excellent, and application costs are minimized with this method, but care is required with rate and water depth.

Cyperus difformis is the major weed of aerial sown rice. Control can be obtained with MCPA, but applications of the herbicide may damage rice, particularly if applied before mid-tillering (10), when the weed may have already competed significantly with the rice (29). Thiobencarb may also be used to control young *Cyperus difformis,* but extreme care is needed to avoid phytotoxicity to young rice seedlings.

Typha spp. is becoming an important weed with shorter rotations (25). Control must be obtained by cultivation or herbicide during the period when no rice is grown.

Other weeds are of minor importance, but there is increasing competition from *Diplachne fusca* (silver grass), *Damasonium minus* (pondweed), *Paspalum paspalodus* (water couch), and Rumex spp. (docks).

Pests and diseases

There are no serious diseases of rice in the growing areas of southeastern Australia, and there are only relatively minor pests which are easily controlled (27).

The most important pest is bloodworm *(Chironomus tepperi).* Larvae of this midge are of particular importance in aerial sown conditions (24), as they chew tips of developing roots and occasionally shoots, seriously reducing plant vigor. There are many alternative chemicals which control this pest effectively, and almost every aerial sown crop would be treated at least once. Other occasional insect pests such as leaf miner *(Hydrellia* spp.) and armyworm *(Pseudaletia convecta)* can be controlled with appropriate insecticides.

Occasionally, snails *(Physastra* spp.) become a serious pest by grazing on young rice, particularly in short rotations following a wet winter. Copper sulfate is used for control. Copper sulfate is also used to control algal growth, which can be an important problem in aerial sown and directdrilled crops. Ducks can be a major pest at establishment in aerial sown crops. No completely satisfactory means of control has been developed; shooting, scare guns, and lights of various types are used.

Small areas are affected by ‘straighthead’sterility each year. This disorder is not generally significant, but some areas are known to be particularly susceptible. The varieties Inga and Pelde are more susceptible to this disorder than either Calrose or M7.

FUTURE AGRONOMY RESEARCH

Rice growing is under pressure in the Riverina region; the cost of water is increasing, water supply is likely to be limited in some seasons, there will be competition from other enterprises for the limited irrigation water supplies in the arid environment, and there is the threat of salinization of the rice areas. These factors, when combined with low rice prices, are placing economic pressure on the whole industry. Opposed to these factors is the prospect of increased yields from newly released varieties such as Pelde and M7. It remains obvious, however, that more efficient agronomic practices are required if the rice industry is to survive.

Rice growing is likely to be restricted to only the least permeable soils, if salinization and percolation losses to the rising water table are to be minimized. This will inevitably lead to shorter rotations on the most suitable areas. Research will therefore be required into reproducing the yields obtained after long pasture history. Heenan (17) has demonstrated that legume pastures produced the equivalent of 40 to 80 kg N/ ha in just 18 months. New crop or pasture species that can improve upon this fixation rate should be sought. P and other elements are also likely to be required with shorter rotations (22).

The performance of rice under restricted irrigation has been the subject of a study over the past three seasons. This research will be particularly important in years of water shortage. Heenan and Thompson (21) demonstrated minimal yield reduction with savings of up to 20% of water when permanent flooding was delayed until the panicle initiation stage. Additional research on weed control in this situation is still required.

Rice growing would fit better with other farm enterprises if sowing could be delayed until mid-November. Pasture could then be utilized during its most active growth stage before sowing rice; a rice - winter crop - rice rotation may be possible. The rice breeding program, based at Yanco Agricultural Institute, is now concentrating on the development of earlier maturing varieties and on a program to determine management strategies for the varieties when they are developed.

Higher yielding, more reliable varieties are required if the rice industry is to remain viable in the face of falling prices. In the short term, this will require the development of N responsive, earlier maturing semidwarf varieties of both grain types. Since low temperature during reproduction is the most important determinant of yield, the development of varieties better able to withstand this limiting factor would lead to greater reliability. Parents are screened for low temperature resistance under controlled conditions, and selection is carried out in a cold-prone area (26). This program resulted in the development of Pelde and is likely to lead to improved cold resistance in future. Improved seedling vigor is also required. A program has commenced to select for improved seedling growth and submergence tolerance, particularly under cold conditions.

Hybrid varieties have not yet been tested in the Riverina region, as the licensing company has not yet produced sufficient seed to allow testing. In the long term, however, these types appear promising. Seed production and distribution is already well organized, seed rates could be reduced for varieties with strong seedlings, and growers have shown a readiness to adopt higher priced technology whenever an economic advantage can be demonstrated.

A major limitation in the management package available to rice growers is the lack of objective techniques for predicting N requirement. Grain yield is depressed by both under- and over-fertilization but there is no satisfactory test of requirement. A N soil test was developed (31), but it has not been widely accepted. Tissue testing was also evaluated, but has not been found to be satisfactory; this is an area of research which deserves immediate attention. The development of a successful method will have important benefits to the entire industry. The evaluation of such a test will only be successful, however, if temperature variables are included in the testing process, as the relationship between N and yield is likely to be affected by the interaction between N and response to low temperatures during reproduction (16).

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Rice Growing in Tropical Australia

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Rice growing in tropical Australia began around 1869 but was sporadic for 100 years. The past 20 years have seen growth to more than 4 000 ha, mostly flooded, in Queensland. Yields average 5 t/ha, with 90% going to the domestic market at a premium price. Most rice research has catered to a highly mechanized industry. Current research thrusts and research needs are discussed, as well as possible developments in the industry. By 1990 an additional 15 000-20 000 ha is expected to be opened in the Burdekin Irrigation Area of Queensland.

Rice growing in Northern Australia commenced around I869 with a commercial venture at Pimpama in Queensland (Fig. 1), small enterprises near the Adelaide River in the Northern Territory (Fig. 2) (2), and shortly afterwards with ventures in the Mackay and Port Douglas areas of Queensland (Fig. 1) (1). These undertakings were mostly unsuccessful; in fact any early rice crop successes (both upland and lowland) could be attributed to the Chinese associated with the various mining communities.

In some areas, particularly in Queensland, small mills were set up to handle the crop. In general, however, rice production throughout Northern Australia was, at best, spasmodic. In 1898 Queensland grew about 350 ha of rice (9, but production declined until about 1917. Shortages during both world wars provided the impetus for a brief flourishing of the industry. This renewed interest was supported by an increase in research.

Some of the problems encountered by the rice industry in Northern Australia are typified by the experience of a private company, Territory Rice, in the period 1952-62. There were difficulties with machine trafficability, crop establishment, plant nutrition, harvest scheduling, and marketing to the extent that, by the end of 1962, the commercial venture ceased.

In 1965, after some years of research, small areas of commercial rice were established in Millaroo Research Station in the Burdekin River Irrigation Area in Queensland (1). By 1967 some 140 ha were grown by farmers. This progressed to the present level of production of approximately 2 000 ha in the Burdekin and 2 000 ha in the Mareeba areas of Queensland. (See Figure 3, which gives the total area under rice in Queensland, and Figures 4 and 5, which show the production figures for the different areas.)

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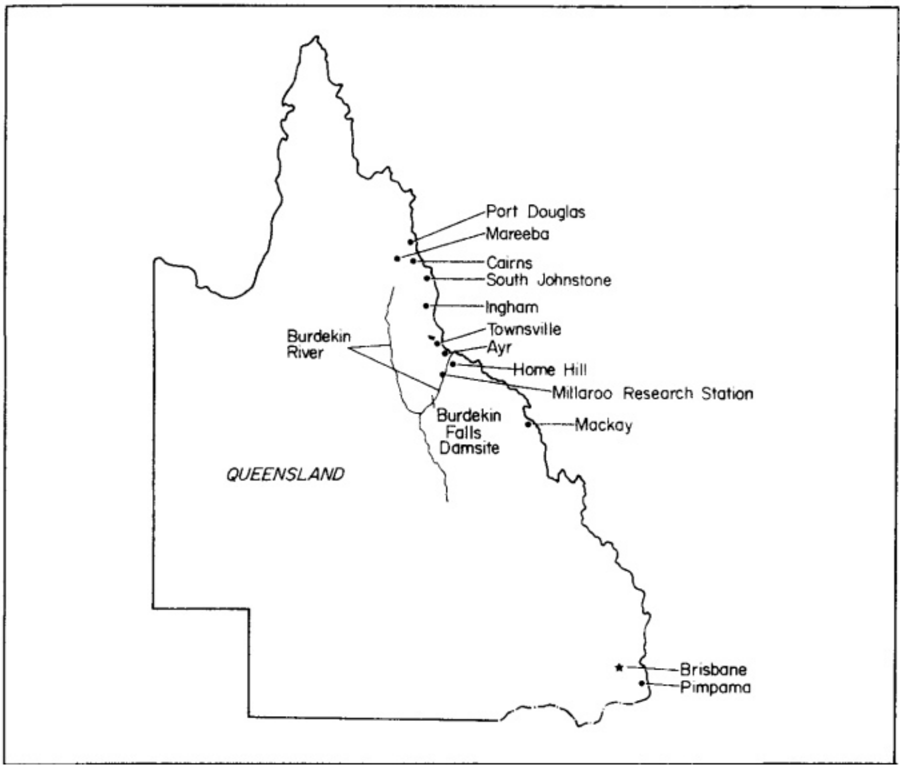
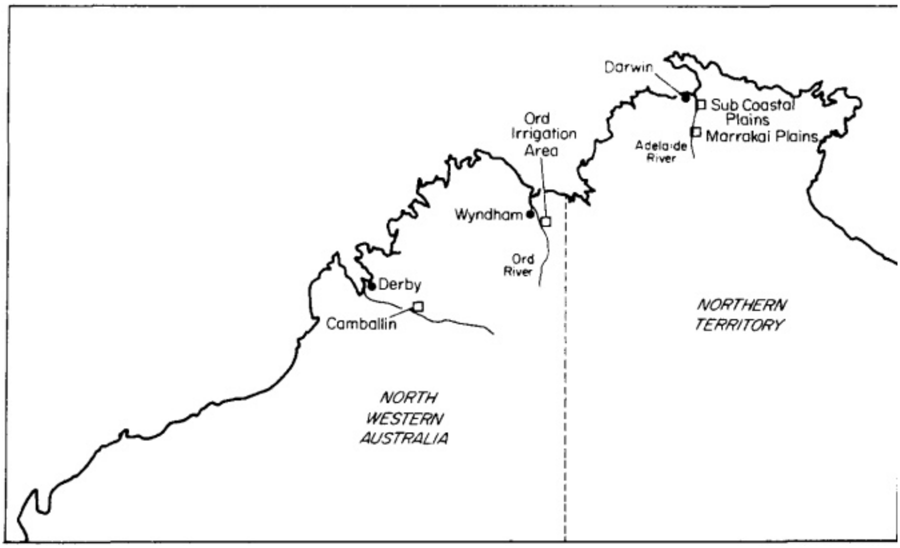
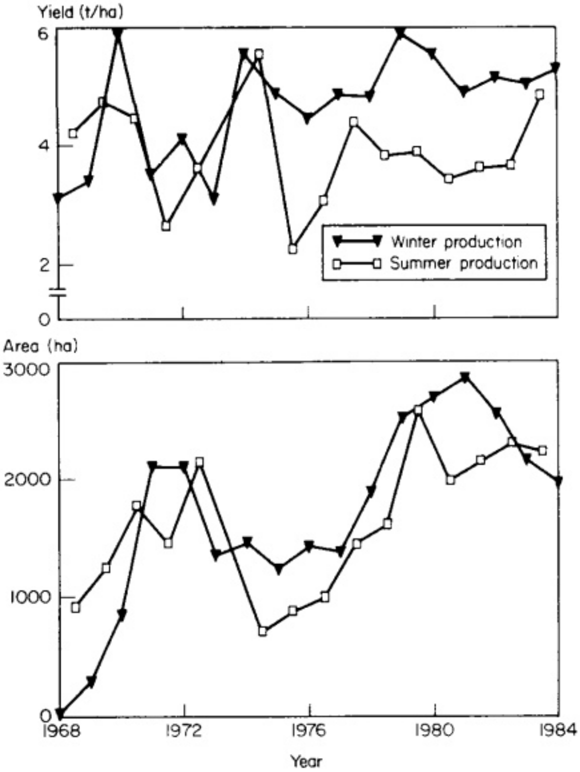


1. Areas concerned with rice growing in Queensland.

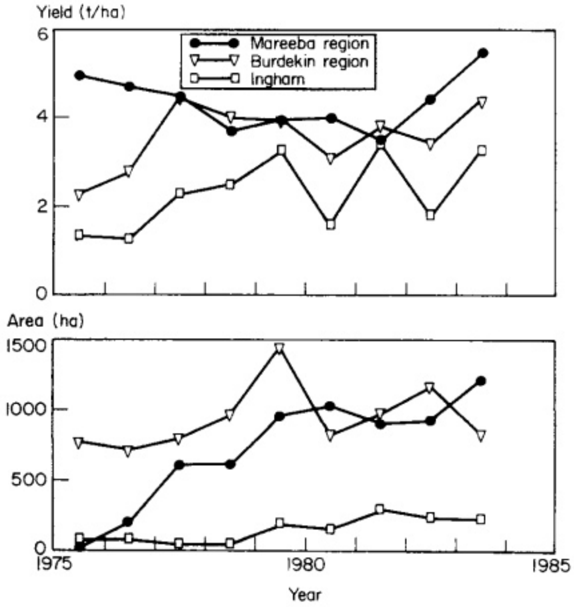


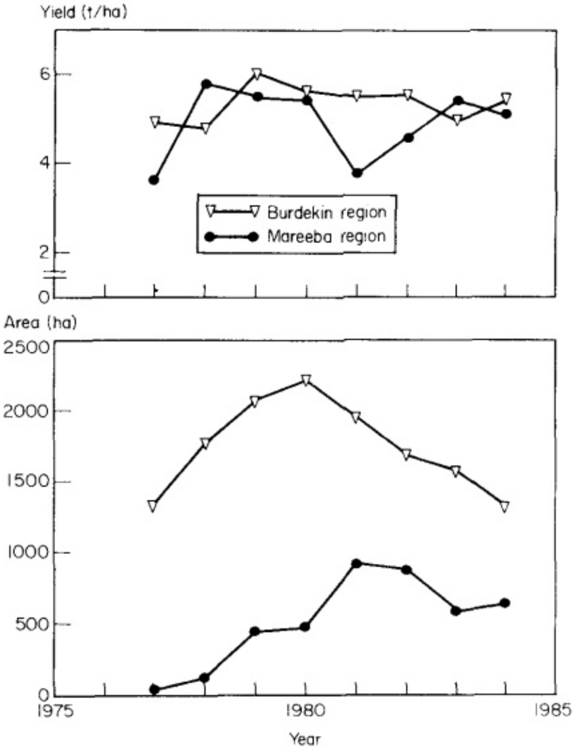
2. Areas concerned with rice growing in the northwest of western Australia and in the Northern Territory.

3. Total area under rice and yield obtained therefrom in northern Queensland.



4. Production figures for the northern Queensland rice industry in summer (wet season).





5. Production figures for the northern Queensland rice industry in winter (dry season).

Despite attempts to grow rice elsewhere in Northern Australia - for example in the Ord River and Darwin regions -- it is only the Queensland industry which has survived. This is probably due to the existing infrastructure and support services which developed around other crops such as sugarcane.

The Queensland industry is now serviced by the Queensland Rice Marketing Board and the product is highly sought after on the domestic market where it sells at a premium price.

THE PRESENT INDUSTRY

Queensland

The industry is centered around three rice growing areas - the Burdekin Valley, Ingham, and Mareeba (Fig. 1). It has been in existence for almost 20 years. In 1984 some 20 987 t of paddy were produced from about 4 174 ha. The total production figures for this industry are shown in Figure 4. Some 90% of the product goes to the domestic market. The industry is based on flooded rice with the exception of the Ingham area where the standard variety Starbonnet is grown under upland conditions.

Two crops a year are grown in the Mareeba and Burdekin districts; one in the wet season (December to May) and one in the dry season (June to December). Irrigation from either underground or surface storages is used.

Ingham produces rice only as a summer crop and grows the standard variety Starbonnet under upland conditions. (Ingham receives in excess of 3 500 mm of rain annually, of which 70% falls in the December-April period.) Production figures for the three regions for the period 1975-84 are shown in Figure 4 (summer) and Figure 5 (winter).

All the Queensland rice is milled and marketed from the Lower Burdekin Rice Producers Cooperative, Home Hill, although the actual marketing and distribution is handled by a marketing agent.

Other industries

A small industry was commenced in the Ord River Irrigation Area (Fig. 2) in the late 1960s but this has now been abandoned (A.L. Chapman, personal communication). This was probably due to the high production costs and the poor varieties grown. This area could produce rice satisfactorily if a suitable variety could be found. Such a venture would be more likely to succeed if another high value crop were grown, so that the unit costs of input could be reduced.

Small areas of rice have been grown in the Darwin area since the closure of the Territory Rice company project. This has mostly been for stockfeed purposes. About 200 ha is grown at present (N.R. Dasari, personal communication).

RESEARCH

Research on rice growing in Australia has largely been based on the need to produce high quality grain within the constraints of a high cost situation. To this end, most of the research has been related to a highly mechanized industry, and this is likely to remain so. Most research has been aimed at improving the yield and quality of rice grown under irrigation.

Western Australia and the Northern Territory

By far the major northern Australian research effort in rice production has been in the Darwin region and in the northwest of Western Australia (4). This is despite the fact that at present no industry exists in these areas. Research has been largely centered on the Adelaide River region in the Northern Territory and the Ord Irrigation Area in Western Australia, with some early work being conducted on the Fitzroy River region in Western Australia.

The major research effort was aimed at genotype evaluation and understanding nutritional requirements. Other work examined cultural practices, irrigation management and water use, grain harvest and quality, insect control, weed control, diseases, crop physiology, and soil chemistry (4).

Much effort was concentrated on the selection and breeding of varieties suited to Northern Australia. At first, varieties suited to southern Australia and the southern USA were tested, but poor results led to researchers looking elsewhere for material, particularly indica varieties more suited to the wet season conditions. This work was carried out mainly at Kimberley Research Station

(KRS) in the Ord River district and the Coastal Plains Research Station (CPRS) on the Adelaide River near Darwin.

As well as genotype evaluation, research at KRS included an investigation of the so-called "Kimberley rice disorder,"later found to be zinc deficiency (3). At CPRS, research priorities included crop establishment and soil problems.

Queensland

In contrast to the Western Australian and Northern Territory effort, the research input in Queensland has been minimal. Early research, conducted around South Johnstone (Fig. 1), involved testing rice varieties under upland conditions (5). Little further work was carried out until 1969 when research into irrigated rice commenced at Millaroo Research Station (Fig. 1). This involved the selection and introduction of new varieties, such as Bluebonnet 50, as well as nutritional work. A small breeding program was commenced in 1981. Other projects include herbicide studies, growth regulator studies, insect studies (brown planthopper, stem borer, and rice bug), disease studies (particularly crown rot), red rice control, and needle nematode control. In addition, some work is being done in nutrition, growth regulators, and rotations (N.R. Dasari, personal communication).

THE PRESENT QUEENSLAND RICE INDUSTRY

In Queensland, rice is drill sown into dry soil and flushed up to three times with irrigation water to germinate the seed. When the crop is about 15 cm high, it is sprayed for weeds (either on the ground or from the air) and half the N fertilizer is applied aerially. Permanent water is then maintained until just before harvest. The crop uses 12-15 ml of water/ha in the dry season and 8-15 ml/ha in the wet season. At panicle initiation (approximately 50 days after sowing for a wet season crop and 70-90 days after sowing for a dry season crop) the second half of the N fertilizer is broadcast into the floodwater. The permanent floodwater is drained when the lower spikelets on the panicle reach the early dough stage (about 10-14 days before harvest). The crop is machine harvested when the grain moisture level reaches 21-22%, and the product is trucked to the mill storage at Home Hill or Mareeba. (Mareeba rice is railed to Home Hill for milling.) At the mill, samples are taken for moisture and quality testing. The mill accepts rice with up to 22% moisture and the grower is paid by weight.

Laser leveling of rice bays is standard practice, the rice contour banks being constructed after this operation. Seeding can be carried out before or after the contour banks are constructed, but most farmers seed first in order to grow rice on their banks. This helps prevent weed growth and enables them to produce 10-20% more rice for the same cost of production.

Varieties currently grown are Starbonnet and Bluebonnet 50 (the latter in Mareeba). Both are high quality long-grain rices bred in southern USA. In the Darwin region about 200 ha of the variety IR661 is grown. About 10 kg P/ha is applied as superphosphate with the seed. From 120 to 150 kg N/ha is applied, half just before permanent flooding and half at panicle initiation. Some farmers apply a mixture at planting and some are still following the older recommendation of applying half their N fertilizer before sowing at a depth of 10 cm. Some farmers are finding it necessary to use zinc fertilizers on land that has been cut heavily by leveling, since this procedure exposes the high pH subsoils (Maltby, personal communication).

The major weed is barnyard grass, *Echinochloa colonum,* which is controlled with propanil applied at the 24 leaf stage of the weed. Other weeds include various sedges (*Cyperus* spp., *Fimbrystylis* spp.), buddah pea (*Aeschynomene indica*), and *Sesbania* spp., all of which are controlled by phenoxy herbicides, and red rice (*Oryza sativa*), for which the major control is burning stubble, with some control being afforded by a preplanting application of molinate at a rate of 7 liters/ ha. Other wild rices (*Oryza rufipogon* and *Oryza australiensis*) are less of a problem than red rice since they can be controlled by cultivation.

The major insect pest in all areas except the Burdekin River area is white stem borer (*Scirpophaga innotata*). It is controlled by applying carbofuran granules at 1 kg/ ha at late tillering. Other insects which can be troublesome are brown planthopper (*Nilaparvata lugens*), armyworms (*Spedoptera mauritia* and *Mythimna convecta*), and rice bug (*Leptocorisa* spp.). Of these, only brown planthopper causes problems, although even it may be readily controlled using an aerial application of carbaryl (Kay, personal communication).

The major diseases of rice in Queensland are narrow brown leaf spot (*Cercospora oryzae*), crown rot (*Gaemanomyces graminis*), sheath rots (*Rhizoc-*tonia *oryzae* and *R. solani*), stem rot (*Nakataea sigmoidea*), and kernel smut (*Tilletia barclayana*). In the Burdekin area the needle nematode (*Paralongidorus australis*) may cause major losses on individual farms, but these losses are not important to the industry as a whole (Shannon, personal communication). The only economically feasible control measure against such diseases is to breed high resistance varieties (Vawdrey, personal communication).

Animals such as ducks and geese may cause damage during the seedling stage, while animals such as brolgas and pigs can cause damage at any stage. Generally such damage is of minor importance.

FUTURE RESEARCH AND INDUSTRY DEVELOPMENTS

In the Northern Territory and Western Australia a major research initiative in breeding and nutrition will be required if rice growing is to become a viable industry. Much of the past research is now irrelevant and in the short term these areas can probably use material from the Queensland breeding program.

In Queensland, genetic evaluation is a high priority research area, while nutrition, particularly N studies, should also be a major research activity. N fertilizer use is inefficient and, as it is a major cost to the industry, it is a very important problem. Other aspects requiring further work include weed control, water control and usage (both are major costs), and cultural practices such as rotations and stubble retention.

The Ord River area in Western Australia has the potential to grow large areas of rice. However, suitable varieties are required and additional crops must be developed in order that the costs of production, fertilizer, etc. are reduced. This is unlikely to happen in the short term. The Darwin area in the Northern Territory is unlikely to develop as a rice producing region in the foreseeable future. The Queensland industry will probably increase from its present size of 4 000 ha to 20 000-25 000 by 1990 with the development of the Burdekin River Imgation Area using water from the Burdekin Falls Dam.

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Nitrogen Budgets for Intensive Rice Growing in Southern Australia

P. E. Bacon and D. P. Heenan

The effect of rice stubble management, and rate and time of fertilization on the fate of ^{15}N-labeled urea was studied within a continuous rice rotation common in southern Australian rice fields. Stubble incorporation increased grain yield by 0.8 t/ha and plant uptake of soil N by 15.5 kg N/ha. Plant response to additions of labeled urea at rates of 0,70, and 140 kg N/ha was essentially linear. Each 70 kg increment increased yield by about 1.8 t/ha, uptake of soil N by about 12 kg N/ha, and uptake of fertilizer N by 24 kg N/ha. The soil supplied 68-82% of the N taken up by the rice; the amount assimilated depended on the rate of addition of fertilizer N. Delaying the time of N application from the onset of permanent water to panicle initiation had little effect on yield but increased the crop's dependence on fertilizer N. The delay increased plant uptake of N by 66%, and the amount of N retained in the soil-plant system increased from 58 to 66 kg N/ ha. Of the applied N, 35% was taken up by the rice plants, 24% was retained in the top 30 cm layer of soil, and 3% was found in the 30-80 cm soil layer. Separate experiments showed that less than 1% of the applied N was volatilized as ammonia and it was concluded that denitrification accounted for the remaining 38%.

Until the 1970s, much of the southern Australian rice crop was grown in rotation with legumes. Since that time, many farmers have grown rice after rice for several years on the same site, and this has resulted in a greater dependence on fertilizer, with typical N application rates increasing from 30-50 kg N/ha to 120-150 kg N/ha. Increased use of fertilizer, plus increased cost per unit of fertilizer, results in N fertilization being the second major cost in rice production (15). Improving fertilizer N use efficiency is therefore more important than ever.

Rice crops in southern Australia are frequently sown into dry soil and given between two and four flood irrigations before being permanently flooded (PF). Recent studies (2,3,4) show that the maximum response to fertilizer N occurs when the N is applied just prior to permanent flooding or within 14 days of panicle initiation (PI). Labeled N studies show that fertilizer use efficiency is very low if fertilizer is applied at the nonrecommended times of sowing (3) or soon after permanent flooding (17). However, there is little information about the fate of N when fertilizer is applied prior to permanent flooding or at PI; and these are the usual times for N application in southern Australia.

This paper reports the results of experiments undertaken to examine the effects of various management options, such as residue incorporation, N

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application rates, time of application, on the fate of fertilizer N in a continuous rice cropping system.

MATERIALS AND METHODS

The experiments were conducted at the Agricultural Institute, Yanco, on a Birganbidgil clay loam (18), an apedal, hard-setting transitional red-brown earth (Dr 2.22; 12), with an impermeable medium clay B horizon 10 cm below the surface. The 0-30 cm layer of soil contained 0.09% N and 1% C, and had a pH of 4.2 in 0.01 *M* $CaCl_2$; exchangeable cations (in mg eq/kg soil) were Ca, 32; Mg, 21; Na, 0.8; and K, 5.

The experimental field had been used for rice cropping (cv. Inga) during the previous three years, and prior to this it had been used for intensive upland cereal production.

Rice stubble was incorporated into half of the plots (each 3.5 m x 9 m) as soon as possible after each rice harvest, while in the other half stubble was burned. These two stubble management treatments were factorially combined with three fertilization times (PF, PI, and a 50:50 split PF, PI), and three N application rates (0,70, and 140 kg urea N/ha, containing 5 atoms per cent ^{15}N). Each of the five replicates of the treatments had 15 cm I.D. polyvinyl chloride microplots inserted 30 cm into the soil prior to PF. The cylinders were placed within rows of rice seedlings and contained four plants per microplot. The height of the tube protruding from the soil surface was such that microplots fertilized at PI could be isolated from the surrounding floodwater.

At maturity the microplots were dug out, and plant tops and roots were separated from the soil. In addition, cores 2 cm I.D. and 75 cm long were taken from the center of the hole from which the microplots (receiving 140 kg N/ ha at PF) had been removed. These cores were divided into 30-55, 55-80, and 80-105 cm segments. All soil was dried, ground to a fine powder, mixed, and subsampled for macro-Kjeldahl N determination (5). The plant material was dried; divided into root, straw, and grain portions; weighed; ground; and analyzed for N content.

Elaborate precautions were taken to minimize cross-contamination. At each step of sample preparation unlabeled material was prepared between each labeled sample. In addition, 100 ml of 0.1 M acetic acid followed by 50 ml of ethanol plus 100 ml of water was distilled prior to each labeled sample (7). Following titration to determine the N content, the titrant containing 2-5 mg of N was acidified to pH 4.5 and prepared for mass spectrometric analysis. The background enrichment was determined on unlabeled material.

RESULTS AND DISCUSSION

Stubble management

There were few significant interactions between residue and fertilizer management treatments; each factor is therefore considered separately.

Stubble incorporation significantly increased grain yield by 0.8 t/ha, plant uptake of N by 18.3 kg/ ha, and uptake of soil N by 15.5 kg/ ha. This suggests that stubble incorporation increased grain yield by increasing the uptake of native soil N rather than by increasing uptake of fertilizer N. The extra soil N could have resulted from at least three mechanisms. Incorporating 10-15 t/ha of rice straw containing 0.4% N each year for three years rather than burning it would return an additional 120-180 kg N/ha to the soil. Stubble incorporation would result in a temporary reduction in the quantity of mineral N in the soil (1) creating an environment favorable for asymbiotic N fixation (16). Some of this N would be released during crop growth (13). The combined input of residue and N would also stimulate microbial activity resulting in more rapid mineralization of organic N as well as immobilization of fertilizer N (10).

Stubble incorporation had little effect on the fate of labeled N except on plots where all fertilizer was applied at PF. On these plots, stubble incorporation resulted in significantly more labeled N being retained in the soil (incorporated, 33.1 kg N/ ha; burnt, 25.3 kg N/ ha, LSD 5% = 4.08). This greater immobilization did not affect the uptake of labeled N and, in this experiment, the IO-week interval between incorporation and fertilization apparently was sufficient to prevent excessive immobilization interfering with N accumulation by the rice plant.

Nitrogen application rate

Plant response to additions of N was strongly linear up to 140 kg N/ ha applied at PF (Table 1,2). This is in contrast to the data of Heenan (8), who obtained the maximum yield with an application of 100 kg N/ ha. This contrast is presumably due to differences in the history of the experimental sites and differences in the weather during the two experimental periods.

Table 1. Effect of N addition on dry matter production and N uptake by rice.

	N application rate (kg/ha)			
	0	70	140	LSD (5%)
Dry matter yield (t/ha)				
Grain	5.47	7.13	9.11	0.69
Straw	6.24	10.18	13.72	1.17
Root	2.62	4.73	6.68	1.04
Total	14.33	22.04	29.51	2.51
Plant N uptake (kg/ha)				
Grain	57.0	69.9	87.5	8.0
Straw	25.7	41.8	56.1	5.7
Root	8.9	15.5	20.0	3.1
Total	91.7	127.2	163.6	14.3

Table 2. Effect of fertilization rate on distribution and uptake of native and fertilizer nitrogen.

	N application rate (kg/ha)			
	0	70	140	LSD (5%)
Plant uptake of soil N (kg/ha)				
Grain	57.0	56.3	59.5	2.4ns
Straw	25.7	33.4	40.0	6.1
Root	8.9	13.6	16.7	2.5
Total	91.6	103.3	116.2	11.8
Plant uptake of fertilizer (kg/ha)				
Grain	0	13.6	28.1	2.9
Straw	0	8.4	16.1	1.9
Root	0	1.9	3.4	0.4
Total	0	23.9	47.6	4.64

Increasing the application of N significantly increased dry matter production of grain, straw, and roots. It also increased the uptake of N into the various plant components (Table 1). Each 70 kg N/ ha increment increased grain yield by about 1.8 t/ ha, giving an average agronomic efficiency of 26 kg grain/ kg N. The linear increase in quantity of straw with increased N rate was maintained up to the relatively high application rate of 140 kg N/ha. Nitrogen uptake also increased linearly in response to an increase in the rate of N. Each 70 kg/ ha of applied N increased assimilation by 36 kg N/ ha, giving an apparent recovery of 51%. Sixty-two per cent of the N taken up by the unfertilized rice was found in the grain, compared with 54% for the fertilized plants (LSD 5% = 4.9). The yields and apparent N recovery are similar to those reported in large scale field trials with this rice cultivar (4).

Increasing the rate of application of fertilizer N increased the uptake of soil N into plant roots and straw (Table 2). Adding 70 kg N/ha increased soil N uptake from 91.6 to 103.3 kg N/ha (LSD 5% = 11.8), while a further 70 kg increased uptake to 116.2 kg N/ ha. This additional recovery of soil N due to application of fertilizer N is relatively common (10) and is believed to be due to microbially induced isotopic exchange between the applied N and the native soil organic N. Increasing the rate of application of fertilizer N also increased the quantity of fertilizer N retained in the soil at harvest. It is interesting to note that the extra 10.3 kg/ha of fertilizer N retained in the soil due to an increase in application rate from 70 to 140 kg/ ha was similar to the extra quantity of soil N (12.9 kg/ ha) recovered by the plants. This provides further evidence for isotopic exchange, rather than enhanced exploitation of the soil by the larger root system produced with higher rates of N.

Increasing the N application rate resulted in strong linear increases in plant N uptake (Table 2). Each 70 kg N/ haincrement increased plant uptake by 24 kg N/ ha; thus plants accumulated 35% of the applied N. This recovery (for urea) is similar to that obtained in studies reported elsewhere (6,11, E. Humphreys, personal communication).

Increasing the rate of application from 70 to 140 kg N/ha increased the proportion of plant N derived from fertilizer from 18 to 32%. Thus, even after four rice crops the soil was supplying 68-82% of crop N. This is similar to the 80% reported (E. Humphreys, personal communication) for an initial rice crop, and is consistent with studies which show that the soil is the major source of N even after long periods of continuous rice cultivation (14).

Fertilization time

Variations in the time of fertilization had a minor effect on yield but a major effect on N uptake by the rice plant (Table 3). Delaying N application until PI increased fertilizer N uptake by 66%. The increase was most pronounced in the grain component, where the percentage of N derived from fertilizer increased from 21 to 34% (LSD 5% = 3.0). This reflects the fact that much of the fertilizer N that accumulated in the grain was taken up after PI (P.E. Bacon, unpublished data). By contrast, the roots had the highest percentage of fertilizer N when N was applied at PF (17%), but only 13% (LSD 5% =2.98) when fertilizer was applied at PI. Root weight decreases after PI (2), so N applied at this time is less likely to accumulate in the roots.

The amount of fertilizer N retained in the soil decreased when application was delayed from PF to PI. However, plots receiving N at PI retained more in the plant-soil system (66.4 kg N/ ha) than did plots at PF (58.0 kg N/ ha, LSD 5% = 7.9).

Fate of fertilizer nitrogen

Of the total applied N, 20% was recovered in grain, 12% in straw, and 3% in roots, and 24% was retained in the 0-30 cm layer of soil. The 41% total loss is similar to that reported elsewhere (6,11) for urea broadcast onto rice soil. Simultaneous studies of ammonia volatilization carried out within the same rice bay as this experiment showed that less than 1 kg N/ ha was volatilized when 100 k urea N/ha was applied at PI (9). Ammonia volatilization is therefore unimportant in this system. Analysis of soil cores to a depth of 105 cm showed

Table 3. Effect of time of application of fertilizer on nitrogen assimilation by rice.

Application time	Total N uptake (kg/ha)	N from soil (kg/ha)	N from fertilizer (kg/ha)
No fertilizer applied	91.7	91.7	0
At permanent flooding	142.9	114.1	28.8
Half at permanent flooding and half at panicle initiation	135.2	104.6	30.6
At panicle initiation	158.2	110.4	47 a
LSD (5%)	17.5	14.4	5.71

that in addition to the 24% of the applied N recovered in the 0-30 cm layer, a further 2% was retained in the 30-55 cm layer and 1% in the 55-80 cm layer. Thus, only 3% of the applied N was below 30 cm and leaching can be disregarded as a loss mechanism in these soils. It is concluded, therefore, that the main mechanism for loss of applied N in this soil was denitrification. The most likely pathway for denitrification loss would be:

Urea Hydrolysis Ammonium Nitrification Nitrate Denitrification N_2

Blockage of the hydrolysis or nitrification steps would reduce denitrification, and chemicals capable of doing this should be tested when they become available.

ACKNOWLEDGMENTS

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Effect of Nitrogen Fertilizer Timing on Crop Growth and Nitrogen Use Efficiency by Different Rice Varieties in Southeastern Australia

D. P. Heenan and P. E. Bacon

An attempt has been made to outline the influence of the timing of N fertilizer application, particularly as it relates to New South Wales conditions, on the efficiency of use of that fertilizer in terms of growth and, most importantly, on final grain yield. There are obvious high correlations between N supply, growth, leaf area index, and final grain yield. Fertilizer N application at sowing or into the floodwater soon after permanent flooding resulted in low N use efficiency and poor rice growth. By contrast, fertilizing just prior to permanent flooding promoted rapid N uptake, increased crop growth, and produced higher yields. In some varieties, however, the excess vegetative growth induced by high levels of N uptake was detrimental to grain yield. This excess growth often resulted in shading of lower leaves and severe lodging of tall rice crops. This problem can be avoided by applying the bulk of the fertilizer at panicle initiation. Nitrogen application at this time stimulated grain production without causing excess vegetative growth.

Nitrogen fertilizer represents one of the main determinants and costs of successful rice growing in the irrigated areas of southern New South Wales (NSW). It is important, therefore, that this fertilizer be used efficiently; underfertilizing or overfertilizing can decrease grain yield. The amount of fertilizer needed to produce high yields depends largely on the previous history of the field and on the variety grown.

One of the main practices used in the past has been to grow rice after a legume-based pasture which can effectively build up the soil N between rice crops. The N in the soil after three or four years pasture can be sufficient to provide all the N requirements of the rice plant during the growth period. The slow decomposition of the organic matter under flooded conditions provides a readily available source of N for rice throughout the season. Long-term legume pastures have often promoted high levels of floret sterility and lodging in some varieties, resulting in low grain yields. This effect is more apparent in aerial sown crops when permanent water is applied earlier than with combine sown crops (4).

Over the past decade the use of legume pastures in the rotation has declined and this has increased the dependence of the rice crop on N fertilizers. It is well known that the efficiency of uptake of N by flooded rice can be very low. A vast amount of work has been carried out on the chemical and biological processes involved in losses of applied N and although these processes are still not fully

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understood, management practices can be developed to improve the recovery of this fertilizer.

NITROGEN LOSSES IN FLOODED-SOILS

This subject is covered extensively by others, so little is said here about the various complex processes involved. Urea is the main form of N fertilizer used on rice in NSW. Its N can be lost by two main processes, ammonia volatilization and nitrification-denitdication. Losses as ammonia gas are considered to be minor under NSW conditions, but they can account for up to 20% if the urea is applied into ponded water after the rice fields are permanently flooded (1 1, 16). Up to 13% of applied urea N can be lost as ammonia when the fertilizer is broadcast onto wet soil several days prior to permanent flooding (9). Topdressing fertilizer onto wet soil may also reduce the movement of N into the soil (3) and severe losses by denitrification can be incurred. Much of the applied N remains at the soil-water interface where it can be nitrified before the soil is permanently flooded; after flooding, the nitrate diffuses down into the anaerobic layer where it can be denitrified. Topdressing fertilizer into ponded water soon after permanent flooding will also result in extensive losses of N via the nitrification-denitrification reactions (15,16). Farmers in NSW therefore avoid applications into ponded water during early vegetative growth and normally apply fertilizer onto dry soil before permanent flooding.

Volatilization losses from plots fertilized with urea at panicle initiation are negligible (9). Extensive canopy development and the low phosphorus content of the floodwater inhibit algal growth and subsequent development of alkalinity in the floodwater. Nitrogen losses at this time appear to be due to nitrification-denitrification rather than to volatilization of ammonia.

NITROGEN REQUIREMENTS OF THE RICE PLANT

There are two main stages of rice growth and development, the vegetative phase and the reproductive phase. The vegetative phase extends from seedling to panicle initiation and is the time during which tiller number, potential leaf area index, and photosynthetic capacity are being established. The reproductive period extends from panicle initiation to maturity and is the period during which the size of the panicle, final grain number, and grain size are determined. Studies with the variety Inga showed that approximately 50% of the N assimilated was taken up by the plant tops by the time of panicle initiation and that 90% had been absorbed by heading (1). The period between panicle initiation and heading is therefore a time of rapid N uptake and coincides with extensive development of an adventitious root mat on the soil surface. This system of fine roots absorbs oxygen and nutrients from the soil-water interface (14). Bacon (1) found a fourfold increase in root material at the soil-water interface between late tillering and panicle initiation. Nitrogen uptake rates of 6-7 kg N/ ha per day were recorded on plants fertilized with 67 kg N/ha at panicle initiation.

The stages of development which appear to be most effectively influenced by N supply are 1) tillering, when a large number of panicles are promoted, and 2) between panicle initiation and heading, when a large number of spikelets per panicle are promoted. The final number of grains will be largely influenced by climatic conditions, particularly during the pollen development phase (7,12). Although there is potential to increase grain size in other grains such as wheat and barley (17), this is not the case with rice. The size and shape of each grain are restricted by rigid glumes whose dimensions are determined about a week before anthesis (1 3). The average grain size is highly heritable and can only be increased by up to 10% by topdressing 3-4 weeks before flowering (12). Nevertheless, N supply during grain filling must be sufficient to maintain photosynthetic activity in the upper three leaves (10). Although carbohydrates stored in the leaves and stems are translocated to the spikelets after anthesis, this contribution to final grain yield is usually less than 50% (4,13). Most of the carbohydrates synthesized for grain filling are therefore produced usually after flowering. Accumulated starch before complete floret formation, however, must be sufficient to ensure pollen development.

TIMING OF NITROGEN FERTILIZER APPLICATION

Correct timing of N fertilizer application involves consideration of plant needs, water management, and the variety chosen. Plant needs have been discussed above. Water management will specify when permanent flooding or anaerobic conditions are imposed. In NSW this depends on the method of establishment. When the crop is sown from the air, pregerminated seed is dropped into the water which remains ponded until physiological maturity. Combine- and sod-sown crops are drilled into dry soil. Two or three flush irrigations follow before the rice field is permanently flooded at about the three-leaf stage.

Growth promotion and yield

During the 1960s the accepted method of fertilizing rice was to apply all the fertilizer at sowing. In many cases, only small rates of application were needed as the soil was highly fertile following several years of pasture growth. Nevertheless, observations suggested that growth and N uptake were greater when the crop was aerially sown and permanently flooded immediately following the application of fertilizer. This led to a number of field experiments, initially by Boerema (4), looking at the most efficient time and method of applying early N (Table 1).

Owing to the high fertility of the soil, grain yields from all treatments were high. However, it was apparent that recovery, vegetative growth, and grain yields were highest when fertilizer was applied just prior to permanent flooding. Boerema concluded that N losses can be most effectively reduced, and growth and yields promoted, by applying the bulk of the fertilizer at the time of permanent flooding.

Further work by one of the authors (1) showed that growth, yields, and N uptake increased as the interval between fertilizer application and permanent flooding was reduced (Table 2).

Table 1. The effect of time and method of application of ammonium sulfate on grain yield, straw dry matter, and apparent recovery of applied nitrogen (4).

Method of application	Grain yield (t/ha)	Straw dry matter (t/ha)	Apparent recovery of fertilizer N (%)
52 kg N/ha drilled with seed	10.7	12.0	16.3
26 kg N/ha banded at 78 cm depth before sowing 26 kg N/ha drilled with seed	10.6	12.4	6.6
13 kg N/ha drilled with seed 39 kg N/ha broadcast on dry surface before permanent flooding	11.3	12.4	30.6
26 kg N/ha drilled with seed 26 kg N/ha broadcast at panicle initiation	11.0	12.0	4.8

Table 2. Effect of applying 67 kg N/ha at different times on dry matter production, nitrogen uptake, and grain yields of Calrose (1).

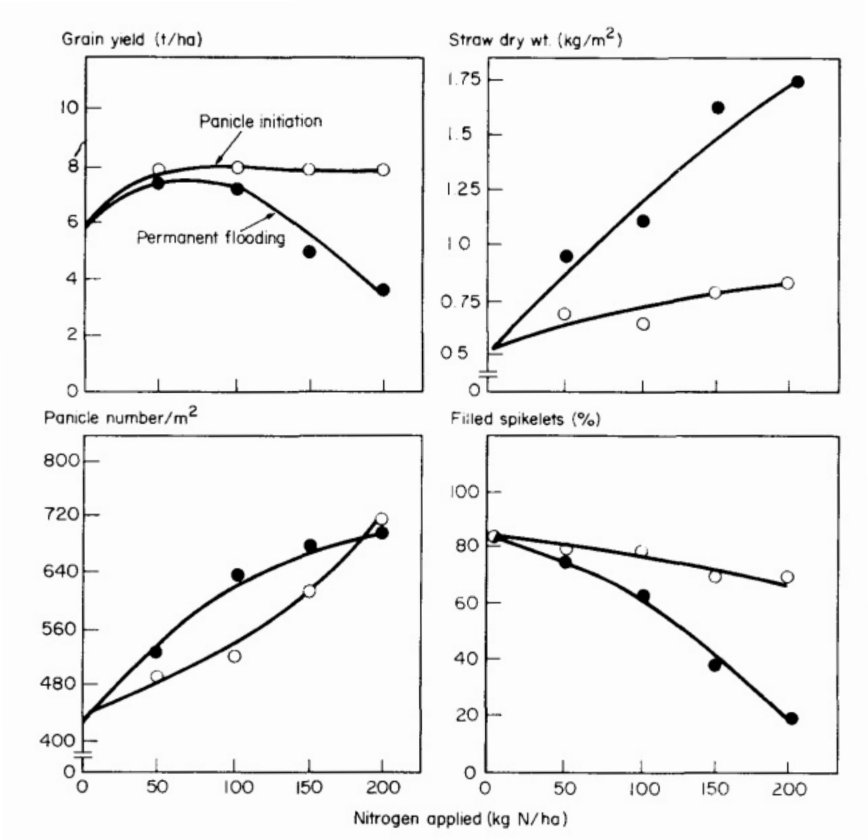
Fertilization time	Dry matter (g/m^2)	Grain yield (t/ha)	N uptake at heading (kg N/ha)
(No fertilizer applied)	1 530	8.53	85
Before first flushing	1911	8.53	84
Before second flushing	1917	8.83	90
Before third flushing	2 148	9.35	99
4 days before permanent flooding	2 327	9.74	107
At permanent flooding	2 273	9.68	104
After permanent flooding	2 218	9.07	90
Midtillering	1 859	9.28	88

It was also apparent that applying N immediately after permanent flooding or at midtillering resulted in reduced N uptake, less growth, and low grain yield compared with applications just before permanent flooding. The low response to N applied after permanent flooding or at midtillering was probably related to extensive N losses due to volatilization and nitrification-denitdication reactions (16). Similar responses to the above have been recorded on other soil types (E. Humphreys, personal communication).

