1. The chemistry and biology of flooded soils in relation to the nitrogen economy in rice fields

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Abstract. Response of lowland rice to sources and methods of nitrogen fertilizer application were summarized for more than 100 experiments. In about $\frac{2}{3}$ of the experiments, the yield increase per kg of fertilizer N was judged to be relatively poor with 'best split' applications of urea. Based on frequency distribution, sulfur coated urea and urea briquets or urea supergranules deep placed more often produced satisfactory yield increases than 'best split' urea, but even with these sources/methods the yield increases were judged to be relatively poor in about $\frac{1}{2}$ of the experiments. There is an enormous potential to increase rice production with no further increases in inputs of fertilizer N if we could learn to match the best method/source of fertilizer with the soil-crop management complex.

About 60% of the yields with no fertilizer N were in the range of 2 to 4 t/ha. Based on the average yield response to urea, this is equivalent to about 100 kg of urea N. It would appear worthwhile to study ways to improve utilization of 'soil nitrogen' since it is already in place on the land and apparently in fairly abundant amounts in many soils.

About 50 experiments with ^{15}N fertilizers were summarized. In almost all cases, the uptake of tagged fertilizer was less than the net increase in N in the above ground matter. In about $\frac{2}{3}$ of the experiments, the addition of fertilizer N increased soil N uptake more than 20% and in $\frac{1}{3}$ of the experiments the uptake of soil N was increased more than 40%. These results lead to much uncertainty about practical interpretation and use of ^{15}N data.

Introduction

The objective of this paper is to describe in a superficial manner some loss mechanism in lowland rice soils and to document some important problems in the N economy of lowland rice fields. Recent publications [2, 3, 4, 15, 28] have documented the state of knowledge of nitrogen balance studies and hence this aspect will not be reviewed here. The emphasis in this review will be on: (a) loss mechanisms and their dependence on transport processes; (b) yield increases per unit of applied fertilizer N; (c) yields in the absence of applied fertilizer N; and (d) behavior of ^{15}N in the lowland rice soils. Since other papers in this publication will deal with specific mechanisms, the emphasis here will be on observations and not explanations; the questions will be asked here, but such answers as are available will be provided in the succeeding papers.

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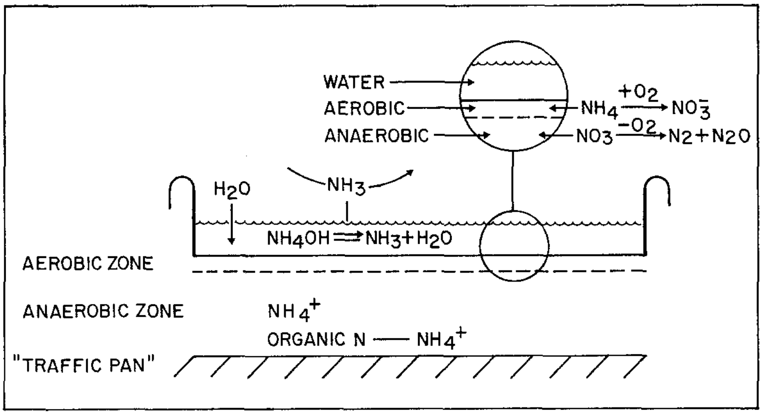

Figure 1. Nitrogen transformations in the ideal paddy.

The ideal lowland rice field

A cross section of an idealized lowland rice field is illustrated in Figure 1 together with the classical N reactions. First, a description of the water regime. In the bunded field shown here and, with ideal water control, there is only minimal and deliberate water movement from the lowland rice field; in some cases water is supplied to a lower field by flow through the upper field but under ideal water control this is managed so that unplanned movement of N is minimal. In an ideal lowland rice field there is a 'pan' at a depth of a few cm which restricts downward percolation (ideally 1 mm/day or less) [18] and lateral movement through the bunds is also not very important. Thus transport of nitrogen by water movement in this ideal lowland rice field is relatively unimportant and the lower limit of the rooting zone is fairly well defined by the 'pan'.

