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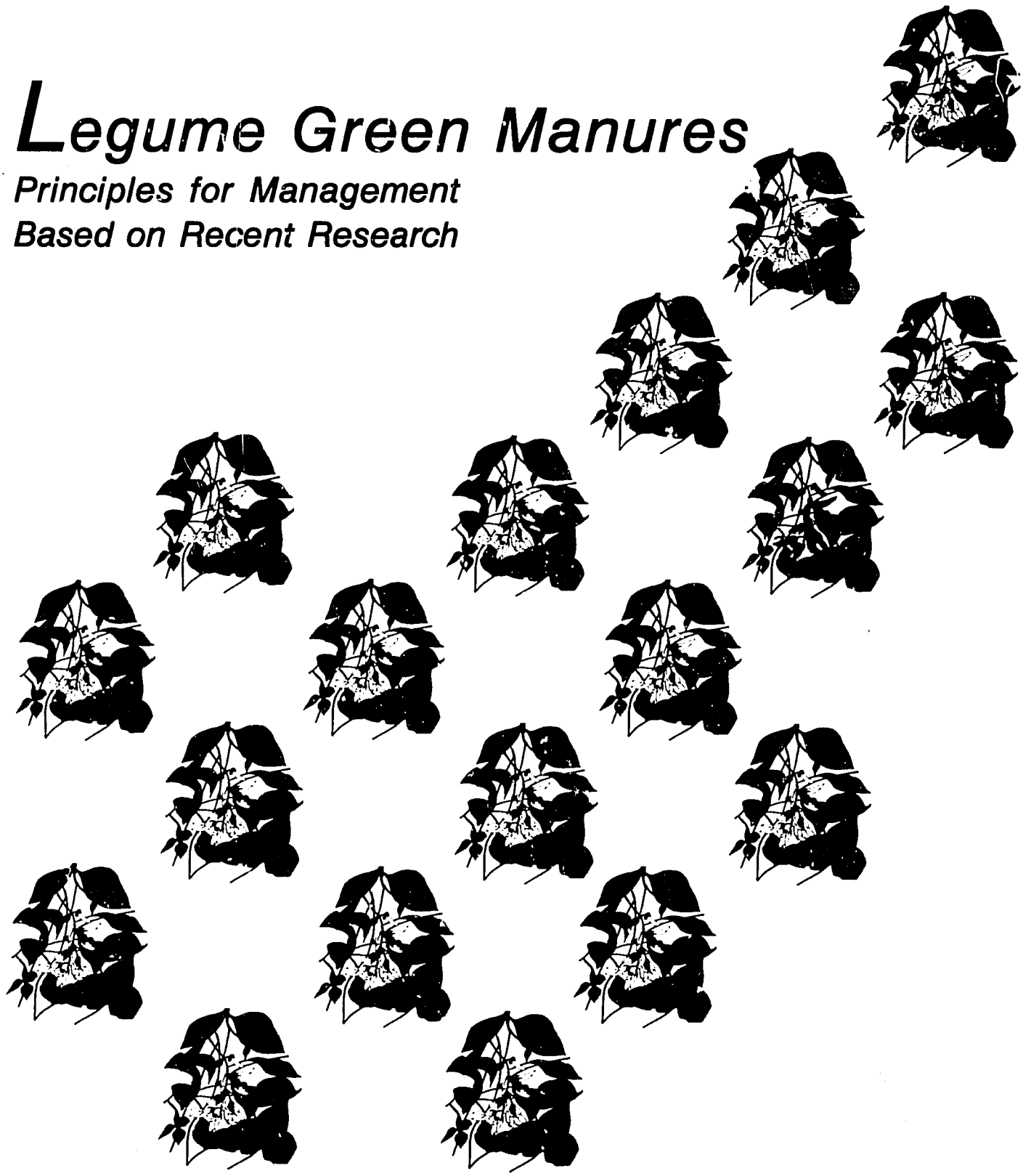
Legume Green Manures

Principles for Management Based on Recent Research



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Legume Green Manures

Principles for Management

Based on Recent Research

Douglas J. Lathwell
Department of Soil, Crop, and Atmospheric Sciences
New York State College of Agriculture and Life Sciences
Cornell University

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Introduction

Until about 1950, legumes were an integral part of most cropping systems in the United States. Legumes provided feed for livestock on the farm and nitrogen for succeeding nonlegume crops such as maize. On most farms, legumes and animal manures were used to manage soil fertility. As American agriculture became more specialized, however, livestock and animal manures disappeared from many farms. Cash crops replaced forage legumes because without animals there was no need for forage. On dairy farms, forage legumes remained an integral part of the cropping system.

During the same period, the fertilizer industry was growing rapidly, largely due to work begun by the Tennessee Valley Authority in the early 1940s. Research at many experiment stations in the United States and abroad showed that concentrated fertilizer nitrogen could replace legumes and manures as a readily available source of nitrogen for nonlegume crops, particularly maize. The result was a rapid intensification of cropping based on fertilizer nitrogen.

Despite its advantages, fertilizer alone may not be the answer to every farm's soil-fertility problems. While fertilizer nitrogen has been widely used in industrialized nations, its availability is limited in the developing world. Manufacturing nitrogen requires large amounts of energy, especially from fossil fuels, and many developing countries have neither the energy reserves nor the means with which to purchase energy inputs. Shipping costs and distribution problems also can preclude the use of fertilizer. In addition, concerns over the environmental consequences of fertilizer use, including

Mucuna, a legume green manure, growing on a farm near Brasilia.

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water pollution with nitrate, have prompted a search for alternatives to fertilizer nitrogen in some parts of the world.

The search for alternative sources of nitrogen has renewed interest in legume green manures, which can fix large quantities of atmospheric nitrogen in plant tissues. When plants decay, this nitrogen becomes available to succeeding nonlegume crops. Nitrogen fixed by legume green manures is inexpensive, once the basic soil fertility is adequate to support their growth. Legume green manures maintain ground cover, usually between cultivated crops, reducing erosion and providing weed control. They improve soil physical conditions and promote mycorrizae on the roots of succeeding crops, increasing soil phosphorus availability. They may also suppress plant pests such as nematodes.

Despite their advantages, legume green manures have been used very little in recent years, for several reasons. Fertilizer nitrogen has been widely available and reasonably inexpensive. In addition, fertilizer nitrogen is relatively easy to transport and apply, and farmers can readily adjust the timing and rate of application to meet the crop's requirements. Legume green manures, on the other hand, require careful management. Soil and climatic conditions must be suitable for legume growth and maximum nitrogen fixation. Legume green manures incur expenses during planting, cultural management, and incorporation into the soil. And, on some farms, legume green manures would displace valuable food or cash crops in the cropping cycle.

This report summarizes aspects of several experiments at the Centro de Pesquisa Agropecuaria do Cerrado (CPAC) at Planaltina, Brazil, where green manure legumes were evaluated as sources of nitrogen for succeeding nonlegume crops. Most of the information reported is taken from the Ph.D. theses of Bowen (1987), Quintana (1987), and Carsky (1989), and from related studies at CPAC. Information from other sites has been used when it offers additional insight into the topics discussed.

