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UPTAKE, TRANSLOCATION, AND INTERACTIONS OF ZINC AND MANGANESE IN CROP PLANTS

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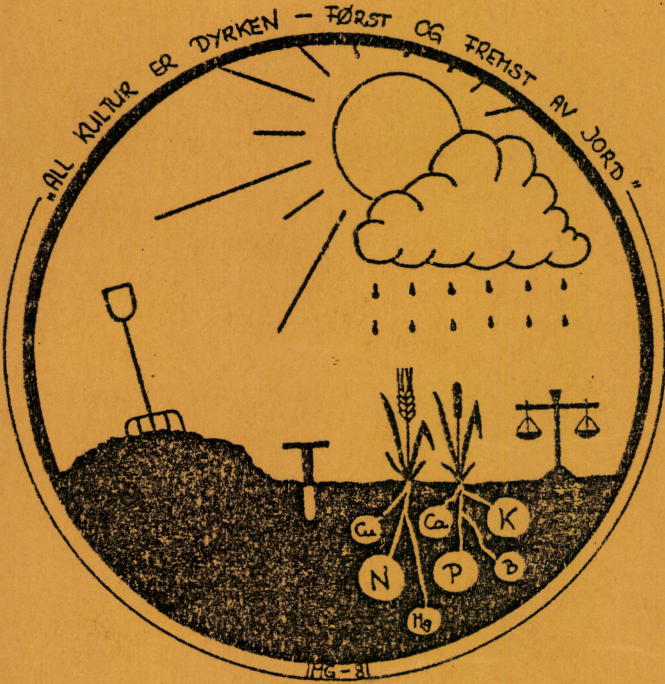

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Introduction

Zinc deficiency is the most widespread micronutrient disorder and it is becoming increasingly important in crop production. In the tropics, it occurs in India, Pakistan, Philippines, and Colombia under lowland rice cultivation. But calcareous soils are particularly prone to Zn-deficiency and in these soils even upland crops are affected. Literature is full of such examples. In India, more research efforts have gone into zinc fertilization than in all the remaining micronutriant deficiency disorders put together. For example, Katyal et al. (1980) reported that out of about 55 000 soil samples analyzed so far, nearly 50 percent fell into zinc deficient category, whereas the deficiency of remaining micronutrient cations was confined to less than 12% of the samples.

Manganese deficiency, on the other hand, is not widespread but it occurs in soils with high pH, high carbonates, low organic matter, light texture, and high phosphates. Mn toxicity in acid and flooded soils has been observed in rice crop (Tanaka and Yoshida, 1970).

The total concentration of micronutrients by far exceed the requirement of crops and availability, uptake, translocation, and presence of interacting ions are important limiting factors in the micronutrient nutrition of crop plants. These aspects, therefore, need closer look in order to find out the causes and mechanisms of micronutrients disorders in the plants.

The purpose of this paper is not to go into detailed mechanisms of uptake, translocation and interactions of micronutrients but primarily to review the results obtained by the author on these aspects. The emphasis will be placed as to how the different growth environments have influenced these phenomena. However, a brief discussion about the uptake and translocation of Zn and Mn will be presented.

Mechanisms of Zn and Mn uptake by plants

Uptake implies movement of an ion into the plant irrespective of the mechanism or the involvement of metabolic processes. Total uptake may be resolved into a metabolic component (absorption) and nonmetabolic component (free space). Also called as active and passive uptake. Passive uptake arise from electrostatic adsorption on cell walls and other surfaces within the apparent free space of roots. This binding is nonselective and nonmetabolically activated. In contrast, active accumulation is highly selective and metabolically activated.

There is considerable disagreement in the literature as to whether Zn uptake is active or passive. But Moore (1972) holds the view that on the balance the evidence suggests that Zn uptake is metabolically controlled. Evidence for active uptake has been presented by Schmid et al. (1965) using barley roots, who observed a steady state uptake rate for Zn typical of metabolic uptake. Zn uptake was considerably reduced by low temperature and metabolic inhibitors (Fig. 1). The same observation was made in sugar cane leaf. In addition, both experiments showed that Cu strongly inhibits Zn uptake. It seems possible that these two ions compete for the same carrier site. Similar competitive effects of Fe and Mn on Zn uptake have been reported in rice seedlings (Giordano et al., 1974). In addition, these workers showed that severe retardation of Zn absorption is brought about by various metabolic inhibitors. This is again indicative of an active process for Zn uptake.

Mn uptake by various plant tissues shows a two-phase process, a rapid initial uptake thought to be passive and a slower, sustained phase thought to be metabolic. The sustained absorption phase was practically eliminated by low temperature or by prolonged N_2 treatment. The initial phase was not materially affected by these two treatments (Skelding and Rees, 1952). Thus there is ample evidence that Mn uptake is metabolically mediated (Moore, 1972). In a similar way to other divalent cation species, Mn participates in cation competition. Magnesium in particular depresses Mn uptake. Liming also reduces Mn uptake not only by the direct effect of Ca^{2+} in the soil solution, but also as a result of the pH increase.

Translocation of Zn and Mn in plants

The form in which Zn is translocated from the roots to the upper plant parts is not known. However, Zn has been detected in xylem exudates of decapitated tomato and soya-bean plants in considerably higher concentrations than in the bathing solution of the roots (Tiffin, 1967). Electrophoretic evidence indicates that Zn is not bound to stable ligands as is the case with Cu^{2+}, Ni^{2+} and Fe^{3+}. In tomato exudates Tiffin (1967) observed that Zn is slightly cathodic and concluded that it is not translocated as citrate, as zinc citrate complexes are anodic. The mobility of Zn in plants is not great. Zinc accumulates in root tissues especially when Zn supply is high. In older leaves Zn can become very immobile.

Mn is relatively immobile in the plant. It is still not clear whether it can be translocated in the phloem to any extent. Tiffin (1972) studied the translocation of a number of heavy metals in tomatoes. In electrophoretic examinations of exudates it was found that Mn migrated towards the cathode. It thus appears that Mn is mainly transported as Mn^{2+} and not as an organic complex.

Manganese is preferentially translocated to meristematic tissues. Young plant organs are thus generally rich in Mn.

Uptake and distribution of Zn and Mn in plants under deficient conditions

In most soils the total Zn content by far exceeds crop requirement and availability is the important limiting factor.

