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CROP RESPONSE TO PHOSPHATE AND LIME ON ACID SANDY SOILS HIGH IN ZINC

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SUMMARY

Beans, lettuce, tomatoes, cotton, maize, and Sudan grass were grown in glasshouse experiments, and potatoes and maize in field experiments on a Zn-polluted sandy soil (pH-KCl 4.3, 36-54 ppm $AcONH_4$-extractable Zn) to study the effects of added P and lime on dry matter production and mineral composition. Moreover, the effects of added P and lime on $AcONH_4$-extractable ('available') soil Zn, and of added Zn on water-soluble ('available') soil P were estimated.

Beans, lettuce, tomatoes, and cotton required both lime and P to overcome the toxic effect of excess Zn, *i.e.* a Zn/P imbalance interfering with P metabolism. Maize and Sudan grass, accumulating much smaller amounts of Zn from the unamended Zn-polluted soil, grew well and responded vigorously to P in the absence of applied lime. Potatoes were intermediate in behaviour. P and lime decreased Zn concentrations in the above-ground portions of all crops, mainly as a result of 'dilution' following a vigorous growth response. Only in cases where lime depressed growth (maize and Sudan grass at the lower P rates) was there some evidence of a direct inhibitive effect on Zn uptake by plant tops.

Soil analyses indicated that the Zn-P antagonism could not be explained satisfactorily on the basis of chemical reactions involving mutual immobilization. It is postulated, therefore, that the Zn-P interaction is mainly a plant physiological characteristic.

INTRODUCTION

There is a wealth of literature on the zinc nutrition of various crops as affected by P and lime (Koukoulakis [9]). However, there is a notable lack of information for crops grown in Zn-polluted soils or given excessive amounts of Zn (Boawn and Rasmussen [4], Henkens [6]). More data on the mechanism of zinc toxicity in plant

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growth are urgently needed with a view to utilizing waste products, such as sewage sludge, on cultivated soils, or reclaiming soils exposed to industrial Zn pollution (Smilde [15]) or spraying residues (Walsh *et al.* [18]).

The object of the present work was to study the response of various crop species grown on a Zn-polluted sandy soil to applied P and lime, and also to determine the effect of applied P on Zn availability, and vice versa, in the presence or absence of lime.

EXPERIMENTAL PROCEDURE

Experiment 1

In this exploratory glasshouse experiment, started in 1971, beans (*Phaseolus vulgaris*) were grown on a Zn-polluted sandy soil from a site nearby a zinc smelter at Neerpelt, Belgium (site 1). The pots contained 6.3 kg of oven-dry topsoil (0–20 cm) with pH-KCl 4.3, 5.9% organic matter, 6 ppm water-soluble P, 170 ppm AcOH-extractable Zn. All pots received adequate amounts of N, K, Mg, B, Cu, Mn, Mo as reagent grade chemicals. Treatments (in 2 replications) included 0, 62.5, 125, 187.5, 250, 375 mg P per kg of dry soil as $Ca(H_2PO_4)_2 \cdot H_2O$ at 0, or 1100 ppm CaO as $Ca(OH)_2$ to raise soil pH by about one unit. In 1972, one replication received fresh P, amounting to half of the rates added in 1971, and additional dressings of the other nutrients. Five bean seedlings were planted in each pot and harvested two months later. Only the yield data for the crop given fresh P will be considered here. In 1973, five lettuce (*Lactuca sativa*) plants were grown in each pot for about six weeks. No fresh P was applied. Pots were watered daily to 70% of maximum water retention. Day and night temperatures varied from 20–30 and 15–20°C, respectively, and relative humidity from 50–75%.

Experiment 2

In this glasshouse experiment, conducted in 1973, tomatoes (*Lycopersicon esculentum*) and cotton (*Gossypium hirsutum*), maize (*Zea mays*) and Sudan grass (*Sorghan vulgare sudanense*) were grown in succession on a similar soil from the Neerpelt area, site 2, somewhat higher in water-soluble P (16 ppm). The pots contained 11.4 kg of oven-dry topsoil. Treatments with P and CaO were similar to those in Expt. 1 (1971 application). Supplemental dressings of the essential nutrients, but no more P and CaO, were added prior to sowing cotton and Sudan grass as second crops. Each pot supported five (tomato, maize, cotton) or forty (Sudan grass) plants which were harvested after about six weeks. Glasshouse temperature was kept at 25–35°C for cotton and Sudan grass. The experiment had a randomized-block design, with three replications (= blocks) per treatment.

