Nitrogen Availability in SAT Soils: Environmental Effects on Soil Processes

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Abstract

In the past, fertilizer needs of crops in India have been assessed by conducting numerous fertilizer response experiments. Recent advances in crop modeling have led to suggestions that the models based on physical environmental factors may be extended to include descriptions of nutrient behavior. One difficulty in this approach is the harsh environment of the semiarid tropics (SAT) and the effect of this environment on processes affecting nitrogen availability in the soil. Another constraint is the dearth of direct measurements and quantitative descriptions of many processes in the field (e.g., mineralization, urea hydrolysis, leaching, denitrification, and ammonia volatilization). Such measurements are urgently needed, with appropriate attention to methodology, to provide information needed for models that include nutrient terms.

Introduction

Nitrogen deficiency is the most important of the nutrient disorders in India (Prasad and Subbiah, 1982; Randhawa and Tandon, 1982), as shown clearly by the dominance of nitrogen in the fertilizer nutrients used (Biswas, 1989). Although most Indian soils are usually deficient in nitrogen for nonlegume crops, widespread fertilizer N use has been confined primarily to irrigated crops and dryland cash crops. Dryland cereals have received relatively little nitrogen, despite examples of large and apparently highly economic responses (Tandon and Kanwar, 1984). One reason for this is the variability in responses (Table 1) presumably caused in large part by variations in rainfall or its intraseasonal distribution (Jha and Sarin, 1984). Cereal responses to nitrogen are noted for their dependence on an adequate moisture regime (Russell, 1984). How to delineate nonresponsive from responsive locations is thus a major question, deserving perhaps the highest priority.

Under irrigated agriculture, the development of sound fertilizer application recommendations (which, judging from the use of fertilizer in India, have been generally well accepted by farmers) was based on the combination of two main factors: the certainty of responses under assured moisture regimes and the results of many hundreds of empirical nitrogen response experiments. However, it would seem that the number of empirical field experiments could have been greatly reduced if modeling approaches had been used.

The accurate assessment of the fertilizer nitrogen needs of crops requires much greater effort, however, under the variable moisture regimes of dryland agriculture than under assured moisture regimes. The major difficulty is that overall effects of moisture and nutrient

Table 1. Summary of Response of Rainy Season Crops to Fertilizer N

Crop	Range of Response (kg grain kg^{-1} N)
Sorghum	3.4 - 43.4
Pearl millet	2.1 - 24.8
Finger millet	5.0 - 42.4
Maize	4.1 - 67.4
Rice	4.5 - 33.9
Setaria	5.9 - 17.9
Sunflower	1.5 - 22.6
Castor	2.9 - 7.2
Groundnut	1.3 - 6.0
Linseed	1.2 - 11.5
Sesamum	1.3 - 5.0

Source: Rao and Das (1982).

interactions are not known, and their probable complexity indicates that modeling should be a much more efficient means of predicting fertilizer needs. The approaches used in modeling, however, require careful consideration to ensure that major factors in the semiarid-tropical environment are fully understood.

Aspects that need particular consideration in the development of models are the harshness of the SAT environment and the marked variations in agroclimate that occur – both through the year and within seasons. Many of the modeling approaches have been developed under temperate climates, with an emphasis on the relationships between crop growth and yield and the physical environment – especially water, light, and temperature. In extending such models to include nutrients, we need to consider the effect of the relatively harsh environment in the SAT not only on plant growth but also on soil processes that influence nitrogen supply. Regrettably, some of these soil processes are somewhat intransigent. Many involve microbiological activity, which is less easy to characterize than physical factors in the environment, and additionally a number of processes present considerable difficulty in the development of quantitative relationships to describe the operation of the process in the field.

The purpose of our paper is not to review the great number of fertilizer response experiments, but instead to indicate some of the past work on processes that affect the supply of nitrogen to plants, especially those processes that may be particularly affected by the SAT environment. These must be considered in any modeling approaches in dryland agriculture where nutrient-water interactions are expected.

