Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics

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Abstract

An agreement was made in 1984 between the Government of Japan (GOJ) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to set up a collaborative research project entitled "Development of Cultivation for Upland Crops in the Semi-Arid Tropics". Within this framework, scientists in the first phase of the project (1984-1989) concentrated their studies on phosphorus (P) nutrition of grain legumes in the semi arid tropics (SAT). During the second phase of the project (1989-1994) the scientists focused on the dynamics of roots and nitrogen (N) in cropping systems, particularly in pigeonpea-based intercropping systems. Pigeonpea-based intercropping is widely adopted by resource-poor farmers in the SAT. Highlights of the five year activities are summarized below.

Using an exponential fitting of profile distribution of root length, it was found that the roots of pigeonpea spread less to the horizontal direction and more to the vertical direction than those of sorghum, pearl millet, groundnut and cowpea. A model based on weather and soil data predicted that the progression of the rooting front of pigeonpea was more rapid for the same physiological age. A kinetic study on N uptake showed that pigeonpea could utilise soil and fertilizer N as efficiently as other crops which lack an ability of biological nitrogen fixation (BNF), suggesting that there would be a considerable competition for N with other companion crops, such as cereals in intercropping. To reduce the competition for external N it is important to increase the dependency of pigeonpea on BNF. Measurement of root respiration showed that pigeonpea would invest a considerably higher respiratory energy for N uptake.

Nitrate (NO_3-N) concentration in the soil solution extracted by using ceramic porous cups was found to be highest at the beginning of the cropping season and it decreased rapidly thereafter. The NO_3-N concentration in the soil solution decreased and a zero value was recorded two months after sowing. It was estimated that an amount of between 100-150 kg ha^{-1} of mineralized N was detected in the soil solution within a 50 cm soil depth, prior to sowing. This suggests that an appreciable amount of N would be available for crop uptake in nutrient-limited Alfisol during the initial growth stage.

The ^{15}N labelling and ^{15}N natural abundance studies showed that the N balance sheet among different N sources for the crops, i.e., soil N, fertilizer N and atmospheric N, would be altered by intercropping, toward a larger proportion of N derived from biological nitrogen fixation. The application of urea to the sorghum row was superior to broadcasting and split applications, and delayed application one month after sowing was superior to basal application (before sowing) in terms of nitrogen use efficiency (NUE) of a component sorghum crop, although biomass yield was not affected. The delayed application is advantageous because if crop establishment fails due to insufficient rainfall, no fertilizer cost is incurred.

To improve resource utilization in intercropping, it was recommended that pigeonpea be intercropped with a crop which has a shallower root system and a higher N uptake efficiency such as sorghum. In addition, delayed N-fertilization to the cereal crop before N disappears from the soil solution, which normally occurs about one month after sowing, is recommended.

Additional key words: semi-arid tropics, intercropping, pigeonpea, root system,
nitrogen balance

Introduction

The SAT is the region where mean annual temperature is above 18ºC and rainfall exceeds potential evapotranspiration for only 2 to 7 months[45)], with moisture balance being kept deficit for the other months. Rainfall is unpredictable and erratic. Not only natural water supply through rainfall, but also nutrient supply from soils are limiting factors for crop production. These constraints keep the land productivity extremely low, resulting in the low development of the infrastructure required for the introduction of irrigation systems. Inevitably rainfed agriculture is predominant farming system in this region.

To reduce the risk of crop failure in a drought year, intercropping of two types of crops that differ in canopy structure and growth duration is a common practice of resource-poor farmers in the SAT[49)]. Although a wide range of crop combinations is adopted in the SAT, a combination of cereals and legumes is recommended mainly due to the economic value of legumes, high potential yield from the cereals and beneficial effects of BNF on soil fertility[47)]. Pigeonpea is considered to be a good component crop for intercropping in Alfisols[6, 42)] as it is characterized by a rather long growing period and a deeper root system[7)] compared to the other crops grown in the region. The initial slow growth which is mainly responsible for the long growing period may be caused by a mid-day saturation of starch accumulation in leaves[21)] and a slow turnover of starch in stems to be utilized under adverse environmental conditions[22, 23, 34)]. Besides physiological studies on the growth pattern of the above-ground parts, the developmental pattern of the under-ground parts, that is root system of the plants, should be well characterized for each component crop used in the intercropping. To achieve an efficient exploitaion of limited soil resources, it would be ideal to combine two crops which display different developmental pattern of root systems.

Among several options available at the farm level, N fertilizer management would be most suitable to achieve an immediate increase in crop production in the area where most of the farmers have no access to irrigation facilities. The SAT soils are usually low in organic matter as compared with temperate soils. Since organic matter is a source of available N in the soil, many soils in the SAT can satisfy only a part of crop N requirement, and therefore N fertilization is necessary to improve crop yields and land productivity. Fertilizer application has long been considered as a risky investment by SAT farmers due to the unpredictable weather, leading to rather scarce studies on fertilizer management especially under intercropping conditions. Moreover N fertilizer management has been seldom studied in relation to inorganic N dynamics in soils which show a considerable fluctuation in the N content during the cropping season. Particularly the content of the soil solution N, which is the closest N pool for crop uptake, will vary greatly and have a significant effect on crop production.

