Maximizing the efficiency of fertilizer use by grain crops

FAO
FERTILIZER
AND PLANT
NUTRITION
BULLETIN

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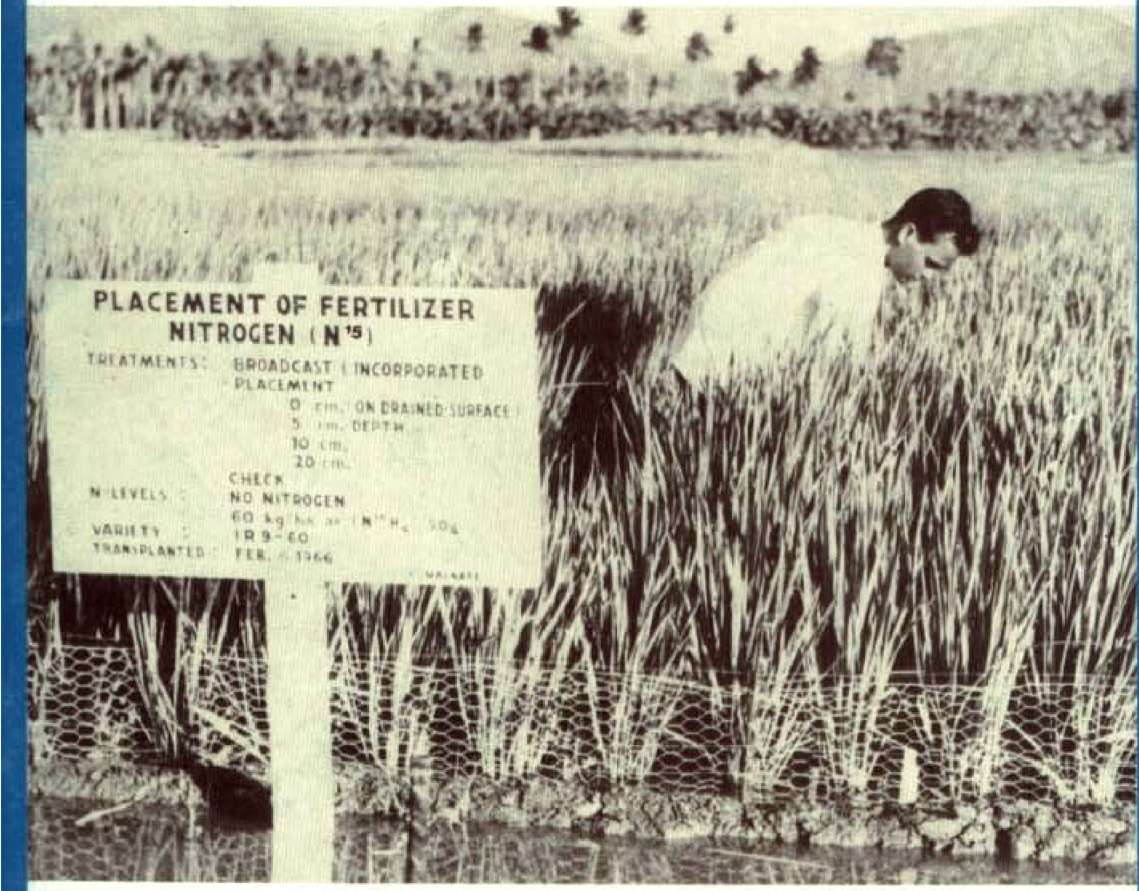

FOOD
AND
AGRICULTURE
ORGANIZATION
OF THE
UNITED NATIONS

Maximizing the efficiency of fertilizer use by grain crops

Fertilizer and Plant Nutrition Service
FAO Land and Water Development Division
and
Joint FAO/IAEA Division of Isotope
and Radiation Applications of Atomic Energy
for Food and Agricultural Development

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ABSTRACT

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The publication summarizes the findings of the Joint/IAEA Division over the last 15 years on fertilizer application techniques on grain crops with a view to maximizing its efficiency. With the increasing costs for energy there is a need for utilizing fertilizer nutrients in the most efficient way. The publication describes and justifies optimum application of Nitrogen (N) and Phosphate (P) fertilizers on rice, maize, wheat, sorghum and millet. Conclusions on Potassium (K) fertilizer application will have to wait for the time when one of its isotopes has been found suitable for long-term field experimental work. 12 figures, 8 tables and 3 photos accompany the text.

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1. INTRODUCTION

Grain crops like rice, wheat, maize, sorghum and millet afford the major portion of the caloric and protein intake in the daily diet of the vast majority of the world's population. The indispensable role of mineral fertilizers in the production of these food grains cannot be disputed. Certainly animal manures and other organic residues are invaluable for the maintenance of soil productivity, but their complete utilization as fertilizer would provide only a small proportion of crop nutrients at present world yield levels. Average yields of grain crops in developed countries have tripled and quadrupled since the 1950s with the development of a chemical industry capable of supplying large quantities of mineral fertilizers at relatively cheap cost to the farmer. It was this advent, and especially of fertilizer nitrogen (N), that also sparked the Green Revolution in many developing countries in the 1960s.

The promised food plenty of the early 1970s faded rapidly with emergence of the world energy crisis. Proceedings of the World Food Conference (Rome, 1974) and the World Conference on Agrarian Reform and Rural Development (WCARRD-Rome, 1979) placed virtually as much emphasis on fertilizer and its accessibility to the farmer as on food per se. As the Director-General of FAO stated at the time of the 1974 World Food Conference: "There is not too great a gap between human starvation due to lack of food and crop starvation due to lack of fertilizer". The FAO Indicative World Plan had given projection of a required 14 percent annual increase in fertilizer consumption in the developing countries from 1968 through 1985. This goal was reasonably being met until 1974 when the combination of restricted supplies and high cost of fertilizers temporarily curbed the trend. Table 1 depicts the disparity in fertilizer use existing in 1977 among the continents of the world and among a selected number of the developing countries. Quite clearly, the food sufficient regions of the world, particularly Europe and North America, can attribute that plenty in no small part to the very substantial quantity of fertilizer nutrients consumed per capita. The majority of the developing countries by contrast use only fractionally the amounts per capita.

Much of the basis for the early 'environmental' clamour against mineral fertilizers has been refuted. Nonetheless, situations have been recorded where excessive or improper use of fertilizer has been detrimental to drinking water resources. Accordingly, it is of utmost importance that fertilizers be used in the most effective way possible: (a) to afford maximum crop benefit and maximum profit to the farmer, and (b) to assure that no environmental harm accrues from that use.

A substantial amount of research has been conducted in the developing countries by the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture and by other FAO technical staff toward establishing efficient fertilizer practice for major food crops in those countries. It is the objective of this bulletin to summarize and develop conclusions from this work, with particular emphasis on the elements N and phosphorus (P) of primary seed, all in the practical context of other available information on effective fertilizer use. Similar conclusions on potassium (K) will have to wait for the time when one of its isotopes has been found suitable for long-term field experimental work.

Table 1 COMPARATIVE FERTILIZER USE PER HECTARE OF ARABLE LAND AND PER CAPITA BY CONTINENTS AND IN A NUMBER OF DEVELOPING COUNTRIES, 1977 [1]

Country or Continent	Fertilizer consumption, kg N + P_2O_5 + K_2O	
	Per arable ha	Per capita
	Continents	
Africa	12.4	6.2
North America	87.2	84.0
South America	38.8	18.4
Asia	45.4	8.9
Europe	210.3	62.7
	Developing Countries	
Algeria	24.4	11.0
Chad	1.0	1.7
Egypt	187.5	14.3
Ethiopia	2.1	1.0
Ghana	10.9	2.8
Ivory Coast	5.2	6.8
Kenya	22.7	3.6
Libya	20.1	20.1
Morocco	22.9	9.7
Nigeria	3.1	1.1
Senegal	20.9	9.6
Sierra Leone	0.4	0.5
Sudan	4.3	2.0
Tanzania	7.3	2.3
Tunisia	9.9	1.2
Zaire	1.4	0.3
Guatemala	62.7	19.3
Haiti	3.6	0.7
Mexico	46.0	16.9
Panama	40.2	12.8
Argentina	2.2	3.0
Brazil	77.4	27.1
Chile	18.0	9.9
Colombia	51.2	11.2
Peru	40.5	8.6
Uruguay	33.1	22.1
Venezuela	45.1	18.6
Afghanistan	6.7	2.7
Bangladesh	37.1	4.4
Burma	6.1	1.9
India	25.3	6.6
Indonesia	35.0	4.2
Jordan	4.0	2.6
Lebanon	80.2	9.1
Pakistan	35.1	9.5
Philippines	32.2	5.8
Sri Lanka	53.6	7.8
Syria	15.0	10.7
Thailand	15.6	6.1
Turkey	46.5	30.9

[1] Derived from 1978 FAO Fertilizer Yearbook

2. DETERMINING FERTILIZER NEED

A first requisite in efficient fertilizer practice is that of knowing which nutrient(s) is/are needed and how much for optimum production of the crop to be grown on the soils involved. The decision is very much crop and soil dependent and on the yield level obtainable by the farming system employed. It goes without saying that few farmers in the developing countries can afford the application of fertilizer nutrients that are not deficient for the current crop, nor can they afford the luxury of heavy application rates that will rapidly build up soil fertility levels.

