Prediction of zinc deficiency in navy beans (*Phaseolus vulgaris*) by soil and plant analyses

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Summary. Navy beans (*Phaseolus vulgaris* cv. Gallaroy) were grown with 7 rates of zinc (Zn) in a Zn-deficient gravelly sandy loam in a glasshouse experiment. The plant shoots were harvested 31 days after sowing and the Zn concentration in each of 4 plant parts (YL, young leaf; YOL, young open leaf; YFEL, youngest fully expanded leaf; and whole shoots) was related to the fresh weight of the shoots. The critical Zn concentrations (mg/kg) in the plant parts determined by the 2 intersecting straight lines model were 21.1 for YL (r^2 = 0.66), 17.1 for YOL (r^2 = 0.83), 10.6 for YFEL (r^2 = 0.91) and 12.5 for the whole tops (r^2 = 0.88). The YFEL was selected as an appropriate diagnostic tissue because it is readily identifiable in the field and had the highest r^2 with fresh weight.

In a second glasshouse experiment, the critical Zn concentration in the YFEL and 5 soil tests were evaluated for their ability to predict the Zn status of navy beans. There were 13 soils from sands to clays with a wide range of chemical properties. The soil tests were 0.1 mol/L HCl, DTPA, EDTA, dilute $CaCl_2$ and soil solution Zn. The concentration of Zn in the YFEL correctly predicted Zn deficiency or adequacy in about 77% of samples. The results from both experiments showed that a critical Zn concentration of 10–11 mg/kg in the YFEL can be used to diagnose the Zn status of Gallaroy navy beans.

It was not possible to recommend a single soil test for prediction of the relative yield of navy beans. A combination of quantity (HCl, EDTA, DTPA) and intensity (soil solution, 0.002 mol/L $CaCl_2$, 0.01 mol/L $CaCl_2$) parameters were able to explain most of the variation in the Zn concentration of the YFEL, a more sensitive measure of nutrient availability than relative yield. EDTA-Zn in combination with 0.01 mol/L $CaCl_2$-Zn explained 90% of the variation in the Zn concentration in the YFEL, while HCl- or DTPA-Zn and 0.01 mol/L $CaCl_2$ explained about 80% of the variation. As soil solution Zn was significantly correlated with 0.002 and 0.01 mol/L $CaCl_2$-Zn (r = 0.75, P<0.01; r = 0.62, P<0.05, respectively), $CaCl_2$-Zn may be used as a more convenient measure of Zn intensity than soil solution Zn.

Introduction

Navy beans (*Phaseolus vulgaris*) are very sensitive to zinc (Zn) deficiency (Viets *et al.* 1954; Moraghan 1984), which decreases crop yield and the concentration of Zn in seeds and delays crop maturity (Boawn *et al.* 1969; Brouwer *et al.* 1981). Response of navy beans to Zn fertiliser in Australia has been measured or observed on a range of soils from granitic sands to krasnozems and black earths (Wade and Bath 1985; Armour *et al.* 1989).

Whilst soil and plant analyses have both been used to predict the likelihood of a response to Zn fertilisation, soil analysis before sowing has the advantage of allowing for Zn application at sowing or early in the life of the crop to prevent yield loss. Because extractants for estimating the amount of soil Zn available to plants have generally been satisfactory only for a limited range of soil types, the use of soil tests for predictive purposes is usually confined to the soil types on which the test was developed (Cox and Kamprath 1972). The most commonly used soil tests are those that measure the quantity component of soil Zn by having a high ionic strength in comparison to soil solution or a wide soil/solution ratio (e.g. DTPA and 0.1 mol/L HCl). However, both Tiller *et al.* (1972) and McGrath *et al.* (1985) concluded that intensity measurements appear to be more suitable than quantity measurements for the prediction of deficiency across a range of soil types. Consideration of both quantity and intensity may allow soil tests for Zn to be used over a wider range of soil types. Calibration of soil tests with navy bean growth does not appear to have been reported.

