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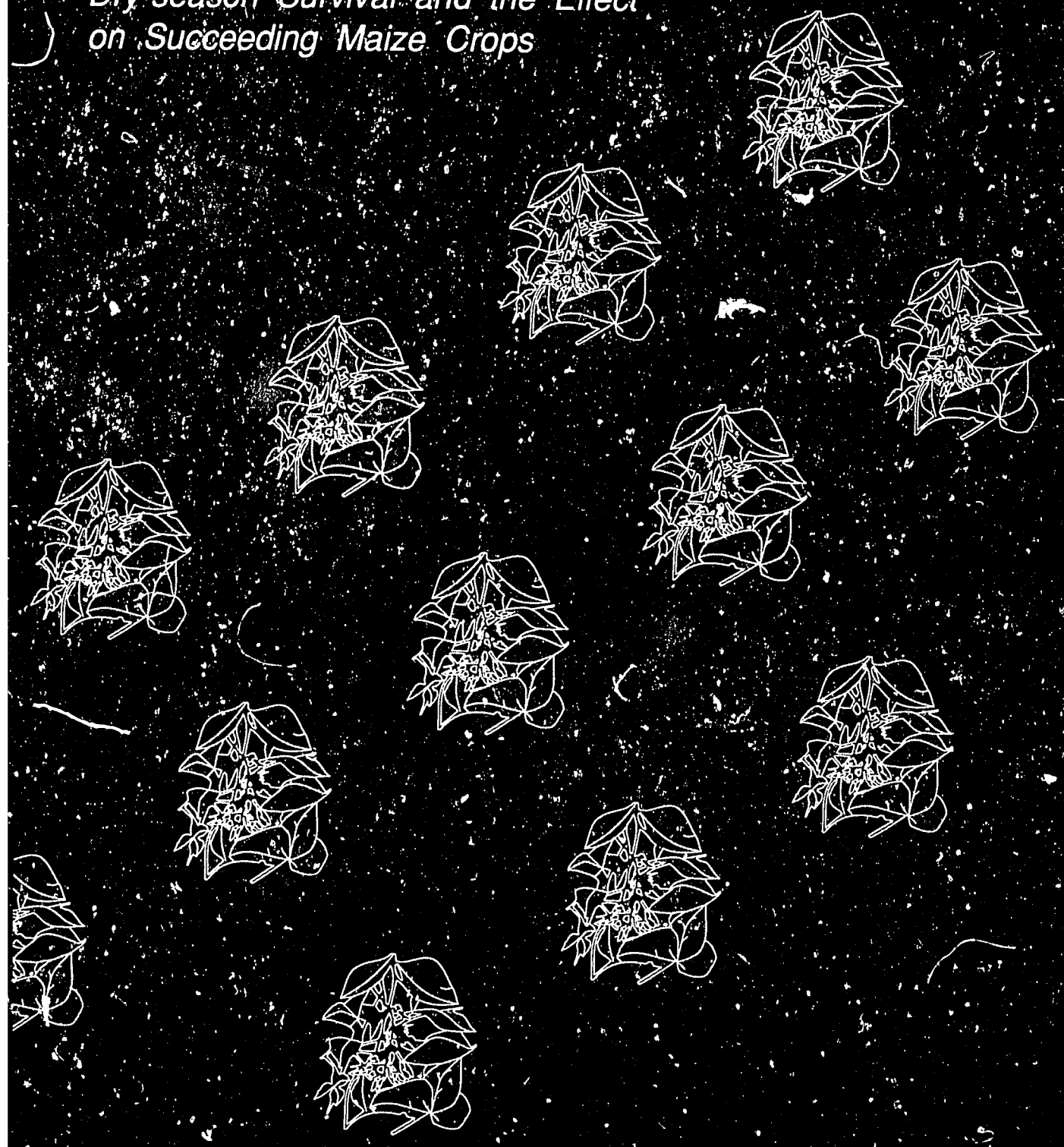
Dry-season Survival and the Effect on Succeeding Maize Crops



Soil Management CRSP Bulletin 92-04

Legume Green Manures

Dry-season Survival and the Effect on Succeeding Maize Crops

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Foreword

Since the inception of the Soil Management Collaborative Research Support Program (CRSP) in 1981, Cornell University has taken a lead role in the program's acid-savanna research. Much of that work was conducted in collaboration with scientists from the Brazilian Agricultural Research Enterprise (EMBRAPA) and its Cerrado Agricultural Research Center (CPAC). Throughout this collaboration, particular attention has been devoted to the nitrogen-use efficiencies and nitrogen-fixing properties of legume green manures.

This report serves as a continuation of an earlier technical bulletin, *Legume Green Manures: Principles for Management Based on Recent Research* (No. 90-01). That volume provided information on the practical management of legumes and demonstrated their ability to supply much of the nitrogen needed by nonlegume crops—an important consideration for resource-poor farmers unable to purchase fertilizer inputs. The current volume identifies legumes that can survive a difficult dry season and provide a substantial portion of the nitrogen required by the succeeding nonlegume crop. In addition to providing homegrown nitrogen, such technology can also help to reduce the progressive soil degradation that occurs when ground covers are not used to stabilize the dry-season landscape. Taken together, these benefits suggest that legume green manures are a key to the economically productive and environmentally responsible management of the savanna soils.

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Roger G. Hanson, Director
Soil Management CRSP
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Acknowledgments

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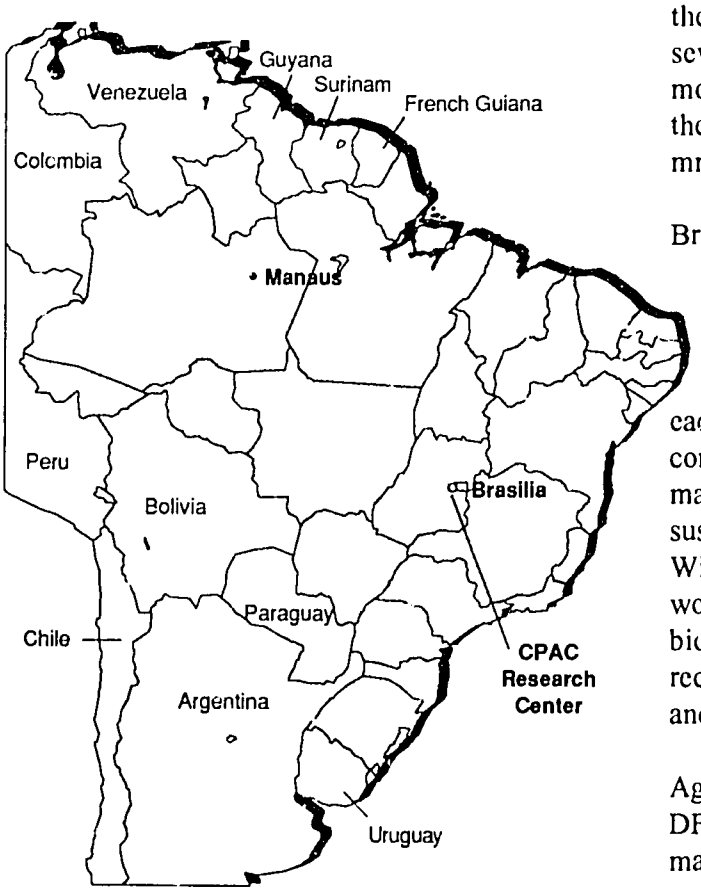
Legumes in Savanna Cropping Systems

Legume green manures have the potential to supply a large portion of the N needed by succeeding nonlegume crops. Properly managed, they can replace much of the fertilizer N now being used or increase the yield potential of nonlegume crops where fertilizer N is either unavailable or too costly. Using legume-rhizobium symbiosis to provide N for succeeding nonlegume crops is not a new practice, but its potential has not been fully explored.

One major constraint to the intensive use of a green manure is that it often displaces a nonlegume food or cash crop. Substantial yield and economic benefits must be demonstrated before farmers will consider this kind of change. To be most economical, green manures should be introduced into the cropping system in ways that do not compete with the major food or commercial crop.



Map of Brazil showing the Manaus site and the CPAC Research Center at Planaltina, near Brasilia.

On the extensive wet-dry areas throughout the tropics, legume use is also constrained by the length of the dry season, which ranges from a few weeks to several months. The vast acid savannas of Brazil's central plateau represent one of the more difficult of these environments: the dry season lasts four to seven months, and rainfall during the three driest months is usually less than 50 mm. Rainfall during the wet season—which ranges from 900 to 1500 mm—is sufficient to grow most annual crops.

Unless irrigation is available, farmland on Brazil's central plateau is generally not used during the dry season, except for pasture or perennial crops. After the wet-season crop is harvested, the land is usually left bare until the rains return. If hardy legumes planted at the end of each wet season can survive the dry season and continue to grow in the following wet season, they may provide a viable management system for sustaining long-term annual crop production. Without displacing food or cash crops, such legumes would increase N in the agricultural system through biological nitrogen fixation, and they might also recycle nutrients and control soil erosion, weeds, and nematodes.

Work at EMBRAPA/Centro de Pesquisa Agropecuaria dos Cerrados (CPAC) at Planaltina, DF, Brazil, has demonstrated that legume green manures can supply much of the N required by succeeding nonlegume crops (Lathwell, 1990). The first priority of the current collaboration was to identify legumes that could be planted near the end

of the wet season—either following the nonlegume harvest or interplanted with the nonlegume crop—and survive the dry season. Such species must either grow throughout the dry season or renew growth at the start of the wet season. The second priority was to estimate the quantity of N contributed by the legume to the nonlegume crop planted at or near the beginning of the wet season. Legumes that provide a high percentage of the N required by the succeeding nonlegume crop would be viable (and valuable) green manures in savanna cropping systems.

Legumes like mucuna that survive the dry season and grow rapidly when the rainy season begins can play an important role in savanna cropping systems.

Screening Legumes for Dry-season Survival

Legume Requirements

Legumes planted at the end of the wet season must germinate quickly and grow rapidly to become well established before the dry season begins. Because little rainfall generally occurs after planting, legumes must use residual water in the soil profile if they are to survive and grow. Consequently, soil chemical and physical conditions must be conducive to rapid and deep root penetration. Constraints to root penetration must be ameliorated before planting the legume.

To maximize the amount of N contributed to a cropping system, the legume must not only survive the dry season, but it must also grow rapidly when the subsequent rainy season begins. Legumes that survive the dry season should be in an advantageous position to initiate such growth since their root systems will already be established. An efficient symbiotic relationship with rhizobia must also occur so that N will accumulate rapidly when growing conditions are favorable.

Attempts to identify species capable of adapting to intercropping systems in Brazil have focused mainly on the Southern Region (Derpsch and Calegari, 1985), where there is no dry season comparable to that in the Central Region. Paterson et al. (1984) report that some legume species survived the dry season in a savanna after being planted at the end of the wet season. Field studies by Torsell (1976) indicate that *Stylosanthes humilis* was able to survive up to 100 days without rain. Although Torsell evaluated legumes as green fodder for dry-season grazing, his results suggest that several legume species might survive the dry season and be useful green manures. In the Brazilian acid savannas, studies of forage species show that *Stylosanthes guianensis* var. pauciflora, *Stylosanthes capitata, Stylosanthes macrocephala, Centrosema macrocarpum,* and *Leucaena leucocephala* are promising dry-season legumes (Andrade, 1986). Likewise *Mucuna aterrima* and *Canavalia ensiformis* survive the dry season in this region and produce up to 8000 kg ha^{-1} of aboveground dry matter (Pereira, 1987). Few observations have been made, however, about the dry-season response of species planted at the end of the wet season.

Experimental Procedure

The climate at CPAC is characterized by a strong wet and dry season. Rainfall averages about 1500 mm, 95% of which normally falls during the October-to-April wet season. Monthly temperatures average 22 °C during the wet season and 20 °C during the dry season.

Two sites were used in screening experiments within the CPAC Research Center: one was on a Dark Red Latosol (DRL site); the other was on a Red Yellow Latosol (RYL site); both were of the suborder Ustox (Macedo and Bryant, 1987). In their native state, these soils provide excellent physical conditions, but they are very acid and highly deficient in P. These severe chemical limitations must be corrected to achieve high production levels. For maximum response, both surface-soil limitations and subsoil acidity must be alleviated. The latter is especially necessary if acid-sensitive plants are to achieve maximum root growth.

Both sites had been cleared of the native Cerrado vegetation and cultivated for several years before the present study. Chemical properties of the two soils (Table 1) show that Ca + Mg content to a 30-cm depth had been increased and that Al content had been reduced compared to native soil conditions (Goedert, 1983).

Seeds of 52 different legumes from several sources were screened for dry-season survival and biomass production. All 52 legumes were sown at each site from 19–21 March 1987. Prior to seeding, dolomitic limestone was incorporated into the soil with a moldboard plow, as were P and K. All legume seeds were inoculated with rhizobium species provided by the microbiology laboratory at CPAC. Planting density within the rows was greater at the DRL site than at the RYL site. Surviving legumes were harvested from 10–11 November 1987 to determine biomass production and N content.

