

Evaluation of Selected Extractants for Boron in Some Queensland Soils

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Abstract

Glasshouse and laboratory studies were undertaken to evaluate a range of extractants for determining the boron status of a suite of predominantly acidic soils. In addition to hot water (commonly used as an extractant for soil boron), hot 0.01 M CaCl₂, 0.05 M mannitol/0.01 M CaCl₂, 0.05 M mannitol (buffered at pH 7.5), 1 M NH₄OAc, 5% (v/v) glycerol and 0.01 M tartaric acid were assessed as extractants since these reagents can complex boron.

Sunflower (*Helianthus annuus* cv. Hysun 31) was grown with three levels of applied boron (0, 0.5 and 1.0 kg B ha⁻¹) in each of 20 soils. Relative dry matter yield, tissue boron concentration, boron uptake and relative boron uptake of control plants (0 kg B ha⁻¹) were determined. Both hot water and hot 0.01 M CaCl₂ extractable boron were related to each of these plant parameters, whereas boron extracted by the other procedures was not.

Levels of boron extracted with mannitol and glycerol were very low in comparison to those displaced from the soil by the refluxing procedures. The inability of mannitol to extract boron from these soils is discussed in relation to the chemistry of mannitol-boron complexes, and it is suggested that mannitol would not be an effective extractant for boron in acid soils.

Soil solution extracts (obtained after equilibration at 10 kPa matric suction) had concentrations <0.1 µg B ml⁻¹. Because of the low concentrations and narrow range across the 20 soils, soil solution boron was not related to plant growth parameters obtained from the glasshouse study.

Introduction

Although boron deficiency has been reported in a number of acidic soils in eastern Queensland (Hughes 1959; Watson 1973; Bartholomew and Nicholson 1976), there is little published information evaluating soil tests for boron in the region. Hot water extraction of boron (Berger and Truog 1944) is a commonly used method of obtaining an index of plant available boron in soils (Cox and Kamprath 1972; Bingham 1982). Unfortunately the method presents difficulties for routine analysis, since extracts free of colloidal material are difficult to obtain and are thus not suitable for analysis by inductively-coupled-plasma atomic emission spectrometry (ICP-AES) or colorimetric techniques. To overcome this problem, Cartwright *et al.* (1983) proposed the use of 0.01 M CaCl₂-0.05 M mannitol extractable boron and noted that this extractant was as effective as hot water extraction in predicting boron uptake by wheat plants in 18 surface soils from South Australia. A similar method (0.01 M CaCl₂-0.01 M mannitol) is now recommended as an index of plant available boron (Bingham 1982).

Other workers (Hingston 1964; Rhoades *et al.* 1970; Griffin and Bureau 1974) have also used mannitol as an extractant for soil boron because of its ability to

complex boron. However, chemical studies (Onak *et al.* 1959; Knoeck and Taylor 1969; Montgomery 1971) on the nature of the mannitol-boron complex have shown that the ability of mannitol to complex boron is dependent on pH, with the concentration of mannitol-boron complex decreasing with decreasing pH. Knoeck and Taylor (1969) concluded that mannitol reacted only with the borate ion (and not with boric acid) to produce the complex. Since the hydrolysis of boric acid to the borate ion $[B(OH)_4^-]$ has a pK value of 9, there will be little or no borate in acid conditions (Evans and Sparks 1983). Thus an unbuffered mannitol solution would not be expected to extract more boron than a water extract from acid soils. Where mannitol has been used as a boron extractant, the soils studied were either alkaline (Rhoades *et al.* 1970; Griffin and Burau 1974) or mainly calcareous and alkaline (Cartwright *et al.* 1983). In an examination of boron adsorption and desorption on clay minerals, Hingston (1964) found that 0.01 M mannitol in 0.01 M $CaCl_2$ was unable to completely remove boron from the clay at low pH values, whereas at pH values of around 8.5–9.0 most of the adsorbed boron was desorbed. The use of mannitol to extract boron from acidic soils has not been fully evaluated.

The ability of other polyhydroxy compounds (e.g. glycerol) and hydroxycarboxylic acids (e.g. tartaric and salicylic acids) to react with borates and boric acid, respectively, has been known for some time (Durrant and Durrant 1962; Kustin and Pizer 1969). There is little evidence in the literature of the potential of these compounds as extractants for soil boron despite the fact that numerous extraction techniques have been used to obtain an index of available boron (Farrar 1975). The aim of the work reported here was to evaluate the suitability of a number of extractants for assessing the boron status of some predominantly acidic soils from Queensland. In particular, we were interested in assessing methods suitable for routine analysis and allowing boron measurement by ICP-AES.

Materials and Methods

The 0–15 cm layer was collected from each of 20 soils known to be low in hot water-soluble boron ($<1 \mu\text{g B g}^{-1}$). Soils were air dried and sieved ($<5 \text{ mm}$) through a plastic screen prior to glasshouse experimentation. A subsample of each was subsequently ground ($<2 \text{ mm}$) and stored for laboratory analysis. Selected characteristics of these soils are presented in Table 1.