Objectives of the project initiated in December 1989 for a period of five years in collaboration with ICRISAT were (1) to characterize the rooting habit and N uptake efficiency of pigeonpea, (2) to analyze the N supplying capacity of soils during the cropping season and (3) to compare the different management options of N fertilizer application such as placement and timing in terms of land productivity and N use efficiency with a view to making appropriate recommendations for N management in the pigeonpea-based intercropping.

Architectural characterization of root systems

Under the resource-limiting conditions prevailing in the semi-arid tropical environments, crops with a deep root system may have an advantage in exploiting soil resources. To characterize the genetic properties of the root system architecture among the crops, the root distribution in terms of length and weight can be determined with various methods such as auger, monolith, trench wall, minirhizotron, and so on, and then compared along the vertical profile of soil. Due to the wide variation in the root data obtained from field experiments and discrepancies in the data obtained by different methods, such comparisons often fail to describe specific properties of root system development for each crop[26]. Genotypic difference in the root system of chickpea was not reproduced in the field as clearly as in the pot experiments mainly due to the inherent variation in the field data[29]. We adopted two different approaches to extract any significant trends related to the root system architecture from highly variable data. One approach is the simulation of root data with an exponential equation which produces the parameters reflecting root architecture[11, 12, 13, 16], and another is a model to predict root system development using soil and weather data[14, 23].

Root profile simulation

Root data along the soil profile were simulated with the exponential equation $\rho = \rho_0 \mathrm{EXP}(-kz)$ where ρ is the root length density at the depth z, and ρ_0 and k are coefficients obtained by the regression (Ito et al., 1991). The coefficients, ρ_0 and k roughly correspond to the rooting intensity at the soil surface and rooting depth, respectively.

The ρ_0 and k values of pigeonpea showed a decreasing trend with relative growth stages (RGS) and were the lowest among the five crops tested throughout the growth period (Fig. 1). The two parameters (ρ_0 and k) clearly indicate the deep rooting character of pigeonpea which develops its solid tap root in the deep soil layers at the expense of extensive root proliferation at the soil surface. At harvest, the k value of pigeonpea became nearly zero (Fig. 1B), indicating an even root distribution throughout the soil profile examined. In other crops, the k value remained constant or started to increase at RGS of 0.8, indicating that there was no further increase in the rooting depth at the later growth stage[24].

Exponential simulation of the rooting profile provides a simple methods to handle a large volume of data, but does not take into account environmental factors such as soil physico-chemical properties and weather conditions which largely affect root development. Thus the results obtained are site specific and therefore limit the genetic comparison of rooting properties across the locations.

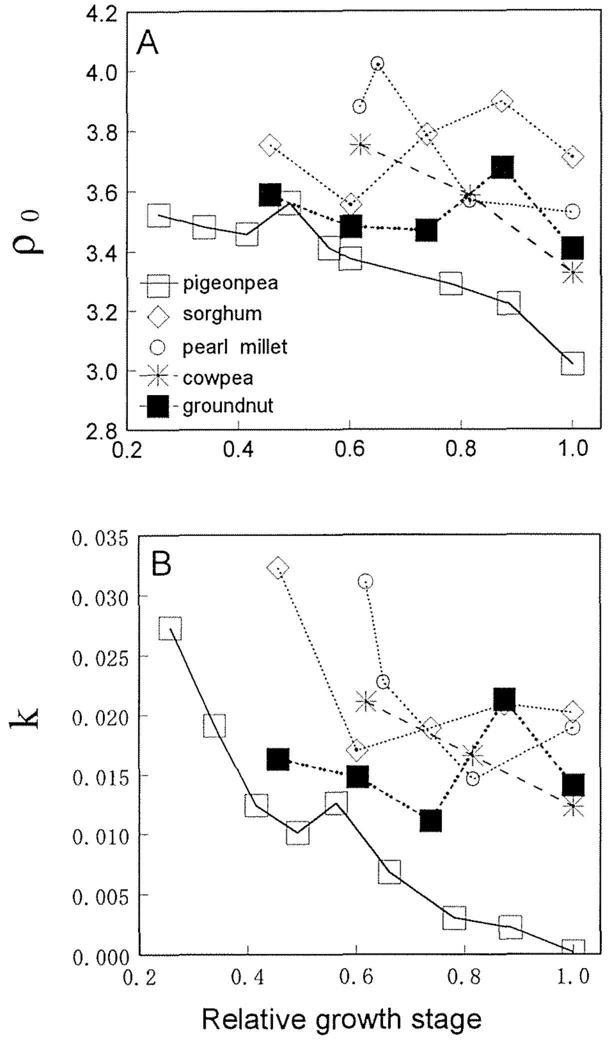

Fig. 1. The coefficients, ρ_0 (A) and k (B) obtained by exponential simulation of the distribution of root length density along the vertical soil profile [$\rho = \rho_0 \mathrm{EXP}(-kz)$, where ρ is the root length density at depth z for five crops grown in sole cropping. For comparison among crop species with different growth duration, the entire growth period was expressed as a unity and referred to as relative growth stage (RGS).

