The Effect of Soil Sterilization and Mycorrhizal Inoculation on the Growth, Nutrient Uptake and Critical Phosphorus Concentration of Cassava

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Abstract

Rooted cassava cuttings, either inoculated or non-inoculated with mycorrhiza, were grown both in a methyl bromide sterilized and unsterilized oxisol which had received eight levels of phosphorus (0-16 t/ha). Without P all plants were extremely P deficient, irrespective of the mycorrhizal treatments. However, at 0.5, 1 and 2 t/ha P, inoculation significantly increased plant growth and dry matter production, especially in the sterilized soil. Non-inoculated plants grown in the sterilized soil remained extremely P deficient even with 2 t/ha P, due to the absence of an effective mycorrhizal association.

In the sterilized soil, inoculation increased dry matter production nearly three-fold and total P-uptake seven-fold at 2 t/ha. In the unsterilized soil, inoculation increased both dry matter production and total P uptake by about 50% at 0.5 t/ha of P. At P application rates of 4 and 8 t/ha, dry matter yields were not significantly affected by treatments, while at 16 t/ha, yields of plants grown in the sterilized soil were depressed.

Mycorrhizal infection of cassava roots, either from indigenous or introduced strains, resulted in a marked increase in the concentrations of P, Ca, Mg, and K in the youngest fully expanded leaves, and in the total plant uptake of these nutrients. The mycorrhizal treatments also affected the critical P concentration in the index tissue, which varied from 0.28% in the sterilized to 0.40% in the unsterilized soil.

The mycorrhizal association was effective in increasing dry matter yield at intermediate P application rates (0.5-2.0 t/ha). Soil solution P concentrations corresponding to these rates ranged from 2 to 52 μM. Under conditions of sub-optimal P supply, the ineffectiveness of the very coarse root system of cassava in P absorption appears to be overcome by mycorrhizal associations.

Introduction

Cassava (*Manihot esculenta* Crantz) has the reputation of producing reasonably well on soils that are too poor to be used for many other crops (Cock and Howeler, 1978). Cassava is also considered a scavenger plant, to be grown as the last crop in a rotation before returning the nutrient-depleted plot back into bush fallow in the slash-and-burn agriculture system still practised in much of the humid tropics (Ofori, 1973). Since it can apparently extract nutrients from very infertile soils, it has often been argued that cassava must have an extremely efficient root system.

Several characterstics contribute to the efficiency of plants in nutrient extract-

ion from soils. A very extensive and deep root system may enable them to explore a larger volume of soil, a fine root system with a large surface area may allow a given volume of soil to be explored more intensively, and differences in physiological absorption capacity per unit of root surface may also have important effects.

Little information is available about extension and distribution of roots of cassava. Campos and Sena (1974) found that cassava roots extended to a depth of 140 cm in an acid oxisol in Bahia, Brazil, but that 96% were present in the top 30 cm. Using a radioactive tracer technique, Ofori (1970) also found that most of the actively absorbing root system of cassava was very superficial and mainly present in the top 10 cm of soil.

Although no measurements have been reported on the length and diameter of cassava roots, simple observation and comparison with root systems of other crops indicate that cassava has a very coarse root system, with relatively thick (mostly 0.25-1 mm in diameter) and poorly branched roots. Microscopic observation also indicates that root hairs are present but not abundant. In plants grown in nutrient solution, they are essentially absent. No data is available on the plant's absorption capacity per unit of root surface.

Recent research in flowing culture units at the University of Queensland determined the effect of various concentrations of NO_3 and NH_4-N, P, K and Ca on growth and efficiency of nutrient uptake of cassava and several other crops. Cassava was found to have a lower uptake rate of P (Jintakanon *et al.* 1979), K (Spear *et al.* 1978) and N (Forno, 1977) than most other crops studied. Edwards *et al.* (1977) also reported that cassava has an external requirement for NH_4, K and Ca very similar to that of other crops studied, but that its external P requirement was higher than that of any other crop with the possible exception of potato. Jintakanon *et al.* (1979) reported that eleven cassava cultivars required for 95% of maximum growth a P concentration in nutrient solution ranging from 28 to 78 μM, while maize, cotton and soybean required only 1.0, 0.6 and 0.6 μM, respectively. Although cassava may have a mechanism for adapting to low fertility conditions, e.g., through a reduced growth rate, a high efficiency of nutrient utilization in dry matter production, a low nutrient gradient within the plant, and a large root-to-top ratio (Edwards *et al.* 1977, Spear *et al.* 1978), it does not appear to be an especially efficient absorber of nutrients, at least when grown in nutrient solutions.

When grown in a P deficient soil to which various amounts of P were added, cassava attained 95% of maximum yield at the same soil-solution P concentration (c 2.5 μM P) as maize, and soybean, indicating that the growth of cassava under natural soil conditions was relatively much better than in nutrient solution (S. Jintakanon, pers. comm.). However, the shape of these yield response curves was affected by the development of Mg deficiency in cassava at the higher P rates. The apparently different behavior of cassava in soil and in nutrient solution suggested that the absorption of P from the soil might involve mycorrhizal associations.

Most natural soils contain spores of indigenous mycorrhiza. Thus, Abbott and Robson (1977a) found spores of vesicular-arbuscular (VA) mycorrhiza in 99 out of 104 Australian soil samples examined. When activated by root exudates mycorrhiza will infect the root system and form arbuscules and vesicles inside the cells of the root cortex (Hepper and Mosse, 1975). From these, hyphae proliferate through the intercellular spaces to the outside of the root and into the surrounding soil. Because of their larger surface area, hyphae can explore the soil more effectively than roots, and the P absorbed is rapidly translocated through the hyphae to the vesicles or arbuscules, which release part of the P to the root. Thus, P uptake by soil-grown cassava might have been enhanced by infection of the root system by indigenous mycorrhiza, while the plants grown in the nutrient solution used by Jintakanon *et al.* (1979) were most likely non-

mycorrhizal. Mycorrhizal infection of roots of field-grown cassava has been found in work at IITA (IITA 1976). More recently Potty (1978) reported mycorrhizal infection of the roots of cassava, sweet potato and edible *Coleus*.