Glasshouse Trials

Pot experimentation, in which a completely randomized design comprising three levels of boron (equivalent to 0, 0.5 and 1.0 kg B ha⁻¹, calculated on an area basis) and four replications, was conducted on each of the 20 soils. Soil was placed in 15 cm diameter polyethylene lined pots and fertilized with N, K, S, Ca, Mg, Cu, Zn, Mn and Mo at rates equivalent to 200, 60, 25, 30, 15, 2, 2, 4 and 0.2 kg ha⁻¹ respectively. Basal P (as NaH_2PO_4) was applied to each soil to ensure non-limiting supply, the rate of application being based on soil test values and experience with soils of similar texture and mineralogy. Following incorporation of basal nutrients into the soil, appropriate amounts of a H_3BO_3 solution were thoroughly mixed with the potted soil to give the above-mentioned rates of boron application. The soil in each pot was then wet with triple-deionized water to a matric suction of 10 kPa and incubated for 1 week at ambient temperature.

Four pre-germinated sunflower seeds (*Helianthus annuus* cv. Hysun 31) were sown in each pot and, after 9 days, the emerged plants were thinned to three per pot. The potted soil was wet to a matric suction of 10 kPa with triple-deionized water on a daily basis.

Plant tops were harvested when the treatments receiving applied boron attained a height of 50–55 cm. This harvesting technique was designed to compensate for differences in growth rates between soils and to subject each soil to approximately the same amount of exploitation. Plant ages at harvest ranged from 22 to 37 days.

After harvesting, the tops were washed in triple-deionized water, dried at 60°C for 48 h and weighed. The dried plant material was ground <1 mm in a stainless steel mill, subsamples dry ashed for 16 h at 500°C and the ash taken up in 10 M HCl. The boron concentration in the diluted sample (2 M HCl) was determined by ICP-AES. A Labtest (Australia) Plasmascan model 700 with a modified Babington (Wolcott and Sobel 1978) nebuliser was used. Instrumental operating parameters were: incident power, 1.2 kW; sample argon flow rate, 0.95 l min⁻¹; coolant argon flow rate, 12 l min⁻¹; wavelength, 208.9 nm.

Table 1. Some characteristics of the soils

Soil	pH	pH	EC ^A (mS m ⁻¹)	Organic ^B carbon (%)	Property ECEC (mmol(+) kg ⁻¹)	% by weight in size fraction (mm)			
	1:5 in H ₂ O	1:5 in 0.01 M CaCl ₂				2-0.2	0.2-0.02	0.02-0.002	<0.002
1	6.1	5.5	6.8	1.0	68	10	20	10	60
2	6.5	5.3	2.4	1.4	108	9	12	9	70
3	6.8	5.7	3.7	0.8	35	60	27	6	7
4	6.9	5.8	1.7	0.3	15	72	23	2	3
5	5.6	4.4	3.5	0.8	16	62	27	5	6
6	5.7	4.2	1.7	1.1	34	37	41	10	11
7	5.0	3.6	0.7	0.1	4	62	36	1	1
8	5.7	4.4	3.5	1.4	95	15	24	21	40
9	6.0	5.0	6.0	3.9	131	20	22	17	41
10	5.9	4.6	1.6	0.7	18	37	41	15	8
11	6.1	5.0	0.7	0.3	17	63	19	1	16
12	6.1	5.2	4.7	1.0	112	18	18	10	54
13	6.6	5.7	9.2	3.2	552	5	18	19	58
14	7.7	6.8	15.7	1.9	306	12	37	20	31
15	6.5	4.9	2.6	0.7	37	47	32	9	11
16	6.9	6.0	2.9	1.2	344	36	38	12	14
17	7.4	6.6	9.4	1.1	201	7	46	9	37
18	4.7	3.7	2.6	0.7	38	58	24	8	10
19	5.8	4.5	1.1	0.5	9	66	27	6	2
20	5.9	4.3	1.6	1.8	28	11	27	42	20

^A 1:5 soil: water suspension.

^B Walkley-Black value.

Soil Analyses

With the exception of hot water, hot 0.01 M CaCl₂ and soil solution extracts, all equilibria were conducted on an end-over-end shaker for 1 h at 23°C and involved the extraction of soil samples (10 g) with 20 ml of the following solutions:

- 0.05 M mannitol in 0.01 M CaCl₂ adjusted to pH 8.5 (Cartwright *et al.* 1983);
- 0.05 M mannitol in Tris buffer (pH 7.5);
- 1 M NH₄OAc (pH 4.8);
- 0.01 M tartaric acid;
- 5% glycerol (v/v) in 0.01 M CaCl₂;
- 0.01 M CaCl₂.

After equilibration, the pH of all suspensions was measured, the suspension was centrifuged for 10 min (relative centrifugal force, 800 g) and the supernatant was filtered through a Whatman No. 40 filter paper. Boron concentrations in the filtered extracts were determined by ICP-AES with standards prepared in the appropriate matrix; in all experimentation polyethylene laboratory ware was used exclusively.