The analysis of plant parts has been shown to be suitable for prediction of Zn deficiency over a range of soils (Brennan 1990). Reuter *et al.* (1982) found that samples of composite plant parts were unsuitable for diagnosis of Zn deficiency in subterranean clover because there were complex relationships between dry matter yield, Zn concentration, time of harvest and Zn supply. They recommended the use of a single plant part of defined physiological age for diagnosis of Zn

deficiency (e.g. youngest open blade for subterranean clover). The main limitation of plant analysis is the short period available for the diagnosis and correction of the deficiency before serious yield loss occurs.

Data on Zn concentrations in shoots of navy beans are limited. Zinc concentration has been measured in whole shoots of navy beans (Moraghan 1984; Leggett and Westermann 1986) and in plant parts of navy beans (Mugwira and Knezek 1971) and red Mexican beans (*Phaseolus vulgaris*) (Viets *et al.* 1954). However, Zn concentrations in a suitable plant part of navy beans have not been related to plant growth or yield to determine critical concentrations.

We evaluated 5 plant parts of navy beans for suitability as diagnostic tissue, and 6 soil tests for their ability to predict the responsiveness of navy beans to Zn.

Materials and methods

An initial experiment was conducted to determine the most appropriate plant tissue, and its critical Zn concentration, for prediction of growth responses of navy beans to applied Zn. A second experiment assessed the ability of soil tests to predict responsiveness to Zn application and the usefulness of the optimum plant tissue concentration previously defined.

Experiment 1. Determination of diagnostic tissue for Zn and critical Zn concentration for navy beans

Fresh weight and Zn concentration of shoots were measured in navy beans grown in a sandy gravelly loam from Talbot (Table 1) with Zn supply varying from very deficient to adequate. Seven rates of Zn as $ZnSO_4.7H_2O$ (0, 0.25, 0.5, 1.0, 1.5, 2.0 and 2.5 mg Zn/kg oven-dry soil) were applied and there were 3 replicates. General glasshouse procedures have been described previously (Armour *et al.* 1989). Navy beans were grown in 2490 g of oven-dry soil in root-cooling tanks at 25°C. After surface application of solutions of Zn and basal nutrients, the soil was allowed to dry and was mixed. *Phaseolus vulgaris* cv. Gallaroy was sown in May 1988 and the shoots were harvested when flower buds were forming 31 days after sowing (DAS). After weighing, the shoots were sectioned into young leaf (YL), young open leaf (YOL), youngest fully expanded leaf (YFEL) and remainder. Zn concentration in each plant part was determined by flame atomic absorption (Allan 1961) after digestion in $HClO_4/H_2SO_4$ (Johnson and Ulrich 1959).

The infectivity of vesicular arbuscular mycorrhizal fungi in roots was determined in each treatment after harvest by the method of Abbott and Robson (1981).

Experiment 2. Prediction of Zn deficiency in navy beans by soil and plant analysis

Navy beans were grown in an experiment with a complete factorial of 13 soils, 3 rates of Zn and 3 replications.

Soils ranging from Zn-deficient to Zn-adequate (0–10 cm) from south-western Western Australia and Queensland were used (Table 1). The Western Australian soils and soil 8 were virgin soils, while the other Queensland soils had been used for more than 20 years for cropping (soils 10, 11, 12, 13) or for permanent introduced pasture (soil 9) without Zn fertiliser. The soils were dried and sieved to <4 mm (Western Australia) or <10 mm (Queensland).

Table 1. Some soil properties (0–10 cm) on an air-dry basis and rates of application of Zn and P in experiment 2

