Estimation of Soil Nitrogen Status in Intercropping Through Soil Solution

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Abstract

Estimating soil nitrogen (N) status in cropping systems by sampling the soil followed by extraction using KCl or $CaCl_2$ has been researched extensively. However, few studies have been conducted to monitor soil- and fertilizer-N dynamics in cropping systems using ceramic porous cups. Nitrate-N (NO_3-N) in soil solution extracted by porous cups is point sampling and could better reflect a steady state between mineralization and plant-N uptake than that extracted using KCl or $CaCl_2$, which are commonly used to estimate the availability of N to plants.

During a 3-year field study to monitor the N-dynamics of pigeonpea/sorghum intercropping on Alfisol, we found that an NO_3-N concentration of 2 to 5 mM (ca. 100 kg N ha^{-1}) detected in soil solution at the onset of the cropping season disappeared from the soil solution 30-40 days after sowing (DAS) compared with basal application. Delayed N fertilizer application to the sorghum resulted in a higher uptake of soil NO_3-N. Our data indicated that 80-90% of N detected in soil solution at time of planting was not utilized by crops. There was no clear evidence of NO_3-N leaching into the deep soil layers because the NO_3-N concentrations detected in the deep soil layers were low. We speculate that an appreciable amount of NO_3-N detected in soil solution in the soil profile at the beginning of cropping season is quickly immobilized, and/or incorporated into the soil organic pool at the early crop growth stage when crop uptake is low.

The question of whether or not the NO_3-N incorporated into the soil organic pool becomes available for crop uptake during the later growth stage, needs further investigation. Therefore, sources and forms of available-N in the soil, the rates of availability and mineralization at the beginning of the season, and the control by rainfall timing and amount, need much more attention in the future. Monitoring N-concentration in soil solution using porous cups provides a better insight into soil-nutrient-plant interaction, and enhances the probability of accurately predicting the amount of fertilizer-N required by crops.

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Introduction

Shifting cultivation and bush fallow, the traditional farming system in most parts of the humid and semi-arid tropics (SAT), has proved to be a stable agricultural system with respect to maintaining soil fertility. Because of population pressure and the increasing demand for agricultural production, this system is being abandoned and replaced by more permanent forms of cultivation. Consequently, the equilibrium between soil, vegetation, and climate with regard to nutrient mining, especially of nitrogen (N) by crops, and regeneration of N-status, is disrupted and soil fertility tends to decline (Sanchez and Salinas 1981).

Application of inorganic N-fertilizers cannot be relied upon to reasonably redress the N-depletion by crops because of economic, logistical, and social (e.g., NO_3-N contamination of ground water) reasons. However, to maximize N-use efficiency by crops, it is possible to establish a stable productivity level with permanent cultivation in the SAT by adopting cereal-legume cropping combinations with little application of N-fertilizer or N-fertilizer management strategies or both.

Nitrogen is most common limiting nutrient for plant growth in the semi-arid agricultural ecosystems. In situations where very little fertilizer-N is applied to crops, either because of economic reasons or unpredictable rainfall, plant-N uptake depends on the supply, dynamics, and control of soil-N availability during the cropping season. Therefore, to better predict the amount of fertilizer needed by crops and the time of application, it is important to monitor and estimate the N-status of the soil before and during the cropping season.

Estimating soil-N status in cropping systems by soil sampling after extraction using KCl or $CaCl_2$ (Bremner 1965; Keeney and Nelson 1982) has been researched extensively; however, few studies have been conducted to monitor soil- and fertilizer-N dynamics in cropping systems using ceramic porous cups (Hansen and Harris 1975). Nitrate in soil solution obtained using porous cups is a point sampling technique and better reflects a steady state between mineralization- and plant-N uptake than when sampled soils are extracted using KCl or $CaCl_2$, which is commonly used to estimate the availability of N to plants (Grossman and Udluft 1991).

In this paper we focused on (a) N forms and pools available to plants during the growing season, (b) different methods to estimate N-status in soil, and (c) the use of porous ceramic cups to monitor N-status in cropping systems on Alfisols. The information obtained is directed towards understanding N-dynamics in soil-plant systems, and to improving N-fertilizer management strategies in a pigeonpea/sorghum intercropping in the SAT.

N- forms and pools available to plants

Knowledge of the major forms of soil-N and the dynamics of the soil- and plant-N pools is central to our understanding of N-acquisition and efficient utilization by plants. Excellent reviews on soil and fertilizer N dynamics, plant-N uptake kinetics and utilization have been recently published (Bacon 1995; Engels and Marschner 1995). In this chapter, we concentrate on soil mineral-N forms and N-flow in cropping systems.