While most of the work reported here was conducted in the Cerrado of Brazil, a tropical savanna, some of the principles discussed will apply to other regions, as well. For the most part, the research has focused on two important factors in the response of maize (*Zea mays* L.) to nitrogen from various legume green manures: the rate of nitrogen mineralization and the efficiency of nitrogen use by a succeeding nonlegume crop. Based on the findings of these studies, this publication attempts to provide some of the information necessary for the practical management of legume green manures.

Research with Green Manures

Potential Legume Green Manure Crops

A vast array of legume species have potential as green manures. In the temperate region many legumes are used mainly as forage for livestock. These include alfalfa (*Medicago sativa* L.), several clovers (*Trifolium* spp.), vetch (*Vicia* spp.), and other less familiar species. Annual dry matter accumulation by these legumes varies from 1 Mg/ha to over 10 Mg/ha under ideal growing conditions. Quantities of N accumulated in the aboveground dry matter range from 20 kg/ha to as much as 300 kg/ha annually.

There are several hundred species of tropical legumes, but only a fraction of these have been studied for their potential as green manures. Legumes used in the experiments reported here were chosen from among the many grown in a nursery at CPAC, so their growth habits were known and seed were available. These included mucuna or velvet bean *(Mucuna aterrima)*, crotalaria *(Crotalaria striata)*, zornia *(Zornia latifolia)*, *Canavalia brasiliensis*, jack bean *(Canavalia ensiformes)*, *Calopogonium mucunoides*, pigeon pea *(Cajanus cajan)*, and tropical kudzu *(Pueraria phaseoloides)*. To evaluate the usefulness of green manure legumes as sources of N for succeeding maize crops, several experiments were carried out at CPAC.

Experimental Sites

The climate at CPAC is characterized by a strong wet and dry season, where 95% of the annual rainfall of about 1500 mm falls during the October to April wet season. Average monthly temperatures are 22°C during the wet season and 20°C during the dry season. The experiments were on Red Yellow or Dark Red Latosols of the suborder Ustox (Macedo and Bryant, 1987). These soils have excellent physical conditions but are very acid and highly deficient in P. Only when these severe chemical limitations are corrected is high production achieved. The experimental sites had been cleared of savanna vegetation and cropped several years before the experiments were established.

Experimental Procedure

Three main experiments were carried out at CPAC: Experiment 1 by Bowen (1987), Experiment 2 by Quintana (1987), and Experiment 3 by Carsky (1989). The experimental procedure used by each is described in detail in their theses. Briefly, several legume green manures were grown and incorporated into the soil. Fallow plots were maintained to follow N mineralization and subsequent inorganic N accumulation in the soil. Maize was planted in other plots to measure N uptake and yield response. Fallow plots were sampled periodically, and inorganic N was measured in the samples. At the end of each experiment, maize was harvested for grain and stover to determine grain yield and N content of the total aboveground dry matter. The relationship between inorganic N accumulated in fallow soil and maize yields and N content of aboveground dry matter grown on cropped plots was determined.

Experimental Results

Green manure legume yields at CPAC

Dry matter produced by the legume green manures in Experiments 1, 2, and 3 ranged from 2.5 Mg/ha with zornia to over 13 Mg/ha with crotalaria. The total N accumulated in the aboveground dry matter in a few weeks to a few months varied from 58 to over 300 kg/ha (Tables 1, 2, 3). The N content of the roots was not measured.

The residues from grain legumes also contain

fixed N accumulated over the growing season. Among the more important grain legumes are soybean (*Glycine max* L.), cowpea (*Vigna unguiculata* L.), dry bean (*Phaseolus vulgaris* L.), peanut (*Arachis hypogaea* L.), and pigeon pea. Much of the fixed N is in the grain with smaller amounts in the residue. Soybeans grown at CPAC (Bowen, 1987) produced nearly 10 Mg/ha dry matter, of which

Table 1. Dry matter and N added to mucuna and soybean residue and subsequent grain yield and N uptake by maize (Bowen, 1987), Experiment 1.

Treatment	Dry matter added	Total N added	Grain yield	Total N aboveground
	Mg/ha	kg/ha	Mg/ha	kg/ha
First crop (dry season)				
None			4.9	120
Mucuna tops (1/2)	4.3	128	5.1	149
Mucuna tops	8.5	252	5.6	168
Mucuna tops + roots	8.8	260	6.3	168
Urea (fertilizer N)		50	5.1	132
Second crop (wet season)				
None			4.6	111
Mucuna tops (1/2 residual)			6.1	136
Mucuna tops (residual)			6.6	146
Mucuna tops + roots (residual)			6.8	149
Mucuna tops	5.6	182	6.8	144
Urea (fertilizer N)		200	6.2	165

Table 2. Dry matter and N added by several legume green manures and subsequent grain yield and N uptake by maize (Quintana, 1987), Experiment 2.

Treatment	Dry matter added	Total N added	Grain yield	Total N aboveground
	Mg/ha	kg/ha	Mg/ha	kg/ha
First crop (dry season)				
None			3.7	69
Zornia	2.5	58	4.7	116
Mucuna	4.9	117	6.3	159
Canavalia ensiformes	5.0	156	6.1	170
Crotalaria	10.3	170	5.8	149
Urea (fertilizer N)		200	6.7	173
Second crop (wet season)				
None (after maize)			1.8	30
Zornia residual			3.0	44
Mucuna residual			6.1	72
Canavalia residual			3.5	53
Crotalaria residual			5.4	92
Urea (fertilizer N)		100	6.4	114
Urea (fertilizer N)		200	7.0	182

Table 3. Dry matter and N added by several green manure legumes and subsequent grain yield and N uptake by maize (Carsky, 1989), Experiment 3.

Treatment	Dry matter added	Total N added	Grain yield	Total N aboveground
	Mg/ha	kg/ha	Mg/ha	kg/ha
First crop (dry season)				
None	—	—	3.3	69
Canavalia brasiliensis	10.0	228	6.6	159
Cajanus	10.4	229	7.0	149
Canavalia ensiformes	8.9	231	6.4	177
Calopogonium	7.3	142	6.1	137
Crotalaria	13.7	306	6.6	180
Mucuna	6.8	152	6.3	130
Pueraria	6.5	116	5.7	112
Urea (fertilizer N)	—	200	7.2	198
Second crop (residual wet season)				
None	—	—	3.1	67
Canavalia b	—	—	3.8	79
Cajanus	—	—	3.9	86
Canavalia e	—	—	4.1	82
Calopogonium	—	—	3.4	72
Crotalaria	—	—	4.3	96
Mucuna	—	—	3.0	67
Pueraria	—	—	2.9	60
Urea (fertilizer N)	—	160	6.9	177

2.5 Mg/ha was grain (Table 4). The grain, however, contained 155 kg N/ha, whereas the residues contained 108 kg N/ha.

Green manure legume yields at other sites

In earlier experiments in Trinidad (Mughogho et al., 1982), cowpeas produced about 3.5 Mg/ha of dry matter, with about 1.8 Mg/ha as grain (Table 4). Grain contained from 45 to 50 kg of N, whereas the residue contained from 15 to 20 kg N/ha.