Soil	Location	Classification[A]	pH (1:5, H_2O)	Organic C (%)	ECEC (cmol(+)/kg)	Soil weight (g/pot)	Field capacity (%)	Zn rate (mg/pot) Zn_1	Zn rate (mg/pot) Zn_2	P rate (mg/pot)
				Western Australia						
1	Talbot	Dy 3.81	5.7	3.0	7.24	2500	25	1.8	3.6	600
2	Wongan Hills	Uc 5.22	5.5	0.6	0.91	3200	13	1.8	3.6	250
3	Dandaragan	Uc 5.21	6.2	0.5	4.46	3300	16	1.8	3.6	600
4	Wongan Hills	Uc 5.22	5.4	0.5	0.67	3300	11	1.8	3.6	300
5	Merredin	Dr 2.33	7.1	1.6	8.21	2800	23	1.8	3.6	600
6	Badgingarra	Uc 5.11	5.5	0.5	1.25	3000	17	1.4	2.8	250
7	Nannup	Dy 3.61	5.7	1.2	1.44	2800	28	1.4	2.8	600
				Queensland						
8	Mt Garnet	Dy 5.81	6.3	1.3	5.00	3300	19	5	10	600
9	Murray Upper	Gn 2.21	5.3	1.9	6.82	2300	28	5	10	800
10	Tolga	Gn 3.11	5.6	1.7	8.18	2300	38	5	10	1200
11	Evelyn	Gn 3.74	4.9	4.4	4.37	2300	43	5	10	2000
12	Upper Barron	Gn 3.11	5.7	3.9	10.06	2300	44	5	10	1200
13	Emerald	Ug 5.12	6.9	1.3	64.4	2300	54	26	52	400

[A] Northcote (1971).

Soils 6 and 7 were incubated after a Zn application of 1 mg/pot (before the addition of Zn rates defined in Table 1), with the aim of producing only a moderate response to subsequent Zn application in light-textured soils. Zn was added in solution as $ZnSO_4.7H_2O$ to the soil surface, mixed after drying and repotted. The soils were watered to 75% of field capacity, sealed with plastic bags and incubated in a glasshouse at 30°C for 4 days. The soils were dried on polythene sheeting in a glasshouse, mixed and repotted and then treated as for the remainder of the soils.

Glasshouse procedures were the same as in experiment 1, except for applied nutrient treatments. Rates of Zn (designated Zn_0, Zn_1, Zn_2) varied with soil type (Table 1). Phosphorus was supplied as KH_2PO_4 for rates of application of <800 mg P/pot, or as equal amounts of KH_2PO_4 and NaH_2PO_4 for rates >800 mg P/pot. $MgSO_4.7H_2O$ was applied at 150 mg/pot and H_3BO_3 at 2 mg/pot.

Soil samples were taken from each pot after addition of nutrients and mixing, and sieved to <2 mm. Seeds were sown in December 1987 and the plants were harvested 22 DAS when flower buds were forming. Samples of YFEL taken at harvest were analysed for Zn content. Relative yield (RY) of shoots was calculated as the yield for each Zn rate divided by the maximum yield for each soil.

The methods used for Zn analysis of soil were: (i) 0.1 mol/L HCl (Tiller *et al.* 1972; 30 min shake at soil/solution ratio of 1:20); (ii) 0.005 mol/L EDTA and 0.01 mol/L $Ca(NO_3)_2$ (Fujii and Corey 1986); (iii) 0.005 mol/L DTPA (Lindsay and Norvell 1978); (iv) 0.01 mol/L $CaCl_2$; (v) 0.002 mol/L $CaCl_2$; (vi) soil solution. Samples for methods (iv) and (v) were shaken for 16 h at a soil/solution ratio of 1:5. The $CaCl_2$ extracting solutions were prepared from a stock solution that had been purified with dithizone/chloroform (Hewitt 1952). Soil solution extracts were obtained with a centrifugation technique (Aitken and Outhwaite 1987). After centrifugation, all extracts were filtered (<0.45 µm; $CaCl_2$ and soil solution extracts were acidified to 0.1 mol/L with HCl) and analysed by flame atomic absorption. Flameless atomic absorption was used when Zn concentrations were less than 0.1 mg/L.

An index of buffer capacity (BCI) was calculated for each soil as Q/I where Q was estimated by HCl-extractable Zn, and I was estimated by the soil solution Zn concentration.

Roots from 1 replicate of each treatment in each soil were examined for infection by VA mycorrhizal fungi by the method described for experiment 1, to ensure that responses to Zn were not confounded by different rates of mycorrhizal infectivity in the soils.