Source-sink imbalance

Although in most cases there is a close positive relationship between vegetative growth and final grain yield, this is not true for all varieties of rice. The long grain variety Inga produced exceptional seedling growth in response to early N fertilization but often very low grain yields. The low grain yields were associated with floret sterility in the panicles. It was suggested that early N applications often promoted excessive vegetative development and excessive shading of the lower canopy leading to reduced assimilate supply (13). This was especially evident when the canopy structure promoted by a high N supply consisted of large droopy leaves (5).

Following reports that delaying the main application of N until panicle initiation resulted in a greater N response in some long grain varieties (18), an experiment was designed to compare early N application with topdressing at panicle initiation for Inga (8). Early N application induced a large vegetative response during tillering and the final vegetative dry matter production was considerably higher than when fertilizer was applied at panicle initiation (Fig. 1). Canopy structure was also different. High rates of fertilizer application at permanent flooding produced long, droopy leaves with a wide angle between leaf and stem. Although grain yields were significantly increased by low to moderate amounts of N applied at permanent flooding, yields were markedly depressed at the high N rates. The number of panicles and florets per panicle were larger and increased with N rate. The effect on panicle number was probably due to a greater survival of tillers produced before panicle initiation.



1. Effect of nitrogen applied at permanent flooding or panicle initiation on grain yield. straw dry weight, panicle number, and per cent tilled spikelets of Inga rice (8).

However, the proportion of florets filled was dramatically reduced by increasing N rate. When fertilizer application was delayed until panicle initiation, grain yield was not depressed at the high N rates. Straw dry weight was considerably less and the proportion of filled florets greater with delayed applications.

Based on the above evidence it was concluded that delayed applications of N at high rates produce higher grain yields than early applications by maintaining a high percentage of filled florets. It was suggested that vegetative response of this variety resulted in shading of the lower leaves in the canopy which caused a low supply of carbohydrates for grain filling.

The recovery of applied N by Inga rice was greater when the fertilizer was applied at permanent flooding rather than at panicle initiation (Table 3). This effect was mainly due to the greater vegetative growth produced when N was applied early. Increasing the rate of application reduced the recovery percentage at both application times, the reduction being greater for fertilizer applied at permanent flooding. At high rates of application, the time of application had little effect on recovery but caused marked differences in grain to straw ratio.

Growers often experience difficulties in topdressing exactly at panicle initiation due to inclement weather, failure to contract the airplane for the right time, etc. An experiment at Yanco showed little difference in N response when the fertilizer was delayed until 14 days after panicle initiation (Table 4) (2). A delay of 21 days, however, reduced the grain yield and delayed maturity. The yields were reduced mainly through effects on floret number, suggesting that the N was added too late to influence floret initiation.

The effect of early N fertilization on floret fertility is influenced by climatic conditions, especially temperature. Experiments in controlled temperature glasshouse chambers showed that while low temperatures at both the microspore stage and anthesis significantly reduced per cent grain set in Inga and Calrose,

Table 3. Effect of nitrogen timing on grain yields and recovery of fertilizer nitrogen in the tops of Inga rice (6).

N applied (kg/ha)	Grain yield (t/ha)	N recovery (%)
At permanent flooding		
0	5.9	-
50	7.2	74
100	7.6	58
150	5.0	36
200	3.7	35
At panicle initiation		
0	5.9	-
50	8.2	49
100	8.1	51
150	8.5	37
200	8.4	39

Table 4. Effect of time of nitrogen application after panicle initiation on grain yield and yield components of Inga (2).

	No fertilizer applied	Application time[a]					
		Permanent flood	PI	PI+ 7 d	PI+ 14 d	PI+ 21 d	LSD (5%)
Grain yield (t/ha)	6.0	6.9	9.0	8.9	8.8	8.1	0.8
Total florets per panicle	106	118	127	115	114	98	13
Filled florets (%)	83	63	79	80	82	82	9.3
Panicles per m^2	450	624	534	522	490	504	70

[a] PI = panicle initiation.

the reductions were greater when the plants were grown under high N conditions (Table 5).

Lodging

Although varieties such as Calrose have the potential to produce high yields under high fertility conditions, excess N can produce lodging of the crop with significant grain yield losses (4). Semidwarf varieties such as M7 can be selected that will tolerate high fertility, are resistant to lodging, and produce high grain yields. Some American experiences suggested that split applications of N fertilizer can reduce plant height (18). As plant height is an important factor in lodging susceptibility (5), we decided to look at the effects of timing of N fertilizer on plant height and the degree of lodging with Calrose and the recently released long grain Pelde.

No comparison can be made between varieties as they were grown under different fertility conditions. It was apparent that split applications of high rates of fertilizer N reduced plant height and the degree of lodging in both varieties (Table 6).

Table 5. Effect of nitrogen and low temperature for four days during the pollen microspore stage and anthesis on per cent grain set of Inga and Calrose (7).

Temperature (°C) and variety	Per cent grain set		
	N_0	N_1	N_2
28°/20°			
Inga	88	83	75
Calrose	93	91	90
12°/12° (pollen microspore)			
Inga	35	27	22
Calrose	53	38	32
12°/12° (anthesis)			
Inga	70	68	68
Calrose	85	75	63

Table 6. Plant height and lodging of Calrose and Pelde as influenced by split applications of nitrogen fertilizer (Heenan, unpublished data).

Nitrogen applied at		Calrose		Pelde	
Permanent flooding	Panicle initiation	Height (cm)	Lodging[a] (0-5)	Height (cm)	Lodging[a] (0-5)
0	0	100	0	126	2
	50	99	1.5	128	4
	100	98	2	128	4
50	0	109	1	131	4
	50	119	3.3	134	4.5
	100	120	3	135	4.5
100	0	125	4	137	4.5
	50	133	4.5	140	4.5
	100	138	5	147	5
150	-	-	-	143	5
LSD (5%)		19	0.5	7.0	0.6

[a] 5 = completely lodged.

Similar trials conducted over different seasons have not recorded any advantage of split applications of high N rates. This suggests that the advantages of split applications of high N rates are dependent on the climatic conditions experienced during the season. Indeed, the degree of N-induced lodging is itself highly dependent on seasonal conditions, particularly temperature.

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Fertilizer Nitrogen Recovery in Mechanized Dry Seeded Rice

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The review is confined to irrigated lowland rice in the temperate countries where all rice production is fully mechanized. Dry seeded rice is subjected to several wetting and drying cycles prior to permanent flooding 3-6 weeks after sowing. Plant recovery of fertilizer N applied at sowing is very poor (3-23%), particularly on soils with a high nitrifying capacity, and yield response is similarly affected. Application of nitrification inhibitors with fertilizer applied at sowing has generally improved efficiency of fertilization. Deep placement of N fertilizer at sowing (or before sowing) has not been properly evaluated. Plant recoveries of fertilizer N applied to the dry soil surface before permanent flooding (3l-50%) are generally higher than those from broadcast applications at transplanting in tropical rice culture. Deep placement of N fertilizer before permanent flooding increases recovery, but the effect of mechanical deep placement on yield awaits confirmation. Recoveries are generally unaffected by rate of N application (within a conservative range). Delaying N application until shortly after permanent flooding decreases recovery in the plant and reduces yield response considerably. However, delaying the application until visual panicle initiation results in increased recovery. Maximum yield responses are obtained with N application before permanent flooding or at panicle initiation; however, it is not always practical to apply a fertilizer at these times.

Dry seeding of rice is practiced in a wide range of cultural systems including rainfed lowland rice (northeast India, Bangladesh, and Indonesia), floating rice, and irrigated lowland rice (USA and Australia) (9). This review is confined to irrigated lowland rice in the temperate countries where all rice production is fully mechanized (9).

In dry seeded rice culture in the USA and Australia the seed is mechanically placed 2-3 cm below the soil surface in rows 15-18 cm apart (drilled) or, in some instances, broadcast onto the soil surface followed by harrowing (19). Approximately half the rice crop in southeast Australia is dry seeded, using either a combine seed drill in a shallow cultivated seedbed or a triple disc sodseeder in pasture, stubble, or cultivated soil. After sowing, the bays are flooded and then immediately drained (first flushing). In southeast Australia the rice is flushed twice on average (S. McIntyre, personal communication), after which the plants are sufficiently well established (approximately three leaves) to withstand permanent flooding. Semidwarf varieties require a longer flushing

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period (18). The flushing period is also extended when seedling growth is slow due to cool temperatures.

Optimal timing of N fertilization varies among rice growing regions and among varieties (9). Common application times and methods in the USA are I) broadcasting and incorporating prior to sowing, 2) drilling at 5-10 cm depth shortly before or at the time of sowing, 3) topdressing onto the dry soil surface before permanent flooding, and 4) midseason topdressing (19). In southeast Australia the recommended fertilization practice for the current major varieties (Calrose, Pelde, and M7) is to broadcast urea on the dry soil surface shortly before permanent flooding (1,4). The recommended practice for the recently replaced long grain variety Inga was to topdress with urea within 14 days after visual panicle initiation (2). It is also quite common for farmers to band a small amount of N fertilizer with the seed. There are some instances where major amounts of fertilizer are applied at sowing or soon after permanent flooding due to conflicting management problems between the end of the wheat season and rice establishment (A. Wray, personal communication). Nitrogen fertilizer accounts for approximately 20% of a farmer's variable costs in rice growing in southeast Australia (27), and fertilizer is typically applied at 50-100 kg N/ ha. Rates exceeding 100 kg N/ ha occur in both southeast Australia and the USA, particularly where semidwarf varieties are grown,

This paper summarizes the results of the few ^{15}N studies reported for dry seeded rice, and includes the results of recent field experiments with combine-sown Calrose, conducted by the authors, on the two major rice soil types in southeast Australia. Fertilizer N recoveries at each of the commonly practiced application times are compared with relevant data from transplanted rice culture. Several factors influencing N recovery at each application time are considered to varying extents, namely, soil type, method of application, N source, amount of fertilizer, and water management.

Much of the data reported here were obtained from rice grown on three soil types. Experiments in Louisiana, USA, were conducted on Crowley silt loam (a Typic Albaqualf) with a pH of 5.8. The two rice soils used in southeast Australia were Wunnamurra clay ('grey clay,' an Entic Pelloxerert) and Mundiwa clay ('red-brown earth,' an Entic Chromoxerert) (38). The grey clay is an alkaline soil (pH 7.8) with a self-mulching surface; textures remain heavy with increasing depth. The red-brown earth has a duplex profile with 10-15 cm of sandy loam over a heavy clay subsoil. The topsoil is acidic (pH 5.8), and pH increases to alkaline with greater depth.

FERTILIZATION AT SOWING

When urea was broadcast onto the surface of the grey soil at sowing and followed immediately by the first flushing, recovery of ^{15}N at physiological maturity was only 3.4% (Table 1). This is among the lowest recoveries that have been recorded for rice (8). The reason was the large loss (80%) of fertilizer N during the flushing period due to the rapid rates of nitrification and denitrification (Fig. 1). Predictably, there was no yield response to fertilization at sowing.

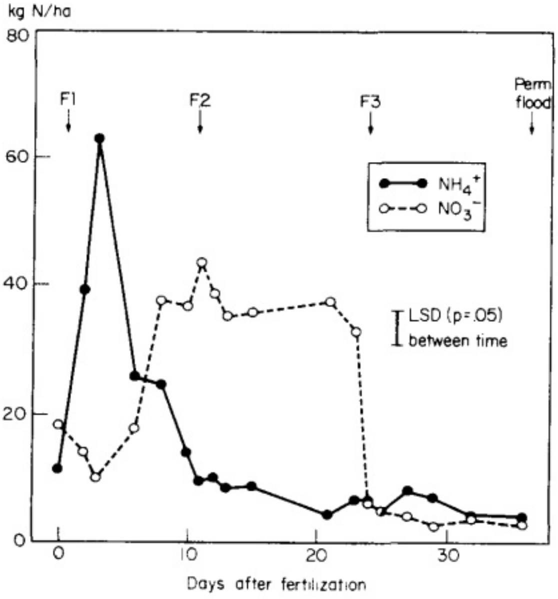
Table 1. ^{15}N recovery in the plant and ^{15}N loss from broadcast urea applied at several times to dry seeded rice. Summary of results from four experiments on two soil types in S. E. Australia.

Time of urea application	Rate (kg N/ha)	^{15}N recovery in plant (%) [a]			
		Grey clay		Red-brown earth	
		Experiment 1	Experiment 2	Experiment 3	Experiment 4
At sowing	50	3.4 (80)			
Before permanent water	50		35 (30)	36 (22)	
	50		40 (26)	36 (22)	
	60				30 (39)
	120				36 (34)
After permanent water	50	28 (45)			
At panicle initiation	50	42 (38)			67 (15) [b]
Split (before permanent water and at panicle Initiation)	60 + 60				49 (27)

[a] Valuer in parentheses are losses. [b] Following application of 60 kg N/ha as unlabeled urea before permanent flooding.

Soil type

The lack of response to fertilization at sowing on the grey soil contrasts with studies on the red-brown earth where fertilization at sowing resulted in significant yield increases (1,4). Apparent recoveries on the red soil were 17% (4) and 10% (l), compared with 2% on the grey soil. The lower recovery on the grey soil is probably due to the effect of pH on nitrification rate (34); the half-life of



1. Mineral N in the top 20 cm of soil following broadcast urea (50 kg N/ ha) at sowing on grey soil (F = flushing with water).

NH_4^+ on the alkaline grey soil was 5.5 days (Fig. 1), compared with 36 days on the acid red soil. These data are in good agreement with the model developed by Horth (4) relating nitrification rate to pH for six Murrumbidgee Irrigation Area rice soils.

Water management

The flushing period in dry seeded rice culture is equivalent to intermittent flooding during the early stages of a rainfed rice crop. Field and glasshouse studies with plants on the effect of intermittent flooding after fertilization have yielded variable results. In greenhouse experiments with transplanted seedlings, Craswell and Vlek (7) and Fillery and Vlek (11) did not find increased losses associated with intermittent flooding for two soils, both with and without plants. In contrast, in a glasshouse experiment by Sah and Mikkelsen (33), intermittent flooding decreased fertilizer N recovery of the plants by 40%. Intermittent flooding in the field increased losses by a factor of 2.5 over continuous flooding (15). The effect of intermittent flooding on recovery was also reflected in yield in the above studies. Patrick et a1 (25) also found decreased growth, yield, and N uptake in-field and glasshouse studies with intermittent flooding on N-deficient soils. However, intermittent flooding on soils high in available N improved yields, and it was speculated that this was due to loss of excess N and alleviation of toxic conditions. These apparently conflicting data seem to be due to the different nitrifying capacities of the soils under the experimental conditions.

Method of fertilization

Considerable yield increases have been obtained with deeper placement of N fertilizer by either broadcasting and incorporation or by drilling of fertilizer at 5-10 cm depth, compared with surface broadcasting, shortly before seeding, in water seeded rice. The success of this method in dry seeded rice would depend on being able to place the fertilizer at a depth where the soil remained anaerobic throughout the flushing period. In a large plot experiment using ^{15}N-depleted ammonium sulfate on the Crowley silt loam, Patrick et a1 (23) drilled the fertilizer 6-8 cm deep at sowing time. The plots were flooded after three weeks, and plant ^{15}N recoveries were only 16.9% at 56 kg N ha and 23.3% at 112 kg N/ha. In southeast Australia banding ammonium sulfate at 7-8 cm before sowing had no effect on the yield of Caloro compared with banding at seed depth (2-3 cm) on an infertile red-brown earth and on a fertile grey clay (3), or on a fertile red-brown earth (4). Factors contributing to this lack of response could have been the high fertility of two of the sites, the extensive flushing period on the infertile red-brown earth, and possible failure to place the fertilizer in a zone which remained anaerobic.

Nitrogen source

Urea and ammonium sulfate. In the 1970-71 IAEA studies (14), average recoveries of N from ammonium sulfate were 18% higher than that from urea. However, in terms of grain yield the relative performances of the two N sources vaned among countries, with significant differences in two of the eight countries.

No reasons for these yield differences were given. In their reviews, De Datta and Magnaye (10) and Prasad and De Datta (28) concluded that, in general, grain yield responses to ammonium sulfate and urea are similar, but with some exceptions. For example, in soils low in active iron, sulfurless fertilizers are preferred (10). On a high fertility red-brown earth soil in southeast Australia both sources, applied prior to the first flushing, gave equal yields (1).

Modified urea fertilizers. The efficiency of N fertilization is often increased using sulfur-coated urea (SCU) instead of prilled urea (PU) in irrigated rice transplanted into puddled soil (e.g., 12). Prasad and De Datta (28) concluded that the advantages of SCU have been more obvious in soils with intermittent flooding and drying. In a series of dry seeded rice experiments on the Crowley silt loam, SCU (with a variety of release rates) was compared with urea and ammonium sulfate (40). All N sources were broadcast onto the soil surface, at various ranges of N rates, and incorporated before sowing. Average yields with SCU were significantly higher than those with PU in three out of six experiments. In a later field experiment on the same soil type, grain yield with SCU was significantly lower than that with PU (5).

Nitrification inhibitors

There are many reports of yield increases and higher N recovery associated with the use of nitrification inhibitors in rice subjected to alternate wetting and drying, particularly in irrigated upland rice (29). In dry seeded rice, losses from fertilizer N applied at sowing are largely associated with nitrification during the flushing period. There are considerable advantages to applying fertilizer at sowing in both the practical aspects and in terms of more vigorous early seedling growth. A nitrification inhibitor which remains effective throughout the flushing period would improve efficiency of fertilization at sowing. Patrick et al (24) found no improvement in yield when either nitrapyrin (2-chloro-6-[trichloromethyl]-pyridine) or AM (2-amino-4-chloro-6-methyl pyrimidine) was added with ammonium sulfate prior to sowing. However, several years later, on the same soil (Crowley silt loam), both Wells (39) and Brandon et al (5) found significant yield responses with broadcast and incorporated urea coated with nitrapyrin, and with broadcast urea followed by spraying the soil surface with nitrapyrin prior to incorporation. Use of the nitrification inhibitor dicyandiamide (DCD) with ammonium sulfate has also resulted in improved efficiency of fertilization at sowing in southeast Australia (4).

FERTILIZATION BEFORE PERMANENT FLOODING

Recovery of N in the plant from ^{15}N-labeled urea broadcast onto the dry soil surface followed by permanent flooding varied from 30 to 40%, with losses of 22-39%, in three field experiments in southeast Australia (Table 1). A wider variation was obtained in the USA, with recoveries of 30-51% and losses of 8.5-50% (26,30,31). These recoveries are higher than the recoveries of N applied at transplanting in tropical rice culture. For example, average recoveries of surface-applied and incorporated N fertilizer in the 1970-71 IAEA studies (14) were 24% and 27% in the dry season, and 23% and 32% in the wet season. Recoveries of fertilizer N surface-applied at transplanting ranged from 11 to 42% (average 22%) in eight field experiments surveyed by Craswell and Vlek (8).

Yield response of the major varieties in southeast Australia to N fertilization is maximal with application before permanent flooding (1,4,13). On the grey soil an agronomic efficiency of 56 kg grain/ kg applied N was obtained in two successive seasons. Similar efficiencies were measured by Cao et al (6). These are among the highest values recorded for rice.

Soil type

Nitrogen recoveries in the plant and N losses were similar on the two southeast Australian soils (Table 1). The major loss pathway is believed to be nitrification-denitrification. Only trace amounts of volatilized ammonia were detected with fertilization before permanent water by Muirhead et a1 (21). It is surprising to find similar recoveries and losses on soils that differ greatly in properties, such as CEC and pH, which influence key processes in the nitrification-denitrification pathway (32). However, the relationship between fertilizer N recovery and soil properties is not well understood. For instance, in a greenhouse study (15) six soils were compared when urea was broadcast and incorporated at transplanting; the soils varied widely in pH, CEC, and organic matter content. N recovery in the plant was 23-26% in the two strongly acid soils, and only 15-16% in the other four soils. There was no obvious relationship between total ^{15}N recovery and soil properties, or between soil properties and N recovery in the plant with deep placed urea supergranules (USG).

Method of fertilization

Deep placement of N fertilizer at transplanting in tropical rice culture has often improved fertilizer N recovery in the plant, sometimes by more than double (e.g., 6,8,14). Deep placement of fertilizer before permanent water is applied in mechanized dry seeded rice culture has received little attention, presumably because of the practical difficulties in trying to band fertilize in an established crop. In southeast Australia banding of PU (5-7 cm depth, band spacing 30 cm, bands across the plant rows) and point placement of USG (1 g) shortly before permanent flooding resulted in significantly increased ^{15}N plant recovery on both the grey and red soils (Table 2). The increased recovery was largely associated with decreased soil immobilization rather than reduced losses. This increased recovery was not reflected in grain yield response on the red soil, but there appeared to be a yield response on the grey soil. Verification of these yield responses is currently being sought in a second series of placement trials.

Nitrogen source and inhibitors

Urea and ammonium sulfate. Reddy and Patrick (31) applied urea and ammonium sulfate to dry seeded rice before permanent flooding. Recovery of ^{15}N in the soil-plant system, as well as grain and straw yields, were similar for both N sources. On the red-brown earth Bacon (1) reported similar yields for both sources applied four days before permanent flooding, but a significantly

Table 2. Effect of placement method on ^{15}N recovery in the plant with urea applied before permanent water on two soil types in S. E. Australia.

Method	^{15}N recovery (% of applied N)	
	Grey clay	Red-brown earth
Broadcast prilled urea	38	36
Banded [a] prilled urea	48	44
Point placed [a] urea supergranules (1 g)	50	48
LSD (P = 0.05)	3	3

[a] At 5-7 cm depth.

higher yield for ammonium sulfate compared with urea when these were applied immediately before permanent flooding.

Modified urea fertilizers. In southeast Australia two field experiments on the grey clay and red-brown earth compared point placement of USG and banding of SCU, IBDU (isobutylidene diurea), and PU before application of permanent water. On the red soil, agronomic efficiencies were similar for all forms of urea (Table 3). On the grey soil, agronomic efficiencies of USG and IBDU were significantly higher than for PU. There was a significant increase in efficiency associated with use of the nitrification inhibitor DCD on the grey soil, while there was no significant increase on the red soil (Table 3).

Nitrogen rate

Reddy and Patrick (30,31) conducted two field experiments in 1975 on the Crowley silt loam, using two rates of ammonium sulfate. When the fertilizer was

Table 3. Effect of form of urea on agronomic efficiency when fertilizer is banded at 5-7 cm depth before permanent water on two soil types in S. E. Australia.

N source [a]	Time of application [b]	Kg grain/kg fertilizer N	
		Red-brown earth	Grey clay [c]
Prilled urea	Sev.	41	51
	Imm.	45	57
USG	Sev.	-	56
	Imm.	46	76
IBDU	Sev.	54	79
	Imm.	49	61
scu	Sev.	39	67
Prilled urea + DCD	Sev.	-	70
	Imm.	54	79
LSD (P = 0.05)		ns (n=10)	19 (n=12)

[a] USG = urea supergranules, scu = sulfur-coated urea, IBDU = isobutylidene diurea, DCD = dicyandiamide. [b] sev. = applied several days before permanent flooding, Imm = applied immediately before permanent flooding. [c] Efficiencies on the grey clay were very high because of the poor performance of the controls.

applied at 100 kg N/ha before permanent flooding, ^{15}N recovery in the plant (51%) was substantially higher than that with a fertilization rate of 60 kg N/ha (33%). In contrast, on the red-brown earth in southeast Australia, doubling the rate of N before applying permanent water did not significantly affect the ^{15}N balance (Table 1). In the 1973-74 IAEA isotope studies on rice fertilization (14) the proportions of fertilizer N recovered by the plants were similar for rates ranging from 25 to 100 kg N/ ha.

Water management

A field experiment comparing conventional water management of dry seeded rice with sprinkler-irrigated rice was conducted on the red soil in southeast Australia (20). Urea N recovery in the plant applied before permanent flooding in the flooded plots was not significantly greater than recovery of urea N applied at the same time in plots receiving sprinkler irrigation three times a week or once a week (Table 4). However, in the conventionally flooded plots the proportion of total N uptake derived from fertilizer applied before permanent water was significantly less (approximately two thirds) than that in the sprinkler-irrigated plots. Recovery of ^{15}N in the soil plus roots of the sprinkler-irrigated plots compared with conventional water management was increased by half to two thirds, resulting in reduced losses of fertilizer N (Table 4). Therefore, the poorer agronomic performance of the sprinkler-irrigated rice on this soil is unlikely to be due to unavailability of fertilizer N because of increased denitrification. This is consistent with the relatively low rate of nitrification in the red soil.

FERTILIZATION AFTER PERMANENT FLOODING

Topdressing with urea on the grey soil a few hours after flooding resulted in a N recovery in the plant of 28% and losses of 45% (Table 1). Similar results on the same soil were obtained in two experiments by Simpson et a1 (35,36), with approximately a half and a quarter, respectively, of the loss as volatilized ammonia. Total N recovery in the plant was increased by two thirds when PPD was added with the urea, but addition of DCD had a negligible effect on urea N

Table 4. Effect of water management on recovery of ^{15}N-labeled urea applied at time of permanent water on the red soil in S. E. Australia.

Water management	^{15}N recovery (% of applied N)	
	Plant tops	Soil
Flooded permanently	30.4	31.0
Sprinkler irrigated three times a week	30.6	45.2
Sprinkler irrigated once a week	25.1	51.0
LSD (P = 0.05)	ns	11.8

recovery (35). The lower recovery of fertilizer N with fertilization after permanent flooding compared with fertilization before permanent flooding (Table 1) was also associated with a much lower soil N uptake. As a result there was a yield decline of 25% when fertilization was delayed until after flooding. Several other studies have also measured a higher response to N applied to a dry soil surface prior to flooding compared with application into the floodwater (1,9,16). The greater efficiency of fertilization before permanent flooding appears to be due to the fact that the fertilizer is carried deeper into the soil: on the grey soil in Experiment 1 (Table 1) the majority of the fertilizer N was rapidly carried below 2 cm with fertilization before permanent flooding, while with fertilization after permanent flooding the majority was located in the floodwater and in the top 2 cm of soil.

MIDSEASON FERTILIZATION

Midseason fertilization (defined here as several weeks before visual panicle initiation) is not normally practiced in dry seeded rice culture in southeast Australia as it is relatively inefficient (1,2). In Louisiana, midseason application of ammonium sulfate at 100 kg N/ha resulted in a 33% N recovery in the plant (30). However, early season application (before permanent flooding) gave a superior recovery (47%) and this was associated with a significantly increased yield over midseason application. In the following two seasons plant recoveries of both urea and ammonium sulfate (60 kg N/ha) applied midseason ranged from 41 to 49% (31). Losses from urea were 10% higher than from ammonium sulfate. There was a large difference between the seasons in per cent loss (38% versus 12%), due to differing retention in the soil, but no reasons were advanced for the difference.

FERTILIZATION AT VISUAL PANICLE INITIATION

In southeast Australia, N recovery in the plant of ^{15}N from urea topdressed within a few days after panicle initiation was 42% and 67% for the grey and red soils, with losses of 38% and 15% (Table 1). On the red soil an additional dose of unlabeled fertilizer had been applied before permanent water, and this was probably a major cause of the higher recovery. The data are consistent with the general trend that fertilizer N recovery tends to increase with lateness of application until around the flag leaf stage (e.g., 14,22). These recoveries were generally higher than plant recoveries of N applied at panicle initiation in tropical rice culture (14, 17, 37). Fertilization at panicle initiation usually produces the maximum yields with the variety Inga in southeast Australian rice culture. For Calrose, fertilization before permanent water or at panicle initiation produced similar high yields (1). However, there are disadvantages with fertilization at panicle initiation such as the cost of applying the fertilizer by airplane, and delayed and uneven maturity due to the lateness of topdressing.

CONCLUSIONS

The recommended fertilization practices in dry seeded rice are very efficient by comparison with common practices in transplanted rice. However, large amounts of fertilizer N are immobilized in soil organic matter, and substantial losses are also incurred. Banding of fertilizer (5-7 cm depth) before permanent flooding significantly improves plant fertilizer recovery; however, it is not certain that the increased recovery is reflected in yield. The major limitations to fertilization before permanent flooding in dry seeded rice in southeast Australia are wet weather during the flushing period and conflicting demands on management because of the clash with the end of the wheat season. There is a need for greater flexibility in fertilizer management to accommodate these problems. Therefore, it would be desirable to improve the efficiency of N fertilizer at sowing. Nitrification inhibitors have proved effective in a number of studies, but they are expensive. A proper evaluation of deep placement of N fertilizers applied before sowing is needed, including an assessment of anhydrous ammonia.

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A Farmer’s Perspective on Rice Growing in Australia

G. Blight

Rice farmers in Australia suffer from decreasing returns, rising costs, and overproduction. Over the last 30 years, returns for rice have fluctuated dramatically. In Australia any substantial rise in rice returns depends on a disaster in another exporting country, such as Thailand or America. Terms of trade are declining, which will probably continue. The key to survival is not only the maintenance of productivity, but more specifically the use of lower inputs to grow the crop. Our biggest costs in growing rice include water, nitrogen fertilizer, herbicides, fuel, and machinery. We use between 13 000 and 16 000 liters/ ha per crop, which means that we spend between $130 and $170/ ha on water. A 10% or 20% reduction in that particular cost would be most attractive. Most farmers are endeavoring to use better layouts and landforming as a means of achieving lower water usage.

Fuel is one of the most overtaxed products that we in Australia use. In the last two years tractor fuel prices to farmers in Australia have increased by 42%, whereas in America farmers have had no such increase. All our increases are due to the complex pricing mechanism that the government has developed for taxation.

Machinery costs in Australia are likewise higher than for our counterparts in America and this again is mainly due to government charges.

In the future, greater use will be made of cooperative machinery pools, and farmers will spread their machinery over a greater area. In other words, small farmers will not be able to continue to purchase adequate machinery from their gross proceeds from one farm unit and will need to work with their neighbors to purchase machinery to adequately service their crops. If that concept does not work, the future will see the development of larger rice farms. In that context it is encouraging that the Water Resources Commission is promoting the relaxation of previously strict regulation of the amount of farming land that each individual farmer could own. That is a positive step towards allowing the better farmers to become bigger and, hopefully, to survive.

With our new varieties in Australia we are using higher rates of N to achieve higher yields. The results are encouraging, but we have a lot to learn about efficiency of N application. Historically, rice farms developed a rice and pasture rotation resulting in a high soil N buildup underneath the subterranean clover pastures which were grazed by sheep and cattle. In those early years the application of N fertilizer was only minimal, was not very costly, and therefore attracted very little research activity. With the advent of larger rice area on all farms, less pasture, and more wheat cropping, the soil N status decreased dramatically. This has meant that farmers have been applying the necessary N

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for the rice crop as urea fertilizer. The questions we all ask ourselves each year are, how much N should we apply to the crop, and when and how should we apply it? From experience we guess how much N to apply in the early stage of the crop. At this stage, urea is applied to a dry soil surface and worked into the soil by flooding. At a later stage of the crop we may, by visual appraisal of its growth and color, decide that it is necessary to apply more N at panicle initiation. At both stages the amount of N to apply is uncertain. The development of predictive soil analysis was encouraged by the rice industry and the Department of Agriculture, but general inconsistency in results doomed it to failure. We are now applying in the range of 150 kg N/ ha which costs about $120/ ha, and results at this stage show us that we are losing 50% of the applied N under present methods. It is frightening to think that $60/ha disappears or is of no value to the crop.

Therein lies the importance of research into more efficient ways of applying N. Recently there has been research work into deep placement of N before permanent flooding which is achieving encouraging results. That method does have some drawbacks in its practical application. It does highlight the actual problem that most rice farmers have in finding methods of N application that can quickly and accurately cover large areas with minimum labor. It should be remembered that in 50% of cases the fertilizer before permanent flooding has been applied aerially, but now a growing number of farmers are using large capacity ground spreading equipment. If we can save up to $30 or $40 per ha by deep placement methods, then there is great encouragement for farmers to exercise some management skills in getting around the problem of application.

One of the effects of continuous cropping and close cropping rotations has been a deterioration of soil structure. Recent work on stubble incorporation has received tremendous attention from farmers throughout the rice growing regions. It now seems possible, by the use of machinery developed over the last five years, to quickly incorporate rice and wheat stubble, and so assist in developing better soil structure and N status. If intensive cropping programs are the answer to maintaining production and the generation of funds to maintain the farm operation, then stubble incorporation might become the most widespread cultivation change in farming methods in the irrigated areas. Unfortunately, even with modern machinery it is a relatively expensive exercise and the long term benefits of such a practice have yet to be clearly identified. It is encouraging that the New South Wales (NSW) Department of Agriculture is keen to see to it that research is continued in this area.

With all the problems we have of increasing costs, maintaining our soil structure, and increasing our yields, the emphasis for researchers has to be to find ways for us to grow our crops more cheaply. Our farmers may have to look towards growing rice crops in the next few years for a return of between $100 and $120/t. At present costs, that is not a profitable exercise. So, when I raise the question in my calculations of what I waste, N seems to come to the top of the list. If we are in fact losing 50% of the benefit of N to our crops, then there lies the first priority for intensive research. The Rice Research Committee within the NSW rice industry is conscious of this problem and has encouraged research both by the Department of Agriculture and the Commonwealth Scientific and

Industrial Research Organization. We are anxiously awaiting significant results, not so that fertilizer companies may suffer, but so that we can keep buying some fertilizer. It is interesting to note that some farmers have determined that biological N fixation might be a practical proposition. I would like to highlight my own intentions in my farm development over the next five years. I am going to return to the old rice - pasture rotations. This is because I believe that the best rice crops, that is the crops with the highest yields, are achieved by sodseeding rice direct into long established pastures. Yields of 12 t/ha are achievable in such rotations and might even be surpassed in the near future. Those yields can be achieved by applying 50 to 100 kg N/ha as urea if soil N is high. Another benefit of such a rotation is the real prospect of using less chemicals for weed control —anothersaving in costs of up to $75/ha. I am confident that, through higher yields and fewer inputs of N and chemicals, I can achieve a cash benefit of about $290.60/ ha on present costs and returns as follows:

Increased yield from 8.12 t/ ha to 10 t/ ha @ $120/t	=	$225.60
Less N (50-60 kg N/ ha less)	=	40.00
Less chemicals (say, 1 crop in 3)	=	25.00
Total benefit		$290.60

The development of high yielding pasture species, both summer and winter, in the last few years now enhances the prospect of achieving very high stocking rates. This has a benefit, of course, not only in helping to fertilize the soil but also in generating extra income per hectare. Unfortunately this type of broad area cultivation practice can be undertaken only by those who have relatively large areas, that is, over 400 ha. In most cases farm sizes are restricted to 200 to 300 ha. Nevertheless, it highlights the concern that farmers have for the high cost of N in rice growing.

Again I emphasize the need for methods that will allow higher yields with lower costs (Table 1). Agriculture has a major role to play in Australia's continued well being. Farmers are dependent on new technology and accept it far more readily than most people recognize. The link between technology, applied research, the environment, and our farm is vital to our future survival.

1 leave you with a small saying: "Nations may battle and the world rock with revolutions, but the land will care for him who cares for it."

Table 1. Costs and gross margin profits per ha for rice, variety M7, machine-sown in the Murrumbidgee Irrigation Area (1985 harvest).

Income ($)	
Grain, 8 t/ha @ $121/t delivered	968.00
Variable costs ($)	
Cultivation	22.95
Sowing	9.98
Harvesting	152.00
Shifting	6.65
Cartage to silo	43.84
Seed (140 kg/ha)	23.80
Fertilizer and application (173 kg N/ha)	135.61
Chemicals (Gramoxone, Molinate, Trichlorpon)	75.02
Water (16 000 liters)	184.32
Total variable costs	654.17
Gross marqin	313.83

Nitrogen Fertilizer Efficiency in Lowland Rice in Indonesia

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The relation between the total amount of unmilled rice produced and the total amount of urea used in Indonesia between 1967 and 1980 suggests that the weight of rice produced per kg of urea applied decreased over time and with increased rate of N. Results from field experiments in West Java and other considerations suggest that this reduction in fertilizer efficiency could have been due partly to proportionally higher losses with higher rates of N through run-off from permanently flooded rice fields, and perhaps mainly to a decreasing efficiency of the rice plant in terms of kg rice produced per kg N taken up when the plant content is elevated. A higher plant N content (kg N/ ha) or concentration (%N) induced a higher percentage of empty spikelets. The practical consequences of the results are discussed.

In 1969, Indonesia was a major importer of rice in order to satisfy its local food requirements. In that year a major effort was initiated by the Government of Indonesia, through the beginning of its first Five-Year Development Plan (Repelita) to become self-sufficient in food production, especially in relation to rice. This was achieved by 1982 through government-supported production programs promoting high yielding rice varieties, higher rates of fertilizers, pest and disease control, improved marketing channels, intensified agricultural extension, credits, and subsidized production inputs.

In this paper we investigate to what extent the use of N fertilizers has contributed towards this increase in rice production, the factors affecting the efficiency of fertilizer use, and the required direction of research to increase this efficiency. Results of field experiments in West Java conducted as part of the AARD/IFDC Joint Project are used in the analysis.

MATERIALS AND METHODS

The data for rice production in Indonesia are from Bernsten et a1 (1); those for urea usage and harvested area are from Partohardjono et a1 (4). Results from five field experiments in West Java were used. Experiments 1 and 2 were located at Sukamandi Research Station during the 1982-83 wet season and 1983 dry season, respectively. Experiment 3 was at Muara Research Station near Bogor during the 1983-84 wet season. In all three experiments the variety IR36 was

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transplanted and the soil kept under permanently flooded conditions after the initial broadcasting of prilled urea (PU) applied at different rates as split dressings (0,3, and 5 weeks after transplanting [WAT]). In addition, different N fertilizer strategies were compared, including deep placement of urea supergranules (USG) at transplanting, and incorporation of broadcast PU.

From 3 WAT, plant samples were taken every two weeks until maturity for determination of dry matter yield and N concentration. At each occasion, 12 hills were cut at ground level, oven dried at 70C. and ground for Kjeldahl analysis.

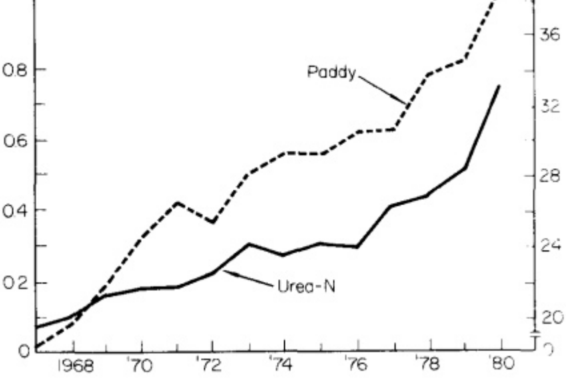
Experiments 4 and 5 were in the Subang district on farmers' fields during the 1984 dry season. The variety grown in experiment 4 was IR54, and in experiment 5 the variety was Cisadane; after transplanting, the soil was kept permanently flooded. Prilled urea was broadcast at different rates at 3 and 5 WAT. In addition, in two urea treatments the floodwater was removed, PU was broadcast, and the floodwater returned 2.5 days later. Plant samples were collected at anthesis in the same way as for experiments 1, 2, and 3.

For some treatments in experiments 2, 3, and 5. floodwater temperatures were determined and water samples collected several times a day; the samples were analyzed for pH, ammoniacal N, and urea N immediately after collection. From the results the vapor pressure of the ammonia above the floodwater (pNH$_3$) was calculated according to Denmead et al (2).

RESULTS AND DISCUSSIONS

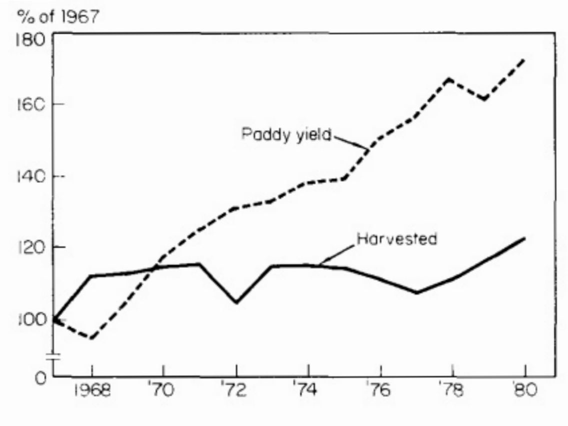
Relation between rice production and urea usage

Between 1967 and 1980 unhusked rice grain (paddy) production in Indonesia increased from 18.4 x 10^6 t to 38.5 x 10^6 t (Fig. 1). This was almost entirely due to an increase in yield per unit area rather than to an increase in cultivated area (Fig. 2). Between 1968 and 1979 the harvested area increased by only 3.5%, while during the same period the yield per ha increased by 70.6%.



1. Paddy produced and urea N used in Indonesia between 1967 and 1980.

2. Relative change of harvested area and paddy yield per unit harvested area in Indonesia. Values for 1967 = 100.

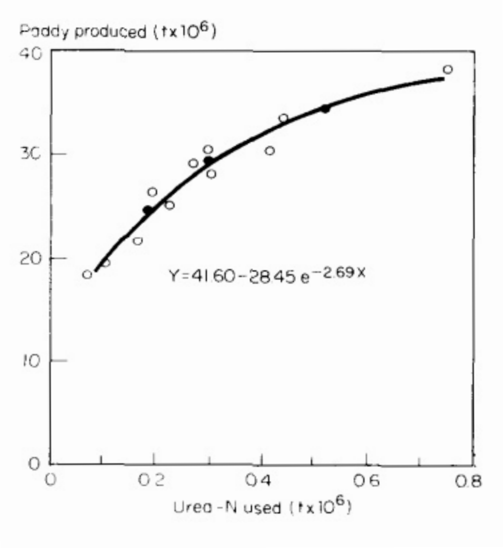


It is almost certain that such a yield increase would not have been possible without the application of more urea per ha, combined with the use of N-responsive modern varieties (Fig. 3). With low inputs of N in the period between 1967 and 1972, an additional 56.4 kg of rice was produced per additional kg N used, while with higher inputs in later years this efficiency dropped to 1 1.7 kg of rice per kg N.

Such a decrease in efficiency from a higher rate of urea application could have been due to elevated N losses from the soil plus floodwater before plant uptake, and / or to a decrease in amount of dry matter or grain per unit of N taken up when the total plant N content is increased. In other words, the efficiency, E, could decrease in either case, where E before plant N uptake is defined as

$$E_s = \frac{\text{kg N applied - kg N lost}}{\text{kg N applied}}$$

3. Relation between urea N used and paddy produced in lndonesia between 1967 and 1980.



and after plant N uptake as

$$E_s = \frac{\text{kg plant dry matter or paddy}}{\text{kg N in plant}}$$

We now look at the different factors that determine these E values in some of our field experiments in West Java.

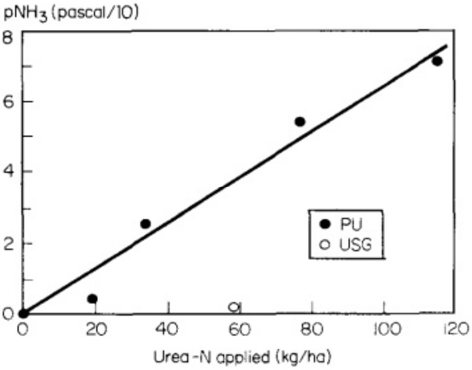
Urea nitrogen efficiency before plant nitrogen uptake

The potential for ammonia volatilization losses under Sukamandi conditions are high for broadcast PU (7). Measurements of pNH_3 when PU was broadcast at transplanting (Fig. 4) indicate that this pressure is linearly related to rate of N applied. Since for a given windspeed ammonia volatilization loss is directly proportional to pNH_3 (3), the results in Figure 4 suggest that this loss is also directly proportional to rate of urea N applied. In other words, in terms of ammonia volatilization E_s remains constant. The results in Figure 4 also suggest that through deep placement of urea the potential for ammonia loss can be nearly eliminated.

Loss of applied fertilizer N through run-off can occur when rice bays overflow due to excessive rainfall, or when there is continuous flow to facilitate water transport to lower lying areas. When such flow occurs, a part or all of the fertilizer N contained in the water of a bay will be removed from that bay and must therefore be regarded as a loss to the farmer.

Our results for applications during transplanting at Sukamandi (Table 1) indicate that with higher rates of urea application a greater proportion of the fertilizer N remains in the floodwater for at least several days. Therefore, the potential for run-off loss increases and E, decreases with increasing rates of applied N. The results in Table 1 suggest also that this vulnerability is due mainly to the retention in the floodwater of a greater proportion of the N in urea form with higher rates of application. In other words, the rate of urea hydrolysis is not increased in proportion to the rate of N applied.

Some farmers in Indonesia remove the floodwater and then broadcast PU onto the soil surface; they leave the soil in this condition for several days. This



4. Vapor pressure of ammonia above floodwater for different rates of broadcast prilled urea (PU) and one rate of deep point-placed urea supergranules (USG). Mean of samplings at near midday on 2, 3, and 4 days after urea application (experiment 2).

Table 1. Proportions of urea nitrogen and ammoniacal nitrogen in the floodwater at transplanting (experiment 2).[a]

Rate of application (kg N/ha)	Form of N	% of applied N				
		1 DAA			2 DAA	3 DAA
		0800 h	1400 h	1830 h	1830 h	1830 h
	UN	35	51	47	27	22
116	AN	16	26	17	27	24
	Total	51	77	64	54	46
	UN	23	26	33	16.5	10
77	AN	12	13.5	12	13.5	15
	Total	35	39.5	45	30	25
	UN	7	16	18	11	7
39	AN	5	11.5	10	12	12.5
	Total	12	27.5	28	23	19.5
	UN	9	7.5	12.5	7.5	4
19	AN	12	13	11.5	13.5	15
	Total	21	20.5	24	21	19

[a] UN = N in urea form, AN = N in ammoniacal form, DAA = days after application.

method of application is known as *macak macak.* Under these conditions (experiment 5), we could not detect any urea in the surface soil 24 hours after the application of different rates of urea. This suggests a very high rate of hydrolysis due to an intimate contact of the urea with the soil. After return of the floodwater 2.5 days later, the amount of ammoniacal N (AN) in the water relative to the amount of N applied did not change appreciably with the rate of applied N (Table 2). This implies that with *macak macak* the potential for run-off losses of broadcast urea is low and is not proportional to the rate of applied N. In more general terms, any delay in urea hydrolysis through increased urea concentration, increase in water depth, or addition of urease inhibitors will tend to make urea more prone to run-off loss.