Experiment 3

This was a field experiment in the Neerpelt area (site 2) with a double latin-square design (32 plots) for the P treatments 0, 110, 220 and 440 kg P per ha, and 4 blocks superimposed for the lime treatments 0, and 2360 kg CaO per ha to raise pH-KCl from 4.4 to 5.2. Lime was applied in November, 1971; P, as triple superphosphate, and basic applications of N, K and Mg were broadcast in March, 1972, some weeks prior to planting potatoes (*Solanum tuberosum*). Samples from the younger leaves were taken in June and the crop was harvested in September, using net plots of 32.5 m^2 to determine tuber yields.

In 1973, the 1972 P dressings were repeated in one half of each Latin square and fresh basic applications of N, K and Mg were given before sowing maize by the end of April. Mid-stem leaves were sampled in August, and the crop was harvested in October, using plots of 28.8 m^2 to determine cob yields.

Experiment 4

An acid sandy soil (pH-KCl 3.9; 3.9% organic matter) low in P and Zn (0.3 ppm water-soluble P, 11 ppm AcOH-extractable Zn) from Someren, The Netherlands, given 175 ppm P as $Ca(H_2PO_4)_2 . H_2O$ was incubated at 25–30°C for three months. The variable treatments were: 0, 75, 150, 300, 600, 1200 ppm Zn as $ZnSO_4 . 7 H_2O$ at 0, or 1000 ppm CaO as $Ca(OH)_2$. Soil samples were taken monthly ior analysis of water-soluble P and $AcOHN_4$-extractable Zn.

Analytical methods

Plant samples were oven dried at 105°C, weighed and ground, and wet-ashed with HNO_3, H_2SO_4 and $HClO_4$. Analyses included P (spectrophotometrically); Zn, Fe, Mn (by atomic absorption), and in some cases N (micro-Kjeldahl).

Soil samples, taken after the crops of beans (Expt. 1, 1972) and maize (Expt. 2), were analysed for pH (1:5 w/v 1N KCl), water-soluble P (after Sissingh[14]), and Zn using the following extractants: 1:10 w/v 0.025M EDTA, 15 min shaking (Laske[10]); 1:2.5 w/v 0.02M EDTA, 60 min shaking (Jensen and Lamm[8]); 1:2 w/v 0.01M EDTA + 1M $(NH_4)_2CO_3$, 30 min shaking (Trierweiler and Lindsay[17]); 1:40 w/v 2.5% AcOH, 15 h shaking (Berrow and Webber[1]); 1:10 w/v 1M $AcONH_4$ (pH 7), 15 min shaking (De Bes and Van Dijk[2]).

In Experiment 3, soil samples from the upper 20 cm layer, were taken after harvesting potatoes (1972) and maize (1973).

RESULTS

Crop yield and chemical composition

In both bean crops (Experiment 1) growth responses to added P and lime were positive and highly significant, and so was their

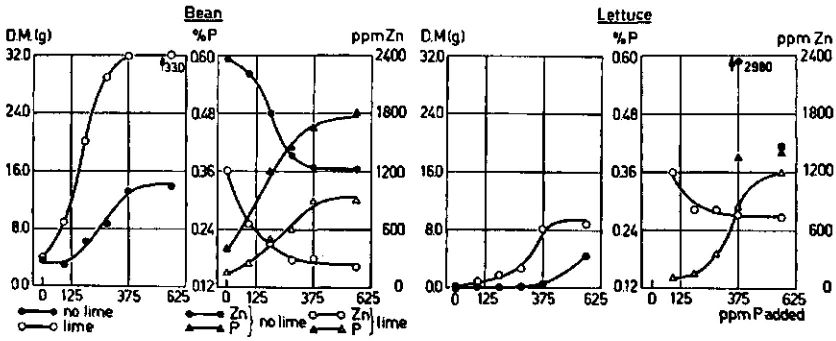

Fig. 1. Dry matter yield and chemical composition of beans (1972) and lettuce (1973), following P and lime application on Zn-polluted Neerpelt soil (site 1, Expt. 1).

interaction. In the absence of lime, the first crop developed badly and hardly demonstrated a P effect.

