Soil Analysis as a Basis for Boron Fertilization of Sugar Beets

By *K. W. Smilde**)

Institute for Soil Fertility, Haren-Groningen, The Netherlands

Introduction

In The Netherlands boron deficiency in sugar beets growing on Pleistocene sandy soils is frequently observed, especially in warm and dry years. In degree of health surveys *Lehr* and *Henkens* (1959) found threshold levels for hot-water-soluble soil boron of 0.30 to 0.35 ppm, the higher value obtaining in warm and dry summers. A series of field experiments by *Henkens* and *Van Brakel* (1963) in the exceptionally dry 1959 summer did not give conclusive evidence as to the value of soil analysis for predicting crop responses to added boron.

The aim of the present study was to investigate whether hot-water-soluble soil boron is an indication of plant-available boron and of heart-rot incidence. It was also intended to test the value of the soil-analysis method as a basis for boron fertilizer recommendations. Field trials were accompanied by pot experiments, especially with a view to controlling soil moisture conditions.

Materials and Methods

Pot experiments

In the first pot experiment (1965) 37 sandy soils differing in pH-KCl (3.8—6.5), organic matter (1.9—9 %) and hot-water-soluble boron (0.11—0.91 ppm) were used. The soils have been specially selected to avoid correlations between these soil factors, as outlined by *Van der Paauw* (1956). Full details are given in a report (with an English summary) by *Van Luit* and *Smilde* (1969). Alle polythene pots (25 l, containing 30—35 kg of soil) received the following quantities of A. R. chemicals: 3 g N (NH_4NO_3), 3 g P_2O_5 (K_2HPO_4), 1.5 g MgO ($MgSO_4 \cdot 7\,H_2O$), 0.4 g $CuSO_4 \cdot 5\,H_2O$, 1.5 g $MnSO_4 \cdot H_2O$ and 0.03 g $Na_2MoO_4 \cdot 2\,H_2O$. The fertilizers were mixed through the top 18 cm of soil. There were eight replicates for each soil and the pots were randomized. Sugar beets (variety Klein Wanzleben) were sown on 26th April and thinned to one plant per pot afterwards; the crop was harvested on 5th October. Plants were watered with demineralized water only and protected from rain water by a removable plastic roof. Soil moisture was maintained at 60—80 % of the maximum water capacity. On 30th June young leaves (3rd to 5th leaf from the heart) and on 5th August young and recently matured leaves were sampled for boron and nitrogen analysis. Heart-rot was first observed on 18th July. An index with figures from 1 (severely affected) to 10 (healthy) was used to express the intensity of the symptoms.

*) *Dr. Ir. K. W. Smilde*, Head Dept. of Fertilization of Arable Crops and Grassland, Institute for Soil Fertility, Oosterweg 92, Haren-Groningen, The Netherlands.

In a second pot experiment (1967) with 15 soils of similar origin as those used before and similarly selected, different amounts of borax (11 % B) were applied, viz. 0, 50, 100 and 250 mg per pot. These amounts, applied in five replicates, are roughly equivalent to 0, 7.5, 15 and 37.5 kg of borax/ha. All other conditions were similar to those of the first experiment. Sugar beets were sown on 11th May and harvested on 16th October. Recently matured leaves were sampled on 2nd August for boron and nitrogen analysis. At this time the first symptoms of heart-(or vein-)rot appeared. After harvesting the crop fresh weights and dry-matter contants of beets and leaves, and sugar contents (beets) were determined, and the intensity of heart-rot symptoms was assessed.

Field experiments

A series of 19 field experiments, 14 of which on soils that were also used in the 2nd pot experiment, was conducted in 1967. Each trial consisted of 20 10 × 5 m^2 plots with the following treatments in four replicates (lattice square): 0, 4, 8, 16 and 32 kg borax (11 % B) per ha. The basic treatment (in kg/ha) was: 140 N (ammonium nitrate limestone), 120 P_2O_5 (double super phosphate), 240 K_2O (muriate of potash 60 %), 100 MgO (kieserite). Sugar beets (varieties Polykuhn or Klein Wanzleben) were sown in the first half of April and harvested by the end of October or the beginning of November. Recently matured leaves were sampled on 4th July and 7th August for boron and nitrogen analysis. At the latter date heart-rot was observed in several experiments. Before harvesting the crop the number of heart-rot plants was counted in each plot. Then fresh weights and dry matter contents of beets and leaves, and sugar contents (beets) were determined.

Analytical and statistical methods

Leaf nitrogen was determined according to the Kjeldahl-Lauro method, and leaf boron according to *Hatcher* and *Wilcox* (1960). The concentrations are expressed on dry matter.