The objective of the work reported here, was to determine the effect of indigenous and introduced mycorrhiza on the growth and nutrient uptake of cassava grown in a soil with various soil solution P concentrations.

Materials and Methods

A P-deficient Oxisol (krasnozem) from Maleny, Queensland, having a pH of 5.0, and with 26 ppm bicarbonate-extractable-P was fertilized with 200 kg N/ha as NH_4NO_3, 100 kg Mg/ha as $MgSO_4.7H_2O$, 200 kg K/ha as K_2SO_4 and 20 kg Zn/ha as $ZnSO_4.7H_2O$. Eight P-treatments were established by addition of $Ca(H_2PO_4)_2.H_2O$ at rates equivalent to 0, 0.1, 0.5, 1, 2, 4, 8 and 16 t/ha of P. After 7 weeks of incubation at field capacity, the soil of each P treatment was thoroughly mixed and 5 kg of moist soil (3 kg air-dry soil) was placed in each of 14 pots. Half of the pots from each P treatment were sterilized with methyl bromide for three days, and then left uncovered for two weeks. Of the seven sterilized and seven unsterilized pots of each P treatment, one of each was used for determination of P concentration in soil solution, while the remaining 6 pots were planted with inoculated or non-inoculated cassava plants.

Two and a half weeks before transplanting to the soil, tip cuttings of cassava cv M Aus 10 were planted in small peat pots containing coarse sand, which were placed in two misting chambers, as described by Forno *et al.* (1976). One week later, when roots had just emerged from the callus, each cutting in one chamber only was inoculated by placing 2-3 g of fresh mycorrhiza-infected cassava roots under the cutting in the peat pot; the same amount of dead inoculum (autoclaved mycorrhizal roots) was placed under the cuttings in the other chamber for the non-inoculated treatment. Ten days after inoculation roots had grown through the peat pot and into the surrounding black plastic beads. After hardening, plants were transplanted to the experimental pots by carefully burying in the surface soil the peat pot containing the rooted cassava cutting. Thus, 32 treatments were established with 3 replications: 8 P levels in sterilized and unsterilized soil, each with inoculated or non-inoculated plants.

Plants were watered to field capacity once or twice a day by weighing. Two months after transfer to the soil, plants were harvested. Youngest fully expanded leaf (YFEL) blades were kept separate from the remaining top, and roots were carefully washed out of the soil and separated into fibrous roots and tuberous roots. These plant parts were dried at 70°C, weighed, ground in a Wiley mill, and 0.3 g of plant material digested in HNO_3 and $HClO_4$ and analyzed for P, Ca, Mg, K and Zn.

One month after planting a sample of soil solution was extracted from sterilized and unsterilized soil at each P treatment, using the centrifugation method described by Gillman (1976). Each sample was analyzed for P by the method of Truog and Meyer (1929), or, for very low P concentrations, by the method of Jintakanon *et al.* (1975).

At harvest, three soil cores were taken from each pot, the non-tuberous roots were carefully washed out and stored in alcohol. They were stained with trypan-blue according to the method of Phillips and Hayman (1970) as adapted by Jehne (pers. comm.). The percent infection was determined by counting the number of infected roots in 4-5 transects of 25 randomly selected stained roots from one replication.

Results and Discussion

At the time of transfer of cassava plants to the P-treated soil, the non-inoculated cuttings were more vigorous and had longer roots than the inoculated plants, possibly due to better growing conditions in their mist chamber. After two weeks these differences had disappeared and plants started to show a response to applied P. In the sterilized soil, especially at low P levels, plants started to lag behind those in the unsterilized soil. At 4-5 weeks, a positive response to inoculation appeared and at 6 weeks the inoculated plants were markedly and consistently more vigorous than the non-inoculated plants, except at the very low and very high P treatments. In the sterilized soil, the non-inoculated plants at 1 t/ha of applied P and below showed symptoms of extreme P deficiency - yellow, droopy bottom leaves and small upper leaves folded inwards and hanging in a vertical position. Above 1 t/ha P plants were more vigorous, and reached maximum plant height at 8 t/ha P. At 16 t/ha applied P, plants in the sterilized soil suffered from what appeared to be salinity. The soil had a white saline crust and the conductivity of the saturation extract was 1.35 mmho/cm in the sterilized soil. The bottom leaves of the plants became chlorotic and necrotic and later fell off. In the unsterilized soil the conductivity at this P level was 0.62 mmho/cm and these symptoms did not appear. Yost and Fox (1978) found no effect of methyl bromide sterilization on available P, but observed a slight increase in NH_4 and NO_3-N, which was also reported by Rovira (1976) and Lopes and Wollum (1976). High inorganic N levels in combination with extremely high P applications may have resulted in the development of saline conditions.

Figure 1 shows the P concentration in soil solution (at field capacity) in the sterilized and unsterilized soils as a function of applied P. The P concentrations in solution increased from about 1 to 727 μM with the application of 16 t/ha of P in the unsterilized soil, while sterilization increased the P concentration in the soil solution on the average by about 15%.