Root model

For a more general comparison of the root system architecture, one alternative is to use a model which takes environmental variables as input for the prediction of parameters related to root system morphology such as profile distribution of length and weight, advance of rooting front, turnover of roots, and so on. The model used in this study basically consists of two components[23)]. The first component is the simulation of dynamic variables in soils such as moisture content and temperature from weather data. The second component is to use these dynamic data sets for the operation of the root model along with certain static parameters for the soil profile and genetic parameters of plants. Since the driving force of the model is the dry matter content and the model is not linked to a shoot growth model at present, the daily dry matter allocation to the roots should be externally input to run the program. Daily dry matter allocation to roots, was computed as the difference in the simulated root mass between two successive days. The internal generation of such inputs is ultimately achieved by plugging into a whole growth model as daily sampling of roots is laborious.

Major model outputs, distribution of root length and weight along the soil profile, were successfully validated with a short-duration pigeonpea cultivar which is now becoming popular in central India as a sole crop[9)]. During the 1994 rainy season, we attempted to validate the model for the simulation of root growth using data obtained from field experiments of five major component crops (pigeonpea, groundnut, cowpea, sorghum and pearl millet) used for intercropping in the SAT. There was a reasonably good correlation between the predicted and observed data, indicating that the model enables to predict accurately the root development across different crop species. Rooting depth is another useful output from the model as it is a labour-intensive measurement in the field. When the rooting depth is compared among the crops selected in this study using the growth stage relative to an entire growth period (referred to as relative growth stage RGS), the rate of advance of the rooting front was fastest in pigeonpea at the early growth stage, followed by cowpea (Fig. 2). Since the observation was made only up to 0.6 m, the simulation of the rooting depth is shown only up to this depth. Pigeonpea and groundnut initially distributed more roots to the surface layer and then rapidly reached a deeper rooting depth, whereas the root development in cowpea was directed vertically downward into the soil layer at the initial growth stage. Pearl millet and sorghum showed a slower gain in the rooting depth compared with the legumes[10)]. The rooting depth of cereals such as millet and sorghum has been reported to increase linearly with time[35)].

Since the model is sensitive to various soil environmental variables, it can be used to predict the response of the root system architecture to changes in the soil water status, caused by temporal waterlogging or drought. One of the major obstacles for wide propagation of short-duration pigeonpea is its susceptibility to excess water in soils which frequently occurs during the wet spell of the rainy season and causes severe root damages leading to decreased productivity. The root length and weight were markedly reduced soon after imposing waterlogging

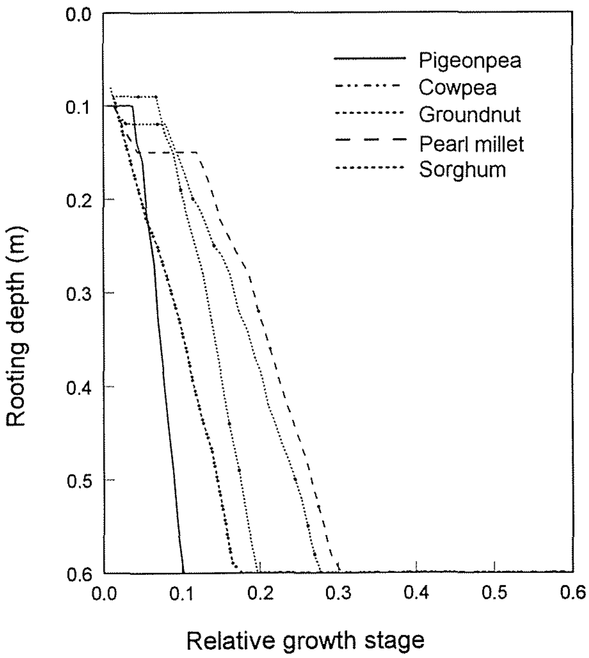

Fig. 2. Advance of rooting front (rooting depth) simulated by the root model.

treatment, but adventitious roots were formed near the plant base to compensate for losses, provided the damage was so severe as to wipe off the plants[31, 32, 33]. The frequent measurement of the root system subjected to the waterlogging treatment was carried out through a minirhizotron observatory tube and attempts were made to fit the data into the model. The model can be also applied to predict the plant response to a water deficit condition as another example of extreme cases. Since the minirhizotron observatory tube can be used for simultaneously monitoring the water dynamics under field conditions[28], the variation caused by the heterogeneity in plants and soils could be minimized. Such data are important for the validation of the model.

