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# PLANT-AVAILABLE BORON IN SOILS AND THE BORON REQUIREMENT OF SPRING OILSEED RAPES

## Selostus: Kasveille käyttökelpoinen maan boori ja kevätrypsin ja -rapsin boorin tarve

INTO SAARELA

Agricultural Research Centre
Department of Agricultural Chemistry and Physics
Jokioinen, Finland

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# PREFACE

This study was carried out at the Institute of Agricultural Chemistry and Physics, Agricultural Research Centre of Finland during 1980—1984. I am deeply grateful to Professor Paavo Elonen, Head of the Institute of Agricultural Chemistry and Physics, for the support he has given me over the years as well as for suggesting the subject of this study to me, and for placing technical assistance at my disposal.

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I would like to thank Professor Antti Jaakkola and Docent Helinä Hartikainen for reading my work and offering valuable constructive criticism.

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My thanks are extended to the Head and the staff of the Institute of Soil Science for performing the soil analyses other than boron and $pH_{CaCl_2}$ determinations, and to the Heads and the staffs of the Research Stations that carried out the field experiments, and to the laboratory personnel of Raision tehtaat for determining the chlorophyll contents in the rapeseeds.

The English manuscript has been linguistically revised by Mr. Daniel McCoy and edited by Mrs. Paula Vogt, M.Sc., to whom I express my appreciation for their expert work.

I would have never been able to start this work without the selfless support of my parents and my uncle during my earlier student years. I am ever-grateful to my wife, my daughter, and my son for their unfliching support throughout the years when I had so little time for my family.

Finally, I wish to thank the Agricultural Research Centre for accepting this study into their series of publications.

Jokioinen, August 1985

Into Saarela

# CONTENTS

# PLANT-AVAILABLE BORON IN SOILS AND THE BORON REQUIREMENT OF SPRING OILSEED RAPES

SAARELA, I. 1985. **Plant-available boron in soils and the boron requirement of spring oilseed rapes.** Ann. Agric. Fenn. 24: 183-265. (Agric. Res. Centre, Dept, Agric. Chem. Phys., SF-31600 Jokioinen, Finland.)

The behavior of boron in soils, and the boron fertilization requirements of spring oilseed rapes were studied under Finnish conditions. Four field experiments, a series of pot experiments, and some laboratory studies were performed.

The sorption of boron by soils increased with increasing pH and fineness of soils, and slowly progressed with time. In 17 soils, the sorption of applied boron (10 mg/l) after a 100 d incubation ranged from 28 to 82 %. From 1 to 50 % of added boron was fixed against the standard hot water extraction. Under field conditions, the movement of applied boron in soil profiles was very slow in heavy clay, and fairly slow also in coarser soils.

In a pot experiment with 30 soils, the uptake of boron by turnip rape closely correlated with the amounts of hot water extractable boron (HWB) in the soils ($r^2$ = 0,82 and $R^2$ with soil pH = 0,89). The absorption of boron by turnip rape was drastically retarded by heavy liming. Under field conditions, boron applied by the common Finnish placement method increased the boron contents in plants much more efficiently than broadcasted boron did, and also appeared to be more toxic.

Growth of the pot-grown plants was already stunted by a boron deficiency in the seedling stage. Severe deficiency brought about by heavy liming, caused turnip rape seedlings even to die before cotyledons were mature. The seed set was efficiently prevented by an inadequate boron supply even if the stems and leaves grew almost normally.

The lowest HWB values which without applied boron sufficed for pot-grown turnip rape to produce maximum seed yields, varied from 0,45 to 0,65 mg/l in acid soils, and from 0,6 to 0,9 mg/l in heavily limed soils. The required contents of boron in the dry tissues of turnip rape were from 18 to 32 ppm in the seedlings, 13 to 17 ppm in the straw, and 22 to 38 ppm in the leaves.

The rates required when boron is applied for spring oilseed rapes by the Finnish placement method were estimated on the basis of HWB, pH, and the texture of soils. The most frequent estimates are at the level of 0,2 to 0,4 kg/ha. An excess of 0,5 kg B/ha is probably nontoxic.

Index words: boron analysis, soil boron, boron sorption, boron fixation, boron movement, boron availability, boron and liming, boron uptake, plant boron, spring oilseed rapes, boron requirement.

## INTRODUCTION

The light nonmetallic element boron was discovered in 1808 and detected in plants half a century later (WITTSTEIN and APOIGER 1857). At the end of the last century its occurrence in plants was known to be common (JAY 1895). The effects of boron applications on plants were probably first studied by PELIGOT (1876). The result of his pilot test showed this element to be highly poisonous to plants, for the leaves of the plants yellowed and the plants died.

The first reports on growth-stimulating effects caused by a small amount of boron appeared at the beginning of this century (e.g. NAKAMURA 1903, AGULHON 1910, MAZE 1915). MAZE even concluded that this element is an essential plant nutrient. The indispensability of boron for plants was demonstrated by WARINGTON (1923). The broad bean plants in her water culture died without forming a seed if no boron was added. The specific role of boron was further assured when none of the 52 elements tested could be substituted for it (BRENCHLEY and WARINGTON 1927).

The agronomic importance of boron was realized in the beginning of 1930's when deficiencies were found in plants growing in natural soils. First KUIJPER (1930) reported that boron prevented the death of the apical growing points of tobacco plants, and soon after BRANDENBURG (1931), in his well-known study, found that the heart rots of beets were physiological plant diseases caused by boron deficiencies.

After the above-mentioned studies, the research of boron nutrition quickly expanded worldwide and borax became a common commercial fertilizer. This was not, however, the beginning of boron fertilization, for imported borax was used in Europe as far back as the early 1500's (BERGER 1949). In 1910's in North America, "boron fertilization" caused economic losses, as the boron in potassium fertilizers had injured crops (SHIVE 1945).

In Finland boron deficiency diseases were first studied by JAMALAINEN (1935 a) who found that the brown heart in rutabaga was caused by a lack of this element. He also studied the effects of boron compounds on fruit cracking in apples and the heart rots in sugar beets (JAMALAINEN 1935 b, 1936 a, b, 1949). A requirement of boron application was also found in clover-mixed grassland for forage (TAINIO 1951, 1955), spring turnip rape and other cruciferous oilseed crops, red beets and celery (SALMINEN 1952), white mustard (KOSKINEN 1952), winter turnip rape (TAINIO 1957), carrots (SALONEN 1961), barley (TAINIO 1961, SIMOJOKI 1969, 1972), red clover for seed (SALMINEN 1959, HÄNNINEN 1962, 1966) and spring cereals (TÄHTINEN 1974). According to HEINONEN (1961), boron deficiency was a cause of iron chlorosis in oats.

The unusual boron requirement of barley (SIMOJOKI 1972) indicated that Finland was one of the most boron-deficient parts of the world. The recently found importance of this micronutrient in forestry (e.g. VEIJALAINEN 1983) provides additional evidence. Today, however, the boron status of Finnish agricultural soils is essentially better than it was 12 years ago, because a small amount of boron has been added in all combined fertilizers since 1972.

The earliest investigations on plant-available boron in soils were mainly directed towards toxic concentrations, because research on the available fraction in deficient soils was restricted for methodological reasons (e.g. EATON 1935). There were no routine tests sensitive enough until BERGER and TRUOG (1939) developed their hot water extraction method (HWB). Today this method is probably the most universally used soil nutrient test.

The HWB method is extensively used in fertilization advisory work in Finland. Statistics from the results show that the extractable contents of boron in Finnish soils have been quite low (KURKI 1972). These findings agreed with earlier fertilization experiments. Presently the increased contents approach an average international level (SILLANPÄÄ 1982, KÄHÄRI 1985).

The HWB method has been used successfully in estimating the amounts of boron absorbed from soils by plant roots (e.g. REISENAUER et al. 1973). Dependencies between the contents of boron in plants and the HWB values of soils (the abbreviation will refer to the method or to values by it) have also been found under Finnish conditions (PAASIKALLIO 1978, SILLANPÄÄ 1982), but the relationships between the yields and the soil test values have not been determined adequately. SIMOJOKI (1972) found a threshold value of 0,2 mg/l of soil, below which a deficiency in barley may occur. This is not, however, applicable for the oilseed rapes, which require more boron than barley does.

The main purpose of this study was to investigate the Finnish oilseed crops' requirements of boron fertilization. Ninety percent of these crops consist of the spring turnip rape (*Brassica campestris* L. v. *oleifera f. annua*) and 10 % are spring rape (*Brassica napus* L. v. *oleifera f. annua*). The increasing area of these oilseed crops under cultivation in Finland has now exceeded sixty thousand hectares. Estimation of the supply of boron from soils to plants, determination of the sufficient contents of boron in plants, and estimation of the sufficient levels of boron in soils for the crops were the principal objectives. Explanation and prediction of the behavior of boron in soils was another aim. The methods of boron application required special attention, as most of the boron applied to Finnish oilseed crops is placed in a combined seed and fertilizer drilling operation, and this nutrient has probably not been previously studied within that system.

To achieve these aims, four field experiments lasting three years, a series of pot experiments, and some laboratory studies were conducted during the years 1980—1984. Spring turnip rape was the main test plant. Spring rape was included in three of the pot experiments and poppy (*Papaver somniferum* L.) in one of the pot experiments. For comparison, some other crop plants were also grown parallel with the oilseed species. The occurrence and chemistry of boron in soils and the role of boron in plants were discussed in brief reviews.

A part of this study was published in a preliminary report in Finnish (SAARELA 1984). In order to avoid unnecessary repetition, some of the original results are not presented in this issue but only referred to in discussions.

## 1. MATERIAL AND METHODS

### 1.1. Determination of boron in aqueous solutions

Various methods have been used in quantitative boron analysis. These methods include, among others, spectrographic, titrimetric, potentiometric, fluorimetric, and spectrometric measurements (EATON and WILCOX 1939, BINGHAM 1982, SHORROCKS 1982, AZNAREZ et al. 1983). In plant physiology, the lack of a suitable nuclide for autoradiography has recently been overcome by means of mass spectrometry and mass spectrography, by separating the $^{10}$B and $^{11}$B (CHAMEL et al. 1981), and using the nuclear reaction $^{10}B(n,\alpha)^{7}Li$, which has allowed tracing of boron in a simple plant cell (KRAKKAI and KÖRÖSI 1983).

The most common methods for determining boron in soils and plants, however, are those based on colorimetry, in which the spectrophotometric measurement is done by use of visible light. Reagents used to form the colored compound with boric acid are, among others, carminic acid, curcumin, dianthrimide, methylene blue, quinalizarine, and azomethine-H (SHORROCKS 1982).

The azomethine-H method has been employed in this study. It is a new method, but is already used in many countries. It had already been studied and in use also in Finland before the present work (SIPPOLA and ERVIÖ 1977, SILLANPÄÄ 1982).

The popularity of this coloring agent is based on a rather good sensitivity to low contents, and remarkably low background interferences (WOLF 1971, JOHN et al. 1975, PARKER and GARDNER 1981). The lack of disastrous interferences allows the analysis to be done without difficult separation procedures, and thus is an essential advantage of the method. Procedures such as ion exchange (TUMMAVUORI and KAIKKONEN 1982), extraction into an organic solvent (WIKNER 1981), and even distillation (EATON and WILCOX 1939, PHILIPSON 1953) have been used to separate the analytically difficult element boron from interfering substances.

Because the measurements with the azomethine-H are done in a diluted aqueous solution, the procedure is safe and convenient compared to other colorimetric methods, which require concentrated sulfuric acid or an organic solvent to develop the measurable color (WOLF 1971, GUPTA 1979 b, BINGHAM 1982, SHORROCKS 1982).

When comparing the methods in analyzing soils and plants for boron, the results obtained by the azomethine-H method have been equal to results obtained by other reliable methods. Comparisons to the carmine method (HATCHER and WILCOX 1950) were made by BASSON et al. (1969), GUPTA and STEWART (1975), JOHN et al. (1975), SIPPOLA and ERVIÖ (1977), GUPTA (1979 b) and PORTER et al. (1981), and to plasma emission spectrometry by GESTRING and SOLTANPOUR (1981 a) and PARKER and GARDNER (1981). With standard plant material, the results have been the same as the certified values if dry ashing had been used (GAINES and MITCHELL 1979, GESTRING and SOLTANPOUR 1981 a), but too high values have been obtained with wet combustion (GESTRING and SOLTANPOUR 1981 a). Recovery of the standard addition has been a hundred percent (JOHN et al. 1975, SIPPOLA and ERVIÖ 1977, PORTER et al. 1981).