Soil boron was determined according to *Berger* and *Truog* (1939), as modified by *Naftel* (1939). The procedure (*J. T. L. B. Rameau*, Lab. for Soil and Crop Analysis, *Oosterbeek*, pers. comm. 1969) was as follows: a 5:50 w/v soil-water suspension is boiled for 10 minutes in a reflux condenser. After cooling and filtration 10 ml of the filtrate to which 5 ml of $Ca(OH)_2$ is added, is evaporated to dryness. The residue is dissolved in 2.5 ml of a mixture consisting of 32 g of oxalic acid and 163.5 g of trichloro acetic acid, dissolved in distilled water and made up to 1 litre. After addition of 1 ml of curcumine solution the fluid is evaporated to dryness. After cooling, the residue is dissolved in 10 ml of trichloro acetic acid/ethyl alcohol (1 litre of ethyl alcohol + 1 g of trichloro acetic acid). After 10 minutes' centrifugation the transmittance is read at 550 nm in a Beckman-spectrophotometer with trichloro acetic acid/ethyl alcohol as a blank.

The results used for testing the method of soil analysis against leaf boron, heart-rot index, crop yields and sugar contents, were analysed according to a numeric graphical method (*Ezekiel* 1950; *Ferrari* and *Sluijsmans* 1955). Yields were expressed as a percentage of the maximum yield obtained by boron application. Each graphical relationship was assessed at the mean level of the independent variable factors (soil pH and organic matter). Interactions between the dependent and independent variable factors may be studied. However, because of the relatively small number of soils in the 1967 experiments it was not considered permissible to divide the soil data into high and low values for pH and organic matter. Within the scope of this article it is only possible to present a limited number of graphs selected from the report by *Van Luit* and *Smilde* (1969).

Results

Pot experiments

In the first experiment a close relationship between hot-water-soluble soil boron and leaf boron was found. This was true for both young and recently matured leaves, sampled before and after heart-rot symptoms first appeared (see p. 1). An illustration for mature leaves, sampled on 5th August, is shown in figure 1. The scattering of the points around the curves could be explained to some extent by variations in soil pH and organic matter, lower leaf boron concentrations being associated with higher values for these soil factors.

Figure 2 shows the relationship between water-soluble soil boron and heart-rot index for the leaves. If soil boron is plotted against heart-rot index for the beets an almost identical curve is obtained (not presented here). According

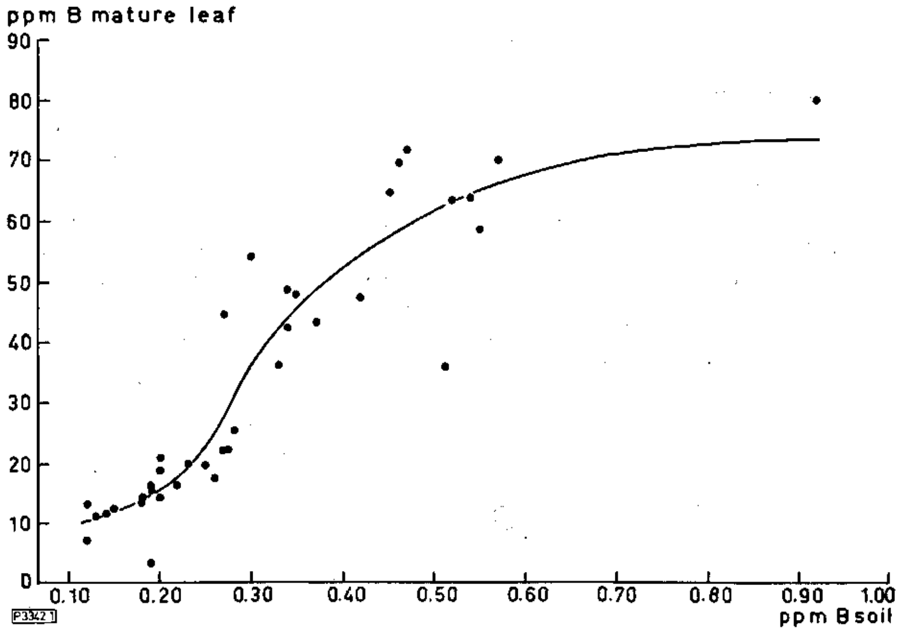

Figure 1

Relationship between soil and leaf boron (mature leaves, sampled on 5th August), 1965 pot experiment