Predicting Nitrogen Supply

Organic N commonly accounts for over 90% of the total N in most soils, and this N is made available to plants through the mineralization process. This process, which converts organic N into ammonium, is carried out by a diverse population of heterotrophic soil microorganisms. Only a very small fraction of the total soil nitrogen is mineralized and thus becomes available to a crop during a growing season. In upland soils, ammonium formed via mineralization is further converted to nitrate, which is subject to several loss mechanisms. Fertilizer N that has been incorporated into soil organic N is also subject to these general processes of mineralization and loss.

The amount of nitrogen available for crop uptake is the total N supplied by soil or fertilizer less that which has been subjected to various loss processes. For convenience we shall describe this amount as the net supply. In India, the predominant data available are numerous estimates of the net supply, obtained by the simple method of measuring crop N uptake. Useful as this information has been for providing a general view of the net N-supplying capacity of Indian soils, it has limitations for the development of models; for these, we may need to consider the major factors that influence each of the important processes that contribute appreciably to the net nitrogen supply. These two approaches are discussed for both soil N and fertilizer N supply.

Net Soil N Supply

Determination of soil N uptake by crops is perhaps the most convenient approach for assessing net soil N supply. Crop uptake of N from non-N-fertilized treatments is determined over a number of years to get a reasonable estimate of the average N-supplying capacity of the soil at one particular location. Measurements based on crop uptake should encompass a range of different seasons in relation to seasonal rainfall and its distribution and the effects of temperature on soil processes. From the amount of soil N taken up by the crop, the net amount of mineralized N could be estimated as a fraction of the total N or organic N content of the soil.

Estimates of the N-supplying capacity of soil using this approach would include allowance for the cropping history of the soil, especially the use of legumes in the cropping system, in addition to seasonal effects – such as soil moisture, temperature, and crop. This type of approach is particularly useful for eventual extension applications. However, for the development of the basic research models necessary for such extension applications, it has severe limitations. The major problem is that the causes of the variations in N supply between years will not be known (and usually are assumed by correlation with "likely" environmental factors) unless studies are made to specifically identify them.

Total Soil N Supply

Estimating the total soil N supply, i.e., seasonal or annual mineralization of soil organic N, is much more difficult than assessing the net supply. Nevertheless, in association with estimates of nitrogen losses, these estimates offer a much better understanding of the factors influencing soil N supplies.

The simplest approach is to predict the amount of nitrogen mineralized on the basis of the total nitrogen content of a soil and the known decomposition rates of organic matter, as given by the equation commonly used to describe the annual changes in soil nitrogen:

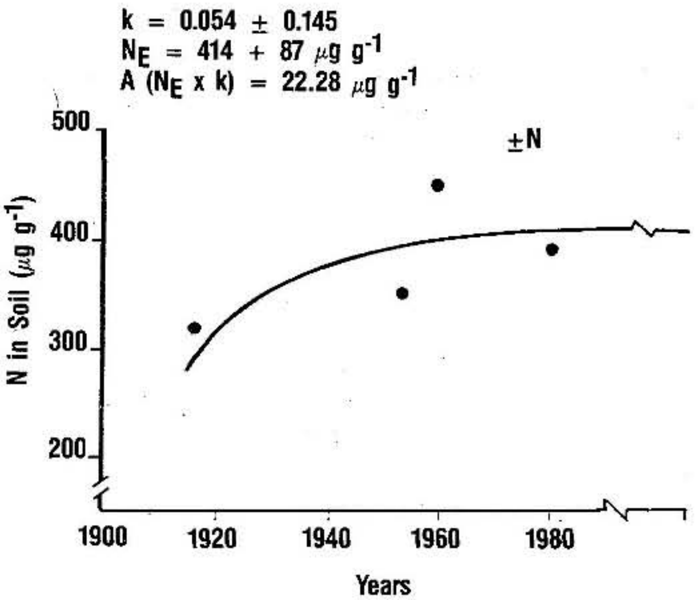
$$dN/dt = -kN + A$$

where k is the decomposition rate.
N is the total amount of soil nitrogen.
A is the annual return of nitrogen.

