Discussion Paper

~~VA~~ mycorrhiza management A new, low cost, biological technology for crop and pasture production on infertile soils?

Centro Internacional de Agricultura Tropical

DISCUSSION PAPER

VA MYCORRHIZA MANAGEMENT - A NEW, LOW COST, BIOLOGICAL TECHNOLOGY FOR CROP AND PASTURE PRODUCTION ON INFERTILE SOILS?[1]

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VA MYCORRHIZA MANAGEMENT - A NEW LOW COST, BIOLOGICAL TECHNOLOGY FOR CROP AND PASTURE PRODUCTION ON INFERTILE SOILS?

I. Introduction - The Problem

More than two thirds of CIAT's mandate area in tropical America (that is between 23°N and 23°S) are occupied by Oxisols, Utisols and Inceptisols. These soils generally have good physical characteristics, but have been weathered over a long time and leached by rainfall, resulting in extreme acidity and infertility. The major soil related chemical constraints are deficiency of phosphorus (P), nitrogen (N) and potassium (K), toxicity of aluminium (Al) and fixation of P.

From the socio-economic view point, the regions with acid, infertile soil have very little infrastructure, which limits inputs of soil additives to increase crop production. This is characteristic for the large savanna and rainforest regions of tropical America. In the Andean mountain regions most of the areas with marginal soils for crop production are cultivated by small farmers with low potential for purchasing lime or fertilizers.

CIAT's concern includes the general welfare of poor urban and rural food consumers in the tropics. CIAT's effort is to increase the production of the region's four principal food commodities - common beans, cassava, rice, and beef - by developing improved crops, and production systems that are appropriate to the actual ecological and economic conditions of the region's farmers (Cit. from CGIAR, 1980). CIAT's strategy emphasizes enhanced production through increased resource productivity on farms with limited resources and on underutilized land areas (CIAT Annual Report 1983), to produce food at low cost per unit.

Without doubt, a reduction of production costs can be obtained by application of biological technologies, which requires low purchased inputs (Nickel 1979). However, on infertile, acid oxisols, ultisols and inceptisols, farmers must add fertilizers to their crops in order to achieve

sustained production; this is also necessary in the most fertile soils of the temperate zones. Many farmers, including small farmers, know that their crops could yield more if fertilizer were applied. But, they either cannot afford to purchase it or do not wish to take the risk involved in applying it.

One way of circumventing this problem is to use low input technology for managing acid infertile soils (Sanchez and Salinas, 1980). These authors suggested six strategies for the management of the most important chemical soil constraint - phosphorus. Five of them are relatively well established. They are: P placement methods, improvement of P fertilization recommendations, less costly phosphorus sources, soil liming to increase the availability of P fertilizer, and selection of plant species and varieties adapted to low P conditions. The sixth strategy proposed was the practical utilization of mycorrhizal associations to increase the use of soil phosphorus and fertilizer P. However, the application of this strategy was not well defined due to lack of research. In 1980 the Cassava Program and in 1982 the Tropical Pasture Program initiated mycorrhizal research at CIAT to look at the practical possibilities of mycorrhizae utilization for the major crop production systems studied by CIAT grown in acid infertile soils. We consider the mycorrhizal association to be a strong biological component of low input technology in tropical agriculture, and that if possible the management of mycorrhizae should be incorporated into all major agronomic practices for managing soil fertility and plant nutrition in the tropics.

II. Distribution of mycorrhizal fungi, their function and importance for the major crops of CIAT

Vesicular-arbuscular (VA) mycorrhizal fungi are known to occur world-wide in all edapho-climatic conditions. However the distribution of different fungal species and population is highly variable even between soils within a small area (Table

1). Large variations have also been observed even within fields. The main effect of the fungi is to grow outside plant roots and thus extract nutrients from a greater soil volume than the plant root alone is able to exploit. Relatively inmobile elements, such as phosphorus, are taken up in larger amounts by a mycorrhizal root than by non mycorrhizal roots. Hyphae of VA mycorrhizal fungi are not known to take up phosphate other than phosphate ions either in soil solution, or held on surfaces in such way that they are in rapid equilibrium with phosphate in the soil solution (Figure 1). However large differences exist among mycorrhizal species and strains in their efficiency of P uptake and thus in the resulting benefit for the crop (Table 2). In general, however, high specificity between mycorrhizal species and plant species is not found; i.e. mycorrhizal strains effective for cassava may also be effective for pasture plants, beans etc. under similar edapho-climatic conditions.

Differences exist between plant species and varieties in their dependence on the mycorrhizal association for P uptake. For CIAT's principal crops this dependency is shown in Table 3. It is clear that cassava and the pasture legume are obligately dependent on a mycorrhizal association under most soil nutrient conditions. Pasture grasses and beans are somewhat less dependent. Upland rice may depend on the mycorrhizal association only under certain conditions.

Thus, it is clear that without mycorrhizal associations, cassava and pasture plants would not yield at all under acid, infertile soil conditions. Beans would yield very little.

III. Concepts for the management of mycorrhizal association for more efficient P uptake

There are two main methods for management of fungal activity in agriculture:

A. Based on the knowledge that VA mycorrhizal fungi are

naturally occurring in all tropical soils and that major crops studied by CIAT, cassava, pastures and beans are obligately mycotrophic (dependent on mycorrhiza for nutrition) in acid soils with low nutrient contents, one possible strategy is to manage the indigenous mycorrhizal fungi by agricultural practices in such a way that the crop plant can obtain optimum benefit from association with them.

B. Since the quality and quantity of the natural mycorrhizal fungi is highly variable in different soils, or even within the same field, a logical strategy is to develop field inoculation techniques with selected, highly effective mycorrhizal fungi adapted to the plant and to the edapho-climatic conditions.

For all CIAT's mycorrhiza-dependent crops both strategies can be applied. We will present summarized results for cassava and pasture plants which have been investigated most intensively.

A. Management of mycorrhizal association by agricultural practices:

Until this time no real attempt has been made to manage the natural mycorrhizal fungal population actively by agricultural practices although most good agricultural practices are likely to stimulate mycorrhiza. Research has been initiated to evaluate the effect of agronomic practices on the indigenous mycorrhizal population.

a. Effect of fertilizer applications on mycorrhizal activity:

Fertilizer P applications can decrease, as well as increase the mycorrhizal root infection, depending on the mycorrhizal species involved in the association. Most native mycorrhizal species are able to utilize low P fertilizer levels for increased crop production, however the response is strongly dependent on the adaptation of the native mycorrhizal species to each level and source

of P fertilizer, as well on the method by which the fertilizer is applied.
Generally, N and K fertilization, as well as lime application, seem to have only a small influence on the mycorrhizal activity, i.e. mycorrhizal root infection and mycorrhizal growth response. However, where K is a limiting nutrient, fertilization of K is necessary to provide a high infection level. The most important aspect of the effect of fertilizer on mycorrhizal fungi seems to be the balance of the nutrients applied to the crop.

b. Effect of cropping system on mycorrhiza.
Little practical information on the effect of cropping systems on the mycorrhizal association is available. Preliminary results showed that crop rotation of cassava with grain legumes favored the mycorrhizal association of cassava. The special interactions between mycorrhizal fungi and intercropped cassava with grain legumes are not well understood. If crops are associated, some mycorrhizal fungi appear to favor one of the associated plants more than the other. Similar results were obtained from pasture grasses associated with legumes.

c. Cultivar differences.
Results indicate that high yield responses of cassava cultivars to small P application levels are only possible when the mycorrhizal root infection is not altered or even when infection is increased by P application. Apparently there are differences and special interactions between cultivars, mycorrhizal infection and P responses of the cultivar. These differential interactions are also observed with various pasture legumes and grasses, as well as with beans.

d. Crop protection.

The effect of some fungicides and herbicides on the mycorrhizal infection and spore population have been investigated. Generally, pesticides can inhibit, as well as stimulate mycorrhizal root infection and spore production. However the interactions are very complex. For example, herbicides can operate directly on the mycorrhiza or indirectly by changing the weed population. Weeds are potential host plants for mycorrhizal fungi. Also, pesticide applications, and this seems to be the most important point, can lead to a change in the mycorrhizal species composition in the field. Thus, increasing the population of an effective species by any pesticide, may have a long-term positive effect on crop production, and vice versa.

The use of technologies to control diseases and pests generally has preference to mycorrhizal considerations due to the simple fact, that for a dead plant mycorrhizae are useless. Thus, breeding for disease and pest resistant varieties must have preference. It may be possible to select pesticides, which protect plants and are beneficial for the mycorrhizal association.

e. Other agricultural practices.

A range of other agricultural practices, such as mulching, burning, land preparation, grazing etc., which have not been intensively investigated, may have slight positive or negative effects on the mycorrhizal population. It seems that the combination of various agricultural practices determines whether an agronomic practice favors mycorrhizal activity or not.

B. Management of mycorrhizal association by field inoculation

Field inoculation is an artificially induced change in the soil mycorrhizal population. By field inoculation one or more mycorrhizal species are

increased locally near the growing plant roots. Thus, before utilizing this management technique many naturally occurring strains from several soil sites must be collected, isolated, multiplied, maintained and evaluated on their effectivity to be beneficial for the crop plant, and for their adaptation to edapho-climatic conditions. A very important point in the evaluation of the isolated strains is the evaluation of its ability to compete with the native mycorrhizal species and other microorganisms. At CIAT, there are now about 300 mycorrhizal strains isolated and maintained in a pot culture collection, and for cassava, the methodology for the evaluation of different mycorrhizal isolates is now well established.

It has been well established that field inoculation can increase cassava yields on acid, infertile oxisols and Inceptisols (Table 4). Considering only the seven trials which were conducted at the same time with 50 kg P/ha as Huila rock phosphate under farmer's field conditions in inceptisols, cassava root yields were increased on the average by 29% (increase from 15.6 t/ha to 20.1 t/ha). In the same soil increases of 26% (average of 4 trials) were obtained when 50 kg P/ha as triple superphosphate were applied.

Inoculated pasture plants established and covered the soil much faster when grown under natural field conditions in an Oxisol. With only 20 kg P/ha, applied as rock phosphate pasture legumes yielded on the average 68% (1.6 t/ha) more fresh material than non-inoculated plants, 3 months after sowing (Table 5). Nodulation with Rhizobium was stimulated by mycorrhizal inoculation. The pasture grass Andropogon gayanus yielded 2.5 t/ha (35%) more when inoculated.

Greenhouse trials with beans also indicate that beans would yield more in the field, when inoculated with selected mycorrhizal strains (Figure 2).

Generally, it was shown by almost all trials that mycorrhizal field inoculation has to be combined with small P fertilizer application (see Table 4 and 5). The potential of mycorrhizal inoculation to decrease the P fertilizer requirement of crops for obtaining maximum yields of non-inoculated plants was clearly shown, in the field (Figure 3). Also, it was shown that it is possible to substitute in the field the application of soluble P fertilizer sources by relatively insoluble rock phosphates when the latter application was combined with mycorrhizal field inoculation (Table 6).

IV. Comparison of the two alternatives for management of the mycorrhizal association

1. Agricultural practices

Each agricultural practice can change the mycorrhizal species composition and population, and possibly in different way depending on the site. Theoretically, after intensive investigation at a specific site, we would be able to give some general recommendations to conserve the mycorrhizal population over long time and to assure crop production. However, to manage the natural mycorrhiza population directly and actively by agricultural practices, knowledge about the mycorrhizal species which were being managed would be required. Thus, if methods were available to define rapidly the status of different mycorrhizal species in each field, management of mycorrhizal fungi by recommendation of certain agricultural practices might be possible. These recommendations could be worked out for all types of soils, either "chemically" fertile or not, and all crops.

However, considering the risk of recommendations which may stimulate mycorrhizal activity without the use of inoculation, we must conclude that due to the vast amount of information needed to do this we cannot have much confidence in this method.

2. Field inoculation technology

We divide this topic with respect to: A. Practical aspects and B. Economic aspects.

A. Practical aspects of field inoculation.

The success of managing mycorrhizal fungi by field inoculation depends on several questions which can be defined as:

a. Where will field inoculation work?
b. What field inoculation methods can be applied?
c. What amounts of inoculum are required?
d. Who will produce the inoculum?
e. Will farmers be able to produce their own field inoculum?
f. Will farmers accept the inoculation technology?

a. Where will field inoculation work?