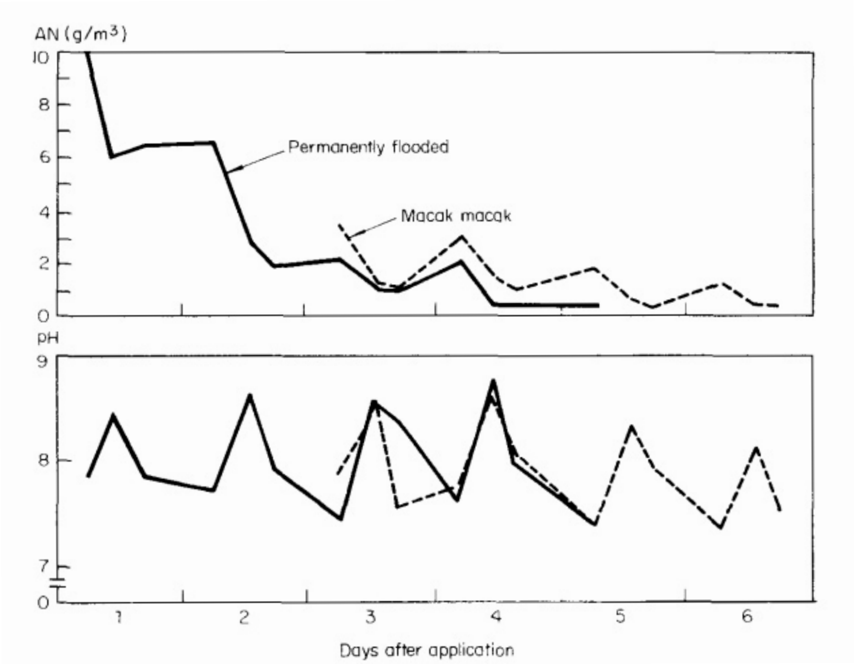
Table 2. Ammoniacal nitrogen in the floodwater from urea broadcast on a drained soil that was reflooded 2.5 days later.

Days after application	Time (h)	% of applied N	
		87 kg N/ha	29 kg N/ha
3	0600	7.7	10.0
	1300	5.7	6.9
	1730	6.7	6.9
4	0600	8.2	8.3
	1300	3.0	2.4
	1730	3.0	7.3
Mean		6.3	7.0

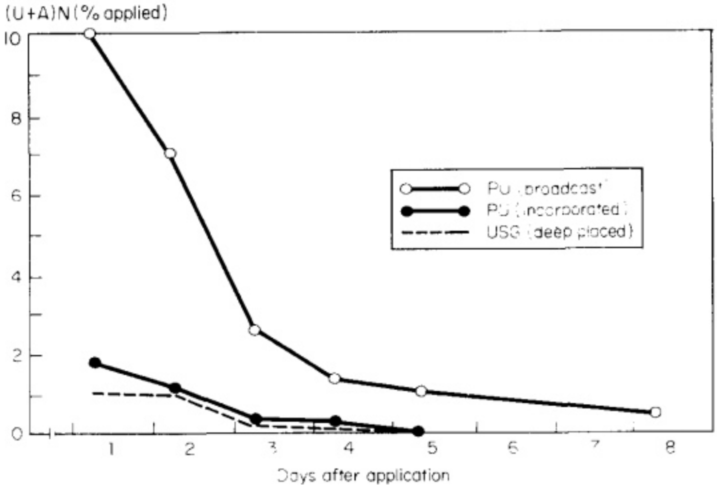
It is not known whether *macak macak* increases or decreases ammonia volatilization losses compared with permanently flooded conditions. Preliminary measurements (Fig. 5) suggest that pNH3 above the floodwater 3, 4, and 5 days after application (DAA) is likely to be higher after macak macak in view of a higher AN concentration in the water and almost.equa1 pH values (except for 1730 h on 3 DAA). What is not known, however. is the potential for NH_3 volatilization during the period when the soil is drained.

Another way of decreasing the potential for run-off losses is by incorporating the urea with the topsoil or by deep placement. In both cases, the concentration of fertilizer N in the floodwater is substantially lowered, and the residence time in the water is shortened (Fig. 6).

With regard to leaching losses, it can be expected that E, will decrease with higher rates of applied N for a given soil. The absorption capacity for the two main ionic N forms (ammonium and nitrate) in the root zone is limited, and consequently a lower proportion of N will be retained in that zone with high rates of N applied. Where leaching is mainly in the ammonium form, limited absorption can take place through immobilization, adsorption on exchange sites, and fixation on clay lattices. This means that E, will tend to decrease with increasing leaching and increasing rate of applied urea. By contrast, when losses occur mainly through biological denitrification, it can be argued that E, might increase with higher rates of N, since for a given soil the denitrification capacity is limited by the amount of organic carbon in the soil.



5. Ammoniacal N (AN) concentration and pH in the floodwater after broadcasting prilled urea at 4.4 kg N/ha. either onto permanently flooded soil or onto drained soil (macak macak) that was reflooded 2.5 days later (experiment 5).



6. Urea n (u) plus ammoniacal N (A) in the floodwater at different times after application of broadcast prilled urea (PU), broadcast and incorporated PU, and deep point-placed urea supergranules (USG), each applied X7 kg N/ ha (experiment 3).

We have very limited information on leaching and denitrification losses in West Java. In one experiment at Sukamandi in which ^{15}N-labeled urea was broadcast at 90 kg N/ ha onto a flooded soil, the ^{15}N not recovered in the soil water system after 10 days was equal to the calculated amount of loss through ammonia volatilization. Furthermore, virtually all ^{15}N in the soil was located in the top 5 cm of the soil and 61% of that was found in the top 2 cm. In other words, losses through leaching and denitrification appear to be insignificant at Sukamandi.

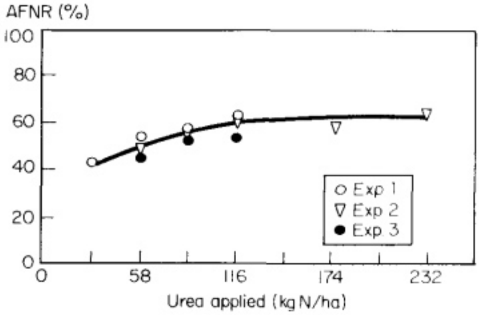
Urea nitrogen efficiency after plant nitrogen uptake

Plant N contents were determined 3, 5, 7, 9, and 11 WAT, and at maturity in experiments 1, 2, and 3. Apparent fertilizer N recoveries (AFNR) were calculated for 7, 9, and 11 WAT and at maturity. Those for 9 WAT would appear to reflect best the actual recoveries since 1) there was no evidence of any further fertilizer N uptake thereafter, and 2) after 9 WAT, i.e., approximately after anthesis, there is a chance of a net loss of N from tops of plants (6).

The results (Fig. 7) do not suggest that there was any difference in AFNR among the three experiments, but there was a trend for the AFNR values to increase with increasing rates of N. This could be due to a limited absorption of N in the soil through immobilization plus ammonium fixation and/ or an increased root system with increasing N inducing a higher uptake of native soil N.

The results in Figure 7 can be seen as a reflection of the effect of urea rate on E_s, i.e., on the loss processes before plant uptake. On that basis it must be concluded that losses of applied N before plant uptake were not proportionally enhanced with increasing rate of urea in our experiments.

The amount of dry matter produced for a given amount of N taken up (again at 9 WAT) did not vary with experimental location (Fig. 8). However, E_p

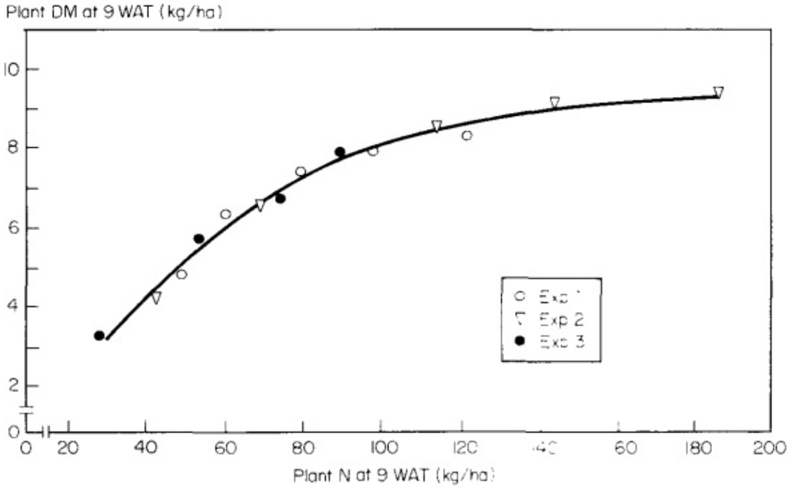


7. Apparent fertilizer N recovery (AFNR) at 9 weeks after transplanting from different rates of prilled urea, broadcast in split dressings (0, 3. and 5 WAT), for experiments 1, 2. and 3.

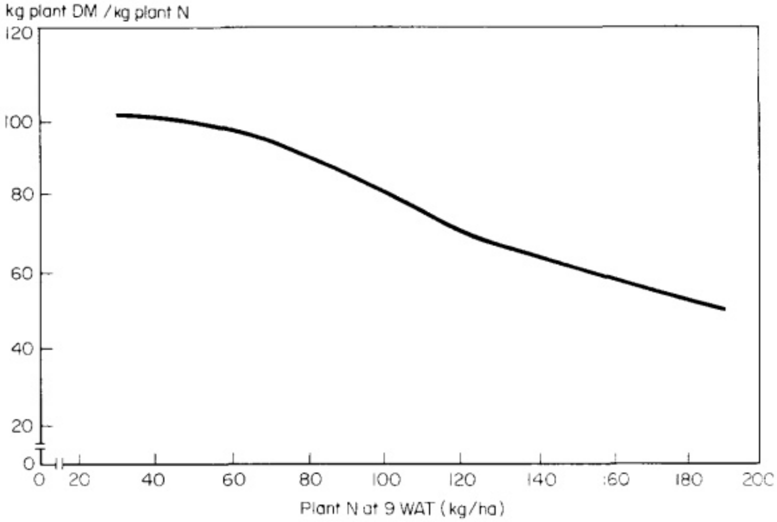
(kg dry matter/kg N taken up) decreased with increasing amounts of plant N (Fig. 9). In other words, the N taken up became progressively less efficient in producing a bigger plant as the plant N accumulated.

Similarly, E, (in terms of paddy) decreased linearly in all three experiments and also in experiment 4 (Fig. 10). When these results are expressed in conventional terms a curvilinear relation between plant N content and paddy yield is obtained (Fig. 11). The linear relations in Figure 10 do not suggest that there is a sudden 'toxic' level of N above which yield production decreases, i.e., the decline in paddy yield in Figure 11 would appear to reflect a physiological phenomenon that is operational at all levels of plant N.

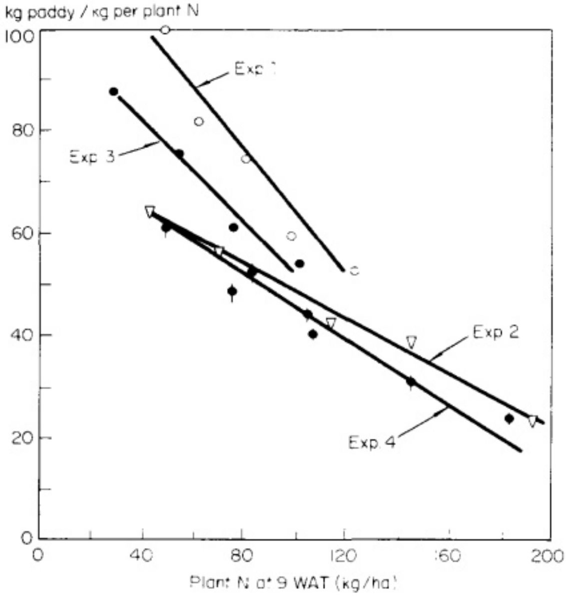
One possibility is that with a higher plant N concentration a higher sterility was induced. This was investigated in experiment 4. The results (Table 3) confirm that a higher percentage of empty spikelets is very closely associated with a higher plant N concentration.



8. Relation between plant N content and plant dry matter at 9 WAT resulting from different rates of prilled urea broadcast in split dressings (experiments I, 2, and 3).



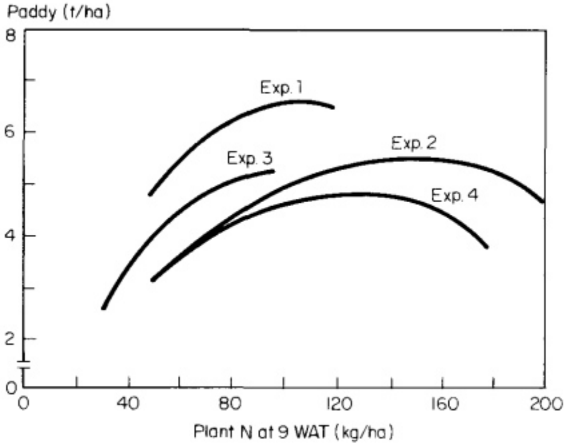
9. Relation between plant N content and dry matter produced per kg of plant N, at 9 WAT, resulting from different rates of prilled urea broadcast in split dressings (experiments I. 2. and 3).



10. Relation between plant N content at 9 WAT and paddy produced per kg plant N, resulting from different rates of prilled urea broadcast in split dressings (experiments 1, 2, 3, and 4).

DISCUSSION AND CONCLUSIONS

The results suggest that the national decrease in urea efficiency for the 1978-1980 period could have been due to run-off losses from permanently flooded fields and/ or to the inherent capacity of the rice plant to produce an equal amount of rice per kg of plant N when the plant N content is increased. With regard to the



11. Relation between plant N content at 9 WAT and paddy yield. resulting from different rates of prilled urea broadcast in split dressings (experiments 1, 2, 3, and 4); derived from results in Figure 10.

Table 3. Relationships between rate of urea applied, plant nitrogen content, plant nitrogen concentration at nine weeks after transplanting, and per cent empty spikelets.

	Correlation	coefficient		
	a	b	C	d
a. Urea rate (kg/ha)	-	-	-	-
b. Plant N (kg/ha)	0.971	-	-	-
c. Plant N (%)	0.995	0.960	-	-
d. Empty spikelets (%)	0.980	0937	0.965	-

former, Walker (5) observed that in Indonesia continuous flow of irrigation water is the rule rather than the exception, i.e., run-off losses of fertilizer N might have occurred on a large scale. However, some farmers use *macak macak* and our results suggest that under such conditions run-off loss does not induce any change in E, with increasing rate.

Unfortunately, not enough is known about the rate of flow of irrigation water and the frequency of drainage of a rice field to be able to predict the importance of run-off losses. If such losses are important, then our results indicate that they can be substantially lowered by incorporation or deep placement of urea. However, both strategies may require equipment to which the average farmer has no ready access. In addition, the cost of either alternative is likely to be such that the farmer must apply most, if not all, of his N at the start of crop growth, something he might be reluctant to do.

With *macak macak,* run-off losses are almost certainly decreased, but this form of urea application is inefficient in terms of water usage, since the floodwater has to be completely removed and replaced later.

In all our experiments, E, was lowered with increasing plant N content (Fig. 9, 10) and therefore with increasing amount of N applied (Fig. 7). It is therefore almost certain that the decrease in efficiency nationally over time (Fig. 3) is at least partly due to a physiological inefficiency in the plant itself. The results of experiment 4, executed on a farmer's field in the Subang district, appear to confirm this. In this experiment, no significant grain yield increases were obtained for urea applications above 58 kg N/ ha. Yet, in the same district, the average rate of application by the farmers was 135 kg N/ha (D. O'Brien, personal communication).

We draw the following conclusions.

- The national increase in rice production was achieved mainly through an increase in amount of urea applied per unit of land. This resulted, however, in a lower efficiency per unit of N applied.
- The decrease in N fertilizer efficiency could be due partly to run-off losses from permanently flooded fields, but almost certainly also to an increasing inefficiency of the rice plant with increasing plant N content and concentration.
- Run-off losses can be diminished through incorporation or deep placement of urea, but these methods of application require further development before they can be introduced.
- Because 'continuous flow' of irrigation water appears to be the dominant form of irrigation in Indonesia, it is likely that incorporation or deep placement of urea will have a much more beneficial effect than field experiments with standing water indicate.
- Run-off losses can also be reduced through application of urea to a drained soil and then flooding the soil after several days (*macak macak*). Whether *macak macak* has any beneficial effect on reducing ammonia volatilization needs to be investigated in view of the widespread application of this strategy in Indonesia.
- Because run-off losses could be an important contributor to a decreased urea efficiency, an assessment should be made of the existing irrigation strategies in Indonesia.
- If the national objective in Indonesia is to use urea more efficiently in lowland rice, then a reduction in rate of application is likely to achieve that aim. If, however, the objective is to maximize rice production, then careful consideration should be given to the rate of N input at which ceiling yields are achieved. Above this rate a yield reduction is likely.

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A Simulation Model of Nitrogen Response of Irrigated Rice

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The growth and yield of irrigated, transplanted rice are simulated with a simple model based on responses to solar radiation, temperature, and N supply. The model is fitted to field data of 23 experimental treatments with different forms of N fertilizer, and different rates, times, and methods of application. The model highlights the importance of crop N concentration during the grain filling period and the competition between grain and foliage. Simulations with the model suggest that for low rates of N supply to the crop, yield is little affected by the time of application, but for high rates of supply, simulated yields decrease with later application.

Nitrogen fertilizer is applied in large quantities to irrigated rice crops in many parts of southeast Asia where it represents a major share of the cash cost of production. The choice of the form of fertilizer and its rate, date, and method of application are important decisions for farmers. Even with exhaustive experimentation it is difficult to be certain that the system has been finely tuned and that the fertilizer response has been maximized. A simulation model, based on processes affecting the growth of rice in relation to its N content, presents an opportunity to search for an optimal response.

DATA AND METHODS

Irrigated, transplanted rice was grown in two field experiments at Sukamandi and Muara in West Java. In both experiments the widely grown cultivar IR36 was supplied at the optimal time with nonlimiting quantities of all inputs except N fertilizer. Each experiment consisted of a randomized block with three replicates. The treatments included a wide range of forms, rates, and splits of N. These experiments were part of a joint project by the International Fertilizer Development Center and the Indonesian Agency for Agricultural Research and Development. Detailed results of the experiments are to be presented elsewhere.

The experiment at Sukamandi, the major Indonesian rice research station located 50 km east of Jakarta on the subcoastal plain, was conducted from December 1982 to March 1983. The experiment at Muara, situated 50 km south

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of Jakarta, was conducted from December 1983 to March 1984. Mean daily global radiation and temperature in the cloudy environment of Muara were 11 MJ/m^2 and 24.5 °C for the crop period, compared with an estimated 16 MJ/m^2 and 27 °C for Sukamandi.

During both experiments above-ground dry matter was harvested from each plot at intervals of 14 days, dried, weighed, ground, and analyzed for N.

MODEL

The model is a modification of the growth equation of Byrne (2), combined with the environmental scalars of Fitzpatrick and Nix (6), and the plant N model of Angus and Moncur (1). The equations and definitions of parameters are presented in Table 1. The key to the N submodel is the specification of an envelope of plant N concentrations which change with development. The upper and lower bounds of this envelope are shown in Figure 1, along with other estimates of these bounds for rice extracted from the literature.

The biological processes are simulated at a high level of aggregation so that the model has few parameters and is sufficiently simple for fitting by statistical methods. We used the function minimization method of Miller (8), known as LMM (based on the Levenberg-Morrison-Marquardt algorithm). The estimated parameter values, standard errors, and units are shown in Table 2.

APPLICATIONS OF THE MODEL

The model was used to simulate the results of hypothetical experiments using the parameters fitted to the Sukamandi and Muara treatments, and an environment

Table 1. The algorithm used for calculating dry matter and yield production in relation to radiation, temperature, and nitrogen supply, and the definitions and units of state variables.
(The parameters a - x are defined in Table 2. Phasic development was simulated only to apply to the particular conditions of these experiments).

$W = [a \,.\, (W-G) \,.\, RI.NI] / (1+ß.W) - g \,.\, Q_{10} \,.\, W$

$DG = DW+d \,.W_{anthesis}.GDEV$

$NI = [1-\exp(-e.RNC)]/[1-\exp(-e)]$

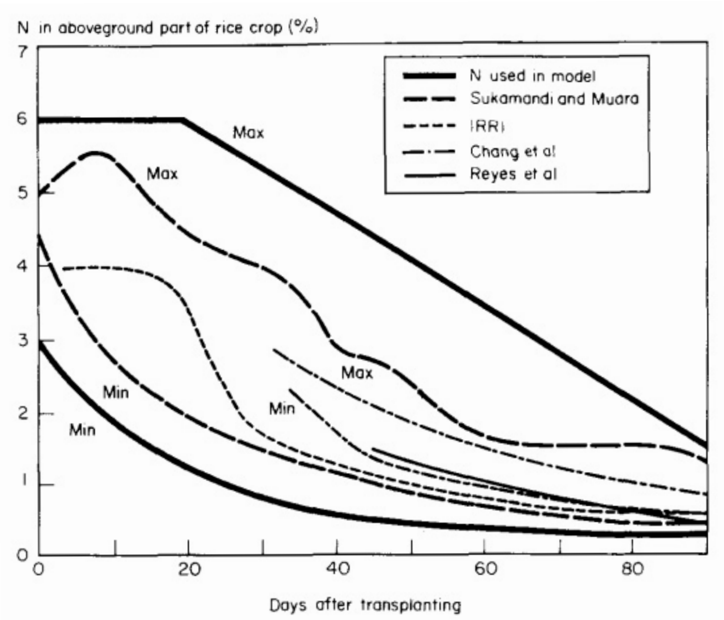
$RNC = [(N-GN)/(W-G) - N_{min}] / [N_{max}-N_{min}]$

$DGN = 0.0096NI.W_{anthesis}.GDEV$

$RI = [1-\exp(-z.RAD/30)]/[1-\exp(-z)]$

$Q10 = 2^{(t-27)/10}$

W	total crop biomass	g/m^2
$W_{anthesis}$	biomass at anthesis	g/m^2
G	grain biomass	g/m^2
N	total crop nitrogen	g/m^2
GN	grain nitrogen	g/m^2
NI	nitrogen index	dimensionless
RI	radiation index	dimensionless
RAD	global radiation	MJ/m^2 per day
GDEV	rate of grain development	1/d



1. The paths of the maximum (Max) and minimum (Min) nitrogen concentrations observed in the experiments, and some values published by IRRI (7), Reyes et al (9), and Changet al (3), with physiological time scales adjusted so that they resemble a transplanted crop with a duration of 95 days.

Table 2. Fitted parameter values, standard errors, units, and correlations between parameters.

Parameter	Meaning	Estimate	Standard error	Unit
a	gross relative growth rate	0.13	0.0041	g/g per day
ß	foliage cover parameter	0.0019	0.00020	1/g
g	maintenance respiration	0.0054	0.0010	g/g
d	proportion straw translocated	0.18	0.01 7	g/g
e	nitrogen response curvature	3.4	0.29	dimensionless
z	radiation response curvature	9.4	1.11	dimensionless

Correlation between parameters

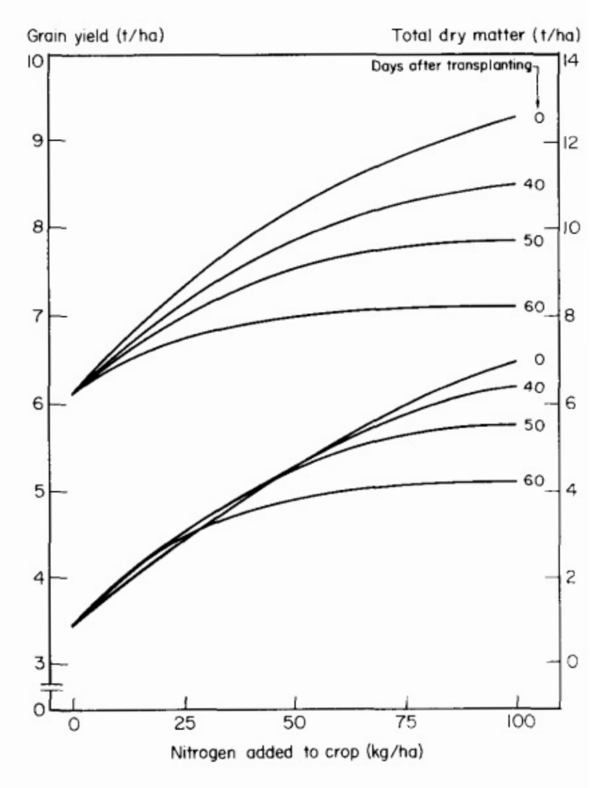
	a	ß	g	d	e	z
a	1.00					
ß	0.26	1.00				
g	0.01	–0.88	1.00			
d	–0.01	-0.15	0.40	1.00		
e	–0.68	0.39	-0.40	0.15	1.00	
z	-0.40	-0.35	0.28	0.09	-0.01	1.00

with mean daily radiation of 16 MJ/m^2, mean daily temperature of 27 °C, and a supply of 50 kg/ ha of N released gradually from the soil to the crop. No losses of fertilizer N from the soil are calculated, and the total amount of N supplied is assumed to be incorporated in the crop.

The results of a series of computed ‘experiments’ on rate and timing of N supply are shown in Figure 2. The simulated yields and dry matter show diminishing returns to the amount of N supplied. The effect of timing shows a more complex pattern, with little effect of timing on grain yield for small applications of N, but a large response to timing for larger applications. The effect of timing on dry matter production shows a steady reduction with delay of supply to the crop.

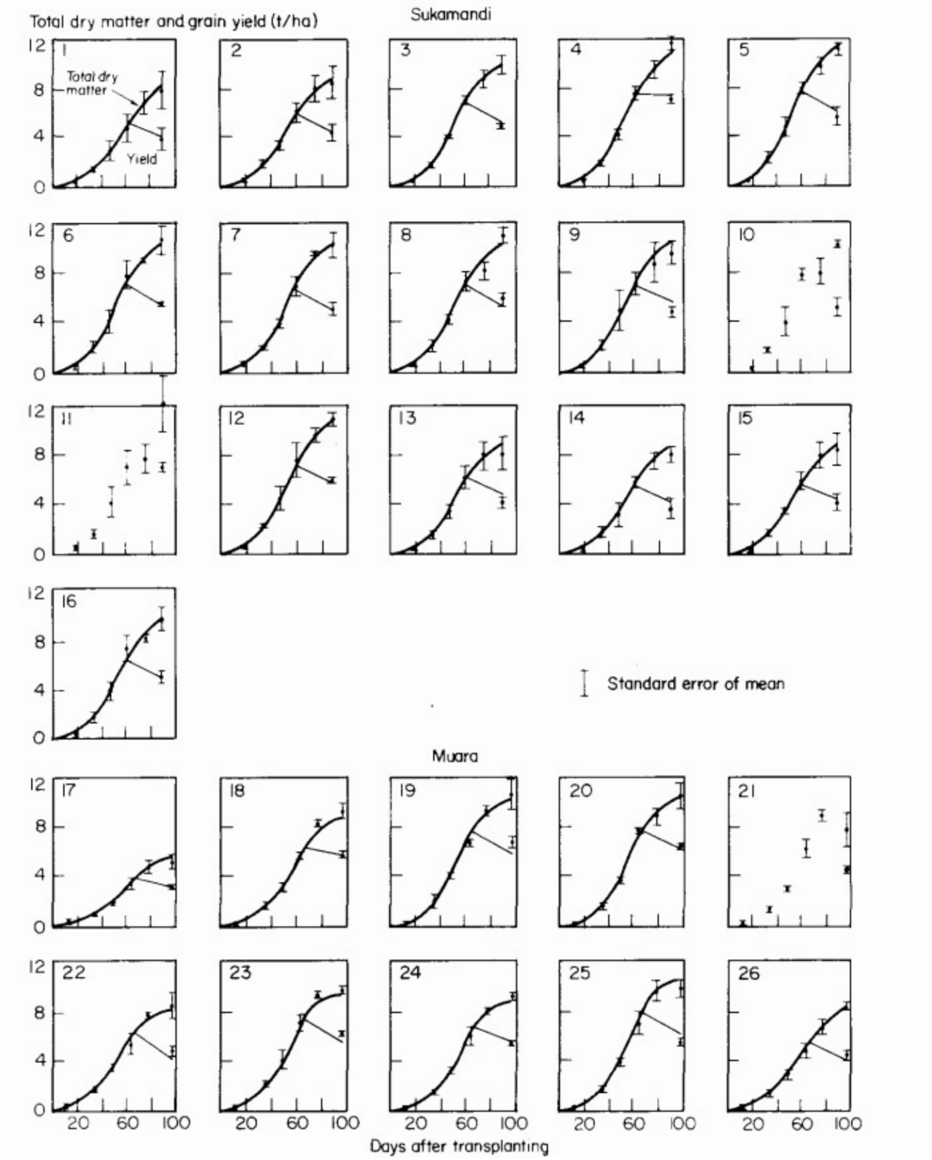
The response of dry matter production to timing is straightforward and implies that the longer N is present in the crop the greater its effect will be. The yield response to timing is more complex. Crops fertilized at different times may accumulate yield in different ways. Low and moderate levels of N supplied to a young crop lead to increased vegetative growth (5) so that the N concentration of the tissue is diluted by carbohydrate with a consequent decrease in assimilation rate. Grain yield is accumulated by a slow rate of assimilation of a large biomass, plus translocation to the grain from other parts of the crop (4). Assimilation rate decreases during grain filling as N is translocated to the grain (10). These processes lead to a relatively low harvest index and to straw of low N concentration.

When low or moderate levels of N are supplied at later stages of crop development, the initial effect is to increase N concentration of the biomass and hence the assimilation rate. Grain accumulates from rapid assimilation by a



2. Simulation of the yield and dry matter production of irrigated rice in relation to nitrogenincorporated in the crop.

relatively small biomass, and translocation makes a less important contribution to yield. Assimilation continues during grain filling because the vegetative material has sufficient N stored to support both storage in the grain and the photosynthetic needs. These processes lead to a relatively high harvest index and straw of top N concentration.



3. Dry weight and yield of all treatments in the experiments at Sukamandi and Muara. The points and standard errors represent measurements, and the lines represent the model as presented in Table 1, with the fitted parameters shown in Table 2. The three treatments without model estimates were not included in the fitting procedure.

High rates of N supplied early lead to the highest simulated yield, but the advantage over application at 40 days after transplanting is not great because young crops simply cannot contain large amounts of N in their tissues, and the effective date of supply to the crop may be much later than the date of fertilizer application. For a similar reason, high rates supplied later cause the biomass to become saturated with N and so give no yield advantage over smaller amounts.

DISCUSSION

The evidence of Figure 3 and Table 2 suggests that the fit to a diverse set of data is adequate. The standard errors of all the pafameters are much smaller than the parameter estimates, indicating that these estimates are significant in a statistical sense. The correlations between the parameters are mostly low, indicating that the model has few, if any, redundancies.

The possible limitation of the model is excessive biological simplicity. There would be advantages in simulating the components of yield such as tiller number and grain number, and the particular sensitivity of the rice crop to stresses in the period prior to anthesis (I I). We have not pursued these aspects because of the difficulty and cost of obtaining data.

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Economic Evaluation of Deep Placed Urea for Rice in Farmers' Fields: a Pilot Area Approach, Ngawi, East Java, Indonesia

D. T. O'Brien[a], M. Sudjadi[b], J. Sri Adiningsih[b], and Irawan[b]

The results from field trials and a survey of farmers in an area of East Java were used to evaluate farmers' fertilizer practices in rice and to determine whether or not there is a role for urea deep placement (UDP) in the study area. Farmers in the area were using high levels of urea (309 kg/ ha) and triple superphosphate (239 kg/ ha); around two thirds were also applying potash and composted rice straw. The rate of N applied was close to the estimated economic optimum application level, which was only slightly less than the estimated yield maximizing level. The agronomic results indicated that for specified rates of applied urea, the increase in yield with UDP over that with broadcast application could be as high as 50% at low rates of N. However, at economic optimum rates of urea, the increasein yield was less than 10%. The economic optimum rate of urea was, however, 25% lower with UDP than with conventional broadcasting. The estimated increase in net return with UDP was about Rp 25 000 ha. These findings imply that if widespread adoption of UDP were to occur there could be a substantial saving in the level of urea consumption with only a slight reduction in national rice production.

The Agency for Agricultural Research and Development (AARD) of the Indonesian Ministry of Agriculture has been conducting on-farm trials throughout Indonesia since 1976 to evaluate deep point placement of urea supergranules (USG) and broadcast application of slow-release sulfur-coated urea (SCU) relative to conventional broadcast application of prilled urea (PU). These trials have been conducted within the framework of the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) in collaboration with the International Rice Research Institute (IRRI) and the International Fertilizer Development Center (IFDC).

Since 198 1 more than 20 trials have been conducted in Indonesia under the guidelines of the INSFFER Fifth International Trial on Nitrogen Fertilizer Efficiency in Rice. These trials have been conducted on research stations and in farmers' fields, during both the wet and dry seasons, over a wide range of soil types and climatic conditions, and using several improved local and IRRI varieties. Improved agronomic efficiency with SCU and USG relative to PU has been demonstrated at many, although not all, of the sites (6.7).

As a consequence of the generally positive results seen through the extensive series of INSFFER trials that have been conducted, it was decided in

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1983 that the focus of further deep placement research should move away from continued multilocational testing to pilot area evaluation of the many factors that need to be considered if a viable urea deep placement technology is to be developed for Indonesian rice farmers.

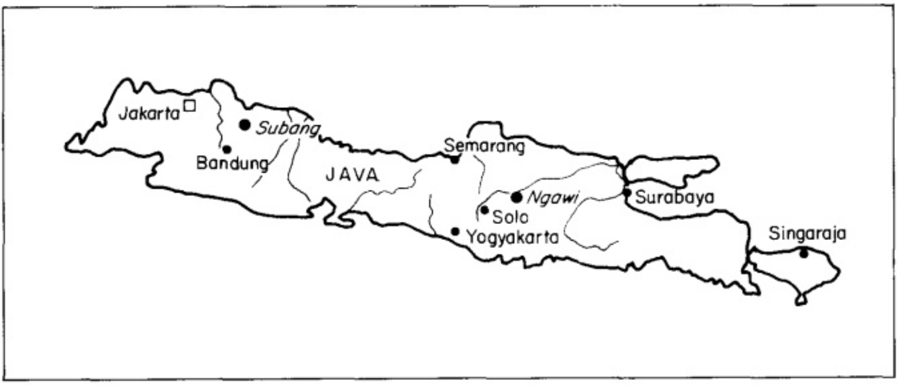
The first pilot area study was initiated at Pegaden Baru, Subang, West Java (Fig. 1) during the 1984 dry season. INSFFER trials conducted in the area during the 1982-83 and 1983-84 wet seasons had shown that rice responded to applied urea and there was potential for deep placement to be successful.

A set of trials in farmers' fields, comparing urea deep placement with the typical farmers' practice and a researchers'best split, was established in the area, and a survey of 30 farmers was conducted to determine their fertilizer practices and socioeconomic conditions. The survey was intended to provide a background against which evaluation of farmers' existing fertilizer practices and the urea deep placement technology could be conducted. The data collected through the survey provided the first information on farmers' conditions and cultural practices in the pilot area (3).

The approach was continued in Subang during the 1984-85 wet season with an additional trial that included treatments modified on the basis of information obtained about farmers' current fertilizer practices. A more comprehensive survey of 60 farmers is to be conducted in the area.

Trials were also initiated at a second pilot area during the wet season at Ngawi, East Java (Fig. 1). A replicated central experiment and three non-replicated satellite trials were established in this pilot area and a survey of farmers was conducted. The results of these activities are presented in this paper.

A description of farmers' crop management practices in the Ngawi pilot area, especially as they relate to fertilizer practices, is presented first. The results of the field trials are then presented. An economic analysis of the existing urea practices and urea deep placement, using the economic parameters determined from the survey and crop yield data from the field trials, is then made. Finally, some conclusions are drawn and implications for further research in the study area are discussed.



1. Locations of urea deep placement pilot areas, Java, Indonesia.

AGRO-ECONOMIC CONDITIONS IN MARDIASRI, NGAWI

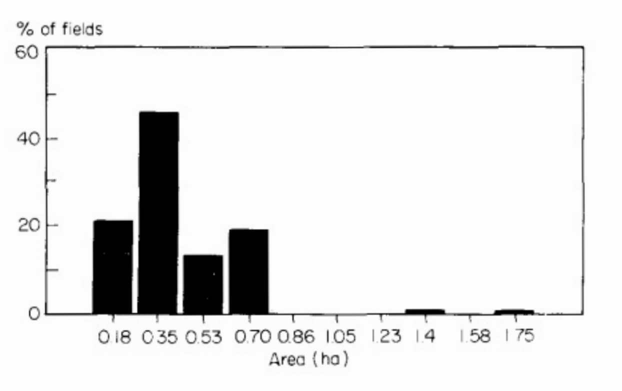
Sixty-two farm households in the rural village of Mardiasri, 5 km from Ngawi, East Java, were surveyed in February 1985. Respondents were asked about their household composition, land areas, tenure arrangements, cultural practices in their rice crops, crop production and disposal, fertilizer purchases, credit arrangements, and prices paid and received for inputs used and rice produced.

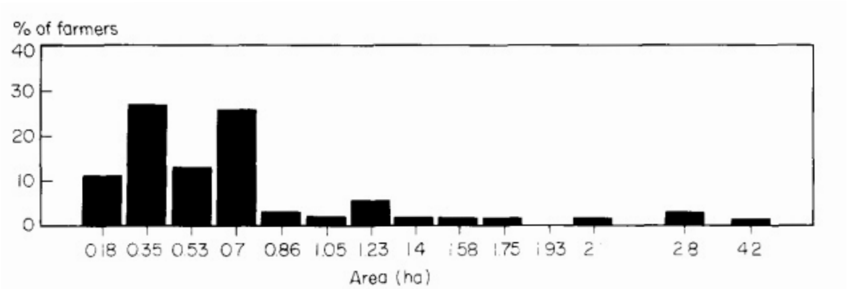
Households and farming areas

The average household size of respondents was 4.9 members. This consisted of 1.7 adult males, 1.8 adult females, and 1.4 children under 12 years of age.

The average area planted to rice per farmer was 0.79 ha, while the average field size was 0.47 ha (Fig. 2). Fifty-two per cent of farmers planted rice on more than one parcel of land (Fig. 3). Fifteen per cent of farmers owned the entire area that they planted to rice during the 1984-85 wet season (Table 1). Sixteen per cent operated a combination of owned land and land that they either rented or sharecropped. The remaining 69% operated all their rice land under sharecropping and/or fixed cash rental arrangements (Table 1). The only sharecropping arrangement reported by respondents was one where the tenant provided all the labor, but the owner and tenant shared the cost of pesticides and fertilizers, and the yield equally after payment of 1/10th of the crop to the

2. Areas of fields planted to rice (see Table I for survey details).





3. Total farm areas planted to rice (see Table 1 for survey details).

Table 1. Tenure categories of land planted to rice.[a]

Tenure categories	Percent of farmers
Owner operator[b]	15
Owner operator and sharecrop tenant[c]	10
Owner operator and fixed-rent tenant[d]	6
Share-tenant	32
Share-tenant and fixed-rent tenant	11
Fixed rent tenant	26

[a] Survey of 62 farmers, Mandriasri, Ngawi, East Java. (1984-85 wet season). [b] An owner operator either owns or is amortizing the land that he operates. [c] A sharecrop tenant is one who operates another's land under an arrangement where the tenant provides all the labor but the landowner and tenant share the cost of chemical inputs and the crop equally. [d] A fixed-rent tenant pays a predetermined amount of cash or rice for the right to operate another's land.

harvesters. The rent paid by fixed rent tenants was around Rp 200 000/ha[1] per rice crop.

Cultural practices in rice

Ninety-two per cent of the farmers' fields were planted to the IRRI variety IR36. The remainder was planted to two improved Indonesian varieties (Cintandui and Semeru).

All fields were manually hoed at least once (Table 2). In 25% of fields the land preparation was done exclusively by either one (5%), two (18%), or three (2%) hand hoeings. In an additional 21% of fields, manual cultivation was followed by a harrowing.

Fifty-six per cent of farmers commenced land preparation with either a rotary tilling or plowing. This initial activity was followed by hoeing and/or harrowing. The most typical system (35%) was rotary tilling followed by hand hoeing and harrowing. When the cultivation was completed, all farmers cleaned their fields by manually dragging the trash from the area.

All farmers transplanted their rice in straight rows with the same spacing between plants in the rows as between the rows (18-24 cm). The fields were marked prior to transplanting by a man dragging a toothed implement (*caplak*) across the length and width of the field. The majority of farmers planted 25- to 30-day-old seedlings (65%). Fifteen per cent planted seedlings at 35 days and a further 11% planted 40-day-old seedlings. All farmers contracted their transplanting to teams, predominantly women, at Rp 17 000 to Rp 19 000/ha plus meals (one meal is worth approximately Rp 200).

Fertilization

All farmers broadcast their urea onto drained fields and did not incorporate the fertilizer after broadcasting. Rates and times of urea application varied widely among the survey respondents. Figure 4 shows the range of rates of urea applied

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[1] Rp 1 000 = $0.91 US (March 1985).

Table 2. Land preparation activities in rice.[a]

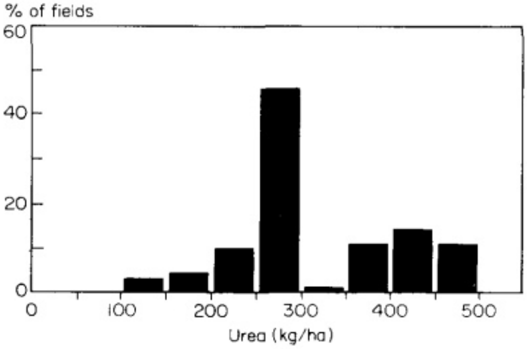
Land preparation activities			Percent of total fields
First	Second	Third	
Hoe			5
Hoe	Hoe		18
Hoe	Hoe	Hoe	2
Hoe	Hoe	Harrow[b]	2
Hoe	Harrow		19
Plow[c]	Hoe		1
Plow	Hoe	Harrow	17
Rototiller[d]	Harrow		1
Rototiller	Hoe		2
Rototiller	Hoe	Harrow	35

[a] Survey of 62 farmers. Mandriasri, Ngawi, East Java (1984-85 wet season). [b] The typical harrow used in Ngawi is a single row implement of six to eight spikes. It is dragged through the field by a water buffalo. [c] The plow is a single furrow implement that turns the soil. It is drawn through the field by a water buffalo. [d] Rototiller is a small hand-held tractor with rotating tynes. Mechanically rotating paddles draw it through the field.

during the 1984-85 wet season. The average rate was 309 kg urea/ ha (142 kg N/ha).

The number of times urea was applied to the rice crop ranged from one to three. It was applied at or around transplanting (1 to 7 days after transplanting [DT]), about two weeks after transplanting, and at panicle initiation. The timing of urea applications can be categorized into six systems (Table 3). The predominant system (43% of fields) was that in which urea was applied in three applications - at transplanting, two weeks after transplanting, and around panicle initiation.

Sixty-six per cent of fields received some fertilizer at transplanting and some urea was applied two weeks after transplanting in 86% of fields. In addition to applying urea, some farmers also applied ammonium sulfate (21% of fields). Of those who did, the average rate was 82 kg/ ha. The majority applied it in one application around two weeks after transplanting or at panicle initiation.



4. Rates of urea application to rice (see Table 1 for survey details).

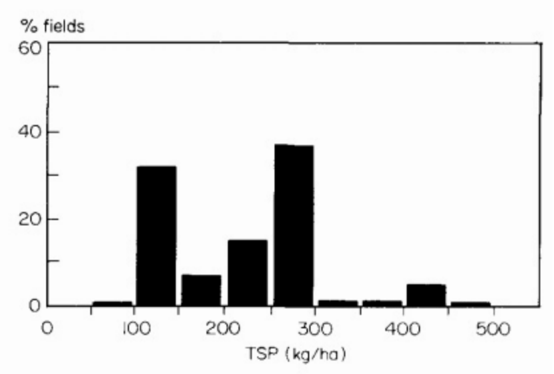
Table 3. Number and times of urea application in rice at Mandriasri.[a]

System of urea application	Percent of fields
One application —two weeks after planting	1
Two applications -	
at planting and two weeks later	13
at planting and around panicle initiation	10
two weeks after planting and around panicle initiation	29
both around panicle initiation	5
Three applications -	
at planting, around two weeks after planting, and around panicle initiation	43.

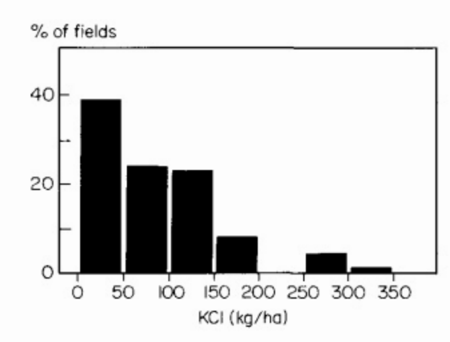
[a] Survey of 62 farmers, Mandriaori, Ngawi, East Java (1984-85 wet season).

All respondents applied some triple superphosphate (TSP) to their rice crops. The average rate was 239 kg/ ha (Fig. 5). More typically (44% of fields), it was applied at transplanting and two to three weeks thereafter. Some farmers (22%) applied it three times.

Potash (KC1) was applied to 64% of fields surveyed. The average rate of application was 128 kg KCl/ha (Fig. 6). Most farmers applied it in a single application at around 30-50 DT.



5. Rates of TSP application to rice (see Table I for survey details).



6. Rates of potash (KCI) application to rice (see Table 1 for survey details).

Organic fertilizer, in the form of composted rice straw, was applied to 64% of the fields in the survey. The average rate of application was 2.5 t/ha.

All farmers intentionally drained their fields prior to fertilizer application. The fields were generally left drained for three or four days after the fertilizer was applied, although a few did not flood their fields for up to a week after fertilizer application.

Water was reported to flow out of farmers'fields into areas that were not cultivated by them in 21% of the fields in the survey. Water was reported to flow into fields from adjacent fields not cultivated by the operator (17%).