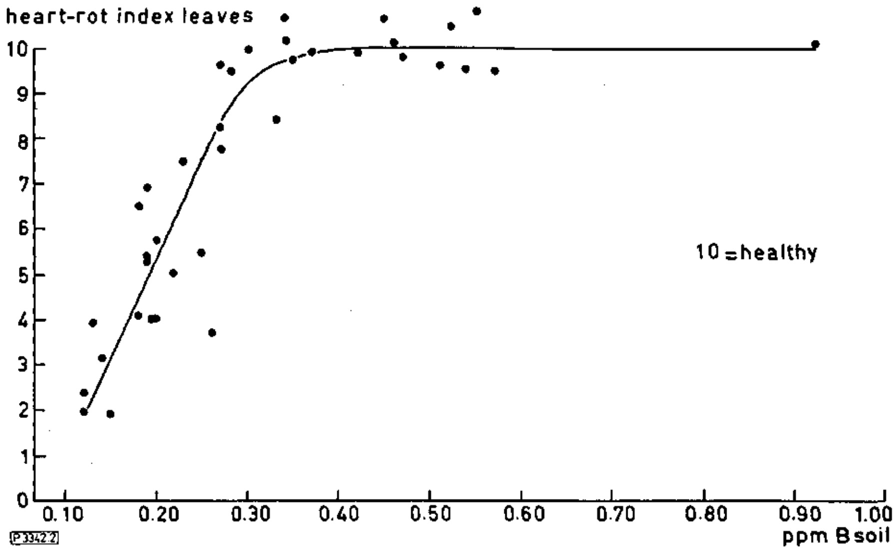

Figure 2

Relationship between soil boron and heart-rot intensity in leaves (observation on 5th October), 1965 pot experiment

to these curves boron deficiency incidence can be accurately predicted by analysing the soil for water-soluble boron, the concentration required for a healthy crop being 0.35 ppm B or more. The intensity of the disorder increased somewhat with higher values for soil pH and organic matter.

When considering the above data a close relationship between leaf boron and heart-rot index could be expected. This can be seen in figure 3 for mature leaves sampled on 5th August. Boron deficiency was found to be associated with leaf boron concentrations lower than 40 ppm. It is noteworthy that the boron concentration of (young) leaves sampled in June is also indicative of the intensity of boron deficiency symptoms appearing later. A "critical" value of 35 ppm B could be read from the graph (not presented here).

In the second experiment application of boron fertilizer increased leaf boron (mature leaves, sampled 2nd August) considerably. When plotting hot-water-extractable soil boron against leaf boron for the different amounts of borax a series of parallel curves is obtained (not presented here). Their shape shows a great resemblance to that in figure 1 (first experiment). A marked effect of soil pH and organic matter on leaf boron was only demonstrated in the control treatment (no borax).

The relationship between water-soluble soil boron and heart-rot index (leaves) at different amounts of added boron is presented in figure 4. Boron

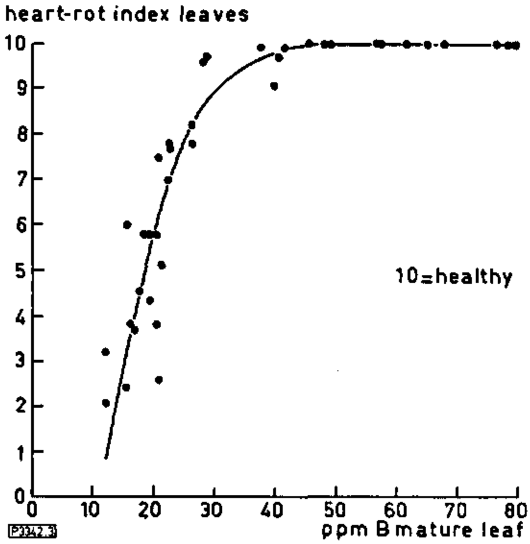

Figure 3
Relationship between leaf boron (mature leaves, sampled on 5th August) and heart-rot intensity in leaves (observation on 5th October); 1965 pot experiment

deficiency occurred on soils with less than 0.35 ppm water-soluble boron if no borax was applied (cf. fig. 2; first experiment). To prevent the disorder, 50 mg of borax per pot (roughly equivalent to 7.5 kg/ha) was needed in soils with 0.25 to 0.35 ppm water-extractable boron, and 100 mg at lower boron levels. Heart-rot intensity tended to increase with an increase in soil pH and organic matter.

Leaf boron and heart-rot index also proved to be closely related, the disorder occurring at concentrations lower than 40 ppm B (cf. fig. 3; first experiment).