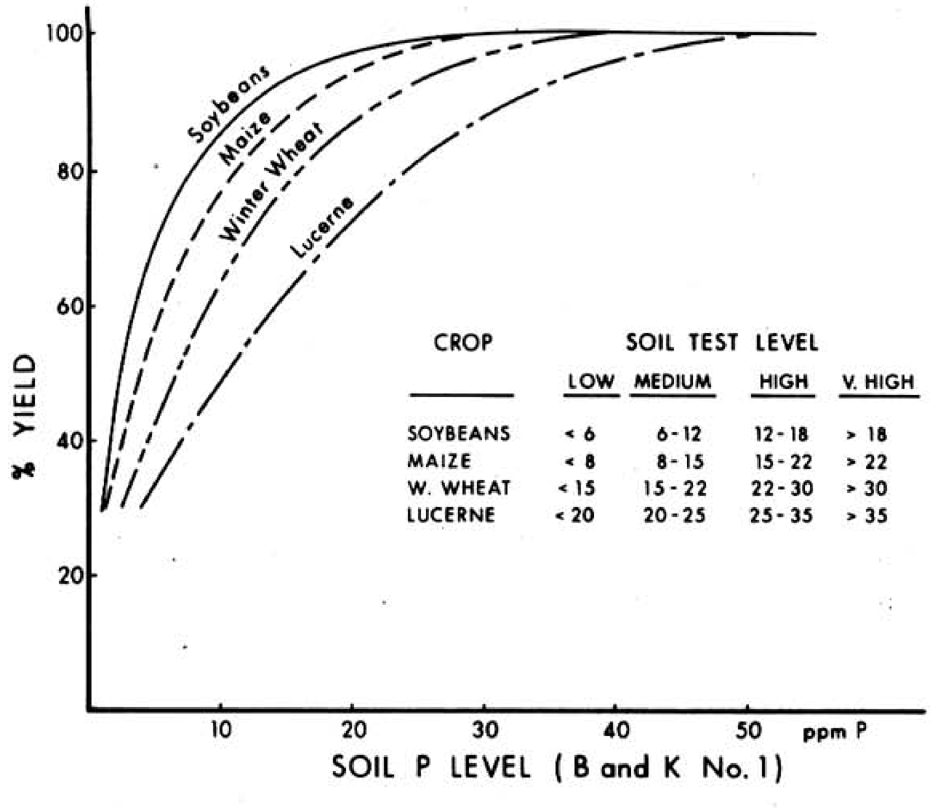
The establishment of a series of field trials by extension and research staff in a given locality will afford useful indication of nutrient needs of that locality and of fertilizer rates likely to be needed. Such sites need to have soil characteristics described as precisely as possible for transferring the information gleaned to similar soil situations in the region. In the very early years of fertilizer use these trials in simultaneously accomplishing a demonstration role have been extremely useful in the developing countries for introducing farmers to fertilizer use.

Fig. 1 Fertilizer trial on upland rice in Sri Lanka

However, the procedure is not infallible. Variations in previous management such as promising cropping history or fertilizer use can create problems in applying the soil fertility information at a different site. Perhaps an even greater limitation to the prediction of fertilizer needs from prior trials in the locality is imposed by subtle differences in soil properties from one field to another resulting from processes in soil formation, which differences are discernible only to the trained soil scientist.

Clearly, a highly detailed soil survey that delineates boundaries where soils change would be very useful in assisting the decision on kind and rate of fertilizer to be applied. Unfortunately, few areas in the developing countries have been surveyed in this way, nor has there been a sufficiency of field trials identified with specific soil types. But even with detailed soil classification information available, differential fertilizer treatments over a few years time with varied residuals remaining in the soil will mask the usefulness of the soil type identification for prediction purposes.

This leaves laboratory analysis of the soil or the plant itself as the potentially most effective alternative for prescription purposes. Soil testing has come to be recognized as the most viable procedure for designating nutrient needs of a given field in most situations, but with some stringent prerequisites. Required are careful measures in soil sample collection and handling and precise correlation and calibration with results of field experiments on soils and crops of the region (Figure 2). In the absence of these requisites soil testing may be little more than a gimmick to aid fertilizer sales. Plant analysis, on the other hand, is proving a useful process in technologically advanced production systems, as with sugarcane, coconut and oil palm production, but poses extreme problems in calibration related to plant geotype, plant part, stage of growth, and environmental conditions prior to sampling. With many plant nutrients, moreover, correction of a recognized deficiency cannot be accomplished in the current crop.



CROP	SOIL TEST LEVEL			
	LOW	MEDIUM	HIGH	V. HIGH
SOYBEANS	< 6	6 - 12	12 - 18	> 18
MAIZE	< 8	8 - 15	15 - 22	> 22
W. WHEAT	< 15	15 - 22	22 - 30	> 30
LUCERNE	< 20	20 - 25	25 - 35	> 35

Fig. 2 Calibration curves for several crops using the Bray and Kurtz no. 1 extraction for P in soil testing under midwestern US conditions

3. EFFECTIVE FERTILIZER PRACTICE

3.1 The Role of Isotopes

In view of the cost factor to the farmer, the energy requirement in fertilizer production, the fact that some elements are non-renewable resources, and the potential for environmental pollution from improper fertilizer practice, it is of utmost importance that fertilizers be used in the most efficient way possible. Isotopic labelling of the fertilizer affords the only direct means for measuring uptake of the nutrient as influenced by chemical carrier, time of application, placement, and concurrently applied ions. Accordingly, this bulletin will focus particularly on those investigations that included isotopic tagging of N and P fertilizers applied to soils in the developing countries (Figure 3). This does not mean that K and the other elements of plant nutrition are not important. By initiating work with N and P utilizing isotopic methods it was envisaged that corresponding studies would essentially be conducted with the others as researchers in the developing countries became experienced and confident with the methodology.

Fig. 3 The establishment of a ^{32}P tracer experiment for flooded rice (in basins) in Hungary for investigating P fertilizer placement

The results reported herein were accomplished largely by field experiments in the developing countries on soils formed mainly under tropical and subtropical climate. The majority of such soils are highly weathered and leached with low buffer capacity compared to soils of temperate regions. Local researchers carried out all of the field operations sending samples to FAO/IAEA Joint Division in Vienna for isotopic ratio analyses (Figure 4).

Fig. 4 A scientist in the Philippines applies radio-isotope-labelled fertilizer to growing rice plants in an experimental farm of the College of Agriculture in Los Baños, near Manila, in attempts to discover better ways of using fertilizer

3.2 Nitrogen

Although one of the most plentiful in nature of all the essential plant nutrient elements with some 67 000 tons in the atmosphere above each hectare of the earth's surface, shortage of available N is more likely to limit crop yields than is that of any other element. There can be no substitute for N in its roles as component of the chlorophyll molecule; as constituent of amino acids, the building blocks of protein; in plant utilization of carbohydrates produced by photosynthesis; and in development of an extensive and vigorous crop root system. The quantity of N removed in food grain crops exceeds that of any other nutrient, and its mobility in solution and gaseous phases gives opportunity for major losses from soil following application as fertilizer. The grower must recognize not only the magnitude of total N required by the crop but as well the time period during which most uptake occurs for assuring maximum utilization. The maize crop, for example, is known to take up almost half of its total N requirement during the three weeks just prior to silking, and shortage during this grand period of growth is certain to restrict yield.

No other nutrient affords such large benefits to be derived from effective management as can be accomplished with N. Although N efficiency was of limited concern to knowledgeable farmers in the mid to late 1960s when fertilizer was cheaper, present prices make it the major requisite cost in modern grain farming. From economic and natural resource standpoints, we can no longer accept a 50 percent utilization value, the recognized norm in N balance studies of the previous decade.

All N in nature contains a small amount of heavy ^{15}N, viz. 0.366 percent, mixed with the predominant lighter ^{14}N. Soil-plant relations research with ^{15}N as a tracer began over 30 years ago but in a very limited way because of high costs of isotope and detection equipment. These costs have been reduced significantly in recent years to the point where the isotope is now recognized as an indispensable tool to the N researcher. It was believed initially that effective tracer work could be accomplished in the field only with N fertilizer containing in excess of one percent ^{15}N, but the coordinated research projects of FAO/IAEA have demonstrated that no more than 0.3 atom percent excess is necessary. This set the stage for full scale field plots using fertilizer tagged with an even cheaper source, i.e. up to 0.366 atom percent depleted ^{15}N below normal atmospheric N or essentially pure ^{14}N. Even with this low percentage there has been no difficulty in measuring crop uptake and utilization in the year of treatment with mass spectrometry. However, measurement of residual effects in subsequent years is not feasible.

The calculation of N utilization of a fertilizer source by a crop is accomplished in the following manner:

$$\%\ \text{N recovered} = \frac{P(fp-s) \times 100}{F(f-s)}$$

where:

P = units of N in plant material
F = units of fertilizer N applied
f = atom % ^{15}N in fertilizer
fp = atom % ^{15}N in fertilized plants
s = atom % ^{15}N in soil (or non-fertilized plants)

Beginning with a 0.366 percent enrichment, accurate detection can be made through an approximate 150-fold dilution, or to between .002 and .003 atom percent ^{15}N. Measurements with a mass spectrometer actually exceed this level of precision, but natural variations in soil ^{15}N mask real uptake differences at such low levels.

Determination of fertilizer N utilization of a crop can be accomplished only with use of an isotopically tagged source. Calculation of the difference between N uptake of a control and that of a treated plot as is done without the isotope overestimates fertilizer utilization due particularly to root stimulation by the N treatment and greater root proliferation of the soil body.

3.2.1 Time of N application

It is of fundamental importance to the farmer to know when fertilizer N should be applied for optimizing its use by the crop and minimizing the potential losses from soil to which the element is subject as displayed in Figure 5. In other words, whatever can be done from the timing standpoint to promote the 'plant uptake' phase of the many transformations represented should be an objective in farming practice.