Rice production and disposal

The range of rice yields for the survey respondents is shown in Figure 7. The average yield was 6 670 kg/ ha. However, some farmers (19%) had yields greater than 8 000 t/ha.

All farmers harvested their crop under the *ceblokan* arrangement, where the harvesters were paid one tenth of the crop. Sharecrop tenants paid half of their crop to the landowners. The average amount retained by the operators after payments to harvesters, landlords, and the irrigation authority was 4 620 kg/ha. The average amount retained per farm family was 3 650 kg, i.e., 745 kg/ person.

Product and input prices

Rice prices quoted by respondents ranged from Rp 85 to Rp 135/kg of unhusked rice. The average price was Rp 103/kg.

Fertilizer costs were as shown in Table 4. The price paid by a farmer for urea was always the same as that paid for TSP. All farmers purchased their fertilizer in the local market and used cash rather than credit.

The wage rate for female labor (hand weeding) was Rp 500/4h plus a meal, compared with Rp 600 to Rp 700/4h plus a meal for the same work by men. If the meal was valued at Rp 200, then the wage rate was Rp 175/h for female labor

7. Rice yields (see Table 1 for survey details).

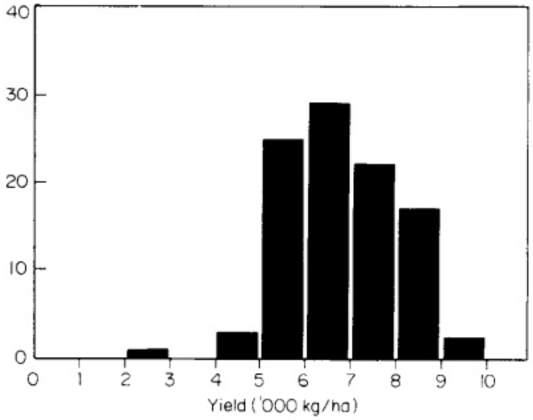


Table 4. Fertilizer costs.

Fertilizer	Cost (Rp/kg)	
	Range	Average
Triple superphosphate	85-98	93
Urea	85-98	93
Ammonium sulfate	94-1 00	98
Potassium chloride	90-1 20	102

and Rp 200 to Rp 225/h for male labor. The wage rate paid to men for hoeing was Rp 1 000 to 1 200/7 h plus three meals. The imputed wage rate for this activity was Rp 229 to Rp 257/h. The cost of hiring a man with an animal and plow or harrow was Rp2 000 to Rp 2 250/3h, plus a meal each for the operator and his assistant. The cost per hour was Rp 800 to Rp 883.

Fertilizer response analysis

Table 5 shows the response function estimated from 74 of the 112 fields in the survey (those fields where ammonium sulfate was applied and where the crop had not been harvested were excluded from the response function analysis).

The responses to TSP and KC1 were estimated to be linear across the range of rates in the survey data. The estimated coefficients indicate that 239 kg of rice were produced for each kg of TSP, and 82 kg of rice for each kg of KC1 applied. Assuming the average prices for rice and each of these fertilizers, there were returns to the operator of Rp 238 per Rp spent on TSP, and Rp 75 per Rp spent on KC1.

Table 5. Regression analysis of rice yield[a] as a function of applied chemical and organic fertilizers.[b,c]

Variable[d]	Coefficient values[e]	
Intercept	- 8 565	
N	182.1 13	(2.384)
N^2	−0.554	(2.275)
P	3.549	(2.191)
K	2.401	(1.397)
0	12 299	(1.994)
NO	−156.748	(1.907)
N^2O	0.472	(1.781)
R^2	0.22	
F ratio	2.67	
n	74	

[a] Dependent variable is kg of rough rice/ha. [b] Survey of 62 farmers, Mandriasri, Ngawi, East Java (1984-85 wet season). [c] Seventy-four of the original 112 observations were included in the analysis. Observations where ammonium sulfate was applied or the crop had not been harvested at the time of the survey were excluded. [d] N = kg applied as urea/ha, P = kg of triple super phosphate/ha, K = kg of potash/ha, 0 = a binary variable (1 if organic matter is applied, 0 if otherwise). [e] t values of the regression coefficients are shown in parenthesis.

The estimated response functions to N applied as urea, at the average rates of TSP and KC1, with and without application of organic matter were as follows: with application of organic matter

$$Y = 4\,719 + 25.365N - 0.082N^2,$$

without application of organic matter

$$Y = -7\,520 + 182.113N - 0.554N^2$$

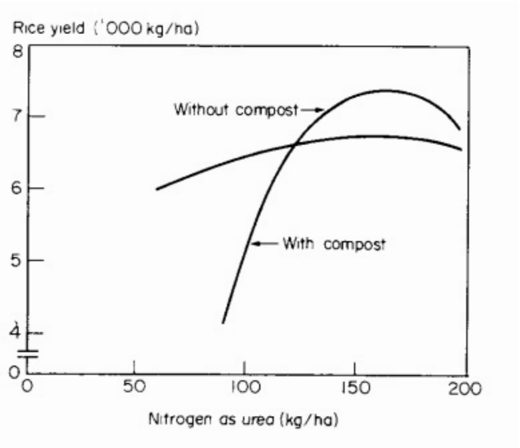
where Y is the amount of rice produced, and
N is the amount of urea N applied (kg/ ha).
These two equations are graphed over the ranges of observed rates of applied N in Figure 8. The yield maximizing rate of N as urea when organic matter has been applied is 155 kg N/ ha for a maximum yield of 6 740 kg N/ ha. If organic matter has not been applied, the yield maximizing level of N is 164 kg/ ha for a yield maximum of 7 380 kg/ ha.

If the average price of urea is assumed, the profit maximizing rates of N as urea are 141 kg/ ha with organic fertilizer and 162 kg/ ha without fertilizer. These rates compare with an observed rate among survey respondents of 142 kg N/ ha (309 kg urea/ ha). The marginal production levels (extra rice produced for the last unit of N applied) at the profit maximizing levels of urea are 2.24 kg rice/ ha if organic matter was applied and 2.62 if organic matter was not applied.

AGRONOMIC FIELD TRIALS AT NGAWI

Materials and methods

The set of 1984-85 wet season trials at Ngawi included a replicated central experiment and three nonreplicated satellite trials. The experimental design for the central experiment was a randomized complete block design with 3 replications of 20 treatments (Table 6). The treatments included a control, 12 broadcast application rates, 5 rates of deep placed urea, and 2 treatments where



8. Response functions estimated from regression analysis of rice nitrogen applied as urea, with and without compost application, with TSP and potash applied at average rates of survey respondents (see Table 1 for survey details).

Table 6. Comparison of broadcast application methods with hand deep placement of urea in rice at Ngawi (1984-85 wet season),

Treatment no.	N rates (kg/ha)	Urea form	Method of application	Mean yields (kg/ha)				
				Central[a]	Satellite 1[b]	Satellite 2[b]	Satellite 3[b]	Aggregate
1	0	Control		3 500	3 150	2 110	2 260	2 760
2	29	PU	Broadcast application (drained plots), 1/2 broadcast at 15 DT, 1/2 broadcast at 45 DT	4 210	4 210	2 380	2 870	3 420
3	58	PU		4 810	4 460	2 990	3 240	3 870
4	87	PU		5 320	4 590	3 100	3 900	4 230
5	116	PU		5 940	4 880	3 840	4 500	4 790
6	145	PU		5 500	5 010	3 840	4 670	4 760
7	174	PU		5 430	5 330	4 090	4 840	4 920
8	29	PU	Broadcast application (drained plots), 1/3 broadcast at 0 DT, 1/3 at 15 DT, 1/3 at 45 DT	4 050	3 690	2 360	2 910	3 250
9	58	PU		4 880	4 940	2 410	3 170	3 850
10	87	PU		5 750	5 280	2 980	4 340	4 590
11	116	PU		5 620	5 790	3 050	4 600	4 760
12	145	PU		5 740	6 050	3 490	5 210	5 120
13	174	PU		5 400	5 810	3 610	5 460	5 070
14	29	SG	Hand deep placed 2 DT into drained field	4 740	4 370	3 510	4 410	4 260
15	58	SG		5 110	5 590	3 810	4 720	4 810
16	87	SG		5 260	5 770	4 050	4 850	4 980
17	116	SG		5 430	5 980	4 280	4 810	5 120
18	145	SG		5 710	6 490	4 720	4 810	5 430
19	58	PU	All incorporated prior to transplanting	5 180	-	-	-	-
20	116	PU	1/2 incorporated prior to transplanting 1/2 broadcast at 45 DT	5 640	-	-	-	-
Grand mean				5 190				4 440
Coefficient of variation (%)				6.4				8.2
LSD (5%)				550				520
F tests: Block				2.60 ns				94.83**
Treatment				10.84**				16.62**

[a] Three replications. [b] Nonreplicated.

broadcast prilled urea was incorporated. The treatments at the satellite sites were the same as those at the central site except that the two incorporation treatments were omitted. The plot size in all trials was 2.8 m x 8.0 m internal.

The locations of the experiments were: satellite 1 at Bongkrejo, satellite 2 at Putat Selawe, satellite 3 at Watu Alang, and the central experiment at Mandriasri.

The experimental areas were plowed and then harrowed twice prior to construction of the bunds and internal irrigation canals. Each plot was then puddled manually using a hoe and feet. The plots were finally leveled and marked for transplanting.

The rice seedlings were transplanted in 20 cm x 20 cm row spacing 23 days after seeding. The dates of transplanting in 1984 were: satellite 1,16 Oct; satellite 2, 18 Oct; satellite 3, 1 Dec; central, 18 Nov.

The PU for treatments 2-7 was broadcast onto drained fields in two equal applications at 15 and 45 DT. Treatments 8-13 received three equal broadcast applications onto drained fields at 0, 15, and 45 DT. The basal applications of PU to treatments 19 and 20 were broadcast and incorporated (by feet) prior to transplanting. The subsequent application to treatment 20 at 45 DT was broadcast but not incorporated.

The USG was applied basally at 2 DT. The plots were left with a small amount of standing water (1-2 cm depth) after transplanting. The urea supergranules were hand deep placed at 10-12 cm depth at the middle of every four hills. The holes formed by insertion of the supergranules into the soil were carefully closed to minimize contact between the urea and floodwater and thus reduce nutrient loss into the water. The plots were irrigated one day after fertilizer application.

Blanket applications of P and K were made to all plots. TSP was applied at the rate of 20 kg P/ ha one day before transplanting. KC1 was applied at 15 DT at 25 kg K/ha. Disease, insect, and pest controls were implemented as needed.

Paddy (unhusked rice) yields were obtained from 4.8-m^2 areas in the center of each plot. Soil characteristics were recorded for each site (Table 7).

Response functions for each method of fertilizer application at each site and across all sites were determined using the ordinary least squares (OLS) regression technique.

Table 7. Soil characteristics [a] at central and satellite urea deep placement trials in rice at Ngawi.

Site		Total N (%)	Organic carbon (%)	pH (water)	CEC (meq/kg)	Soil texture
Central	Mandriasri	0.13	1.31	7.3	341	Clay
Satellite 1	Bankarejo	0.16	1.46	7.3	311	Clay loam
Satellite 2	Putat Selawe	0.13	1.15	7.0	333	Clay
Satellite 3	Watu Alang	0.12	1.30	6.5	344	Clay

[a] soil samples 0-20 cm.

The form of the regression equation (1,8) is:

$$Y = a + b_1N + c_1N^2 + \beta_2N_2 + \gamma_2N_2^2 + \beta_3N_3 + \gamma_3N_3^2 + e \qquad (1)$$

where

Y = paddy production (kg/ ha),
N = N applied by all methods (kg/ha),
N_2,N_3 = N applied by methods 2 and 3 (kg/ ha),
b_1, c_1 = linear and quadratic effects of the common N rates (of the reference method),
ß2, g2 = the additional linear and quadratic effects over the reference method associated with one of the test methods (method 2),
ß3, g3 = the additional linear and quadratic effect over the reference method due to the other test method (method 3),
e = the residual assumed normal with mean zero and constant variance.

The response function for the reference method is derived from the estimated regression equation (1) by setting N_2 and N_3 equal to zero:

$$Y = a + b_1N + c_1N^2 \qquad (2)$$

The equation for a test method was derived from the estimated regression equation by setting the value of N_i (i = 2, 3) of the other test method equal to zero. For example, the response function of the crop with method 2 was determined by setting the value of N_3 at zero:

$$\begin{aligned} Y &= a + b_1N + c_1N + \beta_2N_2 + \gamma_2N_2^2 \\ Y &= a + (b+\beta_2)N_2 + (c+\gamma_2)N_2^2 \\ Y &= a + b_2N_2 + c_2N_2^2 \end{aligned} \qquad (3)$$

The regression coefficients (and their level of significance based on t-tests) were evaluated directly from the least square regression estimates of equation (1). The significance levels of ßi and gi derived from equation (l), provided tests of whether the linear and quadratic effects of the test methods (N_2 and N_3) differ significantly from the linear and quadratic effects of the reference method. This showed whether or not the crop responses to the test methods were different from response to the reference method of urea application.

Two fertilizer efficiency measures were determined in this analysis, viz., input efficiency and output efficiency.

Input efficiency. The comparative input efficiency (CIE) of a test and reference method of urea application was defined as the ratio of the rate of N applied as the test method to that applied by the standard method to obtain the same specified yield (Y').

$$CIE = N'_i/N'_1 \text{ for } Y'_i = Y'_1 = Y' \qquad (4)$$

where

N'_i = the rate of N in the test method needed to obtain yield Y';
N_1 = the rate of N in the standard method of application needed to obtain yield Y',

Y' = the specified yield level; and

Y'_i and Y'_1 = the yields with the test and standard methods, respectively, for rates of applied N of N'_i and N'_1.

Output efficiency. The comparative output efficiency (COE) of a test method and a standard method was defined as the ratio of the yield above that with zero fertilizer from the test method (y'_i) to that of the standard (y'_1) for a specified rate of applied N (N').

$$COE = y'_i/y'_1 \qquad \text{for } N'_i = N'_1 = N' \qquad '(5)$$

where $y'_i = Y'_i - Y_0$

$y'_1 = Y'_1 - Y_0$, and

Y'_0 = the yield when N is not applied (i.e., $N' = N_0$).

For the quadratic response functions (equations 2 and 3) specified earlier, $Y_0 = a$.

Results from field trials

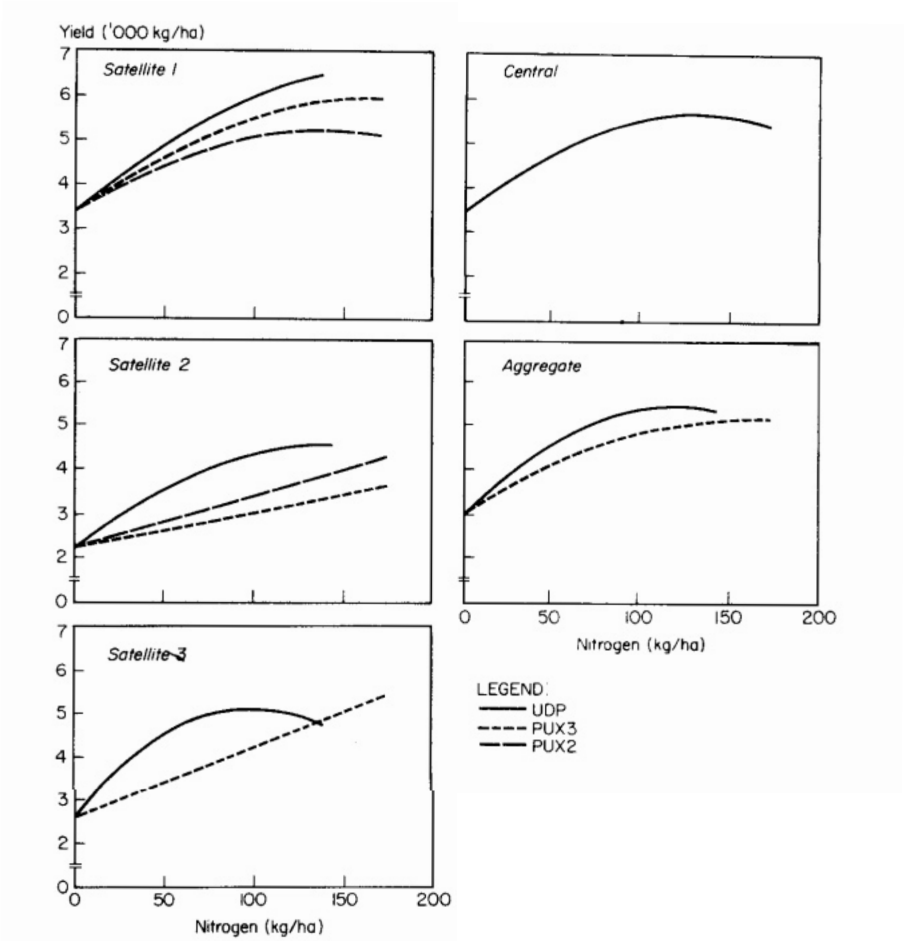
The estimated response functions for the central experiment, three satellite trials, and aggregate of all trials conducted during the 1984-85 wet season at Ngawi are shown in Table 8 and Figure 9. These equations were estimated using three applications of PU as the reference method (equation 1). This method of urea application was typical of that used by Ngawi farmers.

The responses of rice to UDP were significantly higher than those to three broadcast applications of PU at all the satellite sites. The aggregate analysis also showed a significantly higher response with UDP than with broadcast

Table 8. Regression analyses of rice yield [a] as a function of rate and method of urea application (1984-85 wet reason).

Variable [b]	Coefficient values [c]				
	Central [d]	Satellite 1 [e]	Satellite 2 [e]	Satellite 3 [e]	Aggregate
Intercept	3 466	3 294	2 185	2 495	3 027
N^n	33.622	31.169	8.165	16.322	26.451
	(9.1451	(6.298)	(7.104)	(10.518)	(7.243)
N^2	-0.128	-0.091			-0.08 1
	(6.600)	(3.542)			(4.160)
N_2		-5.392	3.535		
		(3.992)	(3.352)		
$N_2{}^2$					
N_3		4.592	26.435	37.097	14.030
		(2.858)	(6.010)	(5.591)	(3.279)
N_3^2			-0.127	-0269	-0.088
			(3.611)	(5.051)	(2.602)
R^2	0.92	0.93	0.94	0.90	0.94
F ratio	79.74	44.10	51.60	43.69	51.05
n	18	18	18		18

[a] Kilogram of rough rice per ha, [b] N is kg of N/ha as urea applied by each of farmers' methods and deep placement. N_2 and N_3 are kg N/ha applied as PU twice, and deep place USG, rerpectively. [c] The t values of the regression coefficients are shown in parentheses. [d] Three replicates. [e] Nonreplicated.



9. Estimated responses of rice to prilled urea broadcast two and three times (PUX2 and PUX3) and urea deep placement (UDP): Central experiment, three satellite trials, and aggregate of all trials at Ngawi.

applications of PU. The regression analysis showed no significant differences between methods of application at the central experiment. The two methods of broadcast application were not significantly different at satellite 3 and in the aggregate analysis. At satellite 1, three applications of PU gave significantly higher yields than two applications; at satellite 2, higher yields were obtained with two applications.

The improved efficiency associated with UDP can be seen from the two efficiency measures shown in Figures 10 and 11. The CIE of UDP relative to broadcast application of PU[2] is about 0.64 at low specified yield levels. It decreases to about 0.50 at the maximum yield for broadcast application[3]. This

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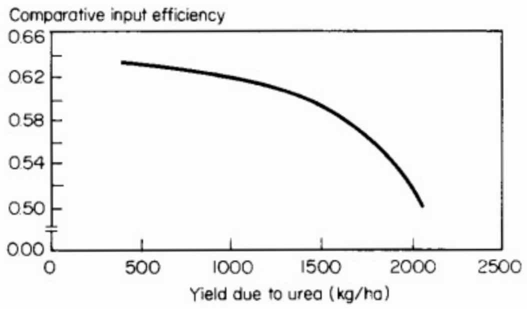
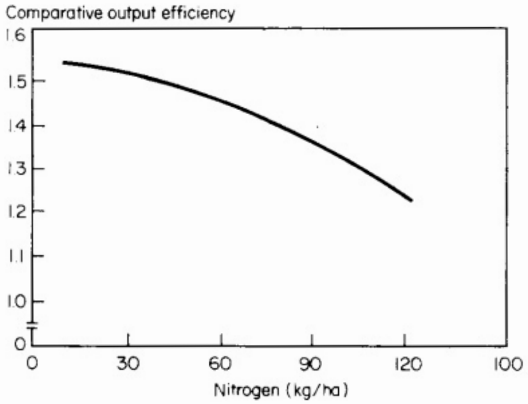
[2] The CIE and COE of UDP are both measured relative to two and three applications of PU in this aggregate analysis because the two methods of PU application were not significantly different from each other.

It is illogical to measure CIE or COE beyond the maximum yield of either the reference or test method of urea application.



10. Comparative input efficiency of urea deep placement relative to broadcast application of prilled urea in rice - aggregate of central and satellite trials at Ngawi.



11. Comparative output efficiency of urea deep placement relative to broadcast application of prilled urea in rice: aggregate of central and satellite trials at Ngawi.

means that the N required if deep placed is about 36 to 50% of that required for the same yield if it were broadcast.

The COE graphed in Figure 11 shows that the yield increment (i.e., the yield due to the fertilizer) with UDP is 1.5 times that with broadcast application at low rates of applied fertilizer. It decreases to about 1.2 at the yield maximizing rate of N (120 kg/ ha) for UDP. This means that the yield due to urea when deep placed is 20 to 50% higher than that for the same rate of broadcast application. The magnitude decreases as the rate of applied urea increases.

ECONOMIC ANALYSIS

In this section, the response functions for deep placed USG and broadcast application of PU, estimated from the regression analysis of the aggregated field trial at Ngawi, are used to determine the economic conditions under which the current and test technologies are the preferred alternatives. The maximum net returns for the two methods of urea application are determined for the prevailing rice price and typical set of economic conditions but with a range of urea prices and application costs. The general form of the net return function is

$$NR = P_y S_y - P_n N - M - WL$$

The definitions of variables in the net return function and their assumed values are shown in Table 9. The response functions for each technology are: broadcast PU,

$$y = 26.451N - 0.081N^2$$

deep placed USG,

$$y = 40.481N - 0.169N^2$$

The effectiveness of placement for each of the placement methods considered in this report is assumed to be the same. That is, the response of the crop to deep placed N, regardless of the method of deep placement, is assumed to follow that estimated for hand deep placement.

Figure 12 shows the maximum net returns for broadcast application of PU and UDP at different assumed urea prices.

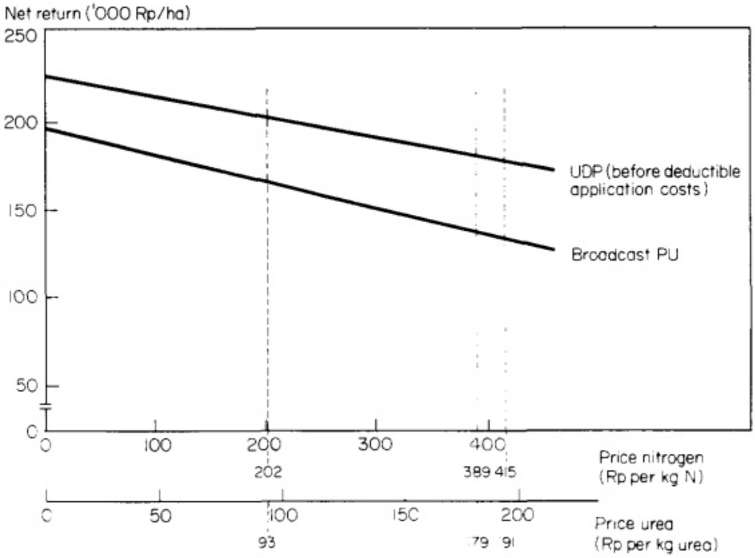
Deep placed and broadcast materials priced at existing price for prilled urea

Figure 12 shows that if the deep placed and broadcast urea materials are priced at the prevailing urea price in Ngawi, UDP will have a higher economic return than broadcast application if it has an application cost of less than Rp 35 000/ha. The estimated cost of hand deep placement, based on wage rate data from the area and assuming 80 h/ha for placement, is Rp 14 000/ha. (It is assumed that women would do the hand deep placing. This assumption is consistent with the observed division of labor in most parts of Indonesia. Women are generally responsible for transplanting and hand weeding, while men perform the heavier tasks, such as land cultivation.) The estimated cost of hiring a man with a draft animal and plow in the Ngawi area for 10 h is Rp 8 000/ha. It is likely that a farmer would be able to hire an applicator and operator for less than this. The indication is that the additional return to UDP would be of the order of RP 20 000 to RP 25 000/ha.

Table 9. Assumed conditions for economic analysis of urea deep placement and broadcast application of prilled urea.

Factor	Assumed value
Wage rates (w)[a]	
broadcast application by men	Rp 200/h
hand deep placement by women	Rp 175th
machine deep placement by men	Rp 229/h
Labor requirements (L)[b]	
broadcast application (x3)	15 h/ha
hand deep placement	80 h/ha
machine deep placement	10 h/ha
Retail price of applicator (M)[c]	Rp 75 000
Price of rice (Py)[a]	Rp 103/kg
Proportion of production received by operator (S)[a]	0.90
Nitrogen applied as urea (N)	142 kg N/ha
Price of nitrogen as urea (P_n)	Rp 199/kg N

[a] For survey details, see Table 1. [b] Source: (4). [c] Source: (2).



12. Net return to urea deep placement and broadcast application of prilled urea determined from aggregate response functions, Ngawi urea deep placement trials.

Urea materials priced at their economic price

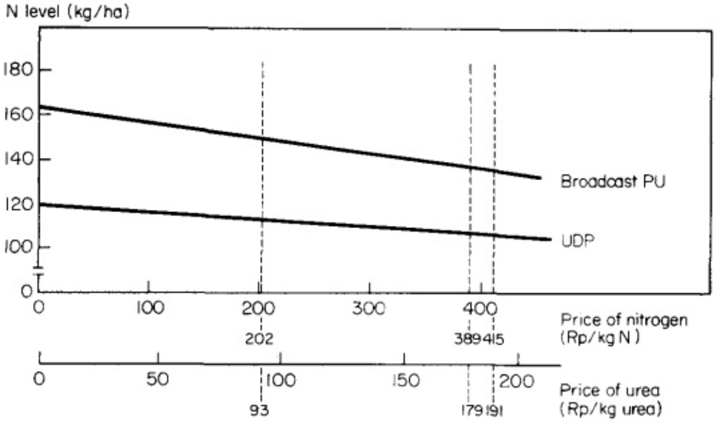
The benefit of UDP relative to broadcast application increases as the price of the urea material is increased. The estimated economic prices of PU and USG are Rp 179 and Rp 191 /kg (5). If the deep placed material (either USG or machine-applied PU) and broadcast material were both priced at the estimated economic price of PU, the margin between the net return to UDP (before subtracting application costs) and that to broadcast application is Rp 45 000/ha. If USG were deep placed and priced at its estimated economic price, the differences between the net return to deep placement (before deducting application costs) and that for broadcast application of PU at its economic price would be around Rp 40 000/ ha.

Yield and fertilizer savings

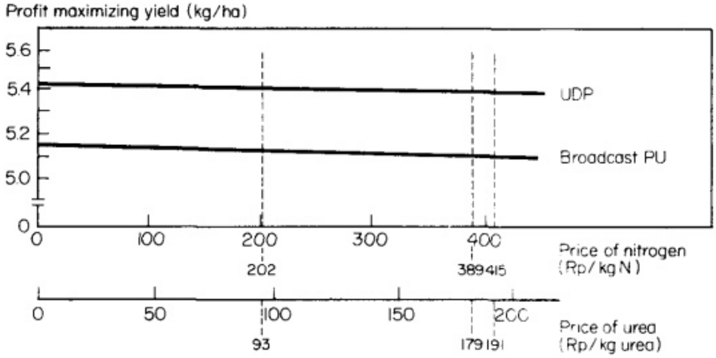
Although the differences between net returns for the conventional method of urea application and deep placement are not substantial, major benefits in terms of levels of rice production and levels of urea applied are apparent. Figures 13 and 14 show the estimated profit maximizing levels of applied N and rice yield over the range of assumed urea prices.

If the urea materials are priced at their current price of Rp 93/ kg urea, the saving in fertilizer, if it is deep placed, is about 80 kg urea per hectare or 25%. The profit maximizing yield from UDP at this price is about 6% or 300 kg/ ha higher than that with broadcast application.

If the current subsidy on urea were removed and PU and USG were marketed at their estimated economic prices, the benefit of adoption of UDP



13. Profit maximizing levels of nitrogen at different urea prices for broadcast and deep placement of urea determined from aggregate response functions, Ngawi urea deepplacement trials.



14. Profit maximizing yields at different urea prices for broadcast and deep placement of urea determined from aggregate response functions, Ngawi urea deep placement trials.

would be reflected in a saving of fertilizer and an increase in production. That is, the adoption of the UDP technology may allow the subsidy to be reduced or removed completely without reductions in rice yields and forfeiture of national self-sufficiency in rice production. The effect of concurrently removing the urea price subsidy and adopting UDP is estimated to be a saving in urea of about 90 kg/ ha and an increase in rice production of about 300 kg/ ha (Fig. 13, 14). Net returns to farmers, depending on application costs for UDP, would remain about the same or increase slightly. There may also be an employment and income benefit to those employed to deep place the urea either by hand or with an applicator.

CONCLUSIONS

The early results from the Ngawi pilot area reported in this paper indicate that higher economic returns are possible with ureadeep placement. However, there is considerable further research required before an appropriate UDP technology can be developed for the area. Two important areas of further research in the pilot area are 1) the role of organic matter under the existing methods of urea application and with urea deep placement, and 2) the most appropriate method of deep placing the material (hand or applicator) and the form of urea (USG, PU, or briquettes) most suited to these methods of application. Perhaps more important than the farm-level implications of UDP are the national impacts that widespread adoption may have on national urea consumption and rice production. The principle of UDP is well understood. Its potential benefits at the farm level have been demonstrated (although further work on methods of deep placement is needed). Little sound analysis, however, has been done on the national impact of UDP under alternative government policy scenarios. This is a crucial area that needs to be addressed before recommendations on adoption of UDP are put forward to government decision makers.

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Effect of Phosphorus and Nitrogen Sources on Yield of Rice in West Sumatra, Indonesia

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Phosphorus fertilizer increased grain yield by causing an increase in 1 000-grain weight. Nitrogen fertilizer increased grain yield by causing an increase in panicle number. Effects were not attributable to fertilizer type or rate.

Two experiments on lowland rice were conducted in West Sumatra during the 1983-84 growing season.

The P sources experiment was conducted on an iron-toxic wetland soil in a newly opened area near Sitiung. The soil (Oxic Dystropept - Fluventic Oxic Dystropept) had a thin (13 cm) brown silty clay loam surface horizon with a pH of 4.5, 83 mg/ kg extractable P, 29 meq/ kg extractable AI, 2% base saturation, 85% AI saturation, 0.63% free Fe_2O_3, and 2 940 mg/ kg total Mn. Phosphorus fertilizers were applied as triple superphosphate or as two types of rock phosphate, each at rates varying between 4.4 and 26.2 kg P/ha. On average, the P fertilizers increased grain yield from 1.6 to 2.35 t/ha, mainly by causing an increase in 1 000-grain weight. There was no difference in grain yields due to type of P source or P rate.

The N efficiency experiment was conducted at 928 m altitude near Sukarami (mean temperature 20 °C) on an Andosol. The clayey surface layer had a pH of 5.5; extractable P of 3.8 mg/kg; extractable Ca, Mg, K, and Na (in meq/kg) of 114, 11, 1.0, and 1.3, respectively; and organic matter of 7.5%. Fertilizer was applied at 0, 29, 58, 87, and 116 kg N/ha, either as urea, sulfur-coated urea, or urea supergranules. On average, the N fertilizer increased grain yield from 4.4 to 5.8 t/ha, mainly by causing an increase in panicle number. There was no difference in grain yield due to type of N source or N rate.

The trials will be continued for several years to obtain long-term effects of applied P and N.

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^{15}N Balance Studies of Fertilizer Nitrogen Applied to Flooded Rice Fields in China

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Zhu Zhao-liang

The fate of fertilizer N in rice fields vaned widely with application method. When ammonium sulfate was applied to calcareous soils, the recovery of N by rice plants was 25-29%, the N retained in the soil was 17-25%, and N losses were 50-54%. On acid soils, the corresponding figures for ammonium sulfate were 29-50%, 20-44%, and 19-43%; those for urea were 18-46% 16-32%, and 21-59%; and those for ammonium bicarbonate were 11-24%, 21-37%, and 36-68%. Obviously, there is a great potential for reducing N loss and increasing N recovery by rice.

The annual output of inorganic nitrogen fertilizers in China has increased to more than 10 million t of N during the last few years. Since it is well known that the recovery of fertilizer N by rice plants is generally very low, much effort has been devoted to the fate of applied fertilizer N and methods of improving fertilizer efficiency. Recently, Craswell and Vlek (3) reviewed the published ^{15}N balance studies on fertilizers applied to rice. However, only 16 sets of experiments were cited, of which only five were conducted in the field. Since the first report from China concerned with fertilizer N balance in rice fields using ^{15}N was published (19), many field and pot experiments have been conducted in this country. Therefore, it is now appropriate to review the data obtained from the field experiments in China. The fertilizers tested were ammonium sulfate, urea, ammonium bicarbonate, and nitrophosphate. The paper concerning the fate of N in nitrophosphate (12) will not be included in the following discussion because it is well known that N loss from nitrate applied to flooded rice soils is very high.

This paper reviews ^{15}N balance experiments done in China on rice with surface broadcast fertilizers, deep placed or incorporated fertilizers, and nitrification inhibitors and surface drainage.

SURFACE BROADCAST FERTILIZERS

When fertilizer N was surface broadcast at transplanting or at the early tillering stage on acid soils, the recovery of N by plants from ammonium sulfate, urea, and ammonium bicarbonate ranged from 40 to 59%, 27 to 40%, and 24 to 34%, respectively (Table 1), and N loss from the soil-plant system ranged from 13 to 40%, 44 to 54%, and 51 to 57%, respectively (Table 2). Thus, the highest plant recovery and the lowest loss were obtained from ammonium sulfate while the

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Table 1. ^{15}N recovered in rice plants from microplot experiments in the field.[a]

Application method[b]	^{15}N recovered (% of applied N)					
	Ammonium sulfate		Urea		Ammonium bicarbonate	
	Calcareous	Acidic	Calcareous	Acidic	Calcareous	Acidic
S. Tr., S. Ti.	23-28	50-59	22-25	27-40	17	24-34
Incorp.	25-29	31-44	29	25-46	-	21-31
D. Tr.	39-75	59-60	26	38-70	-	-
SG. PD. Tr.	-	-	55	63-75	-	-
S. Pl.	58-61	69	62	55-65	-	-
Split	-	29-50	-	18-50	-	11-24

[a] Source: 2, 5, 6, 7, 8, 9, 10, 11, 13, 14, 16, 17, 18, 19, 20. [b] S. Tr. =Surface broadcast at transplanting, S. Ti. = Surface broadcast at early tillering, S. Pl. = Surface broadcast at panicle initiation, D. Tr. = Uniformly deep placed at transplanting, Incorp. = Incorporated into the soil after surface broadcasting at transplanting, Split = Split application, SG. PD. Tr. = Point deep placement of supergranules at transplanting.

Table 2. ^{15}N loss from rice fields (microplot experiments).[a]

Method application[b]	^{15}N loss (% of applied N)					
	Ammonium sulfate		Urea		Ammonium bicarbonate	
	Calcareous	Acidic	Calcareous	Acidic	Calcareous	Acidic
S. Tr., S. Ti.	42-52	13-40	47-48	44-54	70	51-57
Incorp.	50-54	25-43	39	29-59	-	36-50
D. Tr.	3-30	18-20	51	3-43	-	-
SG. PD. Tr.	-	-	21	13-18	-	-
s. Pl.	21-26	21	26	23-30	-	-
Split	-	3-32	-	10-35	-	41-68

[a,b] see footnotes for Table 1.

opposite was true for ammonium bicarbonate. On the other hand, on calcareous soils the N recoveries by plants from ammonium sulfate, urea, and ammonium bicarbonate were 23-38%, 22-25%, and 17% (Table 1), while N loss from the three fertilizers were 42-52%, 47-48%, and 70% (Table 2). Thus, the plant recoveries were considerably lower than those obtained on acid soils and the losses were markedly higher. It should be noted that ammonia volatilization from ammonium sulfate applied onto calcareous soils may be large and close to that from urea or ammonium bicarbonate.

When N fertilizer was surface broadcast at the panicle initiation stage, plant recovery of N was considerably higher than when it was surface broadcast at transplanting or at the early tillering stage (Table 1); the reverse was true for N loss (Table 2). The fertilizer N retained in the soil was only 5-18% when ammonium sulfate or urea was surface broadcast at the panicle initiation stage on the two types of soil; this retention was much lower when the fertilizer was surface broadcast at transplanting or at the early tillering stage (Table 3). In the

Table 3. ^{15}N retained in soil from microplot experiments in flooded rice fields. [a]

Method application [b]	^{15}N retained in soil (% of applied N)					
	Ammonium sulfate		Urea		Ammonium bicarbonate	
	Calcareous	Acidic	Calcareous	Acidic	Calcareous	Acidic
S. Tr., S. Ti.	20-26	12-28	28-30	16-19	13	15-19
Incorp.	17-25	20-36	32	16-32	-	21-43
D. Tr.	22-31	20-22	23	19-31	-	-
SG. PD. Tr.	-	-	24	12-19	-	-
s. Pl.	16-18	10	12	5-1 7	-	-
Split	-	28-68	-	23-54	-	21-45

[a,b] See footnotes for Table 1.

latter case it was 12-30%. Presumably this resulted from the competing processes of N uptake by rice plants and biological immobilization, ammonium fixation, nitrification-denitrification, and/ or ammonia volatilization. When fertilizer was applied at the panicle initiation stage, the amount of N taken up by rice plants was much greater; this resulted in a higher percentage recovery, a lower percentage of fertilizer N retained in the soil, and reduced N loss.

DEEP PLACED OR INCORPORATED FERTILIZERS

It is well known that deep placement of N fertilizer can reduce N loss due to nitrification-denitrification and/ or ammonia volatilization. This is further verified by the data shown in Table 2. Among the methods of deep placement, point deep placement of urea supergranules was most effective, followed by uniform deep placement; incorporation after surface broadcasting was much less effective. For example, the corresponding figures for N loss with these three methods of application were 13-21%, 3-51%, and 25-59%, and the corresponding figures for N recovery by the rice crop were 55-75% 26-75%, and 21-46% (Table 1). Investigations have demonstrated that the amount of fertilizer N which remains in the floodwater after attempts to incorporate it in the soil is considerable (1 , 15). Thus, when incorporation after surface broadcasting was practiced, the proportion of fertilizer N actually incorporated into the soil was lower than with uniform deep placement or point deep placement of supergranules (Table 1). When the fertilizer N was deep placed by any of the methods mentioned above, the differences between the three fertilizers tested in both plant recovery and N loss. were not as large as after surface application at transplanting or early tillering (Tables 1 and 2).

The retention of fertilizer N in the soil after incorporation and uniform deep placement was 1743% and 19-32% (Table 3). These values are close to those for surface application at transplanting or early tillering, but were considerably higher than that for point deep placement, for which it was only 12-24%. The lower percentage of fertilizer N retained in the soil with point deep placement of supergranules can be attributed to the limited contact of the fertilizer N with the bulk of the soil.

NITRIFICATION INHIBITORS AND SURFACE DRAINAGE

In general, the fate of fertilizer N was not affected significantly by the addition of nitrification inhibitors and, at most, the reduction of N loss is around 5-10% of the N applied. This is less than that possible through improvements in application techniques such as the deep placement methods, incorporation, surface broadcasting at the panicle initiation stage, or the use of split applications. Any of these techniques is preferable to surface broadcasting a large amount of fertilizer N at transplanting or at the early tillering stage. Further research is needed to elucidate the causes of the ineffectiveness of the nitrification inhibitors tested in rice fields. To do this we must understand the pathways of fertilizer N loss under different conditions, as well as the behavior of the inhibitors in flooded soils.

Draining the surface water from flooded rice fields midway during the growing period is usually practiced by Chinese farmers to improve the reproductive growth of rice. Obviously, when fertilizer is surface broadcast shortly before the time for drainage, tremendous N losses may be induced. However, our field microplot experiments suggest that the loss of N was not significantly increased by surface drainage at the midgrowth stage when the fertilizer was applied at the early tillering stage. These findings agree with the results reported by Fillery and Vlek (4).

CONCLUSION

Further work is required on the fate of fertilizer N applied to rice, in addition to the development of new techniques for increasing the efficiency of use of fertilizer N.

Emphasis should be placed on the elucidation of the different pathways of N loss from inorganic fertilizers applied to rice grown under different environmental conditions. For this purpose, simplified techniques for in situ measurements of gaseous losses of N from rice fields are urgently needed.

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Denitrification and Ammonia Loss from Ammonium Bicarbonate and Urea Applied to Flooded Rice in China

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Total nitrogen (N) and ammonia loss from ammonium bicarbonate and urea fertilizers applied to flooded rice grown on an acidic soil in China were measured by ^{15}N balance and micrometeorological methods. Ammonia loss from ammonium bicarbonate was greater than that from urea and the amount lost from urea in this study was lower than that reported from other countries. This was presumably because of the low incident radiation and low floodwater pHs in this experiment. Denitrification loss was more important than ammonia loss.

In Asia, urea is the main fertilizer used to supply N to rice (80% of total; 9, 14) but in China, ammonium bicarbonate is still an important fertilizer because it can be produced readily in small local factories. Over one thousand such factories, each with an annual output of 5 000-10 000 t of ammonia, have been established in different provinces to fulfill local requirements for N (10).

Field studies in microplots using ammonium bicarbonate labeled with ^{15}N have shown that N losses can be substantial, especially when the fertilizer is surface broadcast at transplanting; 30-70% of the applied N can be lost (10). While urea appears to be a more efficient fertilizer than ammonium bicarbonate, recoveries of applied N can still be poor (16). The reasons for the poor and variable recoveries of N from these two fertilizers are not known. This paper describes investigations conducted in China to determine the factors responsible for the poor recoveries of ammonium bicarbonate and urea N by flooded rice.

EXPERIMENTAL METHODS

The experimental site and treatments

The experiment was conducted on Lianhu farm in Dan Yang county, Jiangsu Province, China, within a large area of irrigated rice. The surface soil had a pH of 5.4, a total nitrogen concentration of 0.17%, and a cation exchange capacity of 25.1 c mol (Na^+)/ kg.

Two fertilized circular areas, each of 25-m radius and approximately 80 m apart, were separated from the main rice field by earth banks approximately 0.15 m high. These circular areas were used for the comparison of ammonia emission

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(by a micrometeorological method; 6, 8) from ammonium bicarbonate and urea fertilizers applied into the floodwater and incorporated into the soil by harrowing immediately before transplanting rice seedlings. Fertilizer (90 kg N/ha) was applied to these areas on 20 June between 0745 and 0915 h.

Rice seedlings (*Oryza sativa* L. hybrid, Xian You No. 3) were planted by hand at 0.14-m by 0.27-m spacings throughout the entire experimental area and in the surrounding areas. The seedlings were 0.20-0.35 m high and the mean floodwater depth in the circles and surrounding field during the period of observation (20-28 June) was 0.04 m. Additional fertilizer (45 kg N/ha) was applied to the two circles by broadcasting into the floodwater at the panicle initiation stage on 15 July between 1735 and 1855 h. At that stage the rice plants were 50-60 cm tall and the mean floodwater depth was 0.04 m.

Ammonia volatilization

Vertical flux densities of ammonia from the fertilized areas were determined during daylight hours by a mass balance method from measurements of the horizontal transport of ammonia past a sampling mast placed at the center of each plot (4, 5, 6, 8).

Ammonia volatilization from the circular plots during the nighttime hours was calculated by a bulk aerodynamic method using measurements of ammoniacal N, pH and temperature in the floodwater, and wind speeds at 1.2 m above the floodwater (8). During daylight hours the floodwater measurements were made at two-hour intervals, coinciding with the beginning and end of the measurement periods for ammonia volatilization from the circular areas. Mean wind speeds were obtained for the same period. Floodwater samples were taken from all fertilized areas from 10 or more sites and from unfertilized control areas. These samples were analyzed immediately for pH (glass electrode-calomel electrode assembly) and ammoniacal N (ammonia electrode and millivolt meter; 12). The temperature of the floodwater in situ was determined at the time of sampling with a mercury-in-glass thermometer and continuously overnight with thermocouples connected to a data logger.

^{15}N-mass balance technique

Total N loss was determined by applying labeled urea or ammonium bicarbonate containing 12 atoms % ^{15}N excess to microplots located within the two circular areas. The microplots were enclosed by 0.29-m I.D. plastic cylinders; they were inserted into the soil to a depth of 0.30 m and 0.10 m projected above the soil surface. The microplots received 90 kg N/ha at transplanting or 45 kg N/ha at panicle initiation, as labeled fertilizer, and an additional amount of unlabeled fertilizer at the other time of application to a total of 135 kg N/ha. Two hills of rice seedlings were transplanted into the microplots. There were eight replicates of each treatment.

Samples of floodwater, plants, and soil were taken from the microplots for ^{15}N analysis on the dates given in Table 1. At the first sampling, after removal of the floodwater and rice plants, the top 0.15 m of soil was removed from the microplots for analysis. At heading, the 0-0.15 m and 0.154.30 m soil layers were

Table 1. Times of fertilizing and sampling microplots for ^{15}N analysis.

Fertilized at transplanting	Fertilized at panicle initiation	Sampled at cessation of NH_3 loss	Sampled at heading
20 Jun		29 June	24, 25 August
	15 July	20 July	

removed for analysis. At this stage the major roots were separated from the soil by hand and washed free of soil. The plant samples were dried in a forced-draught oven at 70°C, weighed, ground to pass a 0.42-mm screen, and analyzed for total N (2) and ^{15}N (1). After weighing, the soil samples were thoroughly mixed, subsampled, and analyzed for total N (2) and ^{15}N (1).