Application of only 50 mg of borax per pot already raised leaf boron (sampling date 2nd August) to 40 ppm or more. However, on soils with a very low boron status this quantity of fertilizer was not quite sufficient to prevent slight boron-deficiency symptoms from appearing late in the season.

For each soil yield curves were drawn by plotting leaf and net beet yields against the amounts of boron fertilizer applied. From the adjusted curves relative yields were calculated for each borax application as pointed out on p. 2. The scattering of the points around the curves was rather large because of the small number of plants per replicate (5). Mean fresh leaf and net beet yields were 594 and 843 g per pot, respectively, the coefficients of variability of the replicates being 16.3 and 16.8 %.

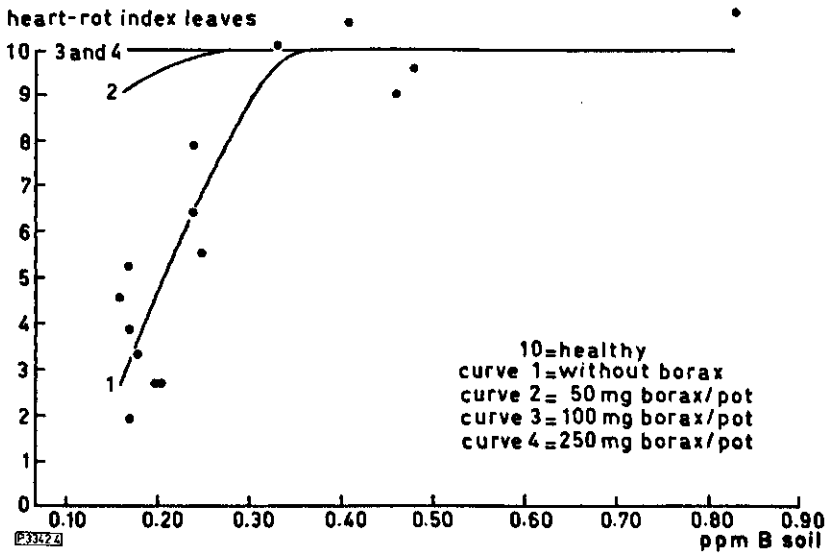

Figure 4

Relationship between soil boron and heart-rot intensity in leaves (observation on 13th October), 1967 pot experiment

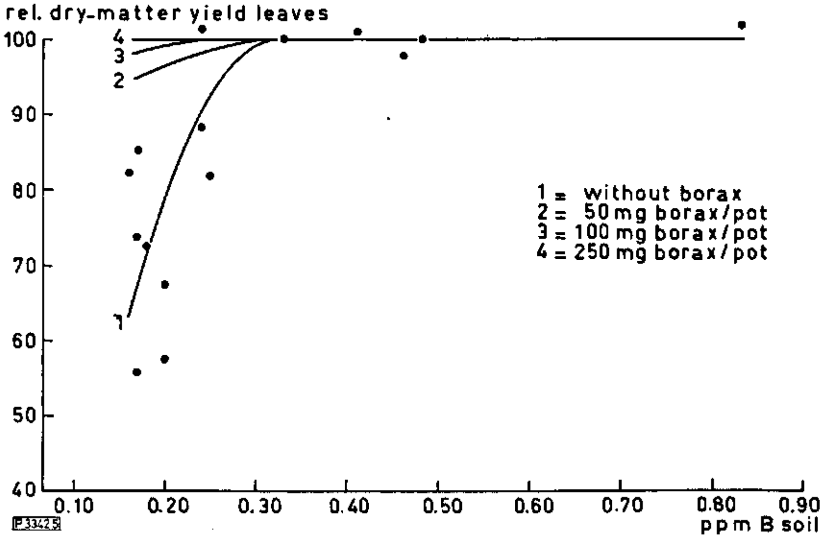

Figure 5

Relationship between soil boron and relative dry matter yield of leaves (yield with 250 mg borax/pot = 100 %), 1967 pot experiment

Figure 5 shows the relationship between water-extractable soil boron and relative dry-matter yield of foliage for different borax applications. For the sake of clearness in this figure the separate data are only presented for the control treatment (no borax). In soils with less than 0.30 ppm water-soluble boron yield reductions up to 40 % occurred if no boron fertilizer was added. To prevent losses, 50 mg of borax per pot was required on soils with 0.25 to 0.30 ppm water-soluble boron and 100 mg at lower boron levels. Similar quantities of boron fertilizer were needed to obtain optimum net beet yields on the various soils (graphs are not presented here). Without added borax losses up to 25 % were found on soils containing less than 0.30 ppm water-extractable boron. An effect of soil pH and organic matter on relative foliage and net beet yields could not be demonstrated.