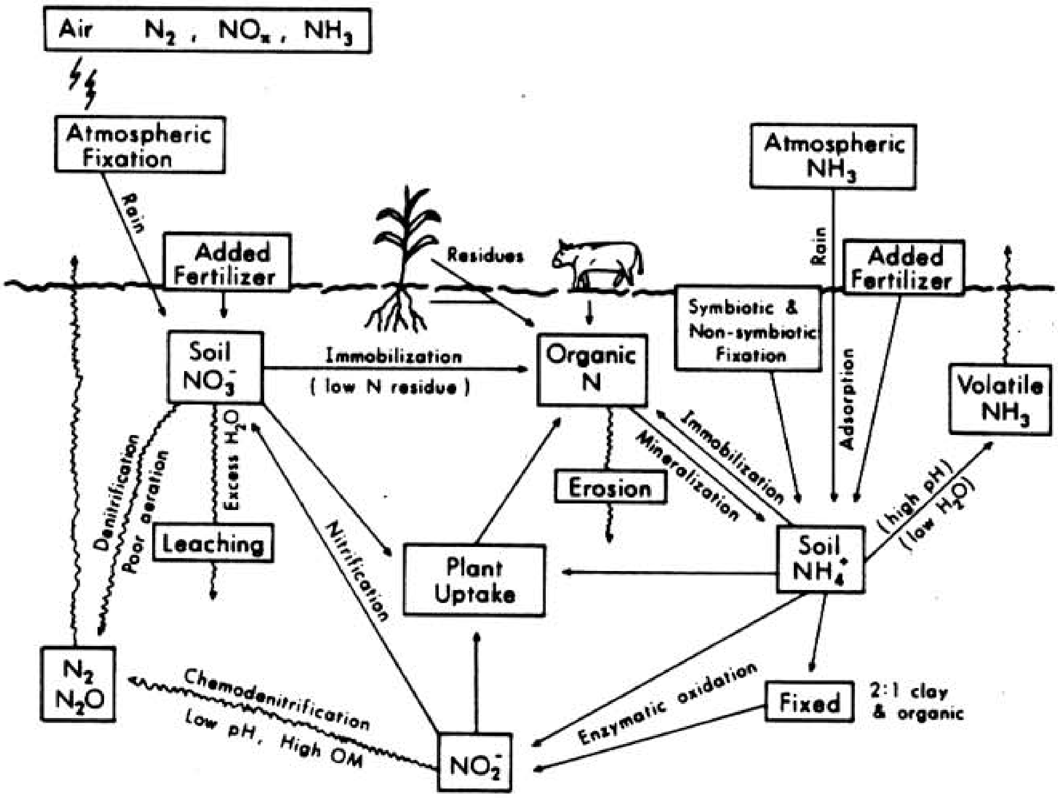


Fig. 5 Transformations of nitrogen in the rhizosphere

i. Rice

Exemplary is a 1964/65 coordinated field study of the Joint Division in 16 countries with rice which compared utilization of a 60 kg N/ha treatment when applied seven different times: all at transplanting (TP), all halfway between transplanting and 2 weeks before primordial initiation (Int), all at 2 weeks before primordial initiation (PI), half at TP and half at Int, half at TP and half at PI, half at Int and half at PI, and one-third at each of the three times. When plants were sampled three weeks after the last N application most locations evidenced highest percentage of N derived from fertilizer from the single dose of ammonium sulphate applied two weeks before primordial initiation. Splitting of N into two or three increments afforded no advantage.

Although yield and total amount of N taken up by the crop are also important factors the use of ^{15}N makes it possible to determine the percent of the N in the plant which is derived from the fertilizer and thus directly measuring the fertilizer use efficiency.

A subsequent more comprehensive study with rice in four countries is reported in Table 2.

Table 2 UTILIZATION OF FERTILIZER N BY RICE WHEN APPLIED IN INCREMENTS AS TAGGED AMMONIUM SULPHATE AT FOUR GROWTH STAGES, 1972-73

Time of fertilizer N application ¹/				Grain N derived from ^{15}N labelled fertilizer				
T_1	T_2	T_3	T_4	Bangladesh	India	Sri Lanka	Thailand	Ave.
	kg N/ha			%	%	%	%	%
25*	25	25	25	7.8	6.6	6.1	10.2	7.7
25	25*	25	25	3.0	4.7	3.1	10.3	5.3
25	25	25*	25	6.0	6.4	3.0	10.9	6.6
25	25	25	25*	8.3	11.8	6.4	17.8	11.1
			LSD (05)	1.7	2.1	1.7	2.1	
			Total	25.1	29.5	18.6	49.2	

¹/ T_1, basal at transplanting; T_2, 3 weeks after transplanting
T_3, midway between T_2 and T_4; T_4 primordial initiation

* labelled with ^{15}N

The basal treatment in this case involved placement at a 5 cm depth at the same time the rice was transplanted, which treatment proved to be superior to surface placement of N three weeks later. But the greatest efficiency in fertilizer N utilization in the grain accompanied that applied at primordial initiation. Quite obviously the rice plant that is experiencing a reasonable level of N nutrition through the vegetative stage is capable of absorbing and translocating to grain this late N increment in a very efficient manner with minimal trapping in vegetative parts. The infusion of N at such a late stage may not accomplish a maximum yield effect but will assure a major effect on grain protein. It would have been interesting in this experiment to have included four additional treatments for yield and uptake comparison where the entire 100 kg N/Ha was applied at the respective times. Quite obvious also is the need for advance information on the soil's N status for projecting amount of N required for satisfying the early vegetative growth requirements in order that optimum yield as well as most efficient N utilization will be accomplished.

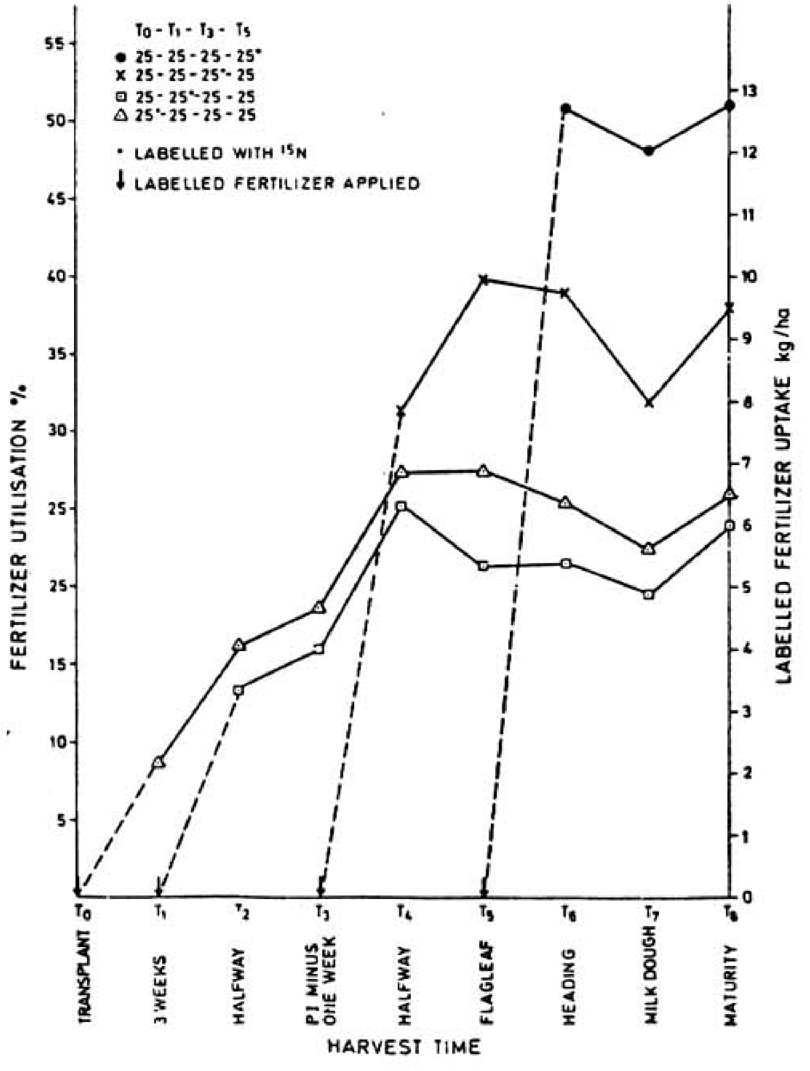


Fig. 6 Uptake of fertilizer N at different growth stages of rice in relation to time of application of the ^{15}N labelled $(NH_4)_2SO_4$ (average of 7 locations)

An extension of the type of information gleaned in the above experiments is displayed in Figure 6 which summarizes uptake by the rice plant of fertilizer N applied at stages during the growth season. Similar field experiments were conducted in seven countries. No difference existed in time or rate of N applied for the various treatments, only timing of the tag, thus no interaction in growth effects could occur. Again, a slight superiority is evident for the N placed as basal treatment at 5 cm depth over surface broadcasting three weeks later. Greatest uptake occurred with that fertilizer applied at and after primordial initiation. Also noteworthy is the very rapid uptake of N applied with flooded rice culture making possible the correction of a recognized deficiency relatively late in the crop season and the improvement in protein content of the grain if desired, both without the problem of increasing lodging.

ii. Wheat

The data of Table 3 from field experiments with wheat in six countries during 1968-69 demonstrate clearly the value of the isotope tag when investigating optimum time for application of different N fertilizer carriers. Grain yield results alone in these experiments would have suggested that $NaNO_3$ and $(NH_4)_2SO_4$ were equally effective at the treatment times employed, further that there was no benefit to be derived from split application. Because of natural field variability and never knowing exactly the proper rate beforehand for the optimum yield (in this case it is apparent that 120 kg/ha if applied at the best time was more than enough), the timing factor is often confounded in field studies where only yield is the criterion for measurement. Note here that the wheat grain desired the largest amount of fertilizer N from the N broadcast at tillering as $NaNO_3$. On the other hand, for $(NH_4)_2SO_4$ to be equally effective to $NaNO_3$ it was necessary that both be incorporated at planting time. The logical explanation is that the $(NH_4)_2SO_4$ remained positionally unavailable to the crop in the soil surface for some time until nitrified with the delayed surface broadcasting compared with the immediate leachability of $NaNO_3$ into the root zone. Additionally, there may have been some volatilization loss of the $(NH_4)_2SO_4$ broadcast on the surface of those calcareous soils represented. Otherwise, as the norm for all locations with both N carriers it is evident that treatment at the boot stage was generally too late for most effective N utilization in the grain. Other studies have indicated an increase in N content of the straw from later N application which may be important when straw is utilized as fodder.