Under semi-arid soil conditions, the predominant form of N available to plants is NO_3-N because ammonium-N (NH_4-N) is rapidly nitrified to NO_3-N. Ammonium-N is the major form of N available to plants under conditions that are unfavorable to nitrification. Nitrogen forms and pools available for plant uptake is diagrammatically presented in Figure 1. The soil solution N pool is in an equilibrium state and the available-N concentration increases at the onset of the cropping season after a long, dry fallow, followed by rainfall. Fertilizer-N (mineral and organic) and N from irrigation water are the main sources of N in soil solution under fertilized and irrigated systems. On the other hand, N in soil solution is being constantly subjected to loss (e.g., by leaching, erosion, denitrification, volatilization, immobilization) and plant uptake. Atmospheric N_2 is a major input to the plant-N pool in cereal/legume or legume/legume intercropping combination systems. On a global basis, Paul (1988) estimated that symbiotic N_2 fixation contributes about 120 Mt y^{1}, whereas N-fertilizer use is approximately 80 Mt y^{-1}. A 3-year experiment on Alfisol at the ICRISAT Asia Center (IAC) showed that in a pigeonpea/sorghum intercropping, 80% of the N accumulated by sorghum was derived from soil, and between 40-80% of the N accumulated by pigeonpea was derived from atmospheric N_2 (Fig. 2). Therefore, of the N forms and pools, mineralizable-and fixed-N are important to farmers of the SAT because they are natural inputs.

N-loss from soil-plant systems

The majority of soils in the African and Asian SAT consists of light textured soils, such as infertile and poorly buffered Entisols and Alfisols or fertile, but difficult to manage,

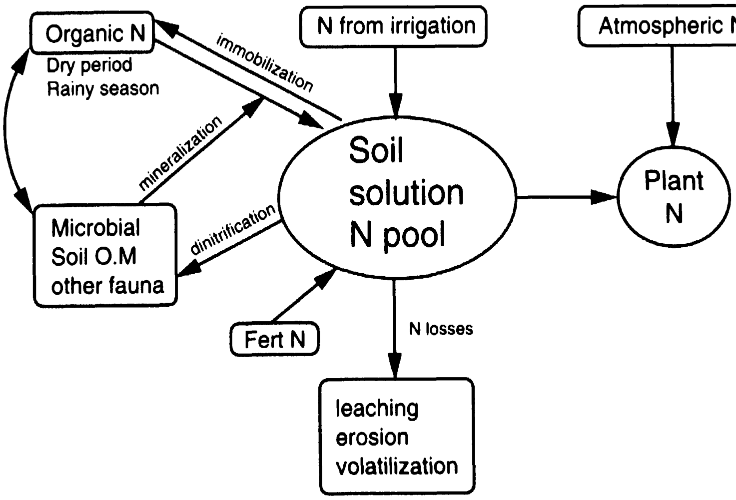

Fig. 1. Sources and pools of N available to plants during the growing season.

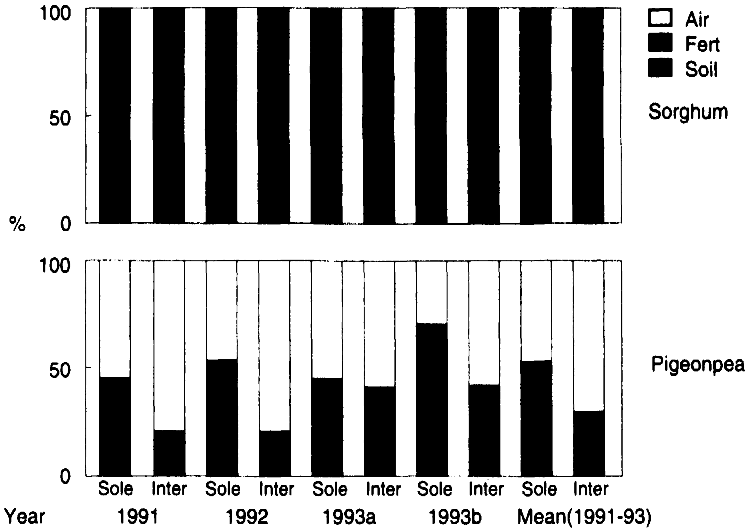

Fig. 2. Sources of N to sorghum and pigeonpea grown as a sole and an intercrop on Alfisols at ICRISAT Asia Center.(Adu-Gyamfi, unpublished data)