Hot water-soluble boron was extracted by the method of Berger and Truog (1944) and the boron was determined using the curcumin complex (Hayes and Metcalfe 1962). Hot 0.01 M CaCl₂-extractable

boron was determined using the method described by Bingham (1982) except that the suspensions were refluxed for 10 min and the boron concentrations in the filtrates were determined by ICP-AES.

Soil solution extracts were obtained by wetting 250 g samples of soil to a matric suction of 10 kPa and incubating the samples (at 23°C) in polypropylene containers for two weeks. Samples were then centrifuged for 45 min (relative centrifugal force, 1000g) in polypropylene jigs similar to those described by Gillman (1976) and the extract was retained for analysis.

Duplicate determinations were conducted for each laboratory measurement and all analyses are reported on an oven-dry (105°C) basis.

Table 2. Mean boron uptake in tops of sunflower plants
Plants were grown with three levels of applied boron (kg ha⁻¹) in 20 Queensland soils

Soil	Boron uptake ($\mu\text{g pot}^{-1}$) for applied boron rates of			Soil	Boron uptake ($\mu\text{g pot}^{-1}$) for applied boron rates of		
	0	0.5	1.0		0	0.5	1.0
1	347	395	457	11	123	334	359
2	250	357	418	12	271	341	364
3	214	452	533	13	397	411	411
4	143	410	491	14	373	440	397
5	168	364	407	15	143	401	540
6	106	342	459	16	226	341	410
7	13	86	125	17	216	270	313
8	231	287	316	18	9	188	256
9	351	389	478	19	79	339	409
10	116	372	519	20	191	331	386

Table 3. Extractable boron and the pH of selected soil : extractant suspensions in some Queensland soils

Boron values are expressed as $\mu\text{g B g}^{-1}$ except soil solution boron ($\mu\text{g B ml}^{-1}$); pH values are in parentheses

Soil	Hot water	Hot 0.01 M CaCl ₂	0.05 M mannitol/ 0.01 M CaCl ₂	0.05 M mannitol/ Tris buffer pH 7.5	1 M NH ₄ OAc pH 4.8	0.01 M tartaric acid	5% glycerol (v/v)/0.01 M CaCl ₂	Soil solution extract
1	0.78	1.40	0.04 (5.5)	0.05 (6.6)	0.27	0.21 (4.6)	0.04 (5.5)	0.02 (5.3)
2	0.43	0.89	0.01 (5.4)	0.01 (6.5)	0.17	0.15 (4.5)	0.01 (5.3)	<0.01 (5.3)
3	0.30	0.29	0.03 (5.9)	0.09 (7.3)	0.16	0.16 (3.7)	0.02 (5.8)	0.04 (6.4)
4	0.24	0.15	<0.01 (6.0)	0.07 (7.4)	0.06	0.10 (3.2)	0.03 (5.8)	0.03 (6.8)
5	0.36	0.23	0.04 (4.5)	0.08 (7.1)	0.14	0.15 (3.0)	0.02 (4.4)	0.05 (4.7)
6	0.25	0.16	<0.01 (4.3)	0.08 (6.7)	0.22	0.18 (3.1)	0.01 (4.1)	<0.01 (4.6)
7	0.14	0.03	<0.01 (3.4)	0.05 (7.3)	0.08	0.02 (2.6)	0.03 (3.4)	<0.01 (4.0)
8	0.93	0.99	0.02 (4.5)	0.04 (5.7)	0.30	0.38 (3.8)	0.08 (4.4)	0.02 (4.9)
9	0.71	1.25	0.01 (5.2)	0.06 (6.0)	0.43	0.49 (4.6)	0.06 (5.1)	0.03 (6.0)
10	0.21	0.14	<0.01 (4.6)	0.10 (7.1)	0.18	0.19 (3.1)	0.01 (4.5)	0.05 (5.1)
11	0.17	0.18	<0.01 (5.1)	0.06 (7.3)	0.10	0.07 (3.0)	0.05 (5.0)	0.02 (5.6)
12	0.65	1.11	0.01 (5.3)	0.06 (6.6)	0.23	0.23 (4.1)	0.08 (5.2)	0.06 (4.9)
13	0.54	1.88	0.06 (5.8)	0.16 (6.6)	0.69	0.20 (5.1)	0.06 (5.8)	0.05 (6.5)
14	0.56	1.04	0.11 (7.0)	0.20 (7.4)	0.35	0.37 (5.4)	0.07 (6.9)	0.08 (7.8)
15	0.18	0.19	<0.01 (5.0)	0.07 (7.1)	0.10	0.10 (3.4)	0.03 (4.9)	0.02 (5.4)
16	0.27	0.42	<0.01 (6.1)	0.08 (7.1)	0.43	0.15 (4.7)	0.01 (6.1)	0.03 (6.6)
17	0.81	1.19	0.09 (6.7)	0.22 (7.3)	0.58	0.58 (4.9)	0.23 (6.6)	0.09 (7.4)
18	0.12	0.14	0.05 (3.7)	0.01 (5.5)	0.49	0.28 (2.9)	0.08 (3.6)	0.02 (3.9)
19	0.13	0.12	0.01 (4.6)	0.12 (7.1)	0.17	0.11 (2.9)	0.04 (4.5)	0.03 (4.7)
20	0.42	0.79	0.02 (4.3)	0.06 (6.4)	0.24	0.46 (3.4)	0.03 (4.3)	0.01 (4.8)

Results

The application of boron significantly ($P < 0.05$) increased the dry matter yield of sunflower in soils 7, 18 and 19 with the yield of the control treatment relative to the maximum yield being 75%, 11% and 76%, respectively. There were marked differences between soils in the plant uptake of boron from the control pots (Table 2). Although, as expected, the application of boron increased boron uptake (Table 2), the magnitude of this increase varied between soils.