Figure 2 shows the effect of P application, soil sterilization and mycorrhizal inoculation on the total dry matter yield of 2-month old plants. In the unsterilized soil, plants responded positively to each increment of applied P up to 8 t/ha, above which dry matter yields remained constant. Inoculation had a beneficial effect only at the intermediate P rates of 0.5, 1 and 2 t/ha. In the sterilized soil, non-inoculated plants did not respond to applied P until the rate of application exceeded 1 t/ha. Dry matter yield then increased rapidly with increasing rates of applied P up to 8 t/ha. At 16 t/ha dry matter yields were suppressed by soil salinity.

In the sterilized soil the inoculated plants remained extremely P deficient at 0 and 0.1 t/ha, but above this level plants responded to increasing amounts of applied P up to 8 t/ha. Dry matter yields were markedly better than in the non-inoculated plants up to 4 t/ha applied P, above which there was no effect due to inoculation. At 2 t/ha P, inoculation increased dry matter yield nearly three-fold. Dry matter production of inoculated plants in sterilized soil was not significantly different from those of the non-inoculated plants in unsterilized soil at most P application rates, which seems to indicate that inoculation essentially replaced the mycorrhizal association lost due to sterilization of the soil.

Microscopic examination of the stained root samples showed a heavy mycorrhizal infection with many vesicles and some external hyphae in the inoculated treatments in both the sterilized and unsterilized soils at the intermediate P rates of 0.1 to 8 t/ha for the sterilized soil and 0.5 to 4 t/ha for the unsterilized soil (Table 1). This pattern tends

to agree with the observed plant yield response. By contrast, the non-inoculated plants were essentially free of any mycorrhizal infection. The presence of few vesicles and virtually no visible hyphae on roots of non-inoculated plants grown in the unsterilized soil is surprising in view of the comparatively good growth and P uptake at intermediate P rates in this treatment. This result may be due to indigenous mycorrhiza with other characteristics such as a slower rate of vesicle formation or to other forms of microbial activity in the soil.

Figure 3 shows the effect of P and mycorrhizal treatments on total P uptake. At P application rates up to 1 t/ha in the unsterilized soil, mycorrhizal inoculation increased total P uptake, but at higher P rates there was no beneficial effect of inoculation. Also, at P rates below 1 t/ha the inoculated plants in the sterilized soil had a lower P uptake than those in the unsterilized soil, but at higher rates of application (except at 16 t/ha) inoculation in the sterilized soil resulted in a significantly higher P uptake than that from the unsterilized soil. Sterilization of the soil resulted in a higher infection by the introduced mycorrhizal strains (Table 1) and improved the efficiency of P uptake, especially at the higher P application rates (except at 16 t/ha). Phosphorus uptake by non-inoculated plants in the sterilized soil was very low even with 2 t/ha of applied P; it improved considerably at 4 t/ha, and was even superior to the unsterilized treatments at 8 t/ha P. In the sterilized soil inoculation had the maximum beneficial effect at a P application rate of 2 t/ha where it increased total P uptake more than seven-fold. In the unsterilized soil, inoculation increased total P uptake by a maximum of 50%, this occurring at a P application of 0.5 t/ha.

The concentrations of P, K, Ca, Mg and Zn in the YFEL blades varied with both mycorrhizal and P application treatments (Table 2). Likewise, total plant uptake of P, K, Ca and Mg also varied with these treatments (Table 3). As expected, the P concentration in the YFEL blade increased with P application rate, reaching a maximum of 0.46% P at 16 t/ha in the non-inoculated plants grown in the unsterilized soil. Inoculation of the unsterilized soil resulted in consistently lower P concentrations in the index tissue, although at the intermediate P levels the total P uptake was higher due to a greater dry matter production in the inoculated treatments. A similar effect of inoculation in the unsterilized soil was observed with the other nutrients: a lower concentration in the YFEL blades, but a higher total uptake with intermediate P application rates, and a lower total uptake at the high P rates.

Sterilization of the soil drastically reduced both the concentration in the index tissue and the total plant uptake of P, Ca and Mg in the non-inoculated plants at intermediate P rates. The K concentration in the index tissue was only slightly affected by sterilization, but the total plant uptake of K was markedly reduced at P application rates up to 2 t/ha. Zinc concentrations were also little affected by sterilization. Inoculation of plants grown in sterilized soil increased the concentration of all nutrients in the index tissue as well as their total uptake at intermediate rates of applied P. It may be concluded that the mycorrhizal association had the greatest beneficial effect on the uptake of P, but it also increased the uptake of K, Ca, Mg and Zn. It cannot be ascertained, however, whether this was due to an increased uptake of all these nutrients through the mycorrhizal hyphae, or whether these hyphae essentially improve only the P nutrition of the plant, which in turn results in a more vigorous plant with a more extensive root system and consequently greater absorption of all nutrients. Similar results were found by Van der Zaag *et al.* (1979), who reported that soil sterilization decreased the P concentration of YFEL blades from 0.30 to 0.11% at low P rates, while K and Zn concentrations decreased by 30 and 10%, respectively. However, they found that plant Ca concentrations were actually higher in the sterilized than unsterilized soil,

which is contrary to the results obtained in the present trial.