The conditions where field inoculation will work are well defined. 1) It is more likely that inoculation will increase crop yields where the quantity and quality of the naturally occurring mycorrhizal population is low. Although it is not yet well defined which soil parameters are correlated with low quantity and quality of mycorrhizae, we know for example that eroded soils and those soils called by farmers "sterile" and "degenerated" are likely to have low mycorrhizal populations. It is also very likely that natural savanna soils have low mycorrhizal populations (Table 7). 2) The crop must be obligately dependent on the mycorrhizal association under the given soil conditions to obtain inoculation response. With cassava, pasture plants and beans this is most likely in all infertile soil conditions. 3) Inoculation responses will occur when suitable agricultural practices are combined with field inoculation. This includes small fertilizer dressings, selection of disease and

pest resistant planting material, crop protection methods, which do not work against the introduced mycorrhizal strain, application of other microbiological components (like Rhizobium) which have a synergistic effect on the mycorrhizal association and crop production. Often, by proper agricultural practices the natural mycorrhizal population can be depressed, and the same practices may favor the introduced strain. 4) Inoculation will work if the mycorrhizal strains which are to be introduced to the field, are selected for the edapho-climatic conditions and for the crop, and if the inoculum is free from pathogens. 5) Inoculation will work, if an inoculation technology is used which, favors the competitive ability of the introduced strain against the competing natural microbial population.

b. Which field inoculation methods can be applied?
Firstly, VA mycorrhizal fungi are obligate symbionts, and cannot be grown on artificial culture media. Sources of mycorrhizal inoculum are: spores, infected roots of host plants, or a soil substrate in which infected host plants have been grown and which contains at the time of utilization a range of infective mycorrhizal propagules, that is: spores, mycelium, infected plant roots. The former two sources of inoculum must be separated from the substrate, the latter is chopped up and homogenized, before utilization as such. The advantages and disadvantages of the three sources of inocula are shown in Table 8.
The inoculum must be brought in direct contact with the seed or placed in the field, in such a way that the sprouting roots of the seed penetrate the inoculum. This can be achieved by coating the seed

with mycorrhizal inoculum (this would be with spores on seeds; by multi-seeded pellets which may contain a mixture of mycorrhizal inoculum, rhizobia and seeds and are appropriate for small-seeded plants such as some pasture legumes) or by placing the inoculum under the seed in the field. The placement method is highly important for the competitive ability of the introduced fungi. At this moment we view the application of infected soil as the most practicable inoculation method.
We do not envisage serious technical problems in applying the inoculant once it is available, and as long as the quantities required are not too large to handle; the inoculum (coated seed or soil substrate) may be applied by hand, which would be more likely to be done by small farmers or mechanically when larger areas are being sown.

c. What amounts of inoculum are required?

Logically, the amount of required inoculum per hectare depends on the crop, the cropping system and the plant density/ha. It is lowest when plants are transplanted after establishment in a seed-bed where the plants can be pre-inoculated. With agricultural crops such as cassava, pasture plants and beans the amount depends on the planting density/ha. In Table 9 some theoretical calculations on a hectare basis are shown. The data for cassava may be most realistic, as some research has been done on that aspect. It is also clear that with pastures the amounts of inoculum may be quite small, depending on the pasture establishment method. The use of multi-seeded soil pellets may reduce the amount of inoculum required.

d. Who will produce the inoculum?

The advantages and disadvantages of inoculum sources, listed in Table 8 affect the producers of inoculum sources. Spores can only be produced by a special inoculum industry which may be combined with a seed industry to coat the grain seed with mycorrhizal inoculum. For the farmer the inoculum will represent a capital cost factor though this may not be high. The other two inoculum sources - infected roots or infected soil substrate - also can be produced by inoculum production industries; however infected roots have a low storage time (2-4 weeks). Infected soil is bulky and could pose problems of transport to the farmer.

An alternative to specialized inoculum industries could be the production of the field inoculum (infected roots or infected soil) by the farmer himself. In addition to informations as to how to do this he would need some materials per ha, such as:

- $25m^2$ land area (which would give 5 ton infected soil substrate; calculated on the base of 20 cm depth and a specific weight of $1g/cm^3$).
- A soil sterilizant to sterilize $25m^2$ land.
- A mycorrhizal starter inoculum with one or more edapho-climatic and crop adapted mycorrhizal species (this starter could be 2.5 kg infected soil with a mycorrhizal spore concentration of 200 spores/g).
- A host plant, to be planted in the $25m^2$ soil, in which after sterilization the starter inoculum was incorporated.
- Small amounts of proper agrochemicals to protect the host plant and to stimulate mycorrhizal production.

In this way the farmer would be able to produce in

about 4-6 months his own field inoculum. The basic requirement for this technology would be that a company would supply those materials at low cost to the farmer. This form of inoculation would reduce the problem of transport of infected soil. The on-farm transport problem could be solved by preparing the inoculum banks in those fields which are to be inoculated; if on-farm tranport were to be a problem, utilization of infected roots from the inoculum bank as inoculum source, could be one solution.

e. Will farmers be able to produce their own field inoculum?

It is possible that farmers would be able to do this. Soil sterilization is not a new technology for extension workers nor for farmers. Many of them know how to sterilize seed-beds for pre-establishment of fruit trees, coffee, etc. However, there would be a need for demonstration how to apply the mycorrhiza and how to maintain the inoculum banks free of contamination.

f. Will farmers accept the inoculation technology?

Acceptance is based on need, confidence for success, economical aspects and may be on knowledge of biological processes. We can divide the topic into the questions as to whether big farmers or small farmers will accept the inoculation technology. Big farmers may occupy most of the fertile soil in tropical America and thus possibly would not need the new technology. However big farmers on acid, infertile soils are more likely to utilize the new technology, because they know that biological techniques are generally of low cost. Also, big farmers would learn very quickly that inoculation

will have a very marked short term effect, which possibly can be prolonged by adequate agricultural practices.

It is also likely that small farmers will accept the new technology, due to the fact that it needs little capital. In any case, the potential of this technology and how it has to be carried out must be shown to the farmers (whether big or small) by demonstration trials. We think that this can be demonstrated to extension workers and farmers as a simple practical technology. This would involve close collaboration with national extension organizations.

B. Economic aspects of management of mycorrhizal inoculation

In practice it will be almost impossible to express the economic value due to mycorrhizal inoculation alone because the conservation of long-term mycorrhizal activity is an integrated part of soil and crop management to maintain fertility and productivity.

Up to the present we only can make some calculations of the economic value of field inoculation with cassava, as results from several trials on farmer's fields (although on an experimental level) are available. For the calculation we consider the application of 5 ton inoculum/ha as infected soil; the inoculum is assumed to be produced by the farmer and the inoculum applied by hand. We assume that selected mycorrhizal strains (starter inoculum) would be available and we exclude the research cost for the new technology.

As shown in Table 10 purchased inputs would be very low in this case. Estimating the additional

man-days required as 20/ha the net return/ha would increase by about US$165 (US$=88 Col. Pesos) due to field inoculation in the first year. We are not yet able to calculate the long-term effect of field inoculation because results of residual effects are not yet available.

As discussed above, expensive soluble P fertilizer can be substituted by cheaper rock phosphates, when latter application is combined with field inoculation. However, Table 11 shows that from the economical stand-point the combined treatment rock phosphates plus inoculation must yield at least about 1.0 ton/ha more than TSP application to become economical (on this fertilizer input and cassava output level). Also in this case possible residual effects of rock phosphate applications and mycorrhizal inoculation are neglected. Even if inoculation responses are not observed in every case, the risk of planting the crop is considerably reduced by inoculation.

V. Conclusions

1. The management of VA mycorrhizal fungi is an important component of managing plant crop nutrition on acid, infertile soils. Moreover, many agricultural practices can influence the mycorrhizal activity, depending on the mycorrhizal strain, the crop and the edapho-climatic conditions.

2. Management of mycorrhizal fungi by field inoculation is economically attractive, and could be practical for both small and large farmers subject to suitable extension.

3. A short-term response is generally obtained by field inoculation; long-term effects are expected, but not yet confirmed due to lack of research. Long-term management by agricultural practices has been practiced ever since agriculture has existed; it is almost impossible to evaluate in economic terms.

4. Management of VA mycorrhizal fungi by field inoculation has lower risks than management by agricultural practices.

5. Farmers will accept inoculation technology, if they are shown how to do it, because of its low capital cost and because it reduces the risk of low crop productivity.

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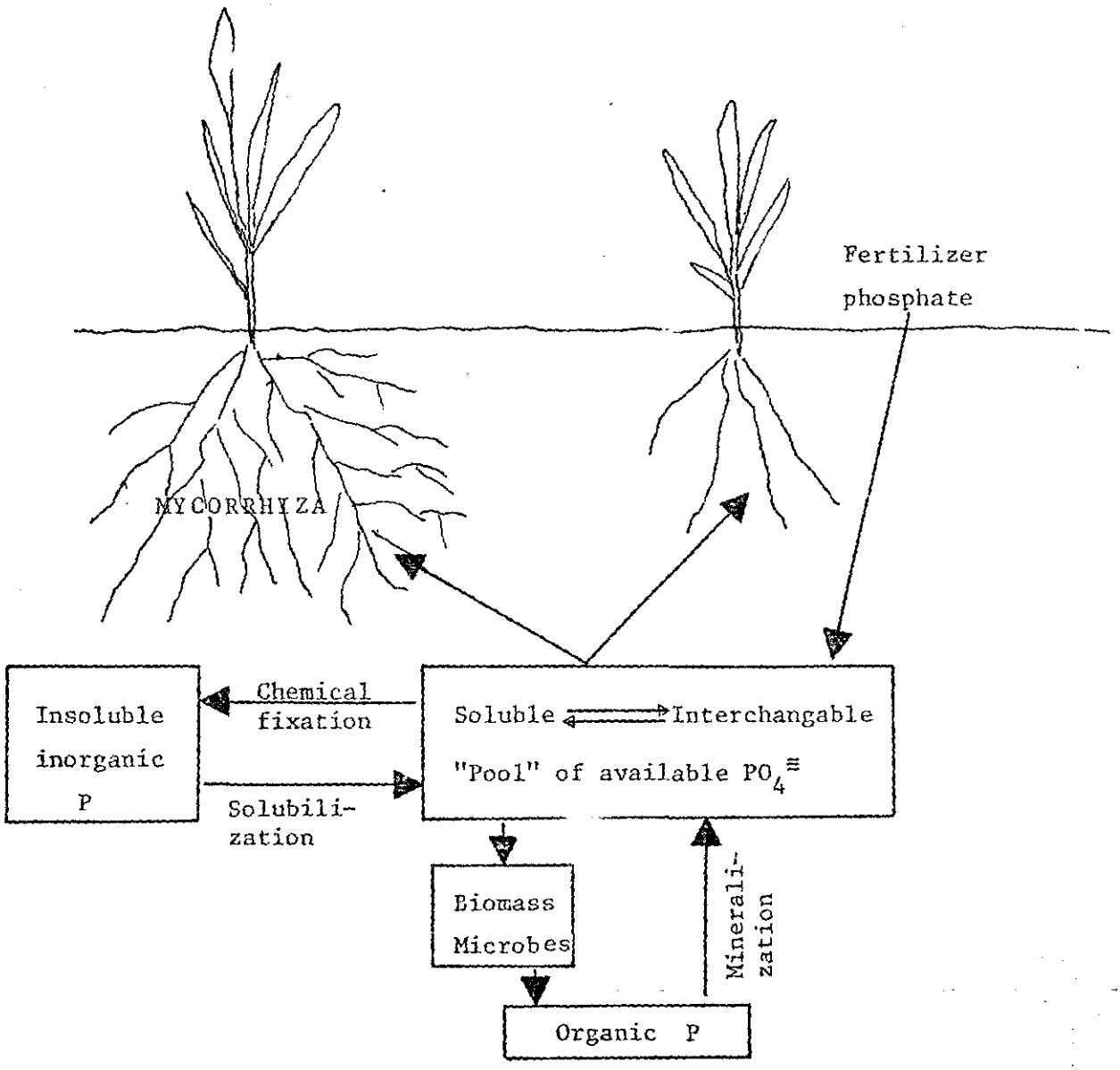


Figure 1 Phosphate cycle (Source: Borie and Barea, 1981)