RESULTS AND DISCUSSION

Total ^{15}N balance

Recoveries of the applied ^{15}N in plants and soil from the ammonium bicarbonate- and urea-treated microplots within the circular areas are given in Table 2. There were no significant differences in total recoveries of applied N between the two sampling dates, indicating that all of the ^{15}N loss occurred within 9 days of application at transplanting. When N was applied at transplanting, significantly more N was recovered in the plants and soil from the urea treatment than from the ammonium bicarbonate treatment (mean 54.6% v mean 41.3%). At crop maturity, 37.8% and 25.4%, respectively, of the ^{15}N applied as urea and ammonium bicarbonate at transplanting was found in the rice plant. Plant recovery and total recovery were increased markedly by applying the fertilizer at the panicle initiation stage (Table 2).

Very little labeled N was recovered in the 0.15-0.30 m soil layer which indicated that leaching of the applied N was insignificant. The small amount of ^{15}N detected in this layer may have been due to ^{15}N in unrecovered plant roots.

Ammonia volatilization

When ammonium bicarbonate was applied into the floodwater and incorporated by harrowing just before transplanting, volatilization of ammonia commenced immediately and proceeded at very high emission rates (up to 2.3 kg N/ ha per hour) during the first few periods of observation. However, the high rates of emission were not maintained and had fallen to low rates (0.14-0.26 kg N/ ha per hour) on the first day after fertilizer application; emissions occurred at even lower rates thereafter. Seventy-three per cent of the total measured ammonia loss occurred during the first eight hours after fertilization. Ammonia emissions from the urea-treated area commenced more slowly and never reached the high rates observed on the ammonium bicarbonate-treated area. The greatest loss (1.28 kg N/ha) occurred on the fourth day after urea application. Except for the first day the rates of ammonia loss from the two

Table 2. Recoveries of ^{15}N in rice plants and soil, and calculated losses from applications of labeled ammonium bicarbonate and urea into the floodwater.

Treatment	Sampling time (days after fertilizer application1		^{15}N recovery (% of applied N)	
			Ammonium bicarbonate-treated plot	Urea-treated plot
90 kg N/ha Broadcast and incorporated at transplanting	9	(1) Recovery in plant tops & roots	4.0 ± 0.4	5.7 ± 1.5
		(2) Recovery in soil (0–0.15 m)	35.6 ± 3.0	46.2 ± 3.7
		(3) Total recovery (i.e. 1+2)	39.6 ± 2.8	51.9 ± 4.4
		(4) Calculated loss [i.e. 100-(1+2)]	60.4	48.1
		(5) Ammonia loss	18.2	8.8
		(6) Calculated denitrification loss (i.e. 4-5)	42.2	39.3
90 kg N/ha Broadcast and incorporated at transplanting	65-66	Recovery in plant tops & roots	25.4 ± 0.6	37.8 ± 3.1
		Recovery in soil (0-0.15 m)	16.4 ± 5.8	19.2 ± 3.6
		Recovery in soil (0.1 5-0.30 m)	1.2 ± 0.3	0.3 ± 0.4
		Total recovery	43.0 ± 5.9	57.3 ± 3.8
		Calculated loss	57.0	42.7
45 kg N/ha Broadcast at panicle initiation	5	Recovery in plant tops & roots	43.9 ± 8.5	61.4 ± 5.3
		Recovery in soil (0-0.15 m)	22.0 ± 6.9	18.1 ± 1.4
		Total recovery	65.9 ± 11.6	79.5 ± 4.6
		Calculated loss	34.1	20.5

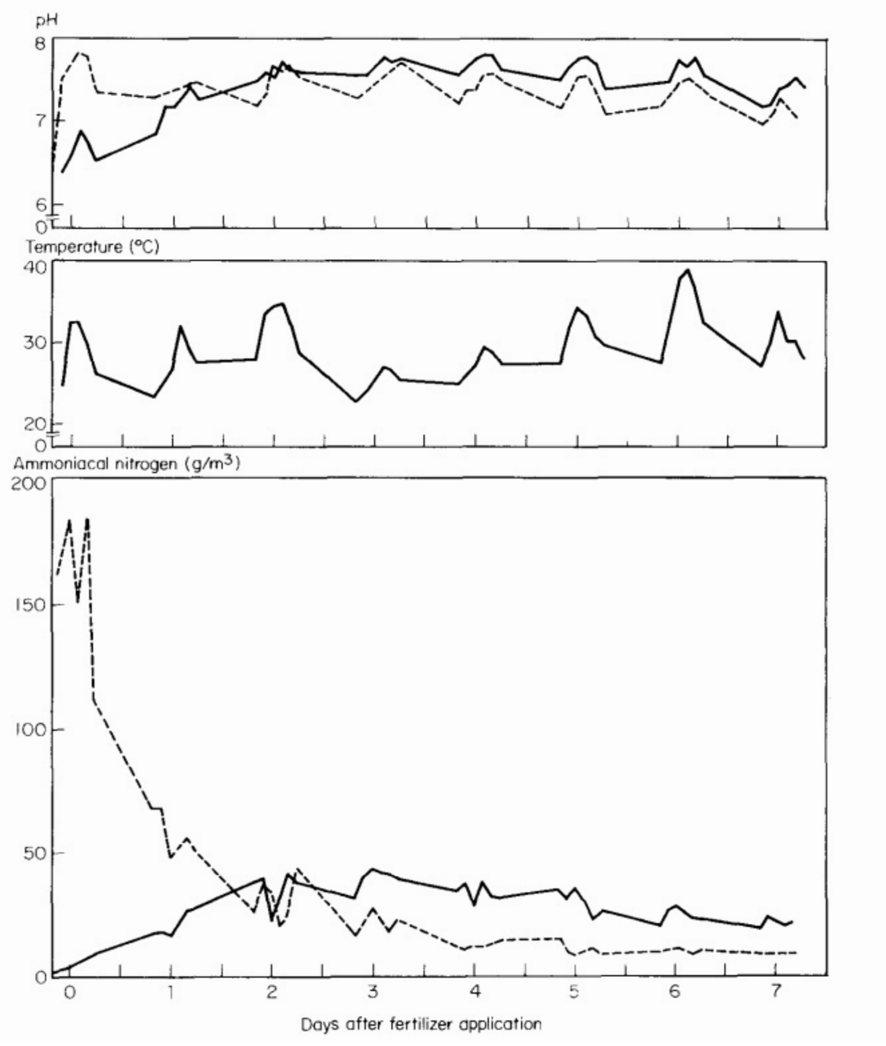
fertilized areas followed the diurnal variation in temperature and pH; wind speeds were generally low.

Of the 90 kg N/ha application, a total of 15.2 and 6.5 kg N/ha was lost by volatilization of ammonia from the ammonium bicarbonate- and urea-treated areas, respectively, during the daylight hours of the study period. Thus, the total measured loss of ammonia to the atmosphere from the preplanting application during this period was 16.9% and 7.2% of the applied N. Additional ammonia would have been lost during the nighttime hours and this was calculated from a bulk aerodynamic formula (8) to be 1.3% and 1.6% of the applied N, respectively. Thus, the total losses as ammonia were 18.2% and 8.8% of the applied N.

The differing patterns of ammonia loss result from the different ammoniacal N concentrations and pHs of the floodwater in the two treatments (Fig. 1). Fertilization with ammonium bicarbonate provided an immediate, appreciable source of ammonium ions and alkalinity, whereas fertilization with urea affected these parameters only after the urea had been hydrolyzed. Immediately after application most of the urea was dissolved in the floodwater (which had little or no urease activity); therefore the urea had to be transported to the soil surface by diffusion or convection before it could be hydrolyzed (3, 13, 15). Thus, there was a delay before the ammoniacal N and pH of the floodwater in the urea-treated area increased appreciably and ammonia gas was produced.

Even though the ammoniacal N concentrations in the floodwater of both treatments reached very high values, apart from the initial burst of activity on the ammonium bicarbonate-treated area, the rates of ammonia emission were rather low. This can be attributed to the comparatively low pH values of the floodwater (6.4-7.8) and these were probably the indirect result of the overcast conditions which prevailed during most of the experimental period. Such conditions, which are typical for this area at this time of the year, suppress the growth of photosynthetic microorganisms which are responsible for the high pH values frequently found in the floodwater of tropical rice fields (1 1). While there was a small diurnal variation in the pH values (Fig. 1) it was much less than that observed in other studies on ammonia volatilization after N fertilization (7, 11, 13).

No leaching of ^{15}N was detected (Table 2) and since runoff from the microplots was prevented it must be concluded that all losses of N occurred in gaseous form. Apart from ammonia volatilization the only known mechanisms for gaseous N loss are biological denitrification (producing nitrous oxide [N_2O] and nitric oxide [NO]), chemodenitrification (producing N_2O. NO, and methyl nitrite [CH_3ONO]), and nitrification (producing N_2O and NO). Production of N_2O, NO, and CH_3ONO in flooded soils appears to be insignificant (13, and I.E. Galbally, personal communication) and thus the difference between total N loss and ammonia loss is essentially a measure of N_2 produced by denitrification. The data (Table 2) suggest that, in this location, denitrification is a more important loss process than ammonia volatilization. The data also indicate that essentially the same amount of N was lost by denitrification from the urea-treated area as from the bicarbonate-treated area.



1. Ammoniacal nitrogen concentration, temperature, and pH of floodwater after application of ammonium bicarbonate and urea into the floodwater and incorporation into soil at transplanting.

CONCLUSIONS

The various results indicate that in this particular Chinese environment, denitrification is a much more important pathway for nitrogen loss than ammonia volatilization. The recovery of fertilizer N can be improved slightly by the use of urea rather than ammonium bicarbonate. New methods of applying both fertilizers are required if efficient use is to be made of the applied N.

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Effects of Microplots on Urea Nitrogen Reactions in Flooded Soils

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The effects of different types of small plots on the transformations and losses of urea N applied to flooded rice were studied in the field. The use of enclosures retarded urea hydrolysis, suppressed the temperature and maximum pH values in the floodwater, and changed the pattern of ammonia volatilization. These effects are due, at least in part, to shading of the floodwater from the sun's rays by the plot walls. The magnitude of these effects varies with plot size and shape, and the material used to construct the plot walls.

Small plots are commonly used for studying the fate of fertilizer nitrogen (N) applied to agricultural crops, especially when labeled compounds are used, because they require little land area and small amounts of expensive compounds. Microplots have been used in a number of studies (e.g., 1, 8, 9, 13, 17) to estimate the redistribution of ^{15}N labeled fertilizer after application to flooded rice fields. Furthermore, because of their reduced dimensions they readily facilitate a comparison to be made between a number of different management techniques (2, 6, 7, 11, 14) and such investigations are an important step towards the ultimate aim of maximizing crop yields.

In rice, it is usual for a large application of fertilizer N to be made early in the development of the crop (i.e., at transplanting or early tillering). At this stage leaf area index is low, and consequently a large percentage of the total incoming solar radiation reaches the water surface. Small plots are often enclosed with metal or wooden frames to prevent mixing of the applied nitrogen with the surrounding soil and water, and the surround usually projects above the normal soil or floodwater surface. It is reasonable to suspect that this barrier will reduce the solar radiation incident on the plot and will modify the physical environment inside the small plot in other ways.

This paper reports an investigation on the effects of different types of small plots on the transformations and losses of urea N applied to flooded rice.

MATERIALS AND METHODS

Two experiments were conducted. In December 1984, observations were made in a flooded rice field at Griffith, NSW, in which a circular plot of 25-m radius had been constructed. Rice (*Oryza sativa* var Pelde) was sown in October in

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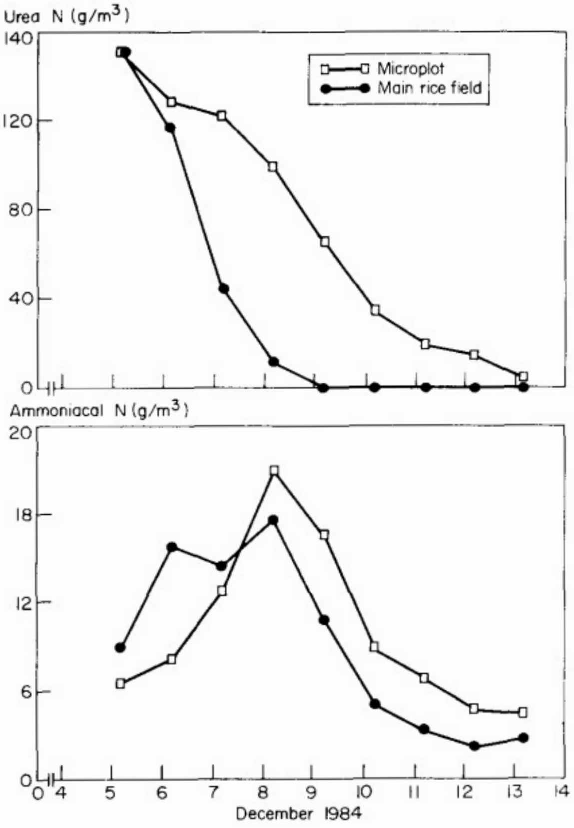
rows at 0.18 m spacing and flooded to a depth of 0.05 m on 27 November when the plants had reached 0.07 m height. Prilled urea (80 kg N/ha) was broadcast evenly into the floodwater in the circle on 4 December.

Square microplots (0.54 m x 0.54 m) made from galvanized iron were inserted into the soil in the circle on 30 November to a depth of 0.25 m so that 0.10 m of the walls extended above the floodwater surface.

In January 1985 an experiment comparing microplots of different shapes and construction was undertaken at the same site described above. Two replications of three types of microplot - 0.54 m x 0.54 m galvanized iron square, 0.33 m diameter galvanized iron cylinder, and a 0.54 m x 0.54 m plexiglass square - were inserted into a previously unfertilized part of the rice field where there was little or no crop. On 7 January these microplots were fertilized with urea at 80 kg N/ha.

The floodwater in the circle (December experiment) and in the microplots (December and January experiments) was sampled at a depth of 0.03 m by withdrawing water through a plastic tube using a syringe. These water samples were analyzed for urea (4), ammoniacal N using an ammonia electrode (12), and pH by a glass electrode-calomel electrode assembly. Observations at the beginning and end of each study period (usually 2 hours) were averaged to give a



1. Urea and ammoniacal N concentrations in the floodwater in the main rice field and in a microplot in the field following the application of fertilizer nitrogen.

mean value for the calculation of ammonia flux densities by a bulk aerodynamic formula (5). Bulk water temperatures at a depth of 0.03 m were measured with a mercury-in-glass thermometer and with thermocouples connected to a data logger.

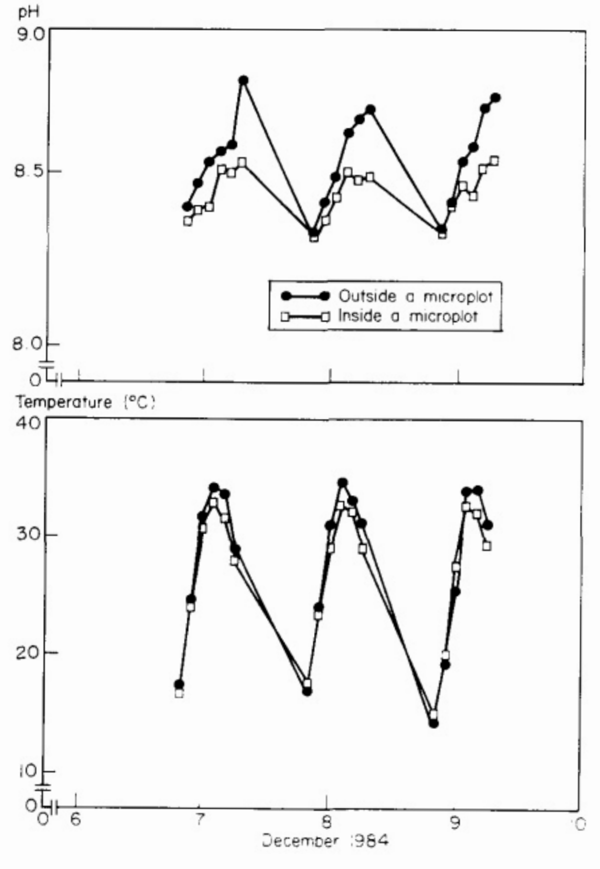
RESULTS

December experiment

Figure 1 shows the urea and ammoniacal N concentrations in the floodwater of a 25-m-radius rice field and inside a microplot located within this field, for a period of 9 days, following the application of urea. Urea hydrolysis proceeded at a slower rate in the microplot compared with the main rice field. As a consequence the concentration of ammoniacal N in the floodwater of the microplot was lower than that in the floodwater of the main field for the first three days. After that time the concentration of ammoniacal N in the microplot exceeded that in the circular plot.

Daytime values of the floodwater pH and temperature in the main field and microplot for three days in the middle of the observation period are compared in Figure 2. There was no significant difference between the pH values or the

2. Values of pH and temperature for the floodwater inside and outside a microplot.



temperatures of the floodwater in the microplots and the main field early in the morning but in the afternoon the pH and temperature of the floodwater in the field reached greater maximum values than those of the floodwater in the microplot. Figure 3 depicts the ammonia flux density calculated by the bulk aerodynamic method for the period 1600-1800 hours on each day from both the main field and the microplot. Losses of fertilizer nitrogen as ammonia gas clearly proceed at very different rates in the microplot compared with the main field.

January experiment

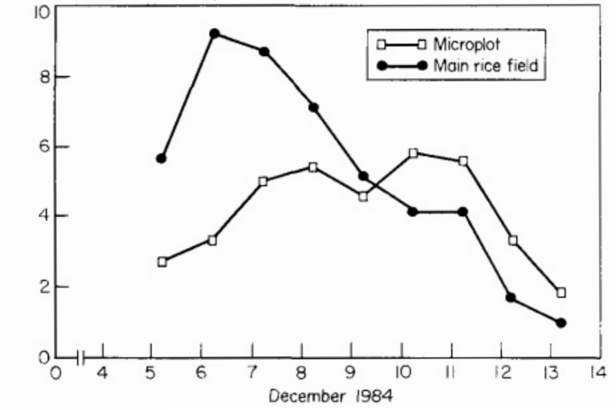
Figure 4 shows the ammoniacal N concentration and the pH of the floodwater in each of the three different types of microplot. Maximum concentrations occurred on or before 10 January and, by this time, substantial differences in the magnitude of the concentration between the different types of microplot had developed. The highest concentrations were in the cylindrical microplot and the lowest were in the plexiglass square.

The pH values of the floodwater in the three types of microplot at 0800 hours, throughout the study period, were not significantly different. However, at 1800 hours, differences were apparent by 9 January, with the pH of the floodwater in the plexiglass square exceeding that in the galvanized iron square which, in turn, exceeded that in the galvanized iron cylinder. These differences persisted and were amplified towards the end of the study period.

Differences in temperature between the three microplot types were observed on each day, with the plexiglass plot always being the warmest and the galvanized iron cylinder always being the coolest (Table 1).

DISCUSSION

The lower temperatures of the floodwater in the microplot compared with the main rice field would result in lower surface temperatures of the soil in the microplot (O.T. Denmead, personal communication). As the soil surface is the site for the hydrolysis of urea dissolved in the floodwater, the reaction may be



3. .Ammonia flux densities from the main rice field and microplot at the time of maximum emission (1600-1800 h), calculated using the bulk aerodynamic formula.

4. Ammoniacal N concentration and pH in the floodwater in 3 types of microplot following the application of fertilizer urea.

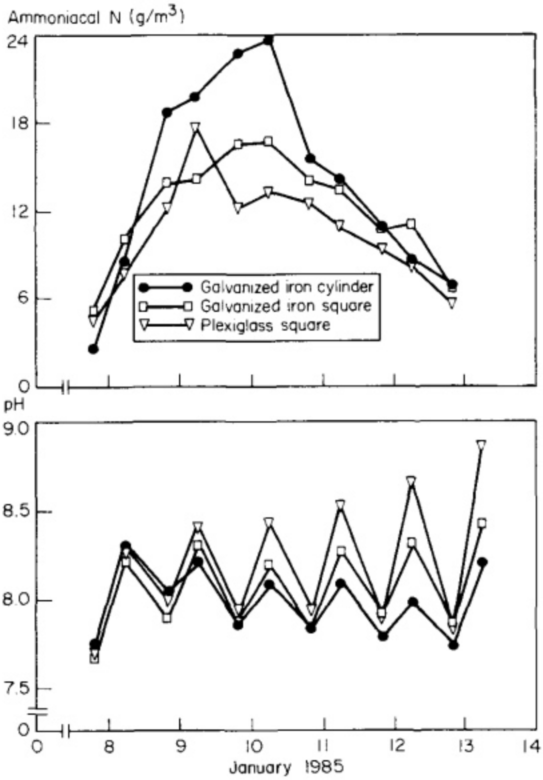


Table 1. Floodwater temperatures (°C) in four enclosures.

Time	Rice field	Plexiglass square	Galvanized iron square	Galvanized iron cylinder
0600	15.7	15.5	15.4	15.0
0800	17.1	17.0	16.9	17.0
1000	24.8	24.3	23.9	24.4
1200	33.5	32.9	32.3	32.5
1400	39.0	38.1	37.7	37.3
1600	40.1	39.0	38.5	37.9
1800	36.7	36.2	35.2	34.7
2000	29.4	29.9	28.8	28.5
2200	24.6	25.2	24.6	24.2
2400	21.7	22.0	21.6	21.3
0200	19.6	19.6	19.4	19.1
0400	17.4	17.3	17.3	16.8

slowed by this reduction in temperature (10) which might result in a reduction in the concentration of ammoniacal N in the floodwater in the microplot. However, the depression in water temperature, and thus surface soil temperature, was relatively small (2 or 3 °C at most) and would not be expected to have a large effect on urea hydrolysis. Thus, it is possible that some other factor, such as reduced mixing of the water body, which would reduce the transport of urea to the soil surface, inhibited urea hydrolysis in the microplot.

The lower ammoniacal N concentrations, temperature, and pH combined to ensure that, initially, less ammonia was volatilized (per unit area) from the microplot (Fig. 3). Then, since the supply of ammoniacal N was delayed in the microplot, the ammonia flux density from the microplot increased and exceeded that from the main field after 9 December.

The observed depression in water temperatures in the microplot probably resulted from the shading of the water by the microplot walls. During the January experiment lower temperatures were observed on each day in the galvanized iron cylinders compared with the square galvanized iron plots, while the highest temperatures, and those closest to the main rice area, always occurred in the clear-walled plexiglass plots.

Differences between the pH values in the three microplots in this experiment were due, presumably, to the effect of shading on the growth of photosynthetic organisms in the water; the greater the shading the lower the growth of algae, etc., and the lower the pH of the floodwater. The highest pH values always occurred in the clear-walled plexiglass plots which should not restrict the input of light energy into the floodwater. The shading leads to a cumulative effect in pH values, with differences between the three types of microplot increasing with each day.

The degree of shading at the soil surface is greater than that at the water surface and this effect increases with water depth. This implies a reduction in solar heating at the soil surface in addition to the reduced transfer of heat from the floodwater to the soil noted earlier. Lowered soil temperature means that reactions such as nitrification and denitrification would also proceed at a slower rate inside a microplot.

One would also expect the wind speed and turbulence (close to the water surface), and mixing of the water inside the microplots to be affected by the shape, size, and wall height of the enclosure. For example, mixing of the floodwater is important if urea is to be transported to the soil surface and hydrolyzed (since the bulk of the urea added was contained in the floodwater, which has little if any urease activity [3, 15, 16]). As noted earlier, the very slow hydrolysis of urea in the microplot compared with the main rice field (Fig. 1) suggests that the mixing of the floodwater in the microplot was reduced.

We conclude that the transformations and transfers of N in small plots can be significantly different from those in a large rice field. It may be expected, however, that as the dimensions of the plot are increased, differences due to shading effects will diminish. Further work is required to establish what constitutes an acceptable minimum plot size and how this varies with geographical location and time of year.

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Integrated Management of Green Manure, Farmyard Manure, and Inorganic Nitrogen Fertilizers in Rice and Rice-Based Cropping Sequences

O.P. Meelu and R.A. Morris

Experimental results on the integrated use of green manure, farmyard manure, and inorganic fertilizer N in rice and rice-based cropping sequences are presented and discussed. Effects of amount, time, and source of N application on fertilizer use efficiency have been outlined. The results indicated that rice generally responded up to 120 kg N/ ha. although responses at lower and higher N levels have been obtained depending on crop season and variety. N application in three split dressings proved better than one or two split dressings, and amide and ammoniacal N sources performed better than nitrate for rice. Urea supergranules were less effective than three split applications of urea, or sulfur-coated urea in a rapidly percolating soil. The need to study site-related parameters and soil characteristics to explain results has been emphasized. The results for green manuring revealed that there was a place for it in the intensive cropping system and that incorporation of green manure resulted in a saving of 60 to 80 kg N/ ha in rice. Although addition of green manure produced a residual effect on the succeeding crop in some places, it did not at other places, and its use requires further investigation. The need to optimize green manure and inorganic fertilizer N combinations for rice cultivation has been emphasized. Application of farmyard manure provided considerable direct and residual effects on crop yields and improved soil fertility.

Rice is the staple food of a large proportion of the world's population and it is a major *kharif* crop of India. Indian soils are generally deficient in nitrogen (N) and organic matter. The common source of humus and N for soil is organic manure, but during the last few decades mineral fertilizers associated with modern rice and wheat varieties have become more popular. However, in the face of the continuing world energy crisis and increasing fertilizer prices, organic manures are once again gaining favor. Farmyard manure and green manure are commonly used organic fertilizers. Farmyard manure is limited in supply for most farmers because of the shortage of farm animals, and thus green manure offers interesting prospects.

Rice is a major consumer of fertilizer N in India but the efficiency of N use is poor. Use of organic manures in rice and rice-based cropping systems therefore becomes all the more important, not only as a substitute for costly fertilizer N but also to improve the physical and chemical conditions in the rice soils.

In the recent past, fertilizer research focused mainly on the nutrient demands of individual crops. In practice, however, farmers' requirements for cereals, pulses, and fodder have to be met, crops are grown in a particular sequence, and the residual effect of manures and fertilizers applied to the

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previous crop should be considered in the formulation of the nutrient requirement of the current crop. The recycling of farmyard manure and the use of green manure integrated with inorganic fertilizer should be taken into account when determining the fertilizer requirements of a particular crop and the long-term effects on soil fertility. This paper reports research on the integrated management of green manure, farmyard manure, and inorganic N fertilizers in rice and rice-based cropping sequences.

NITROGEN MANAGEMENT

Among the important factors affecting the efficiency of N fertilizer are source, and rate and time of application. Experiments on response of rice to N rates indicated that rice generally responded significantly to N up to 120 kg/ha (Table 1). However, the amount of fertilizer required to obtain maximum yield can vary from 80 to 160 kg N/ha depending on the crop, season, and rice variety (16). The efficiency of fertilizer N is determined by the forms applied and the agro-ecosystem in which they are used.

Many studies (Table 2) have shown that nitrate is inferior to amide and ammoniacal sources of N for rice (5, 10, 17). Applications of N which are not

Table 1. Response of rice to N applications.

Location	Yield (t/ha)				CD 5% (t/ha)	Reference
	Control	40 kg N/ha	80 kg N/ha	120 kg N/ha		
Ludhiana (PB)[a]	3.79	1.77	2.90	2.60	0.39	(6)
Kalayani (W.B.)	1.41	0.84	1.70	2.30	0.15	(1)
Pura (U.P.)	3.22	0.52	0.97	1.25	0.14	(1)
Jabalpur (M.P.)	1.34	1.61	2.04	2.53	0.12	(1)
Rudrur (A.P.)	2.32	0.84	0.88	1.09	0.24	(1)
Thanjavur (T.N.)	4.62	0.43	0.64	0.84	0.31	(1)

[a] 60. 120, 180 kg N/ha.

Table 2. Response of rice to different N sources.

N source	Grain yield (t/ha)			
	New Delhi 601120 kg N/ha	Ludhiana 120 kg N/ha	Bhubaneswar	
			Wet season 100 kg N/ha	Dry season 120 kg N/ha
Ammonium sulfate	4.83	-	420	5.59
Urea	4.60	5.33	3.54	4.97
Calcium ammonium nitrate	4.51	5.10	3.10	4.51
Urea treated with soil	-	-	3.92	5.52
CD 5%	0.16	0.14	0.51	0.72

synchronized with the demands of the plant may result in considerable losses of N and low crop yields. Rice plants of medium growth duration use fertilizer most efficiently for grain production during the maximum tillering and flowering stages. The N absorbed by the plant during the vegetative stage is stored for use at later growth stages; a high N supply after panicle initiation tends to decrease the number of filled grains and grain weight. The results of experiments suggest that using split applications of N with one dose at transplanting, one at tillering, and another at panicle initiation is the best strategy for high grain yields, particularly for medium and long duration varieties (10, 13, 22) (Table 3).

Losses of N from urea and low recoveries by the rice plant have led to the development of a number of slow release N fertilizers with the objective of making the amount of N released coincide with that required by the growing plant. Modified urea materials such as sulfur-coated urea (SCU), lac-coated urea (LCU), neem cake-coated urea (NCU), and urea supergranules (USG) are among those developed to increase N use efficiency. Experiments by INSFFER (International Network on Soil Fertility and Fertilizer Evaluation for Rice) collaborators have indicated differing results in different soil, climatic, and management conditions. The results show that no one material can be recommended for use at all locations and they emphasize the need to study site related parameters to explain the results. In a field study with modified urea materials on rice (9) it was found that USG resulted in lower yields than three split applications of urea and SCU on a rapidly percolating soil at the Punjab Agricultural University farm, Ludhiana (Table 4). The poor result with USG was attributed to the leaching of urea beyond the root zone in the percolating water. LCU and NCU were also less effective than three split applications of urea or SCU (Table 4). However, on a slow percolating loamy soil at Gurdaspur there was little difference between the various materials as sources of N for rice (Table 5).

Table 3. Effect of split applications of urea on grain yield of rice. [a]

Applications			Grain yield (t/ha)		
Tr -	Ti -	PI	Ludhiana 120 kg N/ha	Rajendranagar 120 kg N/ha	Pantnagar 100 kg N/ha
0	0	0	2.95	3.06	-
0	1	0	4.73	-	-
1	0	0	-	6.59	4.71
1/12	1/2	0	5.24	-	-
3/4	1/4	0	-	6.66	-
3/4	0	1/4	-	-	4.76
1/3	1/3	1/3	5.5%	7.27	-
1/2	1/4	1/4	-	-	6.00

[a] Nitrogen applied at transplanting (Tr), tlilering (TI), and panicle Initletion (PI).

Table 4. Effect of slow-release fertilizers and management practices on the efficiency of urea applied to rice at PAU, Ludhiana.

Treatment[a]	Grain yield (t/ha)				
	1978	1979	1980	1981	Mean
Control	3.65	2.43	3.39	1.95	2.86
Sulfur-coated urea	6.51	6.32	6.00	6.61	6.36
Urea supergranule	5.64	3.55	4.06	2.99	4.06
Lac-coated urea	5.93	5.10	-	4.96	5.33
Neem cake-coated urea	5.77	4.4 1	5.09	4.55	4.96
Urea (all at transplanting)	5.27	4.39	4.90	-	4.85
Urea (split application)	5.90	5.95	5.21	5.53	5.65

[a] 120 kg N/ha.

Table 5. Efficiency of modified urea materials for rice at Gurdaspur (Typic Haplustalf).

Treatment[a]	Grain yield (t/ha)			
	1978	1979	1980	Mean
Urea (split application)	7.12	5.75	6.26	6.38
Sulfur-coated urea	6.58	6.11	6.24	6.31
Urea supergranule	6.67	5.29	-	5.98
Urea plus N serve	6.70	5.39	5.91	6.01
Mudball-treated urea	5.38	5.93	6.05	5.66
Neem cake-treated urea	6.76	5.39	5.68	5.94
Control	4.82	4.43	4.46	4.57

[a] 120 kg N/ha.

INTEGRATED MANAGEMENT OF ORGANIC MANURES AND INORGANIC FERTILIZERS

Green manure

In intensive agriculture, a farmer may not be able to practice green manuring in the traditional manner, but the practice is feasible in rice-based cropping sequences where there is a fallow period of 40 to 60 days before transplanting the rice. The inclusion of a short-duration crop like mungbean can give the dual benefits of providing grain for consumption and straw as green manure for rice.

Sahu and Nayak (I 9) studied the effect of fertilizer alone or in combination with green manure or farmyard manure on low N responsive traditional rice varieties (Table 6). The data show that applications of green manure or farmyard manure were as effective as an application of 22.5 kg inorganic fertilizer N/ha. Similar results were obtained in China (21; Table 7) and India (18). Beri and Meelu (2) reported three years' results on green manuring using *Sesbania aculeata* in rice -wheat rotations and found that *Sesbania* was equivalent to 60 kg inorganic N/ha in rice (Fig. 1). There was no residual effect of green manuring on the succeeding wheat yield. Singh (20) also did not find a residual effect of green manure in rice - wheat rotations, but Tiwari et a1 (24) in a similar

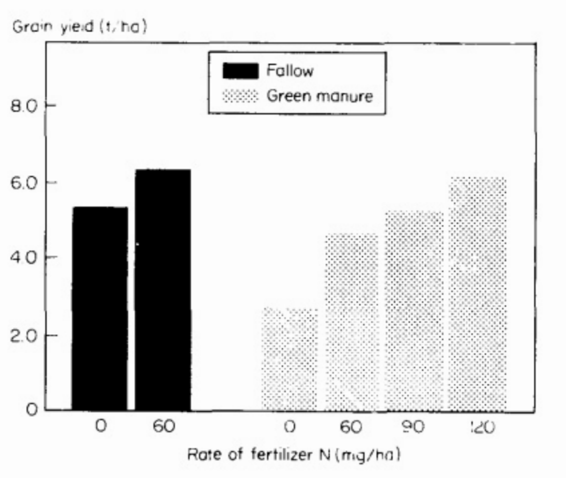
Table 6. Effect of organic manures and ammonium sulfate on grain yield of rice (1956-65).

Fertilizer applied (kg N/ha)	Grain yield (t/ha)		
	Fallow	Farmyard manure	Green manure
0	2.15	2.44	2.51
22.5	2.35	2.47	2.40
45.0	2.36	2.61	2.50

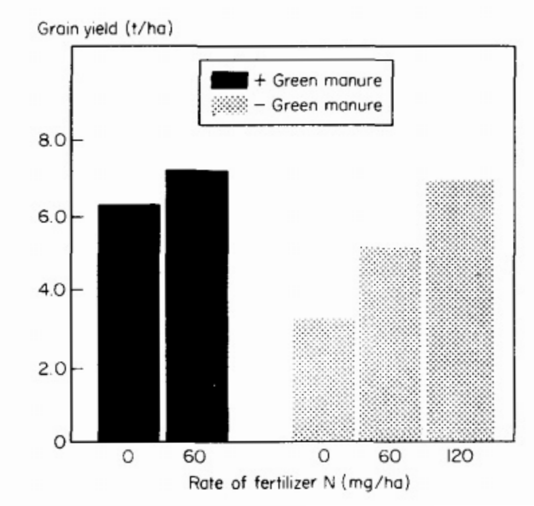
Table 7. Efficiency of organic fertilizers and ammonium Sulfate (mean of 52 trials), China.

Source of N	Yield (kg grain/kg N)					
	First crop			Second crop		
	80 kg N/ha	120 kg N/ha	Mean	80 kg N/ha	120 kg N/ha	Mean
Soybean	14.5	10.5	12.5	9.8	8.8	9.3
Fish scrap	12.3	9.5	10.9	10.3	8.1	9.3
Green manure	10.3	8.9	9.9	7.6	6.3	7.0
Compost	6.6	6.4	6.5	5.8	5.1	5.5
Ammonium sulfate	10.6	7.8	9.2	7.3	7.4	7.4

study found that green manure was equivalent to 80 kg inorganic N/ ha for rice and that it had a residual effect on the succeeding wheat crop in a rice - wheat rotation. Morris et a1 (14) found that mungbean as agreen manure crop for rice was as effective as 80 kg inorganic N/ ha, while Meelu and Rekhi (7) from studies on N management in a wheat - mungbean - rice cropping sequence reported that mungbean yielded 0.86 t/ ha of grain, and incorporation of its straw resulted in a saving of 60 kg inorganic N/ha in the rice crop (Fig. 2).



1. Effect of green manuring on N-economy in rice.



2. Effect of addition of mungbean straw and fertilizer N on rice yields.

Meelu et al (11) reported one year's results of a long-term experiment on the evaluation of eight green manure crops as sources of N for rice, for biomass production, and for N accumulation. Biomass production after 60 days'growth varied from 12 to 46 t/ha, and N accumulation from 50 to 224 kg/ ha. The rice crop responded significantly to inorganic N, up to a rate of 50 kg N/ha. Rice yields in the presence of green manure generally corresponded to the yield obtained with 50 kg inorganic N/ha irrespective of the type of the manure crop. Although the biomass production and N addition in the different green manure crops varied greatly, rice yields were comparable. This suggests that there is a need to investigate the optimum amounts of green manure to apply and the best combination with inorganic N to use; any excess biomass can be used to cover a greater area to produce more rice grain. Meelu et al (12) reported one year's results of another long-term N management experiment started in 1984 at IRRI where rice was grown after a green manure, legume or cereal crop, application of farmyard manure, or fallow treatment. The results indicated that the N requirement of rice and rice yield were determined by the effect of the preceding crop on soil fertility. For example, rice yields were minimal with the zero N treatment after growing maize, maximal following green manure, and intermediate after mungbean, farmyard manure, and weedy fallow. Rice yields after maize increased with increasing application of fertilizer N up to 100 kg N/ ha; those obtained at the high rate of N were comparable to those obtained by rice which followed green manure alone, or which followed legumes, farmyard manure, or weedy fallow and received an application of 50 kg N/ha.

Farmyard manure

The use of farmyard manure and compost to improve rice yields has been practiced by farmers for many centuries. The bulky organic manures contain low nutrient concentrations, but liberal and continuous applications tend to build up the organic matter and nutrient content of soil, and to increase crop production. With the adoption of intensive cropping practices and modern rice varieties which require more N, there is a greater demand on soil N and other nutrients. Supplements in organic manures are not sufficient to meet crop needs; thus it is necessary to use a combination of organic manures and inorganic fertilizers to maintain agricultural production and soil fertility.

Kulkarni et a1 (4) reported results of experiments on the combined use of organic and inorganic amendments in rice -wheat rotations (Table 8). The data showed that on alluvial soils integrated use of 12 t of farmyard manure and 60 kg of inorganic N/ ha produced as much rice as 120 kg fertilizer N/ ha. On red and yellow soils, a saving equivalent to 60 kg each of N, P_2O_5, and K_2O was obtained. Farmyard manure also had a residual effect on the succeeding wheat crop. Padalia (15) studied the effects of applications of fertilizer, compost, and combined fertilizer and compost on rice at the Central Rice Research Institute at Cuttack, India (Table 9). The data show that application of compost was comparable to an addition of 40 kg inorganic N. He obtained a residual effect

Table 8. Effect of combined use of organic and inorganic fertilizers in rice-wheat rotation on farmers' fields (1974-75 to 1976-77).

Crop	Treatment[a]	Grain yield (t/ha) Bhagalpur alluvial soils (means of 87 trials)	Grain yield (t/ha) Manipur red and yellow soils (means of 46 trials)
Rice	F_0 N_0	2.18	3.33
Wheat	F_0 N_0	1.57	0.57
Rice	F_0 N_{120}	4.21	4.41
Wheat	F_0 N_{60}	2.75	1.04
Rice	F_0 N_{120} P_{26} K_{50}	4.97	5.39
Wheat	F_0 N_{60}	3.02	1.36
Rice	F_{12} N_{60}	4.14	5.44
Wheat	F_0 N_{60}	2.95	1.33

[a] Figures at the base of N, P, and K indicate kg/ha. Figures at the base of F (farmyard manure) indicate t/ha.

Table 9. Effect of applications of compost and fertilizer N on rice yields.

Fertilizer applied (kg N/ha)	Grain yield (t/ha) Without compost	Grain yield (t/ha) With compost providing 80 kg N/ha
0	4.1 3	4.54
40	4.57	4.97
80	4.90	5.04
120	4.84	4.83
160	4.77	4.76
Mean	4.64	4.83

Table 10. Available soil nutrients following two years of farmyard manure application to rice in a rice-wheat sequence (12 t manure/ha per year).

Treatment	Organic carbon (%)	Available nutrients N (kg/ha)	P (kg/ha)	K (kg/ha)
Soil at start of experiment	0.228	90	7	146
- FYM	0.229	111	8	151
+ FYM	0.300	164	12	170
LSD (5% level)	0.034	16	1	7

with compost but no residual effect of NPK fertilizer on rice. Teppoolpan and Wasinarat (23) reported the results of a study on the complementary use of compost and inorganic fertilizer on rice in Thailand and indicated that an application of 2 to 6 t/ha compost was equivalent to 25 kg inorganic N/ha. Meelu et a1 (8) showed that combined use of 80 kg inorganic N and 12 t FYM/ ha gave rice yields comparable to 120 kg inorganic N ha, saving 40 kg/ha and producing a residual effect on the succeeding wheat crop. Furthermore, Gill and Meelu (3) reported a buildup in soil fertility following two years of farmyard manure applications to rice in a rice - wheat rotation (Table 10).

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Nitrogen-Sulfur Interactions in Rice

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There are many similarities in the N and S cycles in rice cropping systems, but changes in fertilizer use patterns are changing the magnitude of the N and S inputs. The move to urea, diammonium phosphate, monoammonium phosphate, and triple superphosphate has significantly decreased S inputs. In addition, increased cropping intensity and changes in straw management have important implications for both N and S. Experimental evidence suggests that fertilizer N efficiency is maximized by deep placement whereas S responses are greatest where it is surface broadcast. A set of diagnostic criteria based on total S, total N, and N/S ratio for whole tops sampled at maximum tillering is presented.

The incidence of S deficiency in upland and lowland rice is increasing throughout the world. This is due to a combination of factors which include

- the increasing use of so-called 'high analysis' fertilizers with a low S content,
- increased cropping intensity on more marginal soils, and
- a greater number of investigations where S fertilization is included as a treatment.

There are numerous reports in the literature of S responses in rice, and Blair (1) has cited recorded responses in 15 countries, namely, Australia, Brazil, Burma, Bangladesh, China, Indonesia, India, Japan, Nigeria, Papua New Guinea, Philippines, Solomon Islands, Sri Lanka, Thailand, and USA.

At a seminar on S in Southeast Asian and South Pacific agriculture, held in Indonesia (2), delegates agreed that there were insufficient field data to accurately estimate the magnitude of S deficiency in the region and that the problem was increasing in severity.

Increasing use of N fertilizers and low S-containing 'high analysis' fertilizers is a major factor contributing to the increasing incidence of S deficiency. Examples of the trends in N, P, K, and S consumption in Indonesia and Thailand are presented in Table 1.

This dramatic shift in S consumption is primarily the result of a move from the use of ammonium sulfate to urea, and single superphosphate to triple superphosphate, monoammonium phosphate, and diammonium phosphate.

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Table 1. Changes in fertilizer consumption in Indonesia (1961 to 1973) and Thailand (1961 to 1977).

	Consumption (t)			
	N	P	K	S
Indonesia	+262 652	+8 131	+21 612	–19 797
Thailand	+30 981	+6 278	+3 997	–2 892

SUPPLY/DEMAND RELATIONSHIPS OF SULFUR IN RICE PRODUCTION

The quantity of fertilizer S required to maintain crop production depends on many factors. The major ones are

- the inherent S-supplying capacity of the soil,
- the incidental inputs such as sulfate in rainfall and irrigation water, and atmospheric SO_2 and H_2S,
- S removal in products, and
- the amount and fate of S returned in crop residues.

Sulfur-supplying capacity of the soil

The ability of a soil to supply S to rice crops depends on the turnover rate of S from organic matter, its retention as $SO_4^=$ on the adsorption complex, and the availability of that sulfate to plants.

In natural ecosystems, S demand is low because the growth rate of the native vegetation is slow and the S is efficiently cycled within the system. When this vegetation is cleared there is an increase in the mineralization rate of organic matter, and generally the maximum rate of release of sulfate occurs before there is active crop growth to act as a sink. This, together with removal of organic matter in surface flow, can severely reduce the S available for crop growth in the same manner as N availability is reduced.

Three points concerning sulfate accretion by soils are considered important (7):

- The capacity for sulfate sorption increases with soil weathering. In the case of the Andepts, the order of increasing sorption is Typic Dystrandept < Hydric Dystrandept < Typic Hydrandept; and in the case of soils developed from crystalline materials, the order is Alfisol < Ultisol < Oxisol.
- Well-drained soils usually will not contain sorbed sulfate, even if such soils have developed considerable sorption capacity, unless sulfate accrues to the soil from an outside source.
- Soluble sulfate does not follow the quantity of sulfate in the soil. The same can be said for S availability. Acute S deficiency is associated with a low sulfate saturation percentage.

Incidental sulfur inputs

Measurements of the incidental S inputs in rice-growing regions are nonexistent. Tropical agricultural areas are generally in regions of low industrial activity and so global estimates of S inputs are of little value in calculating regional inputs (7). Also, many of the major rice-producing areas of Southeast Asia are located at low latitudes, where winds are generally light and hence input from sea spray probably low.

Zahari et a1 (25) reported results of a systematic study of S inputs in rainfall in Peninsular Malaysia carried out from October 1981 to September 1982. Their data showed values of 4-7 kg S/ha per yr for the remote inland stations. Areas adjacent to industrial centers recorded 16-19 kg S/ha per yr, and the highest input of 21 kg S/ha per yr was recorded on the East Coast. These values are all far in excess of the 2 kg S/ha per yr recorded in Victoria, Australia (1l), and probably explain the lack of S responses recorded in Malaysia.

A network of rainfall collection stations is being established in Malaysia, Thailand, Indonesia, and Australia as part of an ACIAR-funded project on P and S in tropical cropping systems. Data on the ionic content of rainwater, and SO2 and H2S emission will be collected at two-month intervals from approximately 100 sites. Hopefully these data will give better information on the magnitude of aerial S inputs into the region.

Lack of data also prevents an accurate estimate of the input of S in irrigation water. Yoshida and Chaudhry (24) estimated that the entire S supply for rice production could be met from irrigation water containing 2.7 ppm. On the other hand, Blair et a1 (4) found significant S responses in areas where irrigation water contained 2.8 ppm. S. Hayami (unpublished data) found that irrigation water in Java, Indonesia, vaned from 1.3 to 20.0 ppm S. In South China Lui et a1 (15) found a mean of 1.0 ppm S. Clearly, more information is required before the contribution from this source can be estimated accurately.