Vertisols (Vlek and Vielhauer 1994). Soil organic matter in Alfisols and Entisols is less than 1%. Although the total N content in Alfisol is low, available data (Adu-Gyamfi et al. 1994b; Ito et al. 1994) show that a relatively high concentration of NO_3-N (2-5 mM)•α is detected in soil solution extracted using porous cups (through mineralization of organic matter) prior to the cropping season without application of fertilizer-N. This suggests that there would be natural supply of N to crops during the initial growth stage. However, if this mineralizable-N is not utilized by crops, it is re-immobilized into the soil organic pool and/or leached into the deep soil layers at the onset of the rainy season.

De Datta et al. (1990) observed the disappearance of 91 kg ha^{-1} NO_3-N from a 30-cm soil layer in unfertilized plots when cumulative rainfall within a week after planting exceeded 492 mm. It is not certain whether the 90 kg NO_3-N leached into the deep soil layers or was incorporated into the organic soil pool. Dependency on fertilizer-N by crops could be minimized if the initial amount of NO_3-N is utilized by crops for their N requirements during the initial growth stage. The quantity of N leached depends on the chemical nature of the nitrogenous compounds, N transformations, the reactions with soil that regulates its mobility, and the amount of irrigation water applied.

Nitrogen is also lost through volatilization and surface runoff. Volatilization is associated with the type of fertilizer applied and can be controlled by selecting an appropriate source of N-fertilizer. Arora et al. (1980) estimated that on the average only 1.52 g N ha^{-1} day^{-1} is lost by NH_4-N volatilization. Surface runoff through irrigation and rainfall is the lowest of all the loss mechanisms for N in cropping systems, and may account for almost none to 4% of the applied N. Understanding and perhaps eventually manipulating the transformation between organic- and inorganic-N pools, may provide a way to avoid excess inorganic accumulation and losses. Even though the total annual cumulative rainfall in the SAT is between 500-750 mm, about 40-50% of this rainfall is recorded 30 days after planting, and then followed by a dry spell. Under these conditions, losses of mineralized-N below the root zone is high (Vlek and Vielhauer 1994).

Importance of soil testing for evaluating N-status of soils

Predicting N-availability in soils is difficult due to the small proportion of total soil-N in the inorganic form, the poorly defined nature of soil organic-N compounds, and the complex array of physical, chemical, biological, and management variables that affect N-mineralization. There is still a continuing debate among soil scientists as to the reliability of soil tests in determining the N-status of soils for predicting the response to added N-fertilizer. Soil test values are rough guides for estimating N-fertilizer needs, and thus do not substitute for other information to be used for determining N-fertilizer needs, but do enhance the probability of making a correct decision as to the amount of fertilizer needed and the time of application. High variation in NO_3-N and NH_4-N concentration among replications have been reported on Alfisol (Ito et al. 1994). It is therefore recommended that more samples be taken to neutralize this variation. Although the spatial variability of soil NO_3-N concentration in a field presents a serious limitation to use soil sampling for N as basis for making precise recommendations, it could be used as fertilizer guide. Soil solution NO_3-N is a good index to predict the N-status in soil where mineralizable-N constitutes 49-80% of the total N-available for plant growth (Ruess et al. 1977).

Apart from sampling the soil or extracting soil solution using porous ceramic tubes, the NO_3-N pool in xylem tissues of plants is used to estimate N-status in soil because NO_3-N concentration within these tissues is highly sensitive to soil N supply. Other-N available indices used to predict N-requirements include the late-spring soil NO_3-N test and end-of-season stalk test (Blackmer 1994), pre-sidedress soil nitrate-N test (PSNT), and the total N-content in various plant tissues (Rauschkolb et al. 1974). The use of PSNT to identify N-responsive sites and economically optimum sidedress fertilizer-N rates has been successful in the USA (Meisinger et al. 1992; Sims et al. 1995). Nevertheless, one must be aware that the N pools within the plant are in dynamic equilibrium and that the concentration of a particular constituent is only an indicator of N distribution in a plant at one point in time. Guidelines from soil tests in predicting N-requirements of crops must be used with caution and with a great deal of knowledge about the prevailing conditions.

Soil solution as an indicator of soil-N status

As the "blood circulation of the soil body", the soil solution plays a central role in many soil processes. It is the mobile phase that is responsible for redistributing solutes within the soil. The soil solution is defined as the aqueous liquid phase of the soil that provides the immediate source of nutrients for plants and microorganisms. In addition, nutrient levels in soil solution have been related to plant growth (Adams and Moore 1983).