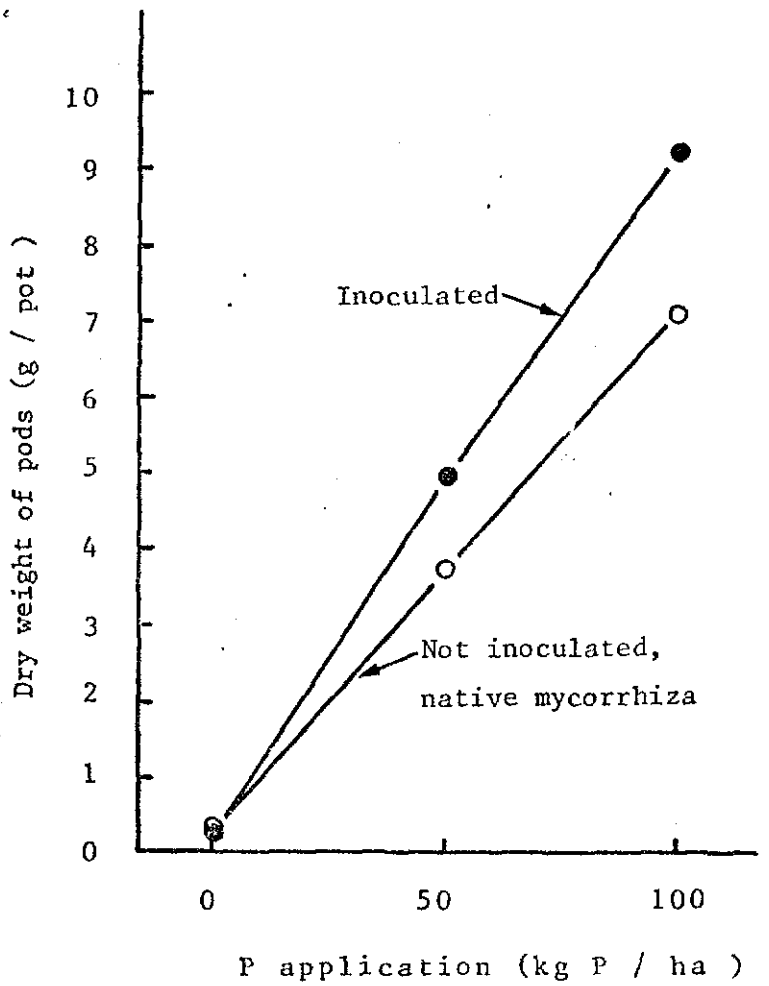


Figure 2: Effect of inoculating beans with Glomus manihotis and application of different levels of P on dry weight of bean pods in a greenhouse trial in unsterilized soil from Quilichao (Source: Mosquera, unpublished)

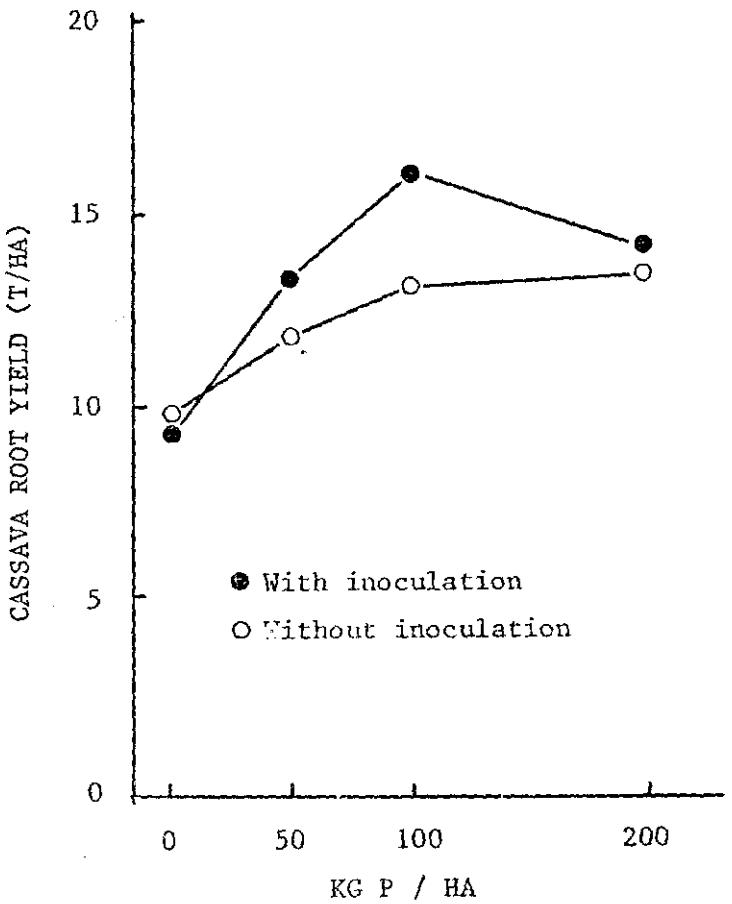


Figure 3 Effect of various levels of P as well as Inoculation on root yield of cassava, MVen 77 in Carimagua (Source: Howeler 1982)

Table 1 Observation of mycorrhizal species population (number of spores / 100 g dry soil) in 9 fields of the Mondomo area (Cauca, Colombia). Source: Sieverding, unpublished

Mycorrhizal species	Site No.								
	#1	#2	#3	#4	#5	#6	#7	#8	#9
1. *Acaulospora* sp.	1035	352	198	1036	270	393	1652	932	79
2. *G. fasciculatum*	1082	755	550	644	557	593	477	875	2665
3. *Glomus* sp.	1	2	2	2	13	170	8	7	1
4. *Gigaspora* sp.	5	8	1	29	29	2	31	9	6
5. Not identified A.	1	0	1	0	0	0	3	1	1
6. *Acaulospora* sp.	2	0	1	5	0	0	1	0	0
7. *A. appendicula*	74	47	28	955	376	38	191	26	54
8. *G. manihotis*	0	0	1	1	1	0	0	1	4
9. Not identified B.	0	0	1	0	0	0	1	0	0
10. *Gigaspora* sp.	0	0	1	0	2	0	0	0	0
11. *Entrophospora* sp.	2	0	1	0	2	3	1	1	0
12. Not identified C.	0	0	2	0	11	0	0	1	0
13. *A. foveata*	2	2	1	2	1	6	3	0	3
Total	2204	1166	788	2674	1262	1205	2368	1853	2813

Table 2 Effect of inoculation with different mycorrhizal isolates on plant shoot dry weight, P uptake, root length and root infection of cassava cv. MPer 245 grown in sterilized soil from Quilichao in a greenhouse trial (Source: Sieverding, unpublished)

Mycorrhizal isolate No.	Isolate code	Top dry weight g / plant	P uptake mg / plant	Total root length m/plant	Root infection %
Not inoc.	NM	0.21	0.22	1.9	-
C-1-1	MAN	4.16	3.58	21.3	64.5
C-11-1	LON	1.24	1.62	12.6	11.5
C-11-2	COL	5.54	4.82	35.1	5.3
C-12-1	LON	5.22	4.32	27.9	7.0
C-12-2	OCC	5.47	5.95	21.9	10.5
C-13-1/2	APP	6.04	5.59	22.9	17.5
C-14	MOR	0.59	1.03	2.8	31.8
C-15-1/2	MEL	4.61	5.19	40.5	32.5
C-16-1	LON	6.32	5.68	44.8	26.0
C-17-1	MAN	3.94	3.92	21.8	62.5
C-17-2	LON	0.69	0.80	4.8	15.5
C-18-1	FAS	3.00	3.06	22.2	70.5
C-18-2	OCC	4.60	4.41	20.5	17.0
C-18-5	LON	4.53	5.09	19.0	53.0
C-19-1	MIC	2.60	3.58	8.4	52.5
C-20-2	MAN	5.61	5.46	19.6	60.0
C-20-3	COL	5.49	4.92	15.9	12.5
C-21	MAR	2.84	3.18	10.4	40.5

Table 3 Effect of inoculation with Glomus manihotis, and P application* on top yields of several plant species (Source: Howeler, CIAT 1980)

Plant species	Dry matter in tops (g / pot)						Mycorrhizal dependence**		
	Non inoculated			Inoculated					
	P_0	P_{100}	P_{500}	P_0	P_{100}	P_{500}	P_0	P_{100}	P_{500}
Cassava	0.34	0.72	0.54	4.33	14.21	16.36	12.7	19.7	30.3
Beans	1.11	3.44	8.29	3.08	18.79	25.01	2.8	5.5	3.0
Stylosanthes sp.	0.08	0.08	2.74	1.25	9.33	12.20	15.6	116.6	4.5
Andropogon sp.	0.15	0.39	34.24	1.26	16.67	32.18	8.4	42.7	0.9
Maize	1.19	8.74	59.35	4.84	34.75	53.57	4.1	4.0	0.9
Rice	3.79	26.63	30.60	3.83	22.36	31.23	1.0	0.8	1.0

*Planted in sterilized soil from CIAT Quilichao, in the greenhouse. Fertilized with 0, 100, or 500 kg P / ha

** Mycorrhizal dependence calculated as: $\frac{\text{Dry matter of inoculated plants}}{\text{Dry matter of non inoculated plants}}$

Table 4: Effect of field inoculation with selected mycorrhizal strains on cassava fresh root yields (t / ha) after one year of growth at different soil sites with the application of different sources and levels of P fertilizer (Means of four replications at each site; control: not inoculated, and inoculated with most effective strain or treatment). Source: CIAT Annual Reports for 1982, 1983; Cassava Program.

Soil sites*	P** source	P level (kg/ha)	Root yields		Most effective mycorrhizal strain No.
			Not inocul.	Inocul.	
Mondomito I		0	26.1	27.3	C-4-2
Carimagua - Yopare		0	9.8	9.3	C-1-1
Mondomito I	TSP	50	29.9	36.7	C-19-1
Mondomito II	TSP	50	7.0	8.2	C-33-1
Agua Blanca I	TSP	50	13.1	18.1	C-1-1
Pescador	TSP	50	18.5	22.9	C-1-1
Carimagua - Alegria	TSP	50	15.9	18.3	C-19-1
Carimagua - Alegria	TSP	100	16.4	19.9	C-4-2
Cariamgua - Yopare	TSP	100	11.6	17.6	C-1-1
Carimagua - Alegria	BS	50	18.0	18.6	C-10
Mondomito II	HRP	50	6.2	9.5	C-10
Agua Blanca I	HRP	50	12.9	16.1	C-1-1
Agua Blanca II	HRP	50	21.2	27.1	C-1-1/C-10
Agua Blanca III	HRP	50	15.6	18.3	C-1-1/C-10
Agua Blanca IV	HRP	50	24.7	31.1	C-3-5
Tres Quebradas	HRP	50	17.7	19.1	C-1-1/C-10
Pescador	HRP	50	11.3	20.4	C-33-1
Carimagua - Alegria	HRP	50	15.9	19.8	C-10
Carimagua - Yopare	HRP	100	11.7	19.2	C-1-1

*Carimagua sites are Oxisols; all others are Inceptisols

** TSP: Triple superphosphate, BS: Basic slag, HRP: Huila rock phosphate

Table 5: Effect of field inoculation with selected mycorrhizal strains on fresh yields (t/ha) of pasture species grown in an Oxisol at Carimagua without or with application of 20 kg P as rock phosphate from Huila (RPH). Source: Saif, CIAT 1983

P application	Field inoculation	Fresh material production		
		Stylosanthes capitata	*Pueraria phaseoloides*	*Andropogon gayanus*
Without	NO	0.3	0.3	0.9
	YES	0.5	0.6	1.2
With RPH	NO	1.5	2.5	7.2
	Yes	3.0	4.3	9.7

Table 6: Effect of field inoculation (Inoc.) and the application of 50 kg P / ha either as triple superphosphate (TSP) or rock phosphate from Huila (RPH) on root yields of cassava cv. CMC 92 at three sites in the Mondomo area (Source: Sieverding, unpublished)

Treatment	Fresh root yields (t / ha)			
	1st. site	2nd. site	3rd. site	Mean
TSP	13.1	18.5	7.0	12.9
TSP + Inoc.	18.1	22.9	8.2	16.9
RPH	12.7	11.3	6.2	10.1
RPH + Inoc.	15.5	20.4	9.5	15.1

Table 7: Mycorrhizal population (infective mycorrhizal propagules per 100 g dry soil) in natural savanna soils in comparison with soil from CIAT-Quilichao and soil from a pot culture with a pure mycorrhizal strain (Source: Sieverding, unpublished)

Soil site	Utilization of soil	Infective mycorrhizal propagules/ 100 g
Carimagua-Reserva	Natural savanna	410
Carimagua-Yopare	Natural savanna	171
Carimagua-Alegria	Natural savanna	72
Carimagua-Tabaquera	Natural savanna	36
CIAT-Quilichao	Cassava trial, planted after pasture legumes	2506
Greenhouse pot culture*		20972

* From CIAT's mycorrhizal strain collection; Pueraria phaseoloides inoculated with the mycorrhizal strain C-1-1 (Glomus manihotis); soil from Quilichao

Table 8. Evaluation of inoculum sources.