Fig. 1, left, illustrates the mutual stimulating effects of P and lime for the second crop of beans. Leaf P concentration was significantly increased by applied P and decreased by lime, whereas leaf Zn and N concentrations were decreased in either case, as shown in Fig. 1 for Zn in the second bean crop. With increasing P rates leaf Zn concentration dropped from 2360 to 1240 ppm in the absence of lime, and from 1220 to 220 ppm with lime applied. It can be calculated, however, that the total amounts of Zn (N) contained in the foliage increased with increasing P rates, thus revealing a growth-induced 'dilution effect' affecting Zn (N) concentrations. As regards Zn, lime depressed both its concentration and total accumulation in the foliage, suggesting inhibition of Zn absorption by the roots or interference with internal translocation.

Trends in dry-matter production and mineral composition for lettuce (Expt. 1) are very similar to those for beans, see also Fig. 1, right. At the lower levels of P with no lime added growth was very poor and not enough plant material was available for analysis. It can be postulated, however, that leaf Zn attained concentrations well over 3000 ppm under these conditions.

In Experiment 2, tomato and cotton behaved in the usual way, demonstrating positive P and lime effects and a positive P × lime interaction, see Fig. 2; top, left. Dry-matter production was very

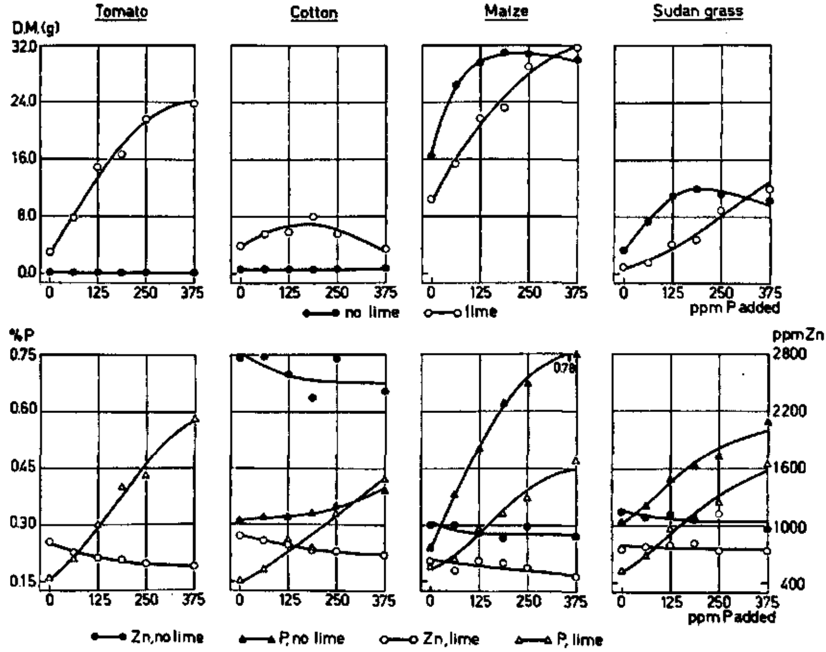

Fig. 2. Dry matter yield and chemical composition of tomatoes, cotton, maize and Sudan grass, following P and lime application on Zn-polluted Neerpelt soil (site 2, Expt. 2 – 1973).

low in the absence of lime, especially so in tomatoes which developed symptoms resembling P deficiency, neither crop benefiting from applied P. Yield data for cotton are somewhat erratic and neither the P effect nor the P × lime interaction attained the 5% level of significance.

As distinct from this pattern, maize and Sudan grass showed a significant positive response to P both in the presence and absence of lime, but more so in the former case (positive interaction), see Fig. 2; top, right. Furthermore, lime significantly reduced yields at the lower but not at the higher P applications. The yield response curves of Fig. 2 (top) indicate a negative lime effect offset by high P and, conversely, a negative effect of high P offset by lime.

Fig. 2 (bottom) illustrates the familiar trends in leaf chemical composition for the various crops, *viz.* P concentrations were significantly increased by applied P and decreased by lime, Zn (Fe, Mn) concentrations were decreased by either treatment. As distinct from lime, P had only a slight effect, significant at 10%, on metal concentrations. In the absence of lime, Zn concentrations in cotton attained values up to about 2800 ppm, as against 1000–1150 ppm in maize and Sudan grass. With lime applied, maximum Zn concentrations in the various crops were rather similar, *viz.* 600–800 ppm.