Sulfur removal in products

Lack of data also limits the value of estimates of S removal in rice grain. Published data on the S content of rice grain vary from 0.09% under deficiency conditions to 0.34% in nonresponsive situations, and grain yields vary from 0.75 to 8 t/ha. The S removed in grain can therefore vary from 0.68 to 27.2 kg/ha.

Sulfur in crop residues

Samosir (20) measured the S harvest index (i.e., S in grain as a percentage of total tops S content) of 61% in IR8 rice grown with a range of S fertilizer rates. This means that rice straw may contain a considerable amount of S. The value of this S to succeeding crops depends on S content and straw management. Stewart et a1 (22) found net immobilization of S occurred when the S content of wheat straw was below 0.15%. This is analogous to the 1.5% N value required for net N mineralization. In a review of published data on rice straw, Blair et al (3) found only two cases where the S content of rice straw exceeded 0.15%. This aspect of S cycling requires closer study.

The move from the use of traditional varieties to high yielding varieties is generally accompanied by a change in straw management. In many traditional areas of Southeast Asia, straw is left in the field and utilized by ruminant animals. The introduction of shorter-season, high yielding varieties, and increased availability of irrigation water means that often two crops per year can be produced, and straw burning becomes a regular practice. No data exist on the impact of this change in straw management on the N and S cycling in rice production.

NITROGEN AND SULFUR TRANSFORMATIONS IN RICE SOIL

Sulfur is present in soils in both inorganic and organic forms, and the proportion of each form depends on a wide range of factors. Sulfur in surface soils is mainly organic, and there is a strong correlation between total S content and organic matter. The two major organic S fractions in soils are hydriodic acid (HI) reducible S, predominantly ester sulfates, and C-bonded S such as cystine and methionine (8). Freney et a1 (9) found that recently applied fertilizer sulfate was incorporated primarily into the HI reducible fractions and that approximately 60% of the S taken up by plants came from the C-bonded fraction.

The CN:organic S ratio is generally found to be 100: 10:1.3 across a wide range of soil types (18). Variations in the N:S ratios between soil groups are less than those for C:N ratios (6, 23).

Because there is a close association between organic N and organic S in soil organic matter, factors that control the mineralization rate of N also control the mineralization rate of S. Sulfate is the only form of S taken up by plants, whereas N can be taken up in the form of NO_3^-, NH_4^+, and urea.

Ammonium ions (NH_4^+) can be held on the soil cation exchange complex against leaching, and this form is an important source of N in reduced soils. Nitrate ions are weakly adsorbed on the soil anion adsorption complex and hence move freely with the soil water. Sulfate, on the other hand, is strongly adsorbed, and this form is the major reserve of plant available S in rice cropping systems.

In soils of variable charge the number of positive charges depends on the pH relative to the point of zero charge (PZC) of the surfaces. This means that sulfate adsorption will decrease as the pH of the soil increases.

In flooded soils nitrate can be reduced to NO_2^- and N_2 in the reduced soil layer. Similarly, $SO_4^=$ can be reduced to sulfide in the same zone. Both can represent a loss to the system. Although the bulk of soil may be at a negative redox potential, the soil within the root rhizosphere is strongly aerobic due to the expulsion of oxygen from the root surface. This aerobic zone protects roots from the harmful effects of H_2S.

AGRONOMIC CONSIDERATIONS

Nitrogen and sulfur deficiency in rice crops

Sulfur deficiency reduces grain yield in rice by reducing tillering, number of panicles, grains per panicle, and grain weight, and in severe cases by increasing empty grains (Table 2). In this respect S deficiency is identical to N deficiency. If deficiency symptoms are apparent on the plant, then S deficiency appears as a yellowing of the uppermost leaves, whereas N deficiency symptoms appear as a

Table 2. The effect of S fertilization on tiller number and yield components in rice (13).

	0 ppm S	80 ppm S
Grain yield (g/pot)	48	160
No. of panicles/pot	28	52
Grains/panicle	132	191
%empty grains	31	26
1 000-grain weight (g)	16.8	20.6
% S in grain	0.026	0.054

yellowing of the lower leaves. Rarely, however, are single deficiencies of N and S observed and for this reason it is often very difficult to rely on visual symptoms.

Several studies (10,12,16) have reported that S uptake was higher on nonflooded than submerged soils. These studies suggested that availability of S was lower in flooded soils due to the reduction of sulfate to sulfide under anaerobic or reduced conditions. In recent studies on nine Australian soils (S. Samosir, unpublished data), it was found that S uptake at 63 DAT was higher under unflooded conditions on six of the nine soils. On the other three soils S uptake was low and there was no effect of flooding. In these same experiments a grain yield response to S was recorded on only one unflooded soil (soil 9), while significant responses were obtained on five flooded soils (soils 1,4,7,8,9) and there was a significant yield depression due to S on two soils high in Fe (soils 5 and 6) (Table 3).

These data indicate the danger of extrapolating results between flooded and nonflooded conditions; care should be taken in interpreting results from soil S tests. Similar comments can be made with regard to N.

Table 3. Rice grain yields obtained in the absence and presence of S under flooded and nonflooded conditions on nine roils from New South Wales.

Soil no.	Soil type	Location	Calcium phosphate extractable S	Grain yield (g/pot)			
				Nonflooded		Flooded	
				−S	+S	−S	+S
1	Black earth	Armidale	19	15.6 a[a]	19.9 a	18.3 a	66.5 a
2	Black earth	Moree	12	23.9 ab	27.6 a	18.7 a	20.2 ab
3	Black earth	Gurley	8	24.6 a	22.8 a	21.6 a	28.4 a
4	Granitic sandy loam	Uralla	5	18.3 a	22.5 a	25.3 a	45.4 b
5	Krasnozem	New England National Park	15	12.8 c	11.8 c	7.3 b	4.5 a
6	Krasnozem	Ebor	15	19.3 ab	14.8 ab	23.6 b	9.2 a
7	Red-brown clay	Jerilderie	8	24.0 a	27.7 a	26.5 a	45.1 b
8	Red-brown sandy clay loam	Jerilderie	8	12.0 a	12.4 a	16.5 a	39.2 b
9	Brown sandy clay loam	Jerilderie	11	20.7 a	27.4 b	30.7 b	51.4 c

[a] Numbers within rows followed by the same letter are not significantly different at P = 5% according to Duncan's Multiple Range Test.

Sulfur fertilization of rice crops

There are many S-containing fertilizers that could potentially be used on rice but at this stage only ammonium sulfate, gypsum, and elemental S are readily available. Experiments conducted with flooded rice in Indonesia (5) have shown that ammonium sulfate, gypsum, and elemental S (<40 mesh) are equally effective when topdressed at sowing. In one experiment, elemental S applied at 20 days before sowing was found less effective (Table 4), presumably due to rapid oxidation and subsequent leaching of S with the opening rains.

In an examination of a wider range of S material using oats as the test plant, Allwright and McCaskill (unpublished data) (Table 5) found the greatest response with a sulfate source (gypsum), and little response to the other sources used. Sources such as sulfurcoated urea (SCU) and elemental S showed some residual effect.

These and other studies (21) indicate that while ammonium sulfate is a satisfactory S source for flooded rice, SCU and S urea melt are unsatisfactory, at least in the formulations used in these studies.

Although short-term experiments have shown ammonium sulfate to be an adequate N and S source for rice, the acidifying effect of this fertilizer can create long-term problems. Many experiments have shown benefits from deep placement of urea. Mixing elemental S throughout the soil, however, is less effective than surface broadcasting (S. Samosir, unpublished data) (Table 6).

Table 4. The effect of S source on grain yield of flooded rice growing at three sites in South Sulawesi, Indonesia.

S source	Grain yield (kg/ha)		
	Site 1	Site 2	Site 3
Ammonium sulfate	2 721 a[a]	5 206 a	4 721 a
Gypsum	2 616 a	4848 a	4 612 a
Elemental S at transplanting	2681 a	5 254 a	4 534 a
Elemental S 20 days before transplanting	-	-	4110 b

[a] Numbers within columns followed by the same letter are not significantly different according to the studentized range test.

Table 5. Yield response of oat tops to a range of sulfatic fertilizers.

Source	Yield (g/pot)			
	40 days		90 days	
	10 kg S/ha	30 kg S/ha	10 kg S/ha	30 kg S/ha
Gypsum	2.98	3.03	3.30	3.20
SCU	0.70	0.68	0.30	1.03
S-Bentonite	0.53	0.20	0.35	0.30
Elemental S	0.30	1.15	0.40	1.40
Foam-S	0.25	0.63	0.03	0.76
S-Urea melt	0	0.20	0	0.25

LSD (0.05) = 0.45

Table 6. Yield of rice fertilized with elemental S applied to the surface or mixed with the roil at a rate of 20 kg/ha (S. Samosir, unpublished data).

Variety	Yield (g/pot)	
	Surface applied	Mixed
IR20	6.80	2.85
IR2755	5.33	3.79
B4-62	7.95	4.50
IR26	6.40	2.41
Mudgo	11.29	7.18

Clearly, more research is required on both placement effects and the residual value of different S sources.

Diagnostic criteria

There is a paucity of information on S levels in rice tissue. Estimates that have been made are summarized in Table 7. There is general agreement between data sets in Table 7. Both show a decline in critical level with crop development. Various authors have suggested a range of criteria to establish the S status of crops, including total S, sulfate S, N/S ratio, and sulfate S as a proportion of total S. In an earlier publication (3) problems of using total S alone as a diagnostic criterion were pointed out. Data collected since then from field-grown rice have supported this view. As a result of this experience it is proposed that the tentative classification proposed by Blair et al (3) be modified to that shown in Table 8. On the basis of current dormation it is felt that the use of total N, total S, and N/ S ratio together as shown in Table 8 allows a rational decision to be made regarding both the N and S status of rice plants when whole tops are sampled at maximum tillering.

The use of multiple criteria has also been proposed for wheat grains (19). From greenhouse studies it was proposed that S-deficient wheat grain would have a total S content of less than 0.12% and a N/S ratio larger than 17:l.

Table 7. Estimates of S content (%) in rice required to produce 90% of maximum yield (critical level).

Stage of growth[a]	Plant part sampled	Estimated critical %S	Reference
21 DAE	leaf blades	0.16	(17)
42 DAE	leaf blades	0.13	(17)
63 DAE	leaf blades	0.1 1	(17)
Maturity	grain	0.12	(17)
Maturity	straw	0.10	(17)
Active tillering	whole tops	0.23	(14)
Maximum tillering	whole tops	0.14	(14)
Maturity	wain	0.1 1	(14)

[a] DAE = days after emergence.

Table 8. Diagnostic criteria to establish the N and S status of rice crops when whole tops are sampled at maximum tillering.

Category	% N	% S	N:S ratio	Status	
				N	S
1	2.1	0.14	15	adequate	deficient
2	2.1	0.14	variable	deficient	deficient
3	2.1	0.14	15	deficient	adequate
4	2.1	0.14	15	adequate	adequate

Table 9. Relative yield and total S, total N, and N/S ratio of rice grain grown in South Sulawesi, Indonesia (G. J. Blair, C. P. Mamaril, and E. O. Momuat, unpublished data).

Parameter	0 kg S/ha	7.5 kg S/ha	15 kg S/ha	30 kg S/ha	60 kg S/ha
% maximum yield	59	65	82	87	100
% S	0.09	0.09	0.09	0.10	0.10
% N	1.59	1.53	1.49	1.49	1.46
N/S ratio	17.7	17.0	16.6	14.9	14.6

Data from field experiments with rice conducted in Indonesia have not shown a strong relationship between grain S percentage and responsiveness. Data from three field sites showed that the relationship between percentage maximum yield (Y) at each site and percentage total S in grain (X) was of the form

$$Y = 100\,[1 - 33.2 \exp(-55.3\,X)]$$

with a correlation coefficient of only 0.491. Part of the reason for this poor relationship was the narrow range of grain total S contents measured in these experiments (viz., 0.083 to 0.097% S).

An example of the data from one site is presented in Table 9. Here, as at the other sites, a substantial increase in grain yield due to S fertilization resulted in no significant change in grain S content and a slight depression in grain percentage N, presumably due to a dilution effect.

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Fertilizer Evaluation for Rice: 1984 INSFFER Trials

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Fortyeight scientists from 18 national programs participated in International Network on Soil Fertility Fertilizer Evaluation for Rice collaborative research trials in 1984.

Response to deep placed urea supergranules (USG) was significantly greater than to best split prilled urea (PU) in 40% of the trials and to broadcast and incorporated sulfur-coated urea (SCU) in 36% of the trials where response to N was obtained in irrigated lowland rice. To produce a yield increase of 1 t/ ha, 33% less N was necessary if applied as SCU during dry season (DS), and 48% less if in wet season (WS). To produce a yield increase of 1 t/ha, 33% less N was necessary if applied as USG during DS, and 56% less if applied during WS.

In rainfed rice, yield responses to SCU and USG were significantly greater than to PU in 18% and 24% of the 33 trials where positive response to N was observed. For a yield increase of 1 t/ ha, 67% less N was required if applied as SCU and 65% less if applied as USG.

Various urea forms and methods of application resulted in similar yields in deep water rice. However, the performance of the test fertilizers at different N levels varied among sites.

No significant yield differences were observed with all the N sources and rates of application in a lone trial conducted on rainfed upland rice.

In a long-term fertility trial in irrigated lowland rice, N remained the major limiting nutrient at all sites. However, there were indications that P was becoming limiting. NPK consistently gave a significant response.

Four trials comparing hand- and machine-applied N fertilizers in irrigated rice were conducted in two countries. Responses to PU and USG hand- or machine-applied were generally greater at high than at low N rate.

In 15 trials on *Azolla* use in lowland rice conducted at 13 sites in 7 countries in 1983-84,15 t fresh *Azolla* /ha applied and incorporated either before or after transplanting increased rice yield as much as did 30 kg urea N/ ha.

The combined inorganic and organic sources of N produced yields comparable to those with pure inorganic fertilizers. The yields of *Azolla* and straw combined with PU were comparable; both were similar and higher than PU alone at 58 and 87 kg N/ ha. However, the yield from Azolla was higher than from straw when applied with USG at both N rates.

The results of the P x lime experiment conducted in a rainfed acid upland soil in the Philippines showed that without lime, only triple superphosphate (TSP) at the highest rate increased yield significantly over the control. With lime, TSP was more effective at medium and high Prates. No significant yield advantage was observed with increased lime application of the same level of P.

In the acid lowland nursery, of the 60 cultivars tested, only 2 (CR 261-7036-236 and IR5741-73-2-3) were rated tolerant of acid lowland conditions under 2 levels (0 and 60 kg/ha) of P.

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The International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) was established formally in 1976 in response to the declining fertilizer supply and increasing prices brought about by the energy crises in 1973-74. The initial objective was to increase fertilizer use efficiency but was later expanded to include the improvement and maintenance of fertility in rice soils. Economically feasible means of improving and stabilizing soil fertility, including the use of inorganic and organic fertilizers, biofertilizers, and biological nitrogen fixation are being tested.

The network consists of participating scientists of the national programs of 10 countries, the International Rice Research Institute (IRRI), and the International Fertilizer Development Center (IFDC). The network performs three main functions: 1) it conducts research trials, 2) it trains scientists, and 3) it organizes site visit tours and workshops. Individual collaborative trials have specific objectives which will be mentioned as the trials are discussed. The objective of the training component is to strengthen the capabilities of researchers and technicians of national programs in the theoretical and practical aspects of soils and their management, fertilizer use, biological N fixation, experimental techniques, and interpretation of results. Site visit tours and workshops are held to enable participating scientists to observe and characterize INSFFER sites, observe soil problems and soil fertility management practices, exchange information on recent development in fertilizer use and soil fertility, and discuss future directions on soil fertility and fertilizer management in rice.

COLLABORATING NATIONAL PROGRAMS AND RESEARCH TRIALS FOR 1984

The INSFFER trials conducted by participating scientists are chosen according to the needs of their national programs on soil and fertilizer management in rice. Consequently, no one collaborator conducts all INSFFER trials at any one time. Fortyeight collaborators from 18 national programs participated in 1984 (Table 1). The trials conducted by them included a number formulated during the 1984 International Network on Soil Fertility and Fertilizer Evaluation for Rice/Soil Management Support Services/Bureau of Soils Workshop held at IRRI and were as follows:

- Fifth Nitrogen Fertilizer Efficiency Trial in Irrigated Wetland Rice (1981)[1]
- Sixth Nitrogen Fertilizer Efficiency Trial in Irrigated Wetland Rice (1984)
- Third Nitrogen Fertilizer Efficiency Trial in Rainfed Wetland Rice (1981)
- Second Nitrogen Fertilizer Efficiency Trial in Deepwater Rice (1982)
- First Nitrogen Fertilizer Efficiency Trial in Rainfed Upland Rice (1984)
- Long-term Fertility Trial in Irrigated Wetland Rice (1976)
- Long-term Fertility Trial in Rainfed Upland Rice (1984)
- Comparison of Hand- and Machine-applied Nitrogen Fertilizers in Irrigated Wetland Rice (1983)

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[1] Year in parenthesis indicates the year the trial was formulated and subsequently implemented.

Table 1. Countries, collaborators, and research trials in 1984 INSFFER program.

Country	Number of collaborator[a]	Number of trial[b]
Bangladesh	1	8
Burma	1	3
Cameroon	1	5
China	3	18
Dominican Republic	1	2
India	20	45
Indonesia	3	16
Liberia	1	1
Malagasy	1	4
Malaysia	1	6
Nepal	1	7
Nigeria	1	7
Pakistan	3	15
Philippines	4	66
Senegal	1	1
Sri Lanka	1	5
Thailand	1	10
Vietnam	3	23
Total	48	242

[a] Includes only the senior investigators. [b] Based on experimental material requested.

- Fifth Trial on *Azolla* Use in Wetland Rice (1983)
- Trial on the Integrated Use of Inorganic and Organic Fertilizers in Wetland Rice (1983)
- Comparison of Phosphorus Sources for Irrigated Wetland Rice (1977)
- Phosphorus and Lime Interaction Trial in Acid Upland Rice Soils (1984)
- Identification and Evaluation of Rice Cultivars Tolerant of Acid Conditions (1982).

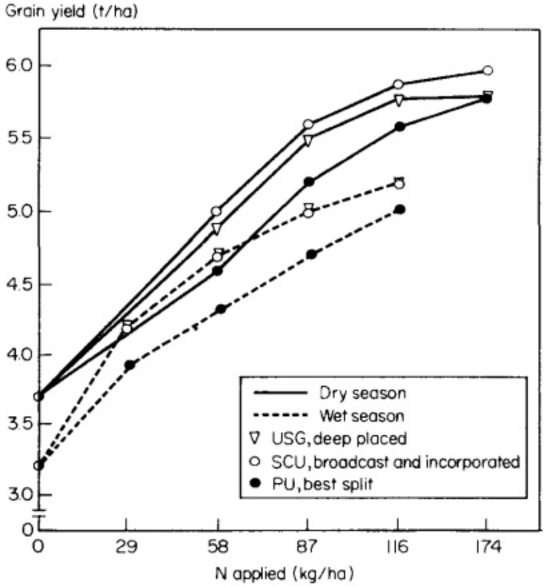
This report will concentrate on the results of the 1984 trials and will briefly review all the results from the time the trials were first implemented.

HIGHLIGHTS OF RESULTS

Fifth Nitrogen Fertilizer Efficiency Trial in Irrigated Wetland Rice (1981)

During the period 1981-83,109 trials were conducted at 67 sites in 10 countries. The average yield responses of rice to sulfurcoated urea (SCU) which had been broadcast and incorporated (B&I), and to urea supergranules (USG) which had been deep point placed (DP) were similar and greater than those obtained with the best split (BS) applications of prilled urea (PU), especially at low rates of N (Fig. 1). Sulfurcoated urea and USG resulted in 35% more rice than PU at 58 kg N/ ha during the dry season (DS) and 46% more rice than PU at 29 kg N/ ha during the wet season (WS).

Evaluation of the results using regression analysis showed that rice responded positively to N in 95 of 109 trials. Yield response to SCU was



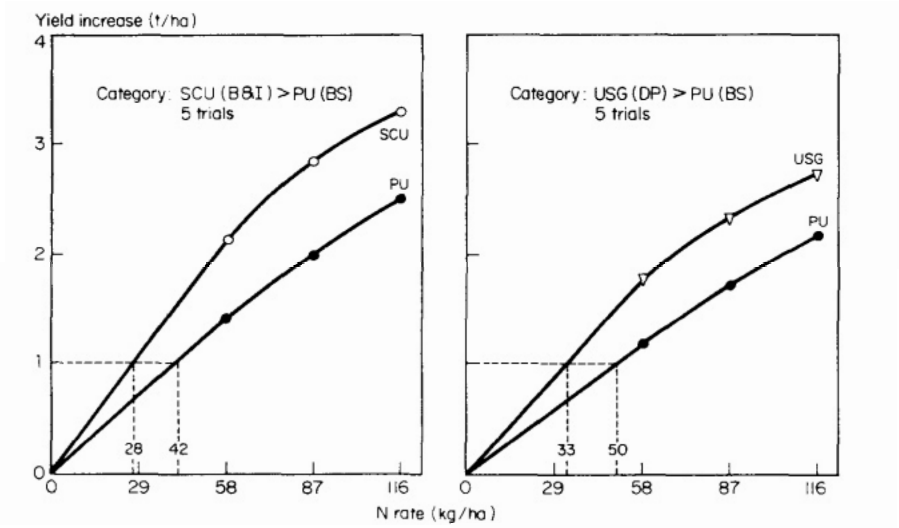
1. Average yield responses of irrigated wetland rice to different forms of urea and rates of application. Data are averages of 16 dry season and 93 wet season trials conducted at 67 sites in 10 countries. (Fifth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Wetland Rice, I981-83),

significantly greater than to PU in 36% of the N response trials and USG was better than PU in 40% of the N response trials (Table 2). The estimated average yield responses to SCU, USG, and PU on trials where the yield response to the test fertilizers was significantly greater than PU during the wet and dry seasons are shown in Figures 2 and 3. Thirty-three and 48% less N was required to

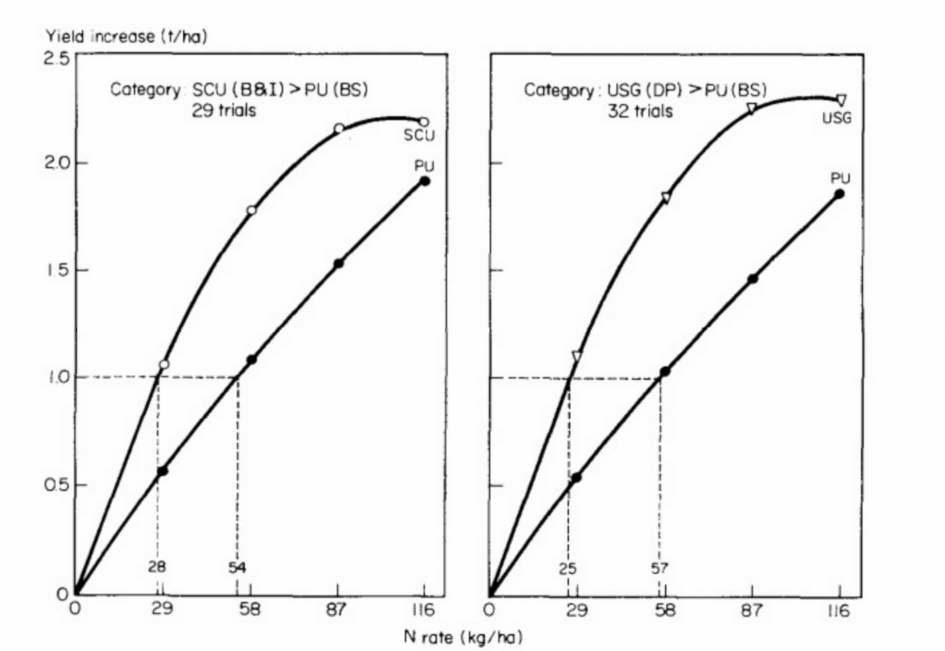
Table 2. Number of trials in which rice responded positively to SCU and USG when compared separately with PU (Fifth international trial on N fertilizer efficiency in wetland rice, 1981-83).

Country	No. of trials[a]			
	Total	Response category		
		SCU>PU	USG>PU	No response
Bangladesh	4	2	2	0
Burma	5	0	0	3
Cameroon	1	0	0	0
China	6	3	4	0
India	35	18	19	1
Indonesia	26	2	5	3
Nepal	4	0	0	2
Philippines	22	8	6	4
Thailand	1	0	1	0
Vietnam	5	1	1	1
Total	109	34 (36)	38 (40)	14

[a] Values in parentheses are percentages of the 95 trials where a polltive response to N was obtained.



2. Estimated average yield responses ofirrigated wetland rice to SCU (B&I), USG (DP), and PU (BS) in trials where yield responses to the test fertilizers were significantly greater than standard PU. (Fifth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Wetland Rice; 1981-83 dry seasons.)



3. Estimated average yield responses of irrigated wetland rice to SCU (B&I), USG (DP), and PU (BS) in trials where yield responses to the test fertilizers were significantly greater than standard PU. (Fifth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Wetland Rice; 1981-83 wet seasons.)

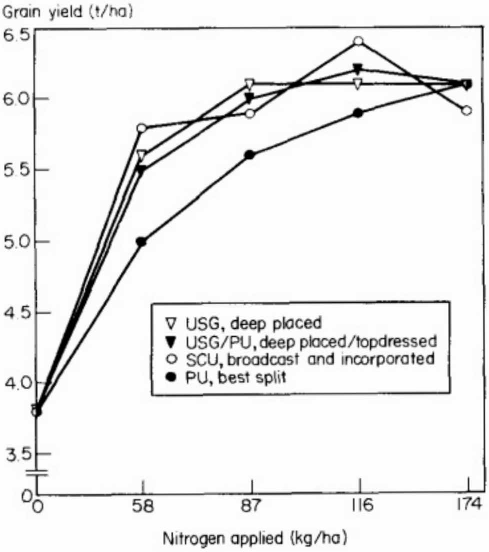
produce a yield increase of 1 t/ ha from SCU than from PU during the DS and WS, respectively. Likewise, 34 and 56% less N was required from USG than from PU to produce a 1 t yield increase during the DS and WS.

During the dry seasons of 1982 and 1983, the treatment USG + PU was added. Prilled urea (29 kg N/ha) was topdressed 5-7 days before panicle initiation (DBPI) and the remainder of the N was applied as USG deep point placed 3 to 4 days after transplanting (DT). Sixteen trials in 7 countries were conducted. In these trials, the average yield responses to SCU (B&I), USG (DP), and USG + PU were comparable and superior to PU (BS) (Fig. 4). The average yield increase at 58 kg N/ ha was 32 kg rice/ kg N from SCU, USG, and USG + PU and 21 kg rice/ kg N from PU. Thus SCU, USG, and USG + PU on average resulted in 53% more yield than PU at-58 kg N/ha.

Regression analysis showed that rice responded positively to N applications in 15 of the 16 trials. Yield responses to SCU, USG, and USG +- PU were significantly greater than to PU in 53, 40, and 60% of the response trials, respectively (Table 3). To produce a 1 t yield increase, 34, 31, and 33% less N was required from SCU, USG, and USG + PU, respectively, than from PU (Fig. 5).

Sixth Nitrogen Fertilizer Efficiency Trial in Irrigated Wetland Rice (1984)

During the 1984 INSFFER workshop it was realized that water regime influences the efficiency of N fertilizer use by rice. The variability observed in previous trials between the best split treatment (broadcast and incorporation of basal amount) and USG or SCU could be attributed to the varying depth of floodwater at the time when the basal amount was applied. Thus the local best split was compared with a standard BS (where 2/3 N is broadcast and incorporated on a drained field and 1/3 is topdressed 5-7 DBPI), SCU (B&I), and USG (DP) at 3 rates of N.

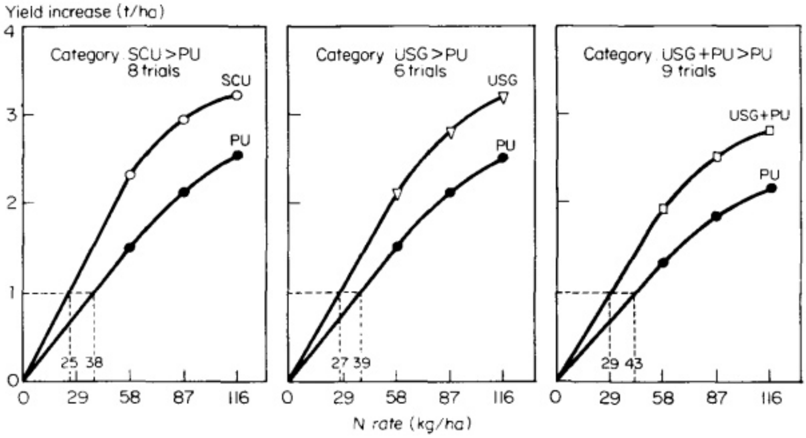


4. Average yield responses of irrigated wetland rice to different forms of urea and rates of application. Data are averages of 16 trials conducted at 16 sites in 7 countries. (Fifth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Wetland Rice; 1982-83 dry seasons.)

Table 3. Number of trials in which rice responded positively to SCU, USG, and USG + PU when compared separately with PU (Fifth international trial on N fertilizer efficiency in irrigated wetland rice, 1982-83 dry season).

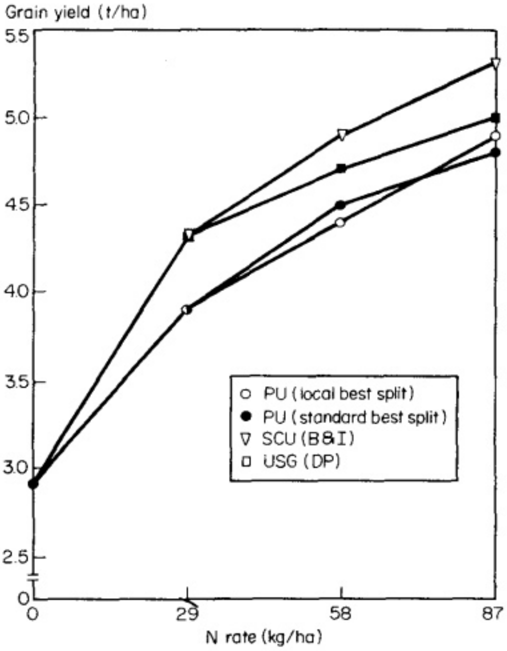
	No. of trials [a]				
Country	Total	Response category			
		SCU>PU	USG>PU	USG+PU>PU	No response
Bangladesh	22		0	1	0
Cameroon	20		0	1	1
China	10		1	1	0
Egypt	10		0	0	0
India	11		1	1	0
Indonesia	32		1	1	0
Philippines	63		3	4	0
Total	16	8 (53)	6 (40)	9 (60)	1

[a] Values in perantheses are percentages of the 15 trials where a positive response to N was obtained.



5. Estimated average yield response of irrigated wetland rice to SCU (B&I), USG (DP), USG + PU/DP and topdressed at 5-7 DBPI), and PU (BS) in trials where yield responses to the test fertilizers were significantly greater than standard PU. (Fifth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Wetland Rice; 1982-83 dry seasons.)

Five countries have reported the results of their trials, conducted at 16 sites in 1984; rice responded positively to N at all sites. The average response of irrigated rice to USG and SCU was similar, but significantly higher than that obtained with the local or standard BS PU at low N rates (Fig. 6). Based on the average grain yield for all sites, the use of SCU and USG at the rate of 29 kg N/ ha resulted in a yield of 48 kg rice/ kg N, whereas PU yielded 34 kg rice/ kg N. Thus 41% more rice was obtained from SCU and USG than from PU at 29 kg N/ ha.



6. Average yield responses of irrigated wetland rice to different forms of urea and rates of application. Data are averages of 16 wet season trials conducted at 16 sites in 5 countries. (Sixth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Wetland Rice; 1984.)

The different proportions of PU and times of application for the local BS treatment used at different sites are shown in Table 4. The 1/2 N basal and 1/4 N topdressed twice treatment did not produce a significant response at any of the test sites (Fig. 7). The 2/3 N basal (with standing water) + 1/3 N topdressed, and 1/3 N basal + 1/3 N topdressed twice local splits were significantly inferior to the standard BS at 58 and 87 kg N/ha in trials 15 and 3, respectively. Applying 1/2 N basal and 1/2 N topdressed proved to be no better than the standard BS at all rates of N in trial 16. There were, however, some inconsistencies in the responses to local BS application of PU even among sites using the same proportion and timing.

In trial 5, the response to deep placement of USG at all rates of N was significantly lower than that obtained with either local or standard BS applications of PU (Fig. 7, 8).

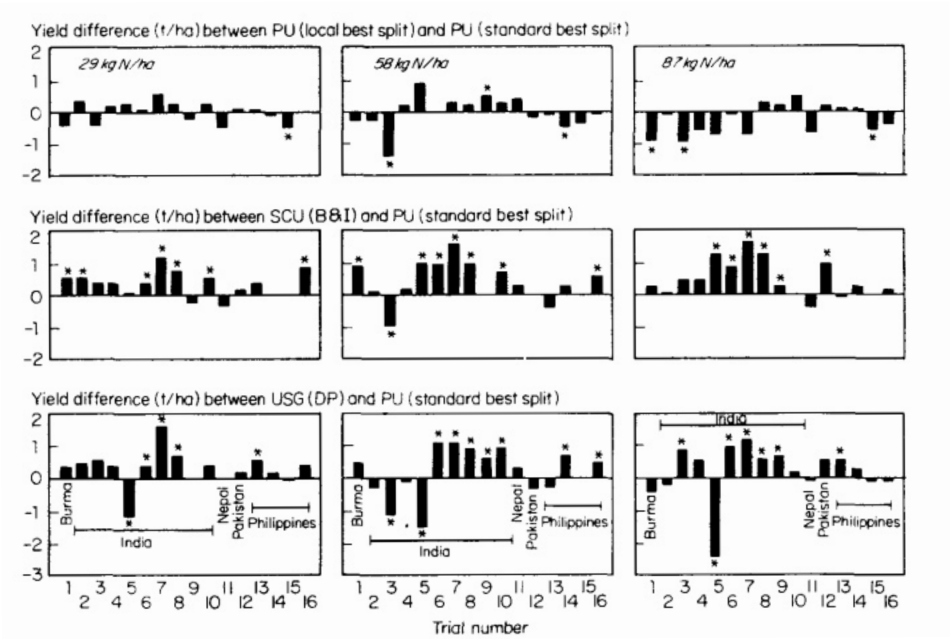
Thud Nitrogen Fertilizer Efficiency Trial in Rainfed Wetland Rice (1981)

Forty-six trials were conducted at 27 sites in 8 countries during the period 1981-84 and a positive response to N was obtained in 42 trials. Average yield responses to SCU and USG were similar, but superior to PU (Fig. 9). At the 29 kg N/ha rate, SCU or USG produced 31 kg rice/ kg N compared with 21 kg rice/kg N for PU. Thus, on average, at this rate of application SCU and USG resulted in 48% more rice than PU.

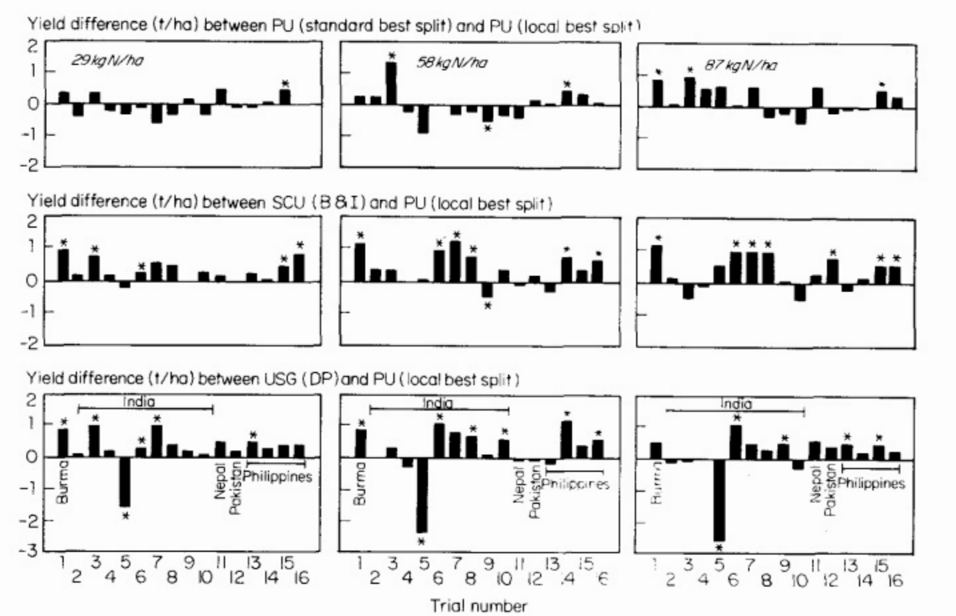
Table 4. Proportions and times of application of local best split treatments for testing in the sixth international trial on nitrogen fertilizer efficiency in irrigated wetland rice 1984.

Time of application and proportions of PU used in local best split treatments	Location of trials[a]
1/4 N basal; 1/4 N topdressed 3 times	Nawagan, India (7)
1/3 N basal; 1/3 N topdressed twice	Aduthurai, India (2) Coimbatore, India (3) Kapurthala, India (4) Ludhiana, India (5) Malan, India (6) Faisalabad, Pakistan (12)
1/2 N basal: 1/4 N topdressed twice	Pantnagar, India (8) Rajendranagar, India (10)
1/2 N basal; 1/2 N topdressed	Raipur, India (9) Calauan, Philippines (13) Los Baños, Philippines (16)
2/3 N basal; 1/3 N topdressed	Kyankse, Burma (1) Khumaltar, Nepal (11) Camiling, Philippines (14) Dingras, Philippines (15)

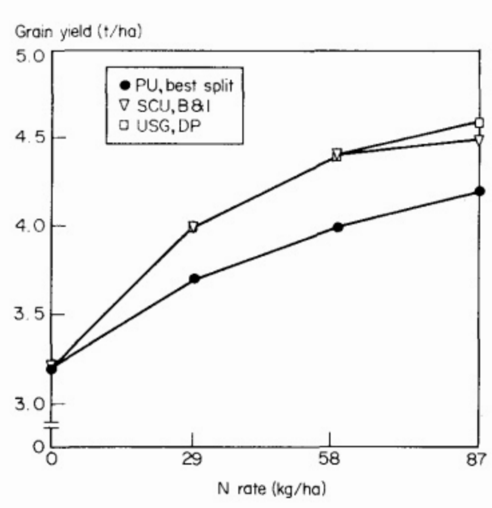
[a] Figures in parentheses indicate the trial number.



7. Grain yield differences between PU (local best split), SCU (broadcast and incorporated), and USG (deep point placed) and PU (standard best split) treatments in 16 wet season trials conducted at 16 sites in 5 countries. (Sixth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Rice, 1984.)



8. Grain yield differences between PU (standard best split), SCU (broadcast and incorporated), and USG (deep point placed) and PU (local best split) treatments in 16 wet season trials conducted at 16 sites in 5 countries. (Sixth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Rice, 1984.)



9. Average yield responses of rainfed wetland rice to different forms of urea and rates of application. Data are averages from 46 trials conducted at 27 sites in 8 countries. (Third International Trial on Nitrogen Fertilizer Efficiency in Rainfed Wetland Rice, 1981-84.)

Second Nitrogen Fertilizer Efficiency Trial in Deepwater Rice (1982)

The effectiveness of PU (B&I), SCU (B&I), USG (DP), and foliar application of urea in combination with basally applied PU were compared in nine trials conducted in three countries. The average nitrogen responses with different urea forms and application rates were significant at all sites. However, the performance of the test materials at different N levels varied from site to site.

In India, at low and medium rates of N, USG produced the highest yield of grain (Fig. 10). The basal application of PU followed by foliar spraying of urea solution was as effective as the remaining sources of N at low rates of application, but performed poorly at medium and high rates of fertilizer application. SCU produced a greater yield than all other sources at the high rate of N application (Fig. 10).

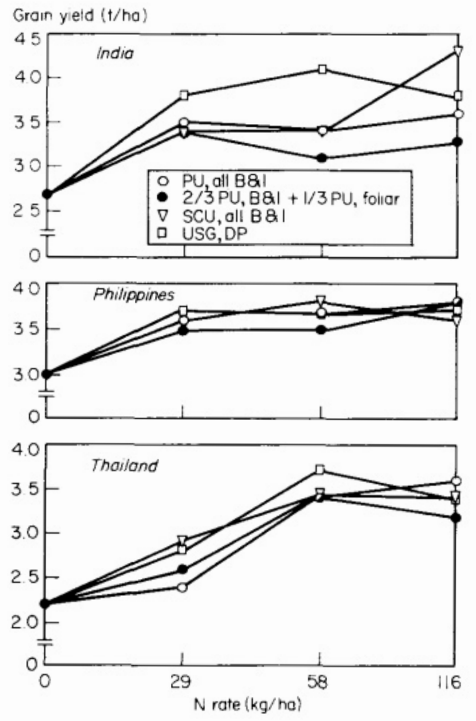
At Los Baños, Philippines, increasing the rate of N application above 29 kg/ ha had little if any effect on yield; USG yielded 3.7 t/ha at all rates of application. Foliar application of urea produced more grain than SCU and USG when all fertilizers were applied at the high rate. At low and medium rates, foliar application of urea produced 0.1-0.2 t of grain less per ha than other forms.

In Thailand, regardless of the form of urea applied, the greatest average yield increases were obtained at the medium rate of N application, with USG producing more grain than the other sources.

First Nitrogen Fertilizer Efficiency Trial in Rainfed Upland Rice (1984)

Realizing the need for proper technology that would apply to less favorable environments, the INSFFER participants during the 1984 site visit tour and workshop decided to conduct collaborative trials on upland rice grown under

10. Average nitrogen responses of rice with different forms of urea and rates of application in 3 countries. (Second International Trial on Nitrogen Fertilizer Efficiency in Deep Water Rice, 1982-84.)



diverse and mostly unfavorable conditions. This trial was initiated with the following objectives:

- to compare the effectiveness of two methods of application of PU, ammonium sulfate, and forestry grade SCU in as many locations as possible;
- to evaluate the effectiveness of ammonium sulfate and PU applied in combination with dicyandiamide, a nitrification inhibitor; and
- to evaluate the yield data, N uptake, and plant development in relation to the soil and other environmental characteristics at the various locations.

The effectiveness of the different N sources and their application methods was evaluated at only one site during 1984. This trial was conducted on an acid upland soil (pH 4.1) in Caliraya, Laguna, Philippines, during WS by IRRI's Agronomy Department. Some physical and chemical characteristics of the site are given in Table 5. Similar yield increases were obtained from all N sources and rates (Table 6).

Long-term Fertility Trial in Irrigated Wetland Rice (1976)

In 1984 the trial was continued at nine sites, three each in China and Indonesia, two in the Philippines, and one in India. Another trial was commenced at anew site in India. An increase in mean grain yield as a result of applications of N, P, and K, individually or in combination, was observed (Table 7). Nitrogen alone gave consistently higher yields than P and K applied singly at all sites. Nitrogen combined with either P or K produced better yields than P and K combined. At all sites, addition of NPK resulted in the highest mean yield compared to nutrients applied singly, or in any combination of two nutrients, except in

Table 5. Some physical and chemical characteristics of the soil from Caliraya, Laguna.

Characteristic	Soil layer (cm)	
	0-20	20 50
pH	4.4	4.1
Organic carbon (%)	3.29	2.75
Total N (%)	0.312	0.250
Exchangeable cations (meq/kg)		
Na	1.4	1.3
K	3.4	3.7
Mg	15.0	13.5
Ca	12.0	9.0
Al	62.4	67.2
CEC (meq/kg)	219	209
Available P (ppm)		
Bray	6.7	6.1
Olsen	1.30	0.64
Available Zn (ppm)	1.9	1.5
Texture	Clay	Clay

Soil classification: Orthoxic Paleuhumult Clayey, halloysitic, isohyperthermic

Table 6. Effect of PU, ammonium sulfate, sulfur-coated urea, and dicyandiamide on rice yield (First international trial on nitrogen fertilizer efficiency in rainfed upland rice, Caliraya, Laguna, Philippines, 1984).

N source [a]	N rate (kg/ha)	Application method	Grain yield [b] (kg/ha)
Check	0	-	991 a
PU	40	Basal, surface broadcast	1 112 a
PU	40	Recommended split [c]	1 068 a
PU + 10% DCD	40	Basal, broadcast & incorporated	1 110 a
PU + 10% DCD	40	Basal, surface broadcast	1 312 a
PU	40	Farmers' split [d]	1 213 a
AS	40	Recommended split	940 a
AS + 10% DCD	40	Basal, broadcast & incorporated	900 a
AS + 10% DCD	40	Basal, surface broadcast	1 056 a
SCU (forestry grade)	40	Basal, broadcast & incorporated	1 142a
PU	80	Recommended split	1 042 a
AS	80	Recommended split	1 265 a

[a] PU = prilled urea, DCD = dicyandiamide, SCU = sulfur-coated urea, AS = ammonium sulfate. [b] Separation of means by Duncan's multiple range test at the 5% level. [c] 3/8 N 10 days after rice emergence (DARE), 3/8 N 30 DARE, and 1/4 N at panicle initiation (PI). [d] 1/3 N DARE, 2/3 N at PI.

Table 7. Effect of nutrient additions on grain yield of rice (First international long-term fertility trial in irrigated wetland rice, 1976-84).

Treatment	Grain yield (t/ha) [a]									
	China			India		Indonesia			Philippines	
	Chengpu (1)	Guan-shan Ping (4)	Shipai (4)	Dilip Nagar (2)	Pant-lagar (1)	Lanrang (11)	Maros (9)	Suka-mandi (5)	Luisiana (23)	Tanay (21)
Control	5.5	3.6	3.6	1.3	4.1	2.5	3.3	3.1	2.8	2.9
N	6.1	4.7	5.0	2.7	7.4	3.2	4.8	4.3	3.9	4.2
P	5.4	3.8	3.7	1.5	4.3	3.2	3.7	3.4	3.1	3.3
K	5.4	4.0	3.8	1.3	4.5	2.9	3.4	3.0	2.9	2.9
NP	5.9	4.6	5.1	2.7	7.1	3.7	4.8	4.8	4.5	4.5
PK	5.8	4.1	3.8	1.5	4.2	2.8	3.5	3.3	3.2	3.2
NK	6.5	4.8	5.0	2.5	7.4	3.2	4.8	4.8	3.9	4.2
NPK	6.2	5.0	5.4	2.9.	7.5	3.9	4.9	5.5	5.0	4.8
NPK+Zn	-	5.1 [b]	-	3.2	7.6	3.2'	4.8	-	-	-

[a] Figures in parentheses after the sites indicate number of trials. [b] Average of two trials only. [c] Average of seven trials only.