Inoculum Source	Advantages	Disadvantages
Spores	- Low inoculum volume? - Low transport costs? - In coating material other microorganisms (Rhizobium) and plant nutrients can be incorporated.	- Not competitive against native mycorrhizae? - Long-term storage only in artificial conditions - Coating of seed is necessary? - Difficult to produce technically? - Production only by industry possible. - Cost intensive?
Infected roots	- Low volume? - Low transport costs? - Simple production technology. - Production on-farm possible.	- Competitive against native mycorrhizae only under certain conditions. - Relatively short time durability. - High labor cost in preparation? - Not mixable with fertilizer. - Danger of pathogens?
Infected soil substrate	- High potential to compete with native mycorrhizae. - Simple production technology. - Production on-farm possible. - Low-cost for production. - Storage for at least one year possible; under right environmental conditions. - Mixable with fertilizer and other microorganisms. - Mixable with certain biocides?	- High volume. - High transport cost, if not produced on-farm. - Danger of pathogens?

Table 9. Amounts of inoculum required for field inoculation of cassava, pastures and beans utilizing different inoculum sources (values are estimated, not yet confirmed with exception for cassava; spores estimated to be coated on seed with max. 1 g coating material).

	Plant density per ha	Spores (coated in 1 g material per seed) (kg/ha)	Infected roots 2 g/plant (kg/ha)	Infested soil* (kg/ha)
Cassava	10.000-15.000	not known if feasible	20-30	2.000-6.000
Pasture plants	1.250-100.000	1.25-100	2.5-200	12.5-4.000
Beans	200.000-400.000	200-400	400-800	2.000-4.000

*Infested soil:- for cassava calculated on the basis of 200-400 g inoculum per plant.
- for pasture legumes/grasses and beans calculated on the basis of 10 g inoculum/plant or with 200 g inoculum per linear meter.

Table 10. Calculation of costs and benefits of mycorrhizal field inoculation of cassava in Mondomo area, Cauca, Colombia. (Nov. 1983)

		Costs Col. Pesos
A.	Additional inputs to cassava/ha.	
1.	Inoculum production by farmer*	
	- $25m^2$ land	not considered
	- Soil sterilizant	550
	- Mycorrhizal starter inoculum 2.5 kg (estimated 80-$/kg)	200
	- Host plant for mycorrhizal multiplication plus agro-chemicals for $25m^2$ land (estimated)	250
	- 10 man-days for inoculum production and preparation before application to the field.	3.500
2.	Additional labor cost to apply the inoculum to the plant, 10 man-days	3.500
	Total cost of field inoculation:	8.000
B.	Additional outputs** due to field inoculation Average root yield increase by inoculation (7 trials) was 4.5 t/ha.	22.500
C.	Increase in net income/ha	14.500

*Inoculum production is not yet done by farmers, production costs are estimated (probably overestimated)

**Cassava: 5.000 - Col. Pesos/t.

Table 11. Economic aspects of substitution of soluble P fertilizer by rock phosphate plus field inoculation.

Data available:

1. Additional input cost for field inoculation per ha:

   8.000 Pesos (Table 6).

   Cost for 50 kg P/ha as triple superphosphate (TSP):

   6.000 Pesos.

   Cost for 50 kg P/ha as Huila rock phosphate (RPH):

   3.100 Pesos.

2. Output (yield)

   5.000 Pesos/t fresh roots.

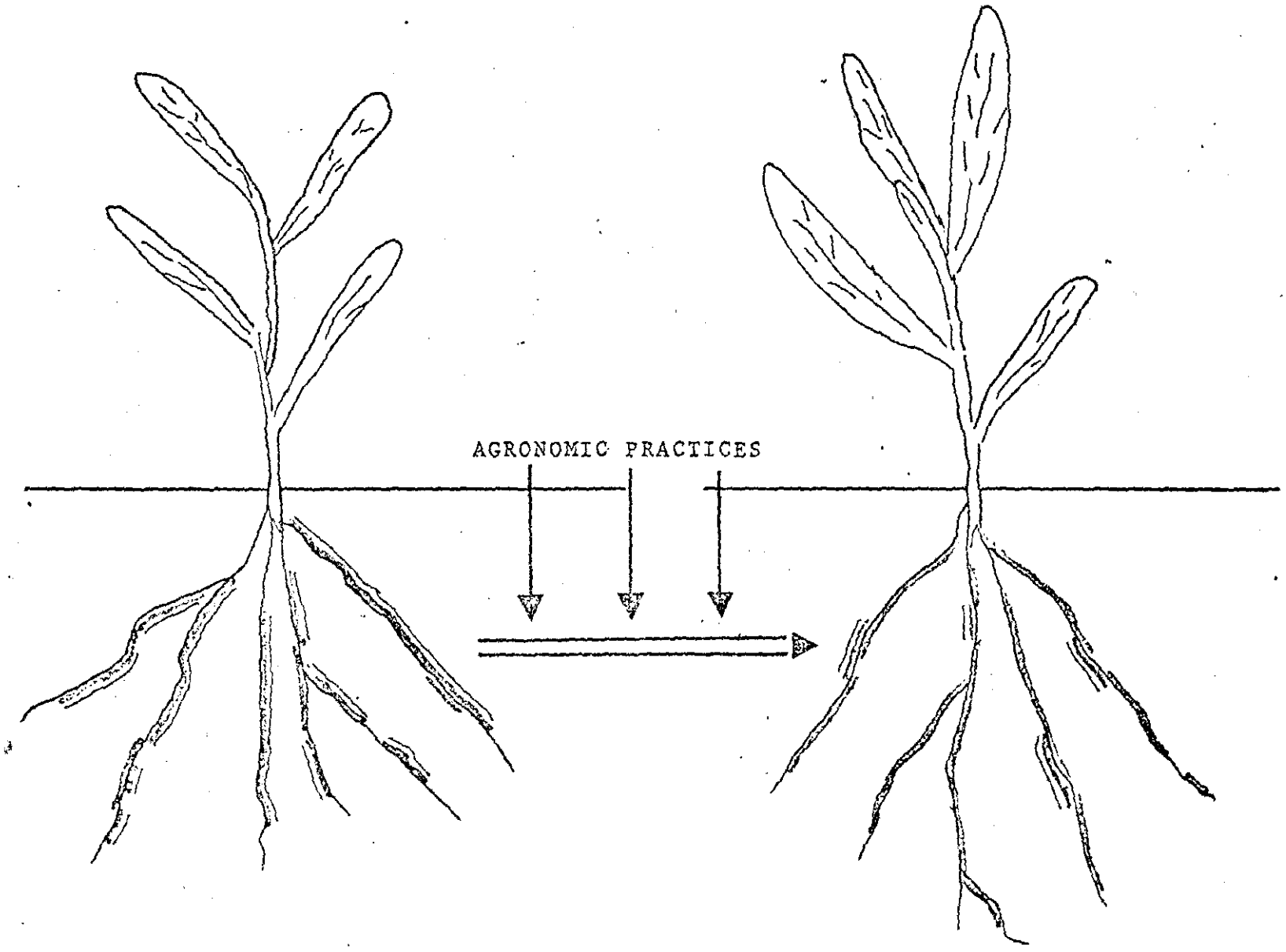
VII. Annex

Content:

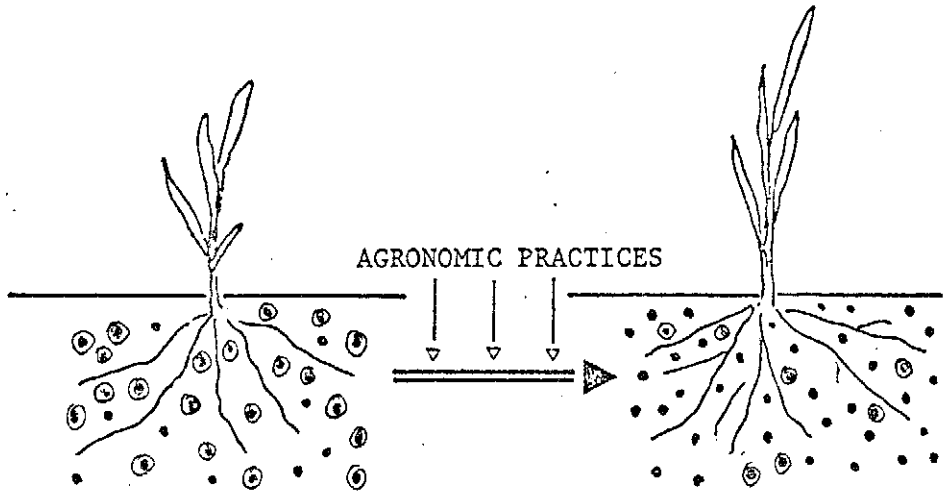
A. Some additional information for managing the mycorrhizal activity by agricultural practices

B. Some additional information for managing the mycorrhizal activity by inoculation.

A. Management of mycorrhizal fungi by agricultural practices



Change of mycorrhizal root infection by agricultural practices



Change of mycorrhizal population by agricultural practices

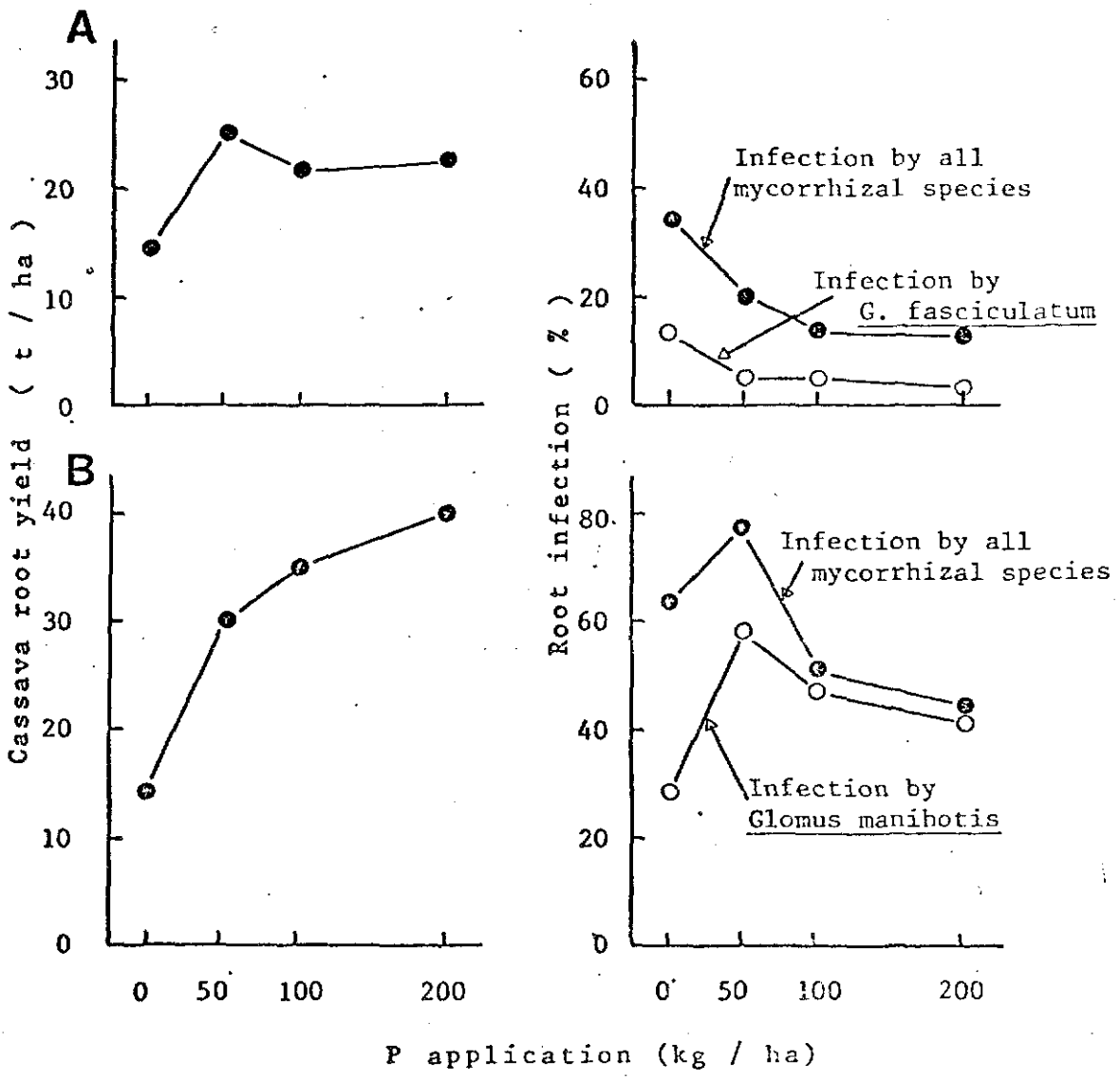


Figure Effect of P application levels on root yields and mycorrhizal root infection of cassava cv. MCol 113 at A. Agua Blanca, and B. CIAT Quilichao (Source: Sieverding, 1982)

Table . Effect of phosphorus fertilization on the percentage root length mycorrhizal in two grass-legume associations in an Oxisol of Carimagua, four years after planting.