This equation, of course, is the simplest. Modifications involve the introduction of terms to include the contributions by fertilizer and changes in the annual return of nitrogen with different crops (Russell, 1975).

The use of this basic approach is hindered by the present level of knowledge for SAT soils. Few measurements of the decomposition constant have been made. By examining nine long-term experiments in India, we could get data from only one – the classic Coimbatore Old Permanent Manurial experiment – for making the appropriate calculations (Kausalya, 1982): the result, k = 0.054, appears reasonable for a continuously cultivated soil in the semiarid tropics, but the error term (±0.145) leaves us with no doubt as to the confidence that we can place on this value (Figure 1). The only other serious study in the semiarid tropics (or subtropics) appears to be the recent work of Dalal and Mayer (1986) who obtained good results for a number of soils including Black Earths (Vertisols) in the subtropical Darling Downs area of Australia.

The second impediment is that most measurements of total soil nitrogen are not accompanied by ancillary measurements of fixed ammonium. For at least some Vertisols, fixed ammonium contents are sufficiently high – 22% in the surface soil, increasing to 40% at depth (Table 2) – that the presence of N in this form needs to be recognized. The role of such fixed ammonium is not known, despite many laboratory measurements of fixed ammonium in soil. We presume that this nitrogen is not easily released and that organic N is the source that should be used for calculating mineralization rates.



Source: Kausalya (1982).

Figure 1. N Content of Soil (0-15 cm) in the Old Permanent Manurial Trial (unirrigated) at Tamil Nadu Agricultural University (TNAU), Coimbatore.

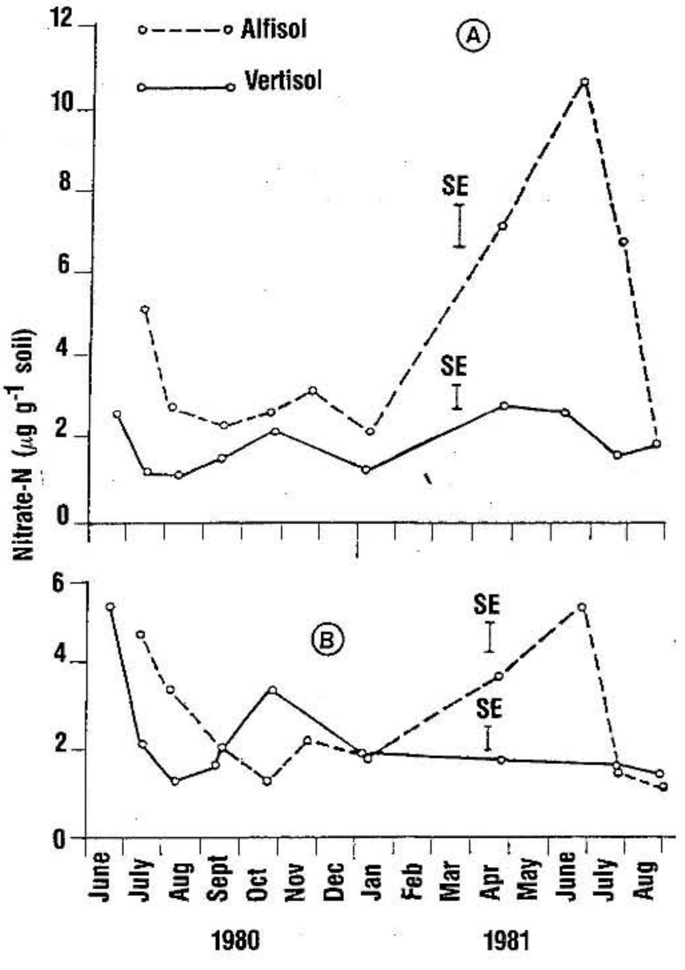
Table 2. Fixed Ammonium in the Kasireddipally Benchmark Profile at ICRISAT Center

Soil Depth (cm)	Fixed Ammonium N (mg kg^{-1})	Organic N (mg kg^{-1})
0-15	113	371
15-30	107	278
30-60	100	231
60-90	99	205
90-120	110	208
120-150	102	174
150-170	100	145

Source: ICRISAT (1983).