Added borax positively influenced sugar content of the beet on soils with less than 0.30 ppm water-soluble boron, but not on soils with higher boron concentrations. At the lowest soil boron levels sugar content was raised from about 14 to 16.5 %. Increases in sugar content were already obtained by application of 50 mg of borax per pot, larger quantities having no additional effect. Relative sugar yields were calculated for each borax application and plotted against water-soluble soil boron. The curves proved to be rather similar to those in figure 5 and, therefore, are not presented here. On soils with less

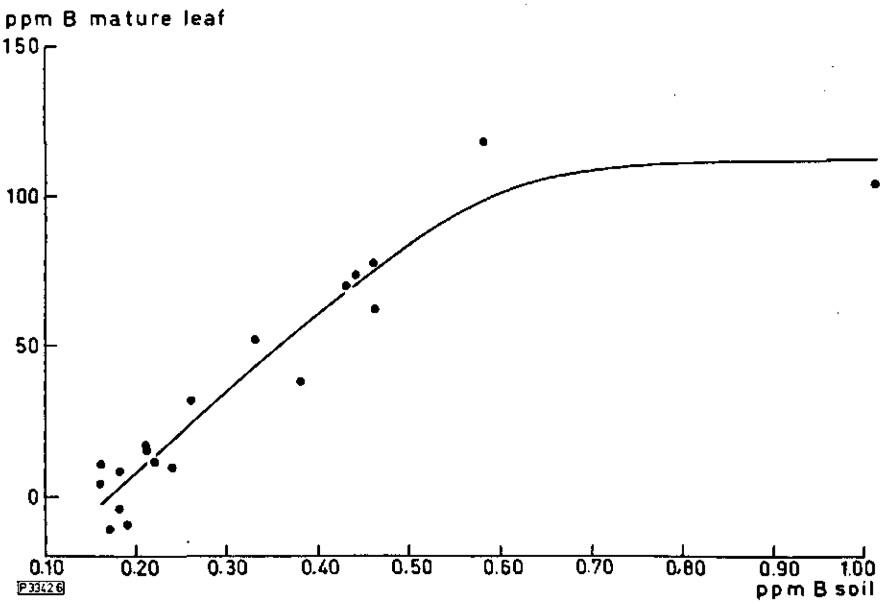

Figure 6
Relationship between soil and leaf boron (mature leaves, sampled on 7th August), without application of borax, 1967 field experiments (19)

than 0.30 ppm water-soluble boron reductions in sugar yield up to 35 % were found if no borax was applied. The losses in sugar production are caused by a decrease both in net beet yield and in sugar content. No effect of soil pH and organic matter on sugar yield was found.

Field experiments

The second pot experiment and the series of 19 field trials were conducted simultaneously and had most soils in common. The field experiments were meant specially to assess the boron fertilizer requirements of sugar beets at different soil boron levels.

Analysis of mature leaves on the control plots (sampling dates 4th July and 7th August) revealed that leaf boron and hot-water-soluble soil boron were closely related, which confirms the results of the pot experiments (fig. 1). An illustration for the second sampling date is given in figure 6. The scattering of the points around the curves was partly caused by soil pH and organic matter.

It was found impracticable to express heart-rot intensity in the plots of the various field experiments in one single scale, as close comparison between the trials was impossible. Therefore, the percentage of plants affected was used as an indication of heart-rot intensity. In figure 7 these percentages have been