iii. Maize

Corresponding studies to those for rice and wheat with maize have revealed that efficiency of banded N at planting exceeds that of N ploughed down as the land is being prepared for planting, further that delayed summer sidedressing of N from the 50 cm growth stage to tasselling resulted in maximum N in the grain derived from fertilizer. Sidedressing of N subsequent to tasselling or at intermediate growth in those cases where the soil remained dry for an extended period after application was decidedly less effective than earlier application. The generally more efficient utilization accompanying nominally delayed treatment is explained in part by the presence of an active root system for immediately absorbing the N, thereby leaving less opportunity for the leaching and volatilization channels of loss to be expressed. The later availability of the N in major

Table 3 GRAIN YIELD AND PERCENT N DERIVED FROM FERTILIZER IN FIELD TRIALS WITH WHEAT STUDYING TIME AND RATE OF FERTILIZER N APPLICATION (1968-69)

Treatment applied at:			Country													
			Egypt		Brazil		India		Italy		Pakistan		Turkey		Average	
Planting	Tillering	Boot	Grain yield	Ndff[1]	Grain yield	Ndff	Grain yield	Ndff	Grain yield	Ndff	Grain yield	Ndff	Grain yield	Ndff	Grain yield	Ndff
kg N/ha			kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%	kg/ha	%
			$NaNO_3$													
40*	40	40	5582	10	1700	32	3257	22	2852	12	2133	15	3742	12	3211	17
40	40*	40		16		58		19		28		21		22		27
40	40	40*		24		13		8		15		20		23		17
60*	60	0	4757	19	1670	35	3315	32	3163	22	2033	23	3863	21	3134	25
120*	0	0	4453	47	1460	74	3013	40	3213	57	1415	50	3118	48	2778	52
			$(NH_4)_2SO_4$													
40*	40	40	5581	10	1343	24	3201	20	2668	27	1561	14	3418	14	2962	18
40	40*	40		14		37		12		17		15		16		19
40	40	40*		24		4		6		5		12		21		11
60*	60	0	5153	19	1253	29	3143	36	3098	36	2213	22	4050	23	3152	27
120*	0	0	5157	41	1028	58	2892	52	3338	58	1053	45	3593	44	2844	50
60	0	0	4985		1170		3072		3040		1748		2703		2786	
0	0	0	3903		190		1775		1658		1745		970		1707	
	LSD(05)		737	5	222	4	486	10	254	4	653	6	584	6		

[1] Ndff = nitrogen derived from fertilizer

* labelled with ^{15}N

quantity also has been found to accent grain formation relative to vegetative development, thereby enhancing the grain to forage ratio. Figure 7 from experiments in Argentina, Brazil, Colombia, Peru and Egypt during 1965-66 is representative of the results obtained with this crop.

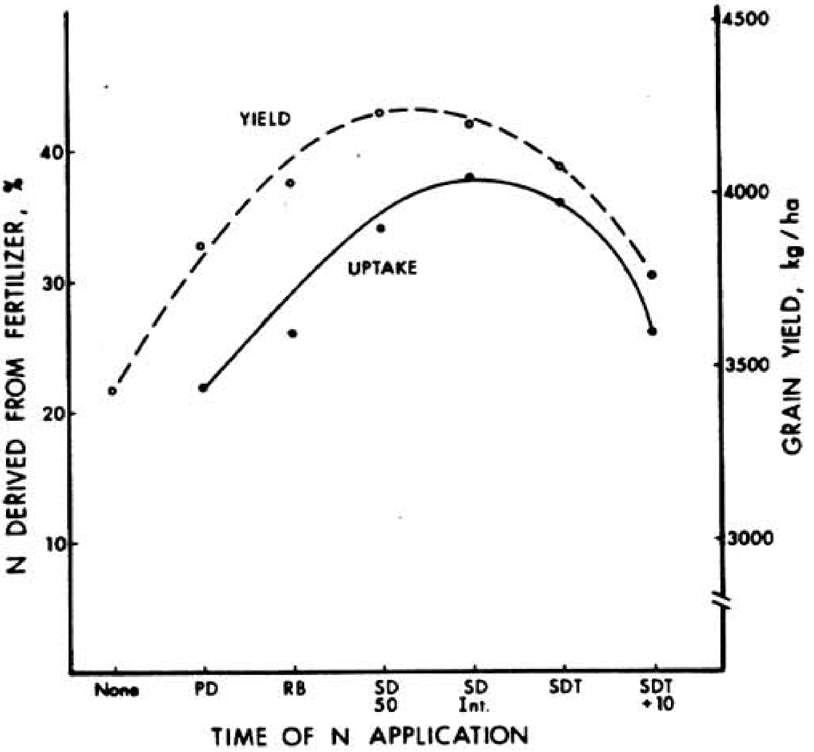


Fig. 7 Influence of time of applying 80 kg N/ha on grain yield and percentage N derived from $(NH_4)_2SO_4$ in field experiment with maize in Argentina, Brazil, Columbia, Peru and Egypt

PD = plough down RB = row band
SD50 = sidedress at 50 cm plant height
SD Int. = sidedress between 50 cm and tassel growth stages
SDT = sidedress at tasselling
SDT+10 = sidedress 10 days after tassel start

iv. Upland rice and millet

We have no record of corresponding isotope tracer studies on upland rice or millet. By reason of the comparable root and top growth morphology of these crops to wheat, however, it is likely that the physiology of N use is similar to that of wheat and we would project similar response to fertilizer N management.

v. Sorghum

Sorghum grown as a grain crop responds to time of N availability identically to maize, the primary difference between the two being a greater capacity for extracting soil N with less demand for fertilizer N by the sorghum.

3.2.2 Placement of N

Preliminary experiments with rice in 16 countries during 1965-66 reveal a decided advantage for placement of an $(NH_4)_2SO_4$ source of N at the 5 cm depth in soil at transplanting compared with surface broadcasting. The difference was least for the three calcareous soils of highest pH among this group, presumably reflecting the more rapid nitrification and ultimate denitrification of the applied NH_4^+ in the alkaline medium. A more detailed study on placement in four countries during 1966-67 further confirmed the benefit for placing planting time N at some depth in the soil. Figure 8 displays a decided advantage for the deeper placement as the plants reached the primordial initiation stage of growth, an advantage that persisted to final grain harvest. The declining utilization with all placement methods after primordial initiation is explained by an expanded root system utilizing an increasing proportion of soil N as the crop developed.

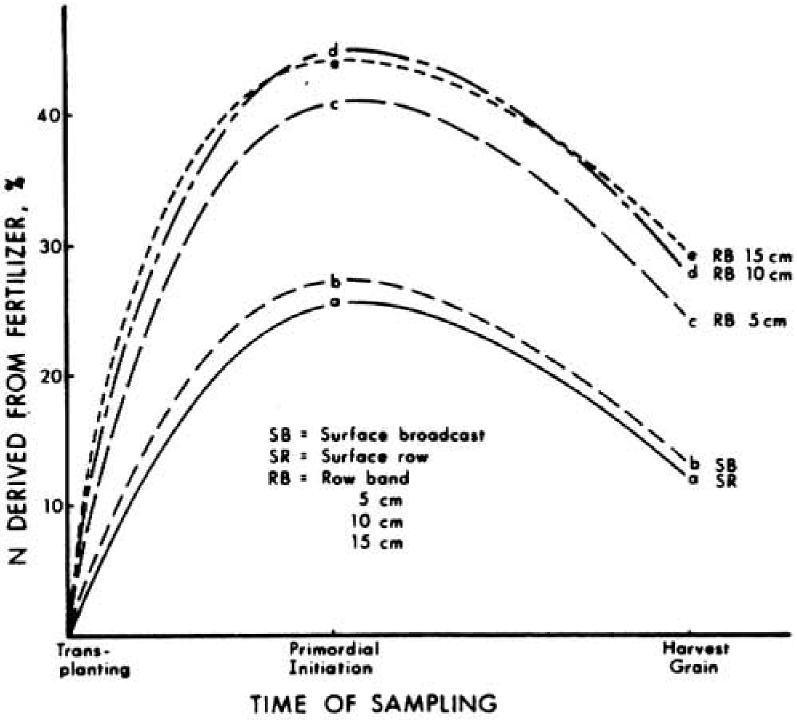


Fig. 8 The influence of placement depth on uptake of tagged $(NH_4)_2SO_4$ by submerged rice (average for experiments in Philippines, Taiwan, Thailand and Madagascar during 1966-67)

Experiments of 1965-66 compared the utilization of fertilizer N by maize when either ploughed down just before planting or banded adjacent to the row at planting. Results from this study in five countries reveal a distinct advantage for placement adjacent to the row (Table 4). The benefit is particularly apparent during early growth stages, tapering off with maturity as the crop's root system proliferated the soil body. Other treatments in these experiments effected a summer sidedressing that, as noted above, was decidedly superior in fertilizer utilization with timing the obvious predominant factor. But in the present comparison with essentially no time differential, concentrating the N in a band limited immobilization and/or losses associated with mixing of the N throughout the soil plough layer.