The azomethine-H method was developed by SHANINA et al. (1967). BASSON et al. (1969) modified the method for routine plant analysis. They found that iron, copper and aluminum are the only interfering substances, and that these could be masked by EDTA. WOLF (1971) extended the method to soil analysis. He used activated charcoal in soil extracts and hydrogen peroxide oxidation in plant extracts for decolorization. Hydrogen peroxide had to be removed completely because it was very detrimental in measuring the content of boron. JOHN et al. (1975) found that ferric iron increased the boron values in spite of the masking. The error was + 5 % when the measured solution contained 2 mg B/l and 200 mg Fe/l. PORTER et al. (1981) also observed significant errors in the presence of EDTA, and even V, Cr, Mn and $NO_2^-$ appeared to interfere if their concentrations were higher than 500 mg/l. The reviewed studies suggested that the ions which are usually present in the hot water extracts from soils or in the plant ash extracts would not interfere.

### 1.1.1. Modifications in azomethine-H method

In the present study, the interferences of the following separate additions were studied (given in mg/l): 10000 K, 4000 Ca, 2000 Mg, 2000 Na, 2000 S, 1000 Al, 1000 Fe, 100 Zn, 100 Cu, 100 Mn, 100 Mo, and saturated $Si(OH)_2$. The major cations were in the form of chloride and the sulphur as $H_2SO_4$, $Na_2SO_4$ and $MgSO_4$. HCl and $HNO_3$ were also compared as the solvent. Each treatment was tested with the standard boron solutions of 0, 0,5 and 2,5 mg/l. The only substance which significantly (more than 3 %) influenced the measured boron contents was iron. The two applied forms, ferri-EDTA and ferrous sulphate, caused the same effects.

When the error caused by iron and its elimination by EDTA-masking was examined as a function of boron concentration in the solution, it was found that the absorbances resulting from $FeSO_4$ and $H_3BO_3$ were independent (Fig. 1). This suggested that the "iron-error" was not a disturbance of the boric acid — azomethine - H reaction, but that uncomplexed iron ions absorbed light. The residual error with EDTA was about 30 % of the error without it. Because EDTA is sparingly soluble in acid mediums, it could not be used in much higher concentrations to improve its masking efficiency (WOLF 1971).

The iron concentration of 1 000 mg/l is much higher than normally occurs in plant ash extracts or in the hot water extracts from soils. However, more powerful extractants, such as a strong acid, could dissolve large amounts of iron from soils. As the "iron-error" increased linearly with increasing iron concentration, it appeared to be independent on dilution of the measured solutions.

The error in the boron values was about 0,1 % of the concentration of iron. This equals 50 ppm B per 5 % Fe, which amount of iron may be dissolved from soils in analyzing them for total boron. If the concentration of iron was known, the error could be calculated. Another correction possibility is to measure the background ab-

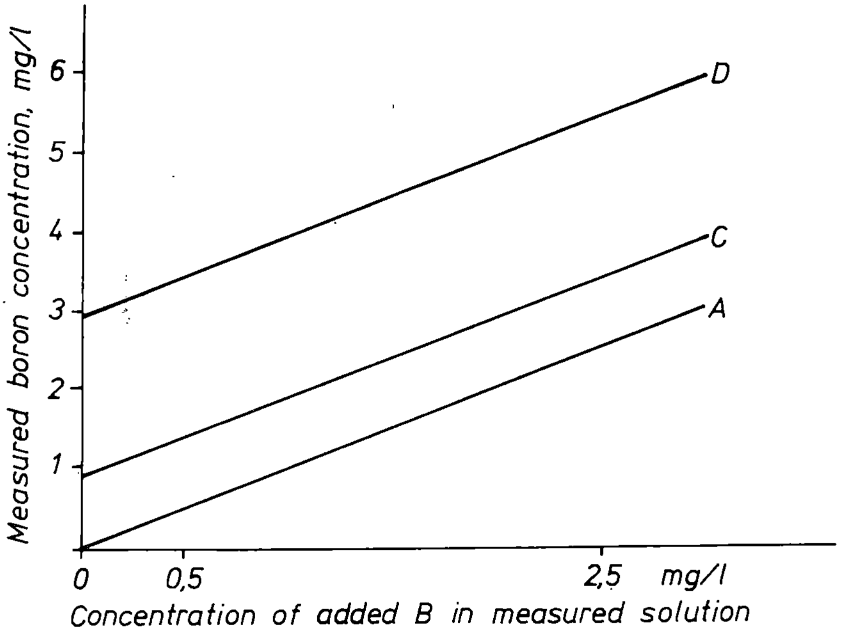

Fig. 1. Interference in determining boron caused by added iron. A = no Fe, C = 1000 mg Fe/l with EDTA, D = 1000 mg Fe/l without EDTA.

sorbances without the azomethine-H reagent and subtract them from the absorbances with the coloring agent.

The experiments indicated good reliability of the azomethine-H method in plant analysis, and supported the reviewed earlier studies in this. In determining boron in soil extracts, on the contrary, the yellowish color or turbidity caused serious problems. The impurities in the measured solutions absorb light and cause too high boron values.

At the beginning of this study, decolorization of the hot water extracts of soils was attempted (according to SIPPOLA and ERVIÖ 1977) by adding activated charcoal to the suspensions prior to boiling. Although all the extracts were not cleared completely, the values obtained for mineral soils fairly closely equaled those of an evaporating — dry ashing — redissolving procedure. In the case of organic soils, the extracts were inadequately decolorized for the colorimetric method.

Charcoal is an additional source of error in the test. SIPPOLA and ERVIÖ (1977) found a slight increase in boron values when standard solutions were boiled with it. Other researchers (GUPTA and STEWART 1975, GUPTA 1979 a, KOZAI and HOSHINA 1981, WATANABE et al. 1981) observed a loss of boron by the same decolorization agent. PARKER and GARDNER (1981) found that the obtained values were too high because of the inefficient decolorization by the activated charcoal.

Because of too serious errors in the colorimetrically measured boron values, this modification of the hot water extraction with activated charcoal was discontinued. The values obtained by it were only used for soil profile assessments. In them the heterogeneity of the soils caused so large errors in sampling that the inaccuracy in the determination became less important.

PARKER and GARDNER (1981) were able to eliminate the errors in the colorimetrically determined HWB values efficiently by substituting 0,02 $CaCl_2$ for pure water. The electrolyte flocculated soil colloids and thus decreased the amounts of fine-divided solid material passing through the filter paper. Thus the filtrates became less turbid and the error-causing background absorbances were reduced.

In this study, the effects of $CaCl_2$ on the turbidity of hot water extracts and boron values were first studied with five soils. The background absorbances decreased about fifty percent, when 0,01 M $CaCl_2$ was substituted for pure water as the extractant (Table 1). The errors in the uncorrected values were eliminated in the same efficiency. The accuracy of the background-corrected values was also improved when the absorbance caused by the boron proportionally increased. The background absorbance increased with increasing content of organic carbon in soil. With low-boron peat it tended to be larger than the residual absorbance. Then the results were obtained from the minor parts of the total absorbance, which certainly increased the errors.

Direct measurement gave similar values to the evaporating — dry ashing — redissolving procedure (Table 1). This agreed with the earlier findings (KOZAI and HOSHINA 1981, WATANABE et al. 1981) that humous material in soil extracts do not disturb color development in the azomethine-H method. Nevertheless, the hot water extracts from organic soils were cleared by dry ashing. This procedure was also applied to the mineral soils in the experiments which included organic soils. All the cold extracts were cleared and concentrated through the evaporating — dry ashing procedure.

Table 1. Soil HWB values obtained with pure water and 0,01 M $CaCl_2$ by evaporating—dry ashing procedure and relative values obtained from direct measurements, with and without corrections for background absorbances.

| Soil type | Organic C % | Extractant | Dry ashing m/l | Relative values by direct measurements (by dry ashing = 100) Corrected* | Uncorrected |
|---|---|---|---|---|---|
| Heavy clay | 2,4 | $H_2O$ | 0,64 | 72** | 181 |
| | | $CaCl_2$ | 0,61 | 98 | 138 |
| Fine sand | 2,3 | $H_2O$ | 0,43 | 74* | 193 |
| | | $CaCl_2$ | 0,49 | 100 | 153 |
| Muddy clay | 10,5 | $H_2O$ | 0,62 | 89* | 331 |
| | | $CaCl_2$ | 0,64 | 92 | 189 |
| Carex peat | 23,3 | $H_2O$ | 0,68 | 94 | 373 |
| | | $CaCl_2$ | 0,70 | 101 | 213 |
| Ligno Carex peat | 31,3 | $H_2O$ | 0,41 | 97 | 569 |
| | | $CaCl_2$ | 0,43 | 88 | 279 |
| Mean | | $H_2O$ | 0,56 | 85 | 315 |
| | | $CaCl_2$ | 0,57 | 97 | 192 |

* Corrected values indicated by asterisks differ significantly from values obtained by dry ashing.
* P = 0,05
** P = 0,01

In measuring the concentration of boron, the coloring reagents and mixing rates according to SIPPOLA and ERVIÖ (1977) gave a linear absorbance with boron concentrations up to 8 mg/l. The volume of the sample was 2 ml, and 4 ml of the buffer-masking reagent and 4 ml of the coloring reagent were added. Thus, there was a fivefold dilution of the sample. However, it was possible to double the concentration of the coloring reagent and reduce its volume accordingly from 4 ml to 2 ml. Then the volume and the final concentration of the aliquot sample could be doubled within the same total volume of the coloring mixture. The sensitivity of the method in small concentrations was thus significantly improved.

GUPTA and STEWART (1975) used much larger aliquot samples compared to the amounts of reagents. Dilution of the samples was then avoided almost entirely. Because azomethine-H causes an absorbance also in the absence of boron, its reduction would be desirable. However, preliminary work (unpublished data) showed a sharp decrease in color intensity with a decrease in azomethine-H concentration. The time needed to reach the maximum intensity was also lengthened and the linear range was much narrowed. The optimum mixing rate was not easy to define, for it seemed to depend on several factors, for instance on various interfering substances.

Color development of the azomethine-H — boron complex was assessed by measuring the absorbances of the same mixtures repeatedly (three coloring times by three measuring times with two replicates). The maximum color intensity occurred 50 minutes after mixing, then the absorbances began to decrease (Fig. 2). This result indicated that an equal standard time from the coloring to the measurement is essential in this method. The time it took to reach the maximum absorbance agreed with earlier results (JOHN et al. 1975, SIPPOLA and ERVIÖ 1977, GUPTA 1979 a). A longer time was required in a test by GAINES and MITCHELL (1979) who used a less concentrated azomethine-H reagent. Temperatures over 20 °C have reduced color intensity (BASSON et al. 1969, JOHN et al. 1975).

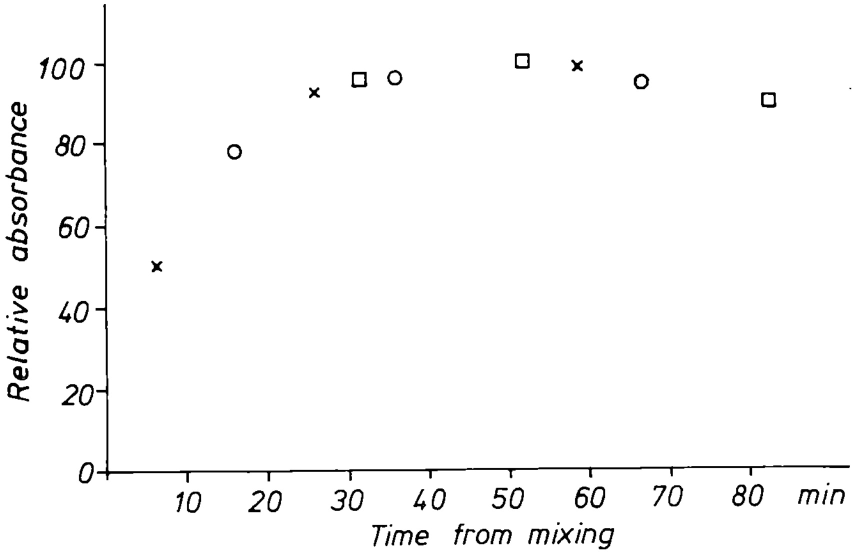

Fig. 2. Absorbance of the azomethine-H — boron complex. The measured solution contained 1 ppm B in 0,01 M $CaCl_2$. (The 0-point on the Y-axis was not absolute zero, reagents alone absorbed 40 % of the absorbance with 1 ppm B.)