Concentration of water soluble Zn in soil solution falls with increasing pH. Liming thus depresses Zn uptake. From the practical viewpoint this is of importance as Zn deficiency occurs more usually on naturally high pH soils or on highly limed soils. Singh & Steenberg (1974a) found good response of zinc in maize grown in a highly limed sandy soil having a pH-value of 7.3 and available Zn and Mn contents of 0.9 and 2.3 ppm, respectively (Table 1). The response in barley was less noticeable. In the same soil, Mn application did not significantly affect the total dry matter yield of maize and barley plants. The distribution pattern of zinc in maize and barley was in the order roots > sheaths > blades (Table 2). The distribution of zinc varies depending upon species and even cultivars and hence the variable results have been reported for other species. In the autoradiographs of maize plants ^{65}Zn was fairly evenly distributed in the main and auxiliary roots with a relatively higher concentration in the root-stem junction. ^{65}Zn was more concentrated in nodes than in internodes, probably due to the comparatively large amounts of vascular tissue in nodes. Also, sheaths and emerging young leaves showed higher concentration than in the older leaves. The distribution of ^{65}Zn in barley was quite parallel to that for maize and patterns were also similar in runners and laterals (Fig. 2). The higher concentration of total zinc absorbed by plants from the soil remained in the roots and was not translocated to the top parts of the plants.

The distribution pattern of Mn in maize and barley was different (Singh & Steenberg 1974b). In maize, the distribution pattern was blades > roots > sheaths, but in barley, pattern was similar to maize only when Mn was not applied and it changed to roots > blades > sheaths when Mn was applied. Higher concentration of Mn in barley roots than in blades may be due to decreased ability of barley to translocate Mn from roots to the blades, as also demonstrated by Ouelette and Dessureaux (1958). They reported that at specific concentrations of Mn in the medium, four clones of alfa-alfa contained approximately the same total amount of Mn, however, the plants least affected by Mn toxicity showed less ability to translocate Mn from roots to tops. The autoradiographs in Fig. 3 illustrate the distribution of ^{54}Mn in maize and barley (lighter stripes across some of the plant parts are due to absorption of beta radiation by cellophane tape). In maize, main and auxiliary roots contained very little ^{54}Mn except that the root-stem junction, where there was a relatively higher concentration of ^{54}Mn. Nodes contained higher ^{54}Mn than internodes and similarly, older leaves had higher concentration than young emerging leaves. Also ^{54}Mn increased from the leaf base to the leaf tip. Compared to transport of ^{65}Zn, ^{54}Mn is less mobile in the sieve tubes of plants.

The capacity of some plants species, for example, rice in accumulating the zinc inside the plant system and, in translocating it to the growing parts of the plants, when needed, was demonstrated by Singh and Singh, 1976 and 1978. In the calcareous soils of India, where rice crop suffered from severe zinc deficiency (Khaira disease of rice) they developed a very effective and less laborious method of zinc supply to rice in Khaira affected lands. They were able to increase the zinc content of rice seedlings by several folds (Table 4). Zinc enriched seedlings when transplanted in the affected lands were able to completely prevent the incidence of Khaira and produce normal yields (Table 4). The required degree of enrichment varied from location to location. At locations with severe incidence of disease such as that presented in Table 4, application of 600-1200 kg Zn So_4/ha of nursery almost completely prevented the incidence of disease and produced normal yields.

Interaction between Zn and Mn and its influence on their translocation in plants grown in a deficient soil

Interaction may be defined as (I) an influence, a mutual or reciprocal action, of one element upon another in relation to plant growth and (II) the differential response to one element in combination with varying levels of a second element applied simultaneously; that is the two elements combine to produce and added effect not due to one of them alone (or a negative effect).

When increasing the supply of one cation species results in lowering the concentration of other cation species is called cation antagonism. This is generally the case in the micronutrients. In plant nutrition the term synergism is often used to describe opposite phnomenon of antagonism. Thus a synergistic relationship occurs between two plant nutrients when the uptake of one is stimulated by the other. How the growth environment can change the nature of interaction between two nutrient cations will be delt in this section.

Singh & Steenberg (1974c) in a study on the interaction between Zn and Mn grown in a zinc deficient soil found that in maize plants, the radioactive and total uptake of manganese was substantially decreased with increasing level of zinc application (Fig. 4). This is similar to the pattern found in total Mn^{54} and manganese content. In barley plants uptake of radioactive and total manganese by sheaths and blades decreased with increasing level of zinc up to 50 ppm level of manganese but not to the 100 ppm level (Fig. 5). There was no particular trend of decrease in roots.

The uptake of Zn^{65} and total zinc by maize were not affected by manganese application. Marginal effects of manganese application on total Zn^{65} uptake from substrate to roots, however, were observed in barley.

By employing the double tracer technique for ion competitors, it can be determined if absorption or translocation of manganese is influenced by zinc and vice versa. Sakaguchi (1965) has used this technique to examine the influence of various anions on the uptake and translocation of strontium and Hawk and Schmid (1967) to study the effect of other cationic species on zinc uptake and translocation in bush bean plants.

If for example, zinc interfered only with absorption this would appear as a reduction in total Mn^{54} uptake. If it interfered with internal translocation this would be indicated by changes in the relative percentage of Mn^{54} in roots, sheaths and blades.

In this study, Mn^{54} and total manganese content and their uptake in roots, sheaths and blades of maize and barley plants, were substantially decreased with increasing levels of applied zinc (Table 5). At the 5 and 25 ppm levels of zinc the Mn^{54} uptake was only 56 and 58 percent of the uptake at the 0 ppm level in maize and 97 and 95 percent in barley. These percentages are the means of three Mn rates.

Application of manganese had less effect on the Zn^{65} content of roots, sheaths and blades of maize and barley, than had the contrasting application of zinc on Mn^{54} content. However, in barley plants, an effect on Zn^{65} content of roots, sheaths and blades was noticeable at the highest concentration (25 ppm) of zinc (Table 6).

It is evident from this study that zinc which competes with manganese ions in maize and barley, exerts its influence mainly at the site of transport of manganese from the substrate into the root. It appears to have little influence on the distribution and/or translocation. Manganese does not play a significant role either in uptake or translocation of zinc in either crop.

Uptake, translocation and interaction of Zn and Mn in barley grown in Zn polluted soils

The objectives of these investigations were to find out the toxicity of zinc to barley and also to measure the availability of zinc from soil and applied zinc. These investigations were also aimed at to find out the effect of excessive zinc on the uptake and translocation of other micronutrients and especially Mn and Fe.

The general chemical properties of the soils are presented in Table 7. The dry matter yield of barley from soils B and C decreased significantly with increased level of added zinc, whereas the yield in soil A remained unaffected (Table 8). The concentrations of total Zn and ^{65}Zn increased with increasing level of Zn in all three soils (Table 8). The amount of available Zn i.e. the "A" value was calculated (Table 9). The "A" values as proposed by Fried & Dean (1952) is an expression of the amount of zinc in the soil having an availability equivalent to that applied Zn. The "A" values were fairly independant of the rate of Zn application and so was the percentage utilization of added Zn. A comparison by correlation of "A" values and soil Zn determined by chemical procedure (Table 7) showed that the two methods were highly correlated ($r=0.999$). This supports the assumption of Fried and Dean (1952) that the "A" value may be a measure of exchangeable cation available to a plant.