Chengpu where addition of N and K produced 0.3 t/ ha more than NPK. Yield responses were evident when N was present in the applied fertilizer. At sites where Zn deficiency was suspected, the addition of Zn did not give any significant yield advantage, and in fact at Lanrang and Maros it even decreased yields.

Comparison of Hand- and Machine-applied Nitrogen Fertilizer in Irrigated Wetland Rice (1983)

The objectives of this trial were to compare hand- and machine-applied PU and USG at a number of locations under varying environmental conditions, and to evaluate the yield, N uptake, and crop growth in relation to the nutrient-supplying capacity of the soil, floodwater composition, and environmental factors.

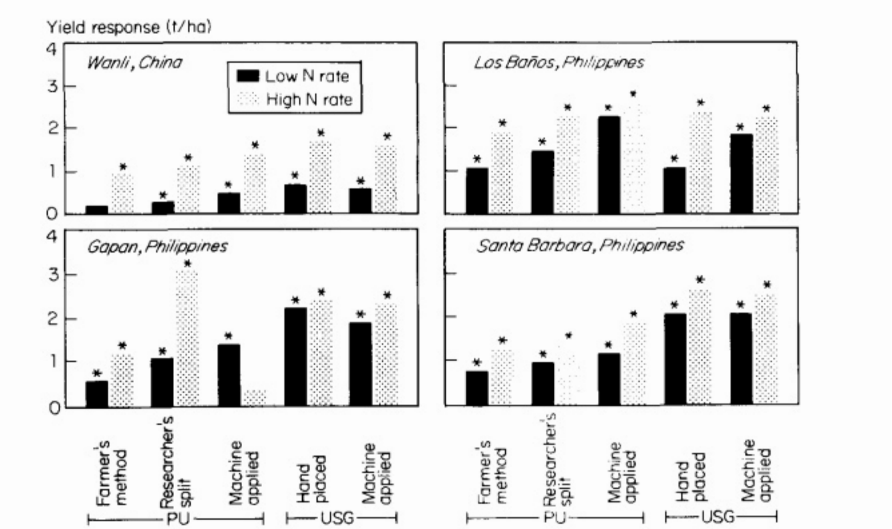
The mean response to applied N was significant at all four sites. Responses to PU and USG, hand- or machine-applied, were generally greater at the high rates of application than at the low rates (Fig. 11).

Four types of fertilizer applicator were tested: the oscillating plunger and spring auger machines were used to apply PU, and the press wedge and deep plunger to place USG. The oscillating plunger and press wedge were tested at Wanli, China, and the others were tested at Gapan, Los Baños, and Santa Barbara in the Philippines.

In Wanli any advantage of machine-applied PU and USG over standard BS PU and hand-placed USG was minimal, and at Gapan machine-placed USG was as effective as hand-placed USG at both rates of N. However, at Los Baños significant yield differences were obtained between machine- and hand-placed fertilizer at low rates of applied N. At Santa Barbara a greater yield response was obtained with PU when it was applied by machine than when applied by hand (Fig. 11). Hand-placed USG produced the highest yield at this location.

Fifth Trial on *Azolla* Use in Wetland Rice (1983)

The objectives of this trial were I) to compare the effects of *Azolla* and chemical fertilizer on the yield of rice grain, and 2) to compare *Azolla* as a source of N



11. Yield response of rice to prilled urea (PU) and urea supergranules (USG) applied by different methods at 2 N rates tested at 4 sites in 2 countries. (First International Trial on the Comparison of Hand and Machine Applied PU and USG, 1984.)

when applied before transplanting and incorporated, and when grown simultaneously with the rice crop.

Fifteen trials were conducted in 1983 and 1984 at 13 sites and, of these, only 11 trials reported the fresh weight of *Azolla* applied. No difference in grain yield was observed between treatments 3, 4, and 5, indicating that an application of 1.5 kg of fresh *Azolla/* m^2, either before or after planting, was equivalent to 30 kg urea N/ha (Table 8). Treatments 7 and 8 gave lower yields than treatment 6 because of the lower *Azolla* biomass in treatments 7 and 8. At eight sites where complete *Azolla* fresh weight data were collected, the average yield difference between treatments 6 and 7, and also between treatments 6 and 8, was 0.4 t/ha. The corresponding differences in fresh weights of *Azolla* between the different treatments were 0.9 and 1.0 kg/m^2.

Trial on the Integrated Use of Inorganic and Organic Fertilizers in Wetland Rice (1983)

This trial was formulated in response to a recommendation made during the 1982 symposium on Organic Matter and Rice. The following were the objectives:

- to evaluate the effectiveness of inorganic N fertilizer applied alone or in combination with *Azolla,* fresh straw, or leguminous green manure at different locations;
- to compare BS and DP urea with or without organic fertilizers;
- to evaluate yield data, N uptake, and plant growth in relation to soil and other environmental characteristics at the various locations; and
- to determine the long-term effect of integrated use of inorganic and organic fertilizers on the soil fertility status and physical properties of the soil.

So far, the results of trials conducted at seven sites have been received. Significant yield responses to inorganic fertilizer alone and to most combina-

Table 8. Response of wetland ria, to nitrogen fertilizer and Azolla applications (Fifth international trial on Azolla use in wetland rice 198884).

Treatments[a]	Average grain yield[b] (t/ha)	Average relative yields[c]
1 No N	2.72	100 (15)
2 30 kg N/ha	3.48	127 (15)
3 60 kg N/ha	4.10	144 (15)
4 30 kg N/ha + 1.5 kg Azolla/m^2 (BT)	4.11	153 (14)
5 30 kg N/ha + 1.5 kg Azolla/m^2 (AT)	3.97	146 (15)
6 Azolla BT + AT	3.97	146 (14)
7 Azolla BT +AT (no incorp.)	3.66	134 (13)
8 Azolla AT only	3.72	135 (15)
SE	0.12	7

[a] BT = before transplanting, AT = after transplanting. [b] Sites #15. 39, and 32 in 1983 are not Included. [c] Figures in parentheses are numbers of trials.

tions of inorganic fertilizer and the two N sources were obtained at the different sites; responses ranged from 0.6 to 4.2 t grain/ha (Table 9).

Additions of straw did not produce a significant yield increase when added with PU at Pantnagar, San Ildefonso, or Victoria, or when added with USG at San Ildefonso. Addition of *Azolla* and inorganic N also failed to produce a significant increase in yield at San Ildefonso when PU was used.

The results show that, in general, *Azolla* effectively replaced urea as a source of N for rice, and in some cases its use resulted in greater yields than when an equivalent amount of fertilizer N was used (Table 9).

Comparison of Phosphorus Sources for Irrigated Wetland Rice (1977)

Significant yield responses to applied P were obtained in the 1983 WS trial in Sitiung, and in the 1984 WS trial at Sukamandi (Table 10). Of the three sources of P tested, only less reactive rock phosphate produced significant yield increases at both sites; the positive response was obtained with 18 kg P/ ha at Sitiung, and with 35 and 53 kg P/ha at Sukamandi. The less reactive rock phosphate produced the best increases at Sukamandi with an average yield increase of 0.4 t/ha. At Sitiung the average yield increases from the three P sources were comparable.

Table 9. Yield response to combinations of inorganic and organic fertilizers (First international trial on the integrated use of organic and inorganic nitrogen fertilizers in irrigated wetland rice, 1984).

Source [a]	Rate (kg N/ha) [b]	Grain yield (t/ha) [c]							
		India			Philippines				
		Coimbatore		Pant-nagar (1)	Los Baños (1)	Pototan		San Ildefonso (1)	Victoria (1)
		Site 1 (1)[c]	Site 2[d] (1)			(1)	(2)		
PU	58	0.8	0.9	2.4	2.7	2.6	0.6	1.1	0.9
PU+Azolla	58	1.7	1.0	3.4	2.8	2.6	1.2	0.2 (ns)	1.0
PU+fresh straw	58	2.3	0.9	1.3 (ns)	2.0	3.1	2.5	0.3 (ns)	0.5 (ns)
PU	87	1.5	3.1	3.0	2.9	3.4	2.4	1.1	1.7
PU+Azolla	87	2.5	3.1	3.7	3.1	3.8	3.1	1.0	1.3
PU+fresh straw	87	2.0	3.1	3.1	2.9	3.9	3.2	1.0	1.2
USG	58	2.2	2.0	2.8	2.7	2.8	1.1	0.8	1.4
USG+Azolla	58	2.1	2.1	3.9	2.4	2.4	2.5	1.4	1.3
USG+fresh straw	58	2.0	2.1	1.8	2.1	3.2	3.0	0.7 (ns)	0.7
USG	87	2.2	4.2	3.8	3.6	3.4	3.6	1.5	2.1
USG+Azolla	87	2.6	4.1	4.0	3.2	4.2	3.7	1.7	1.8
USG+fresh straw	87	3.0	4.1	2.3	3.0	3.9	3.1	1.2	1.1
LSD (5%)		0.6	0.7	1.3	0.6	1.5	0.5	0.8	0.6

[a] PU = prilled urea, USG = urea supergranules. [b] Total applied; organic source fixed et 29 kg N/ha. = [c] Figures in parentheses after the sites are numbers of crops. ns = not significant at 5%. [d] Leucaena was used instead of straw.

Table 10. Grain yield response of flooded rice to different sources of phosphorus in four trials conducted at two new sites in Indonesia during 1983-84 cropping seasons (International trial on sources of phosphorus in flooded rice, 1977-84).

Source[a]	Rate of application (kg P/ha)	Grain yield (t/ha)			
		Sitiung 1983 WS	Sukamandi 1983 WS	Sukamandi 1983 DS	Sukamandi 1984 WS
Control	0	2.4	3.0	4.1	3.5
os P	9	2.6	3.2	3.8	3.4
	18	2.7	3.3	39	3.4
	26	2.7	3.4	4.2	3.4
HRP	9	2.7	3.2	4.0	3.4
	18	2.7	3.1	3.9	3.5
	26	2.5	3.2	3.9	3.4
LRP	18	2.8	3.2	3.9	3.7
	35	2.5	3.4	4.0	4.0
	53	2.6	3.2	3.6	39
LSD (5%)		0.4	ns	ns	0.3

[a] OSP = ordinary superphosphate, HRP = highly reactive rock phosphate, LRP = less reactive rock phosphate.

Phosphorus and Lime Interaction Trial in Acid Upland Rice Soils (1984)

In response to the growing need for an appropriate technology to increase productivity on problem soils, this trial was formulated to determine and evaluate the benefits of liming and P application on an acid upland rice soil.

Three P sources, viz., triple superphosphate (TSP), Christmas Island phosphate rock (CIPR), and fused magnesium phosphate (FMP) at various levels of P and lime were tested by IRRI's Agronomy Department on an acid (pH 4.1) upland soil in Caliraya, Laguna. In the absence of applied lime, only TSP at the highest rate of addition gave a significant yield increase over the control (Table 11). In the absence of lime, increased yields were obtained when TSP was applied at medium and high rates. No significant yield advantage was obtained from increased lime application at the same level of added P.

Identification and Evaluation of Rice Cultivars Tolerant of Acid Conditions (1982)

This trial was initiated with the main objective of evaluating and identifying rice cultivars tolerant of acid soil conditions. Sixty varieties and lines of rice originating from the breeding programs of Bangladesh, Colombia, India, Indonesia, Liberia, Malaysia, Nigeria, Philippines, Sri Lanka, Thailand, and IRRI were tested at nine sites in eight countries. The soil pH at these sites ranged from 2.5 to 5.8.

Of the 60 cultivars, only two (CR 261-7039-236 and IR5741-73-2-3) were rated tolerant of acid lowland conditions at the two levels of applied P (0 and 26 kg P/ha). Eleven of the cultivars received high ratings for phenotypic

Table 11. Effect of phosphorus source and addition of lime on rice production on an acid upland soil at Caliraya, Laguna (First international trial on the interaction of phosphorus and lime in acid upland soils under rainfed conditions. 1984).

P source	P rate (kg/ha)	Lime rate (t/ha)	Grain yield[b] (kg/ha)
Check	0	0	868 f
TSP	9	0	811 f
TSP	18	0	1 092 cdef
TSP	35	0	1273 bcde
-	0	0.75	1 161 cdef
TSP	9	0.75	1 108 cdef
TSP	18	0.75	1 476 abc
TSP	35	0.75	1 644 a
-	0	1.50	950 ef
TSP	9	1.50	1 163 cdef
TSP	18	1.50	1 397 abcd
TSP	35	1.50	1 566 ab
CIPR	18	0	1048 def
CIPR	35	0	1 081 def
CIPR	53	0	1 026 def
FMP	18	0	1 183 def
CV (%)			20

[a] TSP = triple superphosphate, CIPR = Christmas Island phosphate rock, FMP = fused magnesium phosphate. [b] Separation of means by Duncan's multiple range test at the 5% level.

acceptability in the absence of applied P, compared with 21 when 26 kg P/ha was applied.

The average grain yield from all sites ranged from 1.6 (IR13149-43-2) to 4.3 t/ha (IR26) in the absence of applied P, and from 1.9 (IR19743-25-2-2) to 5.6 t/ha (IR3941-25-1) when P was applied.

Country Report: **Bangladesh**

R. B. Diamond

Fertilizer N efficiency for rice is low; in general, only 25 to 35% of applied N is taken up by rice plants. Low efficiencies are principally due to loss of N via ammonia volatilization and denitrification. Fertilizer management practices can influence the magnitude of these loss processes and thus influence fertilizer N uptake and efficiency. The principal objectives of the work described in this report are to determine the efficiency of urea placement into soil relative to split applications of broadcast urea for rice, to test and modify prototype applicators for placement of fertilizer into soil, and to provide training for specialists in fertilizer efficiency research.

RESULTS

Effect of application method

A total of 27 experiments with multiple rates of N were conducted during 1983 boro through 1984 aman seasons to compare the relative efficiencies of the different methods of application. Five on-farm trials were conducted at Cropping Systems Research sites, each consisting of between four and six dispersed replications.

The yield responses and net returns from applications of urea at the rate of 60 kg N/ha are shown by season in Table 1. The bases for the economic estimates are shown in Table 2.

On average, three split applications of broadcast urea at 60 kg N/ ha gave equivalent yield responses to two split applications of urea in each boro, aus, and aman season. Deep placement of urea rather than three split applications resulted in a 45% greater yield response during boro, 28% greater response during aus, and an equivalent yield response during the aman season. In 80 to 90% of the experiments during the boro and aus seasons, deep placement of urea gave a much greater yield response than three split broadcast applications.

The average net returns (value of increased yield over cost of urea and its application) for three split broadcast applications were 5 592, 3 675, and 191 taka/ ha during the boro, aus, and aman seasons (Table 1). However, the average net returns were 42 and 27% greater during the boro and aus seasons when urea was deep placed than when it was surface applied by split application methods.

Outreach Division, International Fertilizer Development Center, Muscle Shoals, Alabama 35660, USA.

Table 1. Yield increases and net returns as affected by method of application of urea (60 kg N/ha).[a]

Location[b] /season	Yield increase (kg/ha)			Net returns (taka/ha)		
	s 83	SB2	BDP	S03	SB2	BDP
IS/83/boro	1 373	1 495	1 908	5 500	6 072	7 705
JS/83/boro	981	1 266	1 621	3 713	5 026	6 394
JY/83/boro	1 179	1 775	1817	4 615	7 348	7 291
MY/83/boro	1 943	1 406	2 645	8 098	5 664	11 066
MD/83/boro	1415	1 378	2 407	5 691	5 538	9 980
JM/83/boro	1 302	1 002	1 384	5 179	3 822	5 315
JY/84/boro	810	1 268	1 476	2 934	5 060	5 934
MY/a4/boro	2 096	2 171	2 733	8 796	9 175	11 665
MD/84/boro	1438	1 192	2 159	5 799	4 714	9 049
Mean	1 393	1 439	2 017	5 592	5 824	8 267
IS/83/aus	1 472	1414	1317	6 493	6 224	5 495
JS/83/aus	503	378	720	1716	1115	2 552
JY/83/aus	1 431	1 585	1 975	6 292	7 067	8 739
MY/83/aus	703	1 030	1 196	2 703	4 332	4 900
MD/83/aus	392	550	546	1 169	1 964	1 694
Mean	900	991	1 151	3 675	4 140	4 676
IS/83/aman	859	775	685	3 470	3 071	2 379
JS/83/aman	656	360	716	2 472	1 029	2 532
JY/83/aman	518	467	738	1 789	1 552	2 639
BG/83/aman	1 365	712	697	5 954	2 760	2 439
RG/83/aman	1 246	1217	1 139	5 380	5 254	4 615
MD/83/aman	502	786	972	1710	3 126	3 792
JM/83/aman	470	700	528	1 553	2 701	1 604
Mean	802	717	782	3 191	2 785	2 857

[a] SB3 = three split broadcast applications (including basal application), SB2 = two split b broadcast applications (no basal application), BDP = All urea deep placed as basal application. [b] IS = Ishurdi, JS = Jessore, JY = Joydebpur, MY = Mymensingh, MD = Madhupur, JM = Jamalpur, BG = Bogra, and RG = Rangpur.

Table 2. Costs of production and income from sale of rice used to calculate net returns from fertilizer applications (obtained from farmer surveys).

Factor	Value
Boro rice (taka/kg)	4.563
Aus/aman rice (taka/kg)	493[a]
Prilled urea for split broadcast (taka/kg N)	12.06[b]
Urea supergranule for basal deep placement (taka/kg N)	13.26[c]
Labor rate (taka/day)	25.00
Labor for one broadcast application (days/ha)	0.50
Labor for deep placement (days/ha)	8.00

[a] Based on 1984 seasonal prices. [b] Based on March 1985 farm market prices plus 15% interest. [c] Based on urea price plus 10% for producing large particles.

Generally, the optimum economic rate of N (i.e., the rate giving the greatest net return per unit of land) was >150 kg/ ha, >120 kg/ ha, and 90-120 kg/ ha during boro, aus, and aman seasons.

Applicator testing

Prototype applicators for placing urea into soil were obtained from the International Rice Research Institute (IRRI), Los Baños, Philippines, and the Fujian Academy of Agricultural Sciences, Fuzhou, China. After preliminary testing, some applicators were slightly modified (Table 3). Evaluation of the performance of the applicators in approximately 150-m^2 plots revealed that all of the continuous feed applicators (deep plunger is intermittently fed) had the capacity to fertilize 0.8 ha/h and were relatively easy to operate. The cupfeed applicators (China cupfeed and IRRI press wedge) provided the best metering accuracy. However, the spring auger and deep plunger applicators resulted in best placement and coverage of the urea (lowest percentage of applied N in the floodwater 24 h after application). The variation in floodwater N concentration where urea was deep placed by hand suggests that proper placement and coverage are important considerations when using this method. The degree of precision achieved when hand placing urea may be one variable which has caused differences in relative efficiencies between methods of application.

Farmer surveys

Surveys were conducted at three Cropping Systems Research sites to assess the fertilization techniques used by farmers. The data were used in the design of on-farm N management trials. All farmers use fertilizers and a high percentage of them use organic manure (Table 4). Of the three major nutrients, the amounts applied decrease in the order N, P, K. At Ishurdi in the boro season, farmers generally apply basal N plus two topdressings of N. At Bogra during the aman

Table 3. Description of fertilizer applicators used in the field trials at the Bangladesh Rice Research Institute in 1984.

Applicator	Source	Type of urea [a]	Capacity (ha/h)	Metering accuracy		Base of operation	Applied N in floodwater [c] (%)
				%[b]	% between hoppers		
Press wedged	IRRI	USG	0.1 5	115	±1	Easy	20
Spring auger [e]	IRRI	Prill	0.17	32-100	±2	Easy	9
Deep plunger	IRRI	USG	0.04	76-81	±12	Moderate	12
Cup feed [f]	China	Briquette	0.13	96-110	±1	Easy	23
Inclined plate	China	Briquette	0.18	-	-	Easy	27
Hand placed		USG	0.029	-	-	-	7-26

[a] USG = urea supergranules. [b] Metered/intended x 100. Range indicates more than one test. [c] Twenty-four hours after application. [d] Furrow openers were modified to prevent soil from logging discharge tube. [e] Agitators were removed because of binding and bending problems. [f] Agitator was disconnacted to reduce required pushing force. [g] Determined from separate test using three plots, each 0.04 he.

Table 4. Fertilization practices of farmers at three Cropping Systems Research sites, Bangladesh, 1984.

	Boro-Ishurdi		T. aman-Bogra		T. aman-Trisal	
	% farmers	kg/ha[a]	% farmers	kg/ha[a]	% farmers	kg/ha[a]
Basal fertilizer						
Manure	70	7 910	97	5 750	100	10 315
N	90	26	97	18	37	15
P	97	26	97	18	77	14
K	93	32	37	22	67	17
S	-	-	0	0	0	-
Zn	-	-	0	0	3	2
Number of N topdressings						
1	97	23	93	25	100	28
2	97	20	13	17	80	62
3	10	16	0	-	10	71
Total N	100	67	100	43	100	90

[a] Average rate used.

season, most farmers apply basal N with one topdressing, while most farmers at Trisal omit the basal application but make two topdressings. At Bogra and Ishurdi most farmers reported that floodwater was more than 5 cm deep at the time of urea application, while at Trisal the reported water depth was less than 5 cm. At all locations weeding is carried out before topdressing and no mixing of urea with the soil is attempted. During transplanted aman, essentially all farmers randomly transplant, and 50% transplant part of the crop in line at Trisal.

CONCLUSIONS

Yield increases with deep placed urea were 45% greater than those obtained with broadcast urea during the boro season and 28% greater during the aus season. Increases in estimated net cash returns to farmers were of similar magnitudes to the yield increases. The results obtained during the aman season were inconsistent and further study is needed. Pending verification in farmers' fields, it appears that there is a great potential to improve urea use efficiency for rice in Bangladesh. Simple hand-pushed applicators for deep placement of prilled urea may be a viable alternative to deep placement of large particles by hand.

Country Report: **China**

***Lin Bao* [a] *and Liu Chung-chu* [b]**

The first trial in China within the International Network on Soil Fertility and Fertilizer Evaluation for Rice was conducted at Fuzhou in 1979. Since that time 29 trials have been conducted in six provinces. Sites have been selected in both the single cropping region around Beijing and the double cropping region of South China (Fig. 1). In the double cropping rice region of China, early rice is grown from April to July, and late rice from July to October (November in some places). Based on the precipitation rates we consider the early season as the wet season and the late season as the dry season.

In this report we summarize the results of the Fifth Nitrogen Fertilizer Efficiency Trial in Irrigated Wetland Rice 1981-1984, the Trial Comparing Hand- and Machine-Applied Nitrogen .Fertilizer in Irrigated Wetland Rice (1983), and the Long-Term Fertility Trial in Irrigated Wetland Rice (1976).

Table 1 gives the location of the sites, times of seeding, transplanting, and harvesting, and the variety used in each of the 21 trials discussed here. Table 2 presents the analytical data for the soils at five of the experimental sites.

RESULTS AND DISCUSSION

Nitrogen efficiency trials

All grain yield data from ten trials on N efficiency showed a significant response ($P<0.01$) to N. The yield from the control plots ranged from 3.53 to 5.91 t/ha with a mean of 4.90 t/ ha. The yield response ranged from 0.68 to 1.96 t/ ha with a mean of 1.36 t/ha.

The results of nine wet season trials showed that deep placed urea supergranules (USG) produced the highest yield when compared with broadcast sulfur-coated urea (SCU) and prilled urea (PU), and this occurred for all application rates (Fig. 2). The yield from SCU was greater than that from the best split application of PU at all rates of N. Figure 2 also shows that the maximum application rate tested (116 kg N/ ha) was not sufficiently high to infer an optimal application rate.

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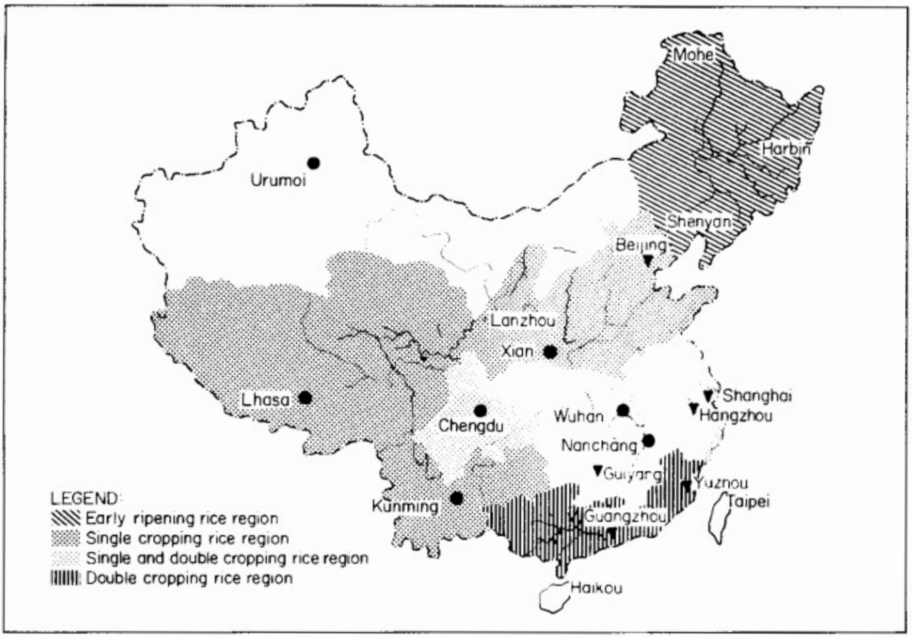
[a] Chemical and Fertilizer Laboratory, Soil and Fertilizer Research Institute, Chinese Academy of Agricultural Sciences, Beijing.China.

Soil and Fertilizer Institute, Fujian Academy of Agricultural Sciences, Fuzhou, China.



1. Location of INSFFER experimental sites in China.

Table 1. Basic information for INSFFER trials in China.

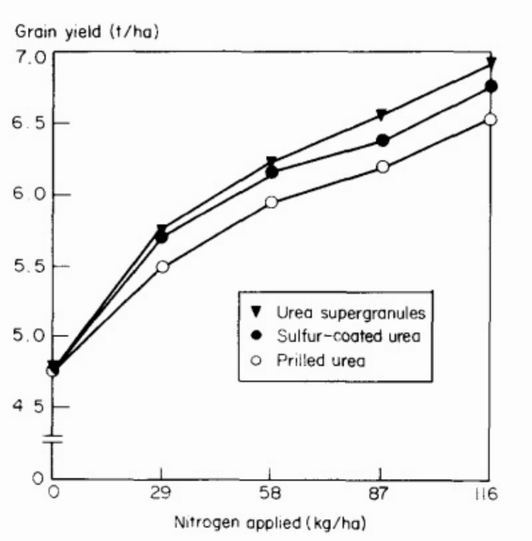
Trial no.	Trial type[a]	Experimental site	Dates			Year	Season	Test variety
			Seeded	Trans-planted	Har-vested			
1	a	Wanli[b]	10 Jul	6 Aug	5 Nov	1981	late	Min zao 6
2	a	Wanli	21 Mar	6 Apr	22 Jul	1982	early	Min zao 6
3	a	Wanli	14 Jul	31 Jul	31 Oct	1982	late	Min zao 6
4	a	Wanli	28 Mar	24 Apr	13 Jul	1983	early	Min zao 6
5	a	Wanli	10 Jul	29 Jul	30 Oct	1984	early	Min zao 6
6	a	Xian Lian[c]	20 Mar	2 May	27 Jul	1983	early	Guang Lu Chen
7	a	Xian Lian	20 Mar	2 May	28 Jul	1984	early	Ai 4
8	a	Xian Lian	20 Jun	2 Aug	23 Nov	1984	late	Ai Chen 804
9	a	Chou Jia Diand	10 May	11 Jun	10 Oct	1983		Nong Ken 2
10	a	Dongzhaocun[d]	15 Apr	6 Jun	5 Oct	1984		Zhong Hua 8
11	b	Wanli	29 Jun	28 Jul	8 Nov	1984	late	Min zao 6
12	C	Guanshanpin[e]		2 May	15 Jul	1983	early	Xianaizao 9
13	C	Guanshanping		6 Jul	16 Oct	1983	late	V 6
14	C	Guanshanping		6 May	18 Jul	1984	early	Zhu Xi 26
15	C	Guanshanping		20 Jul	26 Oct	1984	late	Shuang Gui
16	C	Shipai[f]	3 Mar	13 Apr	16 Jul	1983	early	Shuang Gui 1
17	C	Shipai	30 Jun	27 Jul	18 Oct	1983	late	Qing Er Ai
18	C	Shipai	2 Mar	9 Apr	18 Jul	1984	early	Shuang Gui 1
19	C	Shipai	6 Jul	8 Aug	7 Nov	1984	late	Shuang Gui 1
20	C	Nangang	25 May	24 Jun	30 Oct	1983		Shugeng
21	C	Nangang	21 May	21 Jun	25 Oct	1984		Shugeng

[a] a = Fifth Nitrogen Fertilizer Trial in Irrigated Wetland Rice (1981-84). b = Comparison of Hand- and Machine-Applied Nitrogen Fertilizers in Irrigated Wetland Rice (1983), c = Long Term Fertility Trial in Irrigated Wetland Rice (1976). [b] Fujian Province. [c] Fuyang County, Zhejiang Province. [d] Seijing. [e] Qiyang County, Hunan Province. [f] Guangzhou, Guangdong Province. [g] Qinpu County, Shanghai.

Table 2. Characteristics of the soils at the experimental siter.[a]

	Wanli (1-5,11)	Xian Lian (6-8)	Guanshan-ping (12-15)	Shipai (16-19)	Nangang (20-21)
Experimental site					
pH (1:1)	6.5	6.1	6.3	6.2	7.1
Organic matter (%)	3.9	2.3	1.5	19	3.5
Total N (%)	0.27	0.23	0.09	0.09	0.20
Available p[b] (ppm)	64	38	a	9	16
Exchangeable K (ppm)	56		101	60	128
CEC (meq/kg)	158	92		66	218
Soil texture	Clay	Light clay	Clay	Clay loam	Clay loam
Percolation rate (mm/day)	1.2				1.5

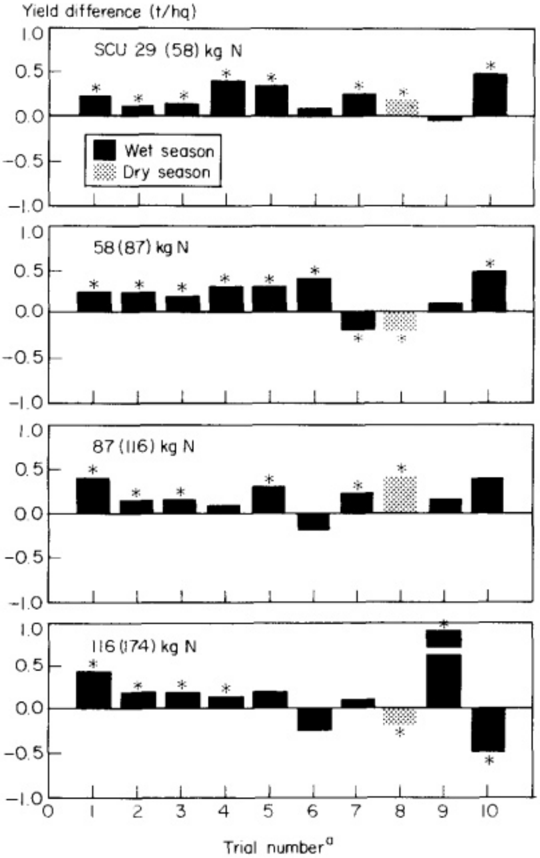
[a] Figures in parentheses below the experimental sites are trial numbers. [b]Olsen's method.



2. Response of rice to urea supergranules, sulfur-coated urea, and prilled urea at 5 rates of application. Data are averages of 9 wet season trials in 1981-84.

Comparison of sulfur-coated and prilled urea. The yield differences between SCU and the best split application of PU are shown in Figure 3. There was one site (trial nos. 1-5, Wanli) where the yield differences between SCU and the best split application of PU were significant at all rates of N in 1981 (late season) and 1982 (early and late seasons). In 1983 and 1984 the yield differences at three levels of applied N were significant. At another site (Xian Lian), three trials, conducted in 1983 and 1984, did not show any advantage of SCU over split broadcast urea. For instance, in the late season of 1983 two rates of SCU gave higher yields than PU, whereas another two rates of SCU gave lower yields. At the third site (Shenyi and Daxin, Beijing) differences between SCU and PU were variable in both 1983 and 1984.

Comparison of deep placed urea supergranules and broadcast prilled urea. Positive effects of deep placement were observed in the five trials conducted at Wanli. Yield differences between deep placed USG and the best split application



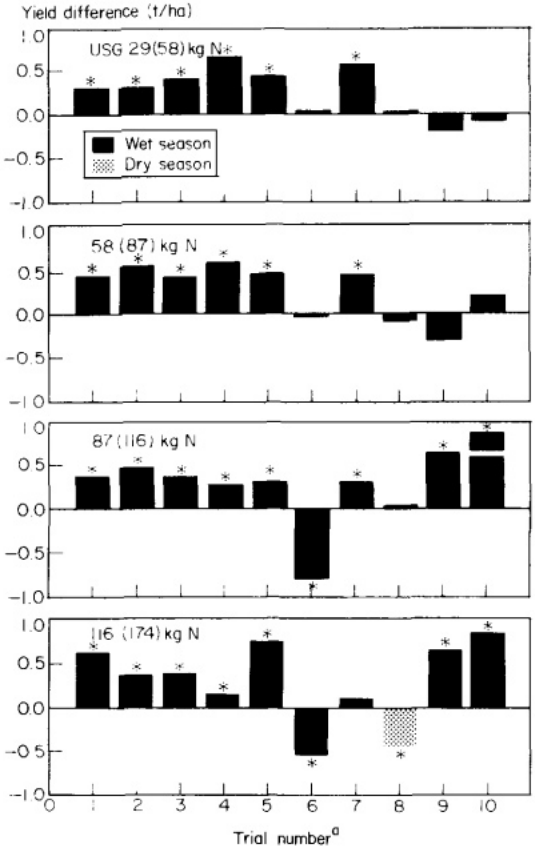
3. Differences in grain yield due to applications of broadcast and incorporated SCU and best split PU. [a] See Table 1.

of urea were significant in all these five trials at all N rates (Fig. 4). At another site, Xian Lian, trial 7 produced significant yield differences between USG and PU at three rates of application. Trials 6 and 8 show a significantly lower yield for USG compared with PU at high levels of application. On the other hand, at Shenyi and Daxin, Beijing, USG produced a significantly higher yield than PU at high N rates.

Hand- and machine-applied urea

Trials were conducted comparing the farmers' method, the researchers' split, and machine application of PU. Additionally, a comparison between hand-placed and machine-placed USG was carried out. The yield response ranged from 0.22 to 1.56 t/ha (LSD = 0.10 at 5%).

Maximum yields were observed for hand-placed USG (5.79 for high and 4.75 for low rates of N). Yields were 5.65 (4.68) t/ha for high (low) rates of machine-applied USG; 5.52 (4.57) t/ ha for machine-applied PU; 5.19 (4.40) t/ ha for PU applied as researchers' split; and 4.96 (4.3 1) t/ ha for PU applied using the farmers' method. The control yielded 4.09 t/ ha.



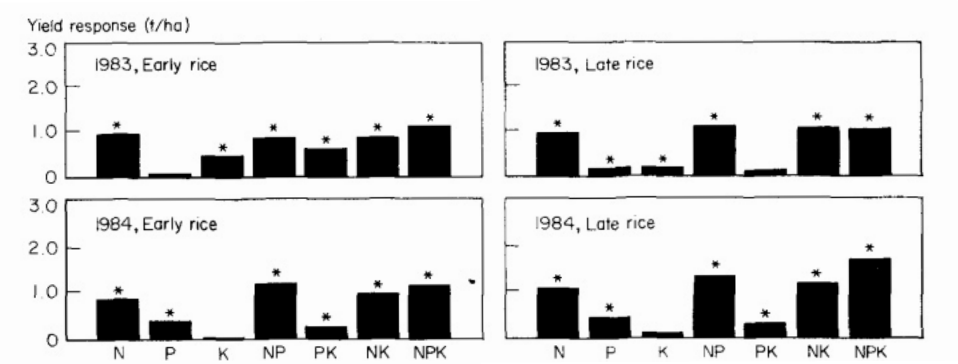
4. Differences in grain yield due to application of deep placed USG and best split PU. Data from 1981-84. ^a See Table I.

Deep placement of N fertilizer has been studied and practiced in China for more than 10 years. Initially, briquettes and granules were produced from N fertilizers, sometimes incorporating mud or other materials. At present we advocate deep placement of the original fertilizer materials rather than producing balls or granules, since deep placement obviously increases the efficiency of N fertilizer, regardless of whether it is granulated or not.

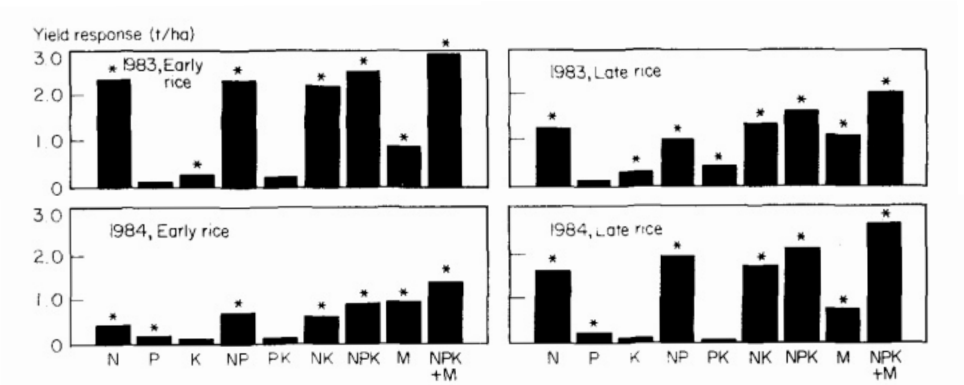
Long-term fertility trials

The INSFFER long-term fertility trials were conducted on three experimental sites; yield differences are illustrated in Figures 5, 6, and 7. It is apparent from the results of two years of experiments (four crops at two sites and two crops at one site) that rice responded to N applications in all trials. The effect of P and K, or PK combined, on yield was generally very low. The effect of applying NP or NK on increasing rice yield was almost the same as applying N alone.

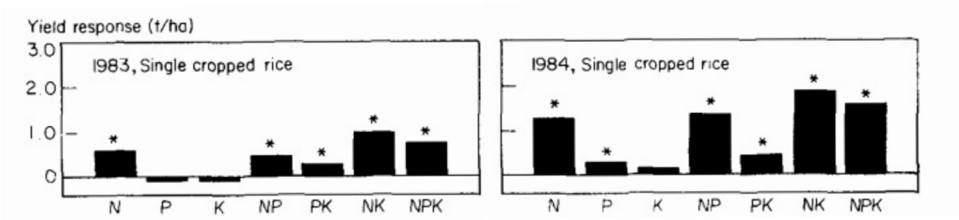
The results of other long-term fertility trials in our national program (Fig. 8) were somewhat different from the above mentioned three trials. The response to N was high, but the responses to K, and sometimes P, were also high.



5. Yield response to applications of nitrogen, phosphorus, and potassium in long-term trials at Guanshanping.



6. Grain yield response to applied nitrogen, phosphorus, and potassium in long-term trials at Shipai. M = manure.

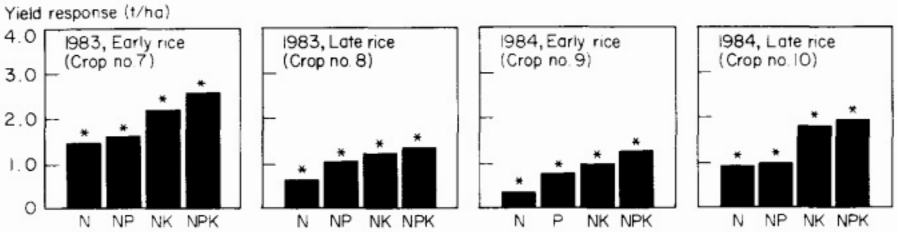


7. Grain yield response to applied nitrogen, phosphorus, and potassium in long-term trials at Nangang.

These results were mainly obtained in farmers' fields and not on experimental stations.

CONCLUSIONS

The response to N in all N efficiency trials was significant. Urea supergranules deep placed and SCU broadcast and incorporated generally produced higher efficiencies than PU best split, but consistent results were obtained at only one



8. Response in yield of rice grain to applied nitrogen, phosphorus, and potassium in long-term trials at Huiyang. Guangdong Province.

site for four years (five crops). At the other two sites, results were quite variable. Increasing the rate of application of N significantly increased grain yield. The rates of N applied in the N efficiency trials seem too low for most rice growing regions of China.

In the long-term fertility trials, N alone gave a significant response; responses to P and K alone, or NP combined, were very low. This is probably due to the high soil fertility of the experimental plots.

The number of experimental sites needs to be increased, and the importance of site characterization and economic evaluation of different forms of N fertilizer and methods of application should be emphasized.

Country Report: **Indonesia**

A.M. Fagi[a], H. Taslim[a], and M. Sudjadi[b]

Indonesia's rice production has more than doubled in the last 16 years to an estimated 25.5 million t of milled grain in 1984. Almost all rice production gains since 1969 have come from the improvement of rice technology through research, fast dissemination of research results, and creation of a favorable rice economy. However, as rice production has increased, so has per capita consumption of rice, indicating that Indonesia will need more rice in the years to come to keep pace with population growth.

During the last 16 years, the wide adoption of modern rice varieties has increased fertilizer consumption. This was partly due to a high fertilizer subsidy, through which a favorable rice-to-fertilizer price ratio was created. Any change in government policy affecting this ratio may also affect fertilizer use. This paper discusses three aspects, viz., 1) the major factors affecting rice production, 2) development of the fertilizer package, and 3) alternatives to farm level fertilizer management for higher efficiency.

FACTORS AFFECTING RICE PRODUCTION

From 1969 to the present, the Government has invested considerably in irrigation rehabilitation and development. However, increases in the harvested area of rice contributed only 25% of the 0.75 million t per year growth in rice production for the period from 1972 to 1981, while the other 75% was due to an increase in yield (7). For the same period, this yield increase can be attributed to the use of modern rice technology.

The use of modern rice varieties has been accelerated and fertilizers have been made available to farmers through an intensification program. In 1983, modern rice varieties covered 83% of the wetland rice area. At present, Indonesia's fertilizer plants produce a total of 4.4 million t of urea, ammonium sulfate, and triple superphosphate (6). The rice-to-fertilizer price ratio obtained has made it profitable for farmers to apply 150-200 kg urea/ ha. Table 1 shows that irrigation, rice varieties, and fertilizers contributed 16%, 5%, and 4%,

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[a] Sukamandi Research Institute for Crops, Sukamandi. West Java, Indonesia.
[b] Centre for Soil Research, Bogor, West Java, Indonesia.

Table 1. Contribution of major inputs to average annual rice production growth from 1972 to 1981 (17).

Rice growing region	X of inputs			
	Irrigation (I)	Variety (V)	Fertilizer (F)	All inputs (IxVxF)
Java	5	9	24	62
Outer islands	27	0	0	73
Indonesia	16	5	4	75

respectively, to annual rice production growth (7). Thus, irrigation water availability, use of modern rice varieties, and adequate fertilizer application are interdependent. It is unlikely that farmers would have used modern rice varieties with high levels of fertilizers, especially urea, without the assurance of irrigation water.

To accelerate the application of modern rice technology, the extension was changed from the 'oil fleck' approach to the farmers' group approach (15). A progressive farmer is a close partner of the extension worker, who voluntarily leads his group.

In 1978, an intensification contest was initiated; farmers formed organized groups within an area of 25-90 ha to manage their fields. They grew modern rice varieties with adequate fertilizers, if necessary with extra inputs, and applied integrated pest and irrigation water management. With better farm management, rice yields in these areas were higher than those in other areas; the highest yield of unhusked wet rice reported was 21.5 t/ha in Padang Pariaman, West Sumatra, in the 1981-82 wet season (Table 2).

FERTILIZER PACKAGES

Research on soil fertility and fertilizers for rice commenced at the beginning of this century with the establishment of the Central Research Institute for Agriculture (CRIA), Bogor, in 1905. In the early days, only N fertilizer was evaluated, at maximum rates of 20 to 40 kg N/ha. It was assumed that other nutrients, particularly K, were adequately supplied by irrigation water (2,4).

From 1957 to 1965, through the Self-supporting Food Crops (SSBM) program, 700 field trials were conducted in 2 100 villages on Java (a set of treatments was replicated three times, and each replication was located in a village). Several combinations of N, P, or K were tested using the improved local varieties Sigadis or Bengawan.

The results of the 1957-1960 trials showed that these varieties did not respond to application of N; a N application at 20 kg/ ha was adequate to get maximum yields. Phosphorus was more effective when applied with N (Table 3). The same trends were observed from the 1961-1965 trials (Table 4). These trials also suggested that improved local rices produced 3-4 t/ha with good farm management and favorable environmental conditions.

Table 2. Rice yields recorded from a 1981-82 rice production contest.

Province	Name of farmers' group	Farm size (ha)	Variety used	Wet grain yield (t/ha)	
				Lowest	Highest
West Java	Dewi Sri	92	Cisadane	6.9	10.7
Central Java	Bina Karya	40	Cisadane	12.5	18.8
East Java	Sejahtera	26	IR54	12.2	17.9
Bali	Jembrana	36	IR36	13.0	17.4
W. Nusatenggara	Setia Tani	26	IR36	10.0	20.3
Aceh	Sentosa	89	IR32	11.2	16.4
N. Sumatra	Dharma Karya	32	IR42	9.8	16.4
W. Sumatra	Kampyng Sabalah	59	IR42	9.1	21.5
Bengkulu	Karya Baru	33	IR38	10.0	20.3
S. Sumatra	Giat Tani	66	IR36	5.1	9.7
Lampung	Sejahtera	33	IR36	11.2	14.1
S. Kalimantan	Sumber Rejeki	25	IR50	5.4	9.7
C. Sulawesi	Harapan Java	43	IR42	7.3	14.0
N. Sulawesi	Masakini	31	IR38	11.8	17.4

Table 3. Grain yield of improved traiditional rice variety Bengawan or Sigadis as affected by fertilizer treatments (averages of villages and years; 6 300 field trials), 1957/58-1959/60.