In soil solution, mineral-N is in a dynamic state. Nitrogen moves in and out of the soil solution though its concentration may remain constant. Fluctuations in NO_3-N levels when soil solution is sampled in situ by suction could better reflect a steady state between mineralizable- and plant-N uptake than sampling the soil and extracting using a salt solution (KCl or $CaCl_2$), which is commonly used to assess the availability of N to plants.

Extraction methods

A considerable amount of research has been aimed at the reliability and accuracy of the soil composition in extraction methods for soil solution (Litaor 1988; Magjid and Christiansen 1993). Care should be taken to ensure that the solution extracted for analysis is not altered by either the preparation of the sample or the method of extraction. Extraction should be done with minimal disturbance of the pre-existing soil solution equilibria and without changing the chemical composition of the soil.

Litaor (1988) comprehensively reviewed the methods of extracting soil solution and the use of different soil solution samplers. The methods include (a) miscible displacement (b) immiscible liquid displacement (c) extraction by centrifugation, and (d) in situ sampling by suction. As stated by Litaor (1988) and Magjid and Christiansen (1993), no single method or device is perfect for collecting the soil solution for all conditions encountered in the field. Therefore, we must understand the methodological differences and, more specifically, when to apply certain sampling methods and not others. Each method needs to be accessed for its (a) ease in applicability, (b) reproducibility of results (c) spatial variability , and (d) ease in interpretation of results in relation to N-dynamics of the system. More experimental evidence is needed in this line of research because there are limited numbers of comparative studies that examine the differences between extraction methods. Among the different extraction methods listed above, the in situ extraction by suction seems to be the most suitable because of its non-destructive nature.

Extracting soil solution by suction using porous ceramic cups

Briggs and McCall (1904) first described the porous cup as an "artificial root". Since then much information on the construction and performance of ceramic tubes has been published (Wagner 1962; Adams 1974; Haines et al. 1982; and Addiscott et al. 1992). In a pot experiment, Ito et al. (1990) showed that porous cup samplers are suitable for monitoring the N-status in upland conditions. Adu-Gyamfi et al. (1993) estimated the N-status in a sorghum/pigeonpea intercropping system on Alfisol after extracting the solution by porous cups, and found the extraction method suitable although some variations were observed among sample solution in different replications. Porous ceramic cups have the following advantages: (a) relatively easy to install, (b) negligible disturbance of soil profile, (c) continuous monitoring from different depths of soil profile owing to non-destructive nature and (d) relatively cheap.

Problems associated with ceramic porous cups reported by Hansen and Harris (1975), Litaor (1988), Grossmann and Udluft (1991) and Majgid and Christensen (1993) include (a) spatial variability in the properties being investigated is often underestimated and must be clarified by sufficient replication, (b) samples obtained provide information on solute concentration at the time of sampling and not on the flux through the sampling zone, (c) samples can be obtained only if the soil is moist enough to allow solutions to be drawn into the ceramic cup.

Cropping system strategy to increase dependency of cereals on soil-N

Cropping systems can be a major factor in regulating NO_3-N movement below the root zone and towards the water table. For a better quantitative understanding of soil mineral-N utilization by crops, and to improve fertilizer-and soil-N use efficiency, we investigated the effect of cropping systems on the depletion of native soil NO_3-N in Alfisol for 3 years.

A medium-duration pigeonpea cultivar (ICP-6), and a grain sorghum hybrid (CSH 5) were sown either as sole sorghum (S), sole pigeonpea (P), or intercrop(I). The proportion of sorghum to pigeonpea in the intercrop was 2:1. Nitrogen was applied at 25 kg N ha^{-1}. Ceramic porous cups were embedded at depths of 0-15, 15-30, 30-45, and 45-60 cm, in all treatments before planting. Soil solution was collected regularly (depending on the soil moisture) from the cups by suction for 3 hrs with a gas-tight plastic syringe and was either analyzed immediately or kept at -20°C until analysis. Nitrate- and NH_4-N concentration in the soil solution was measured colorimetrically with phenol-alkaline and salicylic acid-sulfuric acid, respectively. Profile water content was measured weekly with a neutron probe (Cambell Pacific) at the same depth as the porous cups, and data from the neutron probe was calibrated for volumetric water content.