The effect of Zn on Mn content and uptake in barley was of particular interest. Entirely unexpectedly, Zn increased the Mn uptake (Fig. 6) and hence this affect was further investigated in a detailed study on the effect of Zn on Mn content and uptake and vice versa. The soils designated B and C in Table 7 were used for this study.

An excess of Zn present in the soils, as well as added Zn, had no apparent effect on the growth and dry matter yield of barley, but contributed substantially to the accumulation of Zn and Mn in barley roots and tops. Although Zn and Mn contents of barley in the present work were relatively high, and fell in the accepted toxic range of these nutrients in plants, no apparent toxicity in barley was observed. Manganese levels > 200 ppm in barley shoots have been reported to be associated with Mn toxicity (Gupta et al. 1973). Similarly, Zn levels > 200 ppm have been found to have toxic effects in plants (Chapman 1966). Toxicity of an element in plants is due to an imbalance of nutrients. Williams and Vlamis (1957) have shown that a Mn concentration of 1,000 ppm in barley leaf is normally toxic, but this level of Mn becomes harmless when the plant absorbes Si together with Mn. Ishizuka and Ando (1968) reported that Zn prevented the Mn toxicity symptoms of rice plants and the growth of rice plants depended not only on the concentration of Mn or Zn in the tissues, but also on the ratio of Mn to Zn in the tissue. They concluded that Mn and Zn interacted to reduce the toxicity of each other in the tissues. This may possibly be the reason that despite toxic concentrations of Zn and Mn in barley in the present study toxicity symptoms were not observed. The second point which ought to be mentioned here may be the genetic variability of plant species and varieties. The plant species and varieties differ in their susceptibility to toxicity. Ouellette and Dessureaux (1958) demonstrated that four clones of alfalfa (Medicago sativa L.) differed in their susceptibility to Mn toxicity.

The most striking results of this investigation were that the concentrations of ^{65}Zn and Zn in barley roots and tops increased progressively with increasing level of added Mn. The increases were consistently higher in roots than in tops for both soils, and occurred in proportion to the levels of added Zn and Mn. The concentrations of ^{54}Mn and total Mn in barley roots and tops generally increased with increasing rate of added Zn and Fe. The accelerating effect of Zn on Mn concentration was higher than that of Fe. The increased concentration of ^{54}Mn and total Mn was fairly constant at all levels of Zn and Fe. Since there was no apparent effect of Zn, Mn and Fe application on dry matter yield, total uptake of Zn and Mn are presented in figures 7 and 8. The results presented were contrary to those presented previously (Singh & Steenberg 1974c) for a deficient soil and also contrary to the general theory of ionic competion between these ions in the process of absorption.

To our knowledge synergistic uptake of Zn, Mn, and Fe by plants, as observed in this experiment, has not been reported previously. It is also not clear whether Zn, Mn, and Fe function similarly to Ca in the process of absorption. However, limited data available on micronutrient absorption suggest that the mechanism of uptake is similar to that for macronutrients. Viets (1944) reported that polyvalent cations, which are toxic in growth experiments, exert their effect directly on the protoplasmic membrane or on surface metabolism related intimately to the permeability of the plasma-membrane. The high concentration of Zn in the growth medium may have affected the permeability of plasma membrane and possibly passive uptake was occurring.

It is difficult at this stage to evaluate conclusively the reason for the unusual results presented in this paper. A posible explanation of the promotional effects of Zn, Mn, and Fe on the absorption of their interacting ions is suggested. When Zn is added to the soil, it displaces some of the ions on the exchange complex by simple ion exchange, thus resulting in an increased ambient concentration of, for example, Mn in the soil solution. As root membrane permeability is presumed to increase due to high concentration of Zn in the growth medium, Mn ions may then passively enter the root from the external medium. Such a passive uptake mechanism would not observe the strictures implied by selective absorption, and an increased ambient concentration of soil Mn should result in greater Mn uptake. The uptake of Zn and Fe by barley should behave similarly.

The percentage distribution of Zn, Mn, and Fe between roots and tops of barley was apparently unaffected by the presence of their interacting ions (Tables 10 and 11).

Generally, evidence has been presented in this study which indicated that though Zn, Fe, and Mn in barley appear to have limited influence on translocation within the plant, these ions exert strong synergistic effects at the site of transport.

Summary, conclusions, and future research needs

Since micronutrients disorders are primarily related to their availability in soils and their uptake, translocation, and interaction in plants rather than to their total contents in soils, these aspects of micronutrients and especially for Zn and Mn are discussed. Although there is considerable disagreement in the literature as to whether uptake of Zn and Mn is active or passive, on the balance, the evidences suggest that the uptake of these micronutrients is metabolically controlled.

This is not the complete literature on these aspects and mostly the results obtained by the author are summarized. The response of Zn and Mn application varied according to the species grown and so was the distribution of Zn and Mn in the plants. In general, the distribution pattern of Zn was roots > sheaths > blades but that of Mn was blades > roots > sheaths, however, some deviations from this pattern occurred in barley. The autoradiographs of intact maize and barley plants showed that ^{65}Zn was fairly evenly distributed in the main and auxiliary roots, but, there was a relatively higher concentration at the root-stem junction. ^{65}Zn concentration in nodes was higher than in internodes and higher in young leaves than in older leaves. Distribution of ^{54}Mn differed only in leaves where older leaves contained higher ^{54}Mn than the younger leaves and the contents increased from the leaf base to the top.

Zn and Mn interacted antagonistically to each other in maize and barley grown in a deficient sandy loam soil but the interactions were more pronounced in maize than that in barley. Also, effect of Zn on Mn uptake in both the crops was more marked than that of Mn on Zn uptake. The translocation of either Zn or Mn was very little influenced by the presence of their interacting ions. It was thus concluded that the effect of Zn on Mn uptake and translocation was predominantly at the transport site and not in the internal distribution or translocation. The manganese played a minor role either in transport or translocation of Zn in plants.

A possible new method of Zn supply to transplanted crops which need to be transplanted in deficient soils is discussed.

The uptake behaviour and translocation of Zn and Mn was nearly the same when barley was grown in zinc-polluted soils, but very little toxic effect of excessive zinc was noted on the crop growth. This indicates that the relative concentrations of Zn and Mn or their other interacting ions in the plants seem to play a greater role in preventing the toxicity rather than their absolute concentrations. But entirely, unexpectedly the nature of interaction between Zn and Mn in barley grown in zinc-polluted soils was in contrast to that observed in barley when grown in deficient conditions. The contents of ^{65}Zn and total Zn were found to increase with increasing levels of added Mn and/or Fe and vice versa. The effects of Zn and Mn on Fe uptake were inconsistent. The percentage distribution of Zn and Mn between roots and tops was apparently not affected by the presence of their interacting ions. From this study it was concluded that though Zn, Mn, and Fe ions in barley appear to have limited influence on translocation within the plant, these ions exert strong synergistic effects at the site of transport.