Physiological characterization of root functions of component crops

Nitrogen uptake

Characterization of N uptake is necessary to select a more efficient crop combination in intercropping as there would be a severe competition for N between individual crops under nitrogen-limiting conditions. To characterize the N uptake among different species of plants, the total amount of N taken up by plants during an entire growth period has been often used. To compare the nutrient uptake process *per se*, kinetic parameters on the rate and affinity of membrane transport would be much better indices as they are relatively independent of the dry matter production of plants.

Since nutrient uptake resembles an enzymatic reaction, its kinetics can be quantitatively described using the Michaelis-Menten equation[8]. This kinetic equation considers two parameters, V_{max} and K_m, which are indicative of the maximum rate of uptake and the affinity to the nutrient uptake sites, respectively. The kinetic parameters for N uptake were obtained for component crops commonly used for intercropping, i.e. three legumes (pigeonpea, chickpea and groundnut) and three cereals (sorghum, millet and maize) using ^{15}N as a tracer.

The uptake pattern for both nitrate (NO_3^-) and ammonium (NH_4^+) as a function of external concentration ranging from 0 to 1 mM followed a saturation curve with Michaelis-Menten kinetics for all the crops tested[38]. A detailed study for nitrate uptake with maize root tips[39] showed that the saturation curve could be separated into several more components with the same type of curve exhibiting a multiphasic uptake pattern. Kinetic parameters were obtained using Lineweaver-Burk double reciprocal plots (Fig. 3). The K_m values for NH_4^+ were significantly different between legumes and cereals, but no clear difference was found for NO_3^-. The V_{max} values showed a similar tendency to that of K_m values for

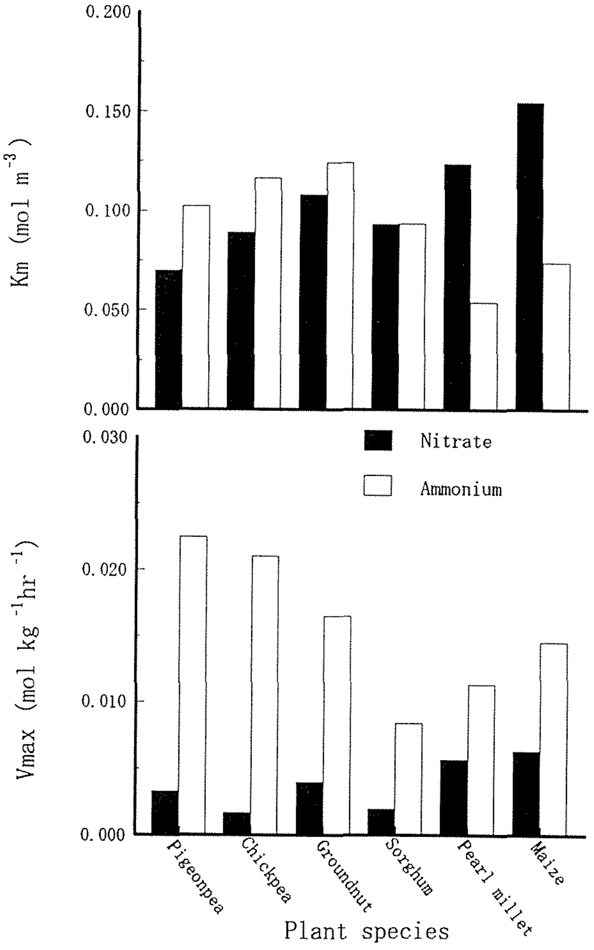

Fig. 3. Kinetic parameters for the uptake of nitrate and ammonium by legumes and cereals. The K_m and V_{max} were calculated from Lineweaver-Burk plots.

the two groups of crops. The kinetic parameters obtained in this study are within the range reported by other researchers. The V_{max} of NH_4^+ was higher than that of NO_3^-, whereas the K_m did not differ significantly. Pigeonpea and sorghum showed a lower K_m to NO_3^- than other crops in the same group, suggesting a higher affinity to exploit the form of N predominant under upland conditions[40].

This study shows that despite its ability to fix atmospheric N_2, pigeonpea shows almost a similar level of utilization efficiency of N from soil to that of other crops. When pigeonpea is considered as a main component of intercropping, the competition for N would be inevitable with other companion crops. In order to reduce the competition and increase the efficiency of N utilization, a combination of a shallow rooted (e.g. sorghum or millet) and deep rooted crop (e.g. pigeonpea) is desirable to maximize the utilization of soil resources.

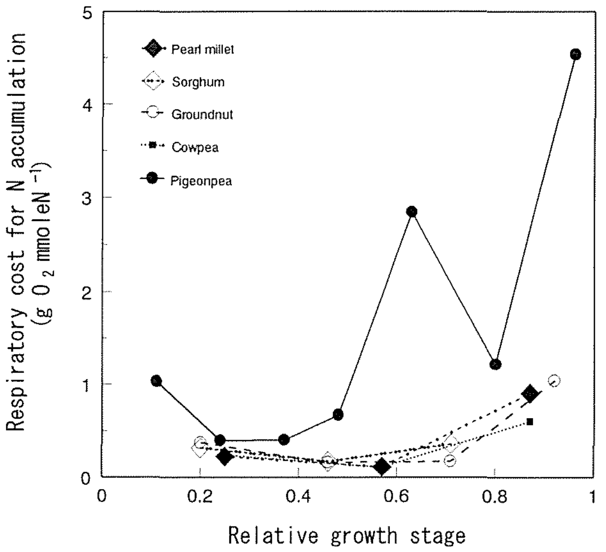

Fig. 4. Respiratory cost for nitrogen accumulation in five crop species. The rate of nitrogen accumulation including nitrogen uptake and biological nitrogen fixation was calculated as the difference between two consecutive sampling points divided by root respiration rate.