The amounts of boron extracted by the various extractants are shown in Table 3. Equilibration with 0.01 M CaCl_2 at 23°C for 1 h resulted in levels of extractable boron $< 0.1 \mu\text{g g}^{-1}$ in all soils (data not shown). The amounts of boron extracted with 0.05 M mannitol in 0.01 M CaCl_2 , 5% glycerol in 0.01 M CaCl_2 and 0.05 M mannitol buffered at pH 7.5 were all very low and, in most soils, were substantially lower than that displaced in the refluxing procedures (Table 3). In general, for a given soil, the level of boron extracted with tartaric acid was equivalent to that extracted with 1 M NH_4OAc .

Soil tests are commonly evaluated by relating relative yields against soil test values. Since only three soils gave significant dry matter responses to applied boron, it was considered necessary to evaluate the soil tests using additional parameters. Owing to the absence of any yield increases with applied boron in the soils studied, Cartwright *et al.* (1983) used the relative boron uptake as a basis for assessing soil tests, i.e.

$$(B_t - B_c)/B_c,$$

where B_t is the boron uptake by treated plants and B_c is the boron uptake by control plants. In the present study, the ability of each extractant to evaluate the soil boron status was assessed by examining the relationship between the level of extracted boron and each of the relative dry matter yield (mean yield of 0 kg B ha^{-1} treatment as a percentage of mean yield with applied boron), relative boron uptake, tissue boron concentration and boron uptake by the control plants. Each of these factors is plotted against hot water-soluble boron and hot 0.01 M CaCl_2 extractable boron in Figs 1 and 2, respectively. Regressions fitted to tissue boron content and boron uptake data had higher coefficients of determination in the case of hot 0.01 M CaCl_2 extractable boron (Figs 1 and 2). The relative boron uptake values shown (Figs 1*b* and 2*b*) were calculated for the case where B_t was taken as that of the 0.5 kg B ha^{-1} treatment. Similar relationships (not shown) were obtained when B_t was taken as that of the 1.0 kg B ha^{-1} treatment. None of the other extractants resulted in a definitive relationship between extractable boron and any of the plant growth or boron uptake parameters and, in the interests of brevity, these plots have been omitted.

The concentrations of boron recorded in soil solution extracts from these soils were low and ranged from $< 0.01 \mu\text{g B ml}^{-1}$ to $0.09 \mu\text{g B ml}^{-1}$ (Table 3).

Discussion

The soils used in this study were collected from tropical and subtropical regions of eastern Queensland and all, except two, had pH values less than 7.0 (Table 1). The low levels of extractable boron recorded in these soils support the view (Lopes 1980) that many tropical and subtropical soils are likely to be low in plant available boron. In particular, boron deficiency is likely to occur on coarse-textured, leached

soils of low organic matter status owing to the fact that boron is easily leached and that boron adsorption on soil minerals is at a minimum at low pH values. The boron extracted from soil with hot water has been related to plant response in numerous studies, and is considered to come from an organic, an adsorbed inorganic and a soluble inorganic pool (Gupta *et al.* 1985). Any alternative extractant should be capable of removing boron from these sources. The results obtained in this study suggest that for acidic, low boron soils, a boiling or refluxing step is required to extract significant quantities of boron. Extractions conducted on