Table 4 UTILIZATION OF TAGGED $(NH_4)_2SO_4$ FERTILIZER BY MAIZE AT VARIOUS GROWTH STAGES WHEN PLACED IN THE SOIL IN TWO DIFFERENT WAYS [1]

Placement	% Ndff at growth stage				
	20 cm	50 cm	T-15	Final harvest	
				Forage	Grain
Plough down	41	42	35	26	22
Banded by row	60	54	47	31	28
"F" test [2]	**	**	**	*	

[1] Mean values for experiments in Argentina, Brazil, Colombia, Egypt and Peru. T-15 = 15 days before tasselling

[2] Significance level: * = 5%; ** = 1%

Experiments in twelve countries during 1971-72 with wheat evidenced very little difference in utilization efficiency of N banded by the seed row and the same amount broadcast and worked in just before planting. Results were the same with an optimum irrigation regime, with limited irrigation and with dry farming culture. Nor were there any differences in grain yield imposed by the varied placement of N at planting.

3.2.3 Chemical Carrier of N

Nitrogen is formulated into several chemical compounds that find their way into the fertilizer distribution system. It is clearly necessary that the farmer be aware of which ones of these are likely to be most effective when used on his soils. Among those commonly found in international commerce are $CO(NH_2)_2$, NH_4NO_3, $(NH_4)_2SO_4$ and $NaNO_3$. The big difference among these is the NO_3^- versus the NH_4^+ ion.

Experiments of 1966/67 compared these sources for rice at sites in fifteen countries with two times and methods of application, at transplanting to a depth of 5 cm and as a topdressing two weeks before primordial initiation (Figure 9).

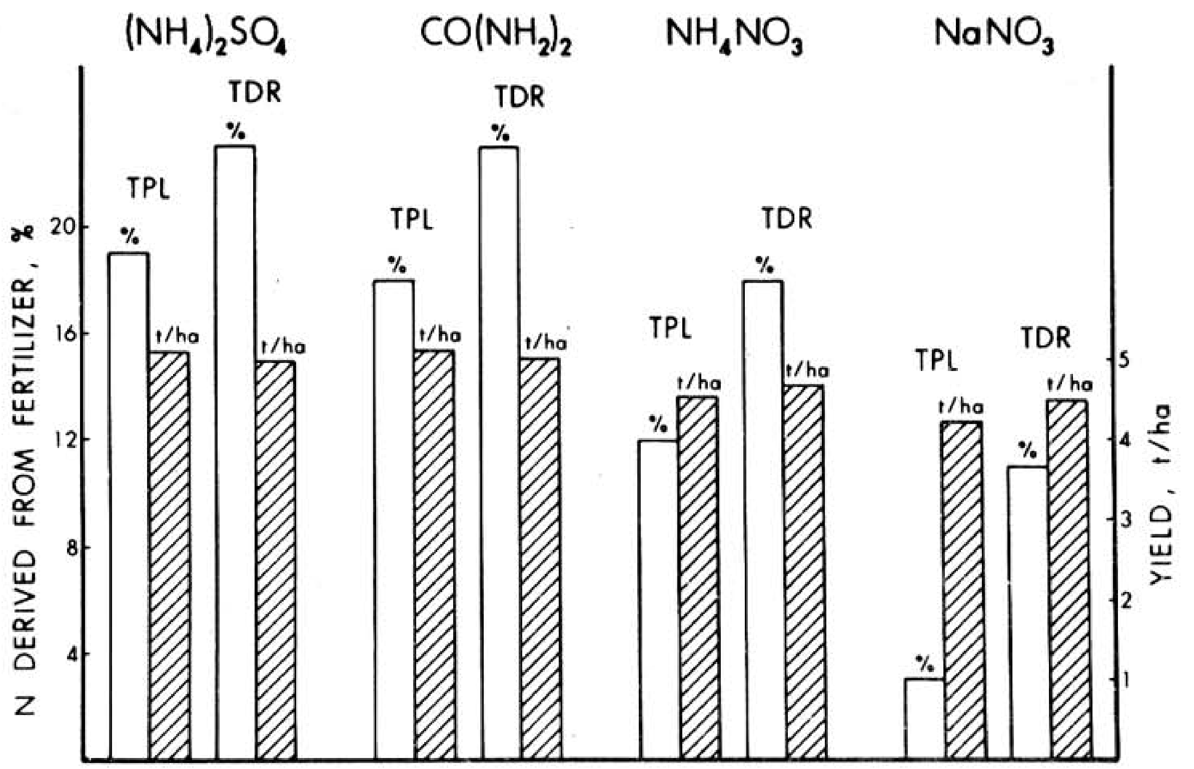


Fig. 9 Influence of chemical carrier on fertilizer N utilization and yield of lowland rice (average for 15 experiments in Burma, Sri Lanka, Taiwan, Egypt, Hungary, India, Italy, Korea, Madagascar, Bangladesh, Pakistan, Philippines, and Thailand, 1966-67)

TPL = applied at 5 cm depth at transplanting
TDR = topdressed 2 weeks before primordial initiation

These experimental results are especially useful for demonstrating the benefit of the isotope tag in nutrient efficiency studies. Yield response to applied N was rather limited at many of these sites such that there is no pronounced difference in apparent effectiveness of carriers with grain yield as the only criterion. By the nutrient utilization values, however, it is evident that $(NH_4)_2SO_4$ and $CO(NH_2)_2$ (essentially a NH_4^+ source because of its rapid hydrolysis to $(NH_4)_2CO_3$) are superior to those sources containing NO_3^-, the $NaNO_3$ being by far the least efficacious and NH_4NO_3 intermediate. Both of the latter were distinctly improved with delayed application, but not sufficiently to warrant their use in submerged rice culture. The $NaNO_3$ with all of its N in NO_3^- form was especially poor averaging about one-sixth as effective as the NH_4^+ source when applied at transplanting and one-half when broadcast shortly before primordial initiation.

A comparison of $NaNO_3$ and $(NH_4)_2SO_4$ applied at different times for wheat has been presented earlier in Table 3. Conclusion in that comparison insofar as carrier is concerned is that both were equally effective when applied at planting under comparatively dry farming conditions. But with delayed application the $NaNO_3$ was superior due to the greater immediate mobility of the NO_3^-. Similar comparison of

$CO(NH_2)_2$ and NH_4NO_3 in 13 countries during 1970/71 revealed equal effectiveness of those carriers in both yield and fertilizer uptake. A follow-up more detailed investigation in 11 countries comparing NH_4NO_3, $CO(NH_2)_2$ and $(NH_4)_2SO_4$ showed similar results with these carriers under three different moisture regimes.

Experiments with maize in eight countries likewise displayed no significant difference in uptake of fertilizer N supplied as $(NH_4)_2SO_4$, NH_4NO_3 and $CO(NH_2)_2$.

The composite results for all three crops where all carriers were incorporated and results elsewhere with sorghum and millet indicate that little if any difference in chemical carriers is likely to exist so long as each is used in accordance with its own limitations, e.g. the required incorporation of $CO(NH_2)_2$ and $(NH_4)_2SO_4$ in soil particularly under alkaline soil conditions. These results confirm those obtained in developed countries of temperate climate.

Otherwise concerning carriers of N, much interest has developed in recent years on delayed release N products that might increase fertilizer use efficiency by the crop and reduce losses due to leaching and denitrification. Sulphur coated urea is one of these products, developed by the Tennessee Valley Authority (TVA) and others, which has been tested rather extensively with rice production in the developing countries. In 106 trials sponsored by TVA throughout Southeast Asia during 1975-78 the SCU provided a return of $6 per dollar extra cost, and afforded significant yield increases over the best split application of urea in 50 of the trials. Further investigations will be required with this and other controlled release products under any existing combination of soil, cropping and environmental conditions before farmer acceptance can be advocated.

3.2.4 Depth of N Extraction from Soil

The depth to which crop roots will function in extracting N from soil is of significance from the standpoints of full crop utilization of residual available N in the rooting profile, appropriate fertilizer rate as influenced by that residual, and the control of N that might otherwise leach out of the root zone to the ground water. Isotopic tagging of N provides the only means of discerning from what zone a crop has derived its N supply and in what proportions. The data of Figure 10 express work conducted in Austria with maize and sugar beets by the Joint FAO/IAEA Division. In this study labelled $(NH_4)_2SO_4$ was injected to the various depths expressed during the maximum vegetative growth stage of the two crops. It will be noted that proportionate use of the applied N decreased appreciably with depth but with major differences among locations. Additionally obvious is the fact that with sugar beets the decline with depth was not as evident as with maize. The location effects could be due to many things, not the least of which being the quantity of residual mineral N in the soil as the crop is planted. With a substantial quantity in the surface horizon the crop will not exert the energy required for substantial absorption at depth, thereby leaving any deep residual more subject to eventual leaching loss from the soil rooting zone.

Ecological studies of the physical distribution of roots in soil have demonstrated that the major proportion of roots by weight is in the surface 30 cm of soil, usually in the order of 80-90 percent, with no more than two or three percent of the total in 30 cm increments below the metre level. The data of Figure 10 are of fundamental interest in showing that the very small percentage of roots at 120 cm can account for 10-50 percent of the N utilization accomplished by the mass of roots at 5 cm. Certainly moisture availability in the rooting zone throughout the growing season is another significant factor involved. Nutrient extraction will be minimal in surface soil dried down to the wilting percentage as the crop becomes increasingly dependent on the few roots in moist soil at depth. Corresponding studies in Nebraska (USA) have likewise shown significant utilization of tagged N from the 180 cm depth by maize so long as mineral N in surface horizons was not high, likewise for sugar beets. In fact, uptake of tagged N has been measured to as deep as 240 cm where unconsolidated soil material existed to that depth. This is a matter of major significance to the beet crop which should be running out of available N as it approaches maturity for assuring maximum sugar set rather than meeting up with a new copious N supply to stimulate more vegetative growth as the roots reach their deepest penetration late in the season.