Monthly rainfall and the number of days on which it rained (from 21 March to 10 November) are shown in Table 2. Rainfall virtually ceased after 15 April and began again on 18 September. The dry season thus provided a severe test of the legumes' survival capabilities.

Table 2. Monthly rainfall during the period legumes were in the field, 1987.

Month	Amount	Days
	mm	
March, 21–31	15	4
April	113	13
May	29	6
June	12	1
July	0	0
August	0	0
September	66	6
October	57	11
November, 1–10	56	5
Total	348	

Results

Of the 52 legumes sown, 37 survived the dry season and continued growing once the rains returned (Table 3). Of the 29 legumes which produced measurable biomass (Table 4), aboveground dry matter ranged from a low of 600 to a high of 5500 kg ha^{-1}. Most of the legumes that failed to survive the dry season were annuals that completed their life cycle prematurely due to drought stress.

Except for *Medicago sativa*, aboveground biomass yields at the DRL site were higher than at the RYL site. Part of the difference could be attributed to the greater planting density at the DRL site. Also, the DRL site exhibits a predominantly kaolinite mineralogy, while the RYL site is predominantly gibbsitic (Rodrigues and Klamt, 1978). In spite of lower yields, legumes that performed best at the RYL site also performed best at the DRL site.

For a green-manure legume to contribute meaningfully to the N requirements of a succeeding crop, we suggest that it must produce at least 2000 kg ha^{-1} of aboveground biomass—or 40 kg N ha^{-1}—for incorporation into the soil before planting the crop. These values were selected arbitrarily. However, a 50% recovery of the biomass N would supply only 20 kg to the succeeding crop, a minimum to produce any real effect on yield.

The following legume species accounted for the 12 highest dry-matter yields in each soil (Table 5): *Cajanus* (4), *Canavalia* (2), *Crotalaria* (3), *Mucuna* (1), *Stylosanthes* (2), and *Tephrosia* (1). At the DRL site, these species substantially exceeded both the above-mentioned production criteria. On the YRL site, however, dry matter did not reach the goal, although N content was at or above the desired amount. Based on visual observations, no surviving legumes appeared N deficient. Biomass N concentration ranged from 16.2 to 35.5 g kg^{-1}.

Table 1. Chemical properties of the soils cultivated with legumes, Dark Red Latosol (DRL) and Red Yellow Latosol (RYL).

Profile	pH (H_2O)		Al		Ca + Mg		P		K	
(cm)	DRL	RYL	DRL	RYL	DRL	RYL	DRL	RYL	DRL	RYL
			me/100 ml				*ppm*			
0–10	5.0	6.2	0.30	0	4.60	4.75	4.0	3.9	56	65
10–20	5.2	6.1	0.39	0	3.92	3.48	3.0	2.0	17	17
20–30	5.1	5.9	0.61	0	2.47	2.34	1.6	1.2	11	14

Table 3. Legumes cultivated during the dry season on two tropical acid savanna soils.

Scientific name	Common name	Status[1]
Cajanus cajan (black)	Pigeonpea	s
Cajanus cajan (common)	Pigeonpea	s
Cajanus cajan (persimmon)	Pigeonpea	s
Cajanus cajan (red)	Pigeonpea	s
Cajanus cajan	Pigeonpea	s
Calopogonium mucunoides		s
Canavalia brasiliensis		s
Canavalia ensiformis		s
Centrosema brasilianum (CPAC 1420)		s
Centrosema macrocarpum (CPAC 1213)		s
Cicer arietinum		n
Cratylia floribunda		s
Crotalaria anagiroides		s
Crotalaria juncea		n
Crotalaria paulina		s
Crotalaria sp.		s
Crotalaria spectabilis		s
Crotalaria striata		s
Flemingia congesta		s
Glycine wightii		s
Indigofera hirsuta		s
Indigofera tinctoria		s
Lablab purpureus		s
Macroptilium atropurpureum	Siratro	s
Medicago sativa	Alfalfa	s
Mucuna aterrima		s
Mucuna cochichinensis		n
Mucuna deeringiana		s
Mucuna sp.		s
Pueraria phaseoloides	Tropical kudzu	s
Rhynchosia schomburgkii CPAC 1495		s
Sesbania aculeata		n
Sesbania sp.		n
Stizolobium niveum		s
Stylosanthes capitata CPAC 1172		s
Stylosanthes guianensis var. *pauciflora*	Estilosantes Bandeirante	s
Stylosanthes guianensis var. *vulgaris* CPAC 1230		s
Stylosanthes macrocephala cv Pioneiro		s
Tephrosia candida		s
Vicia faba		n
Vicia sativa		s
Vigna mungo	Feijão mungo preto	n
Vigna radiata	Feijão mungo verde	n
Vigna unguiculata		n
Vigna unguiculata	Vermelha	n
Vigna unguiculata	Caupi 255	n
Vigna unguiculata	Caupi 256	n
Vigna unguiculata	Caupi black	n
Vigna unguiculata	Caupi oscaroide	n
Vigna unguiculata	Feijão sempre verde	n
Zornia brasiliensis CPAC 1082		s
Zornia latifolia CPAC 894		s

[1] s = legumes survived; n = legumes did not survive.

Mucuna and *Canavalia* species emerged and provided ground cover more rapidly than other species. As the dry season progressed, mucuna shed its leaves, but when the rain started, it grew immediately, and by the time of incorporation, it had established effective ground cover. *Canavalia ensiformis*, an erect legume, also dropped it leaves during the dry season, but it regrew rapidly once the rains began. A climbing legume, *Canavalia brasiliensis*, was quick to establish, remained mostly green during the dry season, and regrew vigorously with the onset of rain.

The *Stylosanthes* and *Tephrosia* species were among the slowest to establish, but both survived and remained green over the dry season; by the middle of

Table 4. Aboveground legume biomass produced at the Dark Red Latosol (DRL) and Red Yellow Latosol (RYL) sites.

Legume (identifier)	DRL	RYL
	($T\ ha^{-1}$)	
Cajanus cajan (black)	3.3	1.9
Cajanus cajan (red)	2.7	2.6
Cajanus cajan (persimmon)	4.5	1.6
Cajanus cajan (common)	3.9	1.5
Calopogonium mucunoides	2.1	1.5
Canavalia ensiformis	3.5	2.7
Canavalia brasiliensis	5.5	2.8
Centrosema macrocarpum (CPAC 1213)	1.6	1.1
Centrosema brasilianum (CPAC 1420)	1.8	1.2
Cratylia floribunda	1.9	0.7
Crotalaria paulina	2.8	1.5
Crotalaria spectabilis	2.7	1.8
Crotalaria striata	3.9	2.0
Flemingia congesta	0.7	0.4
Glycine wightii	1.5	1.2
Indigofera tinctoria	2.7	1.4
Indigofera hirsuta	2.0	1.3
Lablab purpureus	1.3	0.9
Macroptilium atropurpureum	1.9	0.8
Medicago sativa	0.6	1.1
Mucuna aterrima	4.7	2.9
Mucuna deeringiana	2.5	1.2
Mucuna niveum	2.2	0.8
Pueraria phaseoloides	1.2	0.4
Rhynchosia schomburgkii (CPAC 1495)	2.0	0.8
Stylosanthes guianensis var. *pauciflora*	4.2	2.1
Stylosanthes guianensis var. *vulgaris*	4.2	2.4
Tephrosia candida	3.9	1.3
Zornia brasiliensis (CPAC 1082)	2.3	1.1

Table 5. Nitrogen content and aboveground biomass for the most productive of the 52 legumes sown on the Dark Red Latosol (DRL) and Red Yellow Latosol (RYL).

Legumes	DRL		RYL	
	DM	N Content	DM	N Content
	kg ha^{-1}			
Cajanus cajan (common)	3940	81	1525	—
Cajanus cajan (persimmon)	4485	92	1640	45
Cajanus cajan (black)	3265	62	1925	41
Cajanus cajan (red)	—	—	2620	65
Canavalia brasiliensis	5465	119	2765	39
Canavalia ensiformis	3460	73	2695	61
Crotalaria paulina	2820	66	1530	49
Crotalaria spectabilis	2700	61	1840	—
Crotalaria striata	3880	105	1795	47
Mucuna aterrima	4715	94	2855	66
Stylosanthes guianensis var. *vulgaris*	4195	113	2370	54
Stylosanthes guianensis var. *pauciflora*	4180	68	2130	51
Tephrosia candida	3865	103	—	—

the dry season, they had produced extensive ground cover, and once the rainy season began, they regrew rapidly. Of the surviving legumes, only these two did not flower and produce seed while in the field.

Field measurements of gravimetric water content suggest that dry-season survival is related to deep rooting and the subsequent use of subsoil water. Gravimetric water content of the soil profile (Table 6) measured in late August 1987 indicated that legumes had extracted water to a depth of at least 1.8 m. Surviving legumes were thus extracting residual water stored in the subsoil for an extended period of the dry season. These results demonstrate that root growth continued during much of the dry season. While other factors may have contributed to legume survival, chemical improvement of the subsoil due to previous lime and fertilizer applications undoubtedly enhanced deep rooting. Legume species tolerant of subsoil acidity would probably use subsoil water efficiently; however, such tolerance was not considered in this experiment.

Significance of Screening Results

Fifty-two species were screened for their ability to survive a dry season, substantially more than we had expected to find. The 1987 dry season was especially severe: virtually no rain fell from May to August. When the rains began in mid-September, many legumes initiated regrowth immediately, in some instances as soon as a day or two after the first rain.

Thirty-seven legumes survived the dry season and regrew once the rains began; 29 of these grew rapidly and produced a measurable biomass (> 600 kg ha^{-1}). Based on the N content of the legumes at harvest, we assume that N fixation also occurred and that N accumulated. Evidence from supplementary measurements made during the dry season indicate that, in several species, biological activity was sufficient for N fixation to occur. The total N content and the N concentration in the biomass were in the range observed by Quintana (1987) and Carsky (1989). The amounts of accumulated N were high considering the conditions under which the legumes were grown. For each site, at least 12 legumes met or exceeded our criteria for further consideration: biomasses of at least 2000 kg ha^{-1} or N levels of at least 40 kg ha^{-1}. This finding suggests that sufficient legume species exist to match almost any savanna cropping system.

Mucuna aterrima, the *Cajanus* spp, and the *Stylosanthes* spp are forage species (Allen and Allen,

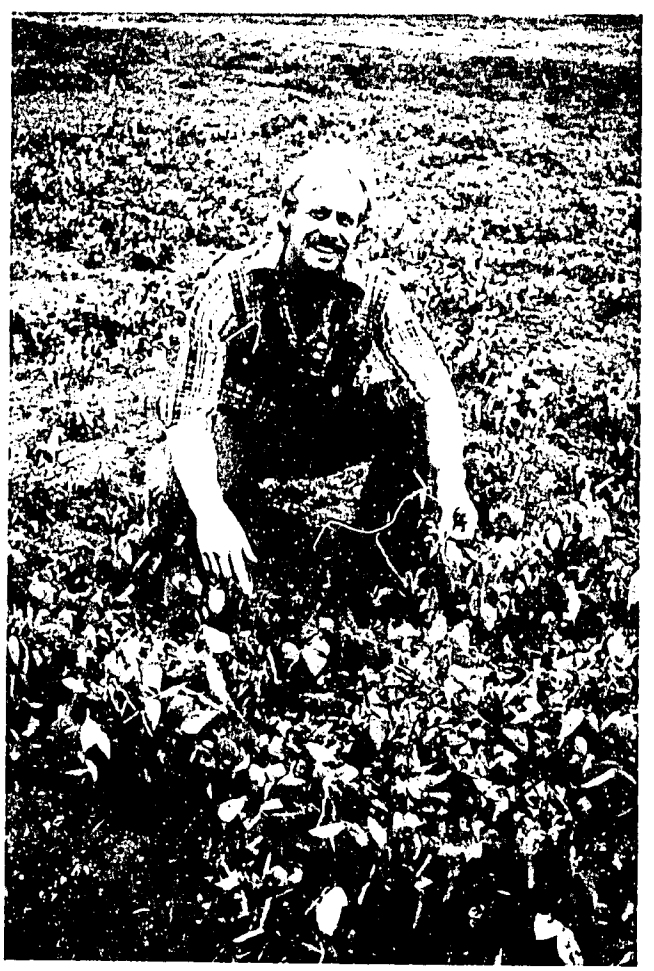
1981). The lack of dry-season forage is one of the main constraints to animal production in tropical acid savannas. If these legumes can provide (a) forage during the dry season and (b) N to succeeding wet-season nonlegume crops, they have the potential to be extremely useful.

Our results indicate that one key to dry-season survival is the ability to extract subsoil water. Several species did so throughout the dry season, in some instances from depths in excess of 1.8 m late in the season. Reduced soil acidity and corrected P deficiency enhance root growth into the subsoil.