The response curves for total leaf P and metals (not presented here), closely resembling those for dry weights (Fig. 2, top), suggest that leaf metal concentrations are largely governed by 'dilution' effects. The general pattern for lime was to depress total leaf P and metals in maize and Sudan grass, and to increase them in cotton and, probably, in tomatoes as well, but there was insufficient plant material to verify this.

Without P, and also with the lower rates of applied P potato plants in the field experiment (Experiment 3) were stunted with purple older and chlorotic younger leaves, as shown by the colour-index figures in Table 1. Both P and lime had a highly significant positive

TABLE 1

Colour index, leaf chemical composition and tuber yield of potatoes in a field experiment (Expt. 3 – 1972) on Zn-polluted Neerpelt soil (site 2) as affected by P (0, 110, 220, 440 kg P. ha⁻¹) and lime

	Colour* index	Leaf composition			Tuber yield (kg. are⁻¹)**	Percentage tubers <35 mm
		% N	% P	ppm Zn		
pH 4.4						
P_0	4.5	4.45	0.31	1298	92.0[a]	27
P_1	6.3	4.77	0.35	1205	129.5[ab]	24
P_2	6.5	5.05	0.39	1251	191.5[c]	17
P_3	8.1	5.58	0.51	1131	265.3[dg]	16
pH 5.2						
P_0	4.6	4.45	0.33	1093	106.8[ae]	25
P_1	6.4	4.85	0.43	1128	191.8[cf]	15
P_2	7.4	5.42	0.44	1128	241.8[g]	13
P_3	8,0	5.56	0.51	1092	291.3[gh]	12

* 10 = 'normal' green

** Figures having indices in common do not differ significantly according to Duncan's multiple range test at 5%

effect on tuber yield. The largest amount of P (440 kg P per ha), almost triplicating yields, was still sub-optimal. The percentage of small tubers (<35 mm diameter) was significantly reduced by either treatment. Foliar analysis revealed a positive effect of P on leaf N and P concentrations. Lime had a similar, but smaller effect. Leaf Zn dropped from about 1300 tot 1130 ppm with increasing P rates in the absence of lime. With lime added, leaf Zn, ranging from 1090–1130 ppm, varied little with P treatment. The Zn levels are probably inflated by atmospheric contamination from the nearby zinc smelter. Relevant data are presented in Table 1.

Stunting and purple discoloration were also displayed by the following crop, maize, not given P or with the lower rates of applied P. Growth index figures (Table 2) at tasseling time suggested a marked response to treatments. However, the effects on cob yield were found to be less spectacular, drought later in the season probably eliminating differences to some extent. The residual (1972) P effect did not reach significance at 5%. By contrast, the combined (confounded) effect of residual plus fresh (1973) P proved significant, mainly because of the yield increase following an application of 880 kg of total P per ha. When comparing residual and fresh P, in the range of applications up to 440 kg of total P per ha, the differences between these two forms were not found to be significant. Lime tended to decrease cob yield in the absence and to increase it in the presence of applied P. These effects were not significant at 5%, however. Leaf P concentration showed a tendency to rise at the highest P rate only. Leaf Zn tended to decrease with increasing P rates. As in the case of the yields, the effects of residual and fresh P on leaf Zn proved basically similar. Lime also reduced leaf Zn, from 2100 to 1850 ppm in the absence of applied P, the highest P rate producing a further reduction to about 1400 ppm (Table 2). This level is markedly higher than that encountered in the pot experiment, probably resulting from atmospheric pollution.

Soil analysis

As shown in Fig. 3, left, applied P raised and lime depressed water-soluble P in the soils from either site of the Neerpelt area. The data may be affected by plant P uptake, however, assuming that absorbed P mainly comes from the water-soluble fraction. As P absorption increased with increasing P rates, resulting from concur-