Nitrogen accumulation and respiration

Since N uptake is a physiological process highly dependent on the supply of carbohydrates from the leaves, the consumption of energy for N uptake will affect other energy-dependent processes such as growth and maintenance. The amount of respiratory energy spent for N uptake may differ among crops adapted to N limiting environments and ultimately affect growth and yield of crops.

Roots of various crops were collected from the field by a monolith sampling method and incubated for two hours in a gas-tight syringe. The reduction of oxygen (O_2) concentration in the syringe was determined with an oxygen meter (Toray F700). The respiration rate of roots usually increases with the distance from the plant base up to 25 to 30 cm and then gradually decreases. Pigeonpea shows a higher rate than sorghum except during the early growth stage[17]. Respiratory cost for N accumulation was calculated for each individual crop (Fig. 4). Pigeonpea showed the highest respiratory cost, indicating that pigeonpea requires more respiratory activities to accumulate the same amount of N. The other four crops including two legumes and two cereals, showed similar values and a seasonal trend. This fact suggests that the higher respiratory requirement for N accumulation in pigeonpea may not be due to biological N_2 fixation[20].

Relatively low values (25-40 mgO_2 $mmoleN^{-1}$) have been reported for respiratory cost[37, 48]. However, a value of 100-400 mgO_2 $mmoleN^{-1}$ was also reported for field pea and maize[30, 46]. The values obtained for four crops excluding pigeonpea in our experiment are almost within this range. Poorter et al.[37] suggested that there would be a considerable difference in the fraction of respiration required for anion uptake between species with rapid growth and slow growth. Their data show that in the latter plant species the respiratory cost for anion uptake is higher than in the former. Respiratory cost for uptake is determined by (1) the ratio between ion influx and efflux, (2) the proportion of energy-dependent and energy-independent uptake mechanisms and (3) the exudation of specific compounds from roots to solubilize ions fixed by soil minerals or humic substances. Since the pigeonpea cultivar used in this study as a main component crop for intercropping required more than 200 days of growth period which is far longer than that of other crops, pigeonpea could be considered as a typical species with slow growth. A specific compound, pisidic acid, is reported to be released from pigeonpea roots to solubilize iron-bound phosphate which is otherwise unavailable to the plant1).

Pigeonpea showed the lowest respiratory efficiency for N accumulation, in other words, pigeonpea may oxidize more carbohydrates to take up the same amount of N than other crops. The higher respiratory requirement for N accumulation might be a physiological adaptation to stressed environments, but inevitably pigeonpea is compelled to reduce carbon allocation to growth and maintenance. This in turn limits the yield potential of this crop.

Nitrogen balance sheet in component crops

In order to maximize productivity under conditions where N is one of the major limiting factors, crop characteristics relating to N uptake should be considered in relation to external environments which are the sources of N to crops. Nitrogen for plant uptake is supplied from three main sources, soil, fertilizer and atmosphere. Nitrogen supply from these three sources should be appropriately shared between the two component crops in intercropping, which in most cases differ in their growth pattern and N requirements. How the two crops share N from the three sources will affect the total crop productivity in the system.

Nitrogen balance sheet from the three sources was drawn using ^{15}N method and compared among various crop combinations. Fractional contribution of N derived from atmosphere ($\%N_{dfa}$) was determined by the natural ^{15}N abundance method and the contribution from fertilizer ($\%N_{dff}$) by the ^{15}N tracer method. The contribution from soil ($\%N_{dfs}$) was calculated from $\%N_{dff}$ and $\%N_{dfa}$ values.

In order to join a more quantitative understanding of the effects of intercropping on N budget of pigeonpea, a N balance sheet was first drawn for pigeonpea and sorghum as an example of intercropping (Fig. 5). The figure shows the amount of N taken up by the individual crops from three different sources in sole cropping and intercropping at four levels of fertilizer N application. It is clearly shown that the assimilation of soil N and fertilizer N by pigeonpea is almost the same as that by sorghum in the sole crop, indicating the potential competence of pigeonpea to exploit soil N. However, under conditions where N is depleted by the component crop (sorghum in this case), pigeonpea increases its dependency on BNF. Appropriate allocation of N from different sources between the component crops is important to maximize the efficiency of N utilization in intercropping systems42, 43, 44).