In the ideal lowland rice field the soil above the pan is well puddled and uniformly mixed, resulting in a substrate whose physical strength does not restrict penetration by roots. It is too viscous to be mixed by thermal gradients and, as pointed out above, flow of water is restricted; transport processes are thus mostly restricted to diffusion and mass flow of water.

Illustrated in Figure 1 is the thin oxidized zone (usually 1 to 20 mm in thickness) normally found at the interface between water and soil (5 pp. 89–91, 7, 20, 26, 27). However the bulk of the root zone is devoid of oxygen and in this zone only anaerobic microbial activity is possible. The multitude of chemical changes associated with anaerobic metabolism are all evident in this zone (22–25).

Mineralization of organic nitrogen in the root zone is often appreciable, as evidenced by yields of crops without fertilizer nitrogen and from mineralization in the laboratory (2, 5 p 103, 6, 27). In a later section yields in the absence of fertilizer N will be discussed more completely.

For our purposes we need to emphasize the rapid and complete reduction of NO_3^- to other forms (predominantly N_2 and N_2O) in the anaerobic zone. This precludes nitrate sources of nitrogen in any except extremely unlikely situations. A second important point is that NH_4^+ cannot be oxidized to NO_3^- in the absence of oxygen. The absence of water flow and stability of NH_4^+ means that NH_4^+ sources of N in the anaerobic zone are not subject to serious losses. This applies both to ammonium sources of fertilizer N and to nitrogen mineralized from organic matter.

The losses of N from the ideal lowland rice field as depicted in Figure 1 are largely restricted to the zone adjacent to the interface between water and soil (5 pp 100–103, 20, 21, 27). Here ammonium sources of N may be oxidized to NO_3^- in the thin aerobic soil zone and perhaps in the overlying water. This NO_3^- is then lost from the system when it diffuses to the anaerobic zone where it is denitrified. NH_3 volatilization from the overlying water is also an avenue of loss [17, 27].

So far the major processes mentioned have been the well known ones of mineralization, nitrification, denitrification, leaching and ammonia volatilization. These are the same processes we discuss in upland soils. How then do lowland rice soils differ from upland soils? Basically the biological processes are the same; or at least similar in many respects. Such differences as there are the result of the interactions (or non-interactions) between transport processes and a number of biological and chemical reactions.

The need to consider several processes simultaneously and the importance of transport processes can be illustrated by the ideal lowland rice field described above. First, consider ammonium nitrogen placed at a depth of 10 cm in the lowland rice field which is maintained in a flooded condition. The rate of transport of oxygen into the soil at the water-soil interface is too slow to satisfy the needs of the aerobic organisms and hence only a few mm of the soil contains any oxygen. Since only a mm or so of water is percolating through the paddy and diffusion of NH_4^+ is relatively slow, the bulk of the ammonia nitrogen remains close to where it was placed originally. The lack of transport mechanism for oxygen and the ammonium have prevented most losses of ammonium.

Now let us consider the same nitrogen broadcast on the surface of the bunded lowland rice with no water flow across/through the bunds. As a means of simplifying the argument let us suppose that added urea fertilizer dissolves immediately in the floodwater and hydrolyses immediately to $(NH_4)_2CO_3$. The concentration of NH_4^+-N in solution is inversely proportional to the thickness of the water and directly proportional to the amount of nitrogen added. We must now consider the rate of transfer across the two interfaces (air-water and water-soil) plus whatever reactions occur within the water. At the air-water interface, NH_3 volatilization is the major loss mechanism [17]. Loss is a function of partial pressure of NH_3 in equilibrium with the water, transport in the air-water interface, and transport mechanisms in the air. The partial pressure of NH_3 is in turn set by a number of variables; probably photosynthesis is the most important since during the day it may deplete the CO_2 in the water more rapidly than it can be replenished by transfer across the interfaces. Loss of CO_2 in turn leads to marked increase in pH. Thus we have the sequence:

Photosynthesis depletes CO_2 → increases pH → increases partial pressure of NH_3 → increases NH_3 volatilization.