P Treatments Kg $P_2O_5 ha^{-1}$	*Andropogon gayanus* + *Pueraria phaseoloides*		*Andropogon gayanus* + *Stylosanthes capitata*	
25	84.65	68.05	87.65	60.20
50	83.50	56.00	79.05	65.80
100	76.05	56.73	77.90	56.41
200	75.71	58.15	75.85	54.68
LSD 0.05	9.86		7.96	
Mean	79.98	59.78	80.11	59.27
LSD 0.05	4.93		3.98	

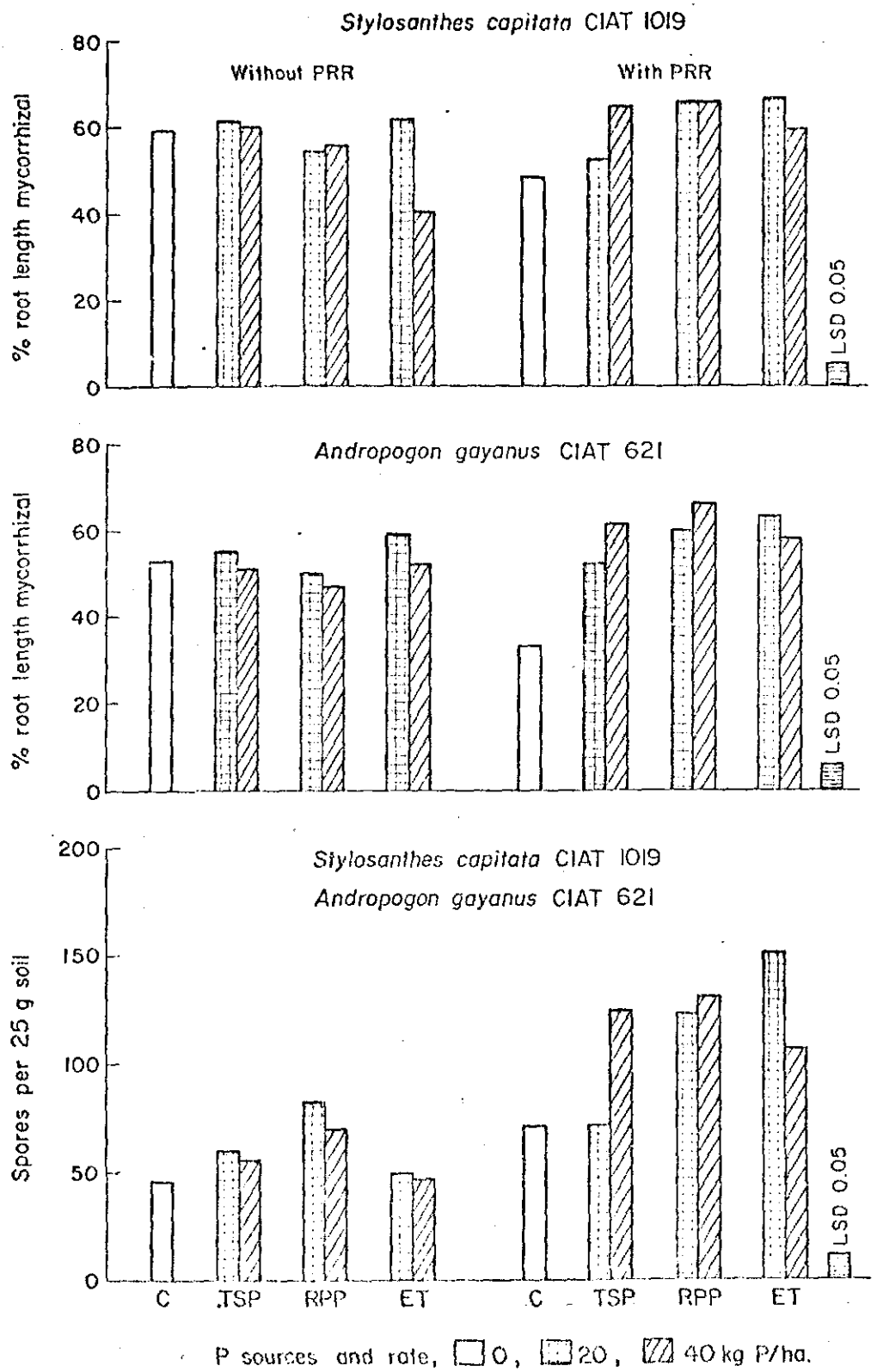


Figure : Effect of different sources of phosphate and plant residue return (PRR) on the native mycorrhizal infection and spore population. C, control; TSP, triple superphosphate; RPP, rock phosphate Pesca; ET, Escorias Thomas.

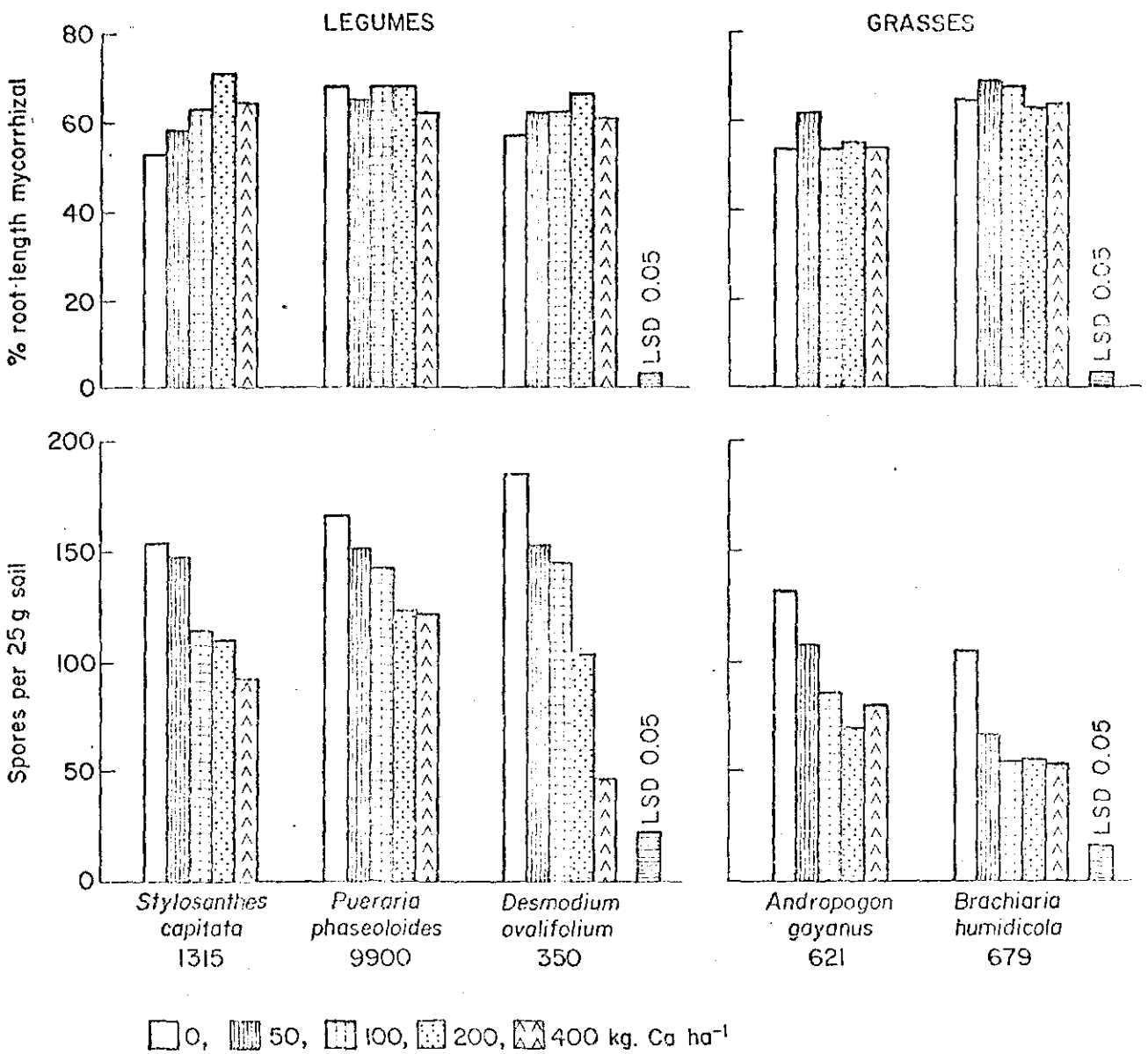


Figure : Effect of Calcium ($CaCO_3$) on the native mycorrhizal infection and spore population in five tropical pasture plants grown in an Oxisol at Carimagua, two years after planting

Effect of liming (1 t / ha) and P application (100 kg P / ha) on mycorrhizal infection of cassava in Mondomo area, Cauca (means of 9 soil sites)

P source	Total infection (%)		Infection (%) by vesicles	
	- lime	+ lime	- lime	+ lime
without P	48.6 (44%)*	42.4 (45%)	3.5 (137%)	2.5 (144%)
TSP	68.4 (33%)	72.7 (30%)	29.3 (87%)	31.4 (67%)
HRP	65.5 (33%)	73.9 (23%)	26.6 (73%)	34.0 (77%)

*Coefficient of variance

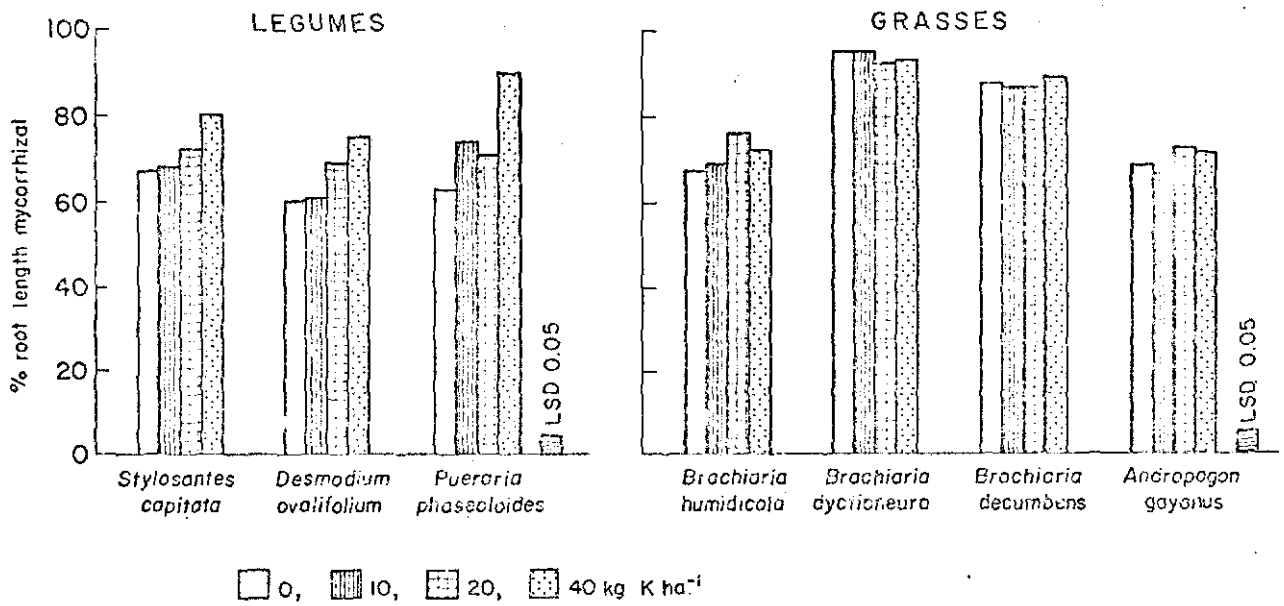


Figure : Effect of potassium fertilization on the native mycorrhizal infection in seven tropical pasture plants grown in an Oxisol at Carimagua, four months after planting.

Table . Effect of NPK fertilization on the mycorrhizal infection and spore population of Endogonaceae in three tropical pasture plants in an Oxisol of Carimagua, two years after planting.