Results from the International Institute of Tropical Agriculture (IITA) in Nigeria were similar to those found in Trinidad (Eaglesham, 1982). In an experiment at the International Crops Research Institute for the Semi-Arid Tropics in India, pigeon pea produced 6 Mg/ha of dry matter, of which 1.6 Mg was grain (Kumar Ruo et al., 1982). Estimated N content was about 40 kg in the grain and 50 kg/ha in the residue. In an experiment at Yurimaguas, Peru, peanut residue contributed from 30 to 50 kg N/ha (Benites et al., 1987). The common bean fixes insufficient N for its own needs, and adding fertilizer N is widely recommended to obtain reasonable yields; therefore, N fixation by these legumes may be unimportant as a source of N for any succeeding crop. In the Midwest United States, soybeans provide 30 to 60 kg N/ha to a succeeding maize crop, an amount not greatly different from that contributed by grain legumes in the tropics.

In both temperate and tropical climates, legume green manures produce large amounts of aboveground dry matter and total N. Under favorable conditions in the tropics, dry matter accumulates rapidly, and in a few weeks large quantities of both dry matter and N are present. Annual dry matter production and N accumulation in temperate regions likewise can be high for adapted legumes. The quantities of N in the residue of the grain legumes, in both temperate and tropical regions, are much smaller than in forage legumes since much of the fixed N is in the grain and, thus, is removed from the field as the grain is harvested.

Table 4. Influence of grain legume residues on grain yield and N uptake by maize.

Plant material	Dry matter added	Total N added	Fertilizer N added	Maize grain yield	Total N aboveground
	Mg/ha	kg/ha	kg/ha	Mg/ha	kg/ha
Experiment 1 - Trinidad					
Fallow	—	—	0	2.5	—
	—	—	120	3.3	—
Maize residue	—	—	0	2.1	—
	—	—	120	3.0	—
Cowpea residue	—	—	0	2.7	—
	—	—	120	3.3	—
Experiment 2 - Trinidad					
Fallow	—	—	0	1.9	35
	—	—	60	2.1	37
Cowpea residue	1.5	17	0	3.1	52
	1.5	17	60	2.9	47
Inoculated cowpea	1.6	20	0	3.2	48
residue	1.6	20	60	3.3	52
Experiment 1 - Brazil					
None	—	—	0	4.9	120
Soybean roots	—	—	0	4.3	84
Soybean residue	7.4	108	0	5.3	116
Urea	—	—	50	5.1	132

Principles for Using Legume Green Manures

Maximizing N Fixation

Under favorable conditions, large quantities of N can be fixed by legume green manure crops. First, legumes must be adapted to prevailing climatic conditions. Genetic diversity ensures that some legume species will be adapted to existing climatic conditions. Second, suitable soil conditions favoring dry matter accumulation are required to achieve maximum N fixation. Obtaining cultural information on the species best suited for a particular climate is a huge task, and often only limited information is available.

Acid soils of temperate and tropical regions typically impose several constraints on dry matter production. They require lime to supply calcium and magnesium or to reduce aluminum and manganese toxicity. For rapid growth and high N fixation, as well as increased drought tolerance, calcium and magnesium must move into the subsoil where they will promote deep rooting and enable plants to take advantage of subsoil nutrients and water (Bouldin, 1979). Many soils are deficient in phosphorus, especially acid Ultisols and Oxisols. The clayey, oxidic Acrustox soil of the Cerrado is highly acid and severely deficient in phosphorus. Adding lime and phosphorus is necessary for good crop production in these soils (Lathwell, 1979a, 1979b). Adequate phosphorus is essential for high dry matter production and attendant N fixation. Large quantities of N can be fixed only when soil conditions are optimal for rapid growth and high dry matter accumulation.

There has been much emphasis on selection of rhizobia to increase N fixation. Available data indicate, however, that if soil conditions are suitable for good plant growth and seed are properly inoculated, large quantities of N can be fixed using indigenous strains of rhizobia.

Crop Response to Legume Nitrogen

Properly managed, legume green manures have the potential to meet much, if not all, of the N requirements of succeeding nonlegume crops. To take advantage of the N fixed by legume green manures, the yield achieved by the nonlegume must be sufficiently high to use the N supplied. Also, mineralization of fixed N should occur at a rate commensurate with growth of the succeeding crop and in quantities that are equivalent to crop requirements at the time of release.

Crotalaria produced much more aboveground dry matter but contained only slightly more total nitrogen than did either mucuna or canavalia.

By comparison, inorganic fertilizer N is completely soluble and readily taken up by plants. It is more vulnerable than organic N to immediate leaching during heavy rains and when it is present in quantities in excess of the needs of crops. To minimize leaching, split applications of inorganic N are made to adjust the quantities of inorganic N in the soil to crop uptake. Matching fertilizer N application to N uptake patterns of crops is straightforward and can be done by the farmer.

In Experiment 1 at CPAC (Bowen, 1987), maize yields up to 6.8 Mg/ha were achieved using the legume green manure mucuna as the only N source (Table 1). Using an adjacent fallow plot to measure N mineralization from legume green manures, the net increase in inorganic N resulting from mineralization varied from 60 to 165 kg N/ha. The first crop of Experiment 1 grown under irrigation during the dry season was managed to minimize leaching of N. Large quantities of inorganic N were found in the control plot at this site, possibly because of mineralization of soil organic matter, but more likely because large quantities of NO_3^- were held in the subsoil due to its high anion retention capacity (D. R. Bouldin, 1989, unpublished data). As measured by total N in the aboveground plant material, 40 to 50% of the total inorganic N found in the fallow plots was taken up by the maize crop. The subsequent maize crop, grown during the following rainy season, took up inorganic N remaining in the soil profile at least as efficiently as the first crop, and maize yields were as high or higher than those from the first crop.

In Experiment 2 at CPAC (Quintana, 1987), four legume green manures were compared for their ability to supply N to succeeding crops (Table 2). The major difference was that zornia produced much less total aboveground dry matter and contained less total N than the other species. Crotalaria produced much more aboveground dry matter but contained only slightly more total N than did either mucuna or canavalia. Yield of the first maize crop grown during the dry season following zornia (4.7 Mg/ha) reflected the lower amount of N fixed, while maize following crotalaria (5.8 Mg/ha) yielded slightly less than maize following either mucuna or canavalia (6.1 and 6.3 Mg/ha, respectively). Yield response of the second maize crop grown during the following

Other Benefits of Legume Green Manures

In addition to providing N, legume green manures offer a number of significant benefits, such as maintenance or improvement of soil physical properties. Legume green manures also provide ground cover, which reduces soil erosion (El-Swaify et al., 1985). Green manures, especially those which have tap roots or root deeply into the soil, may also prevent or help alleviate compaction in intensively cultivated soils (Taylor, 1974).

At IITA, growing a mucuna legume green manure every third crop has resulted in increased maize yields, and yields have been maintained (B. T. Kang, 1988, personal communication). Where mucuna was not part of the cropping system, yield could not be maintained. The green manure apparently provided benefits at least as important as N supply: improved erosion control and the maintenance of soil physical condition. In many alley-cropping situations, erosion control may be a more important benefit than nutrient cycling and conservation.