Figure 4 shows the relationship between total dry matter yield and the P concentration in the YFEL blades. The critical concentration for P deficiency, i.e., the concentration corresponding to 95% of maximum yield, was found to be 0.28% P for non-inoculated plants in the sterilized soil, 0.32% P for inoculated plants regardless of sterilization treatment, and 0.40% P for non-inoculated plants in the unsterilized soil. It is clear that both sterilization and inoculation changed the critical P concentration in the indicator tissue, even though the maximum yield attained was essentially the same in all sterilization and inoculation treatments. In studies on critical K concentration in cassava, Spear *et al.* (1978b) concluded that changes in external K supply with time could affect the critical K concentration in the plant. The observed effects of sterilization and inoculation treatments on critical P concentrations in the present study may possibly result from changes with time in P supply to the plant. It might be argued that if the capacity to absorb P increases with time in mycorrhizal plants infected with either indigenous or introduced strains, then the critical P concentrations would be higher than those of non-mycorrhizal plants like those in the sterilized, non-inoculated treatments. As a consequence, the rate of mycorrhizal infection may affect the critical P concentration in young plants. Work at IITA (IITA, 1976) suggests that the rate of mycorrhizal infection in cassava is slow compared with cowpea, maize and soybean, with 80% infection of cassava by indigenous mycorrhiza achieved only after 90 days.

If the presence of an effective mycorrhizal association significantly alters the critical P concentration in the indicator tissue, this might at least partially explain some of the large discrepancies observed in the critical P concentration determined for the same cultivar grown in non-inoculated nutrient solutions and in the field (CIAT, 1974, p. 92; CIAT 1976, p. 60).

GENERAL DISCUSSION

The results of this experiment suggest that cassava has a very inefficient root system and is highly dependent on the presence of a mycorrhizal association for an adequate uptake of nutrients, especially of P, which largely reaches plant roots by the slow process of diffusion (Barber *et al.* 1963). Van der Zaag *et al.* (1979) also reported a marked reduction in plant growth and in uptake of P, K, S and Zn when the mycorrhizal association of cassava was eliminated by soil sterilization, while Yost and Fox (1979) suggested that cassava and *Stylosanthes hamata* were the two species most dependent on mycorrhizal associations among the seven plant species which they studied.

Several workers (Hayman 1975, Sanders 1975, Daft and Nicolson 1969, Van der Zaag *et al.* 1979, Yost and Fox 1979) have shown that mycorrhizal infections decrease with increasing levels of applied P; conversely, Mosse *et al.* (1976) and Abbott and Robson (1977) reported that in extremely low P soils mycorrhizal associations were not effective in increasing P absorption by plants. Thus, the greatest responses were obtained at intermediate P application rates, as was also shown in the present study. However, little is known about the rate of P concentrations in the soil solution at which roots become effectively mycorrhizal. From the work of Van der Zaag *et al.* (1979) it was concluded that mycorrhizal infection in cassava does not decrease to zero until the P concentration in soil solution exceeds 52 μM as determined by the method of Fox and Kamprath (1970). In the present study, mycorrhizal inoculation was only

effective in increasing dry matter yield in the range from 0.1 to 4 t/ha of applied P. The corresponding soil solution P concentrations ranged from 2 to 52 μM. However, total P uptake was increased by inoculation even at 8 t/ha of P where the soil solution P concentration was approximately 250 μM. In a subsequent experiment at the University of Queensland in which eight cassava cultivars and one cultivar each of maize, rice, cowpea and french bean were grown with and without inoculation with infected cassava roots at four constant P concentrations in flowing nutrient solutions, dry matter yields of all cassava cultivars increased through inoculation only at a P concentration of 1 μM. At 0.1 μM, the solution P concentration was too low for plants to benefit from mycorrhiza. However, root staining showed that inoculated roots were heavily infected and covered with masses of hyphae at both the 0.1 and 1 μM P concentrations. At the two higher concentrations of 10 and 100 μM P, the cassava plants had reached their yield plateau and inoculation had no beneficial effect and did not result in any significant infection, as indicated by the complete absence of vesicles and hyphae from these roots. None of the other four species became infected or showed a yield response to inoculation.

Although the major differences in growth of cassava between the microbiological treatments occurred at rates of P application from 0.5 to 2 t/ha, plants reached 95% of maximum yield in all microbiological treatments and P application rates of about 6 to 7 t/ha. The soil solution P concentrations associated with this level of yield were in the range 95 to 130 μM (Fig. 5). These values are not too greatly different from the solution P concentration of 72 μM found to be necessary for 95% of maximum yield when the same cultivar (M Aus 10) was grown in flowing nutrient solutions (Jintakanon *et al.* 1979). However, the present result is very dissimilar to that of Jintakanon (pers. comm.) who estimated that a soil solution P concentration of 2.5 μM was required for 95% of maximum yield by the cassava cultivars M Aus 7, Seda, Mameya and M Aus 17. Restriction of the growth response to P by Mg deficiency partially explains this discrepancy. The lower solution P requirement of these cultivars, particularly M Aus 7 and Seda, than of M Aus 10 (Jintakanon *et al.* 1979) must be taken into consideration also.

The similar P requirement for 95% of maximum yield irrespective of whether cassava plants were mycorrhizal or non-mycorrhizal in the present study is not unique. Abbott and Robson (1977b) reported similar observations for subterranean clover. Thus, although mycorrhizal infection results in very strong growth responses where P supply is limiting, it appears unable to increase the yield above that possible when the P supply is no longer limiting. Furthermore, mycorrhizal infection does not lower the P supply required for maximum yield.

The benefit of the mycorrhizal association is generally attributed to the ability of hyphae to absorb P outside the depletion zone adjacent to the root surface. However, the beneficial effect of inoculating cassava even in flowing nutrient solution, where constant mixing essentially eliminates the depletion zone suggests that either the hyphal cells are much more active physiologically in absorption of P or that they greatly increase the total absorption surface of an otherwise very coarse and ineffective root system.

Acknowledgement

The authors acknowledge gratefully the help and suggestions of Drs. R. K. Jones and W. Jehne of CSIRO Cunningham Laboratory, St. Lucia, Queensland.

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Table 1. The effect of soil fertilization on per cent infection of roots of cassava cv M Aus 10 which were inoculated with mycorrhiza and grown for two months in an Oxisol at P application rates from 0 to 16 t/ha.