Other factors beyond nutrient supply and moisture availability can influence rooting patterns and activity as well. Certain genetic soil horizons expressing unfavourable physical or chemical characteristics that have resulted from soil formation processes can prove restrictive to root development. Isotopic tagging of nutrients placed in and below these horizons will readily indicate just how inhibitive they may be. Such factor may have been expressed in some of the locations portrayed in Figure 10.

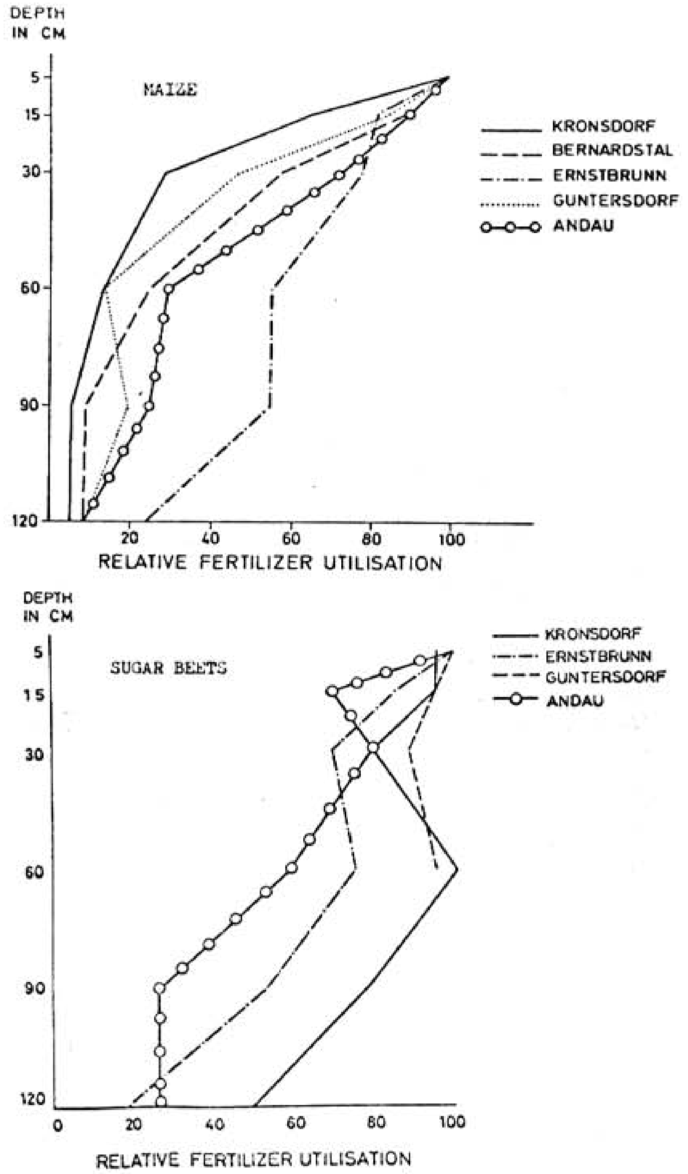


Fig. 10 The relative utilization by maize and sugar beets of labelled $(NH_4)_2SO_4$ placed in equal quantities at varied depth in the soil, with 5 cm placement given a relative value of 100 (5 locations on maize and 4 on sugar beets in Austria)

3.3 Phosphorus

More investigations involving a tag with radioisotope have been conducted with P than with any other element. Explanation lies in the great importance of the element in plant nutrition and the accessibility of the relatively cheap ^{32}P isotope of ideal longevity. The half-life of 14.3 days allows conducting a field experiment through an approximate 100 day growth period, with the isotope having decayed to tracer level at crop maturity leaving no disposal problem. As with N the evaluation of nutrient efficiency involves the determination of a specific activity of the plant material produced relative to specific activity of the original fertilizer material, e.g. cps/g P of the two. Yield of crop does not need to be taken into account in this isotopic dilution comparison.

The element P does not possess the mobility of N in the soil-plant system but the chemical reactions to which it is subject are nonetheless complex, the nature of which are dependent on such chemical properties of soil as pH, and percentage saturation with the elements Ca, Al and Fe. A pH in the range of 6.0-6.5 affords predominant occurrence of the $H_2PO_4^-$ ion of that portion of the soil P present in the soil solution, which ion is most soluble of all P forms in soil and most readily accessible for plant uptake. At low pH solubility of Fe and Al increases allowing combination with any existing soluble P ions into lower availability Fe and Al compounds. As pH exceeds 7.0 with soil saturation of Ca ions the $HPO_4^=$ and ultimately $PO_4^=$ ions of decidedly lower activity predominate (Figure 11). Thus fertilizer P management needs to be directed toward preservation or enhancement of applied fertilizer P solubility to the extent possible.

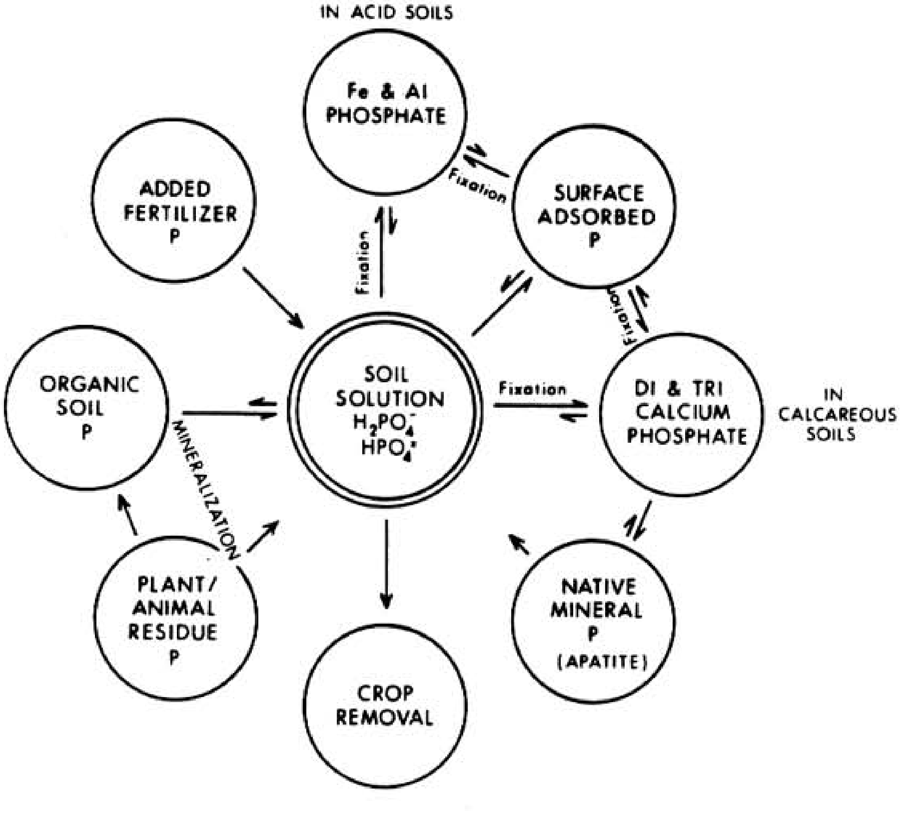


Fig. 11 Equilibrium relations among soil solution P and the various fractions of the element in soil

3.3.1 Time of P Application

Investigations world around with most crops have shown the necessity of having fertilizer P present in the seedling zone as the crop commences growth for assuring maximum crop response to the fertilizer. Because of limited P mobility in all but very sandy and organic soils, attempted placement of later P applications into the seedling zone causes root pruning that shocks the young plant, thereby limiting uptake from the fertilizer source. Nutrient uptake could be assumed to be quite different in submerged rice culture than in the production of other crops on well drained soils. Accordingly; experiments were conducted in ten countries with rice in 1963-64 including seven combinations of application times of ^{32}P-tagged superphosphate.

The results expressed in Table 5 show rice to be quite different from other crops in response to time of P applications. Only when P treatment was delayed until two weeks before primordial initiation was there any loss in P utilization efficiency, and not much even then. The flooded culture apparently allows very efficient uptake of P because of high root activity at the soil surface that compensates for the lack of incorporation into the soil root zone. Thus if for any reason it was not convenient for the farmer to apply the P fertilizer at or before transplanting essentially equal results could be expected from treatment made several weeks later.

Table 5 THE INFLUENCE OF TIME OF APPLICATION ON FERTILIZER P UTILIZATION BY FLOODED RICE

Location	% P dff when applied in kg/ha [1]						
	60 TP	60 Int	60 PI-2	30 TP 30 Int	30 TP 30 PI-2	30 Int 30 PI-2	20 TP 20 Int 20 PI-2
Burma (M)	31	30	22	33	28	30	28
Burma (G)	7	8	6	7	8	8	9
Hungary	12	8	7	12	9	10	10
Korea	19	22	19	23	24	23	23
Bangladesh	66	63	48	64	63	64	60
Pakistan (T)	46	48	41	45	46	43	49
Pakistan (K)	44	46	39	41	45	49	46
Philippines	10	10	9	11	11	11	10
Thailand	82	74	64	22	84	81	85
Egypt	39	27	33	34	35	33	35
Average	36	34	29	35	35	35	36

[1] TP = at transplanting; PI-2 = two weeks before primordial initiation;
Int = halfway between TP and PI-2, applied as tagged superphosphate

3.3.2 Placement of P

i. Rice

There was little agreement among agronomists in the early 1960s on optimum placement of P fertilizer for rice production. A general consenses did exist, however, to the effect that crop response to applied P is less on a soil under submerged conditions than occurs when the soil is drained and aerated throughout the growing season, explained by an increased solubilization of soil iron phosphate under reduced conditions. An obvious related question, then, is just what effect might submerged culture have on fertilizer P availability and with special reference to placement of the P. A greenhouse experiment by the Joint FAO/IAEA Division with soils from eight countries indicated that placement does indeed have a pronounced effect on crop utilization of P from fertilizer, further that availability of P in superphosphate is not modified by flooding from that under aerated conditions.