One of the more interesting potential benefits of legume green manures is their ability to suppress pests such as nematodes. Studies at CPAC have shown that some legume green manures are very effective in suppressing soybean nematodes, resulting in increased yields (Sharma et al., 1982). Farmers in certain areas of Brazil are successfully growing mucuna as a green manure crop with cotton and soybeans to suppress nematode activity. A very active program is under way at CPAC to determine the effect of various green manures on suppression of nematode populations. This work is sufficiently promising that some legume green manure crops may be grown in cropping systems if for no other reason than their effects on nematode suppression.

rainy season corresponded to the original quantities of N added in the legume green manures, although residual effect of the mucuna on maize yield was unusually high. N uptake from mucuna residue was more nearly what might be predicted. The high residual effect of crotalaria could be expected as a higher amount of N remained after the first crop.

In Experiment 3 at CPAC, Carsky (1989) grew several legume green manures in addition to those tested in Experiments 1 and 2. The same procedure was used in this experiment as in the other two. Carsky found yield and N uptake related to N supplied by the legume green manure, and yields up to 7.0 Mg/ha were achieved (Table 3). As in the second experiment, crotalaria contained the most N, but yield and N uptake did not reflect the additional N. In Experiment 3, the residual effect of these plant materials was relatively small as shown by either yield increase or N uptake, although crotalaria was slightly higher than the other legume green manures.

The results of these experiments demonstrate that when conditions are favorable for the growth of maize, there will be rapid mineralization of fixed N and large responses to legume green manure N, resulting in yields up to 7.0 Mg/ha. Yields as high as those obtained with 200 kg/ha of fertilizer N were

Table 5. Amount of mineralized N present in soil from 0 to 70 days following incorporation (Carsky, 1989), Experiment 3.

	Sampling day				
Plant material	**0**	**25**	**42**	**56**	**70**
	N kg/ha				
Canavalia brasiliensis	9	83	115	122	130
Cajanus	3	62	85	68	61
Canavalia ensiformes	9	145	184	191	174
Crotalaria	0	77	113	116	114
Pueraria	2	27	39	34	40
Mucuna	15	63	69	65	65
Calopogonium	2	50	64	67	93

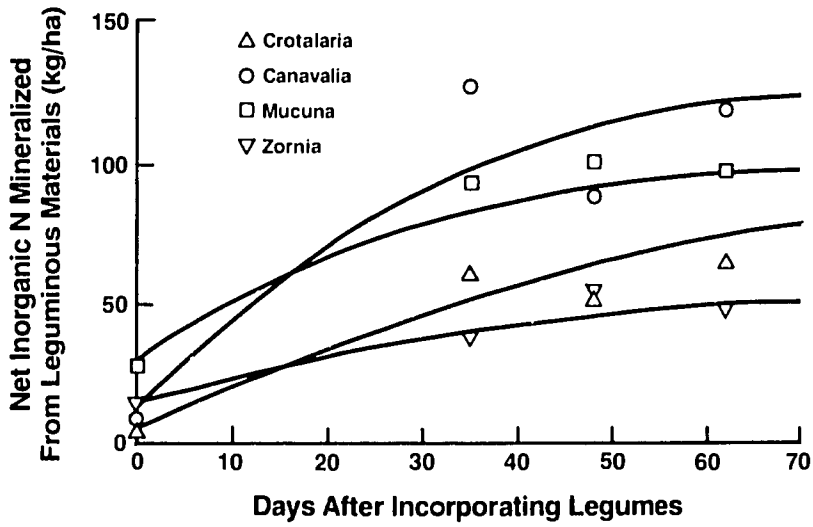

Figure 1. Net inorganic N mineralized from incorporation to 70 days after incorporation in four legume green manures measured in fallow plots, Experiment 2.

found, an indication that as N sources for maize, green manures can be as effective as fertilizer N.

Work in both Trinidad and Brazil (Table 4) demonstrates that grain legume residues provide significantly less total N for the succeeding non-legume than do the legume green manures. In two different experiments in Trinidad, which has a humid forest climate, limiting maize yields were about 3.3 Mg/ha, far lower than at CPAC with its savanna climate. In the first Trinidad experiment, cowpea residue increased maize grain yield only 0.2 Mg, and was less effective than 120 kg N/ha. In the second Trinidad experiment, cowpea residue gave a greater yield response than did 60 kg N/ha. Application of 60 kg N to the cowpea residue had no additional effect on yield. In this experiment, 17 to 20 kg N was added in the residues, and 45 kg N/ha was removed in the grain. In Experiment 1 at CPAC, addition of soybean residue resulted in only a slight increase in maize yield. No increase in N uptake was observed. In this instance, about 155 kg N/ha was removed in the grain, while 108 kg N was incorporated with the residue. Mughogho et al. (1982) concluded that there is little likelihood that a significant portion of the N requirement of succeeding nonlegume crops can be met from the residues of grain legumes.

A large amount of mineralized organic nitrogen remained in the soil 70 days after incorporation of canavalia, a legume green manure.

Mineralization Patterns of Legume Nitrogen

In Experiment 2, accumulation of inorganic N to a depth of 0.6 m was directly related to the total quantity of N added in the material (Figure 1), except in the case of crotalaria. Crotalaria, with its higher C/N ratio, contributed much more total biomass compared to the amount of N added, perhaps influencing the total N mineralized. The general shape of the net N accumulation curve was the same for all of the plant residues incorporated:

Table 6. Percentage of legume green manure residue remaining in soil (Carsky, 1989), Experiment 3.

	Days after incorporation				
Plant material	**0**	**25**	**42**	**56**	**70**
	——% residue remaining in soil——				
Canavalia brasiliensis	96	64	50	46	43
Cajanus	99	73	63	70	73
Canavalia ensiformes	96	37	20	17	25
Crotalaria	100	75	63	62	63
Pueraria	98	77	66	71	65
Mucuna	90	58	39	57	57
Calopogonium	99	65	55	53	35

rapid accumulation occurred during the first 40 to 60 days after incorporation. Little net change in soil inorganic N occurred from 60 days to the last sampling at 167 days (Figure 2). In these soils, where water is adequate and the temperature is favorable for decomposition, the readily decomposable portion of the plant residue is oxidized very rapidly, and inorganic N accumulates accordingly. From 50 to nearly 150 kg N/ha accumulated by 40 to 60 days after incorporation, depending upon the plant residue added.