The azomethine-H — boron complex absorbs light over a rather wide range of wavelengths. Besides at the usual 420 nm, it has been measured at the wavelength of 430 nm (WOLF 1974, GUPTA 1979 a). This method has not been sensitive to a variation of the pH in the solution (BASSON et al. 1969).

### 1.2. Discussion and modification of methods for extracting available boron from soils

Different chemical tests are usually used to estimate the supply of boron from soils to plants, i.e. plant-available boron. Attempts have also been made to develop biological tests. A test by COLWELL (1943) which was based upon deficiency symptoms in sunflower plants, is too laborious for routine work (BERGER 1949), but has sometimes been used in research as a reference method (e.g. SHERREL 1983 a, b). Use of *Azobacter chroococcum* bacterium has not been promising (GUPTA 1979 a).

A large number of solutions have been studied as extractants of the available fraction of soil boron. These solutions include diluted strong acids (PHILIPSON 1953, PONNAMPERUMA et al. 1981), acid sodium and ammonium acetates (WOLF 1971, DREWS and FRANK 1980, SHERREL 1983 a), acid sodium acetate with a chelating agent (WOLF 1982), sodium bicarbonate and dilute calcium chloride with and without mannitol (GUPTA and STEWART 1975, CARTWRIGHT et al. 1983), and ammonium bicarbonate with a chelating agent (GESTRING and SOLTANPOUR 1984).

In my opinion, none of the extractants listed above has proved very useful for humid region soils like those in Finland. PONNAMPERUMA et al. (1981) did obtain a correlation coefficient of 0,956 between the amounts extracted with hot water and those with 0,05 M HCI, but the HWB values ranged up to 25 ppm, and no dependence was shown at the lower end of the wide range.

The acetates studied as extractants of boron resemble the acid ammonium acetate which in Finland is used for testing macronutrients (VUORINEN and MÄKITIE 1955). Testing boron with this same extraction procedure would be very practical. GUPTA and STEWART (1975) and GUPTA and HÄNI (1975) found their acid ammonium acetate method as good as the hot water method, but their comparisons were based on a small number of soils. In recent studies with larger soil materials, the acid ammonium acetate test was inferior to the hot water test (SHERREL 1983 a, b, CARTWRIGHT et al. 1983).

The acid acetates and any buffered solutions are theoretically questionable extractants of boron, because sorption of boron by soils depends strongly on the pH. Nonexchangeable aluminum is extracted from some soils by the acid ammonium acetate (MÄKITIE 1968), and unavailable nutrients may be released jointly. However, CARTWRIGHT et al. (1983) found that their calcium chloride-mannitol test was as good as the hot water method, although the extracting power of mannitol has been found to increase with increasing pH (HINGSTON 1964).

PARKER and GARDNER (1981), who successfully eliminated the error-causing turbidity of the hot water extracts from soils by substituting 0,02 M $CaCl_2$ for pure water, also found that the diluted salt solution extracted the same amounts of boron as pure water did. These results were also obtained by BAKER and MORTENSEN (1966) and CARTWRIGHT et al. (1983). Because soils always contain a diluted salt solution, and not pure water, it may be postulated that such a diluted salt solution is a more natural extractant of soils than pure water.

From the five soils already compared when testing the determination of boron (Chapter 1.1.1.), the two extractants showed similar results (Table 2). Another comparison included twelve samples from three soils. The values were almost the same again (Table 3).

These extractants seemed to be adequately equal in extracting boron so that the results from them may be treated as the same test, named hot water extractable boron (HWB). 0,01 M $CaCl_2$ was used in the latest pot experiments and in the laboratory experiments. The standard extraction ratio of the method (1:2) was applied, but it was based on soil volume, as usually done in Finland (SIPPOLA and TARES 1978, KURKI 1982, SILLANPÄÄ 1982). The common weight-based ratio is too narrow for easy extraction in the cases of light organic soils. The volume-based ratio probably corresponds better to the rooted soil volume in the field.

Table 2. Effects of substituting 0,01 M $CaCl_2$ for pure water as extractant in HWB method (5-min boiling). Relative values with confidence limits of 0,95.

| Soil type | Organic C % | Boron values pure water mg/l | 0,01 M $CaCl_2$ relative values, % |
|---|---|---|---|
| Heavy clay | 2,4 | 0,64 | 94 ± 8 |
| Fine sand | 2,3 | 0,43 | 109 ± 11 |
| Muddy clay | 10,5 | 0,62 | 102 ± 9 |
| Carex peat | 23,3 | 0,67 | 104 ± 8 |
| Ligno Carex peat | 31,3 | 0,38 | 112 ± 12 |
| Mean | | 0,56 | 103 ± 4 |

The standard five-minute boiling time of the method appeared suitable. Decreasing the boiling time would steeply decrease the amounts of boron released into the soluble phase, but the additional release during a continued boiling would be slow or absent (BERGER and TRUOG 1944, GUPTA 1967 b, ODOM 1980). The short boiling time allows a rather inefficient cooling apparatus to be used for refluxing.

For the present study, a simple cooler was constructed using small plastic bottles. These bottles were loosely fitted inside the necks of the quartz boiling flasks, and inlet and outlet tubings were connected to them to circulate the cooling water. The roundbottomed boiling flasks were fitted in aluminum blocks standing on electric plates. About two percent of the extractant was lost during the five-minute boiling. Prolonged boiling caused an increase in the concentrations but no loss of boron from diluted solutions. The resulting increase in the values was ignored in calculating the results. This error was usually insignificant. However, it ought to be taken into account in calculating exact balances. A longer and more efficient cooling system would have held a greater part of the condensed water on its inner surfaces, but not much better in the flasks.

The hot water extraction is more laborious than an extraction at room temperature. Efforts have been made to technically ease this disadvantage (e.g. JOHN 1973). A cold-extraction test would also be an improvement in this respect. An insufficient separation of the immediately available boron in soil solution from the sorbed fraction is another drawback of the hot water test (e.g. HATCHER et al. 1959). This is an important reason why the relationships of the HWB and the uptake of boron by plants may so strongly change with soil texture and pH (WEAR and PATTERSON 1962). This is also why higher HWB values are required in heavy-textured than in light-textured soils (OUELLETTE and LACHANCE 1954, JUEL 1980). For a better indication of the amounts of the immediately available boron, a weaker extractant than hot water should be used.

In the present work, 0,01 M $CaCl_2$ at room temperature (about 20 °C) was studied as an extractant of boron. The relative amounts of boron extracted with two soil : solution ratios (v:v) were compared to the HWB values (Table 3). When the ratio was 1:20, the cold solution extracted almost the same amounts as the hot solution with the standard ratio (1:2). Much less boron was released into the cold extractant when the ratio was 1:5. The concentrations of the extracts were only about fifty percent higher than with the wider ratio, but would have quadrupled if the released amounts had remained constant. The cold extraction with the narrower ratio was relatively most efficient in acid high-boron soils and least efficient in heavily limed soils. These results from three soils are insufficient for generalization, although the effects of soil, boron level and liming level were significant according to analysis of variance.

Table 3. Boron extracting power of 0,01 M $CaCl_2$ as compared to the HWB method. Means and confidence limits (0,95) for double determinations from 12 samples of three soils (loamy clay, fine sand and Carex peat, each with 2 levels of liming and boron application).

| | Extraction procedure | | | | Amount of B extracted | |
|---|---|---|---|---|---|---|
| 'Method' | Solution | Ratio | Temperature | Time | mg/l soil | relative |
| HWB | $H_2O$ | 1:2 | 100 °C | 5 min | 1,18 ± 0,066 | 100 |
| HWB | $CaCl_2$ | 1:2 | 100 ,, | 5 ,, | 1,21 ± 0,044 | 102 ± 4,3 |
| CWB | $CaCl_2$ | 1:20 | 20 ,, | 60 ,, | 1,08 ± 0,072 | 92 ± 3,0 |
| CWB | $CaCl_2$ | 1:5 | 20 ,, | 60 ,, | 0,48 ± 0,037 | 38 ± 1,6 |

Further preliminary work indicated that a longer shaking time is inefficient in increasing the amounts of boron released into this cold extractant. Silicic acid also appeared to be very inefficient, although the results by MCPHAIL et al. (1972) and the observations by PRATHER (1977) suggested that the two molecules ($B(OH)_3$ and $Si(OH)_4$) were mutually exchangeable. The weakness of the silicic acid probably resulted from the low concentration of the sparingly soluble agent. Another possible explanation is that the soils were highly saturated with silicic acid and therefore not sensitive to small additions of it.

After the foregoing reviews and preliminary studies the extraction with cold 0,01 M $CaCl_2$ in an 1:5 ratio for one hour was compared with the hot water extraction in estimating the amounts of boron absorbed from soils by plants. The test was the same as that used by GUPTA and STEWART (1975), except the extraction ratio was based on soil volume instead of soil weight. The method (and the values from it) will be named the cold water extractable boron (CWB).

## 1.3. Ashing of plant tissues for boron determination

In decomposing plant tissues to determine boron, dry ashing is much commoner than wet combustion. The size of the dry-ashed subsample is often one g but an amount as small as 20 mg was used in a microanalytical procedure (LOHSE 1982) and larger samples of low-boron material have been used (GUPTA 1967 a, GUPTA and STEWART 1975, SAARI and PAASO 1980). The ashing temperature has varied from 450 °C (SIPPOLA and ERVIÖ 1977) to 600 °C (GAINES and MITCHELL 1979), and the ashing time from one hour (GAINES and MITCHELL 1979) to sixteen hours (SIPPOLA and ERVIÖ 1977).

For dissolving the ash, hydrochloric or sulphuric acid is used. The volume of the acid has usually been five to ten ml per g of plant material. The concentration of the solvent acid has ranged from 0,1 M (GUPTA and STEWART 1975, SIPPOLA and ERVIÖ 1977) to 11 M (GESTRING and SOLTANPOUR 1981 b). GAINES and MITCHELL (1979) found that the 0,1 M HCl was too weak to dissolve all the boron from the ashes. They obtained better recoveries with the equinormal 0,05 M $H_2SO_4$, because it was also an oxidizing agent.

Sulphuric acid, however, would raise other problems. In the cases with a high content of calcium in the plants, or with added calcium the solution may become supersaturated in respect to the sparingly soluble salt calcium sulphate, which would then begin to precipitate. The precipitation would interfere in the determination of boron, and at least would prevent any meaningful measurements of calcium from the extracts. Therefore, hydrochloric acid at a concentration of 0,5 M was applied. Dissolving effectiveness was improved by a careful manual stirring, and a long dissolving time.

The addition of a base to prevent evaporation loss of boron during the ashing has been found unnecessary for vegetative plant tissues (McHargue and Hodgkiss 1941, Gupta 1967 a). The results by Gopal (1969) were similar for vegetative tissues, but from the seeds of the *Brassica juncea* and other crushed oilseeds, about one third of the boron was lost at 550 °C when no $Ca(OH)_2$ was added. According to Basson et al. (1969) it is advisable to add calcium oxide if the content of alkaline earth metals in the ashed sample is low. Gaines and Mitchell (1979) concluded that an addition of calcium hydroxide is possibly needed when seeds are ashed. Saari and Paaso (1980) made the plant samples alkaline by suspending them in $Ca(OH)_2$ and drying before the ashing.

Besides the risk of boron losses, the volatility of boric acid causes another possibility for errors. Williams and Vlamis (1961) found an electric furnace to be a source of much too high values. The errors increased with the increase of temperature and time. Contamination can be decreased by using high crucibles with lids, avoiding longer-than-necessary ashing times, and igniting the furnace at a higher temperature before ashing the samples (Lohse 1982). A considerable amount of contamination from a furnace was also observed by Schnug (1982). He corrected the errors on the basis of blind determinations from crucibles with $Ca(OH)_2$.

The possible contamination and loss of boron were examined by ashing young ground shoots of turnip rape and ryegrass (1 g) at different temperatures and for various periods of time, with and without CaO (0,1 g). After cooling the ashes were dissolved into 20 ml of 0,5 M HCl and filtered after four hours.