Level of fertilization* kg ha^{-1}	Species		
	Stylosanthes capitata 1315	Pueraria phaseoloides 9900	Desmodium ovalifolium 350
	a) % root length mycorrhizal		
A	79.31	72.72	72.03
B	77.84	69.40	72.67
C	73.39	76.35	74.08
LSD 0.05	not significant		
	b) Spores per 25 g soil		
A	128.0	160.0	179.0
B	123.0	158.0	168.0
C	106.0	140.0	150.0
LSD 0.05	----------	26.7	----------
Mean	119.7	152.7	165.7
LSD 0.05	----------	15.4	----------

* A, N=50, P=11, K=21; B, N=100, P=22, K=42; C, N=100, P=33, K=62 kg ha^{-1}

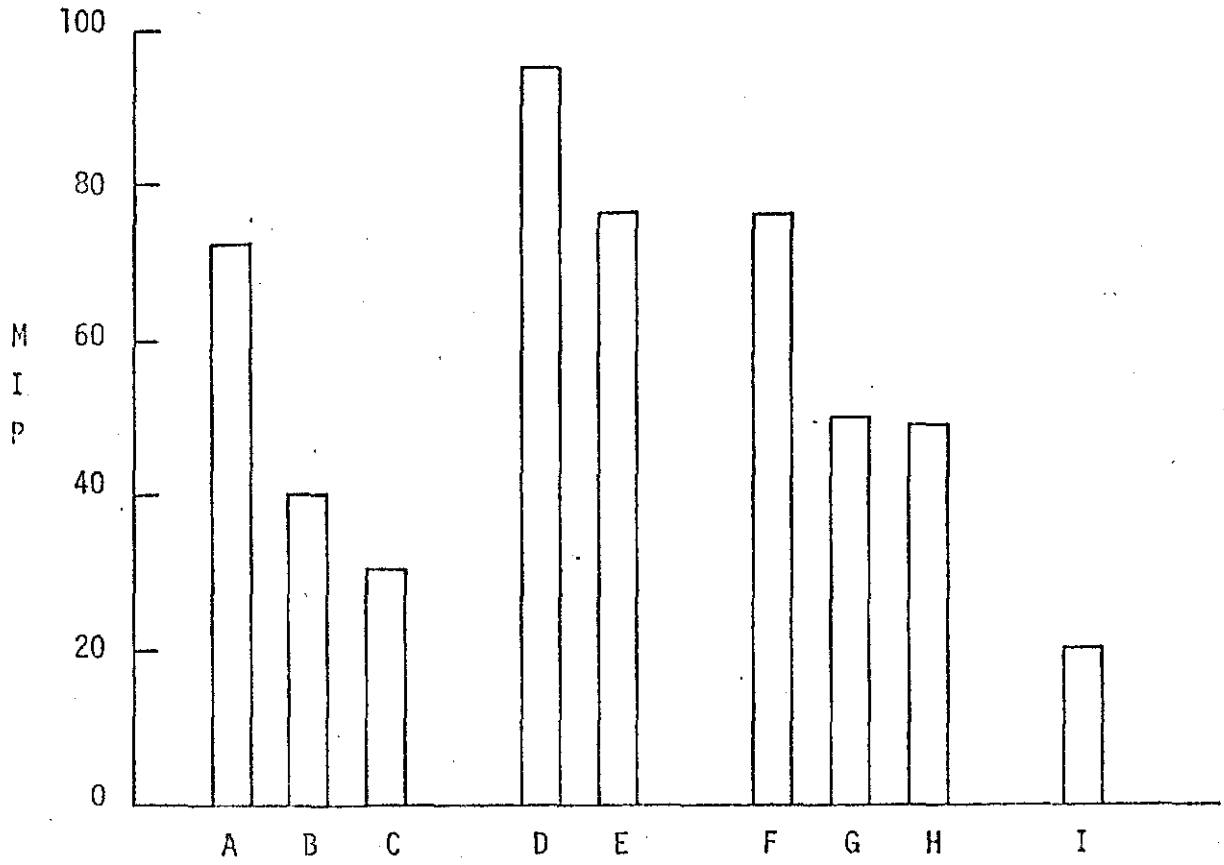


Figure . Effect of vegetation cover on VA mycorrhiza inoculum Potential (MIP) of an oxisol (0-10 cm depth) as measured by P. phaseoloides bioassay at 4 weeks after Planting. A, S. capitata; B, P. phaseoloides; C, D. ovalifolium; D, A. gayanus and P. phaseoloides; E, B. humidicola and D. ovalifolium; F, A. gayanus; G, B. humidicola; H, B. decumbens; I, native savanna.

Influence of different mycorrhizal species on shoot dry matter production of cassava associated with kudzu grown in the same pot (means of 10 replications)

Mycorrhizal species	Shoot production (g / pot)		Relation Cassava: Kudzu
	Cassava	Kudzu	
Glomus manihotis	15.1	10.0	1.5
Glomus occultum	14.0	7.7	1.8
Entrophospora colombiana	10.2	13.4	0.8

Interaction between total fresh yield response of different cassava cultivars to the application of 44 kg P / ha and the root infection by indigenous mycorrhizal fungi at CIAT Quilichao (Source: Sieverding, unpublished)

Mycorrhizal infection (%)								
Decreased			No alteration			Increased		
Total yield response			Total yield response			Total yield response		
Small	Moderate	High	Small	Moderate	High	Small	Moderate	High
MCol 22	MCol 660		MCol 131	MCol 642	MCol 113	MVen 217	MCol 88	MCol 247
MCol 700	MCol 707		MCol 258	MCol 659	MCol 635		MCol 1421	MCol 1226
CMC 40	MCol 1684		MCol 1879	MMex 23	MCol 647		MPan 114	MVen 183
	MVen 83		MVen 270	MMex 59			MVen 246	MVen 287
			ICA-HMC-2				CM 309-41	
							CM 323-64	

Table The percentage of root length mycorrhizal and number of nodules/plant of 22 accessions of pasture plants grown for 15 week in the Reserva at Carimagua.

Species	Ecotype	Percentage root length mycorrhizal	No. of nodules per plant Mean of 15 plants
LEGUMES			
Centrosema macrocarpum	5065	50 ± 5	1
C. brasilianum	5234	64 ± 9	4 ± 3
C. brasilianum	5247	64 ± 8	6 ± 6
C. brasilianum	5236	65 ± 10	4 ± 3
C. brasilianum	5190	43 ± 5	15 ± 8
C. pubescens	5189	43 ± 3	5 ± 3
Desmodium ovalifolium	350	56 ± 3	21 ± 18
D. ovalifolium	350A	56 ± 3	18 ± 18
D. ovalifolium	3784	49 ± 5	15 ± 11
Pueraria phaseoloides	9900	67 ± 10	6 ± 4
Stylosanthes capitata	1019	85 ± 4	6 ± 4
S. capitata	1315	71 ± 7	10 ± 6
S. capitata	1693	71 ± 7	6 ± 6
S. guianensis	1020	84 ± 3	6 ± 4
S. leiocarpa	1087	62 ± 6	8 ± 5
S. macrocephala	1643	64 ± 4	6 ± 4
S. macrocephala	2133	72 ± 7	8 ± 4
Zornia sp.	7847	73 ± 5	40 ± 4
Zornia sp.	9199	52 ± 5	26 ± 15
GRASSES			
Brachiaria dictyoneura	6133	67 ± 4	
B. humidicola	679	50 ± 5	
B. decumbens	606	51 ± 4	

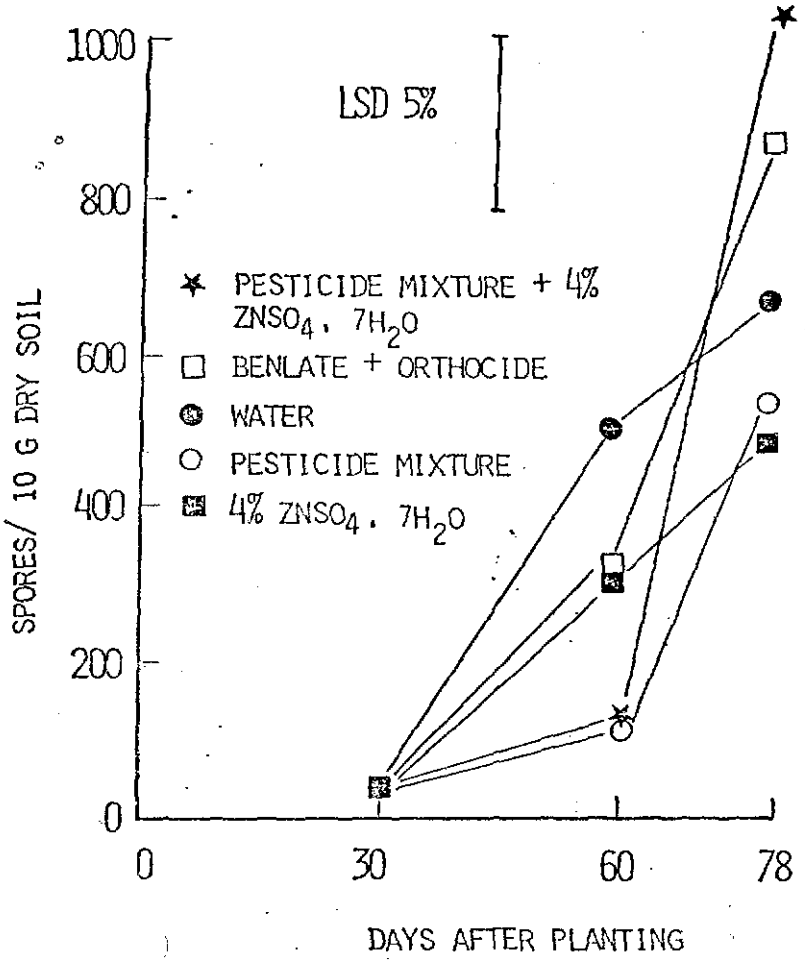


FIGURE MYCORRHIZAL SPORE PRODUCTION OF *Glomus* sp. (STRAIN C-1) WITH CASSAVA CV. M COL 113. STAKES OF CASSAVA WERE TREATED AS GIVEN IN FIG. 6.

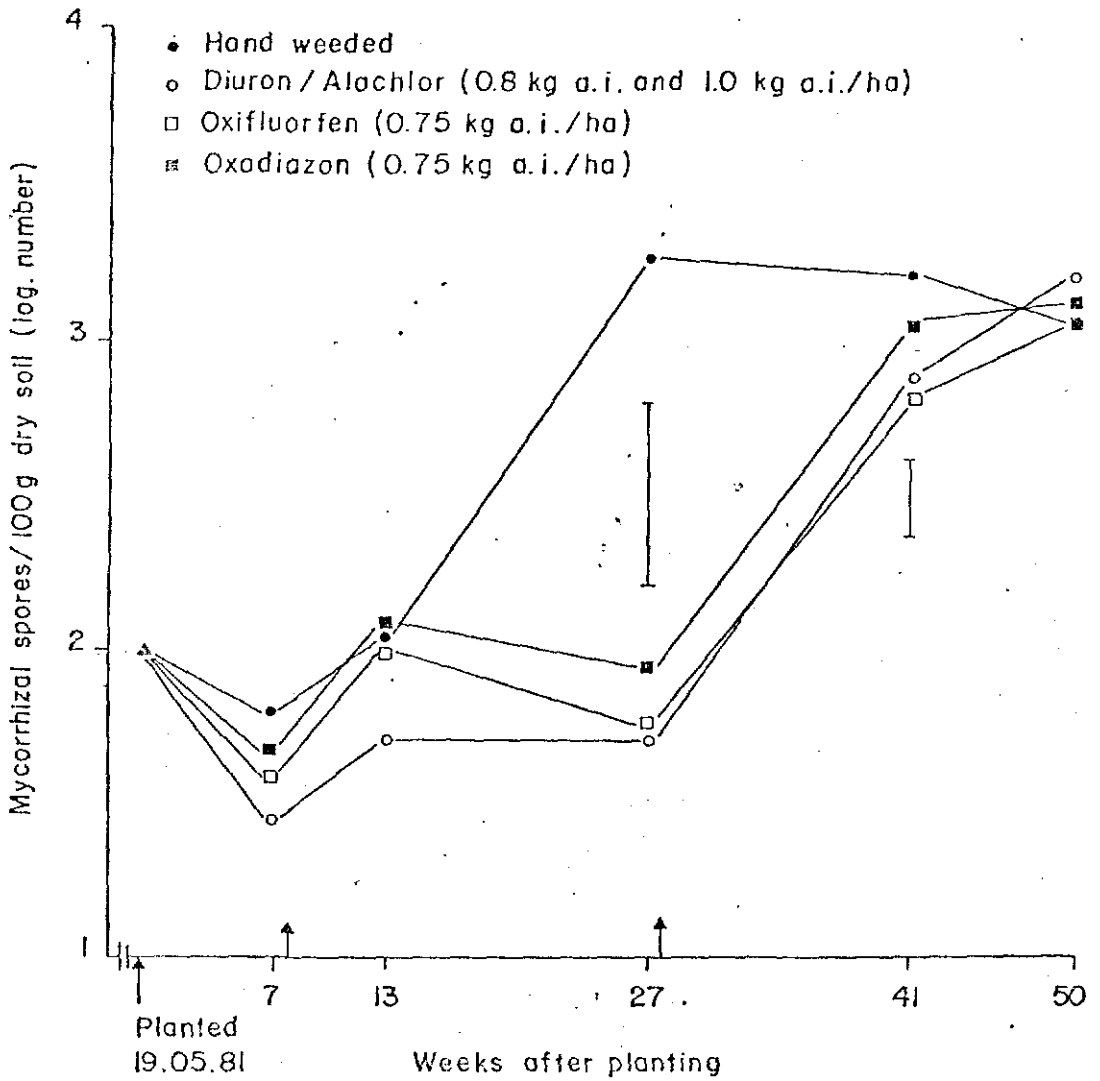
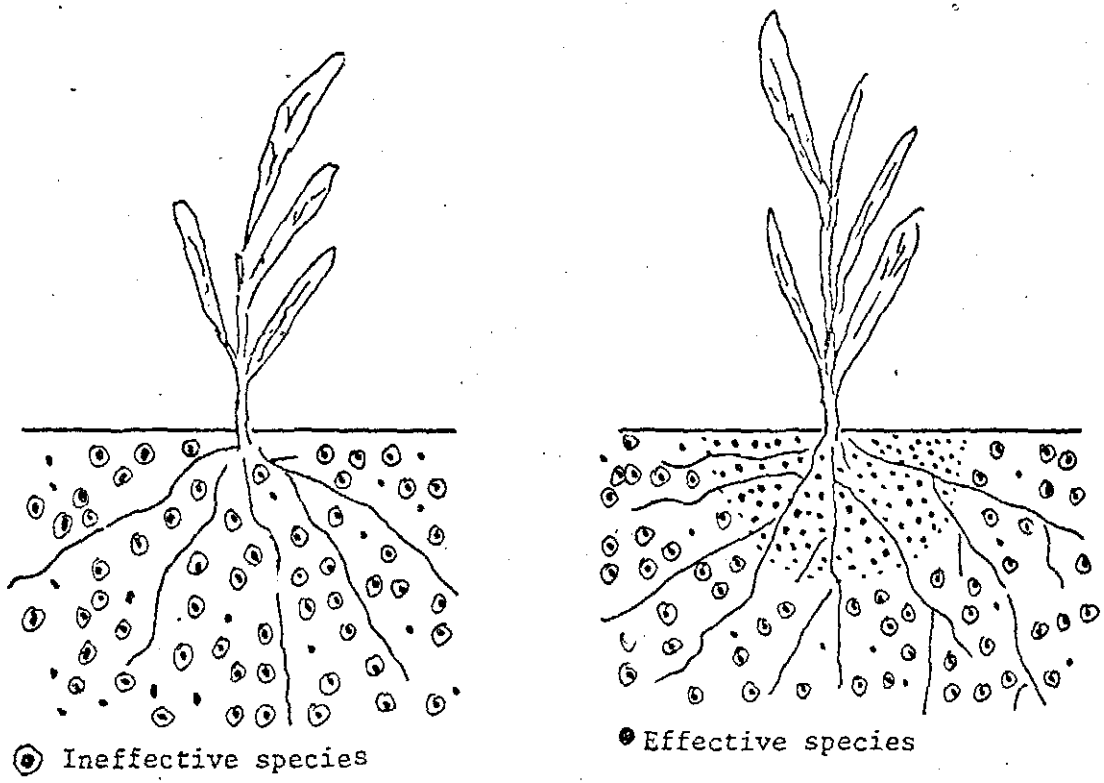