In Experiment 3, very rapid mineralization of N from the several legume green manures occurred. Little or no apparent net accumulation of mineral-

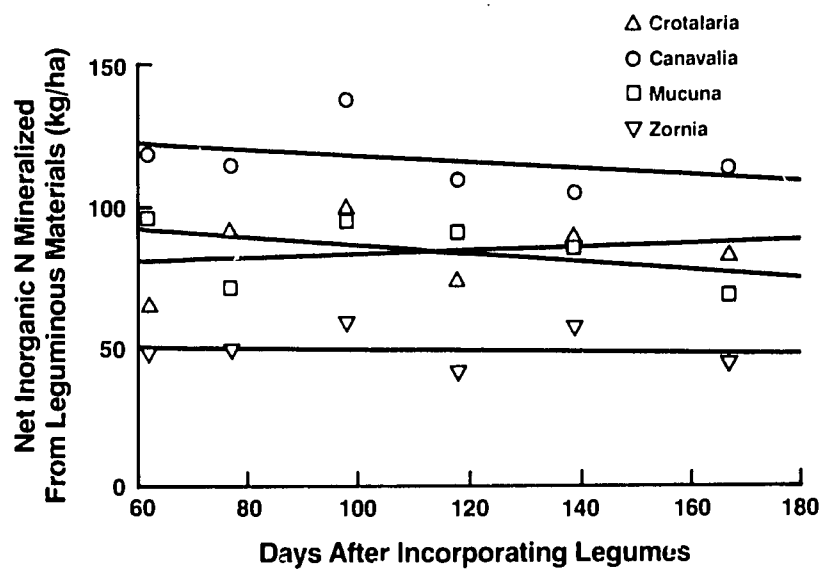

Figure 2. Net inorganic N mineralized from 70 days after incorporation to 180 days after incorporation in four legume green manures measured in fallow plots, Experiment 2.

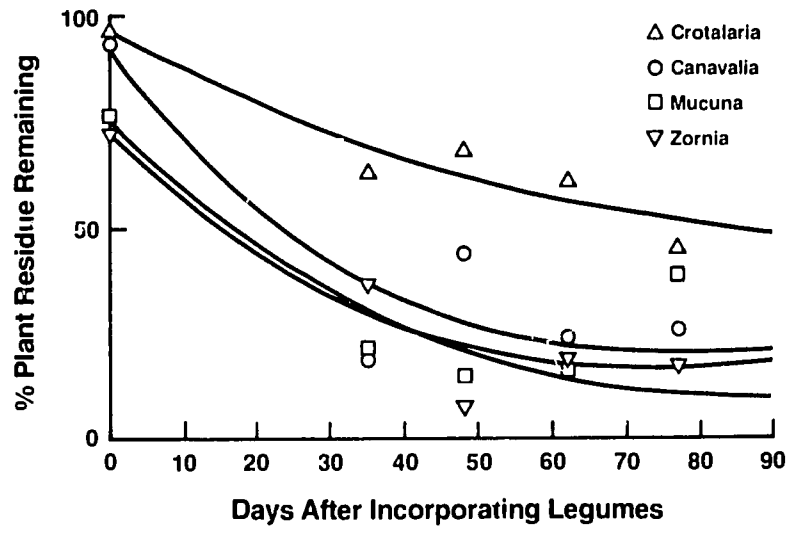

Figure 3. Percentage of plant residue remaining in soil from incorporation to 80 days after incorporation in four legume green manures measured in fallow plots, Experiment 2.

ized N occurred after the 42-day sampling (Table 5). Some additional mineralization may have occurred, although the results 56 and 70 days after incorporation showed little increase in inorganic N. From soil samples taken after 70 days, it was apparent that inorganic N had moved below 0.6 m.

To estimate the quantity of organic N remaining in the soil following incorporation, the net increase in inorganic N was considered to be the amount of N mineralized, and was subtracted from the original organic N added in the legume green manure. The remainder was the amount of organic N remaining, and was converted to percentage of the original amount added to the soil. The results from Experiment 2 (Figure 3) show that only about half the N in crotalaria was mineralized, compared to 75% or more for the other three species. However, in this experiment, the rate of N mineralization from the plant residues was very rapid, with most of it occurring within 40 to 60 days. The rate of release of inorganic N from the rapidly oxidizable fraction of the plant material apparently varies little among the various legume green manures. The accumulation curves for species studied reached their maximum by about 60 days, and the apparent organic N remaining in the residues did not change thereafter. However, the percentage of the total N in the legume green manure residues present in the rapidly oxidizable form did vary among the plant materials (Quintana, 1987).

In Experiment 3, Carsky (1989) found results very similar to those of Quintana in Experiment 2. Much more organic N from plant residues remained in the soil in Experiment 3 at the end of 56 days compared to the amounts found by Quintana (Table 6). Canavalia was the only green manure where apparent mineralization of organic N exceeded 50%. The legume green manures had C/N ratios ranging from 15 to 24. N release as a fraction of total N applied was related to C/N (r^2=0.65). Second-crop maize yields tended to be higher from plant residues with higher C/N ratios, indicating continued mineralization of the residual organic N.

Factors Affecting Crop Production

Results from field experiments on crop response to fertilizer N summarized by Grove (1979) had qualitatively similar yield responses in both temperate and tropical regions. Maize yields in excess of 5 t/ha were common, and 9 to 10 t/ha were achieved with optimum conditions. The increase in N content of aboveground dry matter was 0.56 per unit of applied N over normal rates of application. For maximum efficiency, most of the fertilizer N must be applied just before the period of most rapid plant uptake. The advantages of postplant side-dressing of fertilizer N are increased yield, increased N uptake, and improved recovery efficiency. Management practices to optimize fertilizer N efficiency are within the means of even the most rudimentary management systems.

Compared to fertilizer N, legume green manures limit the number of management options in cropping systems. Legume green manure crops must be grown before planting the succeeding nonlegume crop. The green manure crop must either be cut and allowed to dry and decompose on the soil surface or incorporated into the soil before planting the subsequent crop. Plant materials used in these experiments decompose very rapidly when incorporated into the soil, resulting in rapid inorganic N accumulation in the soil profile. To optimize N uptake, the succeeding crop must be planted as soon as possible after incorporation to minimize potential loss of inorganic N either by leaching beyond the rooting zone or by denitrification.

The first experiment at CPAC (Bowen, 1987) was conducted on a soil with initially very high levels of inorganic N in the profile (Tables 7, 8) and

Table 7. Apparent N recovery from fertilizer N and legume green manure N (Bowen, 1987), Experiment 1.

Treatment	Total N added	Total N in crop	Total N recovered	% N from added N
	kg/ha	kg/ha	kg/ha	
First maize crop				
None	—	120	—	—
Mucuna 1/2 tops	128	149	29	23
Mucuna tops	252	168	48	19
Mucuna tops + roots	260	168	48	18
Soybean residue	108	116	—	—
Fertilizer N	50	132	12	24
Second maize crop				
None	—	111	—	—
Mucuna 1/2 tops	residual	136	25	20
Mucuna tops	residual	146	35	14
Mucuna tops + roots	residual	149	38	15
Soybean residue	182	144	33	18
Fertilizer N	200	65	54	27

resulted in very low recovery of inorganic N. In Bowen's experiment, grain yield approached 7 t/ha, and total N in the aboveground portion of the crop averaged about 150 to 160 kg/ha. Even at these very acceptable yields, excess inorganic N was present in the profile when residues or fertilizer N were added, so that recovery of the added N was very low—around 20% (Table 7). Since the first maize crop was grown during the dry season under irrigation, little or no leaching occurred; residual inorganic N remained in the profile and was used by the succeeding maize crop grown during the following rainy season. Again, sufficient N was available so that recovery was only about 20%. Recovery of fertilizer N applied to the second crop was only slightly higher than the residual legume green manures.