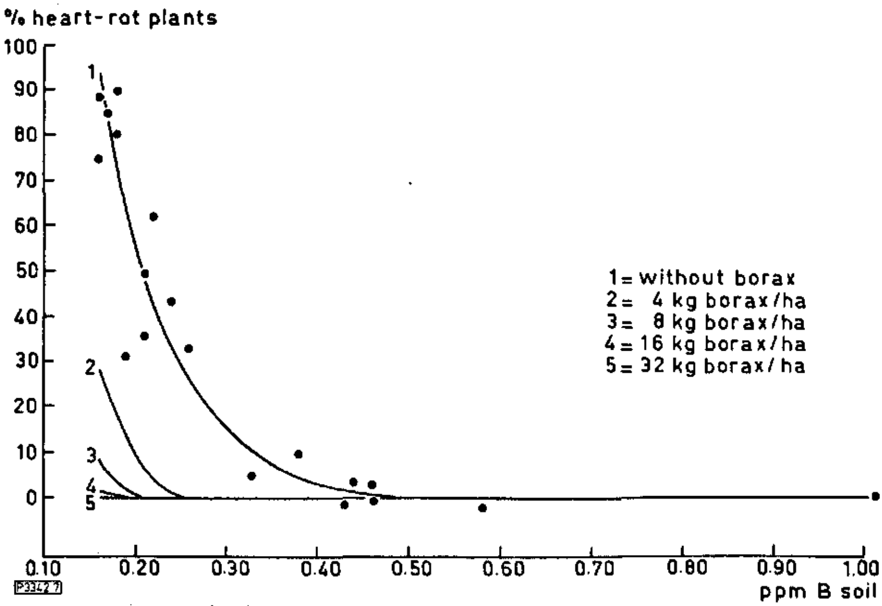

Figure 7

Relationship between soil boron and percentage of plants affected by heart-rot, 1967 field experiments (19) plotted against water-extractable soil boron (the separate data are only shown for the control treatment). Boron deficiency was observed on soils containing less than 0.40 ppm water-extractable boron if no boron fertilizer was applied. Up to 90 % of the plants may be affected. For control, quantities of 4, 8 and 16 kg of borax per ha were required on soils with 0.25—0.40, 0.20—0.25, and less than 0.20 ppm water-extractable boron, respectively. No effects of soil pH and organic matter on heart-rot incidence could be demonstrated.

There was also found to be a close relationship between leaf boron, at both sampling dates, and percentage of affected plants. This is illustrated in figure 8 for plants in the control plots, sampled on 7th August. A steep rise in heart-rot incidence occurred at leaf boron concentrations lower than 35 ppm. For the July sampling, i.e. before heart-rot was observed, a critical level of 40 ppm B was obtained.

In the trials the mean net beet yields were 43 ton/ha on soils with pH-KCl lower than 5, and 55 ton/ha at higher pH values. For each experiment leaf and net beet yields were plotted graphically against the different borax applications.

The graphs showing the relationship between water-extractable soil boron on the one hand, and relative yields of foliage dry matter or net beets on the other, are very similar. This is presented in figure 9 for the foliage; the separate points are only given for the control treatment. Yield depressions up to 25 % for both foliage and beets were found on soils with less than 0.35 ppm water-

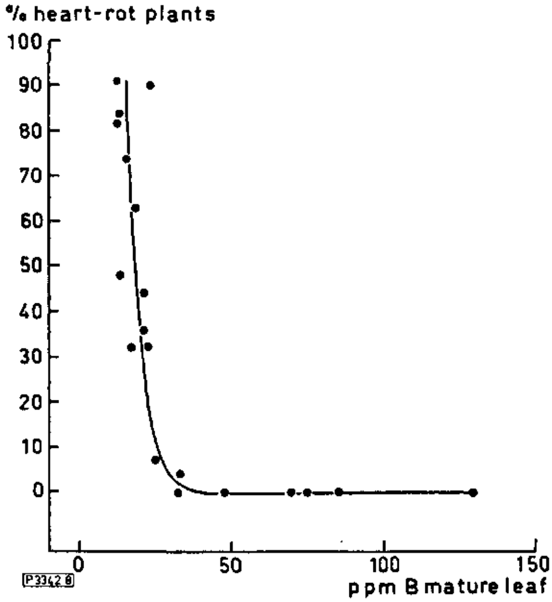

Figure 8
Relationship between leaf boron (mature leaves, sampled on 7th August) and percentage of plants affected by heart-rot (without borax application), 1967 field experiments (19)

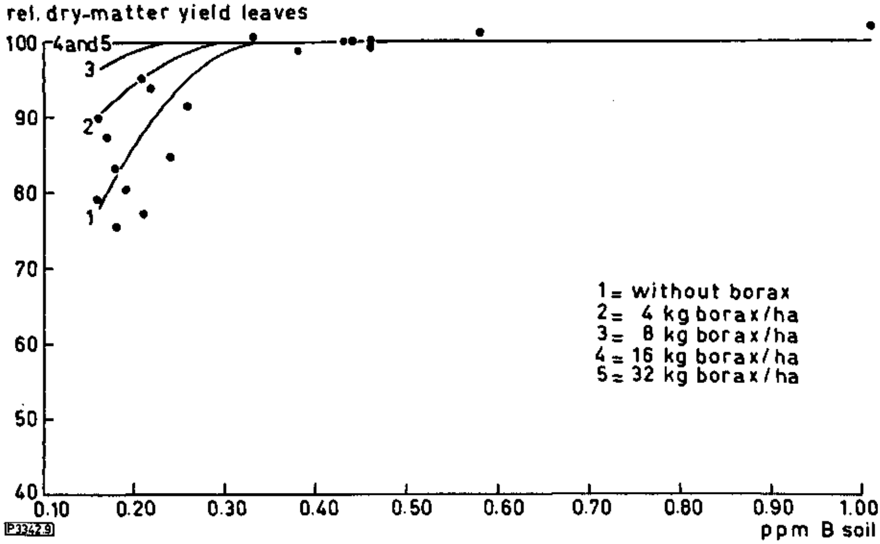

Figure 9

Relationship between soil boron and relative dry matter yield of leaves (yield with 32 kg borax/ha = 100 %), 1967 field experiments (19)