Initial field experiments showed that the NO_3-N levels in soil solution prior to planting ranged from 3-5 mM (90-150 kg N ha^{-1}) at a soil depth of 50 cm (Fig. 3). The NO_3-N levels in soil solution increased 15 days after fertilizer application. Initial levels of NO_3-N in soil depends on the amount of organic-N available for mineralization. Organic-N levels in soil vary considerably depending on the level of native organic matter, the history of cropping, and organic amendments (Sharma et al. 1985; George et al. 1992). For pigeonpea-based cropping system, Rego and Seeling (1996) reported that fallen leaves and decaying roots undergo mineralization during the following cropping season, and supply mineral-N to component cereal crops, but part of the N remains in the soil organic pool. Sharma et al. (1985) reported soil NO_3-N levels of 233 kg ha^{-1} prior to the start of wet season. Soil water fluctuations generally result in a large production and accumulation of soil NO_3-N (Ventura and Watanabe 1978).

During the period of heavy rainfall, most of the NO_3-N disappeared from the soil solution below the 50 cm depth. Figure 4 shows plant-N uptake and our rough estimate of the amount of N in soil solution calculated on an area basis using soil moisture data. Results show a considerable amount of NO_3-N in soil solution at planting. However, there was complete depletion of NO_3-N from soil solution within 50 to 80 DAS, suggesting an active N-dynamics in soil solution. The rate of N-depletion or disappearance was 2 to 3 times faster than N-accumulation by plants, suggesting that an appreciable amount of NO_3-N disappears from soil solution without being utilized by crops during the initial growth stage. De Datta et al. (1990) reported that during 27 days when cumulative rainfall was 492 mm, the native soil NO_3-N decreased from 134 kg N ha^{-1} to 59 kg N ha^{-1} in the top 60-cm layer. Although the NO_3-N concentration in soil solution at the later growth stage was very

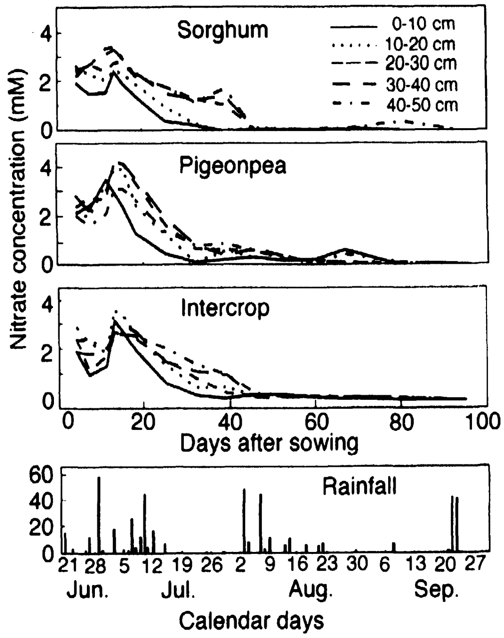

Fig. 3. Nitrate concentration in soil solution collected from solecrops of sorghum and pigeonpea and of intercrops at different soil depths. Nitrogen was applied at 25 kg N ha^{-1}.

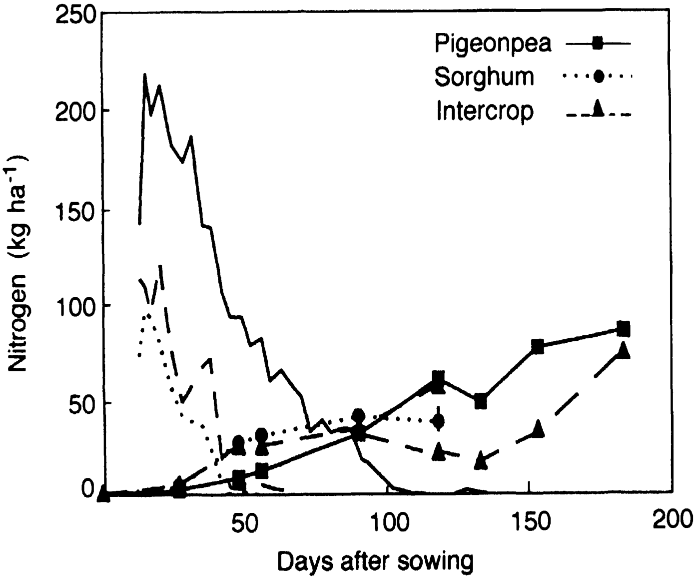

Fig. 4. Nitrate-N amount within 50-cm depth (line without symbols) and N-uptake by crops.

low (not detectable), accumulation of N by the plants continued to increase. This indicates that plants either absorbed NO_3-N efficiently at a low concentration through a carrier-mediated uptake mechanism (Rao et al. 1993, 1996a and 1996b), exploited N from the deep soil layers, or exploited the organic-N pool at the latter growth stage.