Statistical methods

A Mitscherlich equation was used to describe the relationship between fresh weight of shoots and the rate of applied Zn in experiment 1. For experiment 2, the 2 intersecting straight lines model (Griffiths and Miller 1973) was used to describe the relationships between fresh weight of shoots and relative yield and Zn concentration in the YFEL. Zn concentration in the YFEL in experiment 2 was related to measures of quantity, buffer capacity and intensity in the soils with multiple linear regression.

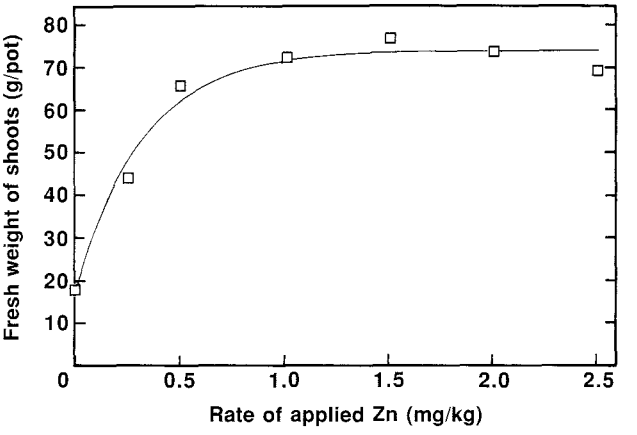

Fig. 1. Experiment 1. The relationship (and fitted Mitscherlich equation) between fresh weight of navy bean shoots and rate of applied Zn. The equation of the line is: $Y = 73.99 - 56.96e^{-3.14x}$ ($r^2 = 0.94$).

Results

Experiment 1. Determination of diagnostic tissue for Zn and critical Zn concentrations for navy beans

Deficiency symptoms. Symptoms of Zn deficiency appeared at 18 DAS and were similar to those described previously (Armour *et al.* 1989) although red veination was not as obvious in this experiment. At harvest, severe Zn deficiency symptoms (stunting, red veination and large necrotic patches on the primary leaves, and faint interveinal chlorosis of the first and second trifoliate leaves) were observed on the nil Zn plants. The symptoms reduced in severity as the Zn rate increased to 1 mg/kg soil. Plants from this treatment had no symptoms, apart from a slight reduction in the growth of shoots, and there were no symptoms at higher application rates.

Fresh weight and Zn concentration of shoots. The application of Zn increased fresh weight of navy bean shoots to a maximum of about 77 g/pot for a Zn application of 1.5 mg/kg soil (Fig. 1). The response curve was well described by a Mitscherlich function. Fresh weight of the plants that received no Zn was 24% of the maximum yield defined by the Mitscherlich function. Infection by VA myccorhizal fungi was too low (< 16%) to affect nutrient uptake (Abbott and