Our results suggest that alternating dry-season legume green manures with wet-season annual crops can sustain long-term annual crop production. This management system not only offers the many advantages of green manure in crop rotations, but it may also offer a additional benefit: dry-season forage.

Table 6. Gravimetric soil water content for bare fallow and mean of *Canavalia brasiliensis*, *Tephrosia candida*, and *Mucuna aterrima* legume plots on 27 August 1987.

	DRL site (kg kg^{-1})		RYL site (kg kg^{-1})	
Depth	Fallow	Legume	Fallow	Legume
(m)				
0.2	.13	.14	.13	.13
0.4	.17	.16	.22	.22
0.6	.19	.17	.23	.22
0.8	.21	.17	.24	.23
1.0	.22	.18	.27	.24
1.2	.21	.18	.29	.25
1.4	.22	.18	.30	.26
1.6	.22	.18	.31	.27
1.8	.22	.18	.33	.28



Mucuna at the end of the dry season.

Legume Potential as a Nitrogen Source for Maize

Experimental Procedure

The screening experiment identified legume green manures that survived the dry season and regrew in the following rainy season. Five species were then selected to test in a legume-maize cropping sequence. Such tests were conducted at the DRL site and at the UEPAE station at Manaus.

DRL Site at Planaltina

A three-year cropping sequence was initiated on the DRL site, following a maize crop that was planted in November 1987 and harvested in March 1988. When the legumes were planted, soil chemical properties were as follows: 5.6 pH (water); 0.27 me of Al 100 g^{-1} of soil; 4.70 me Ca + Mg 100 g^{-1} of soil; 8.5 ppm of P; 45 ppm of K; and 2.56% OM.

Canavalia brasiliensis, Mucuna aterrima, Cajanus cajan, Tephrosia candida, and *Stylosanthes guianensis* (the last with and without simulated grazing) were planted on 21 March immediately after the maize harvest. *Sorghum bicolor* was also planted, thus providing a nonlegume comparison among treatments. Following the onset of the rainy season and subsequent regrowth, green manures were incorporated into the soil (1988 and 1990) or killed and left on the soil surface (1989). Maize was planted in early November and harvested in March at the end of the wet season.

A fallow-plot treatment was used to determine the fertilizer-N response curve. Fertilizer-N rates of 0, 50, 100, and 200 kg N ha^{-1} were applied both to the fallow plots and to plots where green-manure legumes had been grown. Adequate quantities of P and K, along with micronutrients, were added to the soil when the maize was planted. Table 7 lists planting dates of the green manures, measurements of dry-matter production, soil-incorporation dates, and maize planting/harvesting dates for each year of the main experiment. Monthly rainfall for the 1988–90 dry seasons (April through October) is given in Table 8. Monthly rainfall for the 1988–89 through 1990–91 rainy seasons (November through March) is given in Table 9.

Aboveground dry-matter production and N content of the green-manure crops were measured prior to soil incorporation. Aboveground dry-matter production, grain yield, and N content of the aboveground dry matter were determined after each

Table 7. Dates of planting, measurements, incorporation, and harvest of maize and green manures (G.M.).

Year	G.M. Planting Date	G.M. Measurement Date	G.M. Incorporation Date	Maize Planting Date	Maize Harvest Date
Year 1					
1988-89	24 Mar 88	7 Oct 88	1 Nov 88	10 Nov 88	3 Apr 89
Year 2					
1989-90	14 Apr 89	11 Oct 89	No-till 23 Oct 89 (herbicide)	7 Nov 89	2 Apr 90
Year 3					
1990-91	10 Apr 90	22 Oct 90	31 Oct 90	21 Nov 90	9 Apr 91

Table 8. Monthly rainfall amounts and days rain occurred from the date of legume planting until dry-matter (DM) yields were determined and legumes were either incorporated into the soil or killed.

	1988		1989		1990	
Month	Amount	Days	Amount	Days	Amount	Days
	Precipitation, mm					
March 24-31	10	1	0	0	0	0
April[†]	152	13	18	5	47	5
May	8	2	0	0	148	7
June	0	0	12	4	0	0
July	0	0	8	1	68	4
August	0	0	36	7	13	1
September	2	2	59	8	98	9
October[‡]	7	3	14	3	115	5
November[‡‡]	218	14	136	11	169	11
Total to DM determination	179		147		489	
Total to incorporation	390		269		543	

[†] Precipitation from date of planting to April 30.
[‡] Precipitation from Oct 1 to date of DM determination.
[‡‡] Precipitation from Oct 1 to date of legume incorporation.

maize harvest. Depletion of soil-profile water by green-manure crops was measured throughout the dry season. Soil inorganic N content was measured at various times during the experiment.

During the 1988 dry season, the dry weight of nodules found on roots was measured several times, beginning 43 days after green-manure planting. In addition, nitrogenase activity at each sampling date was measured—using the acetylene reduction method—to give an indication of legume N-fixing capability throughout the dry season.

In the 1988 dry season, sorghum matured and seed was harvested in July; the residue was left on the plots. Mucuna began to mature in September; aboveground plant material was then clipped to prevent seed formation and left on the plots. If mucuna is allowed to mature, seed may germinate and become a weed pest to subsequent crops. Cajanus seed also matured and was harvested in September; the residue was left on the plots. Residues of these species remained on the soil surface until the rest of the legume crop was incorporated. Such residues may lose considerable N by any one of several mechanisms (Costa, et al., 1990). In 1989 cajanus grain was harvested in October, and mucuna did not mature until October, when all green manures were killed. During August of the 1990 dry season, sorghum seed was harvested and the residue left on the plots. Cajanus seed was harvested on October 2; again, residue was left on the plots.

In 1988 and 1990, green manures were incorporated with a disk harrow and a disk plow prior to maize planting. In 1989, the green manures were killed with a herbicide, and the residues were left on the soil surface. Maize was planted directly into the residues with a no-till planter.

UEPAE Station

An experiment similar to that at CPAC was established in July 1988 at the UEPAE station, Manaus. The goal was to evaluate five different legumes that could be grown during the Manaus area's short dry season. Soils at the station are highly weathered Oxisols of the Great Group Acrudox.

Table 9. Monthly rainfall during rainy season (maize cultivation).

Month	1988 Amount	1988 Days	1989 Amount	1989 Days	1990 Amount	1990 Days	1991 Amount	1991 Days
	Precipitation, mm							
November[1]	130	10	209	20	70	8	—	—
December	203	19	600	31	103	14	—	—
January	—	—	194	13	170	8	526	27
February	—	—	217	19	164	19	213	22
March	—	—	65	10	179	9	316	25
April[1]	—	—	0	0	0	0	0	0

	1988–89	1989–90	1990–91
Total to maize harvest	809	1302	1246
Total in first 100 days of growing maize	699	1040	912

[1] Precipitation from date of maize planting to the end of the month.
[1] Precipitation from April 1 to date of maize harvest.

Although located in the humid tropics, this region's dry season lasts two to three months, during which nothing is grown. A dry season of this duration is common in many humid tropical areas. Mean annual rainfall from 1971–88 was 2350 mm. The heaviest rainfall occurred from December through May, averaging 275 mm per month. The driest three months were July, August, and September, averaging 110 mm per month. August 1988, however, received only 26 mm of rain, and September only 100 mm. Monthly rainfall from December through May 1989 ranged from 195–405 mm.

Five legumes, *Canavalia ensiformis, Canavalia brasiliensis, Mucuna aterrima, Mucuna cochichinensis,* and *Tephrosia candida* were planted on 20 July 1988, using a randomized block design with four replications. Plots planted to maize without fertilizer N were also included to provide a fertilizer-N response curve. On 11 January 1989 the legumes were cut at ground level and left to form a dead mulch over the plot. Maize was planted in both the legume residue and the previous maize plots on 20 January using a planting stick. Fertilizer N as urea was applied only to the previous maize plots; 20% of the total rate was applied at planting and the rest sidedressed in two equal doses, 25 and 55 days after planting. Maize was harvested on 15 May 1989, and grain yield was measured.

Mucuna growing in a mature maize plot.

Canavalia brasiliensis at the DRL site.

Results

Dry-matter Production by Green Manures

Table 10 lists the aboveground dry matter produced by the five legumes grown in the screening experiment and in each of the three years of the cropping experiment; sorghum growth in the three-year cropping experiment is also included. Thus, four years of aboveground legume biomass production are available for comparing dry-season growing conditions.

In three of the four years, (1987, 1988, and 1990), mucuna and (especially) canavalia produced large amounts of dry matter: from 3400 to 5800 kg of biomass ha^{-1}. Cajanus (including grain) and tephrosia usually produced intermediate quantities of dry matter (> 3000 kg ha^{-1}), except in 1988, when tephrosia yielded about 2000 kg. Only the vegetative residue of cajanus was incorporated into the soil. Stylosanthes produced large amounts of dry matter during 1987 and 1990, over 4000 and 6000 kg ha^{-1}, respectively; in 1988, it produced less than 1500 kg. When stylosanthes was clipped during the dry season to simulate grazing, the aboveground biomass incorporated into the soil was much reduced—although 2100 kg ha^{-1} is considerable. In the two years that sorghum produced a crop, it matured in the middle of the dry season, and seed was harvested. Sorghum dry-matter production was about 4000 kg ha^{-1}, which includes both seed and vegetative portions of the plant. Only 2000 kg of residue was incorporated into the soil.

Table 10. Dry matter produced by green manure crops incorporated into soil prior to planting maize.

	Screening Exp.	Cropping Experiment		
	1987	Year 1 1988	Year 2 1989	Year 3 1990
	Dry matter, kg ha^{-1}			
Cajanus[1]	3940	3235	1060	2400
Canavalia	5465	4260	1845	5840
Mucuna	4715	3440	2170	5655
Stylosanthes	4195	1435	—	6090
Stylosanthes-cut	—	370	—	2100
Tephrosia	3865	2430	340	3965
Sorghum[1]	—	2005	—	2205

[1] Total dry-matter production (with grain) was 3365, 1575, and 3760 kg ha^{-1} in 1988, 1989, and 1990, respectively.

[1] Total dry-matter production (with grain) was 4015 and 3420 kg ha^{-1} in 1988 and 1990, respectively.

In 1989, dry-matter production of all species was severely restricted, and both stylosanthes and sorghum failed to germinate. Only four species produced measurable amounts of biomass, with canavalia and mucuna producing around 2000 kg ha^{-1}. Cajanus and tephrosia produced significantly less dry matter. For both sorghum and stylosanthes, sufficient water had to be available in the surface soil at planting if germination and establishment were to occur. When these species were planted in dry soil that received little subsequent rain, the crop failed.

In three of the four years when adequate rain fell in April after the green manures were planted, all of the species germinated effectively. In 1989, little rain fell in April and none in May, thus limiting the germination and establishment of green manures planted after April 15; in some cases the legumes failed completely. The 1990 dry season was unusual in that at least modest quantities of rain fell throughout the normal dry season. Especially large quantities fell in May, which may help account for the large dry-matter production. In both 1987 and 1988, sufficient rain fell in April to ensure satisfactory germination.

Our results indicate that rain distribution at the end of the rainy season exerts an important influence on dry-season legume survival. Without rain at or

shortly after planting, dry surface-soil conditions are likely to prevent germination and establishment. Although green manures are typically planted near the end of the rainy season, earlier planting could increase their chances of receiving sufficient rainfall. To some extent, of course, planting dates will depend on when the wet-season crop can be harvested.

At Manaus, legumes produced large amounts of dry matter (Table 11). Except for *C. brasiliensis*, total dry matter was substantially higher at Manaus than at CPAC, especially for tephrosia. These differences probably result from Manaus' shorter dry season and the attendant reduction in water stress. Legumes were in the field about the same length of time at both sites.

Nitrogen Content of Green Manures

In both the cropping and screening experiments, the total N content of the aboveground dry matter of the green-manure residues varied widely by species (Table 12). From 1987–90, N contents of canavalia, mucuna, and tephrosia species ranged from 67–142 kg ha^{-1}, canavalia being the highest. Since only the vegetative residue of cajanus was used, somewhat less N was supplied than for other species. In two of the years, stylosanthes supplied over 100 kg of N. Only small yearly variations in N concentration were found. Except for tephrosia, which had a mean N concentration higher than 30 g kg^{-1}, most of the legumes had N concentrations around 20 g kg^{-1}. Thus, N concentration was not a major determinant of N content in aboveground dry matter. Total N contents were much reduced in 1989 due to growth reductions caused by the severe dry season (compare 1988 and 1990 with 1989). Neither the total dry matter nor the

Table 11. Biomass production and total N content of legumes cut and left as dead seeded on soil surface. UEPAE-Manaus, January 1989.

Legume	Dry Matter	N Content
	kg ha^{-1}	*kg ha^{-1}*
Mucuna aterrima	5900	213
M. cochinchinensis	6000	188
Canavalia ensiformis	5800	191
C. brasiliensis	6700	213
Tephrosia candida	10500	424

Table 12. N content of green-manure crops at time of sampling—prior to planting maize.