In Experiment 2 at CPAC (Quintana, 1987), however, with low initial inorganic N levels in the soil profile, the recovery of both fertilizer N and legume green manure N was as high or higher than that reported by Grove (1979) (Table 9). The efficiency of utilization of N mineralized from zornia and mucuna in this experiment was especially high, whereas that from crotalaria was substantially lower. This difference may be related to the slightly slower rate of N mineralization in crotalaria compared to the other legumes (Figure 3).

In Experiment 3, apparent recovery of N added in legume green manures averaged about 40% in the first maize crop, compared to 65% apparent recovery of fertilizer N (Table 10). Apparent recovery of N by the second maize crop grown during the rainy season was negligible, again indicating that little N was mineralized after the initial period, or that mineralized N had moved below the rooting zone of the residual crop. Apparent recovery of fertilizer N added to the second crop, however, was nearly 70% indicating that mineralization of the remaining organic N was low indeed.

In these experiments, apparent recovery of N ranged to 60% of that added in green manures, which is not greatly different from the recovery of fertilizer N. In a discussion of the influence of water on N absorption, Bartholomew (1972) concluded that not more than 60% of the inorganic N in the rooting zone could be absorbed by the crop. To obtain higher efficiencies, water would have to be replenished several times for a large portion of the inorganic N to be moved to plant roots. Duxbury (J. D. Duxbury, 1989, personal communication) has suggested that a portion of the inorganic N in the soil is immobilized in the biomass and thus becomes unavailable to the growing plants. Reduced efficiency of inorganic N results, since subsequent mineralization of the biomass occurs only slowly or at a time when crops do not take up inorganic N. While

Table 8. Inorganic N at 1.2 m in soil profile in fallow soil and in cropped plots at end of cropping period (Bowen, 1987), Experiment 1.

	Inorganic N in profile	
Treatment	Fallow plots	Cropped plots
	kg/ha	kg/ha
First maize crop		
None	274	138
Mucuna tops 1/2	76	141
Mucuna tops	165	160
Mucuna tops + roots	59	82
Second maize crop		
None	148	27
Mucuna tops 1/2 residual	152	27
Mucuna tops residual	167	33
Mucuna tops + roots residual	84	24
Mucuna tops	152	45

Table 9. Apparent N recovery from fertilizer N and legume green manure N (Quintana, 1987), Experiment 2.

Material added	Total N added	Total N in crop	Apparent N recovery	Apparent % N recovery from added N
	kg/ha	kg/ha	kg/ha	
First crop				
None	—	69	—	—
Zornia	58	116	47	81
Mucuna	117	159	90	77
Canavalia ensiformes	156	170	101	65
Crotalaria	170	149	80	47
Fertilizer N	100	123	54	54
Fertilizer N	200	173	104	52
Second crop				
None	—	30	—	—
Zornia	residual	44	14	24
Mucuna	residual	72	42	36
Canavalia	residual	53	23	15
Crotalaria	residual	92	62	36
Fertilizer N	100	114	84	84
Fertilizer N	200	182	152	76

Table 10. Apparent N recovery from fertilizer N and legume green manure N (Carsky, 1989), Experiment 3.

Treatment	Total N added	Total N in crop	Apparent N recovery	Apparent % N recovery from added N
	kg/ha	kg/ha	kg/ha	
First crop				
None	—	69	—	—
Canavalia brasiliensis	228	159	90	39
Cajanus	229	149	80	35
Canavalia ensiformes	231	177	108	47
Calopogonium	142	137	68	48
Crotalaria	306	180	111	36
Mucuna	152	130	61	40
Pueraria	116	112	43	37
N	200	198	129	65
Second crop (residual)				
None	—	67	—	—
Canavalia b	228	79	12	5
Cajanus	229	86	19	8
Canavalia e	231	82	15	6
Calopogonium	142	72	5	4
Crotalaria	306	96	29	9
Mucuna	152	67	—	—
Pueraria	116	60	00	—
N	160	177	110	69

both of these explanations for the higher efficiencies observed may be debated, the results obtained here are consistent with those reported by Grove and Bartholomew.

In all three experiments at CPAC, strong responses to added N resulted, even in the presence of large quantities of inorganic N present in the soil profile. The recovery of N from the legume green manures, especially in Experiments 2 and 3, is encouraging. These data suggest that planting crops such as maize immediately following incorporation of legume green manures is a satisfactory practice.

When quantities of potentially mineralizable N from legume green manures exceed crop requirements for N, the possibility of significant loss of inorganic N is great. Large quantities of inorganic N were found in the fallow plots at the end of the cropping period in all three experiments (Tables 8, 11, and 12). This was the case following both the dry-season irrigated crop and the rainy-season residual crop. However, the quantity of inorganic N in the cropped plots at the end of the growing season was very low, except following the first crop of Experiment 1. The difference between the quantity of inorganic N in the fallow plots and that in the cropped plots was greater than the quantity of N taken up by the maize crop.

Results from the samples taken by Carsky in Experiment 3 show movement of N deep into the profile, where large quantities of inorganic N were found to a depth of 180 cm (Table 12). In addition, N could well be immobilized in the biomass, as suggested by Duxbury (J. D. Duxbury, 1989, personal communication), and not accounted for. The quantity of unaccounted-for N, however, is sufficiently great to be of concern even in these experiments, where the yield potential is high (6 to 10 t/ha).

No evidence is available to predict how the unaccounted-for N may have been lost. When the yield potential is low, as is the case for maize production in the humid tropics (3.5 t/ha or less), the likelihood of large losses is even greater. Since incorporation of legume green manures must precede planting of the nonlegume crop, inorganic N mineralized from legume green manures is more likely to be lost than fertilizer N, even when both are

Incorporating the green manure crop helps reduce the amount of mineralized nitrogen lost through volatilization.

Table 11. Inorganic N at 1.2 m in soil profile in fallow soil and in cropped plots at end of cropping period (Quintana, 1987), Experiment 2.

	Inorganic N in profile	
Treatment	**Fallow plots**	**Cropped Plots**
	kg/ha	kg/ha
First crop		
None	115	14
Zornia	195	27
Mucuna	236	41
Canavalia	257	44
Crotalaria	237	56
Second crop (residual)		
None	213	26
Mucuna	338	56
Crotalaria	369	43

used with optimum management.

Surface application of residues without incorporation may result in large losses of N, probably because of ammonia volatilization from decomposing plant materials. In a greenhouse experiment, Costa (1988) could not account for about 15% of the surface-applied N after 15 days, and 45% after 178 days. The unaccounted-for N was assumed to have been lost by ammonia volatilization. Costa found no evidence that incorporated legumes decompose more rapidly than surface-placed materials.

In alley-cropping systems, annual crops are planted between rows of permanent crops. The permanent crop is usually a rapidly growing shrub or tree that can be pruned back frequently and still maintain growth. Annual growth of the permanent crop is pruned and placed between the rows of the annual crop, serving as a mulch for the annual crop. Among the chief benefits attributed to this system are the nutrients supplied to the annual interplanted crop. Thus, it is reasonable to consider alley-cropping, as described here, to be a form of legume green manuring.