At the soil-water interface, transfer across the interface will be determined by diffusion and mass flow of water. The major parameters are: concentration gradient, mass flow of water, reactions of ammonical nitrogen with the soil and diffusion coefficient of ammonical species in the soil (5 pp. 105, 20, 21). One interesting aspect of diffusion is that initially the fluxes may be into the soil but as the water is depleted of ammonical nitrogen by volatilization, the flux of ammonia may be reversed from ammonical nitrogen into the soil to ammonical nitrogen back to the water.

Turning attention now to nitrification, depending upon the population of nitrifiers and their build-up, more or less of the ammonical nitrogen will be nitrified in the aerobic zone at the soil water interface. Some of the nitrate will then be transported by diffusion into the overlying water and some will be transported by mass flow and diffusion into the underlying anaerobic soil where it is denitrified (5 pp. 105, 20, 21). Thus we have:

diffusion (mass flow) of NH_4^+-N into soil → nitrification → diffusion of NO_3^- to anaerobic zone → denitrification

Based on the foregoing idealized lowland rice system, the placement of ammonium sources of nitrogen in the anaerobic zone of the ideal lowland rice field would be expected to be far superior to surface placements and indeed this has been shown to be true where conditions approach the ideal [23].

Based on reasoning about transport processes, soil chemical and microbial processes, and chemical and photosynthetic processes in the water, wide variation among locations and years would be expected from ammonium nitrogen broadcast on the surface of the ideal lowland rice field. Yield response to fertilizer should be inversely proportional to losses and this variation in losses should lead to variaion in yield response. This in fact is observed as will be documented in subsequent discussion.

A common method of nitrogen placement is the so-called 'basal, broadcast and incorporated'. In this procedure ammonium sources of nitrogen are broadcast on the surface of a fairly well puddled field and then incorporated by some tillage operation. A bit of reasoning, imagination and observation of what farmers do, soon leads to the conclusion that variation of losses among farmers, soils, locations, and local conditions must be enormous because of the interactions among the processes which occur (e.g. variation in degree of incorporation might vary from superficial to uniform mixing with several cm of soil).

The non-ideal lowland rice field

Soil properties and water regimes, which differ from the ideal, add additional variation to behavior of soil and fertilizer nitrogen in lowland rice soils. The range of variation in soil and water regimes has been documented and discussed in detail elsewhere [18]. Examples of variations which are likely to have a major impact on behavior of soil and fertilizer nitrogen follow. In light textured soils, the permeability to water may be high enough that some leaching of nitrogen occurs, although this is not well documented. In other situations with high soil permeability, the oxidized zone may be relatively thick (several cm); nitrification may be extensive in the oxidized zone and the flow of water through the soil insures rapid transport of nitrate to the anaerobic zone where it is denitrified. In still other situations the water management may be imperfect and, during the growing season the soil may undergo enough drying that the ammonium nitrogen is oxidized to NO_3^-; upon subsequent reflooding the NO_3^- is denitrified and lost from the system or else leached from the rooting zone. This mechanism (alternating wetting and drying) may be particularly serious sink for soil nitrogen in regions with wet-dry seasons. Following the dry season the soil will often be wet to field capacity by the initial rains at the beginning of the wet season; mineralization and nitrification may occur relatively rapidly under the favorable water and temperature regimes. Then as the rains increase in intensity and frequency the soil becomes water-logged and the previously mineralized nitrogen is denitrified.

Soil properties and water regimes which vary widely from the ideal are very common both on experiment stations and farmers' fields. Only seldom will one find the combination of soil properties and water regimes which approach the ideal. However, the ideal does provide one extremely important piece of information; it demonstrates beyond a shadow of doubt that there is nothing inherent in the lowland rice field regime which precludes high yields per unit of available nitrogen (whether the nitrogen be from soil organic matter or fertilizer). Thus the ideal lowland rice field with proper water control is in fact a situation where extremely high yield increases can be obtained with ammonium sources of nitrogen properly placed (on the order of 50 to 60 kg grain per kg of fertilizer N).