P applied (t/ha)	Unsterilized Soil	Sterilized Soil
	% infection	
0	0	5
0.1	14	49
0.5	38	79
1	51	65
2	58	77
4	61	45
8	9	57
16	4	14

Table 2. The effect of soil sterilization and mycorrhizal inoculation on the concentrations of P, K, Ca, Mg and Zn in the youngest fully expanded leaf (YFEL) blades of cassava cv. M Aus 10 grown for two months in an oxisol at P application rates from 0 to 16 t/ha

Biological treatment soil / plant	P applied – t/ha 0	0.1	0.5	1	2	4	8	16
	P concentration – %							
unsterilized non-inoculated	0.27	0.33	0.37	0.37	0.36	0.36	0.33	0.46
unsterilized, inoculated	0.26	0.31	0.31	0.33	0.29	0.28	0.32	0.43
sterilized, non-inoculated	0.10	0.10	0.11	0.12	0.13	0.22	0.29	0.36
sterilized, inoculated	0.12	0.18	0.27	0.28	0.32	0.31	0.32	0.38
	K concentration – %							
unsterilized, non-inoculated	1.21	1.12	0.99	0.92	0.94	0.67	0.62	0.57
unsterilized, inoculated	1.18	1.08	0.82	0.82	0.75	0.62	0.61	0.56
unsterilized, non-inoculated	1.03	0.88	0.87	0.92	0.94	0.80	0.70	0.65
sterilized, inoculated	0.99	1.03	0.99	0.99	0.92	0.77	0.81	0.58
	Ca concentration – %							
unsterilized, non-inoculated	0.51	0.50	0.53	0.54	0.55	0.83	1.18	1.37
unsterilized, inoculated	0.46	0.44	0.41	0.48	0.50	0.82	0.89	1.20
sterilized, non-inoculated	0.49	0.38	0.40	0.42	0.41	0.76	0.82	0.92
sterilized, inoculated	0.38	0.47	0.49	0.43	0.64	0.84	0.80	0.95

	Mg concentration – %							
unsterilized, non-inoculated	0.32	0.37	0.31	0.40	0.36	0.45	0.54	0.61
unsterilized, inoculated	0.30	0.30	0.28	0.40	0.38	0.50	0.48	0.53
sterilized, non-inoculated	0.27	0.24	0.23	0.20	0.24	0.46	0.50	0.47
sterilized, inoculated	0.27	0.29	0.29	0.30	0.51	0.52	0.44	0.54
	Zn concentration – ppm							
unsterilized, non-inocualted	79	64	56	48	55	40	35	43
unsterilized, inoculated	79	63	47	46	51	45	38	42
sterilized, non-inoculated	85	60	54	59	59	54	31	37
sterilized, inoculated	83	61	79	68	68	53	41	42

Table 3. The effect of soil sterilization and mycorrhizal inoculation on the total uptake of P, K, Ca and Mg by cassava cv. M Aus 10 grown for two months in an oxisol at P application rates from 0 to 16 t/ha

Biological treatment soil / plant	P applied – t/ha 0	0.1	0.5	1	2	4	8	16
	P uptake – mg/plant							
unsterilized, non-inoculated	15	35	56	66	94	120	161	262
unsterilized, inoculated	17	40	85	76	94	122	167	249
sterilized, non-inoculated	7	8	8	8	14	82	187	247
sterilized, inoculated	8	19	49	47	100	157	206	237
	K uptake – mg/plant							
unsterilized, non-inoculated	113	199	236	274	299	387	372	338
unsterilized, inoculated	125	200	304	309	323	357	367	338
sterilized, non-inoculated	90	99	108	99	162	378	410	352
sterilized, inoculated	75	138	259	257	371	415	414	347
	Ca uptake – mg/plant							
unsterilized, non-inoculated	58	89	129	160	220	401	703	939
unsterilized, inoculated	59	101	173	179	239	506	638	857
sterilized, non-inoculated	69	61	65	63	90	287	560	592
sterilized, inoculated	53	78	142	141	219	398	603	590

	Mg uptake -- mg/plant							
unsterilized, non-inoculated	34	69	27	110	128	171	217	272
unsterilized, inoculated	37	76	128	129	148	214	213	241
sterilized, non-inoculated	30	27	30	25	38	158	253	243
sterilized, inoculated	26	45	86	83	154	225	268	233