The synergistic effects of Zn and Mn are not reported in the literature and they are in big contrast to the general theory of antagonism between these ions in the process of absorption. They need to be investigated and the mechanisms responsible for changing the interaction behaviour of these ions need to be identified. Though these studies indicate that the interactions between Zn and Mn occur primarily on the site of transport, these aspects need to be further investigated involving other macro- and micronutrients and a large number of species and varieties. The hypothesis proposed in the study by Singh and Steenberg (1975) that possibly passive uptake was dominating when the concentrations of Zn and Mn were higher in the soil solution need to be tested and the sites within the plant where Zn and Mn are metabolically active and where excessive concentration of Zn or Mn may interfere with the maximum activity of these nutrients need to be identified. As the magnitude of interaction between Zn and Mn in maize and barley varied, careful studies of species and varietal differences under uniform conditions or in relation to environmental effects need to be carried out.

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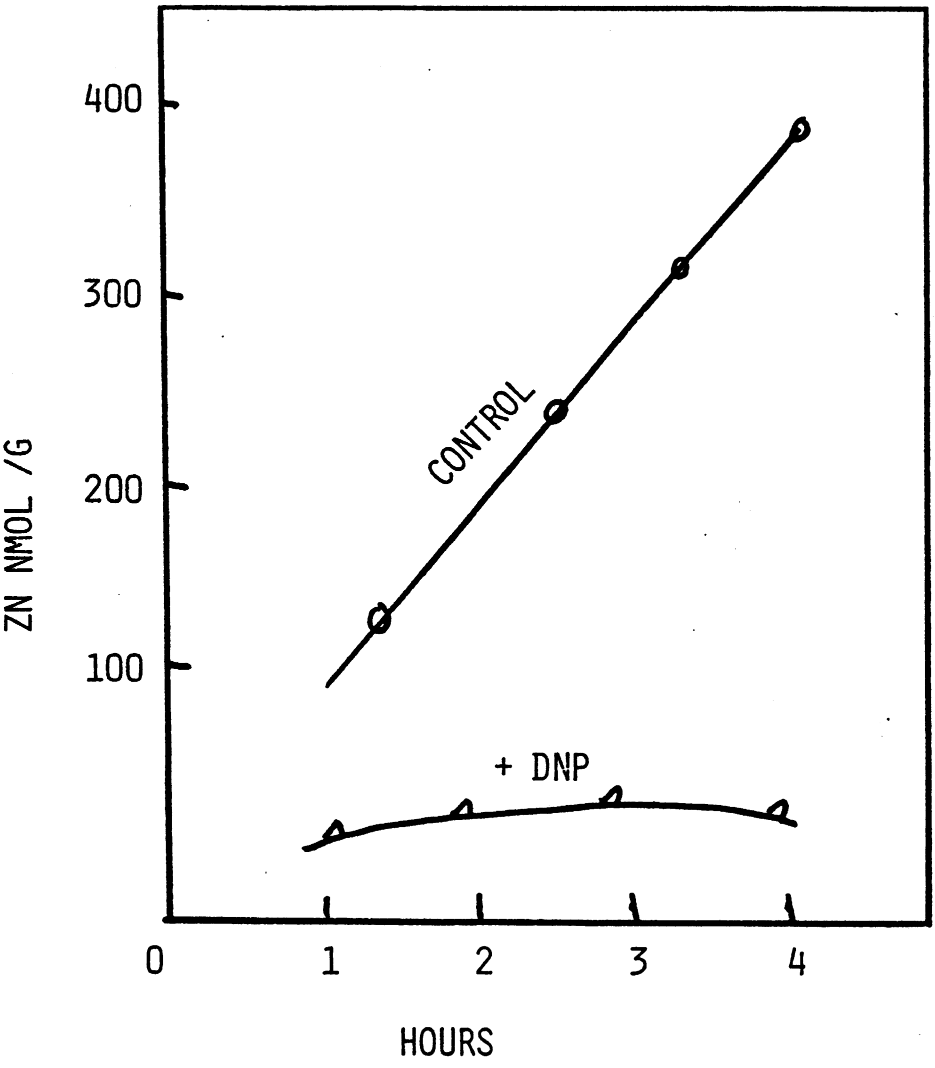

FIG. 1- INHIBITION OF ZN ABORPTION BY DNP
EXCISED BARLEY ROOTS (SCHMI ET AL., 1965)

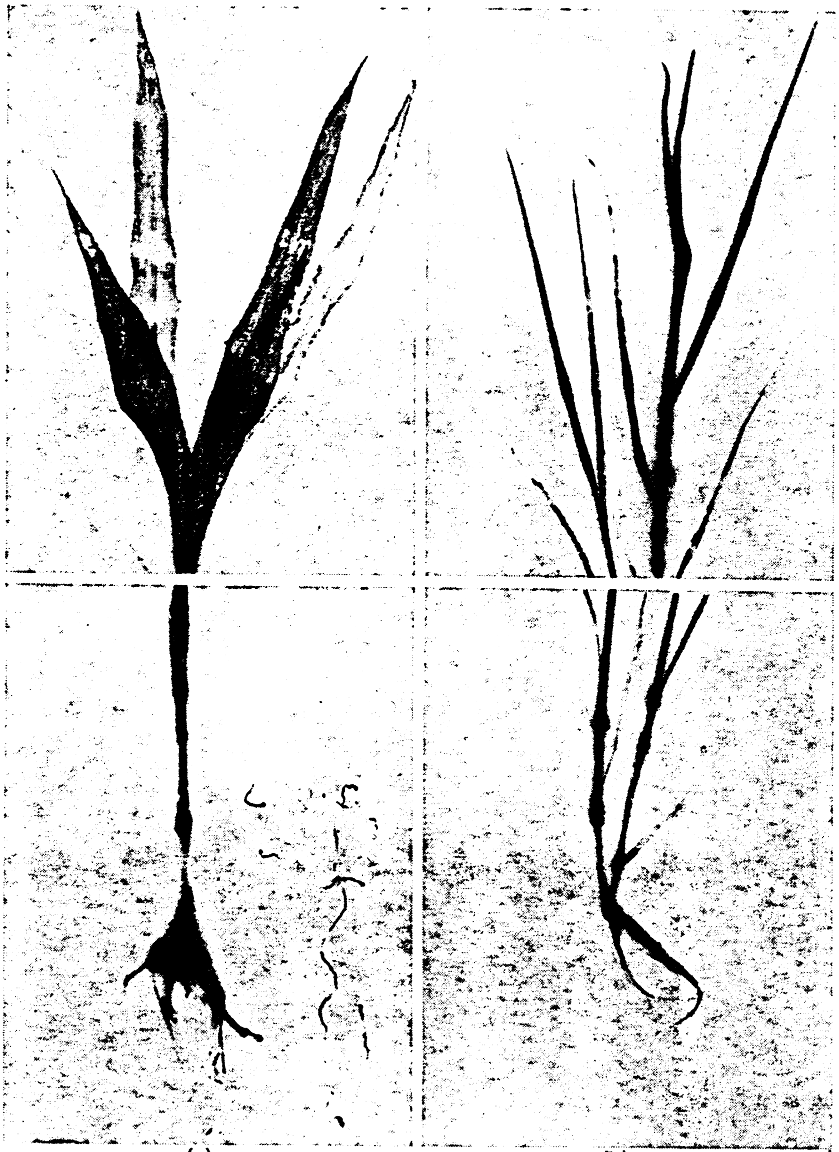
(a) (b)

Fig. 2. Autoradiographs of intact (a) maize, and (b) barley plants supplied with 50 µg of Zn^{65} at 0 ppm level of zinc.