extractable boron if no borax was supplied. To avoid such losses, quantities of 4, 8 to 16 and 16 kg of borax per ha were needed on soils containing 0.30—0.35, 0.20—0.30, and less than 0.20 ppm water-soluble boron, respectively. Relative yields were not influenced by soil pH and organic matter.

As shown above, the critical soil boron level for heart-rot incidence (0.40 ppm) was slightly higher than that for yield depressions resulting from this disorder (0.35 ppm). Therefore, it can be concluded that yield losses are not to be expected in crops remaining fully free from boron deficiency symptoms until harvesting.

Only in two cases sugar content of the beet was increased considerably, i.e. from 16.5 to 18.1 % and from 14.8 to 17.2 %, respectively. In other experiments, also on soils low in boron, the increases were less than 0.5 %. Therefore, relative sugar yields were not calculated and analysed separately.

After harvesting the crop, soil samples in the 20 cm top layer were taken from each plot in all field experiments and analysed for hot-water-soluble boron. The results are shown in table 1, together with the soil boron concentrations before fertilizer application. Theoretical concentrations calculated for a 20 cm arable layer of soil following application of borax (11 % B), are also included. The calculations are based on a ha weight of 2.5×10^6 kg, and no allowance is made for boron absorption by the crop, leaching of boron to

Table 1

Soil boron concentrations (in ppm) before application of borax (11 % B), after harvesting the crop (sugar beets), and concentrations to be expected theoretically (means of 19 fertilizer experiments with 4 replicates for each treatment)

	Before fertilization	At harvesting	Theoretical Value
0 kg borax/ha	0.31	0.27	0.31
4 kg borax/ha	0.31	0.32	0.49
8 kg borax/ha	0.32	0.40	0.67
16 kg borax/ha	0.33	0.54	1.03
32 kg borax/ha	0.32	0.78	1.75

deeper soil layers and fixation. An estimation of crop absorption can be made by using leaf boron concentrations of the 7th August samples, and assuming 13 ppm to be an average boron concentration of the beet (unpublished results). Values of 350 and 740 g of boron per ha were found, respectively, for the control plots and the plots supplied with 32 kg of borax per ha, whilst crop absorption at smaller quantities of added borax lay between these extremes. This would result in a decrease in soil boron of 0.14 to 0.30 ppm, on the assumption that all boron is taken up from the top 20 cm of soil. However, this relatively small crop absorption by no means explains the discrepancy between the soil-boron concentrations actually found at harvesting and the values to be expected theoretically. As will be pointed out in the discussion, movement of boron to deeper soil layers probably is the main factor involved.

Discussion

The close correlation between hot-water-extractable soil boron and leaf boron agrees with the results reported by *Schultze-Grobleben* (1954), *Bucher* (1957) and *Lehr* and *Henkens* (1959), but not with those by *Hamence* and *Oram* (1964). In other crops (lucerne, clover, sunflower) hot-water-extractable soil boron also proved to be a good indication of plant-available boron (*Stinson* 1953; *Quellette* and *Lachance* 1954; *Bucher* 1957; *Riehm* 1957; *Bishop* and *Cook* 1958; *Wear* and *Patterson* 1962; *Maurice* and *Trocmé* 1965; *Miljkovic* et al. 1966; *Baker* and *Mortensen* 1966).

The "critical" soil boron levels, viz. 0.35—0.40 ppm for heart-rot incidence and 0.30—0.35 for yield depressions resulting from boron deficiency, are in line with published data for coarse-textured soils (*Walsh* and *Golden* 1952; *Schultze-Grobleben* 1954; *Bucher* 1957; *Lehr* and *Henkens* 1959). Higher levels may be required on loam soils for sugar beets and other crops (*Ouellette* and *Lachance* 1954; *Bucher* 1957; *Wear* and *Patterson* 1962; *Miljkovic* et al. 1966). This cannot be confirmed by the present data as only sandy soils (less than 10 % particles $< 16\ \mu$) were used.