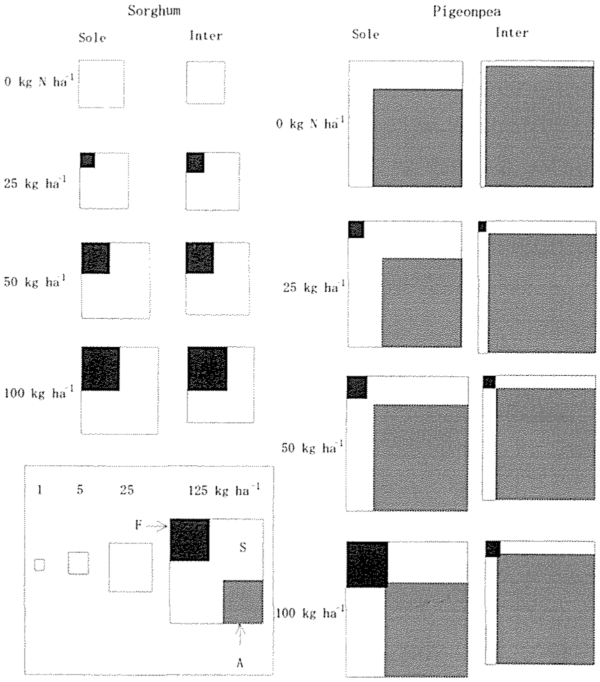

Fig. 5. Diagrammatic representation of N budget in sorghum and pigeonpea in sole cropping (Sole) and intercropping (Inter) at four levels of fertilizer N application (0, 25, 50 and 100 kg N ha^{-1}). The size of each square is proportional to the amount of N taken up by the plants. The squares with 1, 5, 25 and 125 kg N ha^{-1} are given in an inset for semi-quantification of N from atmosphere (A) fertilizer (F) and soil (S),

The $\%N_{dfa}$ of pigeonpea was significantly increased when pigeonpea was intercropped with cereals compared with legumes. The BNF in intercropped pigeonpea was higher than sole crop. The intercropped pigeonpea acquired less N from fertilizer and soil compared to the sole pigeonpea, probably due to the rapid depletion of N by cereal crops which had an extensive root mass at the soil surface. This condition reduced the available N concentration around pigeonpea roots and increased the dependency of pigeonpea on BNF. These results suggest that pigeonpea-based intercropping alters the balance sheet of N from three different sources and that a more efficient utilization of N, could be achieved by appropriate combination of crops and their management[27].

The amount of N derived from both soil and fertilizer (N_{dffs}) was calculated to obtain the ratio of N_{dffs} for component crops over pigeonpea, as indicator of the competitive ability of the component crop for soil and fertilizer N over pigeonpea[25]. The higher the N_{dffs} ratio, the stronger the competitive ability to exploit N from soil compared with pigeonpea. Two cereals (sorghum and pearl millet) had a higher N_{dffs} ratio than the two legumes (cowpea and groundnut). The N_{dffs} ratio for groundnut was below unity, indicating that N exploitation from the soil in this crop was less competitive than in the case of pigeonpea under intercropping conditions. The N_{dffs} ratio was positively correlated with $\%N_{dfa}$ in grain of pigeonpea (Fig. 6). This fact clearly indicates that a higher N consumption by companion crops relative to pigeonpea should have increased the dependency of pigeonpea on BNF.

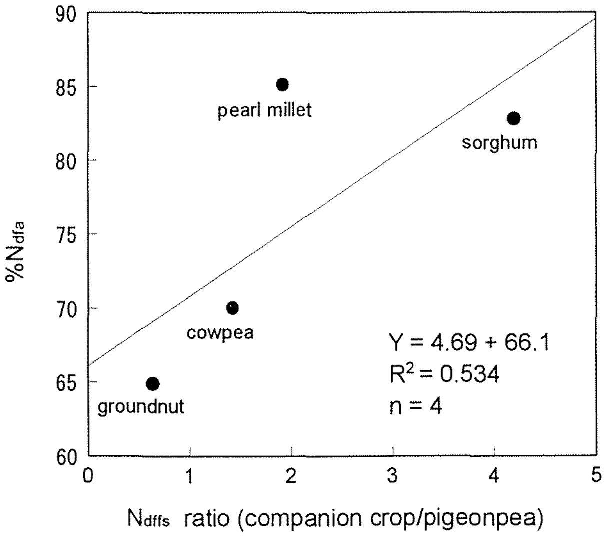

Fig. 6. Relationship between fraction of nitrogen derived from atmosphere ($\%N_{dfa}$) and ratio of nitrogen derived from fertilizer and soil (N_{dffs}) for companion crop over pigeonpea.