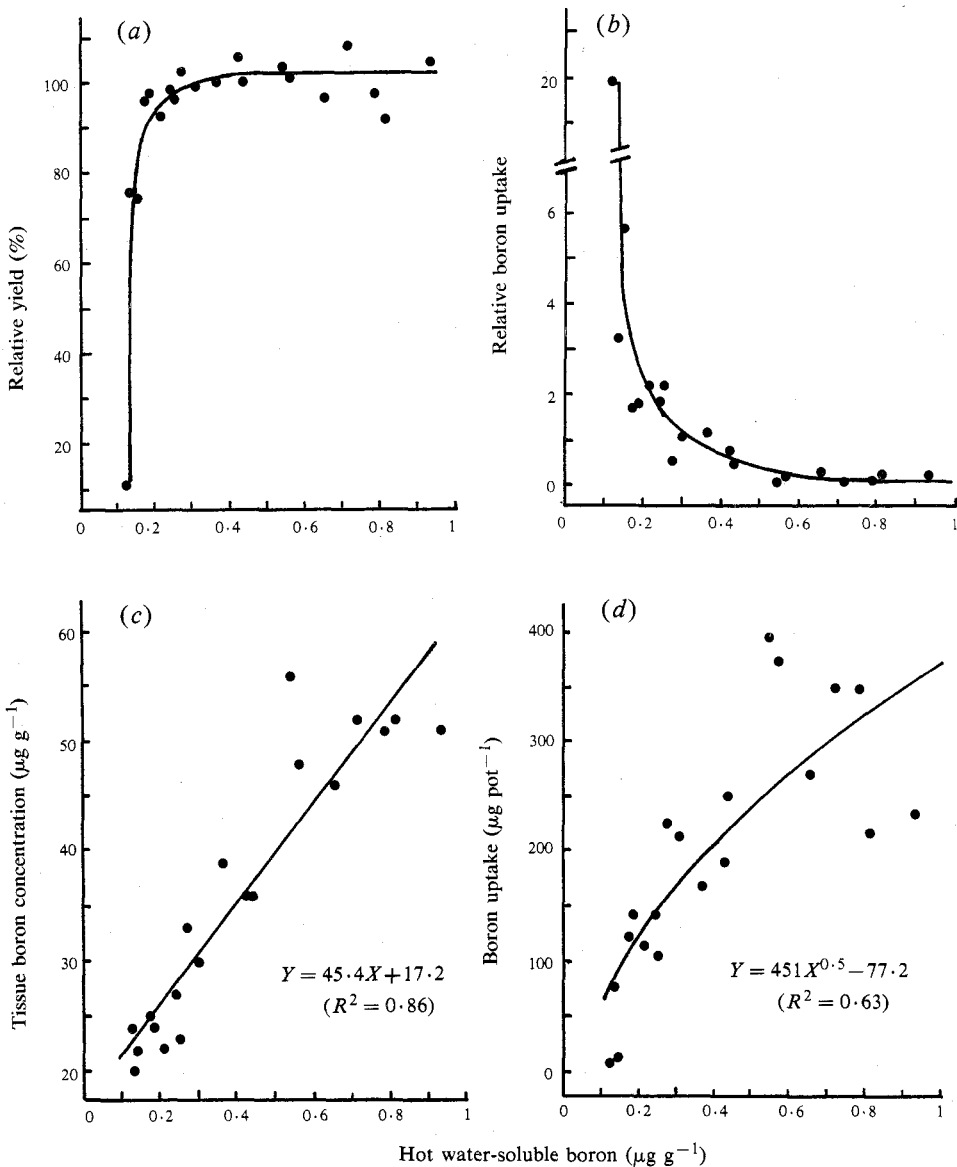


Fig. 1. Relationship between hot water-soluble boron and (a) relative dry matter yield, (b) relative boron uptake, (c) tissue boron concentration and (d) boron uptake of the control plants.

low boron soils at 20°C by Cartwright *et al.* (1983) also resulted in levels of boron well below those obtained with hot water.

For the suite of soils used in this work, 0.05 M mannitol was unable to extract appreciable quantities of boron. In studies by Rhoades *et al.* (1970) and Griffin and Burau (1974), where mannitol was used to extract soil boron, the soils were alkaline with pH values ranging up to 9.6. The work of Cartwright *et al.* (1983), in evaluating the use of mannitol in soil tests for boron, used soils that were predominantly alkaline. The failure of mannitol to extract appreciable boron from