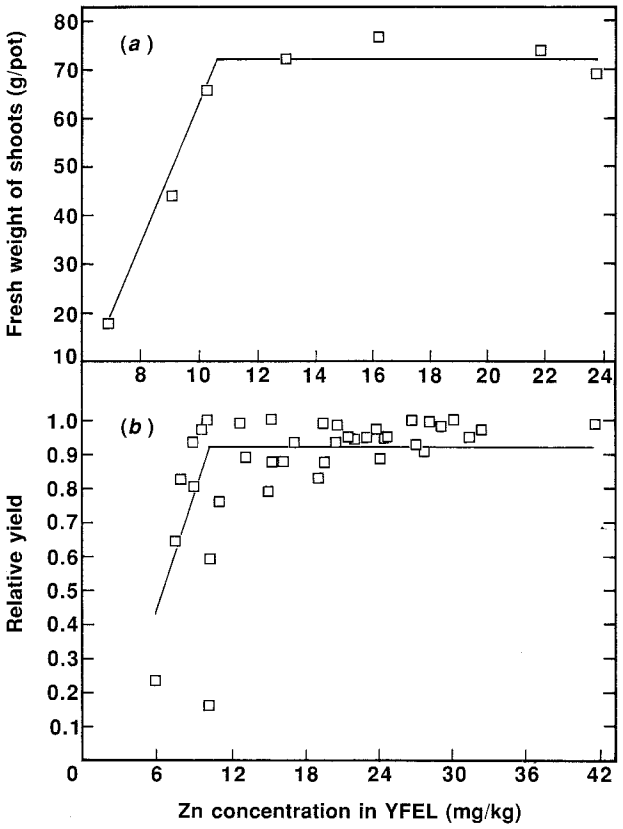

Fig. 2. The relationship between (*a*) fresh weight of navy bean shoots (experiment 1) or (*b*) relative yield of navy bean shoots for Zn_0, Zn_1, and Zn_2 treatments (experiment 2) and Zn concentration in YFEL, and the fitted two intersecting straight lines model. The critical Zn concentrations from the models are (*a*) 10.6 (r^2 = 0.91) and (*b*) 10.1 (r^2 = 0.33) mg/kg.

Robson 1981) and not related to rate of Zn application.

The Zn concentrations in each of the plant parts increased with rate of Zn application up to 0.5–1 mg/kg (Fig. 2*a*, only YFEL data presented). The critical Zn concentrations (and standard errors) in mg/kg determined by the 2 intersecting straight lines model were 21.1 (0.1) for YL, 17.1 (1.4) for YOL, 10.6 (0.4) for YFEL and 12.5 (0.3) for whole tops. The r^2 for the respective plant parts were 0.66, 0.83, 0.91 and 0.88 (P<0.01). YFEL was selected as an appropriate diagnostic tissue because it is readily identifiable in the field and had the highest coefficient of determination with fresh weight.

Experiment 2. Prediction of Zn deficiency in navy beans by soil and plant analysis.

Deficiency symptoms. Zn deficiency symptoms began to appear in Zn_0 plants at 10 DAS (soil 11), 12 DAS (soils 1, 3, 4, 13) and 14 DAS (soils 5, 8). General symptoms were as for experiment 1 but initial symptoms in different soils varied from general chlorosis of the plant to red colouration in the interveinal areas of Zn_0 plants. Deficiency symptoms in plants grown in deficient soils developed rapidly and were seen at harvest in Zn_1 plants of soils 1, 3 and 13 but not in Zn_2 plants. Plants from soil 10 had unusual symptoms from 9 DAS when primary leaves developed sharply defined interveinal chlorosis. These symptoms became slightly paler with each new leaf but were still present on all leaves at harvest. Growth of the plants from soil 10 was not obviously affected but the maximum yield was 79 g compared to yields of 87–110 g for other krasnozem soil types (11 and 12), and the response curve was very flat.

Infection of roots by VAM was low (<8%) in all soils.

Prediction of growth response to applied Zn by concentration in YFEL. Shoot fresh weight was increased by the application of Zn in 8 soils (Table 2). Soils 1, 3, 4, 5, 8, 9, 11 and 13 had a RY for Zn_0 treatments of <0.9 and were considered to be responsive to Zn. The largest increases in fresh weight of shoots from Zn_0 to Zn_2 occurred in soils with the most severe deficiency symptoms (soils 1, 428%; 3, 605%; 4, 166% and 13, 154%). Increases for the remaining responsive soils were 113–126%. Apart from soil 10, all responsive soils showed deficiency symptoms. Zn_1 treatments generally supplied sufficient Zn for maximum growth. Only soils 1 and 9 had a relative yield of less than 0.9 (RY of 0.82 and 0.89, respectively) for this treatment. The critical Zn concentration (and standard error) determined by the 2 intersecting straight lines model was 10.1 (0.5) mg/kg (r^2 = 0.33, P<0.01; Fig. 2*b*).

Relationship between growth parameters and soil tests. The relationships between RY and the Zn concentration determined by soil solution, 0.002 mol/L $CaCl_2$ and 0.01 mol/L $CaCl_2$ soil tests were characterised by a steep initial response, where large increases in RY were observed for small increases in the amount of Zn extracted (Table 2). For HCl, EDTA and DTPA extractants, the relationships between RY and soil test were poorly defined.