There was a tendency for leaf boron to decrease and for heart-rot intensity to increase with an increase in soil pH and organic matter. However, no effect of these soil factors on relative yields of foliage, beet and sugar could be demonstrated. It should be pointed out that, because of the limited number of soils in the 1967 experiments (19), interactions could not be reliably estimated (cf. p. 2). *Lehr* and *Henkens* (1959) found no effect of soil pH on either leaf or water-soluble soil boron, but in later work (*Henkens* and *Van Brakel* 1963) a negative influence on leaf boron was reported. According to *Wear* and *Patterson* (1962) lucerne absorbed less boron per unit of water-soluble soil boron as pH increased. *Walsh* and *Golden* (1952) and *Maurice* and *Trocmé* (1965) state threshold soil-boron levels to increase with increasing alkalinity. Liming of soils was found to promote boron adsorption (fixation) to hydrated iron and aluminium oxides and silicates (*Parks* and *Shaw* 1941; *Scharrer* et al. 1956; *Biggar* and *Fireman* 1960; *Sims* and *Bingham* 1968). However, findings by *Kubota* et al. (1948), *Bucher* (1957) and *Baker* and *Mortensen* (1966) indicate that liming preserves boron against leaching to the sub-soil, without affecting its availability to crops. This is in accordance with results by the author published elsewhere (*Van Luit* and *Smilde* 1969). In this context it is the author's opinion that the disparity between the soil-boron concentrations following fertilization with borax and the theoretically possible values (table 1), is mainly caused by movement of this nutrient to deeper soil layers. Reference is made to some relevant data by *Kubota* et al. (1948), *Wilson* et al. (1951), *Scharrer* et al. (1954/55), *Bucher* (1957), and *Riehm* (1957). In field experiments on sandy soils similar to those in the present study *Henkens* and *Van Brakel* (1963) found only a small or negligible residual effect of borax (32 kg/ha) on soil boron one year after application of this fertilizer.

It is well known that heart-rot more frequently occurs in dry summers than in wet ones (*Hobbs* and *Bertramson* 1949; *Schultze-Grobleben* 1954; *Lehr* and *Henkens* 1959; *Hamence* and *Oram* 1964). In the present study severe boron deficiency symptoms were observed in the pot experiments under optimal soil-moisture conditions. Results by the author published elsewhere (*Van Luit* and *Smilde* 1969) and by *Gupta* (1968) make it unlikely that soil moisture has a direct effect on water-extractable boron. The effect of moisture stress may be explained in terms of an inability of the plant roots to absorb enough boron from the dry surface soil. The (more moist) sub-soil layers are generally lower in organic matter and, consequently, hold less boron (*Hobbs* and *Bertramson* 1949; *Dible* and *Berger* 1952; *Baker* and *Mortensen* 1966).

Summary

Field and pot experiments were conducted to asses the boron fertilizer requirements of sugar beet crops on the basis of soil analysis. It was first verified by leaf analysis whether hot-water-soluble soil boron is an indication

of plant-available boron and of boron deficiency (heart-rot) incidence. The rates of fertilizer required on soils with different boron contents were determined in subsequent field experiments, accompanied by a pot experiment with similar soils. The following conclusions can be drawn from the results:

1. A close relationship was found between hot-water-soluble soil boron and leaf boron, both in pot and in field experiments with sandy soils, varying widely in pH-KCl (3.8—6.5) and organic-matter content (1.9—9%).
2. Soil and leaf boron also proved to be closely related to heart-rot intensity (pot experiments) or percentage of affected plants (field experiments). No heart-rot occurred at water-soluble soil boron levels higher than 0.35 to 0.40 ppm and leaf boron levels higher than 35—40 ppm.
3. There was no reduction in foliage, beet and sugar production, resulting from boron deficiency, if water-soluble soil boron exceeded 0.30—0.35 ppm.
4. Leaf boron tended to decrease and heart-rot intensity to increase as soil pH and organic-matter content increased. Significant effects of these soil factors on relative leaf, beet and sugar yields could not be demonstrated.
5. From the field experiments the following fertilizer recommendations were derived: 4, 8 to 16 and 16 kg of borax (11% B) per ha on soils with 0.30—0.35, 0.20—0.29, and less than 0.20 ppm water-soluble boron, respectively.
6. In pot experiments borax markedly increased sugar content of beets growing on soils low in boron. In field experiments this effect was much less pronounced.
7. There are reasons to assume that a considerable portion of the applied borax moves to sub-soil layers within the course of one growing season.

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