	Screening Exp.	Cropping Experiment		
		Year 1	Year 2	Year 3
	1987	1988	1989	1990
	N content, kg ha^{-1}			
Cajanus[1]	81	57	34	59
Canavalia	119	92	44	142
Mucuna	94	67	62	130
Stylosanthes	113	22	—	108
Stylosanthes-cut	6	—	57	—
Tephrosia	103	73	10	132
Sorghum[1]	—	11	—	58

[1] Total N content (with grain) was 60, 46, and 84 kg ha^{-1} in 1988, 1989, and 1990, respectively.

[1] Total N content (with grain) was 34 ha ha^{-1} in 1988.

Observation. In 1990, N content of sorghum grain was not measured.

N content of the roots was measured in these experiments. Depending on the rooting habits of the different species, considerable variation in both root biomass and N content could have occurred.

The total N content of the legumes at Manaus was higher than at CPAC: mucuna and canavalia species contained about 200 kg ha^{-1}; tephrosia was much higher, containing over 400 kg ha^{-1} (Table 11). The N concentration of the tissue was also higher at Manaus, contributing to the higher total N content. Overall, the results indicate that, under favorable conditions, these legumes can fix large quantities of N in a few months.

Except for the first sampling of mucuna and tephrosia, nodule dry weight (Figure 1) remained low throughout the dry season for all species. The nodule dry weight of mucuna was higher than that of the other green manures for the first 80 days, but late in the dry season, nodule dry weight was low for all species. Nitrogenase activity (Figure 2)—as measured by ethylene evolution (acetylene reduction)—was high in the mucuna and tephrosia nodules at the first sampling date. Activity was low in the nodules of the other species throughout the dry season. These data suggest that while the legume green manures may survive the dry season, little N is likely to be fixed

during this period. Most of the N accumulated by these legumes must have been fixed during regrowth following the onset of the rainy season.

Maize Grain Yield

Maize grain yields in each of the three years following green-manure incorporation are given in Table 13. In all three years, maize grown in fallow plots responded significantly to fertilizer N. In year one, yields were high, approaching 8000 kg dry matter ha^{-1}. Yields were also high in year three: nearly 7000 kg ha^{-1}. In year two, when no-till planting was used, yields were much lower, the highest approaching 5000 kg ha^{-1}. Yields of other annual crops at CPAC

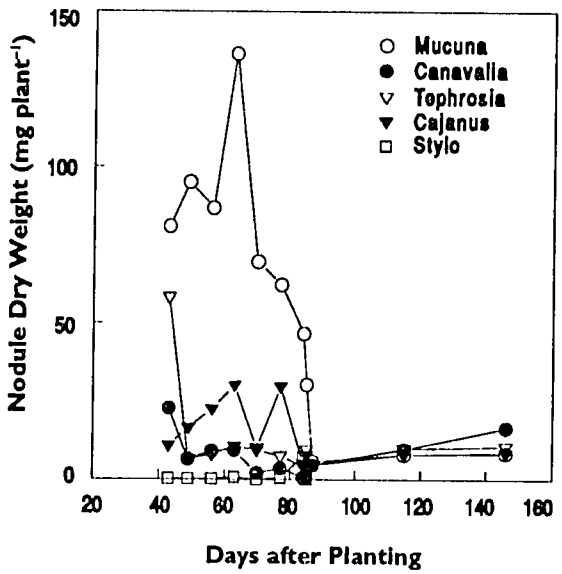


Figure 1. Nodule dry weight of legumes sampled throughout the dry season, 1988.

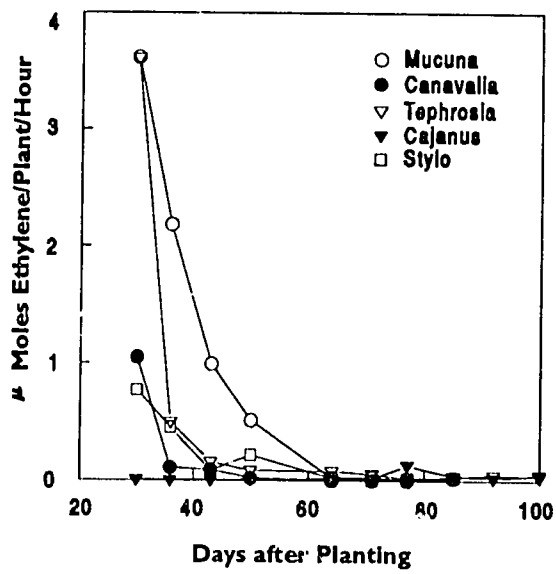


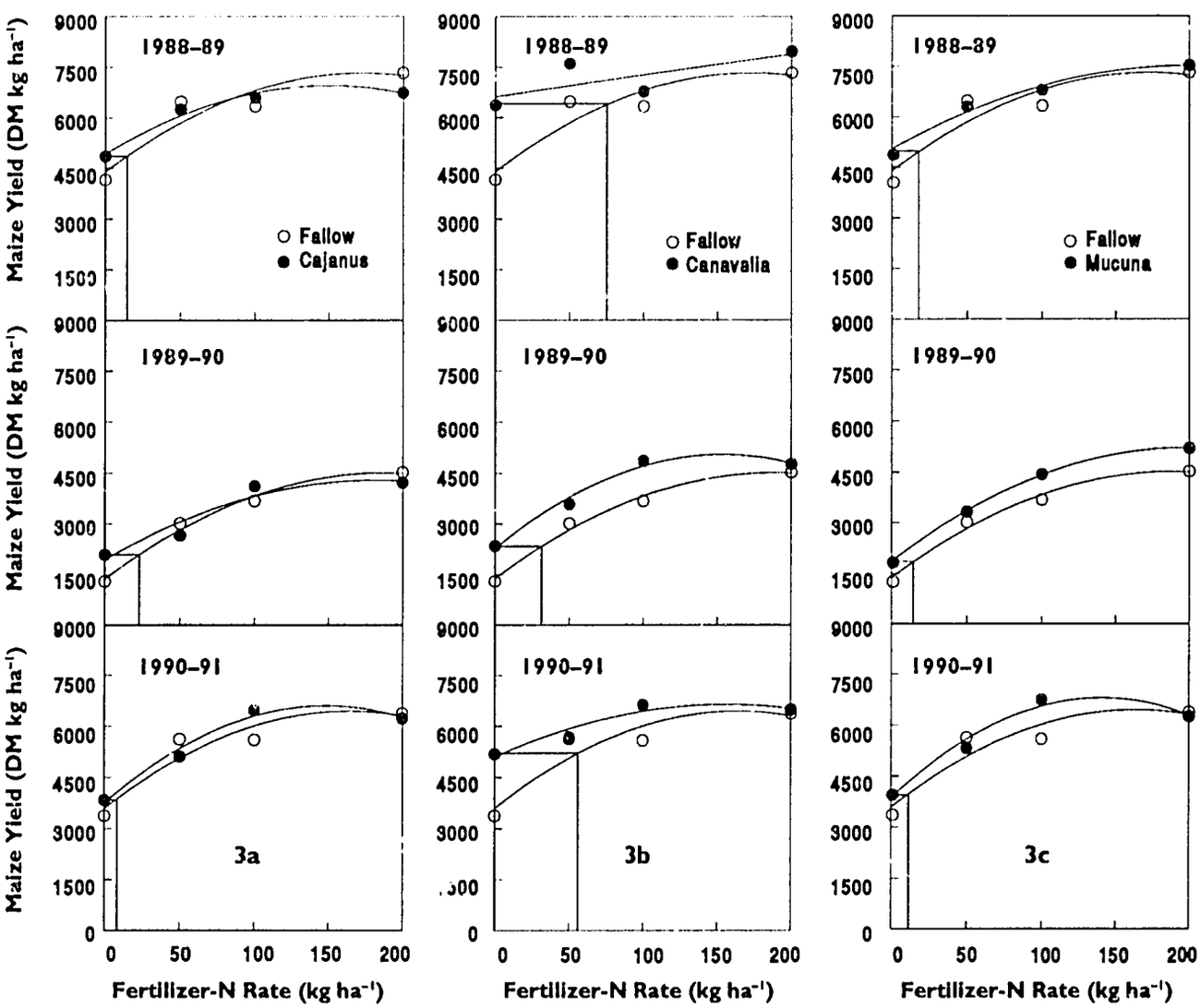
Figure 2. Nitrogenase activity as measured by ethylene evolution of legumes sampled throughout the dry season, 1988.

Table 13. Maize grain yields using green-manure legumes as N sources as influenced by fertilizer-N rate.

Fert. N rate	Maize Grain Yields, dm kg ha^{-1}								
	Fallow	Canavalia	Cajanus	Mucuna	Stylo	Stylo-Cut	Tephrosia	Sorghum	Mean
kg ha^{-1}					*1988-89*				
0	4160	6370	4860	4995	5950	4450	6355	4410	5195
50	6475	7605	6245	6305	6150	6475	6365	6135	6470
100	6335	6775	6590	6805	6405	7075	7375	6650	6750
200	7325	7955	6740	7540	7385	6615	7405	6940	7240
					1989-90				
0	1325	2375	2120	1990	1730	1290	1750	1625	1764
50	3050	3625	2695	3360	2900	2975	3360	3250	3152
100	3725	4920	4165	4485	3320	4150	3735	4475	4122
200	4575	4825	4270	5270	4300	3895	4310	4710	4519
					1990-91				
0	3380	5190	3845	3970	4390	4605	4340	3660	4173
50	5625	5680	5120	5320	5025	6070	5015	4460	5220
100	5590	6625	6470	6740	6025	6410	6105	6070	6255
200	6375	6490	6230	6250	6570	6715	6620	6025	6405

were, in general, lower than normal. Rain may have affected the yields of all crops: it rained every day of December 1989, and total precipitation reached 600 mm (Table 9). The response to fertilizer N, however, was as great as in the other two years. During the three years, nonlegume sorghum had no effect on yields or N response.

In Figures 3a–3f, the maize response to fertilizer N is compared to responses for each of the incorporated legumes for all three years. Best-fit curves using the SigmaPlot graphics program are shown (SigmaPlot, 1989). Maize yield with green manures as the only source of N are placed on the fertilizer-N response curve to show the fertilizer-N replacement value (Carsky, 1990) of these plant materials. In the first and third canavalia crops, the N replacement value was about 80 kg and slightly more than 50 kg of fertilizer N, respectively. The other legumes varied in their N replacement value for the first and third crops, ranging from less than 20 kg to more than 50 kg for the 1988–89 tephrosia and stylosanthes crops. The N replacement value of cajanus was low since only the residue was applied. The N replacement value of mucuna was also low, given its N-supplying ability in other experiments (Carsky, 1990; Quintana, 1988; and Bowen, 1988). Cutting stylosanthes during the dry season to simulate grazing reduced its N contribution to the