No major differences between the eight treatments were found (Table 4). The results were means of two replicates, and all the differences were statistically insignificant, except those between the species. With the lower temperature and the shorter time, the ashes were much and the filtrates somewhat darker than with the other treatments. However, the incomplete decomposition did not affect the results seriously, because the residual organic material was largely filtered out from the extracts without any greater loss of boron.

Table 4. Effects of ashing temperature and time and CaO addition on boron contents obtained from plant tissues (ppm).

| Temperature °C | Time h | Turnip rape No CaO | Turnip rape CaO added | Ryegrass No CaO | Ryegrass CaO added |
|---|---|---|---|---|---|
| 450 | 2 | 38,2 | 38,0 | 15,9 | 16,5 |
| 450 | 16 | 37,7 | 37,6 | 15,7 | 15,4 |
| 520 | 2 | 38,6 | 37,5 | 15,7 | 15,9 |
| 520 | 16 | 37,9 | 37,5 | 15,7 | 15,4 |

The results indicated no loss or contamination, although wide open crucibles were used and the furnace was not ignited before the ashings. In the foregoing and further preliminary testing, the dissolution of the boron from the ashes appeared to be almost complete and the recovery of added boron a hundred percent. The results obtained suggested that a dry ashing at about 520 °C for two to three hours, without a base addition, is suitable for determining boron in vegetative plant tissues.

In some cases the ashes slowly and incompletely turned white, even if the thermometer reading was at 520 °C. The actual temperature may deviate from the ''nominal'' temperature seen on the thermometer, and all places in a furnace are not equally hot. The ashes closest to the door tended to be the darkest. A somewhat higher ashing temperature might result in a more complete and homogenous ashing, and therefore another ashing experiment with a wider temperature range was performed.

One gram of ground turnip rape leaves containing 81 $\mu g$ B (81 ppm) and an amount of boric acid containing 40 $\mu g$ B were ashed both separately and together, with or without 40 mg of $Ca(OH)_2$. To improve the absorption of the additives into the plant tissue, the mixture was first soaked and then dried at 105 °C. The ashing time was four hours and three replicates were made.

In the absence of the base, the pure boric acid was already lost at the drying temperature of 105 °C (Table 5). Extraction of the unashed leaves with 0,5 M HCl caused much too high values, for the extracts were strongly colored with soluble organic substances. The temperatures between 450 and 800 °C gave rather similar values. The only result that differed significantly from the mean was the 85 for the $H_3BO_3$ at 800 °C without $Ca(OH)_2$. The small amount of $Ca(OH)_2$ kept the boric acid from evaporating if the temperature was 600 °C or lower. At 800 °C the ashes were hardened but this did not prevent the boron from dissolving in the acid.

Table 5. Effects of ashing temperature and added base on results of boron determinations. Relative value 100 = 81 $\mu g$ in leaves, 40 $\mu g$ in $H_3BO_3$ and 121 $\mu g$ in leaves + $H_3BO_3$.

| Temperature °C | $Ca(OH)_2$ addition | Relative boron values for Leaves | $H_3BO_3$ | Leaves + $H_3BO_3$ |
|---|---|---|---|---|
| 105 | without | 175 | 2 | 142 |
| 105 | with | 182 | 104 | 143 |
| 450 | without | 98 | 1 | 99 |
| 450 | with | 94 | 101 | 97 |
| 520 | without | 100 | 0 | 100 |
| 520 | with | 97 | 100 | 101 |
| 600 | without | 100 | — | 100 |
| 600 | with | 97 | 100 | 102 |
| 800 | without | 102 | — | 95 |
| 800 | with | 97 | 85 | 101 |

In another test, 2 g of whole turnip rape seeds, 1 g of ground turnip rape leaves, 5 g of ground barley grain and 2 g of ground barley straw were ashed for four hours (Table 6). The chemicals (4 % $Ca(OH)_2$ and 8 or 20 ppm B) were thoroughly mixed into the samples with water.

Table 6. Effects of ashing temperature and added base in determining boron from different plant samples (ppm). B = $H_3BO_3$ addition (8 ppm B in grains, 20 ppm B in straw). Each column tested separately (Duncan 0,05).

| Temperature °C | $Ca(OH)_2$ addition | Turnip rape Seeds | Turnip rape Leaves | Barley Grains | Barley Grains + B | Barley Straw | Barley Straw + B |
|---|---|---|---|---|---|---|---|
| 520 | without | $12,0^a$ | $82^a$ | $2,1^b$ | $7,1^b$ | $3,6^a$ | $22,2^{ab}$ |
| 520 | with | $12,1^a$ | $80^a$ | $2,6^c$ | $11,0^c$ | $4,0^a$ | $24,3^b$ |
| 600 | without | $11,9^a$ | $81^a$ | $1,4^a$ | $3,9^a$ | $3,4^a$ | $18,8^a$ |
| 600 | with | $12,3^a$ | $81^a$ | $2,6^c$ | $11,5^c$ | $4,0^a$ | $24,6^b$ |

No significant loss of boron was recovered from the turnip rape samples. This result differed from the findings with *Brassica juncea* by GOPAL (1969). A possible cause for these contrasting observations was the crushing of the seeds in the earlier study. From the barley samples (Table 6) a remarkable amount of the boron evaporated if no base was added. The evaporation loss increased with an increase in temperature. Endogeneous boron seemed to be bound more tightly than exogeneous boron, and barley straw held this nutrient better than barley grains did.

The results of these three ashing experiments suggested that the evaporation of boron depends on properties of the ashed tissues. If the calcium content was originally or had been increased to more than two percent, boron did not evaporate even at the highest temperatures. Tissues with a somewhat lower calcium content, such as turnip rape seed and barley straw, can probably be ashed without adding a base, in temperatures of 550 °C and lower. Cereal grains seem to require a small amount of exogeneous base to prevent boron loss.

### 1.4. Procedures and reliability of boron analyses

An essential condition for the successful analysis of boron is sufficient protection against contamination throughout the procedure. The chemicals and water used in the analysis are potential sources of contamination. Common analytical grade chemicals are not free of boron. PHILIPSON (1953) found that the best purified chemicals tended to contain more boron than did lower grade chemicals. The probable reason for this was that borosilicate glass equipment had been used in the purification procedures. In the present study the effects of contamination were eliminated by treating each measuring series entirely with the same preparates. The azomethine-H method was found to require well-purified water (WOLF 1974). The water used in the analyses of the present work was distilled with quartz equipment. All the materials which came into contact with the liquid form of samples were boron-free, either of quartz or plastic. Whatman 42 filter paper was used.

The soil samples were air-dried and then ground with a wooden disk on a steel sieve (TARES and SIPPOLA 1978). The soil which passed through the 2 mm openings was taken for the analyses.

For hot water extractable boron, 25 ml of soil was measured with a cylinder (knocked for standard density) and put into 250 ml boiling flasks. Then 50 ml of 0,01 M $CaCl_2$ was added, the soil and solution were suspended by shaking, and the suspension was boiled for five minutes. Immediately after boiling the suspension was filtered. The filtrates from organic soils were cleared in the same way as the cold extracts (described below), except only 20 ml of filtrate was evaporated. As discussed previously, a procedure with activated charcoal was first used.

For cold water extractable boron, 25 ml of soil was put (as above) into 250 ml plastic bottles, 125 ml of 0,01 M $CaCl_2$ was added and the bottles were shaken for one hour (100 times per min 11 cm back and forth), then the suspension was filtered. 50 ml of the filtrate was measured into quartz crucibles, and rendered alkaline with 1 to 2 ml of saturated $Ca(OH)_2$, then evaporated to dryness at 105 °C, and ashed at 520 °C for two hours. After cooling the residues were extracted with 10 ml of 0,5 ml HCl for two hours, and then filtered.

Plant materials were ground through a 1,5 mm sieve (KÄHÄRI and NISSINEN 1978). A standard amount (0,5 to 5 g) of the ground sample was weighed in quartz crucibles. When ashing cereal grains, five percent of $Ca(OH)_2$ was mixed with the ground samples, moistened, and then dried at 105 °C. The crucibles with the plant tissues were put into a cold electric furnace that was heated up to the ashing temperature of 520—550 °C for oilseeds and cereal straw, and to 520—600 °C for vegetative tissues of dicots and cereal grains. The ashing time varied from two to four hours. The cooled ashes were extracted with 20 ml of 0,5 M HCl for four hours. The extracts were stirred manually soon after the addition of the acid and again about two hours later. The ash extracts were filtered into 25 ml plastic beakers without funnels.

To measure the concentration of boron, reagents made from analytical grade chemicals were prepared according to JOHN et al. (1975). For buffer-masking solution, 250 g of ammonium acetate and 15 g of EDTA disodium were dissolved in 400 ml of distilled water, then 125 ml of glacial acetic acid was slowly added. Two or four times those amounts were sometimes prepared.

Azomethine-H reagent was prepared by dissolving 0,9 g of azomethine-H and 2 g of ascorbic acid in 200 ml of distilled water. Duplicate amounts were sometimes made. This reagent was kept in a refrigerator. Most of the azomethine-H used was prepared according to BASSON et al. (1969). A commercial product (Merck) was also used.

For boron standards, stock solutions containing 100 mg B/l were prepared by dissolving 0,572 g of boric acid in a liter of the respective extractant. The series of 4—8 working standards covering the appropriate ranges (up to 8 mg/l) were diluted from the stock solution with the respective extracting solution.

In determining the concentration of boron, 2 ml aliquot extracts were pipetted into 25 ml plastic bottles, 4 ml of buffer-masking solution and 4 ml of azomethine-H reagent were added and mixed by manual agitation. After about 50 minutes, the absorbances at 420 nm wavelength were measured by a Bausch & Lomb Spectronic 88 spectrophotometer, equipped with a 10 mm flow-through cuvette and a digital display. The series were colored and measured in the same order to equalize the color-developing times.

For the background corrections, a water solution of one percent ascorbic acid was used instead of the azomethine-H reagent. The background absorbances did not change significantly during few days' period. The previously discussed more sensitive modification was used in laboratory experiments. In some of the later analyses the procedure was simplified (according to GAINES and MITCHELL 1979) by combining the buffer-masking solution and the azomethine-H reagent with each other. This mixing of reagents did not affect the color development when done immediately before each coloring.

To assess the reproducibility of the results from analyses of plant samples for boron, double determinations were done of 48 turnip rape straw samples from a pot experiment (P9). The mean content of 17,3 ppm and the standard deviation of 0,744 ppm gave a coefficient of variation of 4,3 %. The soil HWB values from two replicate pots of the 30 soils in a pot experiment (P1) gave a mean of 0,60 mg/l and a standard deviation of 0,034 mg/l, and thus a coefficient of variation of 5,5 %. The CWB values from the same soil samples caused an unsatisfactory coefficient of variation, wholly 20 %, as the standard deviation was the same as that for the HWB and the mean was not greater than 0,17 mg/l.

The principal reason for the imprecision of the results in determining the CWB values was the low concentration of boron in the extracts, which necessitated the evaporation procedure. The results could be converted exactly on the basis of known volumes, but even minor contaminations were hazardous because of the very small amounts of boron. The trend of increasing relative errors with decreasing amounts of boron appeared also in plants, in the same way as earlier found by SAARI and PAASO (1980). The applied procedure seemed to be reliable and rather accurate for plant tissues with more than a few ppm boron. The medium and higher values of HWB in soils also appeared to be fairly accurate, especially for mineral soils. The volumetric measurement of soils is rather inexact, especially with organic soils.

### 1.5. Other analytical methods

The particle size composition of mineral soil was determined by ELONEN's (1971) pipette method. The percentage of organic carbon in soil was determined by dry-combustion according to SIPPOLA (1982). Soil pH was measured by glass electrodes in suspension with 0,01 M $CaCl_2$ or water (soil:solution = 1v:2,5v). Extractable macronutrients in soil were determined by using the Finnish acid ammonium acetate method (VUORINEN and MÄKITIE 1955).

The oil content in rapeseeds was measured by a NMR-apparatus. Total nitrogen in oilseeds and other tissues was determined according to the Kjeldahl method using a Tecator apparatus. Chlorophyll content in rapeseeds was measured colorimetrically from a heptane-etanol extract. Contents of Ca, Mg, K, P, Fe, Mn, Zn and Cu in plants were determined according to KÄHÄRI and NISSINEN (1978). Phosphorus was measured colorimetrically using a vanadate method, and the cations were measured by atomic absorption spectrophotometry.