The third impediment is only an apparent hindrance. The factors that determine N mineralization rates in soils include soil moisture, temperature, drying, nature of organic matter (fresh residues, C/N ratio, etc.), and soil depth (and distribution of organic matter with depth). Unfortunately all these factors act simultaneously to influence the amount of mineral N that is released and thus available to plants. Any soil N modeling exercise has to consider the overall effect of these factors on the release of mineral N. There is a dearth of data on the release of mineral N, not only in the field but also under controlled conditions, as well as on how these factors affect mineralization. Unless such data are obtained, researchers may need to resort to the use of laboratory methods for assessing the N mineralization capacity of soils. Such soil test methods – mainly those based on organic C determination, the amounts of ammonium released from soil organic matter by the oxidative action of alkaline permanganate, and aerobic and anaerobic incubation tests – have been useful for predicting nitrogen supply under controlled conditions (e.g., in the greenhouse or under irrigated agriculture). They have generally been less successful for rainfed agriculture (Indian Society of Soil Science, 1984) where the effects of variable moisture on crop growth and N mineralization have not been adequately characterized.

Although these impediments present a daunting task, selective studies on some aspects will be quite worthwhile. Regardless of whether relatively empirical or basic approaches are used to assess soil N supply, some information will be needed on environmental effects that cause major changes in soil N levels. A good example is our studies on the "Birch effect" – the flush of microbial activity that occurs on the wetting of soil that has been severely desiccated. Such a situation occurs in SAT India at the beginning of the rainy season in June, after the very hot (commonly 40°C maximum) and very dry (to <10% minimum humidity) summer season. The most interesting feature is the marked difference between our two benchmark soils – an Alfisol and Vertisol – in their mineralization following rewetting (Figure 2). The difference is reflected in their biomass (Table 3).



Source: Kausalya (1982).

Figure 2. Seasonal Fluctuations in the Nitrate-N Contents of Surface 0-15 cm (A) and Subsurface 15-30 cm (B) Depths of an Alfisol and a Vertisol, ICRISAT Center, 1980/81.

Table 3. Comparison of Biomass-C Contents of Surface Soil (0-15 cm) of an Alfisol and a Vertisol, ICRISAT Center, 1981[a]

Measurement	Alfisol	Vertisol
Biomass (μg C g^{-1} soil)	11.4±1.6	3.4±0.3
Total C (%)	0.35	0.60
Biomass-C (% of total C)	0.326	0.056

a. Sampling dates: Alfisol, August 28; Vertisol, August 25. Values are means from uncultivated and deep-cultivated plots.

Source: ICRISAT (1983).