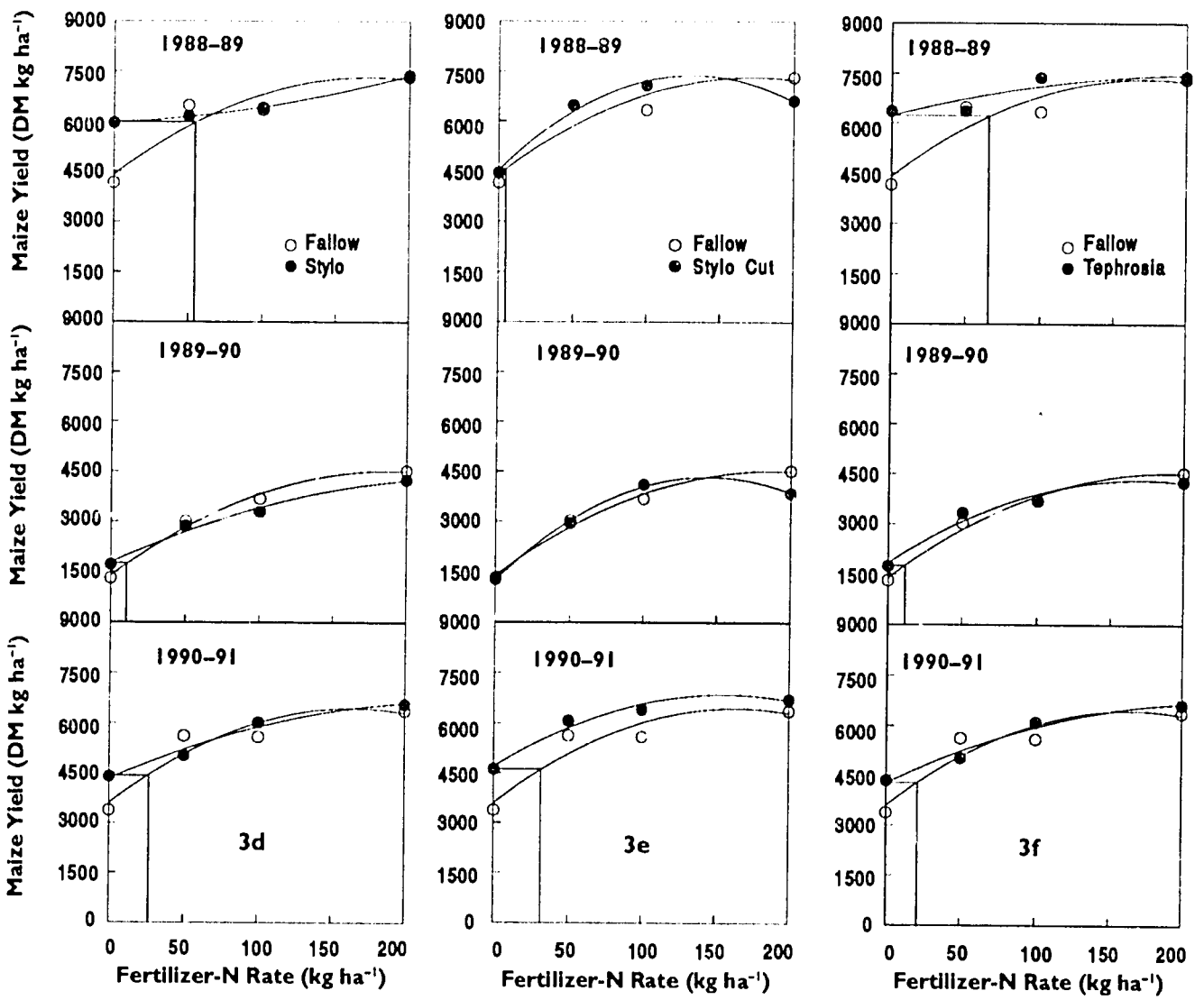


Figures 3a–3c. Yield response of maize to fertilizer N, with and without the addition of legume green manure. The fertilizer-N replacement value is shown on the x-axis: (a) cajanus, (b) canavalia, (c) mucuna. DM = dr .natter.

1988–89 maize crop; in 1990–91, however, the N contributed by the cut system exceeded that of the uncut system. Even though legume dry-matter production was as high or higher in 1990 as in 1988, the fertilizer-N replacement values were higher for the 1988–89 maize crop as compared to the 1991 crop, with the exception of uncut stylosanthes.

The N replacement value of the legumes was low in the 1989–90 maize crop, probably for two reasons. First, much less legume biomass was produced and much smaller quantities of N were added to the soil (Table 12). Second, because no-till planting leaves the residues on the soil surface, substantial amounts of N can be lost (Costa, et al., 1990). Mineralization rate and total mineralization may also be reduced with this system, resulting in lower utilization of the N added in the plant materials. Even so, canavalia supplied 30 kg of N to the maize.

When the response curve for the average of all legumes is compared to the response curve without legumes (Figure 4), the fertilizer-N replacement value of the legumes is about 40 kg in 1988–89, about 20 kg in 1989–90, and about 25 kg in 1990–91. Lower N contributions in 1990–91 than in 1988–89 are surprising since the dry-matter production and N content of the green-manure crops were higher (except for cajanus) in 1990 than in 1988. Both the dry-matter production and the N content of



Figures 3d–3f. Yield response of maize to fertilizer N, with and without the addition of legume green manure. The fertilizer-N replacement value is shown on the x-axis: (d) stylosanthes, (e) stylosanthes-cut, and (f) tephrosia. DM = dry matter.

the surviving 1989 legumes were low, resulting in a small N contribution to the succeeding maize crop. While there were variations among legumes, the average increase in grain yield due to the addition of legumes at the 50-kg fertilizer-N rate was nearly as great as at the zero fertilizer-N rate. Thus, at low fertilizer N rates, the response to the two sources of N was nearly additive. At the 200-kg rate, however, grain yields were the same both with and without green-manure additions.

Total aboveground dry matter closely resembled grain yields (Table 14): the 1988–89 total was slightly higher than the 1990–91 total, and both 1988–89 and 1990–91 totals were substantially higher than the 1989–90 total. The portion of grain to total dry matter was 0.48 in 1988–89 and 0.50 in 1990–91, neither figure being affected by fertilizer-N rate or by green-manure additions. In 1989–90, the portion of grain to total dry matter averaged 0.33 at the zero fertilizer-N level and was not affected by green-manure additions. At both the 100- and 200-kg fertilizer-N rates, the portion of grain to total dry matter was 0.47; it was not affected by green-manure additions. Since green-manure legumes supplied so little N in 1989–90, the zero-N treatment was essentially a control, and under that year's management system, the portion of grain to total dry matter was reduced by N shortage.

The response to fertilizer N at Manaus (Figure 5) is similar to that found at CPAC. Yield without fertilizer N, however, was only 1200 kg ha^{-1}, and the maximum yield with 200 kg N ha^{-1} was just under

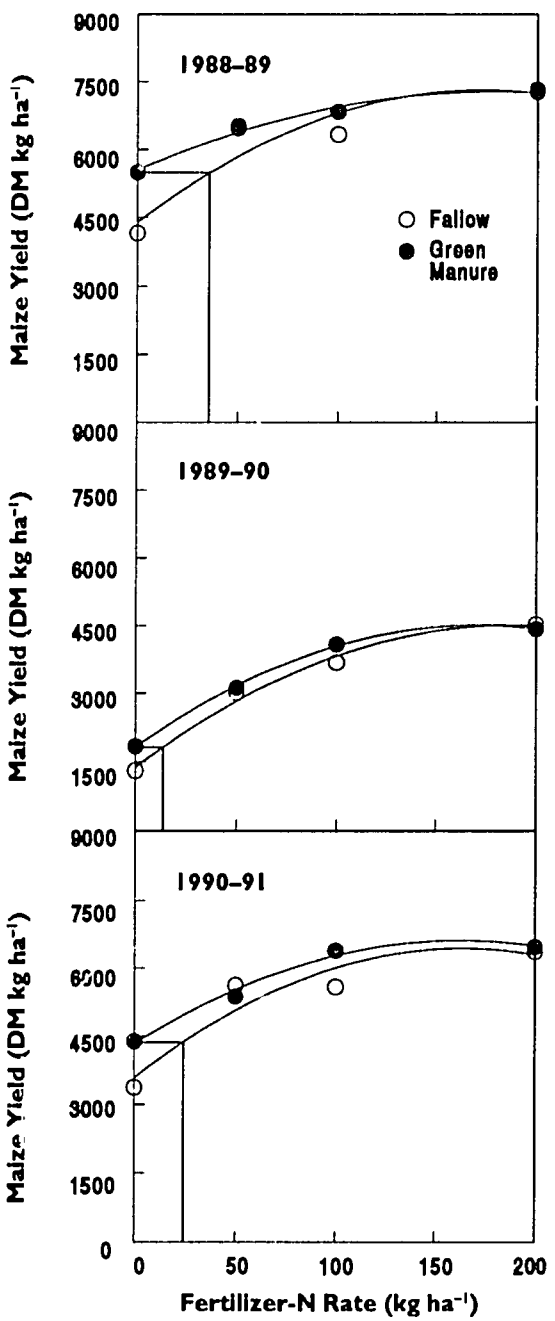


Figure 4. Yield response of maize to fertilizer N, average of all legume green manures and of trials without the addition of legume green manures. Fertilizer-N replacement value shown on x-axis. DM = dry matter.

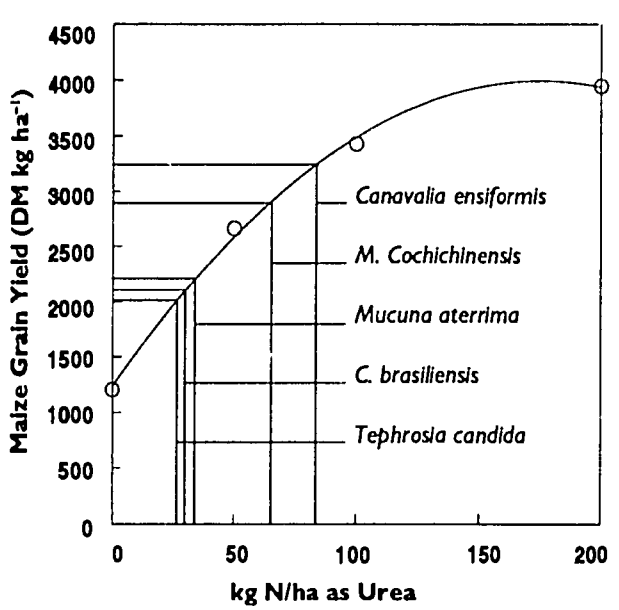


Figure 5. Yield response of maize at Manaus to fertilizer N. Yield of maize with various green manure legumes added as surface mulch is placed on the fertilizer-N response curve to show the fertilizer-N replacement value. DM = dry matter.

Table 14. Total aboveground maize biomass using legume green manures as N sources as influenced by fertilizer-N rates.

Fert.-N rate	Total Aboveground Dry matter, kg ha^{-1}								
	Fallow	Cajanus	Canavalia	Mucuna	Stylo	Stylo-cut	Tephrosia	Sorghum	Mean
kg ha^{-1}					*1988-89*				
0	9520	11125	13410	11285	12350	9820	13000	11125	11455
50	11245	13165	16515	13770	14010	14160	12700	13165	13590
100	13265	14620	15025	14960	13150	14375	15505	14620	14440
200	15080	13665	17290	15945	14450	13845	15195	13665	14890
					1989-90				
0	4150	5715	7535	5270	4605	4195	4955	5715	5270
50	7130	6955	8515	8455	7115	7220	7415	6955	7470
100	8955	9000	8205	10235	7410	8935	8240	9000	8750
200	9435	9665	8435	11785	8920	8175	9170	9665	9405
					1990-91				
0	7870	9010	10450	9255	8720	8945	9275	9010	9065
50	10390	11925	12250	10725	9925	11645	10075	11295	11030
100	10085	12090	13385	12390	12090	11805	12545	12090	12060
200	11250	12085	11340	12300	11920	13200	13190	12085	12170

4000 kg grain ha^{-1}. The fertilizer replacement value of the legumes ranged from about 30 kg N ha^{-1} for the mucuna species and *C. ensiformis* to 85 kg N ha^{-1} for tephrosia. *Canavalia brasiliensis* had a fertilizer replacement value of 65 kg N ha^{-1}.

Results at Manaus compare favorably with those at CPAC, especially considering that the legumes were left as a surface mulch. The legume residue provided excellent soil surface cover, controlling erosion and supressing weeds. In the humid tropics, these functions may be as important as supplying N. As at CPAC, *C. brasiliensis* proved a superior green-manure legume. Based on one year's data, tephrosia appears to be an especially suitable for Manaus.

N Content of the Aboveground Maize

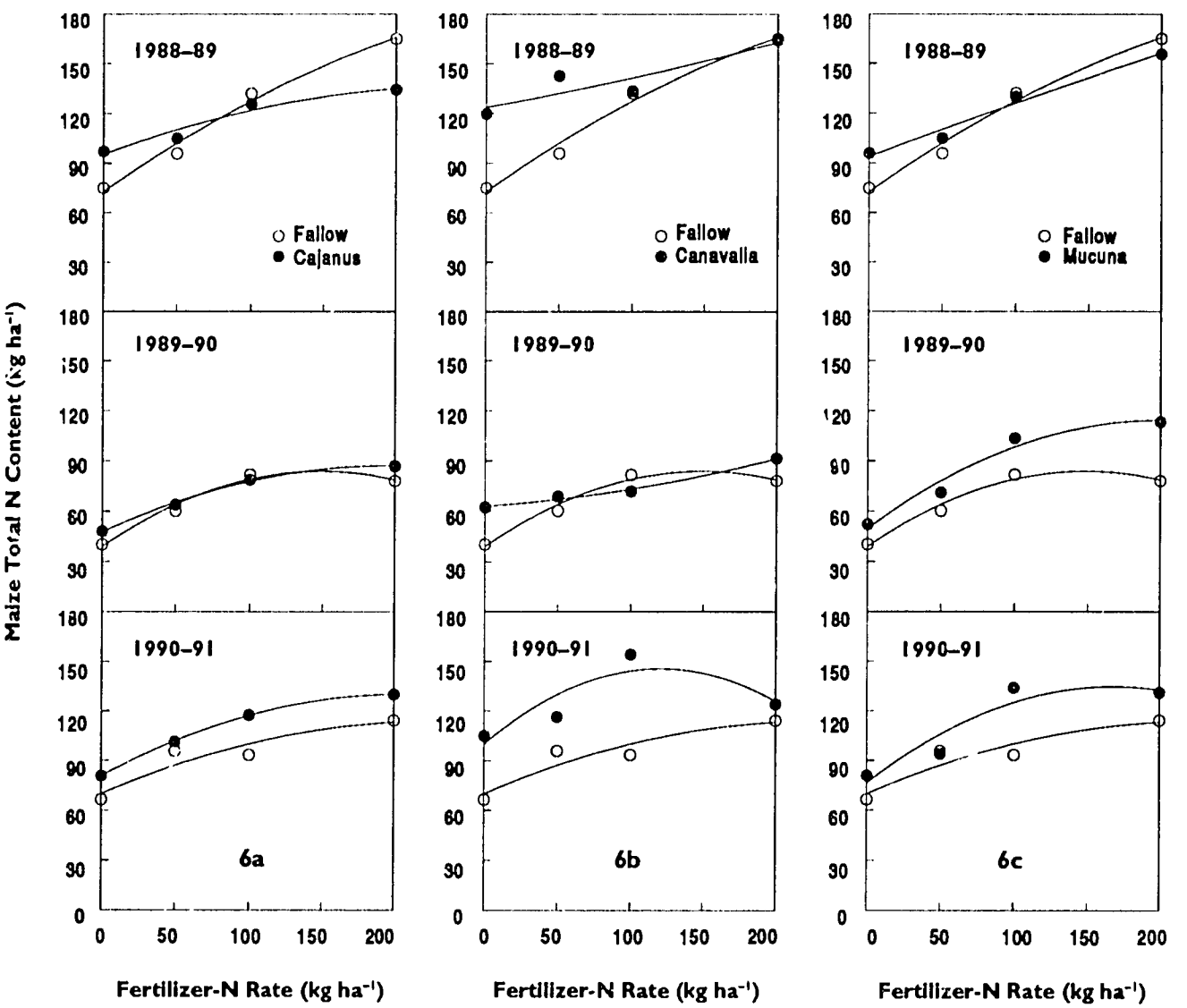
The influence of legume green manures on the N content of maize's aboveground dry matter is given in Table 15. The increases in maize N content compared to the control correspond well with the total N content of the legumes incorporated into the soil. When the total N content of the aboveground dry matter is plotted against fertilizer-N levels using the SigmaPlot program for the best fit of the data (Figures 6a–6f, 7), the curves for 1988–89 are similar to those for grain yield. At the zero and 50-kg fertilizer-N rates, legume green manures increased N uptake, but at higher fertilization rates, little additional N is taken up. For the 1990–91 maize crop, however, adding legume green manures increased N