Soil solution nitrogen dynamics

The soil solution is the aqueous liquid phase of the soil which provides the immediate source of nutrients for plants and micro-organisms and acts as a temporary sink for some of their products. Nutrient levels in the soil solution have been related to plant growth in many studies. Nitrogen from soil and fertilizer is finally released into the soil solution and becomes available to the crops. In the soil solution mineral N is subjected to a dynamic state, which implies that there is always a turnover of N in and out of the soil solution even though its concentration may remain constant. The major inflow processes into this pool include fertilization, mineralization, rainfall and flow from neighbouring layer of soils. The outflow of NO_3^- from it is mainly due to plant uptake, immobilization, volatilization, denitrification and leaching. Although we can only observe the balance of those complex processes, plant uptake seems to affect its pool size most intensively[36], especially near the rhizosphere. Nitrate is a major form of N under upland conditions and the fluctuations of its content in the soil solution could reflect the root development and nutrient uptake activity of roots more clearly than NO_3^- extracted with KCl, which is commonly used to assess the amount of available N to plants[15].

The soil solution was collected regularly (depending on the soil moisture) from ceramic porous cups by suction for 3 hrs with a gas tight plastic syringe. Nitrate in the soil solution was analyzed immediately or kept deep-frozen at -20ºC till analysis[2, 4, 19, 41]. Nitrate concentration was considerably high prior to planting, but rapidly reduced (Fig. 7). Only a trace of NO_3^- was found in the soil solution at 50 DAS, except for the sole cropped pigeonpea. Nitrate concentration in the soil under sole cropped pigeonpea was always higher than in other treatments and nitrate could be detected even after 50 DAS, presumably due to the lower planting density in this cropping system. Since planting density of both crops is the same in an intercrop, a direct comparison may enable to determine difference in N utilization. This result suggests that NO_3^- depletion by both crops may be almost identical. In other words, NO_3^- dynamics in the soil solution may not be changed by nitrogen fixation.

A considerable amount of N, mainly NO_3 (roughly 100 to 200 kg ha^{-1}) was found in the soil solution at the time of planting (Fig. 7). The entire amount of N disappeared from the soil solution within 50 to 100 days, reflecting active dynamics of N in the soil solution during the initial cropping period. Since N accumulation in the crops was much lower and slower, as shown in Fig. 7, most of the N disappeared from the system without being utilized by the crops. The observation may question the suitability of the traditional farming practice of basal application of N fertilizer. Delayed N application may enhance the dependency of sorghum on native soil N thereby increasing the N use efficiency of the system.

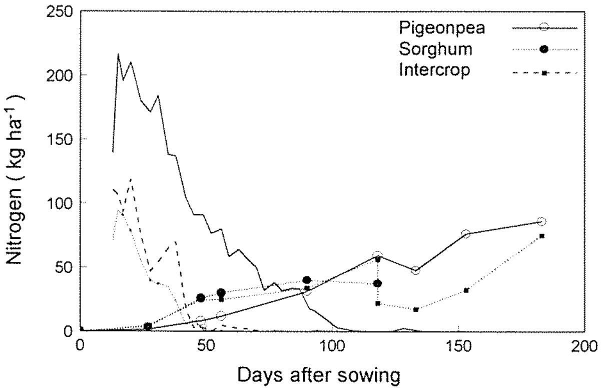

Fig. 7 Nitrogen in soil solution within 50 cm soil depth and amount of nitrogen recovered by pigeonpea, sorghum and intercrop of these two crops. Nitrogen fertilizer was applied at the rate of 50 kg ha^{-1} before sowing. The amount of nitrogen in the soil solution was calculated from the concentration of nitrate and ammonium in the soil solution and the soil moisture content obtained by gravimetric method.

Nitrogen fertilizer management in intercropping

Nitrogen fertilizer application is a management practice that can be easily modified by the farmers in terms of time and method of application. The method of application would considerably affect N fertilizer use efficiency (NFUE) which indicates how much the proportion of N applied as fertilizer is utilized by the crop, and is obtained by $[N_{dff}/N_{applied} \times 100]$. To minimize the amount of N fertilizer which is not utilized by crops, in other words, to increase NFUE, timing of application should be well synchronized with patterns of N supply from soil and crop requirement. In the region where intercropping is commonly practiced, most of the farmers do not apply or apply very low doses (less than 25 kg N ha^{-1}) of N fertilizer due to economic, logistics and social reasons. When applied, the farmers prefer basal to delayed application because they consider that the crops require N for their early growth. As indicated in the previous section, however, an appreciable amount of N is available to the crops at the time of planting at the onset of the rainy season. Obviously a small dose of N at planting is expected to be diluted by the soil N pool leading to a low efficiency of crop utilization. Thus timing of nitrogen application was tested in terms of NFUE and grain yield[3, 5, 18].