Our earlier experiment on Alfisol showed that the NO_3-N concentration in soil solution at a 150-cm depth was not significantly higher than those in the upper soil depths. This suggests that N that disappeared from the soil solution did not leach into the deep soil layers but was probably incorporated into the soil organic-N pool, and hence was not detected in the soil solution. This speculation is supported by the fact that if all the mineral-N that disappeared from the soil solution was lost through leaching, the estimated mineralized-N lost from Alfisol during every cropping season is between 100-150 kg ha^{-1}. This enormous loss of mineralized-N can render most soils unproductive after 20 years. Thus it is speculated that the NO_3-N that is not detected in soil-solution extracts using porous cups after 50 DAS is incorporated into the soil-N organic pool.

For a given treatment, the NO_3-N concentration in soil solution collected under sorghum grown as sole crop and intercrop with pigeonpea was lower than that collected under sole and intercrop pigeonpea. This suggests that sorghum has a higher potential to better utilize soil-N than pigeonpea, especially at the initial growth stages (Fig. 5). In the case of intercropping, the NO_3-N concentration in soil solution was low, clearly indicating the ability of sorghum to exploit more soil-N than pigeonpea. This phenomenon is advantageous to the N-economy of the system, because the depletion of the soil-N at the initial growth stage enhances N_2 fixation by pigeonpea. Several reports have demonstrated that N_2 fixation of pigeonpea is highly improved when intercropped with cereals, over pigeonpea grown as a sole crops (Katayama et al. 1996a and 1996b; Kumar Rao et al. 1987). One possible reason is that uptake of the initial soil NO_3-N by the cereal component reduces exposure of the legume to high N-concentration at the initial stages of crop growth, thereby stimulating N_2 fixation. The results also demonstrate clearly that NO_3-N detected in soil solution at the planting could be better exploited through appropriate cereal/legume cropping system combinations.

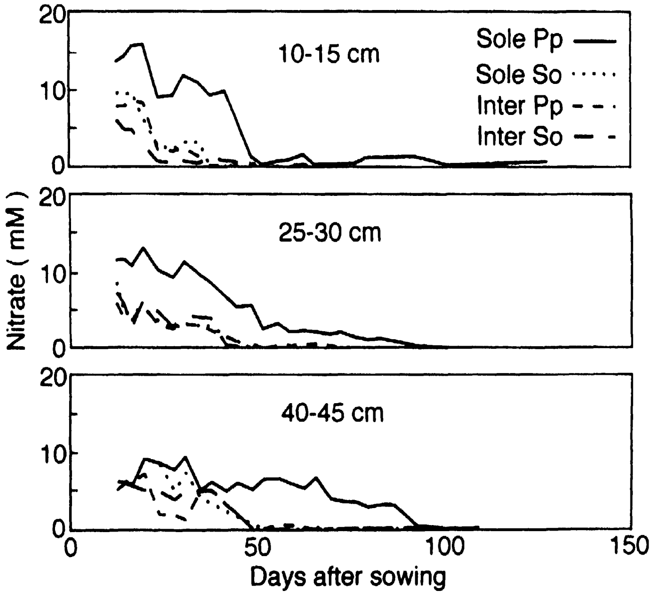

Fig. 5. Nitrate concentration in soil solution collected under sorghum and pigeonpea plants in sole and intercrop at different depths on Alfisol at ICRISAT Asia Center India, in 1993.

Fertilizer management strategy to enhance soil-N use efficiency

In a field experiment on Alfisol at IAC where basal fertilizer application was compared with delayed fertilization (30-40 days after sowing when the NO_3-N in soil solution is barely detectable), we found that by 35 DAS, the nitrate concentration in soil solution of basally applied N at 50 kg N ha^{-1} was equal to treatments where no NO_3-N was applied (Fig. 6). This phenomenon was observed not only in the top soil, but also to a depth of 60 cm. Nitrogen accumulation in plants did not show any significant difference between the 0 N and the 50-kg N treatments during the first 30 DAS (data not shown). This finding raises questions about the fate of N-fertilizers applied at planting to stimulate initial plant growth. Delayed fertilizer application significantly increased dry matter and grain yield and N-accumulation compared to basal application (Adu-Gyamfi et al. 1996a). De Datta et al. (1990) and Singh and Sekhon (1976) reported that delayed application reduced the amount of NO_3-N losses from the upper soil layers.