Table 15. N content in aboveground maize biomass without fertilizer-N application.

Legume addition	1988–89	1989–90	1990–91
	N uptake, kg ha^{-1}		
Cajanus	97	48	81
Canavalia	120	62	105
Mucuna	96	52	81
Stylosanthes	109	50	70
Stylosanthes cut	86	39	70
Tephrosia	119	52	73
Sorghum	76	30	62
Control	75	40	67

uptake more than did fertilizer N alone, even at the 100- and 200-kg rates. Similar trends were observed in the 1989–90 crop, especially for mucuna. With the 1990–91 crop, N uptake was greater at all fertilizer-N rates when legume green manures had been added. Whether this effect would continue can only be conjectured. It should be noted, however, that during the 1990–91 growing season, rainfall was higher than during the 1988–89 growing season, possibly causing more fertilizer-N leaching early in the growing season (Table 9). Both grain and aboveground dry-matter yields were higher in 1988–89 than in the following two years.

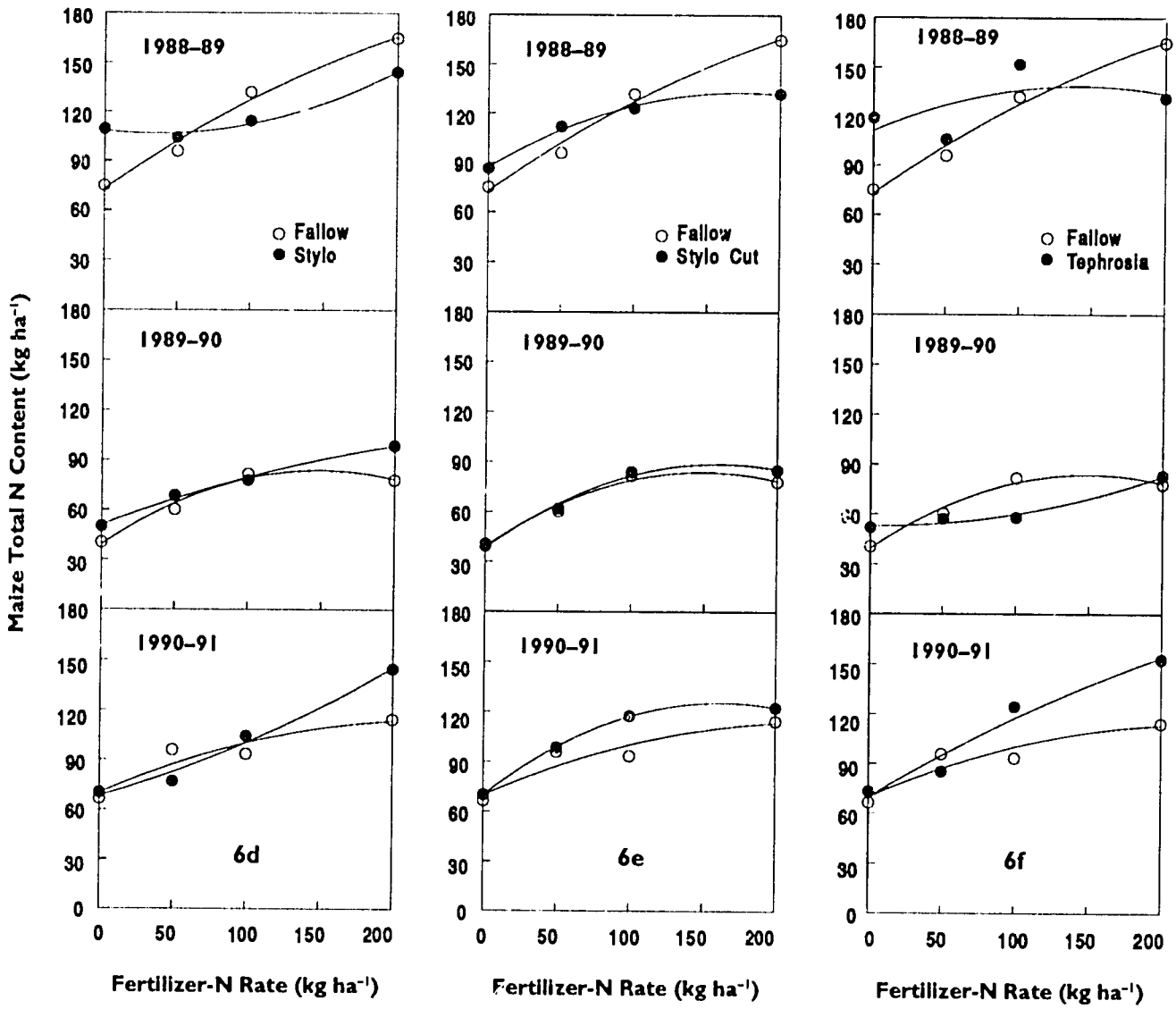
Apparent N recovery from both fertilizer N and legume N was calculated by subtracting the control N content from the N content of maize to which either fertilizer N or legume N had been applied (Table 16). Apparent percent N recovery was calculated as follows: apparent N recovery, divided by the quantity of N applied, multiplied by 100. Recovery of fertilizer N by maize in the range of 50% for the 1988–89 crop was consistent with values reported by Lathwell (1990) in the summary of earlier work at CPAC. Likewise, recovery of legume N was about that of fertilizer N, except for mucuna, which was lower than we had previously



Figures 6a–6c. Total N content of aboveground maize dry matter as infulenced by fertilizer N, with and without the addition of legume green manure: (a) cajanus, (b) canavalia, (c) mucuna.

Table 16. N recovery by maize from fertilizer N and legume N.

	Apparent N recovery					
	1988–89		1989–90		1990–91	
N Source	*kg ha⁻¹*	*Percent*	*kg ha⁻¹*	*Percent*	*kg ha⁻¹*	*Percent*
Cajanus	22	37	8	24	14	24
Canavalia	45	49	22	50	38	27
Mucuna	21	31	12	19	14	11
Stylosanthes	34	100+	—	—	3	3
Stylosanthes cut	11	100+	—	—	3	5
Tephrosia	44	60	12	100+	3	5
Fertilizer N						
50	21	42	20	40	29	59
100	57	57	41	41	27	27
200	90	45	38	19	48	24



Figures 6d–6f. Total N content of aboveground maize dry matter as infulenced by fertilizer N, with and without the addition of legume green manure: (d) stylosanthes, (b) stylosanthes-cut, (c) tephrosia.

found. In 1988–89 mucuna residues remained on the soil surface almost two months before being incorporated, undoubtedly resulting in significant N loss (Costa and Bouldin, 1990).

Lower total dry-matter and grain production using the plow-plant system in the 1989–90 season

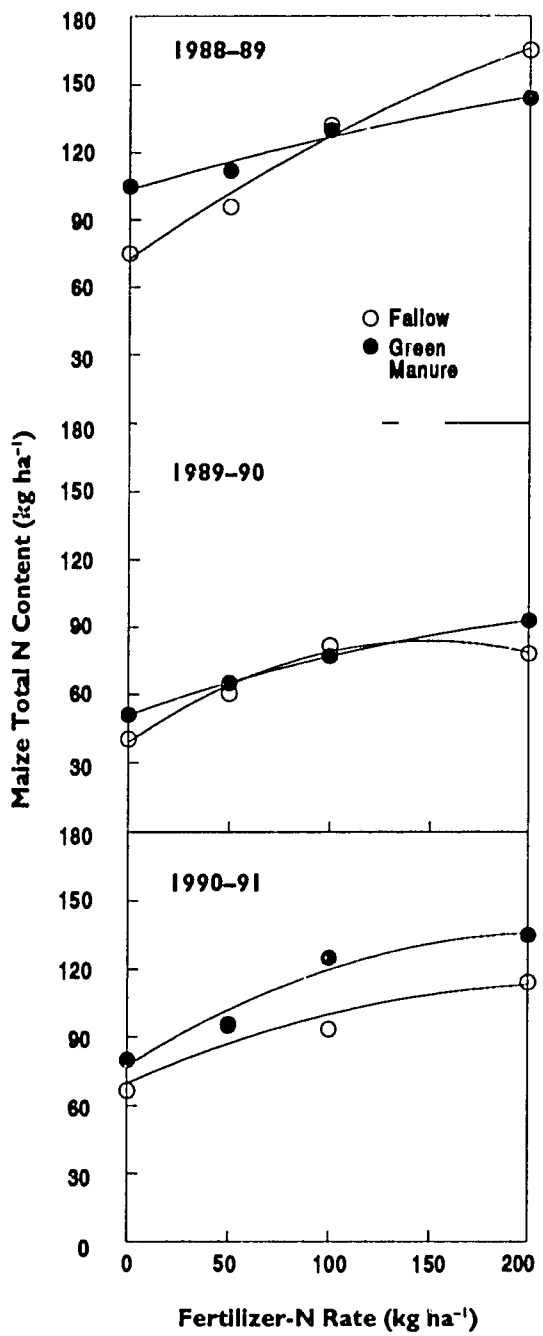


Figure 7. Total N content of aboveground dry matter of maize as infulenced by fertilizer N, average of all legume green manures and no green manure.

likely accounts for the sharply reduced apparent recovery of fertilizer N. Maximum grain yields were only 4500 kg, compared to nearly 8000 kg ha^{-1} in 1988–89. N recovery from canavalia exceeded that from fertilizer N, while recoveries from cajanus and mucuna were slightly lower than the average fertilizer-N recovery at the 50- and 100-kg rates.

Maize yields in 1990–91 were lower than in 1988–89, with a difference of about 1000 kg grain and 2000 kg total dry matter. Fertilizer-N recovery in the 1990–91 crop at the 50-kg rate was high, but at the 100- and 200-kg rates, recovery was only about 25%. Apparent recovery of legume N was very low, with only cajanus and canavalia approaching reasonable levels. At higher N rates, N content in the aboveground dry matter of maize that received both legume N and fertilizer N exceeded the N content of maize receiving fertilizer N alone. This finding suggests that factors other than N-supply could have been limiting yields. Lower fertilizer and legume-N recovery in 1990–91 compared to 1988–89 may be explained by differences in rainfall amounts and distribution during the two growing seasons (Table 9). Considerable time (Table 7) elapsed between measuring and incorporating green manures and the planting of maize, which could account for the manures' reduced effectiveness as an N source. A farmer would likely be able to shorten the interval between incorporating the plant materials and planting of maize to a few days.