The importance of transport processes

The aim of the above discussion has been to emphasize the linkages between biological and chemical processes and transport processes which determine

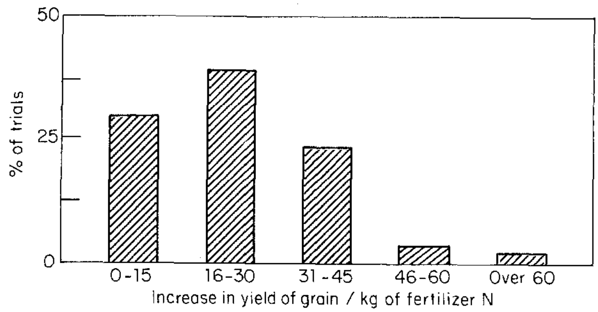

Figure 2. Frequency distribution of grain yield increases per kg of fertilizer N for 109 trials in Asia and Southeast Asia. The increases are for the first increment (28 kg N in wet season, 56 kg N in dry season). Nitrogen was in the form of urea and method of application was considered to be 'best split' by the individual investigators.

the relative importance of the various classical and well known N mechanisms. Furthermore, the differences between upland and lowland soil are not biological processes which are unique to each system but rather the differences are the result of variation in the linkages between the biological, chemical and transport processes which determines the relative importance of the various reactions. In fact one could argue that the kinetics and the relative importance of the various loss mechanisms are mostly determined by transport processes rather than the intensity and capacity of common soil chemical characteristics.

Yield increase per unit of applied fertilizer N

In the final analysis, yield increase of grain per unit of applied fertilizer N is the most important aspect of nitrogen fertilization of rice. Summarized in Figure 2 is a frequency distribution of yield increases reported for the First, Second and Third International Trial on Nitrogen Fertilizer Efficiency in Rice [9–12]. This probably represents the state of the art with conventional sources and methods of application. The source of N was urea and the method of application was what each investigator considered to be the 'best split'. This probably represents something better than farmer management of land preparation, water management, control of pests, variety selection, etc. and we suppose that most farmers would not do this as well as in these experiments.

As an aide in interpretation, 50 kg grain per kg of fertilizer N is considered a practical upper limit [13, 30]. The grain itself will contain about 1.3% N, the straw will contain $\frac{1}{3}$ to $\frac{1}{2}$ as much N as the grain and roots will contain 20 to 30% as much as in the top of the plant. Approximately, the N content of the plant is increased about 1 kg for each kg of added fertilizer N when a

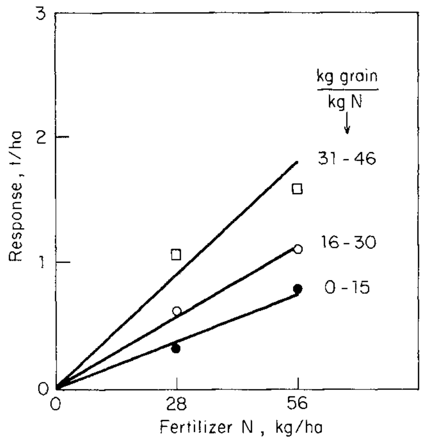

Figure 3. Average response at locations grouped according to kg grain/kg N with 8 locations per groups (International Rice Research Institute 1978b). Points are average of experimental observations, lines are drawn by eye for reference purposes only.

yield increase of 50 kg grain/kg N is obtained. A comparison of this with the results shown in Figure 2 illustrates that only in a very few experiments did the yield increases approach the 'ideal'. In about $\frac{1}{4}$ of the experiments the yield increases ranged from 30 to 45 kg grain/kg N. Thus, there seems no doubt that actual responses were $\frac{1}{2}$ or less of the ideal in approximately $\frac{1}{2}$ of the experiments.