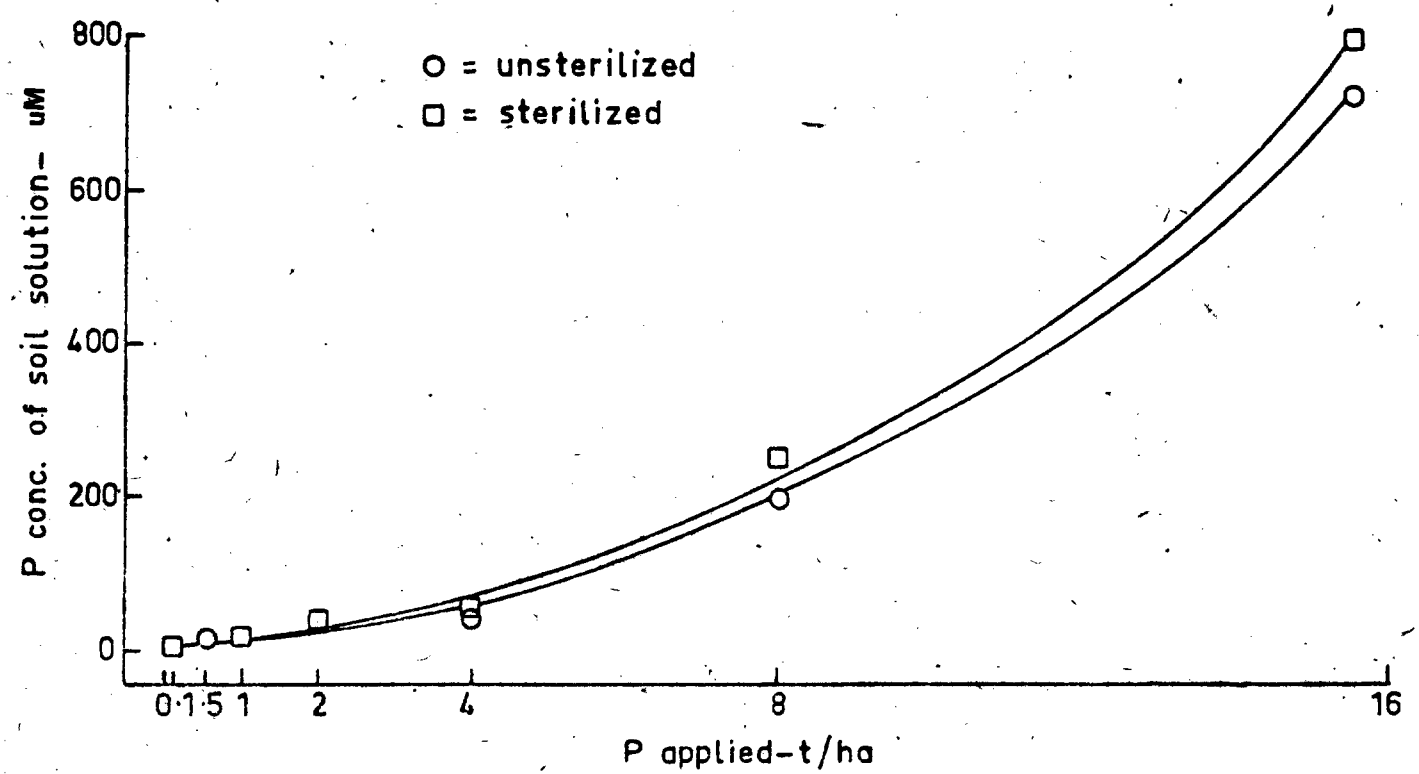

Fig. 1. **Effect of P application rates and methyl bormide sterilization on soil solution P concentrations at field capacity in an oxisol (Maleny krasnozem).**

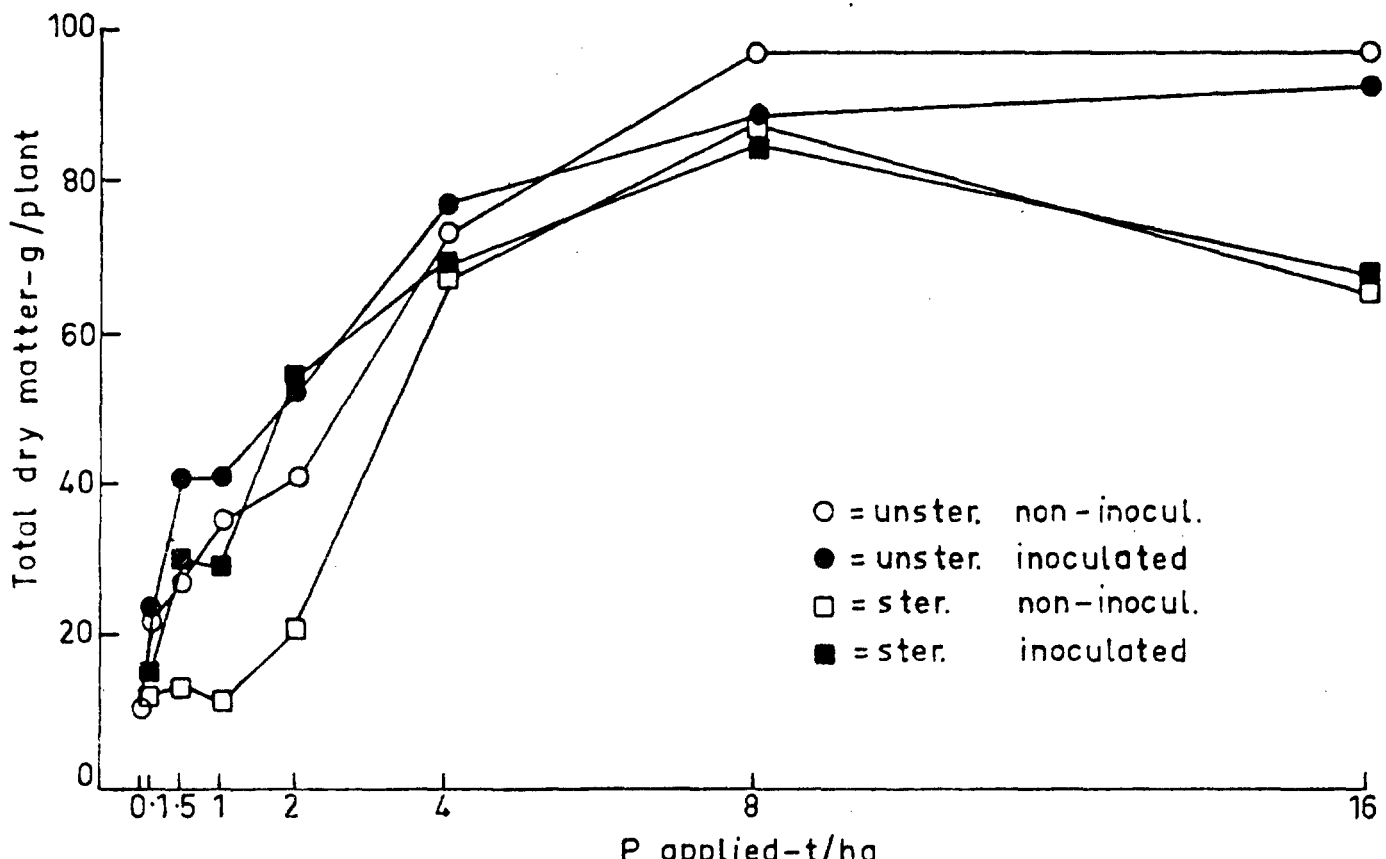

Fig. 2. **Effect of soil sterilization, mycorrhizal inoculation and P application rates on total dry matter production of cassava cv. M Aus 10 grown for two months in an oxisol.**