Our experiment also confirmed that the initial concentration of NO_3-N in soil solution without N-fertilizer applied could be as high as 4mM. An increase in the soil solution NO_3-N due to delayed N-application was detected only in the control (no plants) and pigeonpea treatments (sole and intercrop). For sorghum, it was not detected probably because the nitrate was quickly absorbed by plants. The results further suggest that delayed N-application increased the dependency of sorghum on native soil-N at the initial growth stage, and later application when plant roots are well established increased N-absorption

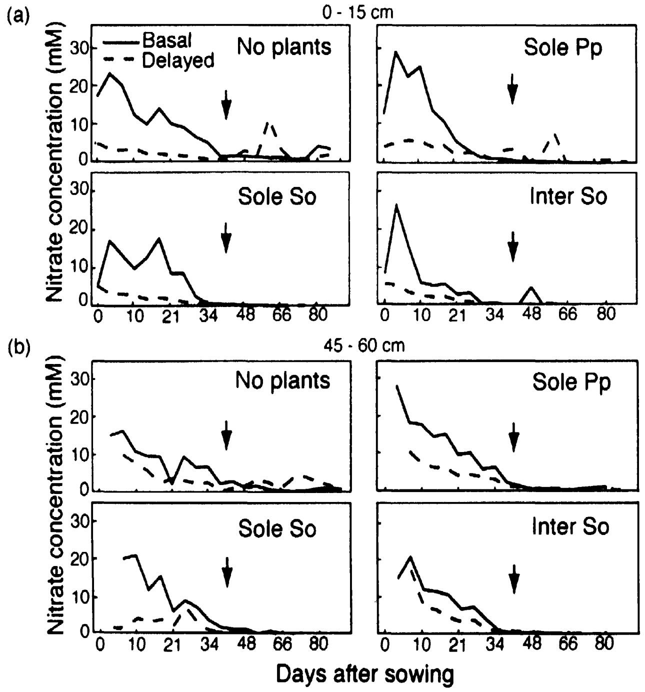

Fig. 6. Concentrations of nitrate-N in soil solution measured at (a) 0-15 cm and (b) 45-60 cm depth with porous cups for sole crop sorghum (Sole So), sole crop pigeonpea (Sole Pp), intercrop sorghum (Inter So), and no plants (control) treatments. Fertilizer-N was applied at 50 kg N ha-1 planting (basal) and at 40 DAS (delayed.). Arrows denote delayed N-application.

and utilization efficiency of sorghum.

Another point of interest in this study is that though the same amount of fertilizer was applied for basal and delayed treatments, the concentration of NO_3-N in soil solution for the delayed treatment was low compared with that for the basal application (Fig. 6). A probable explanation is that fertilizer-N applied as delayed was quickly absorbed by crops, and was therefore not detected in soil solution.

Similar results were observed for NH_4-N which was about 2mM in soil solution in the top soil layer after fertilizer application, but declined sharply with time. The relatively low concentration of NH_4-N in soil water collected under the sole sorghum treatment compared to that under the sole pigeonpea indicates that sorghum has better NH_4-N uptake ability than pigeonpea.

Data from Arora et al. (1980) on the fate of fertilizer-N in the NO_3-N fraction of soil solution using ^{15}N-labeled fertilizer indicated variability in NO_3-N content at soil depths of 50, 150, and 180 cm. The NO_3-N fractions were minimum during the period of Feb-June, maximum in July and November, and almost negligible in January.

Besides time of N-fertilization and irrigation criteria, the depth of the rooting system seems to play a major role in defining NO_3-N loss patterns in soils. Crops to be used as "scavengers" of NO_3-N should be exploited and incorporated in cropping systems.

Effective methods for decreasing soil-NO_3 accumulation

Management practices aimed at increasing the patterns of availability and mineralization of soil NO_3-N in the crop root zone encompass diverse soil and crop management options as well as socio-economic activities (Keeney and Follett 1991). A better understanding of either (a) the supply, dynamics, and control of N-availability to component crops in cropping systems or (b) the effectiveness, risk, economics, applicability, etc. of the various possible alternatives for increasing N-supply to crops would form a sound basis to prevent soil NO_3-N accumulation. Alternatives include multiple fertilizer applications, the use of cover crops or deep rooted crops, genetic selection of improved crop-N use efficiency, chemical additives that inhibit the rate of nitrification, slow release inorganic and organic fertilizers, careful irrigation to minimize leaching, the inclusion of organic matter, manure and crop residues in N-fertilizer recommendations, and land use zoning to lower the density of cropland in a watershed. Thus, appropriate crop and N-fertilizer management will lead to minimum NO_3-N losses and optimize crop production. Our study has shown that intercropping and delayed N-fertilization resulted in a better utilization of native soil NO_3-N by crops.