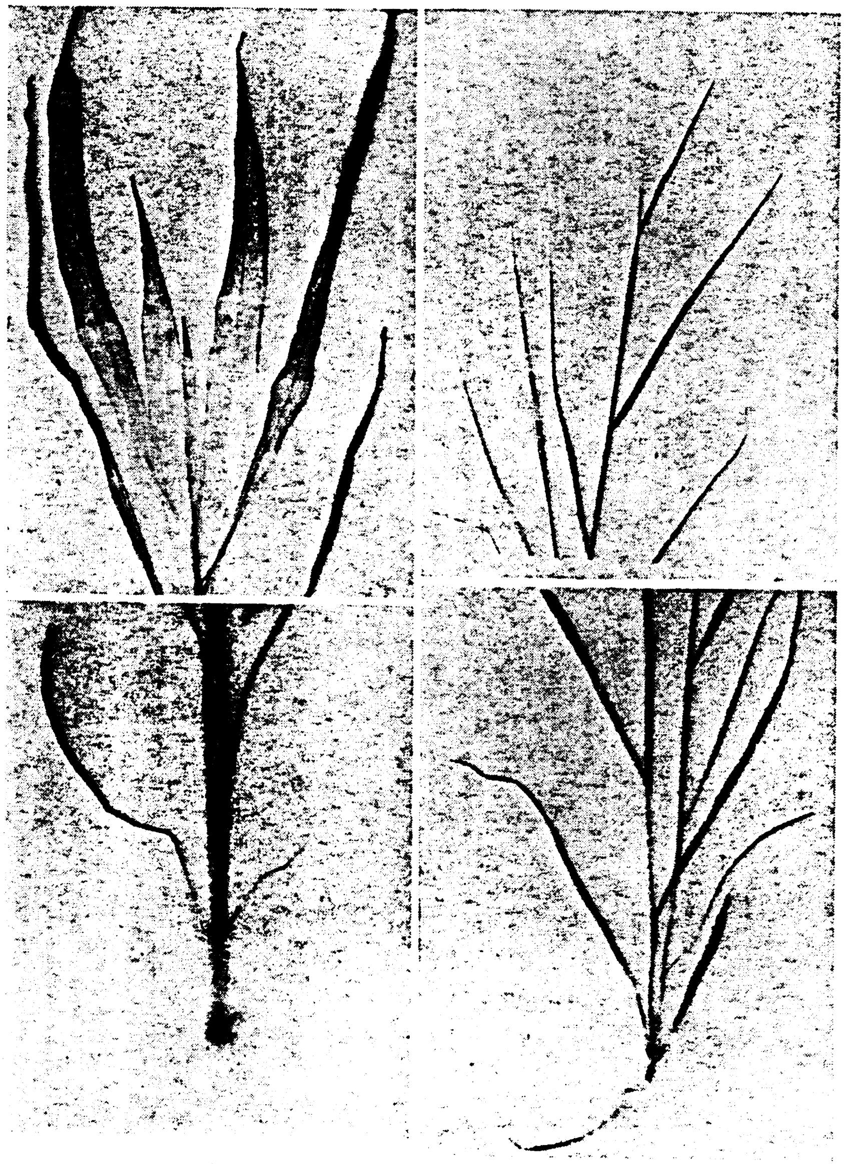

Fig. 3. Autoradiographs of intact maize (a) and barley (b) plants supplied with 20 μc of carrier-free Mn^{54} at 0 ppm level of manganese.

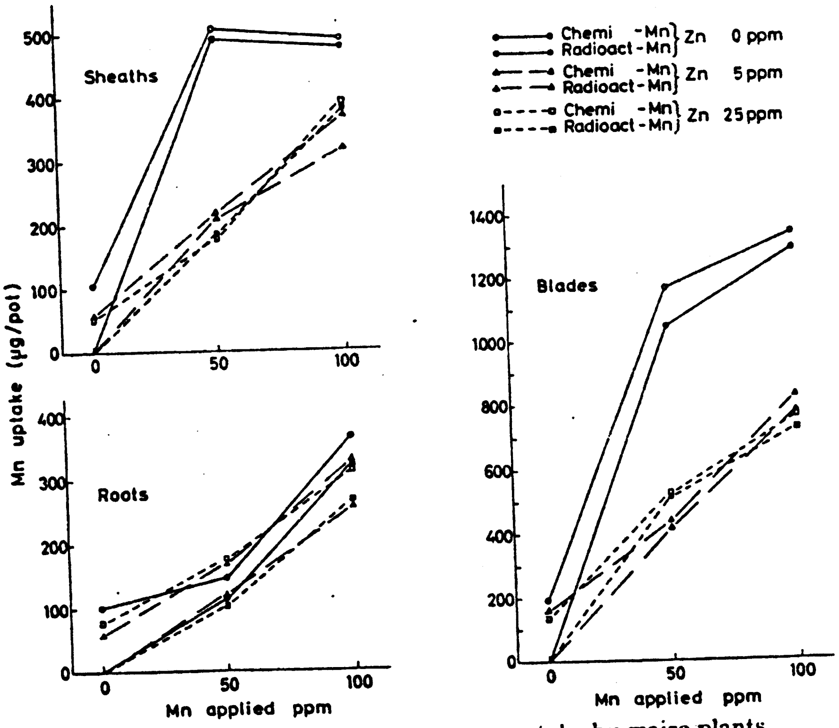

Fig. 4. Effect of zinc on manganese uptake by maize plants.

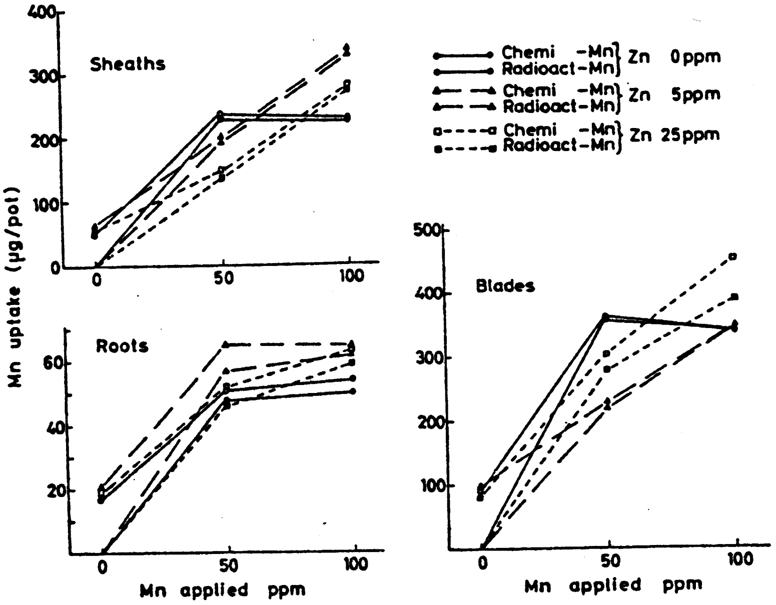

Fig. 5. Effect of zinc on manganese uptake by barley plants.