The results from field experiments with P placement for rice on the same soils are presented in Figure 12. It will be noted that surface application of the P and hoeing the fertilizer into the top few cm of soil just before planting afforded essentially twice the fertilizer utilization of the other application methods. This was a surprising result to most concerned since placement just below the transplant had been expected to be superior. The latter was indeed very effective during early growth but declined rapidly thereafter.

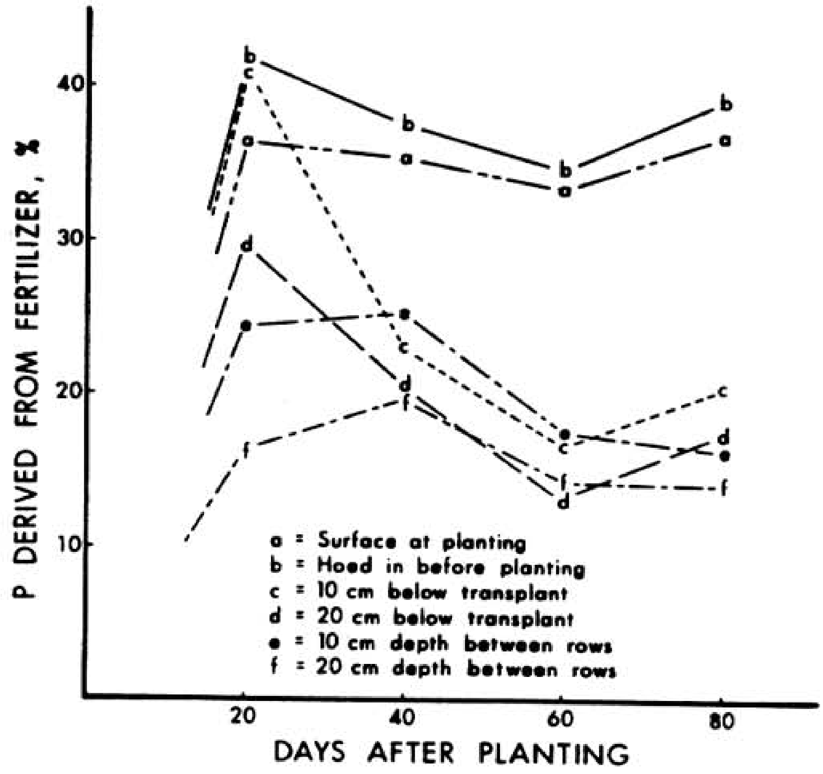


Fig. 12 Influence of placement method on utilization of labelled $Ca(H_2PO_4)_2$ by submerged rice in 8 countries (Egypt, Philippines, 2 in Thailand, 2 in Burma, Bangladesh and Pakistan)

The two locations in Thailand and the one in Egypt evidenced very heavy dependence on the fertilizer source, while the Philippine site showed limited need for the supplement. Actually, a ninth location in Hungary was included in the field investigations but because of the extremely high P level of the soil the utilization of fertilizer P was very low with no significant difference among treatments and accordingly was omitted from the summation of Figure 12.

ii. Wheat

Placement of fertilizer P with wheat was investigated at a number of field sites during 1969-72 with results as expressed in Table 6. The first series of comparisons shows that banding of P with the seed at planting is a fully effective method with no added benefit to be derived from placement deeper in a band below the seed row. The second series suggests that nearly as good results can be expected from a broadcast and hoeing or discing in operation as with row application. This gives the farmer considerable latitude in P fertilizer management to correspond with application facilities available to him. It seems likely that few if any of the soils involved in the experiments were of high P fixing capacity. Where this soil condition exists, banding in a row retards the fixation rate and can usually be expected to enhance fertilizer availability.

Table 6 INFLUENCE OF P PLACEMENT ON UTILIZATION OF FERTILIZER P BY WHEAT

Treatment, kg/ha and P placement [1]				% P dff		Grain yield kg/ha
				Stage 2	Final grain	
				Average 2 sites [2]		
20N + 30P	BS	+	100N later	60.3	30.1	2319
20N + 30P	WS			65.0	28.6	2598
				Average 5 sites [3]		
60N + 30P	BW	+	60N later	33.4	15.3	4291
60N + 30P	WS			34.5	15.9	4361

[1] BS = band below seed at planting; WS = with seed at planting;
BW = broadcast and worked in before planting

[2] Sites in Greece and India

[3] Sites in Greece, India, Italy, Lebanon and Peru

iii. Upland rice and millet

Similar results with P placement for upland rice and millet would be expected as obtained for the wheat crop.

iv. Maize

Early season utilization of ^{32}P tagged fertilizer in maize experiments of the Joint FAO/IAEA Division proved to be highest where the fertilizer was banded at seed level, in contrast to deeper placement of the P or broadcasting on the soil surface. Explanation for this result is the largely lateral early growth of the radicle roots before turning downward into the soil. Thus, interception of fertilizer banded 4-5 cm to the side of the seed by this crop's roots occurs sooner than fertilizer placed deeper. Such banding is especially advantageous in soils with high P fixing capacity compared with complete mixing into the seedling zone as accomplished by discing in or ploughing down the P. The surface area of soil-fertilizer contact is restricted by concentration in the band and thereby the means for soil fixation reactions to occur. Vast differences exist among soils, but as a general average twice as much fertilizer is required with a mixed placement to match the yield response achieved by the row band placement. Obvious care must be practised in assuring that no significant quantity of such banded fertilizer comes in contact with the seed, especially where the fertilizer contains an appreciable N and/or K component.

v. Sorghum

Few if any field tracer studies have been made on P placement for sorghum in tropical/subtropical regions. In temperate regions sorghum does not usually express as striking a response to side-band placement of P as maize and rather responds best to P placed below the seed, which is considered to be a soil temperature related factor associated with planting dates for the two crops.

Band placement of P fertilizer adjacent to the row is probably as efficient as any that can be employed with machine planting of the two crops. Where hand planting and hilling around the plant is practised, however, as in the more humid tropical regions, hill-placement has afforded greater early season uptake from a given amount of applied P than band placement.

3.3.3 Chemical Carrier of P

A large number of chemical formulations of P fertilizer are prepared and marketed by the world fertilizer industry. The grower needs to be aware not only of the cost per unit P in these various products but as well the agronomic effectiveness of the materials on soils of his area. The cost feature is readily evaluated by knowledge of the cost per ton and the percentage nutrient contained. Agronomic effectiveness can normally be determined in a relatively short period of time, as reported in Table 7 for the rice crop. In this case soil was sent to the Joint FAO/IAEA Division's laboratory for growing rice under identical conditions with each soil. All of the soils were initially treated with a uniform rate of tagged superphosphate for comparing the unprocessed phosphate carriers. Then different forms of unprocessed P were mixed with the entire quantity of soil in respective greenhouse pots and soil P delivery capacities determined in the crop produced by difference from tagging of the soils with labelled superphosphate only. The various processed P sources had been tagged uniformly with ^{32}P during manufacture such that their relative utilization could be determined directly after the crop was grown with equivalent P rates applied in the respective carriers.

Results with this study on rice revealed striking differences in P availability of the unprocessed sources related to soil pH. Only on the most acid soils did these

Table 7 COMPARISON OF DIFFERENT P CARRIERS IN AVAILABILITY RELATIVE TO SUPERPHOSPHATE ON SOILS FROM DIFFERENT LOCATIONS

P carrier	Relative P carrier availability in soil from country and pH [1]							Average
	Hungary (6.6)	Pakistan (8.2)	Thailand (4.5)	Brazil (6.2)	Burma (G) (5.0)	Burma (M) (7.8)	Egypt (8.5)	
Unprocessed P sources								
Olinda	1400	>10 000	160	1000				3140
Araxa	3300	10 000	220	910				3608
Araxa Thermo	80	80	100	60				80
Tunis rock	1100	1 200	110	150				640
Florida rock	3300	>10 000	120	240				3415
Bone meal	420	600	120	140				320
Processed P sources								
K metaphosphate + $MgSO_4$			88	50	118	87	75	84
K pyrophosphate			141	174	182	109	104	142
K metaphosphate			180	86	164	110	155	139
K orthophosphate			64	69	82	58	74	69
Basic slag	140	140	120	80				120
Superphosphate			100	100	100	100	100	100

[1] Units of P in respective carriers required to be equivalent to 100 units of P in superphosphate

materials as a group compare favourably with superphosphate. Under neutral to alkaline soil conditions the alkaline P carriers Araxa Thermo and basic slag were the only ones affording a reasonably effective performance while availability of the different rock P materials was extremely low. Among the commercial carriers investigated the metaphosphate and pyrophosphate forms were generally less effective than superphosphate. But mixing some $MgSO_4$ with the K metaphosphate greatly improved its effectiveness, apparently by facilitating the hydrolyzation of meta to ortho P in the soil. The K orthophosphate exceeded superphosphate in its utilization on all soils, presumably related to its greater water solubility. These results were obtained in a rather simple way in a short period of time and give a meaningful answer to the question of P carrier effectiveness on specific soils. Additional measurements of this type would obviously be useful in any given country for comparing all P carriers on the market including especially the ammonium phosphates that are generally predominant among manufactured grades today. Additionally, a band treatment should be included which is normally found to favour the more soluble sources.