Several possible explanations are:

- losses of fertilizer N by leaching and denitrification of N_2, N_2O and volatilization of NH_3
- immobilization of fertilizer N
- poor root distribution/activity in the zone of soil influenced by fertilizer
- poor response because of low yield potentials

The last possibility is examined by looking at the average response obtained in the wet season of the Second International Trial [10] in which about $\frac{1}{3}$ of each of 24 experiments fell into three response categories. The results shown in Figure 3 illustrate that the average response to two increments of fertilizer was approximately linear and hence there seems no reason to suppose that a major share of the poor response can be attributed to low yield potentials.

Illustrated in Figure 4 is the frequency distribution of responses with different methods and sources of fertilizer N from the three sets of trials referred to for Figure 2. This illustrates the generally improved response obtained with SCU and urea supergranules (USG) relative to the 'best split' and that at almost $\frac{1}{3}$ of the locations, the response to USG fell into the 31–45 kg grain/kg N category. Although the SCU and USG represent an

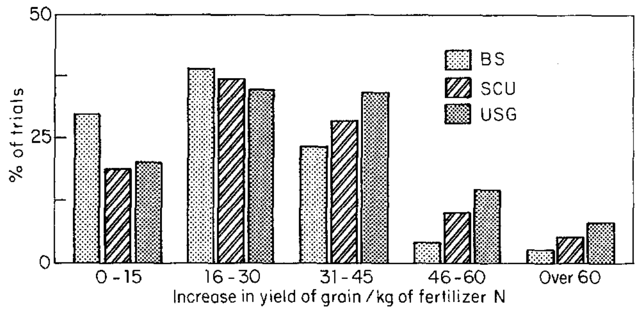

Figure 4. Frequency distribution of grain yield response per kg of fertilizer N for different sources and methods of fertilizer application. B.S. = best split, urea, SCU = sulfur-coated urea, USG = urea supergranules deep placed, 109 experimental observations with B.S., 106 observations with SCU and 74 observations with USG. First increment of fertilizer, 28 kg N/ha in wet season and 56 kg N/ha in dry season.

advancement over the 'best split', at about $\frac{1}{2}$ of the locations the response was on the order of $\frac{1}{2}$ or less of the 'ideal' of 50 kg grain per kg N.

In Table 1, the correlation among the three sources/methods and the means for each is listed. The results indicate that there is considerable difference in behavior among them at the different locations and that response to 'best split' urea and SCU are not correlated with each other even at the 5% level. This indicates two things: (a) that the poor response with 'best split' illustrated in Figure 2 is not entirely a consequence of low yield potential; and (b) whatever cause they behave differently among sources in the same soil. Thus there appears to be no one cause associated with poor response per unit of N for a given soil/experiment, and there are interactions among soils and sources/methods.

There is no evidence from the experiments themselves about the relative importance of three of the factors listed earlier in connection with discussion of Figure 2 (loss of N, N immobilization, ineffective root system). These can only be clarified by studies of soil chemistry, root behavior and crop attributes measured periodically during the growing season. Since there is considerable variability in which sources/method is most effective in a given soil, an association between soil/crop/climate properties and best method/source is essential information in improving response of rice per unit of fertilizer N.

Soil nitrogen

The nitrogen supplied by the soil is sufficient for sizable yields in many situations and in fact, may be equivalent to the yield increases obtained with substantial amounts of fertilizer N (e.g. yields of 3 t/ha without fertilizer N are equivalent to yield increases obtained with 100 kg/ha of 'best split' urea N

Table 1. Correlation matrix and mean responses for 21 experiments in the second international trials (IRRI, 1978b).

	BS	SCU	BQ	Mean kg grain/kg N
BS	1.00	0.37^{NS}	0.53^{**}	29
SCU	0.37^{NS}	1.00	0.49^{*}	33
BQ	0.53^{**}	0.49^{*}	1.00	39

NS = Not significant at 5% level
* Significant to 5% level
** Significant at 1% level
BS = Best split
SCU = Sulfur-coated urea
BQ = Briquets