Because of the initial steepness of the RY/intensity relationships, the effect of buffer capacity was examined. When Zn concentration in YFEL for the Zn_0 treatments was plotted against soil solution Zn (Fig. 3), it was apparent that at the same intensity (i.e. concentration in the soil solution), high buffer capacity soils supported higher YFEL Zn concentrations than low buffer capacity soils. From this relationship, the soils can be classified as having a high, medium or low buffer capacity using the following ranges of BCI: high, BCI >1.0; medium, BCI 0.1–1.0; low, BCI <0.1. Three separate relationships, dependent on BCI, can be defined between YFEL Zn concentration and soil solution Zn (Fig. 3).

When soil solution Zn was combined with BCI, both

Table 2. Zn concentration in soils at planting, fresh weight (FW) of shoots, relative yield, and Zn concentration in YFEL for experiment 2

Soil	HCl (mg/kg)	EDTA (mg/kg)	DTPA (mg/kg)	0.01 mol/L $CaCl_2$ (mg/kg)	0.002 mol/L $CaCl_2$ (mg/kg)	Soil solution (µg/L)	BCl (1000 L/kg)	FW of shoots Zn_0	FW of shoots Zn_1 (g/pot)	FW of shoots Zn_2	Relative yield for Zn_0	YFEL Zn Zn_0	YFEL Zn Zn_1 (mg/kg)	YFEL Zn Zn_2
1	0.24	0.13	0.07	<0.005	<0.005	0.6	0.40	16.3	57.2	69.6	0.23	5.8	7.8	9.8
2	0.13	0.11	0.06	0.027	0.008	3.1	0.04	65.9	65.7	65.8	1.00	9.5	23.7	32.2
3	0.11	0.09	0.05	<0.005	<0.005	1.1	0.10	13.8	78.2	83.4	0.17	7.9	8.8	15.0
4	0.06	0.04	0.02	0.014	0.005	0.6	0.09	43.8	72.7	72.9	0.60	9.3	28.9	41.4
5	0.62	0.70	0.40	<0.005	—[B]	2.4	0.26	57.4	66.2	67.4	0.85	8.8	20.3	24.2
6[A]	0.34	0.32	0.23	0.147	0.063	19.2	0.02	86.1	82.4	82.7	1.00	12.4	24.5	31.3
7[A]	1.70	1.41	0.53	1.60	0.079	10.4	0.16	72.9	61.2	64.5	1.00	19.3	18.8	19.3
8	0.69	0.82	0.44	0.006	0.017	7.1	0.10	77.8	89.4	97.3	0.80	10.3	15.2	21.3
9	1.11	1.16	0.80	0.025	0.010	5.8	0.19	79.7	80.1	90.4	0.88	15.9	23.9	26.7
10	1.54	0.89	0.73	0.006	0.005	0.9	1.71	75.1	78.4	79.3	0.95	12.9	16.8	21.8
11	1.85	0.52	0.98	0.238	0.071	5.3	0.35	87.0	104.5	110.0	0.79	14.7	21.2	30.0
12	6.58	3.78	2.89	0.021	0.017	1.7	3.87	94.8	92.4	90.2	1.00	23.0	26.9	27.5
13	1.00	0.44	0.28	<0.005	<0.005	0.8	1.25	57.6	87.8	88.7	0.65	7.5	20.4	28.1
s.e.	0.08	0.07	0.06	0.003	0.001	1.5								

[A] After initial Zn application and incubation. [B] Cloudy filtrate.

factors were significant in explaining variation in the YFEL Zn concentration (Table 3), but the r^2 was low (0.55). In multiple regressions of YFEL Zn concentration against soil tests, any of the intensity measurements (soil solution, 0.002 mol/L $CaCl_2$, 0.01 mol/L $CaCl_2$) significantly increased the variation in YFEL concentration accounted for by any quantity soil tests (HCl, EDTA and DTPA, Table 3). Quantity and intensity measurements together accounted for 78–90% of the variation in YFEL Zn concentration.

Soil solution Zn was significantly correlated with 0.002 mol/L $CaCl_2$-Zn and with 0.01 mol/L $CaCl_2$-Zn ($r = 0.75$, $P<0.01$; $r = 0.62$, $P<0.05$, respectively) and the 2 $CaCl_2$ methods were themselves significantly correlated ($r = 0.95$, $P<0.001$). BCI was highly correlated with HCl-, EDTA- and DTPA-Zn (r = 0.90, 0.83 and 0.87, respectively; $P<0.001$). HCl-, EDTA- and DTPA-Zn were correlated with each other ($r > 0.95$, $P<0.001$).