3.3.4 Influence of N on P Uptake

Research in temperate regions has reported an enhancement in uptake of fertilizer P when N in the NH_4^+ form is concurrently placed with P in the soil. For investigating this feature in predominantly semi-tropical to tropical environments a series of field experiments with maize and rice was conducted with ^{32}P tagged superphosphate. The N and P materials were applied either mixed together in a band or in separate bands on opposite sides of the maize row or below the transplant in the rice hill. By having both P and N tagged in the maize experiment the opportunity existed for determining whether or not applied P also assisted plant uptake of simultaneously applied N. It will be noted in Table 8 that mixing N and P sources together decidedly increased uptake of the P compared with separate placement in seven of the eight maize experiments. The effect was less pronounced with submerged rice culture but still evident in thirteen of the sixteen locations. However, the joint placement provided no benefit for uptake of the N with either maize or rice. The principle evidenced here is responsible for the commonly observed greater availability of ammonium phosphate carriers over other P carriers with different associated cation, even where a common mono-orthophosphate ion is present in the respective compounds.

Table 8 COMPARISON OF BANDED N AND P FERTILIZERS WHEN MIXED TOGETHER AND PLACED SEPARATELY ON THE % P AND % N DERIVED FROM FERTILIZER IN MAIZE AND RICE PLANTS GROWN IN FIELD EXPERIMENTS (TAGGED AMMONIUM SULPHATE AND SUPERPHOSPHATE THE RESPECTIVE CARRIERS)

Location	% P dfff		% N dff	
	N + P sep.	N + P mix	N + P sep.	N + P mix
		Maize[1]		
Argentina	11	38	24	29
Brazil	31	45	37	43
Columbia	18	30	65	72
Egypt	1	2	14	14
Ghana	40	38	30	24
Mexico	2	8	50	51
Peru	12	33	47	44
Romania	15	21	57	58
Average	16	27	41	42
		Rice [2]		
Burma	4	5	23	28
Sri Lanka	38	50	32	36
Taiwan	6	7	27	27
Hungary	8	14	48	52
India I	10	17	44	47
India II	44	60	46	36
Italy	22	36	15	20
Korea I	8	7	50	44
Korea II	10	12	26	22
Madagascar	67	75	40	37
Bangladesh	56	53	20	22
Pakistan	40	40	33	36
Philippines	8	15	31	28
Thailand	72	82	28	30
Egypt I	18	34	25	25
Egypt II	20	27	33	33
Average	27	33	33	33

[1] Nutrient utilization in the total above-ground maize plant at 50 cm growth stage with 100 kg N and 35 kg P_2O_5/ha applied in bands 5 cm to the side and 5 cm below the seed row.

[2] Nutrient utilization in the total above-ground rice plant after 60 days with 30 kg N and 30 kg P_2O_5/ha applied below the transplant.

4. SUMMARY

The principles in effective fertilizer use are reasonably well known in the temperate regions of the world where the majority of the developed countries are found. Much less is known for the quite different soils of tropical and semi-tropical regions encompassing most of the developing countries. It was for the purpose of bridging this gap that the coordinated research programmes on fertilizer use were conducted by the Joint FAO/IAEA Division. Isotopic methods were employed for measuring directly the uptake of the nutrients N and P in the major food grain crops of those regions, viz. rice, wheat and maize with added projections for sorghum and millet, in the expectation of acquiring more specific answers to the question in the least time. Emphasis was on those two elements since they are the ones known to be most limiting for crop production in the developing world. The field work was conducted by cooperators in the various countries with isotopic ratio analyses accomplished by Joint FAO/IAEA Division staff in the Seibersdorf laboratory near Vienna.

With the increasing costs for energy during the recent past, production and distribution costs for fertilizers have risen without always a corresponding increase in the farmer's product prices. Thus, the need for utilizing fertilizer nutrients in the most efficient way possible has been accentuated, especially so for the small farmer in the developing countries. Beyond the economic aspect, there has been increasing concern about the environmental impact on the earth's systems of increasing amounts of man-fixed N now approaching the total fixed by all natural processes. Studies on N residues by the FAO/IAEA Joint Division are currently underway which will in time provide recommendations for managing these residues in the most expeditious manner without loss in crop productivity. Results to date indicate that minimal losses occur with good fertilizer management.

Timing of N fertilizer studies with the various grain crops under consideration have generally revealed the desirability for delayed application into the crop growing season of a significant portion of the total applied. The existence of an established root system when much of the N is provided means rapid crop uptake of the N with less opportunity for leaching and denitrification losses to occur. Results with delayed application are especially pronounced with the maize crop, less so for rice. Placement becomes a confounding issue with timing in the case of rice, presumably because of the volatilization potential accompanying the required surface broadcasting after the crop is growing. It appears as a general rule that some N at planting followed by the major portion applied in one or more increment just before and during the grand period of growth will afford the best results. The amount required at planting and as a seasonal total will depend heavily on the quantity of residual mineral N in the soil rooting zone.

Most of the work with crop culture under non-flooded soil conditions has evidenced the need for some incorporation of applied N. Positional availability to the crop root and/or minimized volatilization of NH_3 are the usual explanation. Otherwise concerning placement, the concentration of fertilizer N in a band at planting has been found to afford better crop utilization than ploughing down just before planting. Surface placement of N at planting for rice has proved to be especially ineffective, with probable explanation the rapid nitrification of ammonium carriers at the aerated water/soil interface in submerged culture followed by rapid denitrification of the NO_3^- as it moves down a few centimetres into the reduced zone of soil.

Little difference in relative effectiveness of the N carriers $CO(NH_2)_2$, NH_4NO_3, $(NH_4)_2SO_4$ and $NaNO_3$ has been found for the crops grown on aerated soil where the carriers were incorporated. In some cases the NH_4^+ containing and producing types have been utilized less effectively when surface broadcast due to positional unavailability to roots for a period until nitrification occurred if not due to NH_3 volatilization loss. The NO_3^- carriers, however, have been shown to be decidedly less effective than the NH_4^+ types for production of submerged rice because of denitrification of the applied NO_3^- component.

Where no limitation exists in soil depth for root exploration, the amount of root activity for absorbing N to 120 cm depth or lower by various crops is surprising. Despite the presence of 80-90 percent of the total mass of a given crop's root system in the surface 30 cm of soil it has been demonstrated that from 10 to 30 percent of total N uptake can occur from the 30 cm increment of soil around the 120 cm depth even though only 2-3 percent of the total root mass exists in the zone. This evidences the need for growers to be aware of mineral N that is accumulating in the deep root zone so that they can harvest it by adjusting cropping and fertilizer practices to reduce the potential of such deep N being leached to and contaminating the groundwater.

Application of P fertilizer must be made at planting for the wheat, millet, maize and sorghum crops so that it can be available for absorption from the earliest stages of the crop's development. This is in part the result of required placement of the P in the root zone due to its low mobility in soil. Flooded rice presents a different situation, however, where surface broadcasting of the P is fully efficacious and with which treatment can be made almost as late as primordial initiation with essentially equivalent results. Quite obviously there is very strong root activity of the rice plant at the soil surface when flooded, significantly greater than at depths of 10-20 cm in the soil.

Significant differences exist in plant availability of the various chemical carriers of P that exist on the fertilizer market. A described simple method for evaluating those available for purchase in a given locality is to uniformly tag with ^{32}P a group of representative soils of the area in greenhouse pots, then apply equal P rates for the various carriers and determine the amount of tagged soil P and fertilizer P absorbed by the crop. From these data the relative economic value of the respective materials is readily calculated. The procedure allows evaluation of the materials in the precise physical conformation in which they occur on the market, i.e. coarsely granular, powdery, whatever.

One of the most important cultural practices available for enhancing P utilization by the grain crop is the placement of some NH_4^+ with the P carrier in the soil. The phenomenon responsible is especially evident with crop production on aerated soil although still apparent with flooded rice culture. It is responsible for the usually observed higher availability to crops of the ammonium phosphates than other P carriers.

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ANNEX

JOINT FAO/IAEA DIVISION RESEARCH FINDINGS

RECOMMENDATIONS FOR FERTILIZER APPLICATION METHODOLOGY - CEREALS

Fertilizer source(s)	Recommended method of application
RICE (flooded)	
Superphosphates	Surface broadcast just before or at planting (incorporation in the surface is equally effective).
Urea, ammonium sulphate	1/3 banded 5-10 cm deep just before or at planting; 2/3 surface broadcast (in the water). 3 weeks after transplanting at the earliest, preferably later, but not later than primordial initiation.
Nitrate fertilizer (sodium nitrate, ammonium nitrate, nitric phosphates)	Should never be used for flooded rice.
Ammonium phosphate	Placed below the surface just before or at planting.
Natural phosphates (bone meal, rock phosphates)	Use only on acid soils; broadcast and/or incorporated in the soil before planting.
MAIZE	
Urea, ammonium sulphate, ammonium nitrate	1/3 banded 5 cm from seed row and 10 cm deep at planting; 2/3 side dressed at a plant height of 50 cm up to the start of tasseling, 15 cm from plant row, 10 cm deep. Where initial soil Nitrogen reserves are adequate all the fertilizer can be banded 15-25 cm from the plant row 5-10 cm deep any time between plant height 50 cm and tasseling.
Superphosphates, ammonium phosphates	Banded, 5 cm from seed row, 10 cm deep at planting. When ammonium fertilizer is applied simultaneously (not urea) Phosphorus fertilizer should be mixed with the ammonium fertilizer before application in the band.
WHEAT	
Urea, ammonium nitrate, ammonium sulphate	For acid soils under irrigation or high rainfall: Starter amounts (approx. 20 kg N/ha) placed with seed or in a band 5 cm from seed row (5-10 cm deep). The rest of the fertilizer applied at maximum tillering on the surface. For either high pH soils or lower rainfall conditions: All the Nitrogen should be banded. If banding not possible the Nitrogen should be incorporated in the soil prior to seeding. Up to approx. 20 kg N/ha can be placed with seed.
Superphosphates, ammonium phosphates	Placed with the seed or banded near the seed row 10 cm deep at seeding. When applying with ammonium fertilizers (not urea), mix before applying in bands (if more than approx. 20 kg N/ha not with the seed).

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