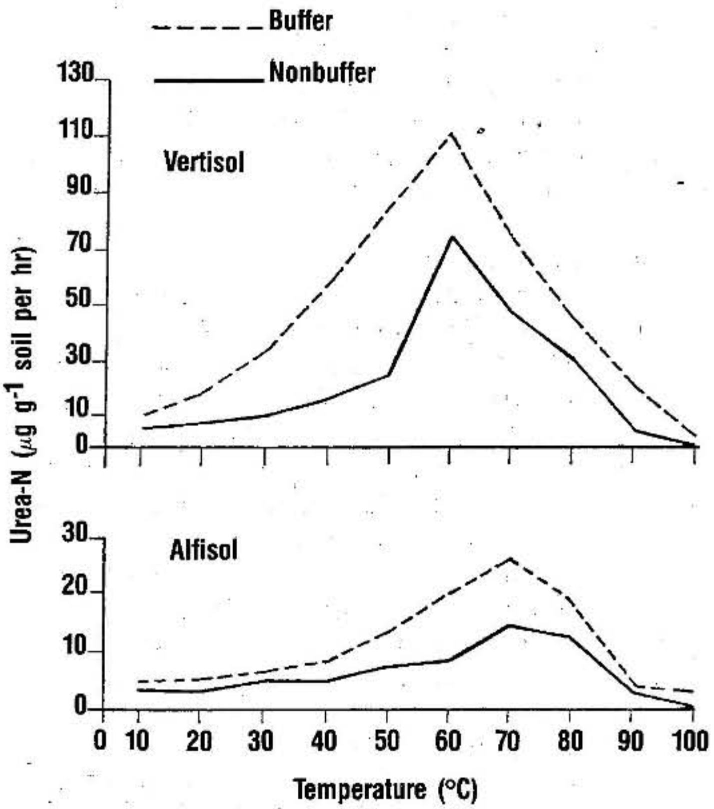
Fertilizer N Supply

The fertilizer N supply term is a much easier one to calculate because we know the total supply (which is the amount that we add). Under favorable environmental conditions, the use of fertilizer by a crop can be relatively efficient because the farmer or researcher can decide when and how to add fertilizer.

Nevertheless, appreciable losses of fertilizer N can occur, and studies of such losses are useful for indicating not only the causes of fertilizer N losses but also the losses of mineral nitrogen derived from soil organic N. These loss mechanisms will be discussed in the next section.

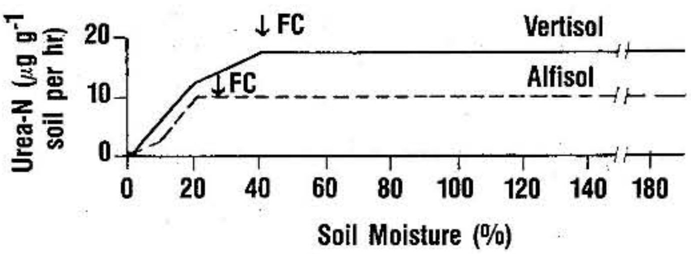
One aspect of fertilizer use needs particular consideration. Urea is the dominant form of fertilizer N used, but its use by plants depends upon the hydrolysis of urea to ammonium and subsequent oxidation to nitrate. Little serious characterization of the rates of these reactions has been made in the field, and such characterization is especially important in developing fertilizer application strategies. Urea and nitrate are readily leached, but ammonium is not; heavy rainfall would cause substantial losses if it occurred immediately after urea application or after conversion of urea entirely to nitrate.

Surprisingly, relatively little information is available on the specific environmental conditions that determine the rate of urea hydrolysis in the field. In the laboratory, urea hydrolysis was found to have a particularly high optimum temperature, 60°-70°C (Figure 3), and the rate was surprisingly constant with increase in moisture content beyond field capacity (Figure 4). Preliminary studies have indicated that laboratory measurements of the hydrolysis rate can be applied to field situations, provided that the soil temperature and moisture conditions in the field are correctly monitored (Jayakumar, unpublished data). The



Source: Sahrawat (1984).

Figure 3. Effect of Temperature on Soil Urease Activity in a Vertisol and an Alfisol. Standard Error for Comparisons at the Same Level of Temperature and Method = 1.9 μg N g^{-1} Soil Per Hour.



Source: Sahrawat (1984).

Figure 4. Effect of Moisture Content on Soil Urease Activity at 37°C. Field Capacity (FC) of Each Soil Indicated by an Arrow.

surprising feature has been the particularly high rate of hydrolysis; 100 kg urea-N ha^{-1} can be hydrolyzed to ammonium within 24 hours. The urea hydrolysis rate is dependent upon the level of urea in the soil up to very high concentrations, i.e., about 2,000 mg urea-N kg^{-1} soil.

Factors Reducing Nitrogen Supply

Around the world, the various loss processes have intermittently attracted enthusiastic attention, primarily because, in some special situations, each of these loss processes can cause substantial reductions in the amount of nitrogen available for crop growth. However, in India, the vast body of literature on crop responses to nitrogen contrasts with the minute number of reports showing that a loss process is important. While the importance of a particular agronomic yield result is frequently attributed to one or more of the soil nitrogen loss processes, almost invariably the evidence is indirect. There is an urgent need for direct measurements of particular loss processes and quantification of the relationships between such losses and environmental and/or agronomic factors. Some of the known data are given below. For these, we draw heavily upon the review by Goswami and Sahrawat (1982) and our own research at ICRISAT Center.