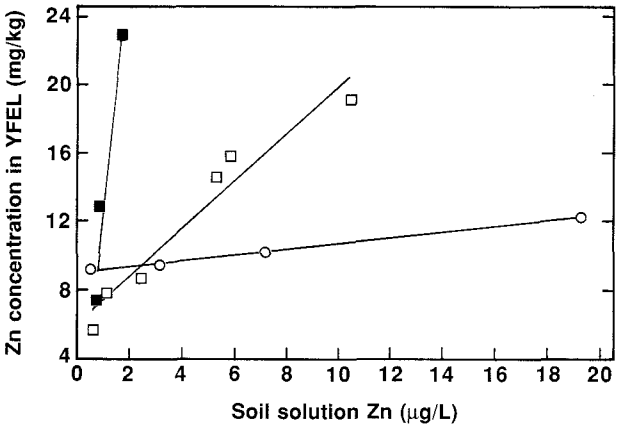

Fig. 3. Experiment 2. The relationship between the Zn concentration in YFEL of navy beans and soil solution Zn. Buffer capacity ratings are low (○), medium(□) and high (■).

Discussion

Prediction of the Zn status of navy beans grown in the 13 soils of experiment 2, using the critical Zn concentration derived in experiment 1 of 10.6 mg/kg in the YFEL, was correct for about 77% of samples. It would have incorrectly diagnosed plants from soil 2 as being Zn-deficient and plants from soils 9 and 11 as being Zn-adequate. The YFEL Zn concentration in soil 8 for the Zn_0 treatment was in the range of the standard error. The critical Zn concentrations in the YFEL determined in experiment 1 with 1 soil (10.6 mg/kg) and in experiment 2 with 13 soils (10.1 mg/kg) were not statistically different ($P<0.01$), so that a critical Zn concentration range in the YFEL of Gallaróy navy beans can be defined as 10–11 mg/kg. These data confirm the usefulness of young plant tissue as diagnostic tissue for Zn in plants, although the advantage of YFEL over whole tops was not as great as that reported by Reuter *et al.* (1972).

The critical Zn concentration range in the YFEL of 10–11 mg/kg for cv. Gallaroy is much lower than the range (i.e. 17–20 mg/kg) reported by Wade and Bath (1985). Our critical Zn concentration in whole tops of 12.5 mg/kg is also less than the range of 18.2–20.2 mg/kg for 3 other navy bean cultivars (Leggett and Westermann 1986). However, in both of these papers

Table 3. Coefficients of multiple regression of YFEL Zn concentration on measures of quantity (HCl, EDTA, DTPA), buffer capacity (BCI, buffer capacity index) and intensity (soil solution, 0.002 mol/L $CaCl_2$, 0.01 mol/L $CaCl_2$)

VAF, variance accounted for

BCI parameter or extractant	Coefficient	Intensity parameter	Coefficient	VAF (%)
BCI	3.321 ± 1.022**	Soil solution	0.492 ± 0.209*	55
HCl	2.470 ± 0.410***	Soil solution	0.355 ± 0.132*	80
HCl	2.173 ± 0.385***	0.002 mol/L $CaCl_2$	71.50 ± 22.88*	83
HCl	2.258 ± 0.429***	0.01 mol/L $CaCl_2$	22.58 ± 9.434*	78
EDTA	4.297 ± 0.687***	Soil solution	0.289 ± 0.128*	81
EDTA	4.002 ± 0.501***	0.002 mol/L $CaCl_2$	74.41 ± 17.14**	90
EDTA	4.262 ± 0.503***	0.01 mol/L $CaCl_2$	27.17 ± 6.384**	90
DTPA	5.554 ± 0.942***	Soil solution	0.337 ± 0.134*	80
DTPA	4.987 ± 0.822***	0.002 mol/L $CaCl_2$	73.60 ± 21.57**	85
DTPA	5.136 ± 0.959***	0.01 mol/L $CaCl_2$	22.39 ± 9.320*	79