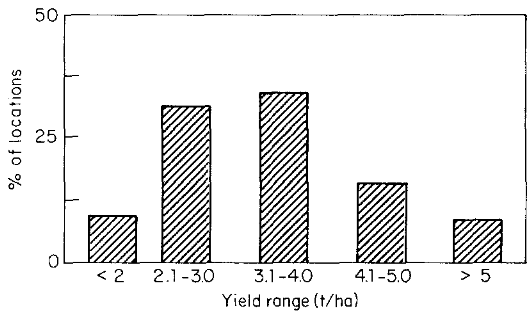

Figure 5. Frequency distribution of yields without fertilizer N in 152 trails in South and Southeast Asia.

when response is 29 kg grain/kg N, the average shown in Table 1). A summary of results from 23 long-term studies showed that 22% of the yields with no fertilizer N ranged between 1 and 2 t/ha, 52% between 2 and 3 t/ha and 26% between 3 and 4 t/ha [15]. Illustrated in Figure 5 are the results from four projects in Asia and SE Asia [9–12] with a total of 152 location-years of results. These results illustrate that approximately 60% of the yields range between 2 and 4 t/ha of rice without fertilizer nitrogen.

The conclusions of this section are the following: (1) the nitrogen supplied by the soil is an extremely important component of rice production; (b) very little research effort is expended on studying how to use soil nitrogen more effectively (or at least reports of extensive research are not found in the literature); and (c) is some fraction of the resources now devoted to fertilizer N were diverted to a study of soil N and its management, then perhaps substantial increases in yield could be obtained with resources already on the land.

Behavior of ^{15}N in lowland rice

The second section cited the lack of information on the general mechanisms responsible for low response per unit of applied N. ^{15}N seems a likely tool to use in such studies and hence the following section is an examination of some uses of ^{15}N reported in the literature. In many ^{15}N studies the response of grain yield per unit of applied N was not a major objective. Thus in this section that parameter will not be used. We will use the parameter 'net change in N in above-ground dry matter per unit of applied N' ($\Delta NP/\Delta NF$) as one parameter and 'change in ^{15}N in above ground dry matter per unit of applied ^{15}N ($^{15}\Delta NP/^{15}\Delta NF$)' as a second parameter.

By definition:

$$\frac{\Delta NP}{\Delta NF} = \frac{NP]F - NP]o}{NF}$$

where NP]F = total N in above-ground dry matter when quantity NF of fertilizer N is added
NP]o = total N in above-ground dry matter when no fertilizer is added

$$\frac{^{15}NP}{^{15}NF} \times 100 = \frac{^{15}NP/f}{^{15}NF}$$

where ^{15}NP is the total amount of ^{15}N in above-ground dry matter, f atom % of ^{15}N fertilizer N and ^{15}NF is quantity of fertilizer tagged with ^{15}N which was added.

In effect, the first quantity is the net effect of the fertilizer addition on the accumulation of N by the above-ground dry matter while the second quantity is the fraction tagged nitrogen which is accumulated by the plant.

Figure 6 summarizes the relation between these two parameters from data found in the literature [1, 3, 8, 14, 16, 19, 29]. Very clearly the uptake of ^{15}N by the plant underestimates by a considerable amount the net effect of the fertilizer on accumulation of N by the plant. The discrepancy between the two is made up of ^{14}N from the soil. The frequency distribution of the ratio of soil N with fertilizer [= total N in plant minus (total ^{15}N in plant/f)] to soil N without fertilizer (= total N in plant when no fertilizer is added) is shown in Figure 7. Thus the addition of fertilizer N markedly enhances the apparent uptake of soil N; in about $\frac{1}{2}$ of the experiments the enhancement was 40% or more.

One interpretation of the latter is that additions of fertilizer will lead to rapid depletion of the soil N (in case the fertilizer N not taken up by the plant is lost from the soil and hence does not balance the enhanced soil N uptake). This interpretation does not seem to be consistent with experience.