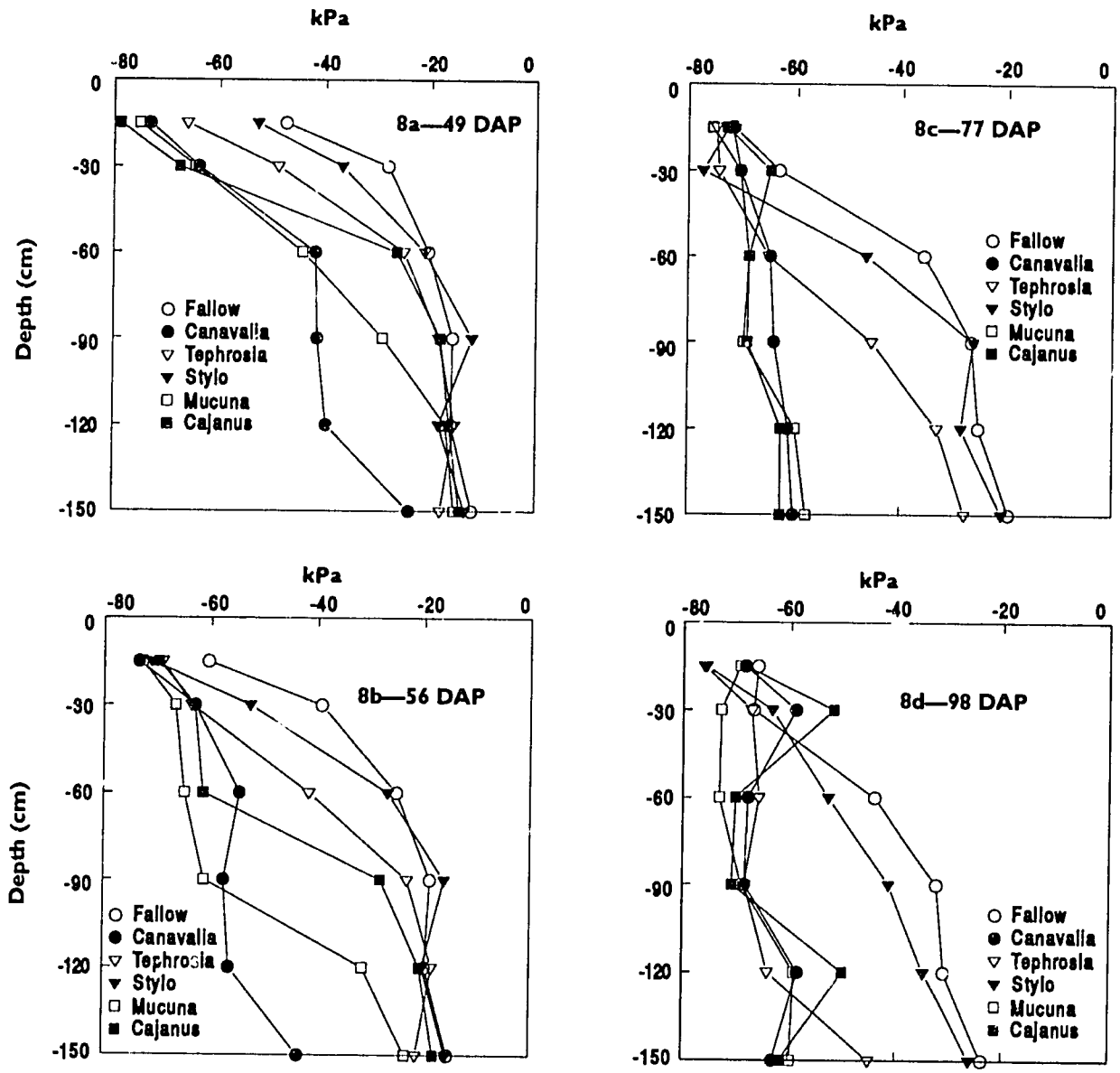
Canavalia has much to recommend it as a dry-season legume: it has a high yield potential even under adverse conditions (e.g. 1989), and it supplies N to the succeeding crop. Mucuna also has a high yield potential under adverse conditions, but it did not perform as well as an N source as it has in previous experiments. Although tephrosia and stylosanthes gave unexplained inconsistent results in these experiments, they both show sufficient promise to be considered further. At Manaus, tephrosia was especially promising.

Cajanus is a grain legume, and if it is harvested for grain only, the residue is available to supply N for the succeeding crop. In this experiment, half of the total dry matter produced and over half the total N were removed in the grain. Of course, this limits cajanus' value as a green-manure crop; however, there may be situations where it will fit into the

cropping system to supply (a) grain and (b) N for a succeeding crop.

Soil Water Extraction by Legumes

During the 1988 dry season, soil water pressure was measured several times after the green manures were planted; measurements were taken at depths ranging from 15 to 150 cm. Soil water pressure at 49, 56, 77, and 98 days after planting (DAP) is shown in Figures 8a–8d. By day 49, canavalia, mucuna, and cajanus had lowered the water content of the soil's top 30 cm substantially more than had stylosanthes and tephrosia—when each was compared to the fallow plot (Figure 8a). At depths of 60 cm or greater, the water potential under cajanus, stylosanthes, and tephrosia was similar to the fallow plot, indicating that the roots of these plants had not penetrated below 60 cm at 36 days. At 120 cm, the water potential under mucuna was similar to the fallow plot; at 90 cm, it was somewhat lower, an indication of rooting and water extraction. Under canavalia, however, the water potential at 90 to 120 cm was



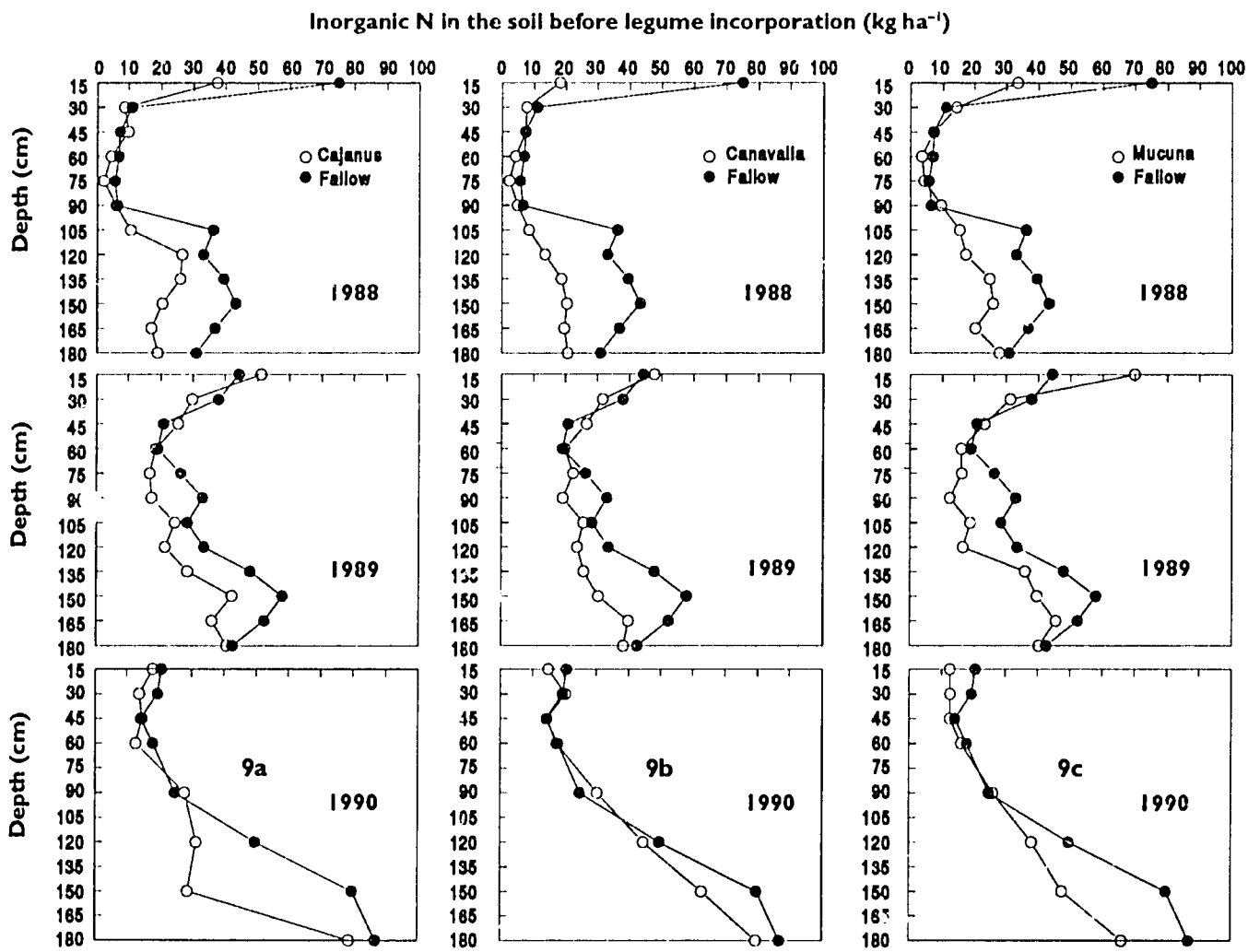
Figures 8a–8d. Soil water pressure measured to a depth of 150 cm throughout the dry season as affected by growth of legume green manures: (a) 49 days after planting (DAP), (b) 56 DAP, (c) 77 DAP, (d) 98 DAP.

lower than for other species, indicating that its roots had penetrated to at least 120 cm and that it was extracting water from the soil to this depth.

At 56 DAP, both mucuna and canavalia had extracted water to a depth of 90 cm, and canavalia had lowered the water potential substantially to a depth of 150 cm (Figure 8b). Other species had little impact on water potential below 60 cm. By 77 DAP, canavalia, mucuna, and cajanus had rooted to and were extracting water to a depth of at least 150 cm, as revealed by the reduced water potential to this depth (Figure 8c). Tephrosia and stylosanthes extracted only minimal quantities of water below 90 cm.

By 98 DAP, the soil water potential of the top 60 cm of all treatments had reached approximately the same value, probably the limits of the tensiometers installed in the plots (Figure 8d). The water content of the soil under all legumes other than stylosanthes was similar to a depth of 150 cm and was substantially lower than in the fallow plot at all depths below 30 cm, an indication that all these species had rooted to a depth of 150 cm and that water was being extracted to at least this depth. Stylosanthes had extracted water to a depth of 60 cm, but the water potential from 60 to 150 cm was little different from the fallow plot, suggesting that roots had not penetrated much deeper than 60 cm.

As observed in Table 10, dry-matter production of canavalia and mucuna was much greater than that of other legumes. Undoubtedly, this difference is related to their ability to extend roots rapidly into the subsoil and use residual subsoil water. Both

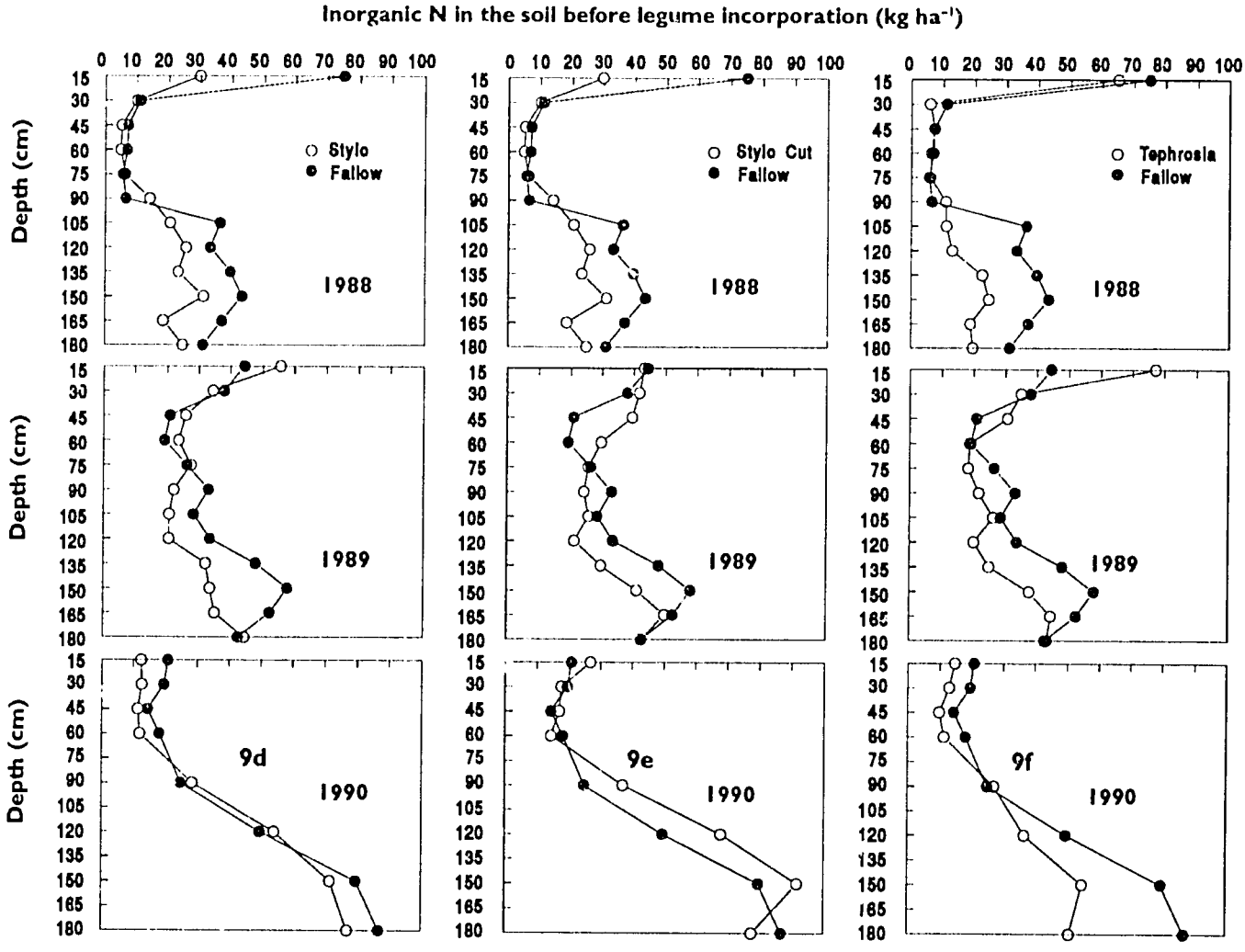


Figures 9a–9c. Inorganic N content of the soil at each 15-cm increment to a depth of 180 cm—prior to legume incorporation: (a) cajanus, (b) canavalia, (c) mucuna

cajanus and tephrosia extracted water to at least 150 cm, but only at 98 DAP, considerably later than canavalia and mucuna. Stylosanthes, in 1988 at least, extracted little deep water, and its dry-matter production was lower than that of the other species.