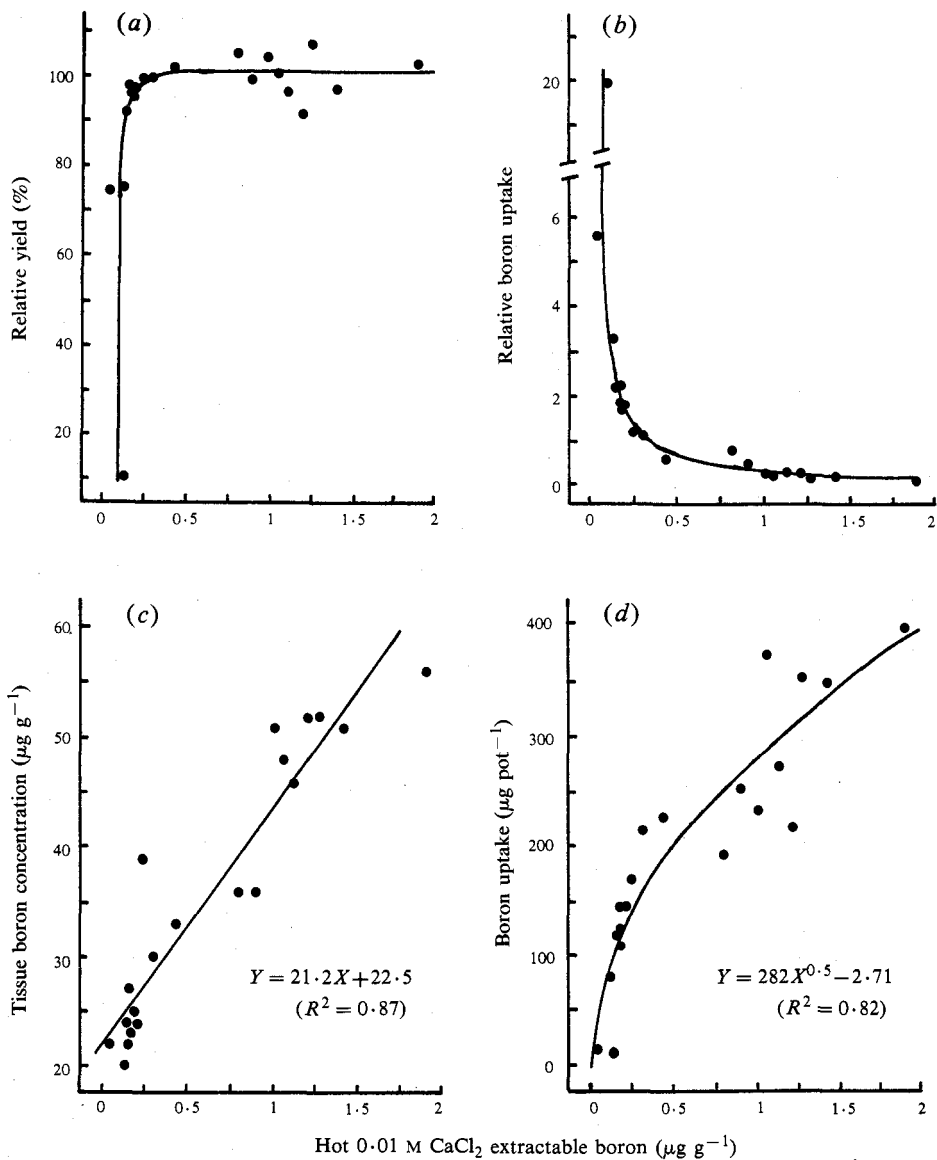


Fig. 2. Relationship between hot 0.01 M CaCl₂ extractable boron and (a) relative dry matter yield, (b) relative boron uptake, (c) tissue boron concentration and (d) boron uptake of the control plants.

the soils used in the present study may be explained by an examination of the literature pertaining to the chemistry of the mannitol-boron complex. Onak *et al.* (1959), using nuclear magnetic resonance spectroscopy, showed that only in basic solution is appreciable mannitol-boron present. Knoeck and Taylor (1969) obtained proton magnetic resonance spectra that indicated no mannitol-boron complex formation in the presence of undissociated boric acid and considered that mannitol reacted only with the borate anion. These studies supported an earlier potentiometric examination of the mannitol-boron complex (Deutsch and Osoling 1949) which concluded that mannitol reacted with the borate ion. Montgomery (1971) computed the pH dependence and composition of solutions of borate and mannitol and derived relationships that showed the ability of mannitol to complex boron is at a maximum at pH values >8 . Although, in the presence of excess mannitol, complex formation occurs under acidic conditions, the concentration of the complex decreases with decreasing pH (Montgomery 1971). The 0.05 M mannitol extractant was initially adjusted to pH 8.5; however, it is unbuffered and the soil : extractant suspension attains a pH similar to that obtained using 0.01 M CaCl_2 at a 1 : 5 soil/solution ratio (Tables 1 and 3). Thus, since there would be little or no borate ion in acid soils, it is not surprising that mannitol was unable to enhance the extraction of boron from our soils. These results and a consideration of the chemistry of the mannitol-boron complex indicate that unbuffered mannitol does not aid the extraction of boron from acidic soils.

If a soil/mannitol suspension could be buffered at an alkaline pH it might be expected to extract more boron. In an attempt to achieve this, we equilibrated the soils with mannitol in Tris buffer at pH 7.5 (buffering the soil at higher pH values resulted in coloured extracts). Although in a 1 : 2 soil/extractant suspension there was insufficient buffer to maintain the pH at 7.5 (Table 3), greater amounts of boron were extracted by mannitol in most soils when the presence of a buffer shifted the pH to higher values (Table 3). The contention that the ability of mannitol to complex soil boron is pH-dependent is supported by the fact that boron extracted with mannitol in the presence of Tris buffer was exponentially related to suspension pH ($Y = 0.0004e^{0.75x}$, $R^2 = 0.52$, $P < 0.001$). The results obtained here are in agreement with the findings of Bloesch (1985) who noted that mannitol was only effective in decreasing boron adsorption on goethite and gibbsite at pH values greater than 7. Glycerol (5% in 0.01 M CaCl_2) also failed to remove significant amounts of boron from these soils (Table 3) and it appears that, like other polyols, glycerol-boron complex formation involves reaction of the polyol with the borate ion (Kustin and Pizer 1969).