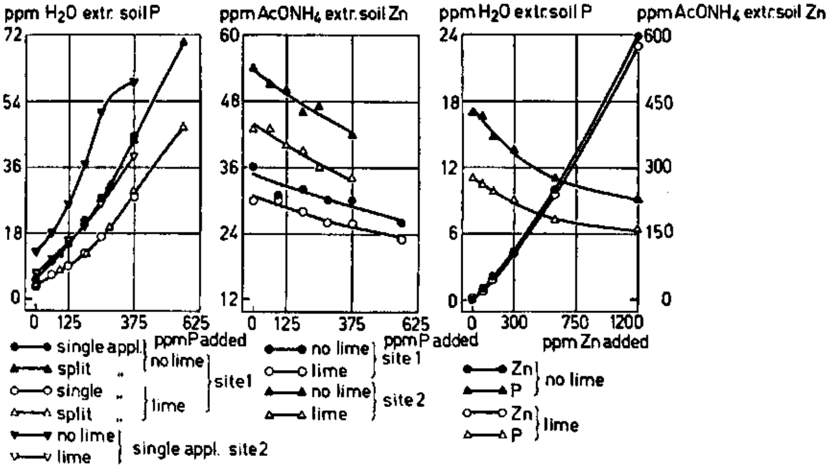

Fig. 3. *Left and centre*: Water-soluble P and $AcONH_4$-extractable Zn as affected by applied P and lime in Zn-polluted Neerpelt soil. Samples taken after harvesting beans (Site 1, Expt. 1 – 1972) and maize (site 2, Expt. 2 – 1973).
Right: Water-soluble P and $AcONH_4$-extractable Zn as affected by applied Zn and lime in an incubation experiment with Someren soil not subjected to Zn emission (Expt. 4).

rent rises in both dry matter production and P concentration (*cf.* Fig. 1 and 2), the P effect is somewhat larger than would appear from the curves in Fig. 3. Similarly, the depressive effect of lime may be larger or smaller, depending on the effect of lime on P uptake.

As regards site 1 (Expt. 1), Fig. 3, left, also presents the effects of single (1971) and split (1971 + 1972) P dressings on water-soluble soil P. When plotting the *total* amounts of added P, irrespective of application time, against soil P all points fall on the same curve, suggesting an equilibrium in the soil P system soon after P application. Admittedly, the evidence would be stronger were it not for the interfering effect of plant P absorption. On the other hand, additional soil analyses during the winter period without crop growth corroborated this evidence.

Data for water-soluble P als affected by P and lime in the field experiment, largely confirmed those of the pot experiment (site 2), with somewhat lower values for the treatments without lime, and will not be discussed.

TABLE 2

Growth index, leaf chemical composition and cob yield of maize in a field experiment (Expt. 3–1973) on Zn-polluted Neerpelt soil (site 2), as affected by residual (1972) and fresh (1973) P (0, 110, 220, 440 kg. ha^{-1}) and lime

	Growth index*	Leaf composition			Cob yield (kg. are^{-1})
		% N	% P	ppm Zn	
pH 4.4					
P_0	5.2	3.10	0.26	2107	60.6
P_1 (residual)	6.2	3.12	0.27	2272	53.4
P_2 ,,	7.2	2.99	0.26	1896	63.4
P_3 ,,	7.4	3.02	0.27	1878	56.0
P_{11} (residual+fresh)	6.2	3.26	0.28	2118	50.8
P_{22} ,,	6.9	3.10	0.27	2038	59.4
P_{33} ,,	8.5	3.18	0.32	1608	75.1
pH 5.2					
P_0	4.2	3.30	0.27	1851	47.2
P_1 (residual)	5.0	3.37	0.28	1726	56.9
P_2 ,,	6.2	3.23	0.27	1808	55.1
P_3 ,,	7.2	3.04	0.26	1642	62.0
P_{11} (residual + fresh)	7.2	3.25	0.21	1740	69.8
P_{22} ,,	6.8	3.12	0.27	1804	56.0
P_{33} ,,	9.0	3.28	0.30	1420	93.6

* at tasseling time, 10 = optimum growth

Determination of soil Zn, following extraction with the various reagents listed in Table 3, indicated that leaf Zn in beans (site 1, Expt. 1) and maize (site 2, Expt. 2) was best correlated with 1 *M* $AcONH_4$-extractable soil Zn. Therefore, this Zn fraction was used in further studies on the P-Zn interrelationship in soils.

Fig. 3, centre, shows that both added P and lime depressed $AcONH_4$-extractable soil Zn. These effects were found to be highly significant. P has a somewhat lesser and lime a larger effect when considering that plant Zn absorption is also affected by these treatments, as discussed above. It seems justified to conclude, however, that the overall effects of P and lime are relatively small and that much larger applications would be required to reduce 'available' soil Zn to non-toxic levels (Fig. 3, right, Someren soil).