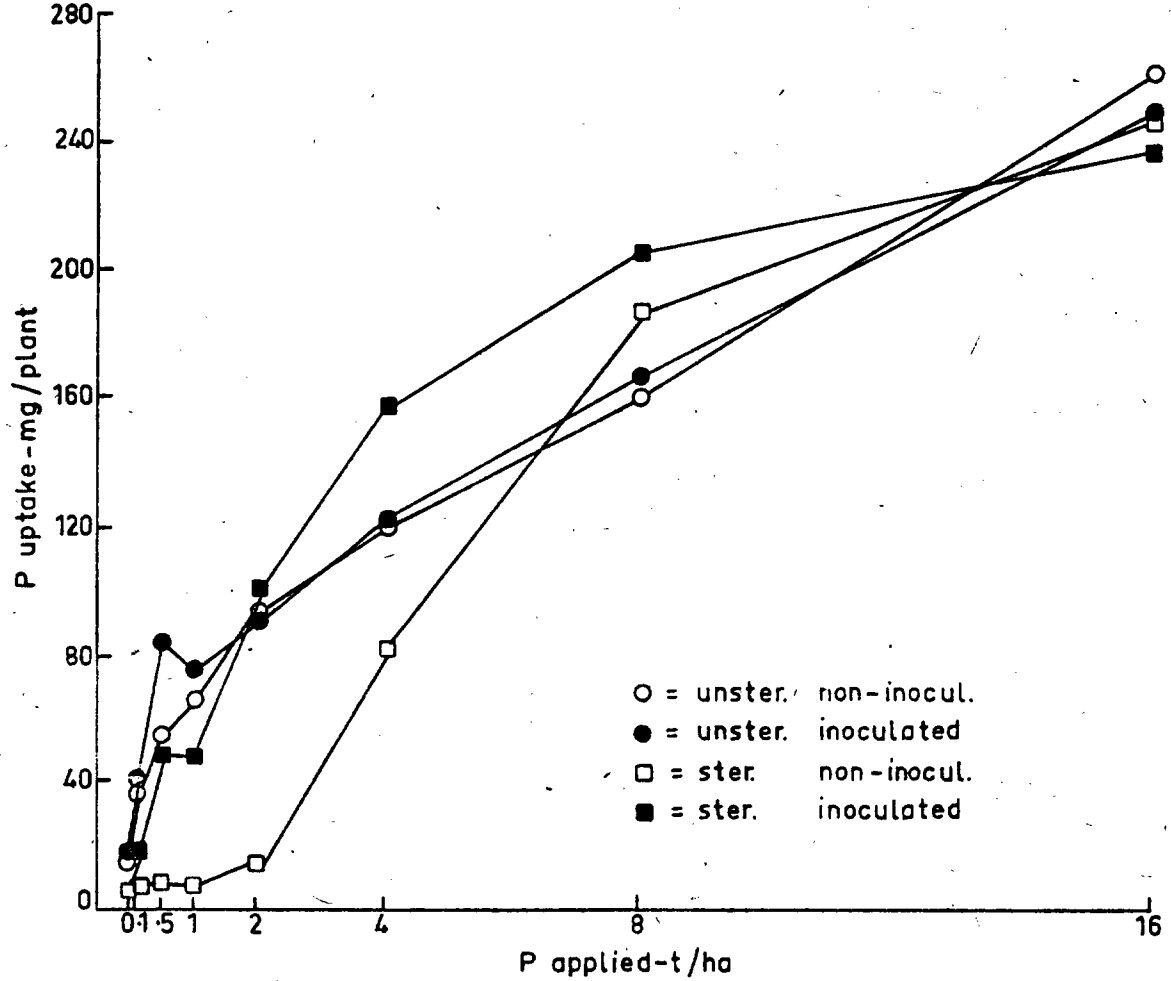

Fig. 3. **Effect of soil sterilization, mycorrhizal inoculation and P application rates on total P uptake by cassava cv. M Aus 10 grown for two months in an oxisol.**