Limited data are available to evaluate the benefits of the mulch as a nutrient source in alley-cropping systems. Kang et al. (1985) at Ibadan, Nigeria, were able to maintain maize yields at 2 t/ha over three years with prunings of leucaena, compared to 0.5 t without prunings. About 110 kg N were added to each maize crop with the leucaena cuttings. Where 80 kg of fertilizer N was added in addition to the leucaena cuttings for a total addition of about 190 kg N, maize yields were from about 2.6 to nearly 4.0 t/ha. While no data were presented, N recovery from the leucaena cuttings must have been low. Palm (1988), in a study at Yurimaguas, Peru, reported that only 15% of the N in surface-applied *Inga* cuttings was recovered by a rice crop to which the cuttings had been applied.

Although the limited evidence available indi-

Table 12. Inorganic N in soil profile in fallow soil and in cropped plots at end of first and end of second crop (Carksy, 1989), Experiment 3.

	Fallow plots		Cropped plots	
Plant material incorporated	N accum. 1.2 m	N accum. 1.8 m	N accum. 1.2 m	N accum. 1.8 m
	kg/ha	kg/ha	kg/ha	kg/ha
First maize crop	After 152 days		After 174 days	
None	80	105	16	
Canavalia brasiliensis	279	318	14	
Cajanus	202	232	17	
Canavalia ensiformes	323	376	19	
Calopogonium	188	224	14	
Crotalaria	296	335	19	
Mucuna	181	213	15	
Pueraria	141	199	13	
Fertilizer N (200 kg/ha)			17	
Second maize crop	After 321 days		After 357 days	
None	139	194	16	18
Canavalia brasiliensis	178	360	16	20
Cajanus	241	387	12	12
Canavalia ensiformes	234	436	14	15
Calopogonium	208	282	17	19
Crotalaria	185	365	34	34
Mucuna	179	304	14	15
Pueraria	145	264	10	11
Fertilizer N (160 kg/ha)			21	32

cates that recovery of N from surface-applied residues is low, increased yields are often observed. More importantly, increased yield level is maintained for several crops, according to the data of Kang et al. (1985). Surface-applied residues provide cover, reduce erosion hazards, and moderate water loss and surface soil temperature. Much of the reported work with alley-cropping is done in the humid tropics, and the intercrop is most often maize. Limited N requirements of maize in the humid tropics and loss of N by ammonia volatilization from surface-applied cuttings result in very low N utilization in alley-cropping systems.

Potentials and Problems in Cropping Systems

The experiments at CPAC demonstrate that a number of legume green manures will, with proper management, fix large quantities of N. Under proper management and favorable conditions, this N becomes available to the subsequent nonlegume crop in quantities sufficient to meet its requirements without the addition of fertilizer N. Carsky (1989) found that canavalia alone could provide the equivalent of about 200 kg N/ha (Figure 4 and Table 3). Other benefits of green manure crops in cropping systems include erosion control, improved physical condition, increased water infiltration and water-holding capacity, and, at least temporarily, increased cation-exchange capacity (Motavalli, 1989). The ability of some legume green manure crops to suppress plant pests of certain crops may enhance the value of these green manures far beyond their value as an N source alone.

The experiments also indicate that using legume green manures in cropping systems will present a number of problems, and the management requirements of green manure crops are no less stringent than those of the subsequent nonlegume crop. Inoculation is required to achieve adequate nodulation in the legumes, and the soil's physical and chemical environment must be adequate if the legume is to approach its capacity for N fixation.

Good management is also required to take advantage of the N fixed by legume green manures. The quantity of N supplied by legume green manures is determined by its rate of growth and the length of time it is allowed to grow. Various species grow at different rates and fix N at different rates, so growers can exercise some control over the quantity

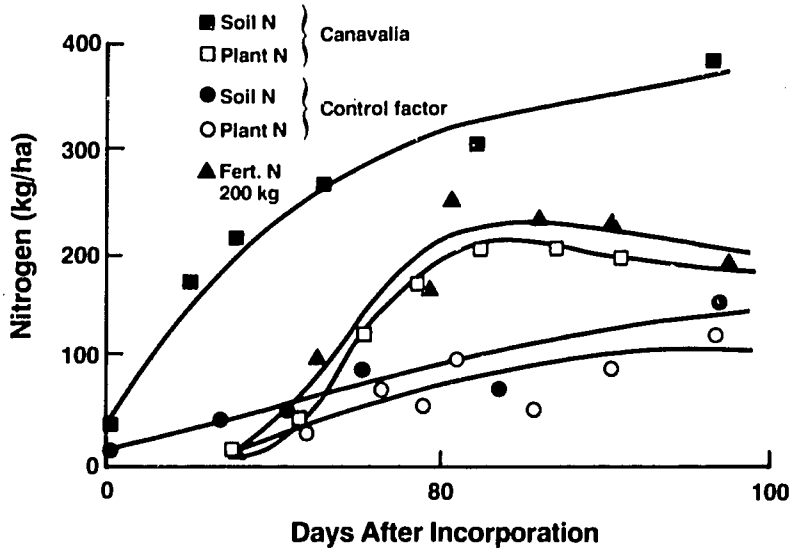

Figure 4. Accumulation of N in fallow soil (control and with canavalia incorporated) and accumulation of aboveground N in maize (control, with canavalia incorporated, and with 200 kg/ha of fertilizer N) (Carsky, 1989), Experiment 3.

of N applied by selecting the legume species that most nearly meets the N requirements of the subsequent nonlegume crop. The actual quantity of N released to crops is determined by the rate of mineralization of the plant residue. If legume green manures are incorporated into the soil, the N they supply can only be applied before planting the succeeding nonlegume crop.

When large amounts of organic matter are incorporated and the residues mineralize rapidly, inorganic N as NO_3^- may accumulate (Figure 4). Two problems result: First, the total quantity of inorganic N may exceed the quantity that will be taken up by the nonlegume crop; second, N mineralization may occur more rapidly than the crop can use it, especially early in the growth cycle when demand by the crop is low. At such times, large quantities of N may be lost by leaching. Any excess NO_3^--N left in the profile at the end of the cropping period is also subject to loss by leaching and possibly by denitrification. (NO_3^- leaching and sorption are discussed in more detail in the inset below.)

Possibly the most important management decision facing the farmer is how to incorporate the legume green manure crop into the cropping system without sacrificing a nonlegume crop. The green

Leaching and Sorption of Nitrate

In highly weathered Ultisols and Oxisols, sorption apparently can reduce the leaching of NO_3^- from the soil profile. Experiments at CPAC routinely have included NO_3^- analysis of soil samples from a depth of as much as 2 meters. During the wet season, NO_3^- was leached fairly rapidly from the upper 30 to 45 cm of soil and accumulated below 90 cm, an indication that NO_3^- sorption was occurring in the lower portions of the soil profile (Figure 5). These data were from fallow plots in which different green manures had been incorporated at the beginning of the previous dry season (Carsky, 1989).