The effect of applied Zn, with and without lime, on water-soluble P was studied in an incubation experiment (Experiment 4), using a soil from Someren with similar characteristics as the Neerpelt

TABLE 3

Correlation coefficients for the relationship between plant Zn concentration and soil Zn concentration, as determined with various extractants in Zn-polluted Neerpelt soil

	1:10 0.025 M EDTA	1:2.5 0.02 M EDTA	1:2 0.01 M EDTA + 1 M $(NH_4)_2CO_3$	1:40 2.5 % AcOH	1:10 1 M $AcONH_4$
Beans (site 1)	−0.0713	0.0870	0.7253	0.3197	0.8375*
Maize (site 2)	0.1086	0.5377	0.8651*	0.3365	0.8664*

* significant at 5% level

soils, but not subjected to Zn pollution. An uniform application of 175 ppm P was given to raise water-soluble P to a level approximating that of the Neerpelt soils.

Fig. 3, right, shows that applied Zn markedly raised $AcONH_4$-extractable soil Zn, slightly less so in the presence of lime, and significantly lowered water-soluble P. The effect of Zn on soil P proved to be significantly larger in the absence than in the presence of lime. It should be pointed out, however, that the overall decrease in water-soluble soil P is small, amounting to only a few ppm in the range of $AcONH_4$-extractable Zn levels corresponding with those from the Zn-polluted Neerpelt soils (36–54 ppm). Therefore, these data present little evidence for P precipitation as the main cause of P starvation on Zn-polluted soils. Soil samples from the same treatments, taken one, two and three months after Zn addition, contained almost identical amounts of water-soluble P, suggesting an equilibrium in the soil P system soon after P application.

DISCUSSION

Bean, lettuce, tomato, and cotton plants largely failed to grow if the Zn-polluted sandy Neerpelt soil was not limed. Apparently, both lime and P were needed to alleviate Zn toxicity in suppressing excessive accumulation of Zn in plant tissues. Although Zn toxicity is obviously the main cause of plant failure, in lettuce, accumulating up to 1300 ppm Mn, and perhaps also in beans, Mn toxicity may also be involved, This possibility can be excluded for the other crops studied on the basis of plant analysis. In this context the work by Lee and Page [12] with cotton affected by Zn toxicity (leaf Zn 1721 ppm) on a polluted sandy peach orchard soil, containing 45 ppm (0.05*N* HCl + 0.025*N* H_2SO_4) extractable Zn, is relevant.

Maize and Sudan grass represent a rather different group of plant species in accumulating much smaller amounts of Zn from the unamended Zn-polluted soil, and responding vigorously to P also in the absence of applied lime. Potatoes take an intermediate position, yielding consistently higher when both lime and P were applied.

Interestingly, Boawn and Rasmussen[4] raising 0.005*M* DTPA-extractable soil Zn to 246 ppm upon addition of 500 ppm Zn to an alkaline soil supporting various crop species, found maize and sorghum to accumulate more Zn and to be less tolerant to Zn toxicity than lettuce and tomatoes, whereas potatoes and beans were affected least. Plant tops contained 763, 1084, 665, 514, 336 and 235 ppm Zn, respectively. Except for potatoes and beans, these levels were also associated with significant yield depressions. In maize and sorghum significant yield decreases occurred with about 550 ppm Zn in plant tops, the soil containing 146 ppm 0.005*M* DTPA-extractable Zn or more. Walsh *et al.*[18] report no yield depressions in bean and maize crops grown on a loamy sand following application of 363 kg Zn per ha, in imitating 81 years of fungicidal treatment. The leaf tissues contained 444 and 160 ppm Zn, respectively, and the soil 47 ppm 0.05*M* DTPA- extractable Zn.

The nature of Zn toxicity is rather complex. Zn may upset Fe metabolism [6 7 11], but this is not likely to be a general phenomenon [5]. In the present study symptoms resembling those of Fe deficiency were only observed in potatoes. A Zn/P imbalance, interfering with P metabolism, would appear to be a more general feature of Zn toxicity [4]. This conception is supported by the P starvation symptoms in the crops studied here, *i.e.* stunting with or without purple discoloration. Similarly, an upset P/Zn balance, resulting from excessive P accumulation, is known to induce Zn deficiency [3].