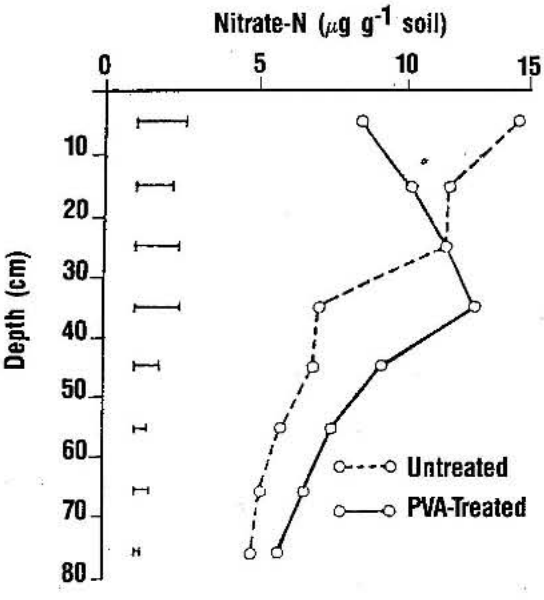
Leaching

Leaching, perhaps the oldest recognized cause of N loss, can result in substantial losses of nitrogen that are neutral (urea) or anionic (nitrite and nitrate) in form. For dryland agriculture in the SAT, losses by leaching depend upon the coincidence of heavy rainfall and the occurrence of high concentrations of such soluble N in the soil. Clearly, the use of some type of probability analysis, in association with knowledge of the forms of soil nitrogen, is required. Of note, however, is the absence of data on leaching losses from dryland agriculture in India. For example, all ten studies cited by Goswami and Sahrawat (1982) on leaching relate to irrigated agriculture or greenhouse studies; not one reported field measurements of leaching under dryland agriculture.

Highly relevant for dryland agriculture is the result of our simple study at ICRISAT Center (Figure 5). The poor structure of Alfisols is well known. Although improvement in structure may increase infiltration, with possible beneficial effects on crops because of better water resources, this additional entry into the soil may cause leaching of nitrate to a greater depth and thus place it beyond the reach of plant roots.

Denitrification

No direct measurements of denitrification have been reported under dryland agriculture in India; this contrasts



Source: ICRISAT (1983).

Figure 5. Movement of Nitrate-N in Nontreated and PVA-Treated Alfisol Under Natural Rainfall, ICRISAT Center, 1982.

with several reports demonstrating appreciable losses under paddy rice culture (De Datta and Patrick, 1986). Deficits in the recovery of ^{15}N-labeled fertilizer N are a common means of indicating losses; losses of almost 30%–from a Vertisol in a particularly wet year–can probably be attributed to denitrification (Table 4).

Substantial losses by biological denitrification can be expected on heavy-textured soils (such as Vertisols) in the higher rainfall areas of India, based on comparisons of this environment with others in which gaseous losses of nitrogen have been directly measured (Burford et al., 1981) or estimated by deficits in ^{15}N recovery (Craswell and Strong, 1976) from similar heavy clay soils in England and Australia. Because the indirect methods of assessing such losses are associated with considerable uncertainty, direct measurements of denitrification losses are urgently needed for the development of models.

Table 4. Effect of Method of Urea Application on Recovery of ^{15}N-Labeled Fertilizer N; Vertisol, ICRISAT Center, Rainy Season, 1981

Method of Fertilizer Application[a]	Recovery of Fertilizer N: Plant	Soil	Loss
	------ (%) -----		(%)
Broadcast	31	42	27
Broadcast + incorporated	30	45	25
Split-band	55	39	6
SE±	1.6	2.7	

a. 72 kg N ha^{-1} applied to sorghum (CSH 6).

Source: Moraghan et al. (1984).