The weight of 1 000 seeds was calculated from the average weights of four counted lots of 100 seeds. For the germination percentage of seeds, 100 seeds were germinated on moist filter paper in petri dish, and the germinated seeds were counted.

### 1.6. Establishment and conditions of field experiments

The effects of different rates and methods of boron application on soils and plants were investigated in four field experiments. The properties of the soils at the experimental sites are given in Table 7. The two clay fields are part of the experimental area of the Department of Agricultural Chemistry and Physics at Jokioinen (61° 45' N, 23° 30' E). The fine sand field in Mietoinen is located at the South-West Finland Research Station on the southwestern coast of Finland, and the loam field in Kokemäki at the Satakunta Research Station in Western Finland, a hundred kilometers northwest of Jokioinen.

In three of the four trials, four boron fertilization treatments were studied with and without liming employing a split-plot design (Table 8). The fertilization treatments were established by

Table 7. Properties of surface soils at field experiment sites.

| | Jokioinen Heavy clay | Jokioinen Loamy clay | Mietoinen Fine sand | Kokemäki Loam |
|---|---|---|---|---|
| Particle size composition, % | | | | |
| —0,002 mm | 70 | 43 | 26 | 24 |
| 0,002—0,02 mm | 15 | 26 | 14 | 31 |
| 0,02 —0,2 mm | 7 | 22 | 58 | 42 |
| 0,2 —2 mm | 8 | 9 | 2 | 3 |
| Organic carbon, % | 4,1 | 3,1 | 1,8 | 1,8 |
| pH values in | | | | |
| $H_2O$ | 6,3 | 6,2 | 5,7 | 6,2 |
| $CaCl_2$ | 5,6 | 5,5 | 5,0 | 5,4 |
| Extractable nutrients, mg/l | | | | |
| P | 12 | 19 | 11 | 11 |
| K | 380 | 240 | 170 | 150 |
| Ca | 2900 | 2000 | 1100 | 1500 |
| Mg | 550 | 360 | 120 | 290 |
| B | 0,69 | 0,97 | 0,62 | 0,64 |

Table 8. Treatments in the boron fertilization-liming experiments at Jokioinen, Mietoinen and Kokemäki.

A Liming
$a_1$ No lime
$a_2$ Liming at the beginning of the experiment

B Boron fertilization
$b_1$ 0 % B in NPK each year
$b_2$ 0,05 % B in NPK each year
$b_3$ 0,2 % B in NPK each year
$b_4$ $b_1$ + four times the boron amount of $b_3$ as a store dressing before the first sowing

applying granulated NPK fertilizers containing similar amounts of other nutrients, but increasing amounts of boron. A large amount of boron was dressed also separately in the first year to test its toxicity to the turnip rape and to investigate its retention and movement in soils, and to study its residual effect in the second and third years (in Mietoinen, the dressing was repeated annually).

Ten boron fertilization treatments were studied at the other site in Jokioinen (heavy clay) using a randomized blocks design. These treatments included 0,01, 0,05, 0,1, 0,2 and 0,4 % B in the placed NPK fertilizers, and separate boron broadcastings in the first year at the rates of 1,4 kg/ha and 2,8 kg/ha (equaled the 0,2 and 0,4 %). The 0,4 % and 2,8 kg/ha were also combined to form another treatment. Foliar application was also included at two rates, as given in the details in Table 28. Only a boron-free nitrogen fertilizer was applied to this field in the third year.

The NPK fertilizers were placed in a combined seed and fertilizer drilling operation according to the common Finnish practice (ELONEN 1983). In this system, the fertilizer rows are 25 cm apart and the seed rows 12,5 cm apart. The fertilizers were in the middle of every second space between the seed rows and about 7 cm below the soil surface. The NPK percentages in the fertilizers were 16—7—13. The distribution amount (kg/ha/a) was 700 in Jokioinen, 625 in Mietoinen and 600 in Kokemäki. The store dressings were applied as a solution of Solubor, or as Fertilizer Borate mixed with sand and broadcasted manually, and incorporated into the soil by combidrilling (except at Kokemäki, where it was done after sowing).

Ground limestone was used as liming material: calcite from Lohja in Jokioinen, calcite from Parainen in Mietoinen, and dolomite from Siikainen in Kokemäki. The amounts per hectare were 10 tons in Jokioinen, 8 tons in Mietoinen and 7 tons in Kokemäki. The distributed lime was incorporated into the surface soil by harrowing in the usual way for seedbed preparation. The liming materials were analyzed for boron content by dissolving them into 2 M HCl. The dolomite from Siikainen contained a substantial amount of boron, 102 ppm, while the calcite from Lohja contained only 9 ppm and that from Parainen 13 ppm. Availability to plants of the boron in the limes was studied in a pot experiment (P9).

The field experiments were established with four replicates. The sizes of the (sub)plots were 25—35 $m^2$. An unharvested area at least 0,5 m wide was left between the plots in the second and third years. The turnip rape cultivars, and the dates of sowing and harvesting are presented in Table 9. Weeds and pests were controlled chemically. The experiments were harvested with a combine. The seed yields were weighed and their moisture percentages determined gravimetrically. The listed yields were converted to the moisture level of 9 %.

It is not recommended to successively cultivate rapes in the same field for more than one or two

Table 9. Turnip rape varieties, sowing and harvest dates of field experiments.

| | | Jokioinen Heavy clay | Jokioinen Loamy clay | Mietoinen Fine sand | Kokemäki Loam |
|---|---|---|---|---|---|
| 1980 | Variety | Candle | | | |
| | Sowing | 15.5. | | | |
| | Harvest | 8.9. | | | |
| 1981 | Variety | Ante | Ante | Torch | Ante |
| | Sowing | 21.5. | 17.5. | 26.5. | 20.5. |
| | Harvest | — | 7.9. | 25.9. | 9.9. |
| 1982 | Variety | Ante | Ante | Ante | Ante |
| | Sowing | 3.6. | 13.5. | 26.5. | 21.5. |
| | Harvest | — | 9.9. | 14.9. | 15.9. |
| 1983 | Variety | | Emma | Emma | Emma |
| | Sowing | | 7.5. | 20.5. | 30.5. |
| | Harvest | | 25.8. | 3.9. | 20.9. |

years. The most distinct disadvantage of the uncommon turnip rape monoculture was an increasing abundance of chickweed (*Stellaria media*) in the loamy clay field in Jokioinen. Some individual plants suffered from club root in the loam field in Kokemäki in the third year.

No severe drought period occurred during the four years, because the precipitation level during the early summers was higher than average (Table 10). The unusually heavy and frequent rains led to detrimental wetness in the compacted heavy clay field in Jokioinen, and consequently caused very uneven growth. All yield data from this experiment was rejected, but the tracing of applied boron in the soil succeeded and justified the continuation of this experiment to the third year.

## 1.7. Outlines and techniques of pot experiments

The series of pot experiments was started according to a step by step strategy. First the experimental techniques were improved and learned in detail and their applicabilities were examined. After this preliminary work the main experiments were planned and carried out. Finally, the series was finished with some complementary tests.

In 1980—81, a preliminary experiment was performed to study the effects of increasing amounts of applied boron on various plants growing in fine sand. The toxicity of boron was

Table 10. Mean temperature and precipitation in Jokioinen during growing seasons (ANON. 1980—1984).

| Month | 1931—60 | | 1980 | | 1981 | | 1982 | | 1983 | | 1984 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | °C | mm | °C | mm | °C | mm | °C | mm | °C | mm | °C |
| Apr. | 2,2 | 33 | 4,7 | 15 | 0,9 | 7 | 2,1 | 43 | 4,8 | 22 | 4,2 |
| May | 8,8 | 39 | 7,0 | 20 | 11,2 | 19 | 8,5 | 71 | 11,0 | 44 | 12,6 |
| June | 13,7 | 42 | 16,4 | 131 | 12,1 | 115 | 11,2 | 25 | 13,3 | 84 | 13,1 |
| July | 16,2 | 70 | 16,2 | 36 | 16,2 | 104 | 16,4 | 84 | 16,6 | 41 | 14,8 |
| Aug. | 14,7 | 74 | 13,9 | 76 | 13,5 | 88 | 15,6 | 111 | 15,0 | 58 | 13,8 |
| Sept. | 9,7 | 61 | 10,5 | 58 | 9,5 | 15 | 9,7 | 67 | 11,0 | 86 | 9,2 |
| May to August | | 225 | | 263 | | 326 | | 291 | | 335 | |

Table 11. Outlines of pot experiments.

| Experiment | Comparisons | Replicates/pots | Years | Special objectives |
|---|---|---|---|---|
| P1 | 30 soils | 2/60 | 1980—81 | B tests of soils and plants |
| | 30 soils, 2 B applications | 1/60 | 1982 | |
| P2 | 3 soils, 3 limings, 2 B applications | 3/54 | 1980—81 | Soil-B-pH-time relationships |
| | 2 soils, 3 limings, 2 B applications | 3/36 | 1982 | |
| P3 | 7 "limings", 3 B applications | 4/84 | 1981—82 | B-pH-Ca-time relationships |
| P4 | 3 oilseed species, 3 B applications | 4/36 | 1981 | Comparison of species |
| | 7 additional B applications | 4/28 | 1981 | Methods of B application |
| P5 | 5 soils, 2 limings, 2 B applications | 3/60 | 1982 | Field-pot comparison |
| P6 | 3 soils, 7 limings, 2 B applications | 2/84 | 1982 | Soil-B-pH-Ca relationships |
| P7 | 11 var. of 7 species, 2 B appl. | 3/78 | 1982—83 | Species and varieties |
| P8 | 2 limings, 2 B applications | 3/12 | 1983 | Testing a soil |
| P9 | 4 limings, 4 B applications | 3/48 | 1984 | Availability of limestone B |

Table 12. Soils of pot experiments. Means and standard deviations given for P1. Letter F following origin indicates soils taken from field experiments.

| Experiment | Soil type (count) | Org. C % | Clay % | pH (CaCl$_2$) | HWB mg/l | Origin |
|---|---|---|---|---|---|---|
| P1 | Clays | 4,9 | 50 | 5,4 | 0,83 | |
| | (8) | ± 3,6 | ±15 | ±0,6 | ±0,27 | |
| | Coarse min. | 2,5 | 10 | 5,1 | 0,54 | |
| | (14) | ± 1,2 | ± 9 | ±0,8 | ±0,26 | |
| | Organic | 33,6 | — | 4,2 | 0,47 | |
| | (8) | ±10,3 | — | ±0,5 | ±0,14 | |
| | All soils | 11,4 | — | 5,0 | 0,60 | |
| | (30) | ±14,7 | — | ±0,8 | ±0,27 | |
| P2 | Loamy clay | 3,2 | 43 | 5,0 | 0,95 | Tikkurila |
| | Fine sandy till | 3,8 | 4 | 4,7 | 0,49 | Tohmajärvi |
| | Carex peat | 44,6 | — | 4,0 | 0,42 | Pelso |
| P3 | Sandy clay | 3,4 | 47 | 4,8 | 0,52 | Jokioinen |
| P4 | Carex peat | 46,9 | — | 4,5 | 0,28 | Rovaniemi |
| P5 | Loamy clay | 3,1 | 43 | 5,5 | 1,11 | Jokioinen F |
| | Fine sand | 1,8 | 26 | 4,7 | 0,64 | Mietoinen F |
| | Loam | 1,8 | 24 | 5,3 | 0,56 | Kokemäki F |
| | Fine sand | 2,7 | 14 | 5,0 | 0,22 | Mixed |
| | Carex peat | 45,6 | — | 5,1 | 0,21 | Mixed |
| P6 | Loamy clay | 3,1 | 43 | 5,5 | 1,11 | Jokioinen F |
| | Fine sand | 1,8 | 26 | 4,7 | 0,64 | Mietoinen F |
| | Carex peat | 42,8 | — | 4,4 | 0,80 | Jokioinen |
| P7 | Carex peat | 42,8 | — | 5,0 | 0,85 | Jokioinen |
| | Carex peat | 45,6 | — | 5,1 | 0,21 | Mixed |
| P8 | Heavy clay | 0,5 | 79 | 5,4 | 0,12 | Jokioinen F |
| P9 | Carex peat | 42,8 | — | 4,7 | 0,40 | P7 no B |
| | Carex peat | 42,8 | — | 4,7 | 0,75 | P7 0,8 mg B/l |

demonstrated in a complementary experiment in 1983. The other pot experiments are listed in Table 11. Each experiment aimed at a particular objective. The whole series of different pot experiments was planned for investigating the soil-plant relationships of original and applied boron. The boron requirement of turnip rape was determined on the basis of the combined results of several experiments.