The amounts of boron extracted with tartaric acid were higher than those removed by either mannitol or glycerol (Table 3) and this may be attributed to the ability of tartaric acid to complex H_3BO_3 (Kustin and Pizer 1969; Acree 1971). Additionally, the low pH of tartaric acid extracts (Table 3) would enhance desorption of boron and possibly result in the dissolution of some boron containing minerals. Although 1 M NH_4OAc extracted similar amounts of boron to those with tartaric acid, there is little evidence in the literature indicating that NH_4OAc can complex boric acid. Some researchers have used ammonium acetate extractable boron to predict plant response and boron uptake (Gupta and Stewart 1975; Cartwright *et al.* 1983), while others have had less success with this extractant (Bartlett and Picarelli 1973; Sherrell 1983). Neither tartaric acid nor 1 M NH_4OAc

extractable boron was related to relative dry matter yield, relative boron uptake, boron uptake or tissue boron concentration, and thus these extractants appear to be unsuitable for evaluating the soil boron status on these soil types.

Of the soil test procedures evaluated in this work, hot water and hot 0.01 M CaCl_2 were far superior to the other methods as predictive tests. Data obtained with hot CaCl_2 resulted in slightly better relationships between extractable boron and boron uptake, relative boron uptake and tissue boron concentration (Figs 1 and 2). In soils with relatively high clay content (>20%) hot 0.01 M CaCl_2 extracted more boron than hot water (Tables 1 and 3). The longer refluxing time in the case of hot 0.01 M CaCl_2 (10 min) compared with the hot water extraction (5 min) and the higher ionic strength of 0.01 M CaCl_2 may possibly explain these differences. That boiling time has a marked effect on extractable boron in high clay soils has been demonstrated by Wikner (1986). Extraction with hot CaCl_2 also results in flocculation of colloidal material and the extracts can be filtered immediately after the refluxing step. In all of the soils tested in this study the filtered extracts were clear and could be analysed by ICP-AES. In a recent investigation of extraction procedures for soil boron, Schuppli (1986) also noted that hot CaCl_2 (0.02 M) extraction of soils reduced background colour in most of the soils tested. Cate-Nelson separations (Cate and Nelson 1971) of data shown in Figs 1a and 2a resulted in coefficients of determination of 0.65 and 0.64, respectively, indicating, in both cases, that above 0.14 $\mu\text{g B g}^{-1}$ a yield response was unlikely. These relationships, although derived from glasshouse experimentation, suggest that critical levels established previously for hot water extracts may be applicable to 0.01 M CaCl_2 extractable boron. This remains to be verified in field experiments.

In a recent review Gupta *et al.* (1985) indicated that, since it had been observed that plants responded only to boron in soil solution (Hatcher *et al.* 1959; Ryan *et al.* 1977), the relationship between soil solution boron and relative yield may provide a more universal means of predicting the soil boron status. However, in the studies by Hatcher *et al.* (1959) and Ryan *et al.* (1977), the various levels of boron in soil solution were achieved by leaching the soil with water containing a range of boron concentrations (0.1–10 $\mu\text{g B ml}^{-1}$) and, although yield reductions due to boron toxicity occurred, none of the plants were boron deficient. In the work reported here boron concentrations in soil solution extracts obtained from untreated soils were low (<0.1 $\mu\text{g B ml}^{-1}$) and some extracts contained levels of boron below the detection limit ($\approx 0.01 \mu\text{g ml}^{-1}$) of ICP-AES (Table 3). Because of the low concentrations and narrow range, these data do not provide a satisfactory basis for use in a predictive capacity. Unfortunately the quantities of extract obtained from most soils were insufficient to permit a concentration procedure and we were therefore unable to better differentiate the boron levels in soil solution. Although the levels of boron in the soil solution of these soils are low, the concentrations measured are in close agreement with those normally used in flowing culture solutions to maintain adequate plant growth (Asher 1978). The idealized relationship between soil solution boron and relative dry matter yield of Gupta *et al.* (1985) suggests that below about 2 $\mu\text{g B ml}^{-1}$ plant growth will be restricted owing to inadequate boron. Data obtained in the present study indicate that the threshold level between deficiency and adequacy will be considerably lower. The use of soil solution boron to predict boron deficiency may be limited by the analytical procedures required to measure such low levels.