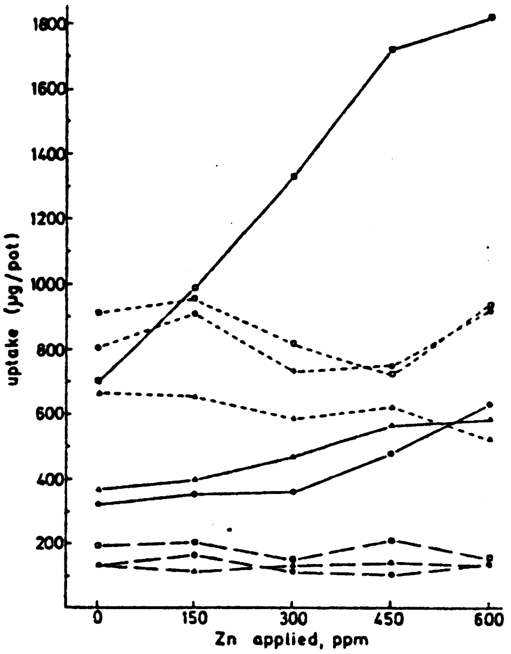

Fig. 6.Effect of zinc application on Mn, Fe, and Cu uptake by barley.

○	Soil A
△	Soil B
□	Soil C
——	Mn
· · ·	Fe
- —	Cu

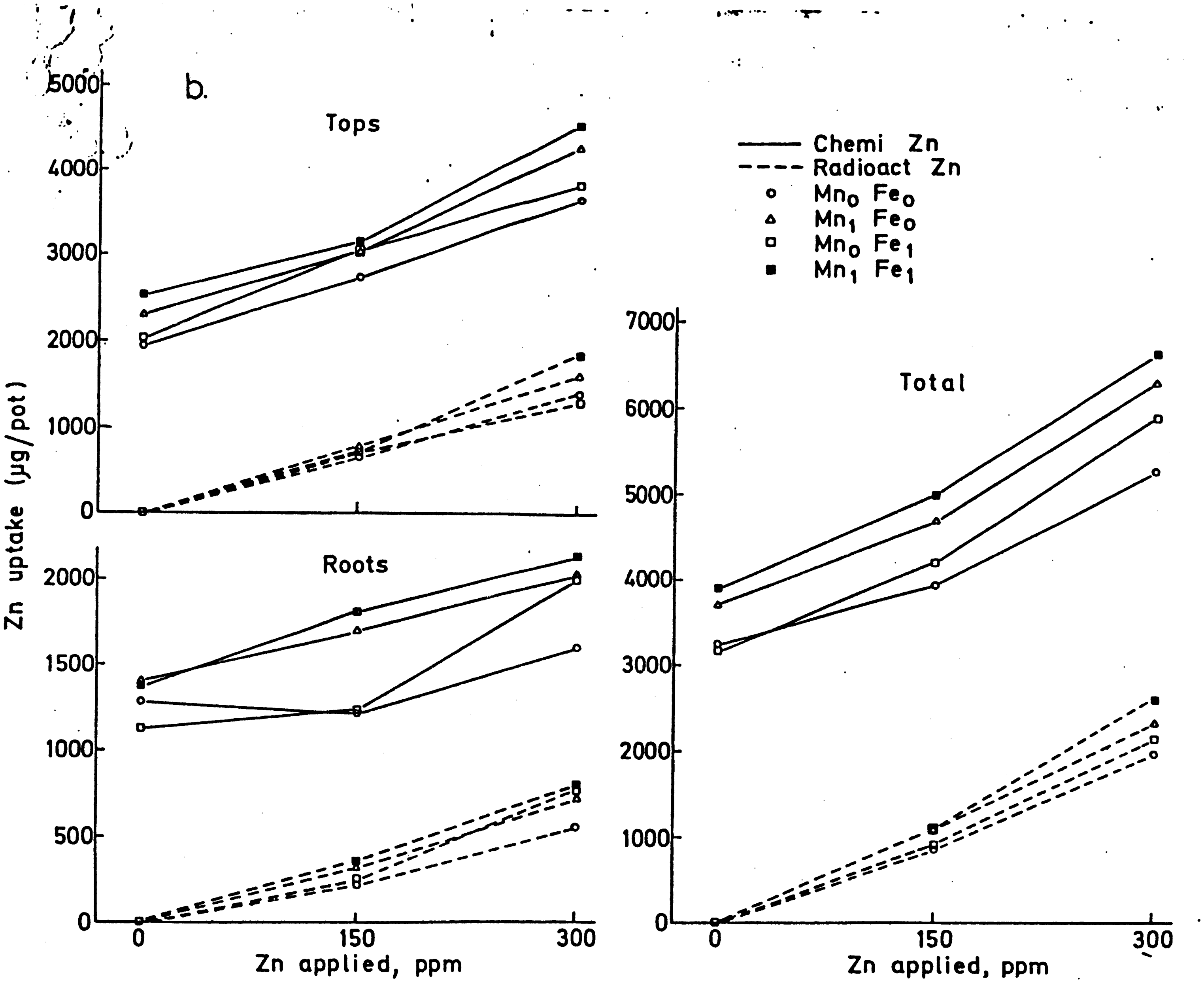

FIG.7. EFFECT OF ZN, MN AND FE APPLICATION ON ^{65}ZN AND TOTAL ZU UPTAKE NY BARLEY.