Soil Inorganic-N Content

In each of the three years prior to incorporation of legume green manures, soil samples were taken to a depth of 180 cm at 15-cm increments. Soil inorganic-N content for each depth is given in Figures 9a–9f. In 1988, inorganic-N content of the fallow plot was about 10 kg N ha^{-1} per 15-cm increment to a depth of 90 cm, except for the surface 15 cm, which contained about 75 kg. Below 90 cm, however, inorganic N content increased markedly to between 40 and 50 kg ha^{-1} per 15-cm increment. Thus, the entire 180-cm profile contained nearly 350 kg of inorganic N (Figure 10a) prior to maize planting. In contrast, under canavalia, inorganic N in the soil's top 15 cm approached 40 kg, while from 30 to 180 cm, it varied from 5 to about 25 kg per 15-cm increment. The total inorganic-N content in the profile was thus about 150 kg (Figure 10a). Soil inorganic-N contents under mucuna and tephrosia were similar to that under canavalia. Under stylosanthes, N content below 90 cm was little different from that under the fallow. Under cajanus, levels were intermediate between those for the fallow and for canavalia. Large quantities of inorganic N were present deep in the soil profile prior to this experiment. Apparently these deep-rooting legume



Figures 9d–9f. Inorganic N content of the soil at each 15-cm increment to a depth of 180 cm—prior to legume incorporation: (d) stylosanthes, (e) stylosanthes-cut, (f) tephrosia.

green manures were recycling N and accumulating it in both the roots and the aboveground biomass. How much of the biomass' total N content can be attributed to recycling or to biological N fixation is uncertain. The quantity of N stored in the various legume root systems is unknown. These data provide further evidence that several of these legume green manures root deeply and extract both water and N from considerable depths.

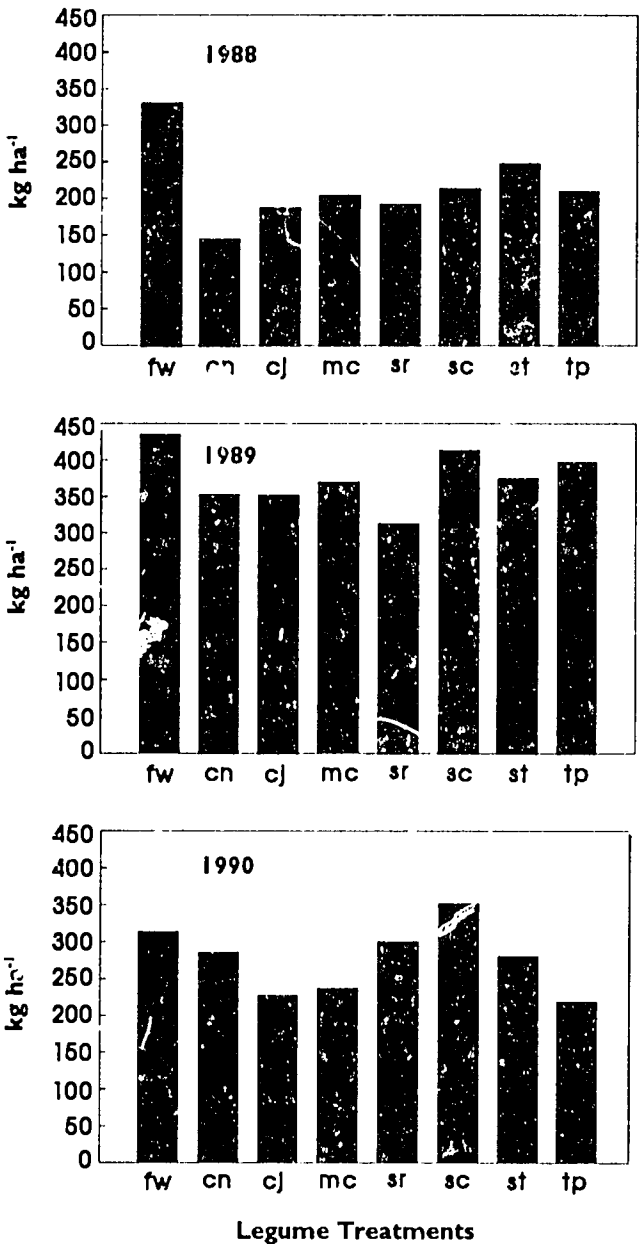


Figure 10. Total inorganic N content of the soil profile to a 180-cm depth (before incorporation), 1988–90. Fw = fallow; cn = canavalia; cj = cajanus; mc = mucuna; sr = sorghum; sc = stylo-cut; st = stylo; tp = tephrosia.

Compared to the 1988 data, sampling results for 1989 and 1990 show less evidence that legume green manures recycled soil inorganic N. In the 1989 dry season, those legumes that germinated and survived grew less well than in other years (Table 10) so that their total N content was less. Although dry-matter production was high for the 1990 dry season, there was less evidence of inorganic N recycling than in 1988. In all three seasons, large quantities of inorganic N were found in the soil profiles both under fallow and under legumes (Figures 10). At the start of the growing season, total inorganic N was more than sufficient to produce the maize yields obtained if it had been recovered by the growing maize crop. Cahn, et al. (1992) have shown that these subsoils effectively retain NO_3^- anions. One can only conclude that maize did not root deeply enough to reach much of the N deep in the profile or that much of the inorganic N was lost before the maize crop could take it up, presumably by moving out of the rooting zone.

Several green manures root deeply and extract both water and N from considerable depths.

Discussion and Significance of Results

We found a large number of legume green-manure species that can be planted at the end of a wet season, either after a crop is harvested or just before harvest. Most of these legumes will germinate and become established, survive a subsequent dry season, and grow again when the wet season begins. Under favorable conditions, the best legumes may produce over 5000 kg ha^{-1} of dry matter and contain over 100 kg of N.

Our hypothesis was that vigorous legumes planted at the end of the wet season would germinate and rapidly extend roots into the subsoil. Their survival would depend on their ability to extract residual water from the subsoil. Growth and N-fixation levels after the onset of the following rainy season would depend on the length of time the legumes were allowed to grow before being incorporated into the soil.

Of the five species we selected for intensive evaluation, *Canavalia brasiliensis* and *Mucuna aterrima* germinated and rapidly extracted water from the subsoil to a depth of at least 180 cm. The other species (*Cajanus cajan, Stylosanthes guianensis,* and *Tephrosia candida*) grew more slowly and only later in the dry season removed water deep in the profile.

Several other species planted in the screening experiment survived the dry season and accumulated considerable biomass early in the wet season, when dry-matter measurements were made. Species which did not survive usually flowered, set seed, and completed their growth cycle before the end of the dry season. Mucuna tended to shed its leaves and develop new ones throughout the dry season. It also tended to flower and set seeds; thus, some of the renewed growth may have been from new plants growing from seed developed over the dry season. This could be true of other species as well. Of the 37 species that survived the dry season, at least half produced sufficient biomass to be useful where dry-season survival is desired.

Variations in the dry season can have dramatic effects on legume germination and survival. In 1989, when essentially no rain fell immediately after the legume green manures were planted, some species failed to germinate, and those that survived grew poorly. In the other three seasons, when rainfall was sufficient for effective germination, all species survived the dry season. When sufficient water is available in the surface soil for this kind of germination, the species we tested will survive an intense dry season.

For adequate germination and subsequent rapid establishment, legumes must be planted as soon as possible following harvest of the wet-season crop. In certain circumstances, planting before the wet-season harvest may be necessary to achieve good germination. Presumably, the shorter the dry season the more likely a large number of species will survive. In those years when the dry season begins early and the surface soil dries rapidly, fewer species will survive. Our results suggest that *Canavalia brasiliensis* and *Mucuna aterrima* perform well over a wide range of dry-season conditions.

In 1988, maize recovered as much as 80 kg ha^{-1} from canavalia and an average of 40 kg for the five legumes. In 1989–90, when no rain fell subsequent to planting, germination failed or growth was severely limited. Combined with no-till plow-plant, this failure resulted in little contribution of legume N to maize. Legumes accumulated large amounts of biomass over the 1990 dry season, but N recovery by the subsequent maize crop was low. Recovery of fertilizer N was also low. Nonetheless, maize took up about 50 kg of N from canavalia.

Thus, although some recovery rates of legume green-manure N were disappointing, this management system shows sufficient promise for us to

recommend it. To achieve the maximum N contribution, legumes must be allowed to grow as long as feasible after the rainy season begins. To prevent N loss, residues must be incorporated into the soil quickly rather than remaining on the soil surface. To obtain the highest N efficiency, maize should be planted as soon as possible after incorporating residues.

Several legumes extracted water from considerable depths in the soil profile. Residual water in the profile or water at depths below the rooting zone of the rainy season crop provided the main water source over the dry season. Favorable conditions, both chemical and physical, must exist if legumes are to root deeply enough so that they can extract sufficient water to survive. If rainy-season rainfall is insufficient to meet the water requirements of the wet-season crop, reductions in subsoil water caused by the legume could limit production of the primary crop. Such reductions did not occur at CPAC, but where wet season rainfall is more erratic, reduced subsoil water could limit production of the primary wet-season crop.

In the fallow plots, large quantities of inorganic N were found at depths of 90–180 cm prior to maize planting. Considerably less N was found at these depths under the legumes, especially those that rooted deeply, an indication that the legumes recycled N as they extracted water from these depths. Below 90 cm, maize seems to have extracted little N—as indicated by the large response to fertilizer N in each of the three maize crops: in the fallow plots at CPAC, large quantities of inorganic N are routinely found in the subsoil, and it may or may not be utilized by growing crops. If green manures grown over the dry season can recycle this N, then the management system offers yet another advantage.

On the wet-dry savannas, soil is typically left exposed during the dry season; consequently, it is highly vulnerable to wind erosion—and to water erosion should rain happen to fall. Water erosion is most likely to occur at the beginning of the rainy season since the soil remains exposed until the wet-season crop cover is established. Green-manure crops which grow during the dry season can provide soil cover and thus reduce the risk of wind erosion. In addition, renewed or increased growth can occur as soon as the first rain falls, providing cover until the green-manure crops are incorporated into the soil. Planting the wet-season crop immediately after incorporating the green manure further minimizes the possibility of water erosion at the beginning of the rainy season. Using a minimum tillage procedure in which the residues are left on the soil surface can also reduce the possibility of water and/or wind erosion. This practice, however, often leads to a significant loss of N from the residues—probably the result of ammonia volatilization. Under most conditions, then, we recommend incorporating the green manures into the soil before planting the wet-season crop.

Legume biomass production in the humid tropics around Manaus—where the dry season is much milder and shorter—exceeded production under the savanna conditions at CPAC. Not only did the legumes fix large quantities of N, but biomass left on the surface protected the soil and suppressed weeds. Low N recovery was offset by the large amount of N contained in the residues; thus, fertilizer-N replacement quantities were similar to those at CPAC.

The economics of using legume green manures will depend on many variables:

- the availability and cost of fertilizer N,
- the suitability of given legumes to specific conditions,
- the availability of seed,
- the farmer's ability to incorporate residues into the soil,
- the amount of water in the soil profile,
- the chemical and physical conditions in the soil profile,
- the farmer's management skills.

Where sources of fertilizer N are limited or very costly, legume green manures offer an obvious alternative. When many variables are involved, the choice of a particular management system will be site-specific, and, consequently, the economics will need to be evaluated for each farmer or for each farming region.

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