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References

- Acree T. E. (1971). The chemistry of sugars in boric acid solutions. *Adv. Chem. Ser.* **117**, 208-19.
- Asher, C. J. (1978). Natural and synthetic culture media for spermatophytes. In 'CRC Handbook Series in Nutrition and Food'. (Ed. R. Miloslav.) pp. 575-609. (CRC Press: Cleveland, Ohio.)
- Bartholomew, B. L., and Nicholson, A. J. (1976). Boron deficiency in tobacco. *Queensl. Agric. J.* **102**, 273-6.
- Bartlett, R. J., and Picarelli, C. J. (1973). Availability of boron and phosphorus as affected by liming an acid potato soil. *Soil Sci.* **116**, 77-83.
- Berger, K. C., and Truog, E. (1944). Boron tests and determination for soils and plants. *Soil Sci.* **57**, 25-36.
- Bingham, F. T. (1982). Boron. In 'Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties'. (Ed. A. L. Page.) pp. 431-47. (Am. Soc. Agron.: Madison, Wisc.)
- Bloesch, P. M. (1985). Adsorption and desorption of boron by goethite and gibbsite. M. Ag. Sc. Thesis, University of Queensland.
- Cartwright, B., Tiller, B. A., Zarcinas, B. A., and Spouncer, L. R. (1983). The chemical assessment of the boron status of soils. *Aust. J. Soil Res.* **21**, 321-32.
- Cate, R. B., and Nelson, L. A. (1971). A simple statistical procedure for partitioning soil test correlation data into two classes. *Soil Sci. Soc. Am. Proc.* **35**, 658-60.
- Cox, R. F., and Kamprath, E. J. (1972). Micronutrient soil tests. In 'Micronutrients in Agriculture'. (Eds J. J. Mordvedt, P. M. Giordano and W. L. Lindsay.) pp. 289-317. (Soil Sci. Soc. Am.: Madison, Wisc.)
- Deutsch, A., and Osoling, S. (1949). Conductimetric and potentiometric studies of the stoichiometry and equilibria of the boric acid-mannitol complexes. *J. Am. Chem. Soc.* **71**, 1637-40.
- Durrant, P. J., and Durrant, B. (1962). 'Introduction to Advanced Inorganic Chemistry.' (Longmans: London.)
- Evans, C. M., and Sparks, D. L. (1983). On the chemistry and mineralogy of boron in pure and mixed systems: a review. *Commun. Soil Sci. Plant Anal.* **14**, 827-46.
- Farrar, K. (1975). A review of extraction techniques used to determine available boron in soils. *Agric. Dev. Adv. Ser. Q. Rev.* **19**, 93-100.
- Gillman, G. P. (1976). A centrifuge method for obtaining soil solution. CSIRO Aust. Div. Soils, Div. Rep. No. 16.
- Griffin, R. A., and Burau, R. G. (1974). Kinetic and equilibrium studies of boron desorption from soil. *Soil Sci. Soc. Am. Proc.* **38**, 892-7.
- Gupta, U. C., Jame, Y. W., Campbell, C. A., Leyshon, A. J., and Nicholaichuk, W. (1985). Boron toxicity and deficiency: a review. *Can. J. Soil Sci.* **65**, 381-409.
- Gupta, S. K., and Stewart, J. W. B. (1975). The extraction and determination of plant available boron in soils. *Schweiz. Landwirtsch. Forsch.* **14**, 153-69.
- Hatcher, J. T., Blair, G. Y., and Bower, C. A. (1959). Response of beans to dissolved and adsorbed boron. *Soil Sci.* **88**, 98-100.
- Hayes, M. R., and Metcalfe, J. (1962). The boron-curcumin complex in the determination of trace amounts of boron. *Analyst* **87**, 956-69.
- Hingston, F. J. (1964). Reactions between boron and clays. *Aust. J. Soil Res.* **2**, 83-95.
- Hughes, J. D. (1959). Boron studies on a krasnozom soil in Queensland. *Queensl. J. Agric. Sci.* **16**, 79-84.
- Knoeck, J., and Taylor, J. K. (1969). Aqueous boric acid — borate-mannitol equilibria. *Anal. Chem.* **41**, 1730-4.
- Kustin, K., and Pizer, R. (1969). Temperature-jump study of the rate and mechanism of the boric acid-tartaric acid complexation. *J. Am. Chem. Soc.* **91**, 317-22.
- Lopes, A. S. (1980). Micronutrients in soils of the tropics as constraints to food production. In 'Soil-related Constraints to Food Production in the Tropics'. pp. 277-97. (IRRI: Los Banos, Philippines.)
- Montgomery, R. (1971). Stability constants of some carbohydrate and related complexes by potentiometric titration. *Adv. Chem. Ser.* **117**, 203-7.

- Onak, T. P., Landesman, H., Williams, R. E., and Shapiro, I. (1959). The B^{11} nuclear magnetic resonance chemical shifts and spin coupling for various compounds. *J. Phys. Chem.* **63**, 1533-5.
- Rhoades, J. D., Ingvalson, R. D., and Hatcher, J. T. (1970). Laboratory determination of leachable soil boron. *Soil Sci. Soc. Am. Proc.* **34**, 871-5.
- Ryan, J., Miyamoto, S., and Stroehlein, J. L. (1977). Relation of solute and sorbed boron to the boron hazard in irrigation water. *Plant Soil* **47**, 253-6.
- Schuppli, P. A. (1986). Extraction of boron from CSSC reference soils by hot water, dilute $CaCl_2$ and mannitol- $CaCl_2$ solutions. *Can. J. Soil Sci.* **66**, 377-81.
- Sherrell, C. G. (1983). Assessment of plant-available boron in some New Zealand soils. *N. Z. J. Agric. Res.* **26**, 191-5.
- Watson, B. J. (1973). The bean boron deficiency story. *Nth. Moreton Hortic. Digest* **13**, 2-3.
- Wikner, B. (1986). Pretreatment of plant and soil samples a problem in boron analysis. Part 2: Soils. *Commun. Soil Sci. Plant Anal.* **17**, 697-714.
- Wolcott, J. F., and Sobel, C. B. (1978). A simple nebuliser for an inductively coupled plasma system. *Appl. Spectros.* **32**, 591-3.

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