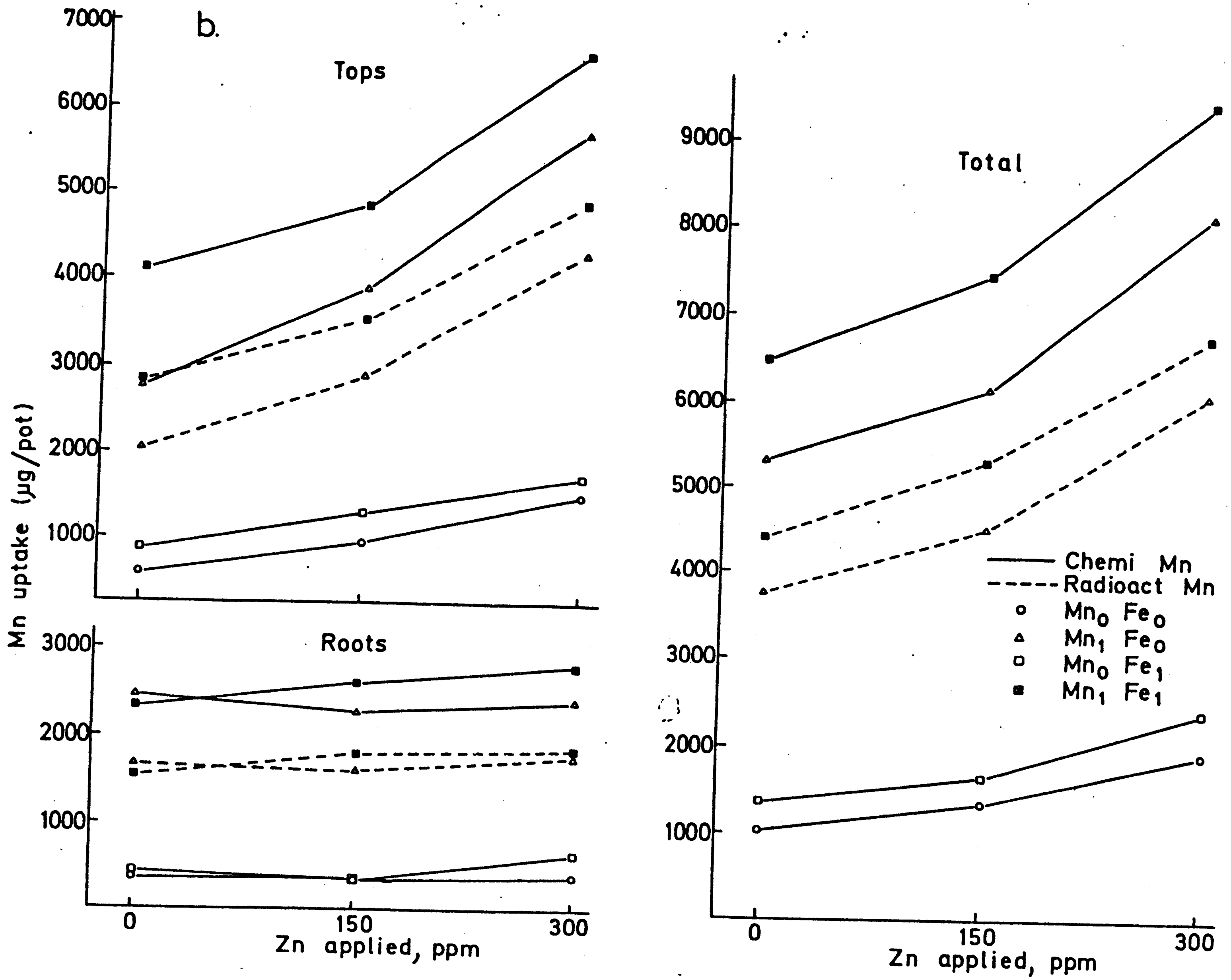

Fig.8. Effect of Zn, Mn and Fe application on ^{54}Mn total Mn uptake ny barley.

TABLE 1 EFFECT OF ZINC APPLICATION ON THE TOTAL DRY MATTER YIELD OF MAIZE. (SINGH & STEENBERG, 1974)

ZN RATE PPM	TOTAL DRY MATTER YIELD (G/POT) 3 WEEKS AFTER PLANTING	6 WEEKS AFTER PLANTING
0	4.27	15.93
0A	4.36	12.10
5A	5.77	17.51
25A	5.42	18.53
LSD	1.0	4.01

A = ACTIVITY OF ^{65}ZN (50 μC/POT)

TABLE 2

The effect of zinc application on the total zinc content and distribution in maize an barley plants. (Singh & Steenberg 1974).

Zn rate ppm	Plant	Total zinc content (ppm)		
		Ist harvest		
		Roots	Sheaths	Blades
0	Maize	60,8	24,0	16,3
0A		80,6	34,4	17,8
5A		91,9	44,5	28,5
25A		232,4	93,0	43,9
LSD		66,5	30,6	6,1
0	Barley	129,6	37,3	16,5
0A		136,8	47,4	18,5
5A		124,0	75,7	26,6
25A		216,2	136,0	67,4
LSD		--	30,0	23,2

A = activity of Zn ^{65} (50mc/pot).

TABLE 3

THE EFFECT OF MANGANESE APPLICATION ON THE TOTAL MANGANESE CONTENT AND DISTRIBUTION IN MAIZE AND BARLEY PLANTS. (Singh & Steenberg 197).

Mn rate ppm	Plant	Total manganese (ppm)		
		Ist harvest		
		Roots	Sheaths	Blades
0	Maize	27,6	24,0	64,6
0A		26,4	23,8	67,9
50A		202,3	109,3	280,7
100A		289,9	129,7	329,1
LSD		45,8	15,5	26,8
0	Barley	31,4	27,8	53,8
0A		31,8	23,6	43,9
50A		158,1	75,5	141,1
100A		342,8	87,0	172,6
LSD		109,3	17,4	11,7

A = activity of Mn ^{54}(20 uc/pot)

TABLE 4 . EFFECT OF ZINC APPLICATION ON ZINC ENRICHMENT OF RICE SEEDLINGS AND THEIR PERFORMANCE IN A ZINC DEFICIENT SOIL

ZN CONT.(PPM) MEANS OF FO & FI			SOIL APPLICATION KG ZINC SUL./HA OF NURSERY	YIELD IN QUINTAL/HA (MEAN OF 4 REPLICATION)		
				GRAIN		
ROOTS	LEAF SHEATHS	LEAF BLADES		F_0	F_1	MEANS
61.6	56.6	48.3	0	5.12	14.50	9.81
90.0	63.6	68.2	75	19.25	28.00	23.62
125.0	63.8	98.6	150	20.00	13.50	16.75
181.2	148.2	108.3	300	15.50	17.00	16.25
269.8	191.6	150.0	600	25.25	30.50	27.87
353.2	284.9	173.2	1200	40.25	49.00	44.62
376.6	307.6	167.2	2400	43.00	52.00	47.50
			MEANS	24.50	29.91	

C.D. AT 5% = 20.77

FO = NO FOLIAR SPRAY F_1 = THREE FOLIAR SPRAY. SOURCE: SINGH & SINGH (1976 AND 1978)

Table 5. The effect of zinc application on Mn^{54} uptake, distribution and/or translocation in maize plant (Singh & Steenberg 1974)