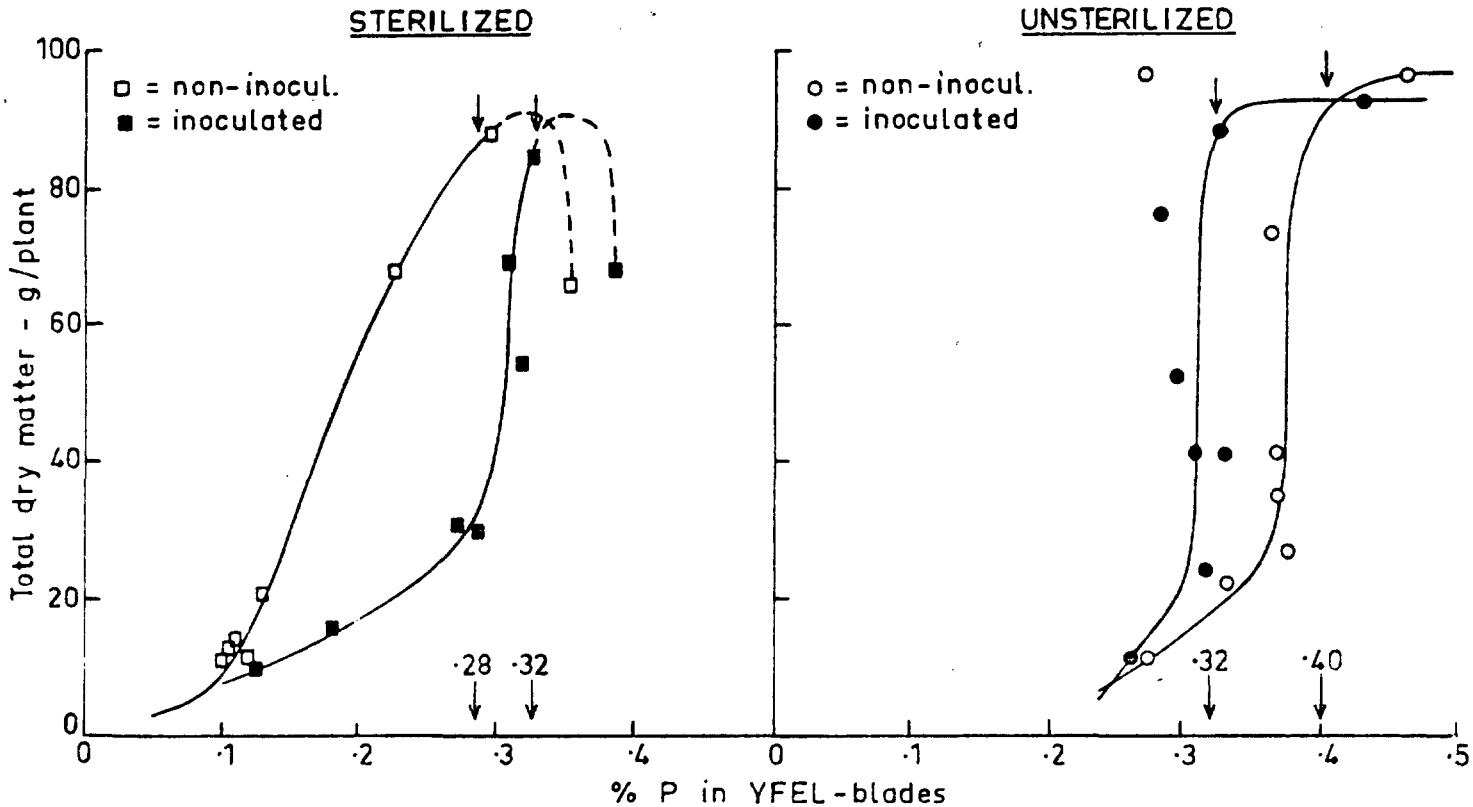

Fig. 4. Relation between total dry matter production and the P concentration of youngest fully expanded leaf (YFEL) blades of two months old cassava cv. M Aus 10. Arrows indicate critical P concentrations corresponding to 95% of maximum yield.

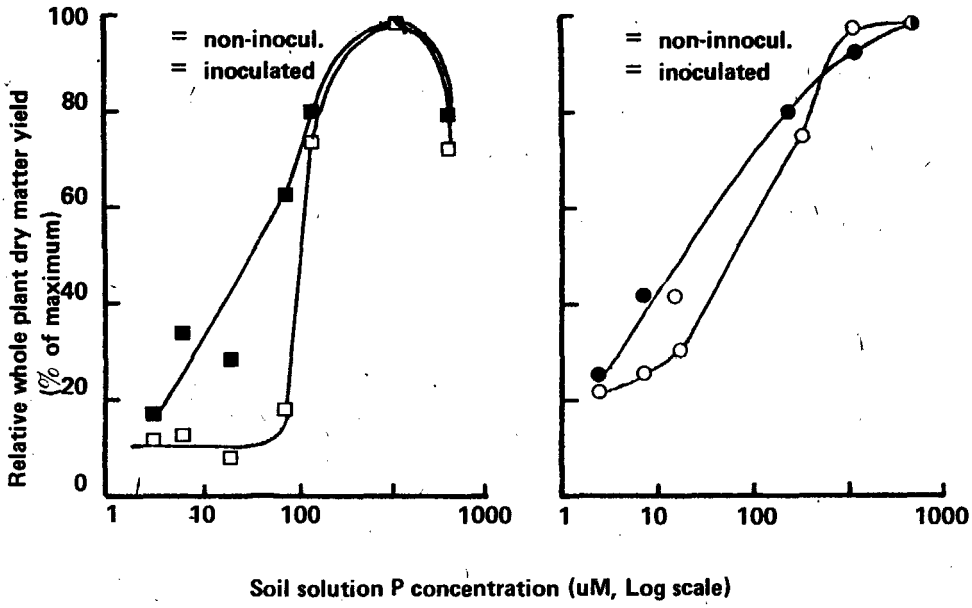

Fig. 5. The effect of soil sterilization and mycorrhizal inoculation on the relationship between relative whole plant dry matter yield and soil solution P concentration of cassava cv. M Aus 10 grown for two months in an Oxisol at P application rates from 0.1 to 16 t/ha. Soil solution P concentrations associated with 95% of maximum yield are (uM): sterilized, non-inoculated 100, sterilized, inoculated 95, unsterilized, non-inoculated 100, unsterilized, inoculated 130. Data for the nil P rate are not included, because the soil solution P concentration was below the limit of detection