Nielsen and Jensen (1990) reported that late-harvested crops decreases the potential of NO_3-N leaching. Sowing a catch-crop to prevent the soil lying bare over the off-season aimed at reducing accumulation of NO_3-N may not be applicable in the SAT because of the long dry spell after the harvest of crop (from January to May). Accurately controlled availability fertilizers (CAFs), such as Resin coated fertilizers (POCFs, polyolefin resin coated fertilizers), have been used to optimize NO_3-N losses from the root zone. Shoji (1994) reported that in Japan, the use of POC-NH_4NO_3 to tea-growing fields decreased NO_3-N leaching loss by 60-70%; however no such studies have been conducted in the SAT.

Modeling nitrate movement

Computer models are now used to monitor and quantify the movements of NO_3-N in soils. Many scientists have attempted to model and predict NO_3-N movement with various degrees of success. Ability to predict N-dynamics in soil-plant systems has obvious application to the prediction of fertilizer requirements for cropping systems and has been excellently reviewed (Addiscott et al. 1992; Tanji and Nour El Din 1991; Godwin and Jones 1991; Matus and Rodriguez 1994, and Section V of this book). Models to estimate or quantify N-dynamics in cropping systems should be viewed only as a guide to improve fertilizer-N management practices in the SAT (Fig. 7).

Conclusions and future directions.

This paper has presented the current knowledge on soil solution-N dynamics and plant-N uptake in cropping systems. It is clear from our study that plants use only a small fraction of the mineralized NO_3-N that accumulates in soil prior to planting. We observed that although NO_3-N was not detected in soil solution at the later crop growth stage, N-accumulation by plants (especially by cereals) continued to increase. We speculated that mineralized soil NO_3-N that is not utilized by crops is incorporated into the soil organic-N pool, and later becomes available for plant uptake. Furthermore, our study provides evidence that soil NO_3-N could be better exploited through cropping system combinations

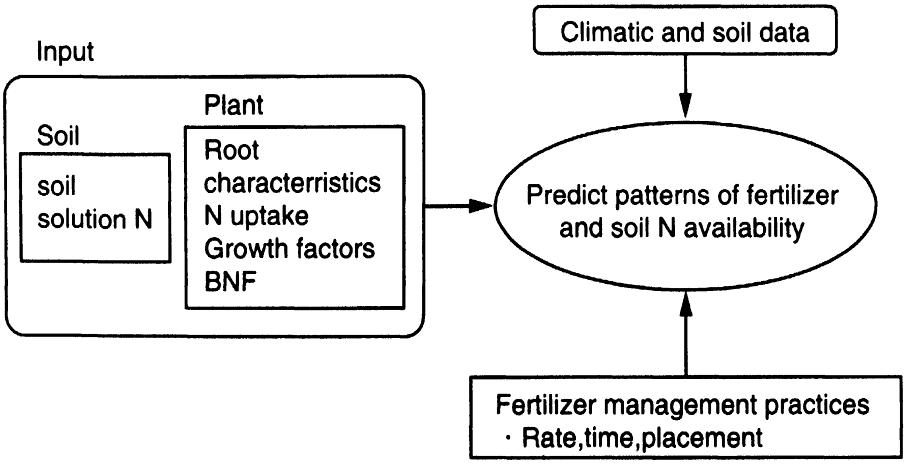

Fig. 7. A proposed model to estimate or quantify N-dynamics.

and appropriate fertilizer management strategies. Future areas requiring intensive research include:

- the use of labeled N-fertilizers to determine the fate of the initial mineralized soil-N detected in soil solution, and to quantify the amount of mineralized, and organic, and microbial-N in intercropping systems during the different stages of crop growth. This will help us understand the relationship between soil solution NO_3-N and plant-N uptake,
- comparison of the amount of NO_3-N extracted using KCl or $CaCl_2$ and that extracted using ceramic porous cups, and
- development of a model to predict N-availability in soil and N-accumulation in plants using climatic and soil data, and fertilizer management practices. The output of the model could serve as a guide to improve fertilizer-N management practices in the SAT.

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