The properties of the soils used in the pot experiments are presented in Table 12. The 30 soils used in pot experiment P1 originated from various parts of Finland. Twelve of them were taken in the spring of 1980, and the others were remainders of earlier pot experiments. An assortment of various soil types was collected. One of these was a Sphagnum peat, two were subsoil sands, and the others were surface soils from cultivated fields. The physical and chemical properties of the 30 soils were listed in the preliminary report (SAARELA 1984, p. 118—120).

Six liter plastic pots were used in all the experiments except P6. The volume of soil was about five liters. The pots were made from common pails by punching a 15 mm hole in the bottom. The hole was covered so that the excess of the added water could flow through it into a separate pot below from which it was returned to the soil. The pots were placed on movable tables and provided with frames to support the plants. Parts of this system are shown in Figs. 10 (p. 236) and 21 (p. 239).

The appropriate quantities of soils were forced through a 15 mm (peats 20 mm) sieve and homogenized carefully. Equal portions of soil were weighed and the applied liming materials and fertilizing solutions were thoroughly mixed into them.

The soils were then put into the pots and compacted lightly, and then 25 seeds per pot were placed onto the leveled surfaces, using an instrument constructed for this purpose. Finally, the seeds were covered with a 1,5-cm layer of soil. When the rape seedlings were 10 cm high, their number was reduced to ten per pot. The removed seedlings were analyzed for boron, and in some cases for other nutrients.

Water solutions containing the applied nutri-

Table 13. Amounts and chemical forms of nutrients added to a pot (5 l soil) yearly before sowing.

| Nutrients in mg/pot | Salts |
|---|---|
| Solution I (in 30 ml) | |
| N 1500 | $NH_4NO_3$ |
| K 1500 | $KNO_3$ |
| P 400 | $(NH_4)_2HPO_4$ |
| Solution II* (in 20 ml)** | |
| Mg 400 | $MgSO_4 \cdot 7H_2O$ |
| Na 80 | NaCl |
| Fe 20 | $FeSO_4 \cdot 5H_2O$ |
| Cu 20 | $CuSO_4 \cdot 5H_2O$ |
| Zn 20 | $ZnSO_4 \cdot 7H_2O$ |
| Mn 20 | $MnSO_4 \cdot H_2O$ |
| Mo 2 | $Na_2MoO_4 \cdot 2H_2O$ |
| S ~600 | |
| Cl ~120 | |

* Half of these amounts in the second and later years
** 0,2 % of $H_2SO_4$ was added to keep Fe and Mn in solution

ents were measured and added to the soils with a dispenser. The solutions and amounts of nutrients normally used for basic fertilization are given in Table 13. To prevent possible evaporation of ammonia, solution I was added first and solution II on it soon after. Boric acid was used as boron fertilizer. Insoluble liming materials were weighed separately for each pot. At the beginning of the flowering stage of turnip rape, 500 mg of K per pot was added as $KNO_3$. Some days later the amount of N was increased to 500 mg per pot by adding $(Ca(NO_3)_2$. 100 ml per pot or more of water was added with these top-dressings each time. Both top-dressings were excluded from barley and $(Ca(NO_3)_2$ was excluded from leguminous plants. The crops cut prematurely were not top-dressed.

The amounts of nitrogen and potassium applied were high (1500 mg/pot ~500 kg/ha). About 850 mg of the N was nitrate, which together with sulphate and the chloride lowered the osmotic potential of the soil solution. This effect is determinated by the equation below:

$$\pi = CiRT$$

where $\pi$ = osmotic potential (J $kg^{-1}$)
C = concentration (mol $kg^{-1}$)
i = relation of total ions to anions
R = gas constant (8,31 J $K^{-1}$)
T = temperature in Kelvin (t + 273)

The amounts of the three soluble anions in mol per pot (n) were 0,061 mol nitrate, 0,019 mol sulphate and 0,003 mol chloride, a total anion content of 0,083 mol. The coefficient i depended on the ratio of $M^+$ and the $M^{2+}$ cations in the solution. It was about 1,7 if the $M^{2+}$ cations slightly dominated. When n and the amount of water in kg per pot (m) are substituted for C and the common lower potential limit of available water (—1500 J$kg^{-1}$) is entered with the values above, the solution for m shows that the soluble anions rendered 0,229 kg of water unavailable to the plants. This equaled about 5 % of the volume of soil in a pot.

The harmful effects of too large amounts of soluble salts were also observed experimentally in preliminary tests. Thus it was proved that large amounts of $CaCl_2$ are unsuitable to a pot experiment. A plan to study the ''pH effects'' and the ''calcium effects'' of $CaCO_3$ by comparing it with $CaCl_2$ was rejected and unsuccessful experiments avoided.

Deionized water was used for irrigation. Proper management of water conditions in the pots was found to be important for optimum growth. Before the emergence of seedlings the irrigation had to be done very gently so as not to compact the soil surface. When the leaf canopy of the big-leaved plants was at its maximum, the pots had to be irrigated twice a day during the sunny warm periods.

Sowing was mainly done between the 14th and the 20th of May, but the turnip rape in P4 was sown on the 25th of May, and in P6 on the 18th of June. When not separately stated, the turnip rape variey was 'Ante'. The pots were kept under a glass shelter. When cropped for more than one season, the pots were stored outdoors over the winters.

In the experiment with small pots (P6), the plants were cut in the bud stage (25 cm high). In 1980, P1 and P2 were cut six weeks after sowing (in full bloom) and re-sown for another similar harvest. Full ripeness was reached in all other cased (excluding some extreme boron deficiencies). Turnip rape was usually harvested in late August.

The immature plants were dried on steel sieves at 105 °C. The mature plants were let to dry in large paper bags in a warm room. Thus the seeds stayed live. After two to four weeks, when constant weights had been reached, the dried plants were weighed. Residual moisture was determined gravimetrically (at 105 °C) to obtain dry matter yields.

The rapes shed their leaves before their seeds ripen. This was a disadvantage in these plants in the pot experiments, because a considerable part of the nutrients taken up from the soil were lost via the fallen leaves. The need to catch the fallen leaves appeared in the preliminary experiment (SAARELA 1984). In 1981 the leaves were collected daily and saved separately from each pot. However, some mixing of the leaves could occur during windy periods. To completely avoid mixing, the pots would have to be isolated with nets. In the later years the pots were cleared of fallen leaves before every irrigation but the leaves were thrown away.

The amount of boron which was lost with the unanalyzed leaves would have shown a complete boron-balance, but the balance would still have been affected by different variables for instance, wind-carried petals and dust, possible evaporation or dry precipitation of boron, the boron added with chemicals, and irrigation water.

### 1.8. Statistical methods

Most of the results were computed using a VAX 11/780 computer and SPSS/SPSS$^X$ statistical programs (NIE et al. 1975, HULL and NIE 1981, NIE 1983). Duncan's test was used to test the differences between the treatments (DUNCAN 1955).

The results which did not differ significantly from each other at the five percent risk level are indicated by the same letter. Each soil in a given experiment was usually tested separately. Two ranges were calculated to test the differences in the field experiments with a split-plot design. The treatments in the same whole plots were tested on the basis of the standard error of the subplots as usual. A weighed mean of errors of the whole plots and the subplots was used to test the differences between the treatments in different whole plots, according to COCHRAN and COX (1966, p. 298—299). The two comparisons were done independently. Both these have indicated a significant difference if no common letter occurs. Complete randomization was applied in the pot experiments.

The confidence limits of 95 % are given (in parenthesis) for some regression coefficients and for the results of the laboratory experiments. The results from the analysis of variance (F-test) are indicated by asterisks. One asterisk means that the risk level is 1—5 %, two mean 0,1—1,0 % and three less than 0,1 %. In the graphs, the segments of lines show the confidence limits of 95 % (if not otherwise stated).

Total and partial correlation analyses and stepwise multiple regression analysis were used to examine the relationships of soil properties with boron. Plant variables were plotted with soil variables using the SPSS linechart subprogram (DRACH and SOURS 1981). Multiple regression values were included in the transformations plotted.

# 2. BORON IN SOILS

## 2.1. Occurrence and chemistry, a review

### 2.1.1. Occurrence

Boron is a lithophile element enriched in the silicate crust of the earth. Igneous rocks usually contain one to 30 ppm B (RANKAMA and SAHAMA 1950). The average content of boron according to KRAUSKOPF (1973) is 5 ppm in basalts, 15 ppm in granites, 20 ppm in limestones, 35 ppm in sandstones, 100 ppm in shales, 10 ppm in the whole crust, and usually between 7 and 80 ppm in soils. According to

AUBERT and PINTA (1977), the lowest contents of boron in igneous rocks are about 1 ppm, and terrestrial sediments contain 5 to 12 ppm, but marine sediments much more, up to 500 ppm. Highly variable boron contents, from less than one to 300 ppm, have been found from Finnish parent rocks and soils (SAHAMA 1945 a, b, LOUNAMAA 1956).

The most abundant boron-containing mineral in igneous rocks is a boro-aluminosilicate named tourmaline (RANKAMA and SAHAMA 1950). It is present in soils also, but as a material that weathers slowly, it does not have much value as an immediate source of boron to plants (BERGER 1949). Boron is also a substitute for other atoms in silicates. Contents up to 300 ppm without tourmaline crystals have been found in serpentine (SAHAMA 1945 a). The easily soluble low-temperature minerals with crystal water, such as borax, kernite, colemanite and ulexite, are usually not present in soils of humide regions (KRAUSKOPF 1973).

The total amount of boron in soils varies usually from 2 to 250 ppm, most often from 20 to 50 ppm (AUBERT and PINTA 1077). Less than five percent of it is generally available to plants (EVANS and PARKS 1983). In a large global study by SILLANPÄÄ (1982), the hot water extractable boron (HWB), which is an estimate of the available amount, averaged 0,75 mg/l. The mean value in 90 Finnish wheat fields was 0,55 mg/l in the same assessment.

According to the statistics of advisory tests done by Viljavuuspalvelu Oy, the average HWB value in Finnish agricultural soils was 0,36 in 1966—70, 0,39 in 1971—75, 0,48 in 1976—80 and 0,63 in 1981—84 (KURKI 1972, 1982, KÄHÄRI 1985). The increase in the mean was a result from the previously mentioned boronation of commercial fertilizers. According to fertilizer sale statistics (TAKAMÄKI 1984), the average (per hectare per year) distribution of fertilizer boron was about 80 g in 1970—71, 210 g in 1972—78 and 350 g in 1979—84.

The HWB value in Finnish soils varies in soil types and in regions obviously less than any other nutrient test value (SIPPOLA and TARES 1978, KURKI 1982). The chemical assessments agreed with earlier fertilization experiments in red clover seed production, which had revealed a boron deficiency at several sites in all soil types throughout Southern and Central Finland (HÄNNINEN 1962). Boron application to the same crop has been much less important in Denmark (STABEL et al. 1970). This indicated the poor boron status of Finnish soils in relative terms.

According to WIKNER's (1983) estimations the amount of boron deposition from air (per hectare per year) is more than 10 g in South-Western Finland, 5 to 10 g in Central Finland and the western coast, and less than 5 mg in the eastern and northern parts of the country. The deposition is too small to have any significant effects on intensive agriculture, at least within a short period. In natural ecosystems, on the contrary, this input may be important. For example, the boron content of the ombrotrophic water pools in mire complexes decreases the further the distance is from the sea (TOLONEN 1974). The deposition may be very large locally because of industrial emission (ERIKSSON et al. 1981).

Although the mean HWB values are rather similar in different soil types and regions, the values of the single samples have varied quite widely (KURKI 1972, 1982). Presently the common level ranges from 0,2 to 1,0 mg/l. Fortunately, the proportion of the lowest values have become much less frequent, because the increase due to the general small applications has been relatively largest with the lowest original amounts.

The local variation in boron status depends on the natural properties of the soil and human activity. The total amount of boron has been found to be only weakly reflected in the HWB values (GUPTA 1968). The balance between the additions to and removals from the soil is obviously a more important factor. The additions vary greatly because of highly varying rates of fertilizer boron distribution. Different crops deplete different amounts of this nutrient from their growth medium. The depletion is very low in cereal grains, only about 5 g/ha/a, but up to 300 g/ha/a in sugar beet and clover. An estimated average of Danish crops was 40 g/ha/a (HENRIKSEN 1970). A variable rate of leaching undoubtedly is an important cause of variation in the boron status of soil.