* $P<0.05$; ** $P<0.01$; *** $P<0.001$.

the critical Zn concentrations were estimated from only 2 rates of Zn application. Wade and Bath (1985) measured the Zn concentration in the laminae of the YFEL rather than the leaf, and Leggett and Westermann (1986) harvested the shoots after 73 days. Navy bean cultivars vary in their sensitivity to Zn deficiency. For example, the range of yield increases with Zn application in 6 navy bean cultivars was 143–210% (Leggett and Westermann 1986).

For these soils, which represent a very wide range of agriculturally significant soils, it was not possible to recommend a single soil extractant for prediction of Zn deficiency in navy beans. The relationship between relative yield and quantity measurements was not consistent, and all of the intensity measurements had a steep initial response. EDTA in combination with 0.01 mol/L $CaCl_2$ explained the most variation (90%) in Zn concentration of YFEL of the quantity/intensity combinations. HCl or DTPA and 0.01 mol/L $CaCl_2$ explained about 80% of the variation. The 0.002 mol/L or 0.01 mol/L $CaCl_2$ solutions may be used as a more convenient extractant than soil solution for measurement of the soil Zn intensity. The use of 0.002 mol/L $CaCl_2$ has the advantage of a higher correlation with soil solution Zn than 0.01 mol/L $CaCl_2$ but with some soils (e.g. soil 5) it was difficult to obtain a clear filtrate in 0.002 mol/L $CaCl_2$.

Absolute plant parameters such as nutrient content and nutrient concentration are more sensitive indicators of nutrient availability than relative parameters such as RY. Of the absolute parameters, Zn concentrations in the YFEL were available for this experiment. For both YFEL Zn concentration and RY, it would be expected that at the same intensity, soils of high buffer capacity would have greater Zn availability than soils of low buffer capacity, because the former soils would maintain intensity despite the absorption of Zn from the soil solution by plant roots. A soil test which reflects Zn availability to the plant must therefore be a composite index combining both intensity and buffer capacity. The results of experiment 2 indicate that an intensity-based soil test (such as soil solution Zn or 0.002 mol/L $CaCl_2$) requires an estimate of buffer capacity to estimate Zn availability adequately, whereas soil tests which primarily estimate quantity (e.g. HCl-Zn) require the addition of an intensity estimate. This situation is analogous to the evaluation of soil tests for P, and either of 2 approaches may be adopted. One can either combine estimates of intensity and quantity or buffer capacity in multiple regression equations to describe nutrient availability as suggested by Moody and Barry (1983), or find an empirical soil test which is highly correlated with nutrient availability in that particular situation and which gives a composite measure of quantity and intensity (eg. Holford and Crocker 1988). As BCI was significantly correlated ($P<0.01$) with the quantity soil tests (HCl, EDTA and DTPA), the quantity soil tests may be used instead of BCI (Table 3) Perhaps narrower soil/extracting solution ratios and lower extractant concentrations for the quantity tests would improve the correlation of these empirical tests with Zn availability..

These data confirm the conclusions of Tiller *et al.* (1972) for wheat and clover and McGrath *et al.* (1985) for clover that consideration of the intensity of Zn in the soil is required to develop a soil test that will predict Zn responsiveness over a range of soil types.

Conclusions

A critical concentration of 10–11 mg/kg in the YFEL can be used to diagnose the Zn status of Gallaroy navy

beans. None of the soil tests assessed were able to predict Zn deficiency when considered alone. However, combining EDTA-Zn with 0.01 mol/L $CaCl_2$-Zn in a multiple regression accounted for 90% of the variation in Zn concentration of the YFEL. If 4.3 (EDTA-Zn) + 27.2 (0.01 mol/L $CaCl_2$-Zn) is less than 2.7 (from Table 3), then it may be inferred that a Zn deficiency in Gallaroy is likely (i.e. the predicted YFEL Zn concentration will be less than the critical concentration of 10 mg/kg). The coefficients of this equation need to be verified under field conditions.

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