The results of soil analysis (p. 9) indicate that the Zn–P antagonism cannot be explained satisfactorily on the basis of chemical reactions leading to mutual immobilization. Moreover, the water-soluble ('available') P fraction in the Neerpelt soil, especially on site 2, is rather higher than the dramatic P response would suggest. Finally, the pot experiments distinctly show that P had no depressive effect on total Zn absorption by the above-ground portions, but did reduce their Zn concentration, resulting from vigorous growth stimulation. It is postulated, therefore that the Zn–P interaction is mainly a plant physiological characteristic. A more comprehensive study of the relative distribution of Zn in the various plant parts would be necessary to reveal a possible role of P in immobilizing Zn in the root cells or impeding translocation of Zn to the shoots [13 16].

However, in a previous study by one of the authors [15] this mechanism was not found to operate for Zn in some broadleaved and coniferous tree species.

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REFERENCES

1 Berrow, M. L. and Webber, J., Trace elements in sewage sludge. J. Sci. Food Agr. **23**, 93–100 (1972).

2 Bes, S. S. de, en Dijk, P. A. van, De bepaling van zink d.m.v. atomaire absorptie in water, grond en gewas. Proefst. Groenten- en Fruitteelt onder Glas, Naaldwijk (1973).

3 Boawn, L. C. and Leggett, G. E., Phosphorus and zinc concentration in Russett Burbank potato tissues in relation to development of zinc deficiency symptoms. Soil Sci. Soc. Am. Proc. **28**, 229–232 (1964).

4 Boawn, L. C. and Rasmussen, P. E., Crop response to excessive zinc fertilization of alkaline soil. Agron. J. **63**, 874–876 (1971).

5 Brown, J. C. and Tiffin, L. O., Zinc deficiency and iron chlorosis dependent on plant species and nutrient-element balance in Tulare clay. Agron. J. **54**, 356–358 (1962).

6 Henkens, Ch. H., Zinkovermaat op bouwland; ***with a summary***: Excess zinc on arable land. Landbouwk. Tijdschr. **73**, 917–926 (1961).

7 Hewitt, E. J., Metal interrelationships in plant nutrition I. Effects of some metal toxicities on sugar beet, tomato, oat, potato and marrowstam kale grown in sand culture. J. Expt. Botany **4**, 54–64 (1953).

8 Jensen, H. L. and Lamm, C. G., On the zinc content of Danish soils. Acta Agr. Scand. **11**, 63–81 (1961).

9 Koukoulakis, P. H., Effects of P–Zn interaction and lime on plant growth in the presence of high levels of extractable zinc. Rept. Inst. for Soil Fertility, Haren (Gr.), The Netherlands **4–1973**, 1–65 (1973).

10 Laske, P., Arbeitsvorschrift zur Vorbereitung der colorimetrischen Cu und Zn Bestimmung im EDTA-Auszug. Staatsschule für Gartenbau und Gartenbauwissenschaft Suttgart/Hohenheim, Pers. Comm. (1970).

11 Lee, C. R., Craddock, G. R., and Hammar, H. E., Factors affecting plant growth in high-zinc medium. I. Influence of iron on growth of flax at various zinc levels. Agron J. **61**, 562–565 (1969).

12 Lee, C. R. and Page, N. R., Soil factors influencing the growth of cotton following peach orchards. Agron. J. **59**. 237–240 (1967).

13 Pauli, A. W., Roscoe Ellis Jr., and Moser, H. C., Zinc uptake and translocation as influenced by phosphorus and calcium carbonate. Agron. J. **60**, 394–396 (1968).

14 Sissingh, H. A., Analytical technique for Pw method used for phosphate status of arable soils in the Netherlands. Plant and Soil **34**, 483–486 (1971).

15 Smilde, K. W., Phosphorus and micronutrient metal uptake by some tree species as affected by phosphate and lime applied to an acid sandy soil. Plant and Soil **39**, 131–148 (1973).

16 Stukenholtz, D. D., Olsen, R. J., Gogan, G., and Olsen, R. A., On the mechanism of phosphorus-zinc interaction in corn nutrition. Soil Sci. Soc. Am. Proc. **30**, 759–763 (1966).

17 Trierweiler, J. F. and Lindsay, W. L., EDTA-ammonium carbonate soil test for zinc. Soil Sci. Soc. Am. Proc. **33**, 49–54 (1969).

18 Walsh, L. M., Stevens, D. R., Seibel, H. D., and Weis, G. G., Effect of high rates of zinc on several crops grown on an irrigated plainfield sand. Comm. Soil. Sci. Plant Anal. **3**, 187–195 (1972).