In Denmark, the boron leaching rate was estimated to average 30 g/ha/a (JENSEN 1974). As low a rate as 10 g/ha/a was measured from lysimeters in Poland (RUSZKOWSKA et al. 1977). It was previously presumed that boron is easily leached from Finnish soils or soils in humid regions in general (e.g. HOVI 1947 and SILLANPÄÄ 1972 in their reviews). The observed increase in the level of the HWB, however, did not agree with this supposition. In humid regions, the surface soil generally is richer in extractable boron than are the deeper layers (SILLANPÄÄ 1972, JENSEN 1974, SHERREL 1983 a).

### 2.1.2. Chemistry of plant-available fractions

In the aqueous medium of soil, boron forms stable covalent bonds with oxygen. Boric acid is probably the predominating compound in soil solution excluding strongly alkaline soils. It is a trigonal planar molecule formed through $sp^2$ hybridization of the three outer electrons. Completion of the octet ($sp^3$ hybridization) causes a tetrahedral structure. This is the mechanism in the formation and the structure of the borate anion $B(OH)_4^-$. Boric acid si a "Lewis" acid but not a "Brönsted" acid and is very weak acid ($pK_a$ about 9,2). Polyborate complexes are formed in concentrated but not in diluted solutions (e.g. KEREN and BINGHAM 1985).

The boron in soil solution is probably the only fraction which is immediately available to plants. A major proportion of the available amount is bonded to solid soil materials in a labile form which can be released in soil processes. Knowledge about the chemistry of this active fraction of soil boron is mostly obtained by testing how soluble additions of this nutrient are sorbed by different synthetic and natural soil components, and by various types of soils.

Hydrous oxides of aluminum and iron are the most efficient inorganic soil components to sorb boron (SCHARRER et al. 1956, SIMS and BINGHAM 1968 a, METWALLY et al. 1974 b, KLUGE and BEER 1979). The aluminum system usually retains more than the iron system. This difference may be a result of the more numerous hydroxide groups in hydroxy aluminum. The boron retaining capacity of a fresh hydroxy aluminum precipitate decreases with aging, probably because the surface area of the hydrous oxide diminishes with crystallization (SIMS and BINGHAM 1968 a). Drying the precipitate with boron has increased the amounts sorbed (METWALLY et al. 1974 c).

Boron is also retained by clay minerals, but in smaller amounts than by the amorphous oxides of aluminum and iron. Among the clays, illites (hydrous micas) and vermiculites with their expanding layers have the highest boron sorption capacities (SCHARRER et al. 1956, HINGSTON 1964, SIMS and BINGHAM 1967, KEREN and MEZUMAN 1981, KEREN and O'CONNOR 1982). Aluminum and iron coatings and impurities increase the sorption capacity in clay minerals (SIMS and BINGHAM 1967, 1968 b, KEREN and GAST 1983).

The sorption capacities of all the above-mentioned substances increase greatly with inceasing pH. Sorption of boron is maximum between pH 7 and 8 by aluminum, between 8 and 9 by iron, and between pH 7 and 9 by clays. After these maxima the sorption decreases with further increase in pH. At high pH levels, magnesium hydroxide clusters are other probable sorption sites (RHOADES et al. 1970 b). According to METWALLY et al. (1974 b) silica may also sorb boron in alkaline mediums. On the other hand, silica competes for binding sites with boron, and thus decreases its sorption (MCPHAIL et al. 1972). The presence of calcium ions may increase boron sorption in alkaline mediums (KLUGE and BEER 1979, KEREN and O'CONNOR 1982).

The increase of the sorption capacity with increasing pH is generally assumed to be a result of the formation of the borate anions, ($B(OH)_4^-$), and a greater reactivity of these anions. HINGSTON (1964), however, found no direct evidence for this and noted that with the increasing pH, new sorption sites for the boric acid molecules may have formed. On the other hand, according to METWALLY et al. (1974 a), an anionic exchange mechanism is possible even in acid mediums. The decrease of the sorption above the pH of maximum is probably caused by the more concentrated hydroxide ions which compete for the sorption sites (e.g. KEREN and MEZUMAN 1981). Even aluminum may form competing anions in alkaline mediums ($Al(OH)_3$ and $B(OH)_3$ are equally strong acids).

Adsorption on the surfaces as boric acid molecules or borate anions is probably the principal mechanism of boron retention. Complexing with "cis" hydroxyls of inorganic polymers has been thought to occur (SIMS and BINGHAM 1968 a). According to these authors, boron may be incorporated into hydroxy aluminum and iron polymers as a member in the chain. However, recent studies by BEYROUTY et al. (1984) indicated that a chemical bonding on the surface was the main sorption mechanism.

An entry into the clay mineral lattice may also take place, obviously through replacing aluminum and silicon atoms in the tetrahedral position (HARDER 1961, COUCH and GRIM 1968). A complex Ca-B-Al-silicate is possibly precipitated in mixed alkaline systems (PARKS and SHAW 1941, KLUGE and BEER 1979).

The sorption of boron by organic matter takes place through formation of organic complexes. A ring compound is formed with cis-diols and 2-oxy acids (PARKS and WHITE 1952). The sorption capacity increases with increasing pH (e.g. EVANS and SPARKS 1983).

## 2.2. Sorption and desorption by soils

Sorption by solid materials prevents the leaching of nutrients from soils. The capacity of soils to sorb boron is found to increase with increasing contents of amorphous aluminum compounds (HATCHER et al. 1967, HARADA and TAMAI 1968) fineness of texture, content of organic matter, cation exchange capacity, and content of soluble salts (BIGGAR and FIREMAN 1960, PRASAD 1978, ELRASHIDI and O'CONNOR 1982, PARKER and GARDNER 1982). The sorption greatly increases with increasing pH (e.g. KLUGE and BEER 1979) but can also take place with acid reactions (BINGHAM et al. 1971, SCHALSCHA et al. 1973).

The sorption of boron is more or less specific, being essentially independent of the presence of various anions (EATON and WILCOX 1939, BINGHAM and PAGE 1971, SCHALSCHA et al. 1973). It increases with time, and is partly irreversible in some soils (BIGGAR and FIREMAN 1960, ELRASHIDI and O'CONNOR 1982).

### 2.2.1. Adsorption isotherms

Adsorption isotherms have been applied to boron sorption studies since the 1950's (HATCHER and BOWER 1958). The most widely used isotherm, the Langmuir equation, has been found to describe the sorption of boron over a limited concentration range (e.g. BIGGAR and FIREMAN 1960, SINGH 1964, PRASAD 1978, ELRASHIDI and O'CONNOR 1982), while the Freundlich equation has fitted over a wider range (SINGH 1971. ELRASHIDI and O'CONNOR 1982).

The isotherms have most often been used to investigate toxic concentrations of boron in soils, but attempts have also been made to estimate the requirement of fertilization by them (SHUMWAY and JONES 1972). Further, boron sorption studies may be useful in explaining and predicting the behavior of this nutrient in soils.

The Langmuir equation can be written in linear form as

$$\frac{C}{X} = \frac{1}{kb} + \frac{C}{b}$$

where X = mg B sorbed per liter of soil
C = equilibrium B concentration in mg/l
b = adsorption capacity in mg per liter of soil
k = constant related to the bonding energy

The dimensions are usually based on soil weight. Now they were based on soil volume in order to obtain more comparable values in organic soils.

The Freundlich equation is

$$X = kC^{\frac{1}{n}}$$

Table 14. Boron sorption constants according to two adsorption equations. $X_O$ = initial soil boron (see text).

| Soil number | Soil type | Clay % | pH ($CaCl_2$) | HWB mg/l | $X_O$ mg/l | Langmuir b | Langmuir k | Freundlich k | Freundlich n |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Heavy clay | 73 | 5,8 | 0,94 | 1,04 | 5,1 | (0,63) | 1,7 | 1,5 |
| 2 | Heavy clay | 66 | 5,4 | 0,88 | 1,22 | 9,1 | (0,24) | 1,7 | 1,2 |
| 3 | Muddy clay | 64 | 4,6 | 0,56 | 0,60 | 1,7 | (0,13) | 0,8 | 1,6 |
| 4 | Loamy clay | 46 | 5,8 | 1,07 | 1,07 | 5,3 | (0,60) | 1,7 | 1,5 |
| 5 | Loamy clay | 43 | 4,9 | 0,95 | 0,95 | 3,3 | (0,60) | 1,0 | 1,4 |
| 6 | Loamy clay | 33 | 5,9 | 1,22 | 1,12 | 5,5 | (0,37) | 1,3 | 1,4 |
| 7 | Loam | 25 | 5,0 | 0,42 | 0,72 | 1,6 | (2,32) | 0,9 | 2,1 |

where k and n are constants and the other symbols correspond to the above definitions. A more convenient working equation is the linear form

$$\log X = \frac{1}{n} \log C + \log k$$

In order to determine the boron sorption isotherms, 10 ml of soil was suspended in 100 ml of 0,01 M $CaCl_2$ containing increasing amounts of boron (0, 0,5, 1, 2, and 5 mg/l) and shaken for 20 hours, then filtered and the boron content in the filtrates determined. The equal volumes of the soils were weighed on the basis of their bulk densities (obtained from the weights of three 25 ml lots of soils).

The sorbed amounts were computed from the changes in the solution concentrations. However,

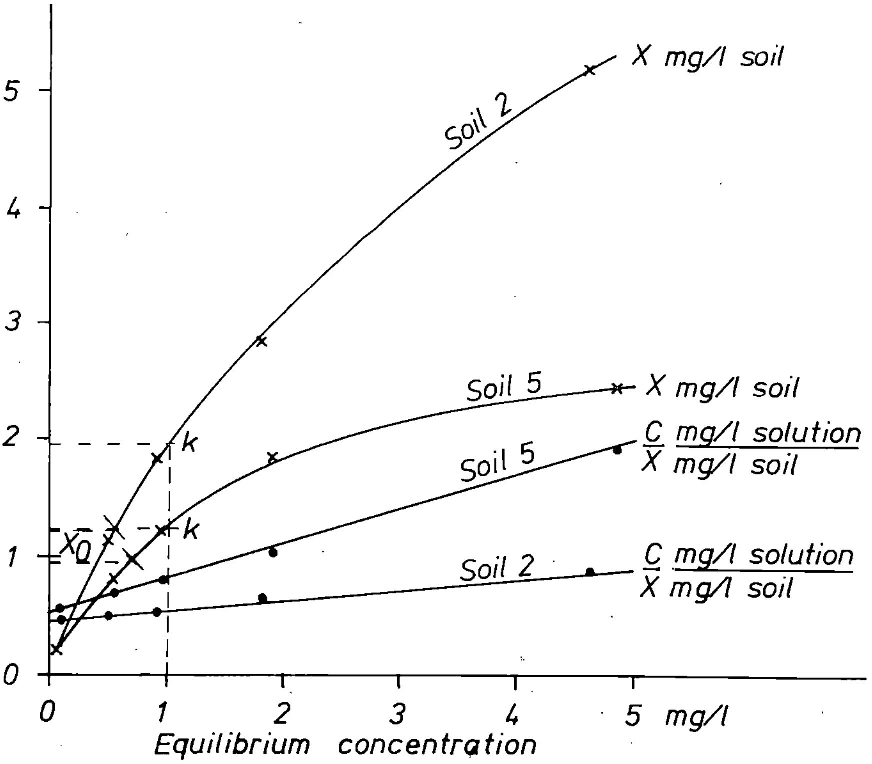

Fig. 3. Boron sorption by two soils.
Curve X = sorbed amount in mg/l soil
$\frac{C}{X}$ = line of the Langmuir equation
$X_0$ = original B in soil
k = Freundlich constant

the boron that was initially present in the soils had also to be taken into account in calculating the equations. First, the HWB value was added to the sorbed amounts and the C/X values calculated. Then their fit into the Langmuir equation was graphically checked. If the C/X values with the lower equilibrium concentrations deviated from the line, further corrections and checkings were made. The values of original ''adsorbed'' boron obtained through this adjustment were usually close to the HWB values (Table 14). In addition to the seven soils listed, the experiment comprised eight other soils, but the acid organic and acid coarse-textured mineral soils did not retain enough boron to calculate the constants.