Ammonia Volatilization

A priori, many researchers have expected losses by ammonia volatilization to be large in soils of the Indian SAT, especially if urea was applied by spreading granules onto the soil surface. Some Alfisols have a light-textured surface soil, and the increase in pH associated with urea hydrolysis would be expected to promote quite substantial losses, especially if the surface dried. Although Vertisols are heavy textured and have a high cation exchange capacity, and thus would be expected to absorb ammonia, their soil surface is alkaline and would be expected to promote ammonia volatilization. Yet few losses by ammonia volatilization have so far been clearly identified over the past 8 years of research in the IFDC/ICRISAT collaborative project at ICRISAT Center.

To quote from Goswami and Sahrawat's (1982) review, "It should be emphasized that there have been few studies on ammonia loss under field conditions, and these have been hindered by lack of techniques. . . ." We can add that, of these few studies of ammonia loss, most have examined flooded soils. Further, in addition to stressing the need for studies on dryland soils with typical variations of moisture and temperature, we emphasize the need for selecting correct techniques because of the reactivity of ammonia gas.

Direct measurements of ammonia volatilization are needed to determine the importance of this mechanism of nitrogen loss. The relevance to the semiarid environment is shown clearly by the diurnal fluctuations in losses (McGarity and Rajaratnam, 1973).

Immobilization

It is only in recent years that immobilization has been recognized clearly as a major source of N inefficiency in the immediate utilization of fertilizer N added to the soil. The proportion of fertilizer N immobilized can be as high as 40% (Table 4; Jansson and Persson, 1982), which is in agreement with the results of many N-uptake experiments. About 50%-60% of fertilizer N is recovered in a crop where losses are not suspected. Of course such immobilized N will be subsequently mineralized, but at a slow rate as with other organic N.

Interactions

The quantification of the extent and nature of nitrogen mineralization and losses in agricultural soils has been so limited that direct measurement of the various processes must be a first priority for any soil research in this area. Until this has been done and the operation of processes clearly understood in the field situations, hypotheses cannot be developed about the many interactions that we suspect will be very important.

One example of the types of interactions that will require careful consideration involves the mineralization and leaching of nitrogen in an Alfisol at the beginning of the rainy season. The first rain will cause a flush of nitrogen mineralization – the "Birch" effect – resulting in rapid accumulation of nitrate in the surface soil (Figure 2). The next rain, depending upon its amount and timing, may result in some leaching of nitrate. The entry of subsequent rainfall into the soil, and leaching, will depend on the soil surface structure as modified by treatment with the soil conditioner polyvinyl alcohol (PVA) (Figure 5), which in turn will depend upon whether the initial cultivation of the soil has commenced.

Ideally, therefore, any model to calculate fertilizer requirements will take into account the structure of the surface soil in order to determine whether such mineralized N will be accessed by roots growing downwards or whether it will be leached beyond the depth of root exploration.

Many other examples could be given, but that given above provides an indication of the complexity of the interactions involved in modeling nitrogen in the SAT environment. It requires very little imagination to picture the range of weather conditions at the beginning of the rainy season and to ponder the effects that these have on components of the soil N supply in addition to the examples given in Figures 2 and 5.

Concluding Comments

In this paper, we draw attention to the urgent need for direct measurements of a number of processes in field situations, including mineralization, urea hydrolysis, ammonia volatilization, denitrification, and leaching. Failure to quantify these soil processes will result in the inability to build accurate models for describing responses of crops to nitrogen.

One of the reasons for lack of information on nitrogen processes in SAT soils is an emphasis in recent research on agronomic studies or on laboratory studies alone. Inadequate emphasis has been given to the need for linking laboratory research to field experiments so that descriptions of soil processes are available to explain various aspects of responses (or lack of responses) to fertilizer N.

In proposing a sharper focus of research so that we can better understand soil mechanisms, there is a need to stress the importance of attention to methodology. Past research on nitrogen has produced some notable examples of the use of incorrect methods giving results that misled researchers for quite a few years afterwards. For the approaches needed in the future – the quantitative description of processes important for modeling nitrogen – failure to address the issue of methodology could be disastrous. Given an appropriate emphasis on direct measurements of processes, and attention to methodology, a great gap in our current knowledge of the soils of the SAT will be filled. This knowledge is, of course, essential for the development of models of crop behavior in response to the soil, water, and atmospheric environment.

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