Delayed urea-N application till 40 DAS resulted in a higher NFUE in sorghum than a basal application (Table 1). The NFUE of sole crop pigeonpea was higher (14.6) than that of intercrop pigeonpea (1.8-3.9), because fertilizer was applied only to the sorghum rows in the case of the intercrop treatment. Delayed N fertilization also enhanced the dependency of pigeonpea on atmospheric N_2 (Data not shown). Grain yield and total N content of sorghum in sole crop and intercrop were increased by delayed N

Table 1. Effect of timing of urea application on grain yield (t ha^{-1}), nitrogen fertilizer use efficiency (NFUE, %), and total N amount (kg ha^{-1}) of sorghum and pigeonpea in sole and intercrop on Alfisol at ICRISAT Asia Center, India, in 1993

Treatment	Grain yield		NFUE		Total N	
	Sorghum	Pigeonpea	Sorghum	Pigeonpea	Sorghum	Pigeonpea
Sole crop						
BAS[a]	4.16	2.78	15.0	14.6	96	249
DEL[b]	4.58	2.43	32.2	14.7	104	240
Intercrop						
BAS	3.73	2.08	10.2	3.90	87	204
DEL	4.35	2.37	32.4	1.80	108	202
Standard Error (±)						
N[c]	0.146	0.10	2.54	1.61	4.51	18.0
CS	0.159	0.05	0.31	0.30	0.83	7.9
N x CS	0.214	0.13	2.94	1.89	5.28	22.0
Statistical significance						
N	***	NS	***	**	*	NS
CS	NS	NS	*	**	NS	NS
N x CS	NS	NS	NS	*	NS	NS
Coefficient of variation (%)						
N	7.1	3.8	3.8	9.0	1.6	6.4
N x CS	9.2	10.1	44.1	68.0	12.5	20.6

[a] BAS: Basal application of 50 kg N ha^{-1} at sowing (banding)
[b] DEL: Delayed application of 50 kg N ha^{-1} at 40 DAS (banding)
[c] N : Time of nitrogen application; CS: cropping system
*** $P<0.001$, ** $P<0.01$, *$P<0.05$, NS: Not significant

application[5].

Concluding remarks

During the 5 year period of study, intercropping always gave a higher land productivity expressed by land equivalent ratio (LER) than the corresponding sole crop except in one case where the crops were severely damaged by the pod borer (*Helicovarpa amigera*). Although intercropping is such a promising cropping system, very little work has been done so far to elucidate the mechanism controlling the high productivity in intercropping. Most of the work on intercropping is focused on the accumulation of empirical knowledge. We have attempted to fill this gap by providing a scientific basis for better utilization of soil resources. Obviously a larger number of studies should be carried out to achieve our research target. However, we believe that the outcome from our five year project provides some future directives towards the understanding of N dynamics in intercropping systems, and for the improvment of fertilizer N management strategies in intercropping in the SAT.

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半乾燥熱帯における作付け体系内の根と窒素の動態

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摘　要

日本政府と国際半乾燥熱帯作物研究所（ICRISAT）の間には，1984年に「半乾燥熱帯における畑作物栽培の改良に関する研究」という課題で拠出金による特別研究プロジェクトに関する合意がなされた。この研究課題に沿って，第２期のプロジェクトが1989年から1994年にかけて実地された。研究は，作付け体系特にキマメを中心にした間作体系内での根と窒素の挙動に着目し行われた。キマメを中心にした間作体系は資源に乏しいこの地域の農民に広く受け入れられている作付け体系である。５年間にわたるプロジェクトの研究成果を以下に抜粋する。

根長の土層内分布を指数関数に当てはめることにより，キマメの根はソルガム，トウジンビエ，ラッカセイ，ササゲに比べ水平方向よりも垂直方向により多くの根を展開することが明らかにされた。気象や土壌データに基づく予測モデルによると，キマメの根の先端は同じ生理的年齢で比べた場合，他の作物よりもより速やかに土層下部に進展する。窒素吸収の動力学的研究はキマメも窒素固定能が欠如した他の作物と同程度に土壌や肥料からの窒素を利用する能力があることを示した。このことは，キマメの窒素固定が何らかの理由で抑えられた場合には，間作を構成する作物の間で強い窒素の競合が起こることを示唆している。この競合を少なくするためには，キマメの窒素固定依存度を高めることが重要であると考えられる。

土壌水中の硝酸濃度は作付け初期に最高値を示し，その後急速に減少する。播種後２ヶ月以内には土壌水中には硝酸はほとんど検出されなくなってしまう。土壌水中に出現する窒素量の最大値は，土層50cm内で100から150kgと算出される。このことは，養分に乏しい赤色土においても生育初期においては，かなりの量の窒素が作物に有効な形で存在することを示している。

窒素肥料として一般的に用いられている尿素を禾本科作物の畝側のみに施肥する方法は，窒素利用効率といった点から，全層や分割施肥よりも優れている。また元肥施肥を播種１ヶ月後位に遅らせる方法は，播種前の施肥よりも優れており，しかも土地当たりの生産性にも影響を与えない。元肥施肥を遅らせることは，降雨不足で作物の苗が全滅した場合にも，肥料という貴重な投資資源を失うことだけは最低限避けられるという利点がある。

本研究の成果を基にして，間作体系内における資源利用の改善のために，キマメをソルガムのような浅根性でより高い窒素吸収効率を有した作物と組み合わせること，窒素肥料を禾本科作物の畝側に，土壌水から窒素が消失する前の通常播種後１ヶ月位に投与することが提唱された。

キーワード：半乾燥熱帯，間作，キマメ，根系，窒素収支