During the dry season, the plots were irrigated periodically, and considerable NO_3^- accumulated. The data demonstrating NO_3^- sorption were collected 203 to 354 days after incorporation of the legume green manure. Precipitation during this period was 134 cm. Laboratory studies with samples taken at Manaus (D. R. Bouldin, 1989, unpublished data) showed negligible NO_3^- sorption in the surface 30 cm, but sorption increased with depth. At a depth of about 1 meter, 40 to 60% was sorbed when the soil contained about 100 kg/ha of NO_3^-.

Using measured precipitation (134 cm), estimated evaporation (22 cm), and drainage (107 cm), Bouldin (D. R. Bouldin, 1989, unpublished data) developed a leaching model that includes NO_3^- sorption. Using this model, estimated mineralization was 80 kg N/ha and leaching loss at 180 cm was 60 kg N/ha. While these results should be interpreted with caution, they do indicate that NO_3^- leaching was very sensitive to estimated NO_3^- sorption and relatively insensitive to estimated water movement. In fact, computed NO_3^- loss will not agree with experimental results unless the model includes significant NO_3^- sorption increasing with depth. Similar results were obtained using data from Experiments 1 and 2 and from Manaus.

These observations have several important implications for green manure management and N management in general. First, sorption of NO_3^- retards but does not prevent leaching. Nitrate N tends to accumulate below 45 to 60 cm and moves slowly beyond this depth into the soil profile. Second, NO_3^- at greater depths presumably will be available to roots growing at these depths. However, uptake of sorbed NO_3^- probably will be slower, and possibly less efficient, than uptake of NO_3^- from surface layers of soil. Nitrate sorption reduces the mobility of NO_3^- and hence its movement toward plant roots by mass flow or diffusion. If sorption is sufficient to retard most leaching, one productive legume green manure could supply sufficient N for two modest nonlegume crops, if those crops were deep-rooted enough to tap sorbed N in the soil profile. While all of these possibilities are speculative, they are sufficiently significant to warrant further investigation.

manure crop should be grown at a time when it will not displace a nonlegume crop or at a time when no other crop is grown. Under rainfed systems in the wet-dry climates, it may be possible to plant a green manure crop at the end of the rainy season so that it survives on residual moisture and regrows when the rainy season begins.

To test this hypothesis, an experiment to screen legumes for dry-season survival was carried out at CPAC using 52 different legumes. As many as 37 different legumes survived a five-month dry season and began growing when the rains came (Burle et al., 1988). With the best-adapted legumes, regrowth over a six-week period beginning at the start of the rainy season reached 5000 kg/ha, and total N in the aboveground dry matter exceeded 100 kg/ha. Yields of maize grain following incorporation of regrowth of legume green manures surviving over the dry season reached 7.4 t/ha without added fertilizer N (Burle et al., 1989). This work is continuing and offers a promising means of using green manures without sacrificing a nonlegume crop.

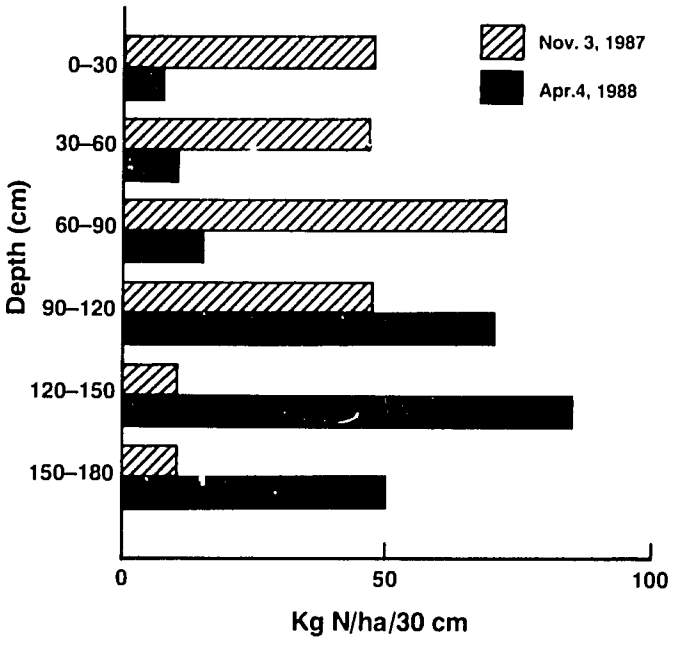

Figure 5. Inorganic N content of profile to depth of 180 cm, samples taken 3 November 1987 and 4 April 1988. Estimated mineralization during the interval was 80 kg, and estimated leaching loss beyond 180 cm was 60 kg/ha. During this period precipitation was 134 cm, estimated evaporation was 22 cm, and estimated drainage beyond 180 cm was 107 cm (Carsky, 1989), Experiment 3.

In systems where fertilizer N is scarce or unavailable, total productivity may be greater where some portion of the land area is used to produce a green manure each cropping period. Kang et al. (1985) found that one hectare of alley-cropped land produced as much as 4 ha without alley-cropping. Other work at IITA showed the benefits on maize production of a mucuna green manure crop incorporated every third year. These benefits very likely were greater than the N effect alone (B. T. Kang, 1988, personal communication). Although farmers are reluctant to devote portions of their land to green manure crops, doing so may result in greater total productivity on their land.

Incorporating large amounts of plant material into the soil is a formidable task, particularly where implements and labor are limited. The evidence available suggests that it is important to incorporate the legume into the soil in order to minimize direct losses of N. Recovery of N from surface-applied plant material may average no more than 15%.

Plant material, whether incorporated into the soil or applied to the soil surface, undergoes very rapid decomposition. In all of the annual plant species in the experiments reported here, the rapidly decomposable material was largely gone within 60 days. The quantity of more resistant material remaining varied among plant species, but the rate of N mineralization from the readily decomposable material was not different among species.

To maximize the utilization of N, the plant material must be incorporated into the soil so that peak mineralization occurs as nearly as possible to the time when the succeeding crop's demand is highest. This usually means that planting should follow incorporation as closely as possible.

Because some legume green manures can survive the dry season, farmers can integrate them into a cropping system without sacrificing a food crop. The legume shown above survived a long drought and regrew rapidly when the rains resumed.

Conclusion

Even though organic nitrogen poses more management problems than does fertilizer nitrogen, the studies discussed in this report strongly support the conclusion that legume green manures have a place on many farms. The number of legume species available, with their diverse growth characteristics and potentials for nitrogen fixation, enables farmers to select a green manure adapted to almost any particular climate and cropping system. In many cases, green manures can supply all of the nitrogen necessary—a significant contribution, especially in regions where nitrogen fertilizer is costly or unavailable. And, because legume green manures can help control weeds and pests and improve soil physical conditions, their use offers benefits far beyond the value of the nitrogen they supply.

While the work reported here provides a basis for managing nitrogen from legume green manures, there are several areas in which more information is needed. Further research into nitrogen cycling, sorption, and leaching would improve our ability to manage nitrogen in the soil and make more of it available to crops. And a range of crops and cropping systems using legume green manures should be studied under various soil and climatic conditions to provide a broader range of management options. As our skill in managing them increases, legume green manures will no doubt achieve a prominent place in sustainable agricultural systems throughout the world.

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