Fertilizer treatment (kg/ha)			Grain yield (t/ha)		
N	P	K	West Java	Central Java	East Java
0	0	0	3.35	2.55	2.98
20	0	0	3.75	2.94	3.48
40	0	0	3.79	3.18	3.69
0	9	0	3.73	2.79	3.22
20	9	0	3.92	3.05	3.31
40	9	0	4.09	3.33	3.57
40	9	7	4.60	3.07	4.22

Table 4. Grain yield of improved traditional rice variety Bengawan or Sigadis as affected by fertilizer treatments (averages of villages and years; 8 400 field trials), 1961/62-1964/65.

Fertilizer treatment (kg/ha)			Grain yield (t/ha)		
N	P	K	West Java	Central Java	East Java
0	0	0	3.75	2.78	3.05
30	0	0	4.09	3.31	3.71
60	0	0	4.05	3.74	4.25
0	13	0	4.08	2.98	3.29
30	13	0	4.32	3.43	3.82
60	13	0	4.41	3.88	4.34
30	13	25	4.41	3.48	3.93
60	13	25	4.69	3.85	4.41

The introduction of 'miracle' rices IR5 and IR8 in 1963 has changed the concept of farm management from low-input, traditional rice farming to high-input, modern rice farming. Modern rice technology was developed from a series of experiments conducted at the experimental farms of Central Research Institute for Food Crops (CRIFC). The results of the experiments suggested that

- the response of modern rices to N, P, and K depended on the fertility of the soil; in general rice responded more to N applications in the dry season than in the wet season;
- planting, maximum tillering, and panicle initiation were critical stages for N application, while those for P and K were uncertain; and
- modern rice varieties grew and produced well when planted as 20- to 25-day-old seedlings with 20 x 20 cm or 25 x 25 cm spacings, utilizing two to three seedlings per hill; environmental conditions did not significantly influence those cultural techniques.

A complete set of modern rice cultivation techniques was verified in major rice growing regions in farmers' fields in the form of demonstration plots followed by 50-ha demonstration farms. Gradually, demonstration farms were expanded to become demonstration areas.

Thousands of field trials on the response of modern rice varieties to NPK fertilizers were conducted in rice growing areas throughout Indonesia, using a central composite rotatable design. Current fertilizer packages were developed from these trials and adapted to local conditions.

THE ROLE OF INSFFER TRIALS IN THE FUTURE OF RICE PRODUCTION IN INDONESIA

Up to the 1981/82 fiscal year, the Government had spent more than one billion US dollars on subsidies for fertilizers, chemicals, and agricultural products, out of which 60% was for fertilizer and chemicals. The price of one kg of urea was US$0.09 with the subsidy and US$0.18 without it.

Because of the low price of fertilizers and the influence of the rice production contests, most farmers applied urea at more than the recommended rates. In major rice growing districts (Banyuwangi and Magetan, East Java) most farmers surrounding the multilocation tests of urea supergranules applied 350 to 450 kg/ha. These rates were about double the recommended ones.

If the fertilizer subsidy is removed, which is likely to happen in the near future, farmers will have to pay US$ 62.50 for 350 kg of urea. They will have to spend more if they apply triple superphosphate (TSP) and KC1 in addition to urea. Although the floor price of unhusked rice was increased from US$ 0.12 in 1984 to US$ 0.80 in 1985, excessive rice production in the 1984-85 wet season caused a drop in the price of rice. Therefore, the future of rice production in Indonesia may face two critical situations.

- Farmers may reduce the amount of urea they apply or use an incomplete fertilizer formulation to decrease production costs, and as a result rice yields will decrease.

- Farmers will continue to apply large quantities of urea or complete fertilizer but the price of rice will increase to compensate for the higher production costs.

Consequently, alternative technologies for farm level fertilizer management have to be developed to improve the efficiency of fertilizer utilization. Trials conducted within the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) will assist in this development.

Long-term fertility trials

Starting from the 198 1 dry season, long-term fertility trials were conducted at the Sukamandi Experimental Station. The main soil type (Vertic Tropaquult) has low fertility, as indicated by an acidic soil reaction, medium cation exchange capacity (CEC), low organic matter content, and low available P and exchangeable K. IR36 was used as a test variety. The results presented in Table 5 (13) showed that applications of P and K were as effective as application of N in increasing yields in the first planting season (198 1 dry season). In the following seasons, rice responded to applications of P and K when applied with N and vice versa. Complete application of N, P, and K maintained rice yields at the highest level throughout the six planting seasons. The results also suggested that K was necessary in every dry season planting; P was needed after three crops. Under the dry conditions experienced during 1982-83, when irrigation water was limited, P, or K, or P and K applications permitted rice yields to exceed 3.5 t/ha.

The design of the long-term fertility trials conducted since the 1971 dry season was unrealistic in terms of the rates of P and K tested (3). The results of nine years of trials showed that N was needed in most soils. Out of 18 successful trials on Oxisols, 12 required additional P and K. Ten out of 15 trials on Inceptisols and 14 out of 17 trials on Vertisols required P and K.

Sources of phosphorus

The Gresik fertilizer plant has an annual production capacity of 975 000 t of TSP. Rock phosphate, the raw material for TSP, was imported from the Middle

Table 5. Long-term effects of N, P, and K on grain yield of IR36 at the Sukamandi Experimental Station (14).

Fertilizer rate (kg/ha)[a]			Grain yield (t/ha)[b]					
N	P	K	1981 DS	1981/82 WS	1982 DS	1982/83 WS	1983 DS	1983/84 WS
0	0	0	3.1 c	3.0 d	1.9 c	4.7 c	2.6 d	3.3 d
90/120	0	0	3.9 b	4.0 c	2.8 b	5.6 b	4.0 bc	4.8 bc
0	18	0	3.9 b	3.5 cd	1.9 c	4.6 c	28 cd	3.9 d
0	0	33	4.2 b	2.5 e	1.6 c	4.2 c	2.3 d	3.3 d
901120	18	0	4.8 ab	4.7 b	38 a	6.1 b	4.8 a	5.9 a
0	18	33	4.9 a	2.9 de	1.9 c	4.9 c	2.7 cd	4.0 cd
901120	0	33	4.9 a	4.9 ab	3.8 a	6.2 b	4.3 bc	48 bc
901120	18	33	5.1 a	5.3 a	4.0 a	7.7 a	5.3 a	6.5 a

[a] Rates of N applied are 120 kg/ha in the dry season (DS) and 90 kg/ha in the wet season (WS).
[b] Means followed by common letter In a column are not significantly different et the 5% level,

East. Savings could be made if rock phosphate could be applied directly and be as effective as TSP.

Studies on the effect of several sources of P indicated that the relative effectiveness of rock phosphate was lower than that of TSP. Rock phosphate at 53 kg P/ha was as effective as TSP at 13 kg P/ha. There was no residual effect of rock phosphate at 53 kg P/ha, in contrast to that of TSP at high rates (5).

A recent study on sources of P at the Sukamandi Experimental Station indicated that Cirebon phosphate, which has a low P content (3%), was least effective in the 1982-83 wet season (14). It was as effective as TSP and Phosmax for the following planting season (Table 6). Unfortunately, data for the 1984 dry season cannot be reported because of serious rat damage of the rice crop. The residual effect of Cirebon phosphate cannot be assessed until all treatments are evaluated.

Nitrogen efficiency

Studies on N efficiency using sulfur-coated urea (SCU) started in the 1973 dry season on the Inceptisols at the Mojosari Experimental Station. The results showed that IR5 receiving SCU at 60 kg N/ha or prilled urea (PU) at 120 kg/ ha gave comparable yields (9).

In 1975, the International Rice Research Institute (IRRI) initiated an international collaborative study on N efficiency. Urea in mudballs, urea briquettes, and SCU were tested along with PU (best split and band placement) at low, medium, and high rates. The average results of nine experiments conducted during the 1975-1978 period showed that urea in mudballs, urea briquettes, and SCU at low rates were as effective as PU at higher rates (10).

After the development of urea supergranules (USG), experiments were conducted for several seasons at various locations using USG instead of mudballs. In general, deep placement and slow release formulations increased N

Table 6. Effects of three phosphorus sources at various rates on grain yield of IR36 at the Sukamandi Experimental Station (14).

Fertilizer	Rate (kg/ha)	Grain yield (t/ha)					
		1981/82 WS	1982 DS	1982/83 WS	1983 DS	1983/84[a] WS	1984/85 WS
	0	4.88 abcd	3.39 a	4.74 c	3.28 ab	5.13 b	5.46 b
TSP	9	5.24 abc	3.98 a	5.46 abc	2.58 c	5.29 ab	6.47 a
TSP	18	5.71 a	3.88 a	5.45 abc	2.98 bc	5.11 b	5.73 ab
TSP	27	5.52 ab	3.94 a	5.57 ab	3.30 ab	5.74 ab	5.80 ab
Phosmax	9	5.12 abcd	3.64 a	5.40 abc	3.43 ab	5.43 ab	6.09 ab
Phosmax	18	5.15 abcd	3.90 a	4.82 bc	3.30 ab	5.26 ab	5.73 ab
Phosmax	27	4.75 bcd	3.92 a	5.06 abc	3.60 ab	5.35 ab	5.90 ab
Cirebon phosphate	18	4.62 cd	3.86 a	5.31 abc	3.88 a	5.87 ab	6.08 ab
Cirebon phosphate	27	4.35 d	3.97 a	5.47 abc	3.78 a	6.00 a	6.12 ab
Cirebon phosphate	53	4.62 cd	3.94 a	5.67 a	3.08 bc	5.64 ab	6.31 a

[a] Data of the 1984 dry season are not presented because of serious rat damage. Means followed by a common letter In a column are not significantly different at the 5% level.

efficiency for rice. Both USG and SCU at medium rates (58 kg N/ha) were as effective as PU at 116 and 174 kg N/ha (11, 12, 13, 14).

Economic analysis (8) at four locations in 1980-81 and at two locations in 1981-82 suggested that 1) an increase in yield and/or a reduction in the amount of N required to obtain a specified yield was possible with USG and SCU, and 2) favorable economic returns were obtained from USG and SCU applications when both existing and economic prices on fertilizer and rice were resumed.

The results of the overall research on N efficiency formed a sound basis for the initiation of demonstration plots in the 1984 dry season. CRIFC, the Centre for Soil Research (CSR), Directorate of Food Crops Production, extension offices at provincial and district levels, and farmers participated in this affair. A set of treatments (58 kg N [USG], 87 kg N [urea/USG], 116 kg N [urea/ USG], and 174 kg N [urea]) was replicated four times and each application was placed in a separate village within a 10 000 ha extension unit. The results (Tables 7 and 8) showed that deep placement of USG at 58 kg N/ha gave a higher yield than broadcasting of PU (best split) at all levels. Farmers and extension workers were impressed with crop performance in the USG treatments, but they noted that 1) rice in the USG plots took longer to mature, and 2) USG took longer to apply than PU.

Table 7. Effects of urea supergranules (USG) and prilled urea (PU) at various nitrogen rates on grain yield of IR36 at four villages in Banyuwangi district, East Java, 1984 dry season.

Nitrogen rate (kg/ha)	Grain yield (t/ha)				Mean
	Setail	Genteng Kulon	Genteng Wetan	Kembi ritan	
58 USG	5.78	5.42	5.02	5.60	5.46
87 PU	5.33	4.92	3.67	4.92	4.71
87 USG	5.65	5.29	5.10	5.73	5.42
116 PU	5.65	4.79	2.63	4.24	4.32
116 USG	6.38	5.65	5.75	5.96	5 94
174 PU	5.72	4.76	3.64	3.75	4.47

LSD (5%) = 0.71 LSD (1%) = 1.05 CV (%) = 9.9

Table 8. Effects of urea supergranules (USG) and prilled urea (PU) at various nitrogen rates on grain yield of IR36 at four villages in Magetan district, East Java, 1984 dry season.

Nitrogen rate (kg/ha)	Grain yield (t/ha)				Mean
	Panggung	Suko widi	Rejo mulyo	Mangge	
58 USG	4.96	6.59	2.71	6.25	5.13
a7 PU	4.27	5.66	2.53	5.10	4.39
87 USG	5.73	6.48	3.15	6.91	5.57
116 PU	4.82	6.18	3.13	5.38	4.88
116 USG	5.49	6.97	3.63	7.76	5.96
174 PU	4.86	6.20	3.40	6.04	5.12

LSD (5%) = 0.56 LSD (1%) = 0.78 CV (%) = 7.2

Evaluation of urea deep placement applicators

A comparison of different types of applicators at Sukamandi Experimental Station indicated that 10, 10, 15, and 80 man hours/ ha were required for the deep placement of 58 kg N/ha as urea using a spring auger, press wedge, Chinese cupfeed, or hand placement, respectively (Fig. 1; 7, 16). Of these methods, the press wedge gave the lowest fertilizer N concentration in the floodwater (17). This comparison, together with others at Dramaga and Pusakanegara, suggests that more development and tests are required before the use of applicators for deep placement can be recommended.

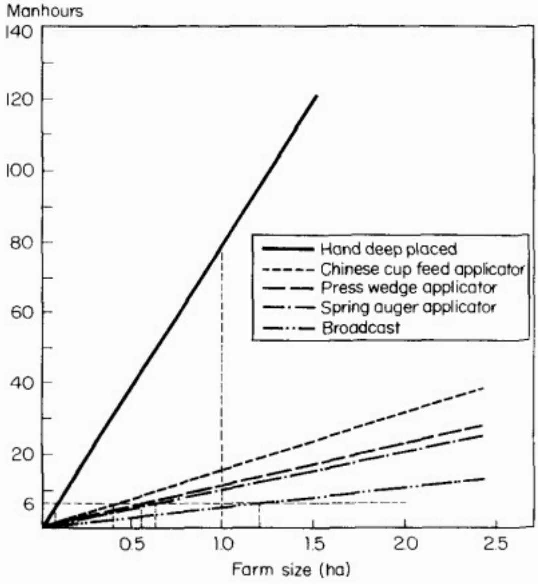
CONCLUSIONS

Improvement of fertilizer efficiency has been a major concern in Indonesia's current five year development plan (1984-88) because of the following.

- Fertilizer subsidies may be removed in the near future, thereby increasing fertilizer prices.
- Credit packages will be removed gradually, and this will put constraints on some inputs such as fertilizers.

Although considerable improvements in fertilizer efficiency have been made through better water management, improved farmers' organization and extension, and use of efficient rice varieties, the Government recognizes that further improvements are still possible and necessary.

INSFFER trials have stimulated the application of alternative technologies for rice production in Indonesia. Final decisions for the appropriate fertilizer



1. Operating times for broadcast, hand deep-placed, and machine deep-placed urea in rice; estimates from applicator test at Sukamandi Experimental Station, 1984 dry season.

management for the different edaphic and climatic conditions in Indonesia can only be made when the results of the current long-term trials can be assessed.

In terms of grain yield, deep point placement and slow release fertilizers have increased the fertilizer N efficiency in many experiments in Indonesia. The acceptability by farmers of deep placement awaits further development of applicators. Their use by farmers would have the additional benefit of creating a local machinery industry.

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Country Report: **Philippines**

J.C. Bunoan, Jr.

Of the annual fertilizer demand in the Philippines, nitrogen (N) is the major nutrient required (about 75% of the total) and 45% is estimated to be consumed in the rice industry, principally as urea. The recommended N fertilizer rates for our National Masagana Rice Production Program are 60 and 90 kg N/ha for the wet and dry seasons, respectively.

In a recent study on rice soils by Fitlery et a1 (2), it was shown that up to 47% of the N applied was lost by ammonia volatilization within 10 days after broadcasting urea into the floodwater 2-3 weeks after transplanting. A peak loss rate of 0.84 kg N/ ha per hour was obtained on the third day after broadcasting. A considerably lower rate of NH_3 loss (10-11%) was recorded when urea was topdressed prior to panicle initiation. When urea was incorporated into the soil prior to transplanting, NH_3 volatilization losses were reduced to 15-20%. Cao et a1 (1) reported that when urea supergranules were deep placed, 73% of the fertilizer N was recovered by the rice plants during the dry season and 65% in the wet season.

In 198 1, in collaboration with IRRI, the Soil Fertility Division of the Bureau of Soils started conducting INSFFER trials on N efficiency in farmers' fields. So far, a total of 51 field experiments have been conducted. These investigated N fertilizer efficiency in rainfed and irrigated rice areas, use of urea applicators, *Azolla,* and integrated organic/ inorganic N sources. Twenty-six field experiments were completed successfully, 9 are in progress, and 16 trials were damaged due to infestation, drought, or lack of sufficient irrigation water at critical stages of plant growth.

The main objective of these trials is to improve the efficiency of N fertilizers for wetland rice by evaluating the different forms of urea, time and methods of application, and integrating organic and inorganic N sources with emphasis on the use of *Azolla.*

EXPERIMENTAL

The procedures for the various types of experiments are set out in the INSFFER fieldbook. Three sources of fertilizer N were used in these trials, namely, prilled

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Soil Fertility Division, Bureau of Soils, Ministry of Agriculture and Food, Manila, Philippines.

urea (PU), 46% N; sulfur-coated urea (SCU), with 36.7% N and a release rate of 22.1% in 7 days; and urea supergranules (USG), 46% N in 1.0 g and 2.0 g sizes.

The fertilizer treatments were: 1) best split application of PU —twothirds incorporated into the soil before transplanting and one third applied as a topdressing one week before panicle initiation;. 2) SCU broadcast and incorporated into the soil at the last harrowing; and 3) USG deep point placed in the soil at 10-12 cm depth 2-3 days after transplanting at a point in the center of every four hills.

The application rates (kg N/ ha) for the various experiments were: rainfed wetland rice, 29, 58, and 87 kg/ ha; irrigated wet season wetland rice, 29, 58, 87, and 116 kg/ha; irrigated dry season wetland rice, 58, 87, 116, and 174 kg/ha; applicator trials, 58 and 87 kg/ ha; utilization of *Azolla,* 30 and 60 kg/ ha for the wet season, and 45 and 90 kg/ ha for the dry season; and integrated inorganic and organic fertilizers, 29, 8, and 87 kg/ ha.

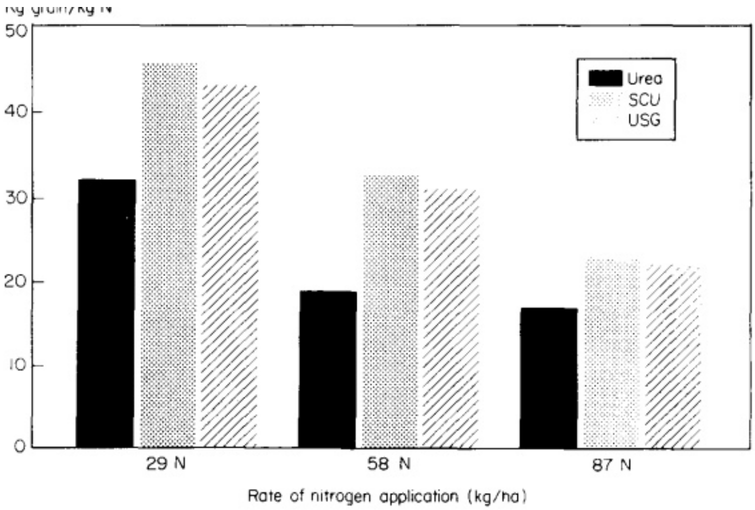
RESULTS AND DISCUSSION

The results of the various INSFFER trials on N fertilizer efficiency conducted since 1981 are shown in Table I and Figures 1-3.

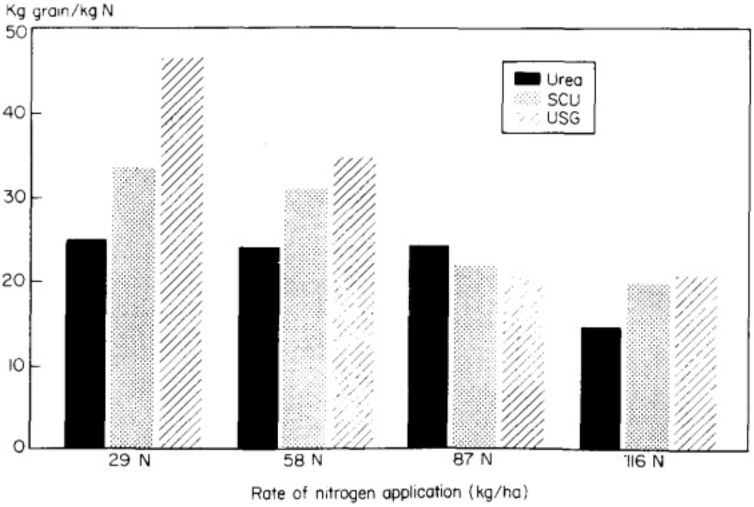
Table 1. Effect of nitrogen treatment on mean yield of rice grain.

Form	Rate (kg N/ha)	Mean grain yield (t/ha) [a]		
		Irrigated wetland rice		Rainfed wetland rice
		Wet season [b]	Dry season [c]	Wet season [d]
Control		3.23 f	3.30 d	3.20 e
PU	29	3.95 abcdef	na	4.12 d
	58	4.64 bcde	4.86 c	4.30 cd
	87	5.36 abc	5.76 cd	4.68 bc
	116	5.01 abcd	6.07 ab	na
	174	na	628 ab	na
SCU	29	4.22 abcd	na	4.53 cd
	58	5.04 abcd	5.66 abc	5.12 a
	87	5.12 abcd	6.24 ab	5.18 a
	116	5.56 ab	6.39 a	na
	174	na	5.78 ab	na
USG	29	4.59 de	na	4.45 d
	58	5.26 abc	5.46 bc	498 ab
	87	5.06 abcd	6.14 ab	5.11 a
	116	5.61 a	6.08 ab	na
	174	na	5.82 ab	na

[a] Symbols a-f apply to Duncan's multiple range test at 1% level, separately in each column. [b] Trials conducted at Binalonan, Pangasinan (1981). Aaurias, Cebu (1982). Moalboal, Cebu (1982), Oar, Albay (1982), Carman, Davao del Norte (1983). Bayombong, Nueva Viscaya (1984). [c] Trials conducted at Oas, Albay (1983). Urdaneta, Pangasinan (1983). Gapan, Nueva Ecija (1984). Bayombong, Nueva Viscaya (1984). [d] Trials conducted at Casiguran, Sorsogon (1982). Mangeidan, Pangasinan (1982). Santo Tomas, Davao del Norte (1982), Mangatarem, Pangasinan (1984).



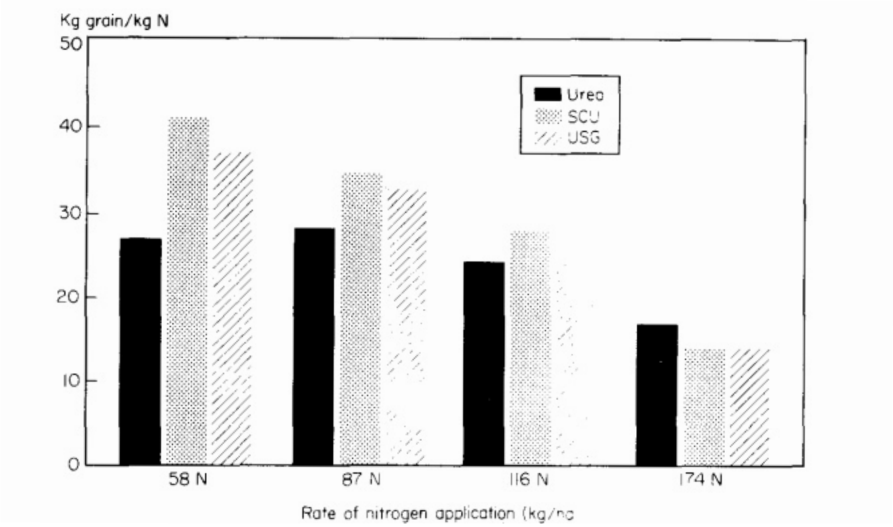
1. Efficiency of 3 methods of urea application (kg rough rice: kg N applied). Average of rainfed experiments at 4 locations.



2. Efficiency of 3 methods of urea application (kg rough rice/kg N applied). Average of irrigated wet season experiments at 6 locations.

Experiments with rainfed transplanted rice

The mean grain yields of wetland rice in rainfed trials from four locations during the wet seasons of 1982 and 1984 are given in Table 1. With all sources of N fertilizer, there was an increasing trend in grain yield from the lowest application rate of 29 kg N/ ha to the highest rate of 87 kg N/ ha. Low grain yields were



3. Efficiency of 3 methods of urea application (kg rough rice/kg N applied). Average of irrigated dry season experiments at 4 locations.

obtained using PU compared with yields obtained using SCU or USG. Grain yields obtained with SCU and USG were not significantly different.

It will be noted that PU was the least efficient form as it resulted in increases of 32, 19, and 17 kg of rough rice per kg N at 29, 58, and 87 kg N/ha applied, respectively (Fig. 1). It took 87 kg N/ha of PU to produce the same yields as those obtained using SCU and USG at 58 kg N/ ha.

Irrigated wet season experiments

Analysis of the mean grain yields from wet season trials conducted at six locations is shown in Table 1. Grain yields of more than 5.0 t/ha were obtained with applications of SCU and USG at 58 kg N/ ha. A comparable grain yield of 5.36 t/ha was obtained with PU at 87 kg N/ha. There were no significant differences in grain yields due to method of application at the higher rates of N. The efficiency of USG appeared to be better than SCU at 29 and 58 kg N/ ha, in agreement with wet season comparisons on irrigated rice elsewhere (Fig. 2). Prilled urea consistently gave 24-25 kg rough rice per kg N at 29, 58, and 87 kg N/ ha.

Irrigated dry season experiments

A pooled analysis of yields from irrigated dry season experiments at four locations is shown in Table 1. Significantly higher grain yields were obtained with SCU and USG than PU at low rates of applied N. but at higher rates (116 and 174 kg N/ ha) there were no significant differences between N sources. It was necessary to apply PU at a rate of 116 kg N/ha to obtain a grain yield comparable to that when SCU or USG was applied at 87 kg N/ha. It will be noted in Figure 3 that at 58 kg N/ ha, SCU and USG gave an average of 12 kg rough rice more per kg N than did PU, a 44% increase in efficiency. At 87 kg N/ha, SCU and USG were about 21% more efficient than PU.

Nitrogen applicator experiments

The effects of different methods of N application on mean grain yield at two irrigated locations (Gapan, Nueva Ecija, and Santa Barbara, Pangasinan) during the dry season of 1984 are shown in Table 2. The pooled analysis indicated that there were no significant differences between the different methods of N application, although the trend was towards higher grain yields with PU at 87 kg N/ha, and with hand placement of USG at both application rates.

Hand placement of USG at 87 kg N/ha was the only treatment that was statistically better than "farmers' practice" with 58 kg N/ha. Hand placement produced a 76% increase over the unfertilized control.

A possible cause of poor performance by the spring auger and the oscillating plunger for PU was the uneven release and distribution of the fertilizer in the rows. The deep plunger was more efficient than the press wedge for injecting the USG balls into the soil, but mechanical difficulties in operating the machine resulted in uneven spacing between the rows. The press wedge did not place the USG balls deeply into the soil and balls were sometimes seen at the surface of the soil.

Azolla experiments

The results of studies on *Azolla* utilization by wetland rice are shown in Tables 3 and 4. Initial studies at two locations during the wet seasons of 1981 and 1982 showed that *Azolla* N can substitute for inorganic fertilizer N when utilized at 20 t fresh *Azolla*/ha in combination with 30 kg urea N/ha, or as two or three

Table 2. Comparison of effects of different methods of urea placement. Nitrogen applicator trials, Gapan Nueva Ecija, and Santa Barbara, Pangasinan, dry season 1984.

Treatment	Mean grain yield (t/ha)[a]	
	58 kg N per ha	87 kg N per ha
Control (N = 0)	3.27 c	
Prilled urea		
Farmers' practice	3.97 bc	4.49 abc
Best split	4.30 abc	5.46 ab
N applicator methods		
Spring auger	4.56 abc	4.39 abc
Oscillating plunger	4.44 abc	4.21 abc
Urea supergranules		
Hand placement	5.37 ab	5.75 a
N applicator methods		
Deep plunger	5.24 ab	5.51 ab
Press wedge	4.84 abc	5.49 ab

[a] Mean of two locations. Symbols a-c apply to Duncan's multiple range test at 5% level.

Tabla 3. Comparative effects on grain yield and efficiency of fertilizer and Azolla. Means for two locations (Pangarinan and Albay), using two plant spacings, wet season 1982.[a]

N treatment (kg N/ha)	Plant spacing (cm)	Grain yield (t/ha)	Total Azolla biomass (t/ha)	Increase in yield per t Azolla (kg)	Efficiency (kg rough rice per kg N)	
					Fertilizer	Azolla
1. Nil (control)		3.4 c	-	-	-	-
2. 60+30+30 as urea	20x 20	4.8 ab	-	-	23	
	40x 10	5.1 ab	-	-	28	
3. 30+30+30 as urea	20x 20	4.4 b	-	-	33	
	40x 10	4.2 b	-	-	26	
4. 30+30+30 as urea plus 56 as fresh Azolla[b]	20x 20	5.9 a	20	75		27
	40X 10	5.3 ab	20	55		20
5. 3 crops of Azolla (A-R-A-A) incorporated[C]	20x 20	5.1 ab	36	47		17
	40x 10	5.1 ab	36	48		17
6. 2 crops of Azolla (R-A-A) incorporated[c]	40x 10	4.66	23	51		18

[a] Symbols a-c apply to Duncan's multiple range test at 1% level. [b]Fresh *Azolla pinnata* at 2 kg/ m^2 incorporated one week before transplanting (1 t = 2.8 kg N). [c]Blanket application of 14 kg P, 25 kg K, 1 kg Zn/ha. Rotation: A = Azolla, R =transplanted rice.

Azolla crops grown to full cover and soil incorporated before and after rice transplanting.

The comparative effect of *Azolla* N in combination with reduced rates of fertilizer N, and as the only N source, is shown in Table 3 for the two locations using two distances of planting during the wet season of 1982. It will be noted that in treatment 4, a reduced fertilizer N rate of 30 kg N / ha plus 20 t *Azolla*/ ha, soil incorporated before transplanting, gave significantly higher grain yields of 5.9 t/ ha and 5.3 t/ ha at 20 x 20 cm and 40 x 10 cm plant spacings. The increases due to *Azolla* N were 1.5 t/ ha and 1.1 t/ha for the two plant spacings with an efficiency of about 20-27 kg rough rice per kg *Azolla* N.

When *Azolla* alone was used as a N source, with one crop soil incorporated before transplanting and two crops grown to full cover and later incorporated into the soil, grain yields of 5.1 t/ ha were obtained for both distances of planting; this was a 50% increase in grain yield over the control. The total *Azolla* biomass incorporated was about 35 t/ ha which was equivalent to 98 kg *Azolla* N with an efficiency of 17 kg rough rice per kg of *Azolla* N. Two crops of *Azolla* with a total biomass of about 23 t/ ha after transplanting gave only 1.2 t/ ha, i.e., a 35% grain increase over the control with an efficiency of 18 kg rough rice per kg *Azolla* N. There was no significant effect of the different plant spacings on yield of grain.

During the dry season of 1983, one *Azolla* trial was conducted and the results are shown in Table 4. The fertilizer rate of 90 + 30 + 30 kg N/ha gave significantly higher grain yields of 5.86 t/ha and 5.66 t/ha for the two plant spacings but did not differ from the reduced fertilizer rate plus 20 t *Azolla*/ha

Table 4. Comparative effects on grain yield and efficiency of fertilizer and Azolla. At Malanay, Santa Barbara, Pangasinan, using two plant spacings, dry season 1983.[a]

N treatment (kg N/ha)	Plant spacing (cm)	Grain yield (t/ha)	Total Azolla biomass (t/ha)	Increase in yield per t Azolla (kg)	Efficiency (kg rough rice per kg N)	
					Fertilizer	Azolla
1. Nil (control)		3.08 c	-	-	-	
2. 90+30+30 as urea	20x 20	5.86 a	-	-	31	
	40x 10	5.66 ab	-	-	29	
3. 45+30+30 as urea	20x 20	5.02 abc	-	-	43	
	40x 10	4.82 bcd	-	-	39	
4. 45+30+30 as urea plus 56 as fresh Azolla[b]	20x 20	5.46 abc	20	22		8
	40x 10	5.33 abc	20	26		9
5. 3 crops of Azolla (A-R-A-A) incorporated[c]	20x 20	4.55 cd	22	65		23
	40x 10	4.68 cd	22	71		26
6. 2 crops of Azolla (R-A-A) incorporated[c]	40x 10	4.30 d	13	95		34

[a] Symbols a-d apply to Duncan's multiple range test at 5% level. [b] Fresh *Azolla pinnata* at 2 kg/m^2 incorporated one week before transplanting (1 t = 2.8 kg N). [c] Blanket application of 14 kg P, 25 kg K, 1 kg Zn/ha. Rotation: A = Azolla, R = transplanted rice.

incorporated before transplanting. Azolla N contributed about 0.5 t/ha grain yield, i.e., 50% less than in the wet season with an efficiency of about 22 kg rough rice per kg *Azolla* N. The use of Azolla alone as a N source (treatments 5 and 6) resulted in lower grain yields than the expected 5.0 t/ha. This was due to the low biomass and the fact that no third Azolla crop was soil incorporated due to infestation. Also, during the dry season of 1984, a pooled analysis of average grain yields from two locations showed no significant differences among the recommended fertilizer rate, half that rate plus 20 t *Azolla*/ ha, and growing and incorporating two or three crops of *Azolla* alone.

The results from these Azolla trials showed that *Azolla* can be grown and utilized throughout the crop year, both in the wet and dry seasons, and assured the potential of *Azolla* N as a substitute for mineral N in rice production.

CONCLUSIONS

In experiments on N fertilizer efficiency, sulfur-coated urea (SCU) and urea supergranules (USG) gave comparable high grain yields at the low application rates of 29 and 58 kg N/ ha in rainfed and irrigated wet season crops, and at 58 and 87 kg N/ ha in the dry season. It took a higher rate of application for prilled urea (PU) to equal the grain yields of the two other N sources at the lower rates, but above 87 kg N/ha the sources were equally effective.

Comparing efficiencies as kg rough rice produced per kg N, SCU tended to be slightly better than USG in rainfed and in irrigated dry season rice crops, but in the wet season irrigated crop studies the trend was reversed. The use of N applicators for both PU and USG showed promise for fertilizer deep placement after minor improvements on each of the IRRI prototypes that were examined.

All the experiments with *Azolla* confirmed its effectiveness as a substitute for 50% of the recommended amount of fertilizer N. Fertilizer could even be totally replaced if three *Azolla* crops could be grown fully and soil incorporated before and after rice transplanting.

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Country Report: **Thailand**

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Because of the great need for information on the nutritional requirements in Thai rice growing systems, Thailand started participating in the INSFFER program in 1976. By 1984, a total of 79 trials had been conducted over 21 sites (Table 1). Briefly, the trials can be grouped as follows: Nitrogen Fertilizer Efficiency Trials in Rice (31 experiments), *Azolla* Use in Wetland Rice (29), Comparison of Phosphorus Sources for Irrigated Wetland Rice (17), Phosphorus and Lime Interaction Trial in Acid Upland Rice Soils (l), and Long-term Trial on Sulfur Fertilization in Wetland Rice (1). Significant responses in grain yield have been obtained from applications of nitrogen and phosphorus and incorporation of *Azolla,* but no clear indication of a response to sulfur was obtained.

RESULTS AND DISCUSSION

Nitrogen fertilizer efficiency for irrigated rice

In Klong Luang (1975-78), the high rate of application of urea in mudballs gave the highest yield increases, 1.1 t/ha during the wet season and 1.0 t/ha during the dry season. In both seasons and at both rates of application, urea applied in liquid bands produced the lowest yield increase. Urea supergranules (USG) performed better than sulfur-coated urea (SCU) and prilled urea (PU) during the dry season, but SCU performed better than any other form during the wet season at the low N rate. However, at the high rate of application, SCU, USG, urea mudballs, and ammonium sulfate gave equally high yields. At Pan, for both rates of application, SCU, USG, and urea mudballs gave similar yield responses. At Chumpae, however, urea mudballs at the low and high rates of N gave the highest yield increases, while USG deep point placed gave little or no yield response at all.

At Klong Luang in 1978-79, average responses to different N treatments ranged from 0.7 to 1.8 t/ha. Highest yield response of 1.8 t/ha was obtained from incorporated SCU at the high rate. In 1980 at the same location, no significant yield differences were obtained between SCU or USG and PU applied best split, in either wet or dry season trials using rates of 27, 54, 87, and 108 kg N/ha.

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Table 1. Number and type of INSFFER experiments in Thailand.

Sites	N efficiency					P sources 197782	PX lime 1984	Long term S 1984	Azolla 197984
	Farm level 1984	Irrigated 1975-82	Rainfed 1979-82	Deep water 1981-82	Upland 1984				
Ayutthaya	1								
Chianat	1								
Chumpae		1	4						2
Fang					1		1		
Huntra				2					
Klong Luang		11				9			
Khon Kaen									1
Kuan Gut									2
Lopburi	1								
Nakorn-Srithamaraj									1
Pan		3							2
Pathumthani	1								
Phimai									2
Prajenburi				1					
Rachaburi	1								2
Rangsit		1		1		8			3
Sakhon-Nakorn									3
Sanpatong									3
Supanburi	1								
Surin								1	4
Ubon									4
Total	6	16	4	4	1	17	1	1	29

At Rangsit in 1981 (Table 2), the range of yields was a little greater than in previous experiments and significant differences in grain yield were observed between the three methods and forms of urea application at all rates. Deep point placed USG outyielded PU by 0.7 and 0.8 t/ha at 29 and 87 kg N/ha, respectively, while incorporated SCU gave a significant yield increase of 0.9 t/ha over PU at 116 kg N/ha.

Nitrogen fertilizer efficiency for rainfed rice

Yield responses to different N treatments in 1979 ranged from 0.4 to 1.5 t/ha. Plowsole application of PU at 54 kg N/ha produced the highest yield response, but no significant differences were observed between forms of urea at a specific rate of application.

In 1980, PU, SCU, and USG, at all rates of application, produced equally low yields ranging from 1.3 to 1.6 t/ha. There were no significant yield differences between SCU or USG and PU at any rate of N.

Further experiments were conducted at Chumpae in 1981 and 1982. Significant differences between SCU or USG and PU were observed in the 1982 trial only (Table 3). Significant yield increases of 0.5 t/ha for SCU and 0.6 t/ha for USG were obtained at 58 kg N/ha.

Table 2. Effect of nitrogen treatment on grain yield of rice, Fifth Nitrogen Fertilizer Efficiency Trial in Irrigated Wetland Rice, Rangsit, Thailand, 1981 wet season.

Form of urea[a]	N rate (kg/ha)	Method of application	Grain yield (t/ha)
Control	0	-	1.3
PU	29	Best split	2.3
SCU	29	Broadcast and incorporated	2.7
USG	29	Placement at 10-12 cm soil depth	3.0
PU	58	Best split	3.3
SCU	58	Broadcast and incorporated	3.1
USG	58	Placement at 10-12 cm soil depth	3.7
PU	87	Best split	3.6
SCU	87	Broadcast and incorporated	4.2
USG	87	Placement at 10-12 cm soil depth	4.4
PU	116	Best split	3.7
SCU	116	Broadcast and incorporated	4.6
USG	116	Placement at 10-12 cm soil depth	4.2
		LSD (5%)	0.6

[a] PU = prilled urea, SCU = sulfur-coated urea, USG = urea supergranules.

Table 3. Effect of fertilizer treatment on grain yield of rice, Third Nitrogen Fertilizer Efficiency Trial in Rainfed Wetland Rice, Chumpae, Thailand, 1981-82.

Treatment no.	Form of urea[a]	N rate (kg/ha)	Method of application	Grain yield (t/ha)	
				1981	1982
1	Control	-	-	2.1	1.5
2	PU	29	Best split	2.6	2.3
3	scu	29	Broadcast and incorporated	2.8	2.5
4	USG	29	Placement at 10-12 cm soil depth	2.9	2.4
5	PU	58	Best split	2.8	2.6
6	scu	58	Broadcast and incorporated	3.2	3.1
7	USG	58	Placement at 10-12 cm soil depth	2.9	3.2
8	PU	87	Best split	3.6	3.4
9	scu	87	Broadcast and incorporated	3.3	3.7
10	USG	87	Placement at 10-12 cm soil depth	3.4	3.4
			LSD (5%)	0.6	0.3

[a] PU = prilled urea, scu = sulfur-coated urea, USG = urea supergranules.

Nitrogen fertilizer efficiency for deep water rice

There were significant responses to N in all experiments on deep water rice (Tables 4 and 5). The highest yield increase of 2.7 t/ha over the control was obtained at Rangsit from USG deep point placed at 116 kg N/ha. At Huntra, the highest yield increase of 1.5 t/ha over the control was obtained from SCU broadcast and incorporated at 58 kg N/ha. Significant differences between the effects of SCU or USG and PU were observed only at the low rate (58 kg N/ha) at Rangsit. In Klong Luang, both materials yielded significantly less than PU at

Table 4, Yield of deepwater rice as affected by nitrogen treatment, First Nitrogen Fertilizer Efficiency Trial in Deepwater Rice, 1980-81.

Form of urea[a]	Method of application (58 kg N/ha)	Grain yield (t/ha)	
		Huntra	Prajinburi
Control	-	1.9	1.3
PU	Broadcast and incorporated	2.7	1.7
SCU	Broadcast and incorporated	3.4	2.5
112 PU + 1/2 SCU	Broadcast and incorporated	2.9	2.2
PU	213 broadcast & incorporated, 1/3 foliar	1.9	1.3
113 PU + 213 SCU	2/3 broadcast & incorporated, 113 foliar	3.2	2.1
USG	Placement at 10-12 cm soil depth	2.6	1.6
PU	With soil, broadcast & incorporated	-	-
	LSD (5%)	0.5	0.5

[a] PU = prilled urea, SCU = sulfur-coated urea, USG = urea supergranules.

Table 5. Effect of applied nitrogen on yield of deepwater rice (Second Nitrogen Fertilizer Efficiency Trial in Deepwater Rice, 1982-83).

Form of urea[a]	N rate (kg/ha)	Method of application	Grain yield (t/ha)	
			Klong Luang	Rangsit
Control	-	-	2.6	1.7
PU	29	Broadcast and incorporated	2.6	2.2
PU	29	2/3 broadcast & incorporated, 1/3 foliar	3.0	2.3
SCU	29	Broadcast and incorporated	2.8	3.0
USG	29	Placement at 10-12 cm soil depth	3.0	2.7
PU	58	Broadcast and incorporated	3.2	3.6
PU	58	2/3 broadcast & incorporated, 1/3 foliar	3.2	3.5
scu	58	Broadcast and incorporated	3.2	3.6
USG	58	Placement at 10-12 cm soil depth	3.4	4.0
PU	116	Broadcast and incorporated	3.2	4.0
PU	116	213 broadcast & incorporated, 113 foliar	3.2	3.3
scu	116	Broadcast and incorporated	2.4	4.3
USG	116	Placement at 10-12 cm soil depth	2.5	4.4
		LSD (5%)	0.5	0.4

[a] PU = prilled urea, SCU = sulfur-coated urea, USG = urea supergranules.

the highest rate. Foliar application of urea solution at 5-7 days before panicle initiation did not give any additional yield advantages.

Phosphate sources for wetland rice

Average yield responses to repeated application of P ranged from 0.7 to 1.2 t/ha at Klong Luang and Rangsit. Responses to residual P (after cessation of P application) ranged from 0.7 to 1.1 t/ha in Klong Luang, and from 0.6 to 1.7 t/ha in Rangsit. At both sites, comparable yield increases were obtained from ordinary superphosphate and the less soluble P sources - highly and less reactive rock phosphates (LRP). Results of residual trials at both sites showed the LRP gave the highest residual effects.

Table 6. Yield of 8 treatments tested in the Third and Fourth International Trials on Azolla Use in Rice, Thailand. INSFFER, 1981-82.

No.	Treatment	Spacing (cm x cm)	Mean yield (t/ha)	
			Third[a]	Fourth[b]
1	Control	20 x 20	1.6	2.a
2	60 kg N/ha, 3 splits	20 x 20	2.4	3.8
3	60 kg N/ha, 3 splits	10 x 40	2.2	3.7
4	2 kg fresh Azolla/m^2 , incorporated before transplanting, plus 30 kg N/ha	20 x 20	2.3	3.6
5	The same as #4	10 x 40	2.4	3.6
6	Azolla grown before and after transplanting, and after full cover, incorporated	20 x 20	2.0	3.6
7	The same as #6	10 x 40	2.1	3.5
8	Azolla grown twice after transplanting	10 x 40	1.7	3.3

[a] Average of 3 trials. [b] Average of 5 trials.

Azolla use in rice

Based on the average yields of eight trials conducted at eight different sites in 1979 and 1980, split application of urea at 60 kg N/ha gave a yield increase of 1.1 t/ha. However, this yield was comparable to that obtained with *Azolla* alone, incorporated before and after transplanting, or the combined effect of *Azolla* incorporated before or after transplanting plus urea at 30 kg N/ha. In 1981, at three sites, incorporation of fresh *Azolla* at the rate of 20 t/ha together with 30 kg N/ha as urea produced yields comparable to split application of urea at 60 kg N/ha regardless of plant spacing (Table 6). *Azolla* alone, applied before and after transplanting, or applied after transplanting only, produced yields similar to *Azolla* plus 30 kg N/ha. The positive responses obtained were due to the added N and did not vary with plant spacing. The same trend was seen in the results of the five trials conducted in 1982. The average yields of five trials conducted at three sites in 1983-84 showed the same trends as those observed in the earlier trials.

CONCLUSIONS

Significant responses in rice yield to applications of N were obtained but there is no clear indication of the best form of urea to use. Applications of 2 kg of fresh *Azolla* per m^2 resulted in increased grain yield and its use appeared to be equivalent to about 30 kg N/ha. Rice responded significantly to applications of phosphorus but no clear indication of a response to sulfur was obtained.

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