Probably at least part of the discrepancy shown in Figure 7 can be attributed to accumulation of more or less ^{15}N by the biomass with release of

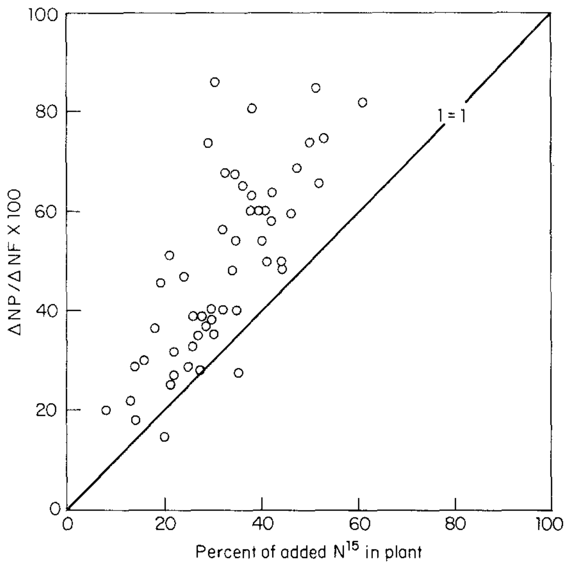

Figure 6. Net increase in total N in above ground dry matter per unit of applied fertilizer N plotted against percent of the ^{15}N added in the fertilizer which is found in the top of the plant. Points are experimental observations, line is 1:1 line drawn for reference purposes only.

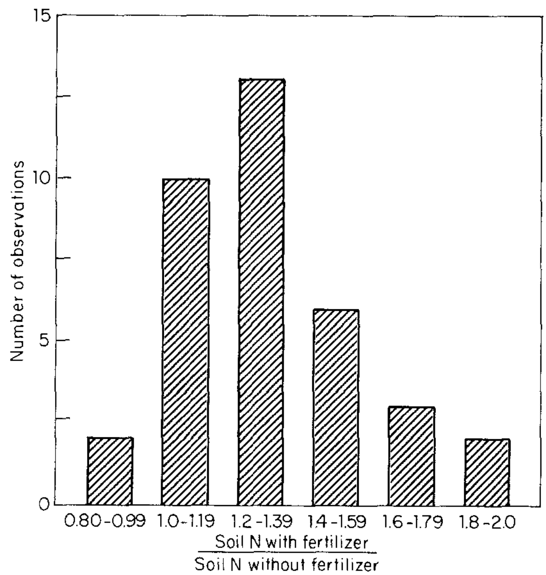

Figure 7. Frequency distribution of ratio of soil N in plant with fertilizer to that in plant when fertilizer is added.

approximately the same amount of ^{14}N from the biomass essentially an exchange process, with net mineralization – immobilization being small relative to the exchange of ^{15}N in the inorganis soil pool for (organic) ^{14}N in the biomass.

Regardless of the reasons, there can be no doubt that ^{15}N fertilizers are *not* reliable predictors of *net* effects of fertilizer additions on accumulation of N by the plant. It follows from this that ^{15}N tagged fertilizers are not useful in making economic interpretations of fertilizer N additions since economic yield increases are to some extent dependent upon increases in accumulation of N in the above-ground dry matter. Thus ^{15}N appears to be a useful to the extent that it enables us to differentiate among the various reasons for differential response to sources/methods of applied fertilizer N. However, the results cited above indicate that some important questions remain to be answered about how to interpret ^{15}N data.

Conclusions

1. In a substantial number of location-year experiments, grain yield increase per unit of applied fertilizer N is unacceptably low regardless of source and method of application.

2. The reasons for poor performance appear to vary among sources/ methods of application at a given location and among locations.

3. The reasons for poor performance of fertilizer nitrogen can only be determined by study of soil-crop factors during the season at several locations where soil-crop-management factors vary widely among locations.

4. There is an incredible potential for increasing grain yield of rice with no further increases in inputs of fertilizer N if we could learn how to match the best method/source of fertilizer with the soil-crop-management complex.

5. The nitrogen supplied by the soil is an extremely important factor in rice production. More research needs to be devoted to the 'care and management' of soil nitrogen.

6. The interpretation of ^{15}N data seems unclear. However, ^{15}N must be developed as a useful research tool in lowland rice systems in order to achieve the objectives listed above.

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