Plant	Part	Mn rate ppm	Zn rate ppm					
			0		5		25	
			Uptake µg/pot	% of total	Uptake µg/pot	% of total	Uptake µg/pot	% of total
Maize	Roots	0	0.7	10	0.2	4	0.2	5
		50	114.7	7	118.7	16	103.9	13
		100	320.8	15	258.9	19	265.3	19
	Sheaths	0	1.9	26	1.1	24	1.0	24
		50	493.1	30	213.3	28	188.7	23
		100	476.9	23	322.9	24	377.7	28
	Blades	0	4.6	64	3.2	71	2.9	71
		50	1048.2	63	418.5	56	519.9	64
		100	1288.6	62	777.4	57	728.3	53
	Total	0	7.2		4.5		4.1	
		50	1656.0		750.5		812.5	
		100	2086.3		1359.2		1371.3	

Table 6. The effect of Mn application on Zn^{65} uptake, distribution and/or translocation in barley plant (Singh & Steenberg 1974)

Plant	Part	Zn rate ppm	Mn rate ppm 0		Mn rate ppm 50		Mn rate ppm 100	
			Uptake µg/pot	% of total	Uptake µg/pot	% of total	Uptake µg/pot	% of total
Barley	Roots	0	0.04	16	0.03	10	0.03	14
		5	18.1	8	17.7	9	14.0	8
		25	60.8	10	61.5	10	51.5	8
	Sheaths	0	0.1	42	0.2	60	0.1	43
		5	127.9	60	117.3	61	111.6	60
		25	400.0	64	357.7	60	412.4	67
	Blades	0	0.1	42	0.1	30	0.1	43
		5	68.1	32	57.2	30	59.3	32
		25	160.7	26	177.0	30	151.2	25
	Total	0	0.24		0.33		0.23	
		5	214.1		192.2		184.9	
		25	621.5		596.2		615.1	

TABLE 7. CHEMICAL CHARACTERISTICS OF SOILS

CHARACTERISTICS	SOILS		
	A	B	C
PH	6.2	6.9	6.7
ORGANIC CARBON (%)	4.3	5.5	3.9
P-AL (MG/100 G)	41.0	67.0	62.0
K-AL (MG/100 G)	26.0	8.7	15.0
EXCHANGEABLE CATIONS (ME/100 G):			
K	0.60	0.26	0.36
NA	0.09	0.09	0.08
CA	10.50	27.35	13.49
MG	1.42	1.51	0.59
H^+	8.10	0.00	4.50
ZN (PPM)	684	710	545
MN (ACT) (PPM)	211	74	134
FE (PPM)	12.1	4.5	6.6
C (PPM)	34.8	18.0	24.2

SOURCE SINGH& LAG (1976)

TABLE 8. EFFECT OF ZINC ON DRY MATTER YIELD AND ZINC CONTENT OF BARLEY

TREATMENTS	YIELD (G/POT)			TOTAL ZINC (PPM)			^{65}ZN (PPM)		
	SOIL A	SOIL B	SOIL C	SOIL A	SOIL B	SOIL C	SOIL A	SOIL B	SOIL C
ZN_0	9.71	10.74	10.84	320	191	233	0.006	0.005	0.006
ZN_1	9.48	10.02	10.88	426	233	302	73	39	70
ZN_2	9.68	9.92	9.83	561	279	404	161	81	158
ZN_3	9.83	99.87	9.94	657	328	453	272	132	210
ZN_4	10.13	9.16	10.08	737	379	489	364	179	244
HSD AT 0.05	NS	0.82	0.87	87	67	131	46	46	62

ZN_0, ZN_1, ZN_2, ZN_3, AND ZN_4, ARE 0, 150, 300, 450, AND 600 PPM OF ADDED ZN, RESPECTIVELY.

SOURCE SINGH & LAG (1976)

TABLE 9. INFLUENCE OF ZINC APPLICATION ON SOIL ZINC "A" VALUES AND UTILIZATION OF FERTILIZER ZINC BY BARLEY

TREATMENTS	SOIL ZINC "A" VALUES (PPM)			PERCENTAGE UTILIZATION OF ADDED ZINC		
	SOIL A	SOIL B	SOIL C	SOIL A	SOIL B	SOIL C
ZN_0	(685)*	(706)	(523)	-	-	-
ZN_1	727	748	499	0.18	0.10	0.20
ZN_2	748	734	467	0.21	0.11	0.21
ZN_3	648	670	521	0.24	0.11	0.18
ZN_4	617	671	605	0.25	0.11	0.16

* VALUES IN BRACKETS ARE THE MEAN OF "A" VALUES.

THE VALUES OF ZN_0 TO ZN_4 ARE THE SAME AS IN TABLE 8.

SOURCE SINGH & LÅG (1976).

Table 10. Influence of Zn, Mn, and Fe on percentage uptake of Zn in roots and tops of barley

	Percentage uptake			
	Soil A		Soil B	
	Roots	Tops	Roots	Tops
Treatment	Total Zn	Total Zn	Total Zn	Total Zn
Zn_0 Mn_0 Fe_0	42	58	40	60
Zn_0 Mn_1 Fe_0	46	54	38	62
Zn_0 Mn_0 Fe_1	37	63	35	65
Zn_0 Mn_1 Fe_1	42	58	35	65
Zn_1 Mn_0 Fe_0	35	65	30	70
Zn_1 Mn_1 Fe_0	40	60	36	64
Zn_1 Mn_0 Fe_1	31	69	29	71
Zn_1 Mn_1 Fe_1	39	61	36	64
Zn_2 Mn_0 Fe_0	38	62	30	70
Zn_2 Mn_1 Fe_0	38	62	32	68
Zn_2 Mn_0 Fe_1	36	64	34	66
Zn_2 Mn_1 Fe_1	44	56	32	68

Zn_0 = 0 ppm Mn_0 = 0 ppm Fe_0 = 0 ppm
Zn_1 = 150 ppm Mn_1 = 300 ppm Fe_1 = 200 ppm
Zn_2 = 300 ppm

Source Singh and Steenberg (1975).

Table 11. Influence of Zn, Mn, and Fe on percentage uptake of Mn in roots and tops of barley

	Percentage uptake			
	Soil A		Soil B	
	Roots	Tops	Roots	Tops
Treatment	Total Mn	Total Mn	Total Mn	Total Mn
Zn_0 Mn_0 Fe_0	46	54	38	62
Zn_0 Mn_1 Fe_0	52	48	46	54
Zn_0 Mn_0 Fe_1	35	65	34	66
Zn_0 Mn_1 Fe_1	45	55	36	64
Zn_1 Mn_0 Fe_0	32	68	27	73
Zn_1 Mn_1 Fe_0	38	62	37	63
Zn_1 Mn_0 Fe_1	35	65	21	79
Zn_1 Mn_1 Fe_1	40	60	35	65
Zn_2 Mn_0 Fe_0	29	71	21	79
Zn_2 Mn_1 Fe_0	30	70	30	70
Zn_2 Mn_0 Fe_1	33	67	28	72
Zn_2 Mn_1 Fe_1	38	62	42	58

The values of the treatments are given in Table 10.

Source Singh & Steenberg (1975).