Figure Effect of hand weeding and herbicides on native mycorrhizal production in a cassava field with cv. MCol 638 at CIAT-Quilichao. (Bars indicate LSD 5%. Arrows indicate dates of hand weeding for checks without herbicide application).

B. Management of mycorrhizal activity by inoculation



Change of mycorrhizal species composition by INOCULATION

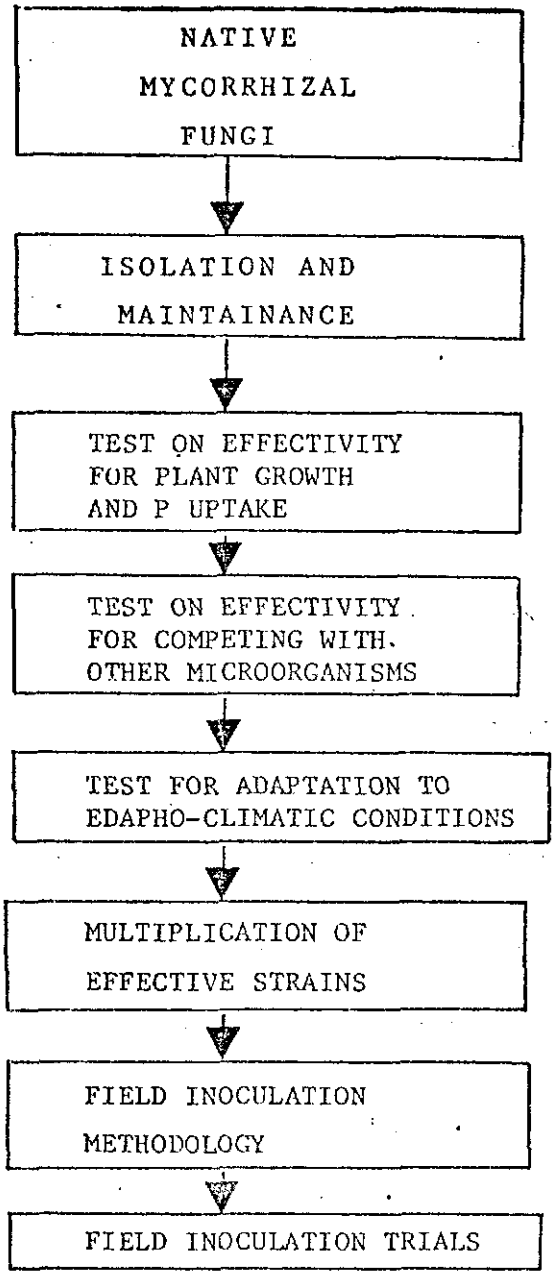


Figure : Flowdiagram of selecting mycorrhizal strains for field inoculation

Table : Total dry weight (g / pot) and P uptake (mg / pot) of eight forrage plants grown in an unsterilized Oxisol without and with additional mycorrhizal inoculation (Greenhouse trial, Source: Saif, unpublished)

Plant species	Dry weight		P uptake	
	Not inoc.	Inoc.	Not inoc.	Inoc.
Stylosanthes capitata 1315	2.00	4.18	0.71	1.38
Zornia sp. 7847	4.47	8.35	1.52	2.64
Pueraria phaseoloides 9900	4.75	6.45	1.78	3.11
Desmodium ovalifolium 3780	3.12	5.26	1.74	1.97
Centrosema macrocarpum 5065	3.04	4.91	0.98	2.01
Brachiaria humidicola 679	9.70	12.14	2.06	4.36
Brachiaria dictyneuora 6133	8.50	11.62	1.47	3.04
Andropogon gayanus 621	3.26	5.15	0.63	1.65

All values for inoculated and non-inoculated plants are significantly different $P < 0.01$

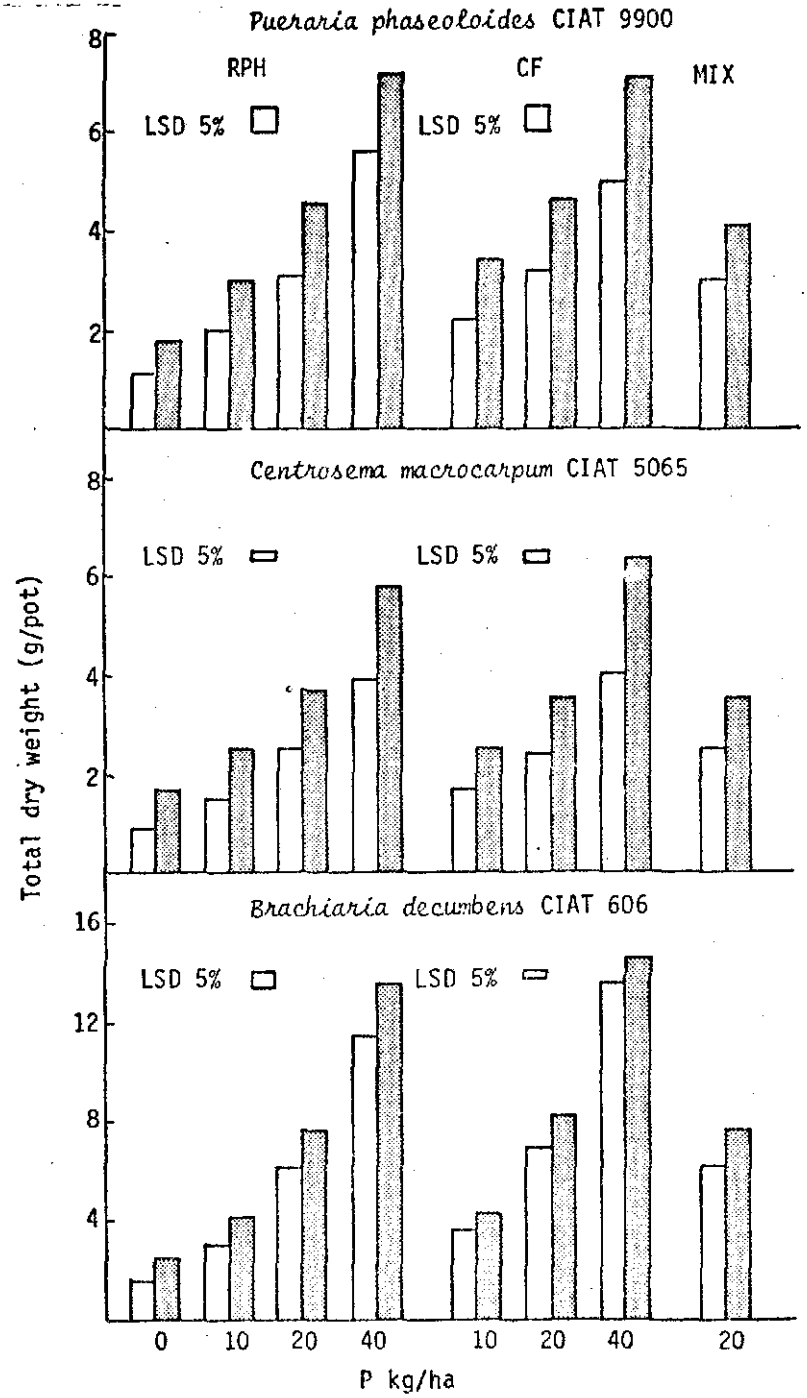


Figure . Total dry weight (g/pot) of *Pueraria*, *Centrosema* and *Brachiaria* grown in unsterilized Oxisol in pots. RPH, rock phosphate Huila: CF, calfos; MIX, 1:1 RPH and CF. ☐ ,non-inoculated; ▭ , inoculated with mycorrhiza.

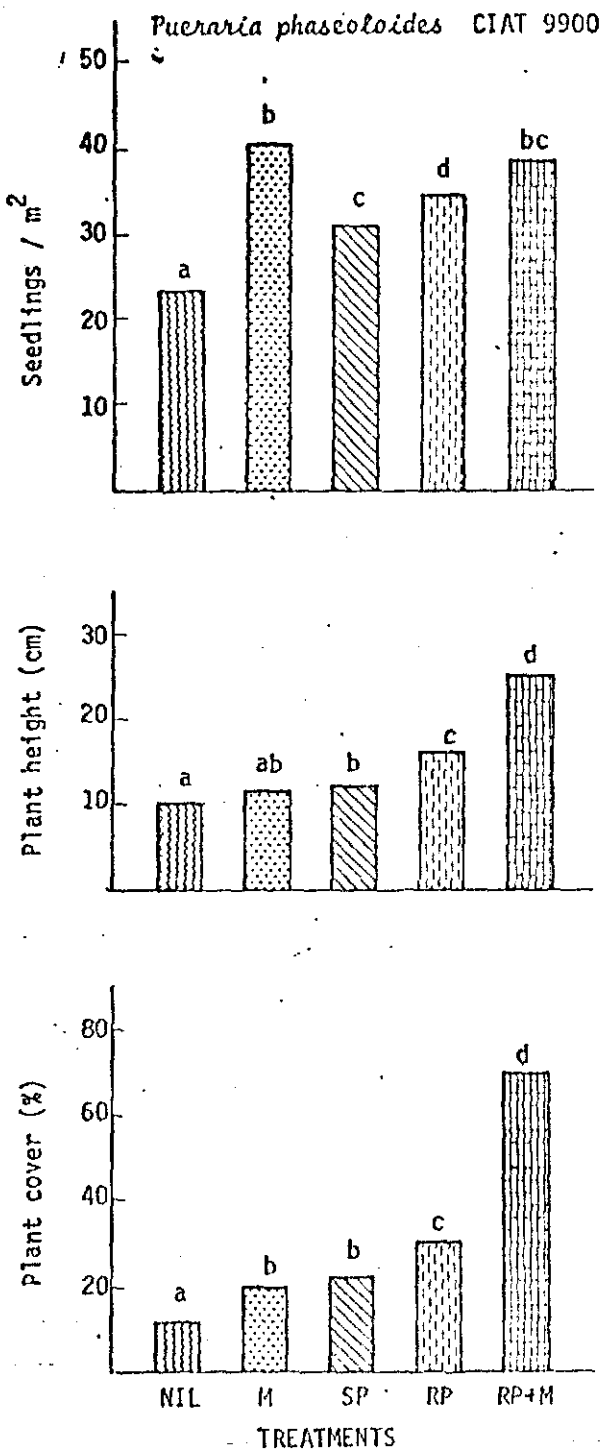


Figure : Number of seedlings established, plant height (cm) and plant cover of *P. phascoloides* CIAT 9900, 10 weeks after sowing. NIL, 0 P; M, inoculated with mycorrhiza (0 P), SP, soluble phosphate, RP, rock phosphate Huila and RP+M, rock phosphate plus inoculation with mycorrhiza. P rate 20 kg/ha. Different letters represent significant differences.

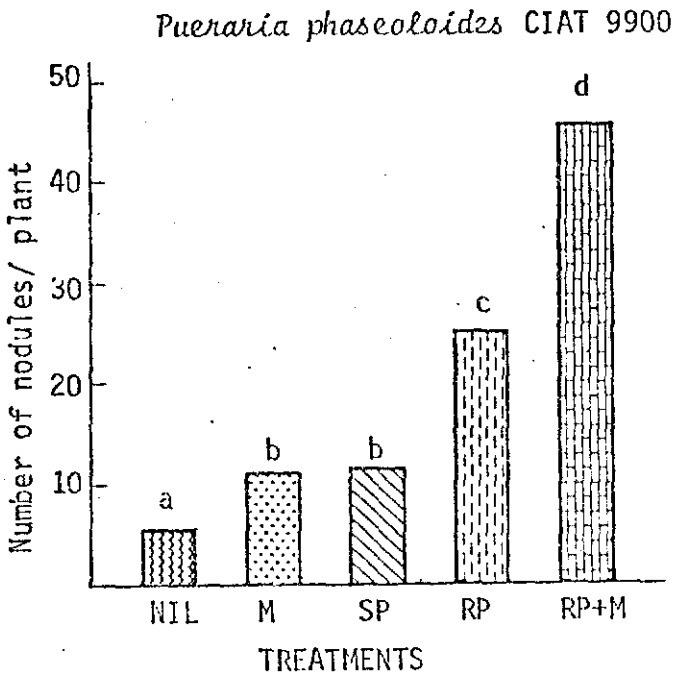
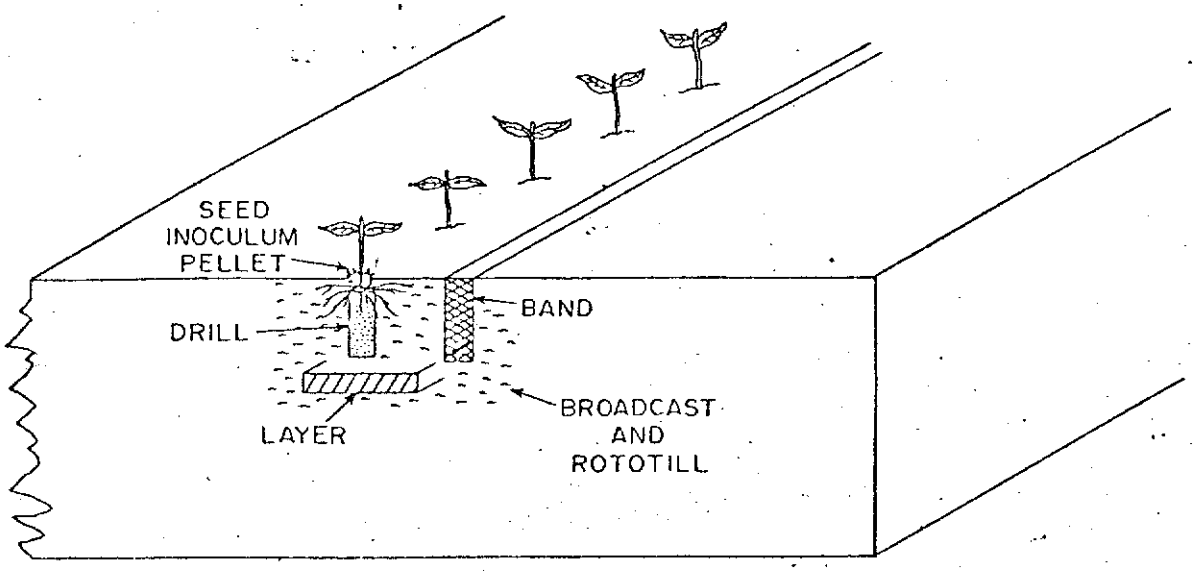


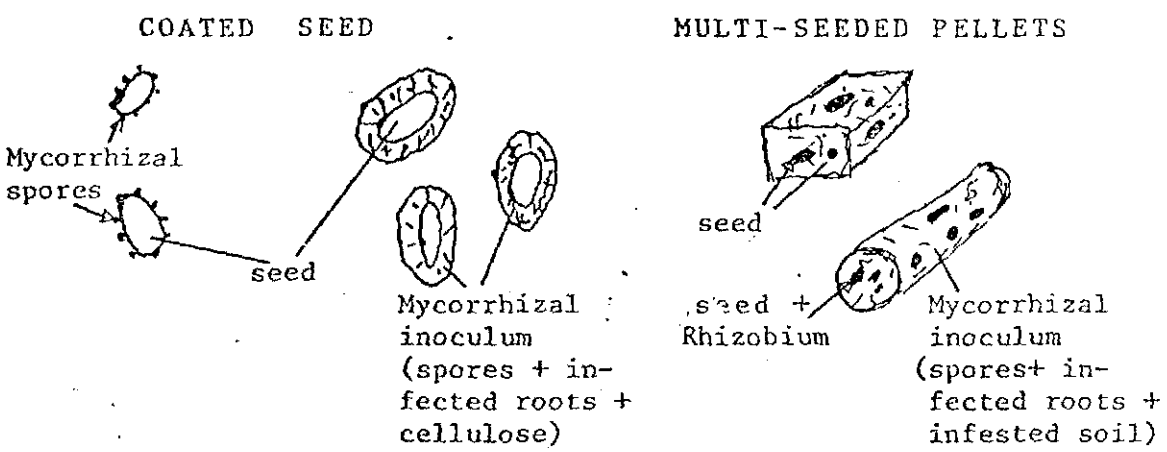
Figure : Number of nodules/plant of P. *phaéoloides* grown in unsterilized Oxisol under field conditions for 3 months. For explanation see Figure .

YIELD INCREASE (%) DUE TO FIELD INOCULATION

Species	P application (kg / ha)	
	0	20
Stylosanthes capitata	67 %	100 %
Pueraria phaseoloides	100 %	72 %
Andropogon gayanus	35 %	35 %

FIELD INOCULATION METHODS



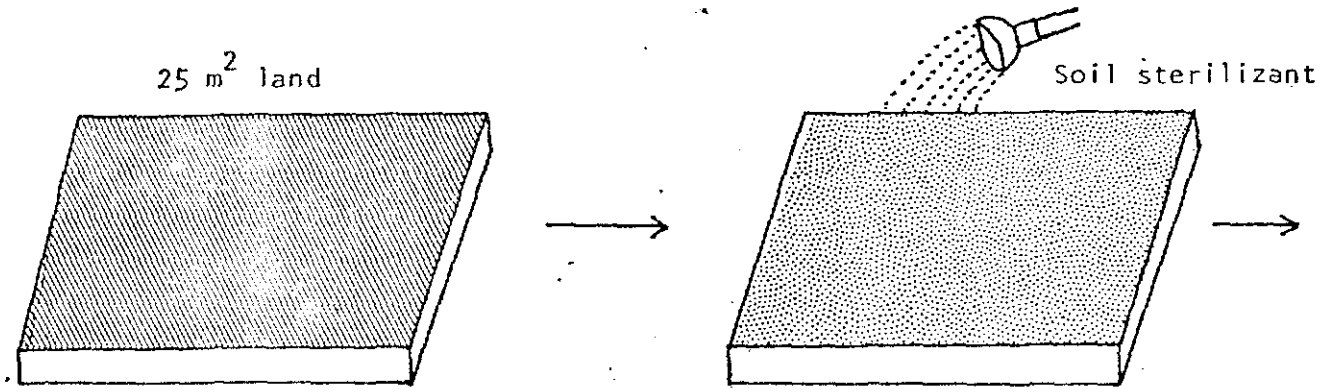

COATED SEED
MULTI-SEEDED PELLETS
Mycorrhizal spores
seed
Mycorrhizal inoculum (spores + infected roots + cellulose)
seed
seed + Rhizobium
Mycorrhizal inoculum (spores+ infected roots + infested soil)

INOCULUM SOURCE	PROBABLE PRODUCERS OF INOCULUM.	
	Inoculum industry	Farmer*
Spores	YES	NO
Multi-seeded soil pellets	YES	NO
Infected roots	YES	YES
Infected substrate	YES	YES
Starter inoculum for farmers	YES	NO

* After obtaining starter inoculum and technical know-how

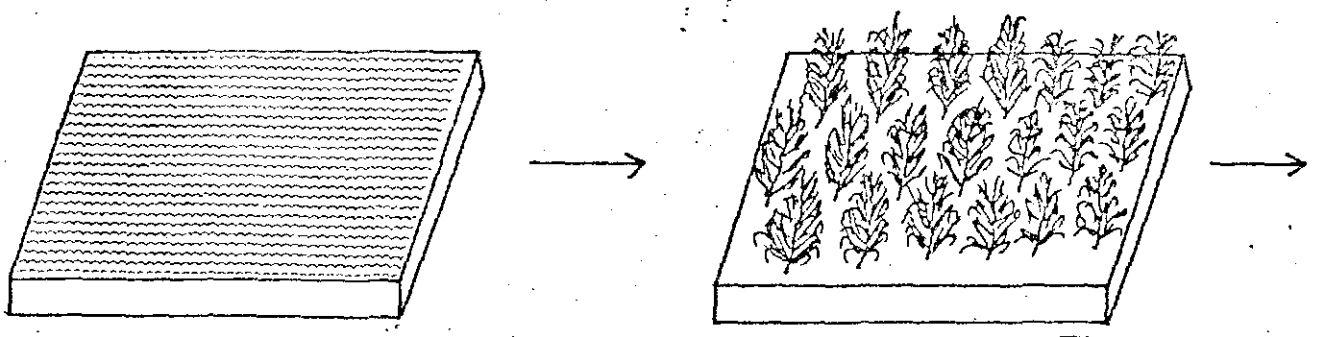
HOW TO PRODUCE 5 T INOCULUM ON-FARM

(THEORATICAL MODEL)



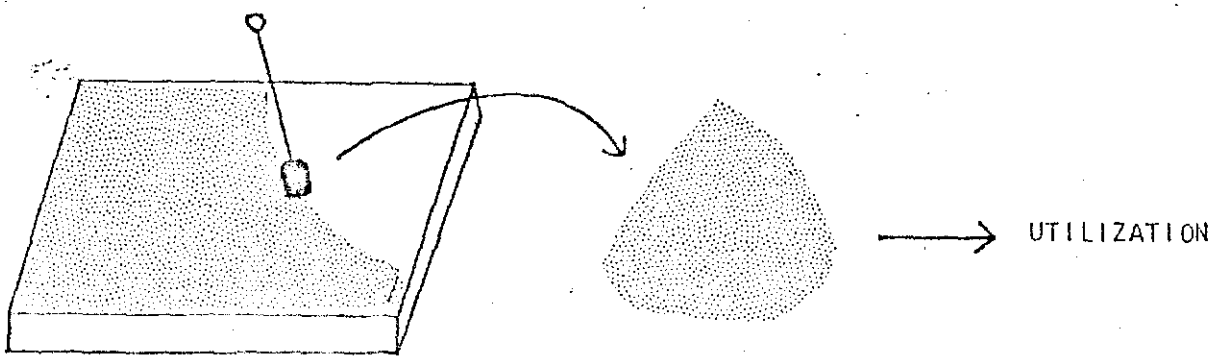
Preparation

Application & incorporation



Incorporation of starter inoculum (2.5 kg) after 2-3 weeks and planting

Maintaining for 4-6 months application of proper agro-chemicals



Harvesting

Homogenization

Total cash input = 1000,- Pesos