Results from two of the soils are illustrated graphically in Fig. 3. They show that the original soil content of boron covered a major part of the boron that was sorbed when the solution concentration was one mg/l, which is equal to the Freundlich constant k, as log C is zero when C is one. A comparison with the $X_O$ values and the Freundlich k in Table 14 led to the same conclusion.

According to the theoretic base of the Langmuir equation, the constant b showed the maximum amount which may be adsorbed in any concentration. With such heterogenous systems as soils, the values should, however, only be considered as empirical relative values. Two important restrictions of the equation are, the limited linear range, and the nonexistence of any true equilibrium within moderate time periods. The Langmuir k is related to the bonding energy, but its significance is very questionable here because of the adjustment of the initial contents.

The obtained sorption constants (Table 14) are about the same as those found in other studies using similar soils for texture and pH, but higher values have earlier been obtained with neutral and alkaline soils (HATCHER and BOWER 1958, BIGGAR and FIREMAN 1960, RHOADES et al. 1970 a, PRASAD 1978, ELRASHIDI and O'CONNOR 1982). Much higher maximum sorptions have been observed in some amorphous soils (BINGHAM et al. 1971).

### 2.2.2. Slow sorption and desorption

Although the weak sorption of boron by the acid Finnish soils (Chapter 2.2.1.) agreed with earlier results, a contradiction arose to the pot and field experiments of the present study (these will be acknowledged in Chaper 2.3.). In some pot experiments, boron appeared to be efficiently retained even in acid soils. The fairly slow movement of boron in the soil profiles in the field experiments, and the general increase in the level of HWB values in the whole country, have also indicated a retention of some degree.

The principal reason for the different results was probably the time factor, which allowed a slowly proceeding retention to become effective in the long-term experiments. In order to investigate the evident slow retention of boron in soils, some incubation experiments were performed in 1984.

The laboratory incubation experiments included four surface soil — subsurface soil pairs and four other surface soils. All 12 soils were included without liming and five of the surface soils with heavy liming (3 g $CaCO_3$/0,5 l). The selection of soils and treatments is presented in Table 15. The pH values of these 17 different

Table 15. Soils and liming in incubation experiments. Soil codes indicate origin (F = from field experiment with the same soil type, Chapter 1.6., P = from pot experiment, Chapter 1.7.), depth (a = surface soil, b = subsoil) and liming (final L = with and without, others only without).

| Soil | Soil type | Org. C, % | Clay, % | Remarks* |
|---|---|---|---|---|
| F-HCaL | Heavy clay | 4,1 | 70 | |
| F-HCb | Heavy clay | 0,6 | 79 | P8 |
| F-LCaL | Loamy clay | 3,1 | 43 | P5 |
| F-LCb | Loamy clay | 0,5 | 44 | |
| P3-SCaL | Sandy clay | 3,4 | 47 | P3 |
| F-LaL | Loam | 1,8 | 24 | P5 |
| F-Lb | Loam | 0,4 | 25 | |
| F-FSa | Fine sand | 1,8 | 26 | P5 |
| F-FSb | Fine sand | 0,4 | 26 | |
| P1-FSa | Fine sand | 1,5 | 9 | |
| P1-Ma | Mull | 23,3 | 14** | |
| P1-CPaL | Carex peat | 46,9 | 0*** | |

* Pot experiments in which the same soils are studied (Chapter 1.7.)
** As converted to g/100 ml soil
*** Value used in statistical calculations (not determined)

soils and treatments are listed in Table 16 and HWB values in Table 19.

In the first part of the incubation experiment, 100 g of air dry soil (mull 40 g and peat 20 g) was put into 0,5 l plastic pots. Two treatments were formed by adding (as $H_3BO_3$) 0 or 1 mg B per pot ($\approx$ 10 mg B per liter of soil). Two replicates were made. The soils were saturated with water and mixed well, then let to dry somewhat and maintained approximately at field capacity by adding water twice a week. Watering was discontinued after three weeks so that the soils became air dry about the 30th day from the beginning. The dried soil clods were broken into smaller than 4 mm aggregates.

One fifth of each soil (about 20 ml) was put into 100 ml plastic bottles, then 50 of 0,01 M $CaCl_2$ was added , the pots were shaken for half an hour, stored for 19 hours, shaken another half an hour, filtered and the content of boron in the filtrates was determined. Unincubated samples of each of the 17 soils were also extracted in the same way with 0,01 M $CaCl_2$ solutions containing 0 or 4 mg B/l. The latter boron addition equaled that of the 1 mg per pot prior to the incubation.

The remainder of the incubated soils (about 80 ml) were re-moistened and kept near field capacity under plastic sheets for 62 days, then allowed to dry again. The extraction was done as above to the filtering stage. Now the extracts were first centrifuged in the extracting vessels, then filtered and analyzed for boron. Thereafter the extraction was repeated four times. The first four extractions lasted two days with four manual shakings and the fifth extraction lasted two weeks with daily shakings.

The same 17 soils were used to test the effects of drying on boron sorption by soils. The same amounts of soils as in the first part of the experiment ($\approx$ 100 ml) were suspended with 250 ml of 0,01 M $CaCl_2$ containing 4 mg B/l and kept at 35 °C. The amount of water was kept constant in one treatment with tight lids, while it evaporated to dryness in the other treatment during six to seven days. On the seventh day, the original amount of water was added to the dried pots and suspended with the soils. These and also the wet-stored suspensions were agitated four times during the following 20 hours, then filtered and analyzed for boron.

The two equilibrium concentrations in the incubation experiments did not allow the previously-used adjustment of the original amounts of ''adsorbed'' boron in soils. The Freundlich constants presented in Table 16 were calculated using the HWB values as the initial amounts. Possible errors due to this approximation should be taken into account in interpreting the results, but the differences between the two contact times are probably quite reliable.

Table 16. Soil pH values and Freundlich constants for boron sorption after contact times of 20 hours and 100 days.

| Soil | Soil pH ($CaCl_2$) | Time 20 h k | n | Time 100 days k | n |
|---|---|---|---|---|---|
| F-HCa | 5,4 | 2,8 | 1,8 | 4,3 | 1,3 |
| F-HCaL | 7,2 | 3,1 | 1,6 | 10,1 | 1,0 |
| F-HCb | 5,4 | 2,6 | 1,1 | 5,3 | 0,9 |
| F-LCa | 5,5 | 2,2 | 2,0 | 3,1 | 1,5 |
| F-LCaL | 7,2 | 2,7 | 2,0 | 6,4 | 1,2 |
| F-LCb | 6,0 | 2,1 | 1,1 | 3,1 | 1,0 |
| P3-SCa | 4,7 | 1,9 | 1,4 | 4,1 | 1,0 |
| P3-SCaL | 7,2 | 2,6 | 1,1 | 12,0 | 0,7 |
| F-La | 5,3 | 1,2 | 3,0 | 2,9 | 1,5 |
| F-LaL | 7,3 | 1,3 | 1,7 | 3,8 | 1,1 |
| F-Lb | 5,7 | 0,8 | 1,2 | 1,7 | 0,9 |
| F-FSa | 4,7 | 1,3 | 1,8 | 1,7 | 1,5 |
| F-FSb | 4,7 | 1,0 | 1,4 | 1,3 | 1,3 |
| P1-FSa | 4,4 | 0,7 | 1,9 | 1,6 | 1,1 |
| P1-Ma | 4,6 | 1,7 | 2,4 | 2,8 | 1,6 |
| P1-CPa | 5,4 | 1,4 | 2,2 | 2,1 | 1,6 |
| P1-CPaL | 7,3 | 2,1 | 2,1 | 6,6 | 1,1 |

The Freundlich constants determined after the contact times of 20 hours and 100 days indicated a marked increase in sorption with time (Table 16). The k values were much higher with heavy liming than in acid soils. For acid soils with the 20 h time, the values are about the same as the foregoing results. In Table 17 the amounts retained from the solution are given in percent of added boron.

The differences in the extent of sorption in 20 h and in the longer aerobic incubations were the combined effects of time and drying. Drying with boron has increased the sorption of boron by hydroxy aluminum precipitate (METWALLY et

Table 17. Boron sorption by soils with different drying treatments and times of contact, in percent of added boron. Confidence limits of 0,95 below (for single determinations after 8 day incubation they were calculated using the highest standard deviation in parallel analyses).

| | No drying | | Drying and rewetting | | |
|---|---|---|---|---|---|
| Soil | 20 h | 8 d* | 8 d* | 30 d | 100 d |
| F-HCa | 35 | 56 | 44 | 62 | 58 |
| F-HCaL | 44 | 79 | 75 | 82 | 80 |
| F-HCb | 48 | 64 | 53 | 70 | 69 |
| F-LCa | 25 | 35 | 25 | 49 | 46 |
| F-LCaL | 35 | 62 | 55 | 72 | 70 |
| F-LCb | 42 | 55 | 40 | 52 | 56 |
| P3-SCa | 35 | 52 | 37 | 61 | 62 |
| P3-SCaL | 49 | 79 | 72 | 80 | 82 |
| F-La | 12 | 30 | 16 | 39 | 46 |
| F-LaL | 22 | 50 | 39 | 59 | 60 |
| F-Lb | 20 | 37 | 24 | 41 | 43 |
| F-FSa | 18 | 20 | 10 | 30 | 32 |
| F-FSb | 18 | 17 | 6 | 25 | 28 |
| P1-FSa | 8 | 15 | 5 | 26 | 36 |
| P1-Ma | 19 | 26 | 22 | 39 | 42 |
| P1-CPa | 17 | 21 | 36 | 29 | 34 |
| P1-CPaL | 30 | 58 | 79 | 69 | 71 |
| | ±(3,5 | 5 | 5 | 4,3 | 2,1) |

* Temperature risen

al. 1974 c), and by soils (BIGGAR and FIREMAN 1960). An increase of sorption by drying can also be expected on the basis of a shift of the equilibrium.

The drying in the eight-day incubation, however, favored desorption of boron from the mineral soils (Table 17). An explanation for this result was that the soil — boron bonds were stabilized by hydration water which was partly lost in the dehydration process. The violent soaking when rewetting the soils was also a possible cause of desorption. In the peat soil retention was increased with drying. These different results from the peat may have been caused by an irreversible dehydration.

It has been claimed that the sorption equilibrium of boron in soils is reached within a few hours. This was clearly not true with the soils of the present study. An increase in sorption with time has been also found by BIGGAR and FIREMAN (1960). Various soils, of course, may react in different ways, but defective methods have possibly led to incorrect conclusion in some earlier studies. A slowly proceeding sorption after a rapid initial reaction may have remained unnoticed in the usual ''preliminary study'', although the slow reaction would have led to an appreciable sorption within a long period of time.

When comparing the sorption values of the individual samples (Table 17) with the respective soil characteristics, the effects of pH (Table 16) and clay percentage (Table 15) are clearly distinguishable. Soils from the subsurface layers retained slightly more than surface soils from the same sites. An obvious reason for this difference was the higher initial level of boron in the surface soils (Table 19). According to the sorption values of peat, the organic matter seemed to have sorbed boron very efficiently when limed heavily.

Statistically the extent of the sorption in 20 h was most closely correlated with the clay percentage (r = 0,78), while the simple correlation coefficient for pH was no higher than r = 0,50. Sorption in 100 d, on the contrary, correlated more closely with pH (r = 0,78) than with clay (r = 0,56). The percent of organic carbon and the initial boron in soil (HWB, Table 19) did not significantly correlate with the sorption of boron in the linear total model, but together with pH and clay they increased the coefficient of determination ($R^2$) from 0,74 to 0,86 (20 h) or from 0,79 to 0,88 (100 d). The statistically significant coefficients in the multiple regression equations were positive for organic carbon and negative for HWB. Thus the organic matter seemed to have increased sorption, and the initial HWB in soil decreased it in the present soil material.

The results from successive extractions of the soils, after the 100 d aerobic incubation with boron, are given in Table 18. The extracts contained not only the boron that was released in this step, but also the diluted residuals from the previous extracts. The highest concentrations in the second extraction were released from the soils of medium boron sorption capacities, but the last extraction gave the higher concentrations the higher the sorption percentages after the first extraction.

The desorption percentages by the soils with different sorption capacities were noticeably

Table 18. Desorption of boron in repeated extractions of soils with cold water after a 100-d incubation with boron. Confidence limits of 0,95 below. Numbers 2 to 5 indicate successive extractions.

| Soil | B in extracts mg/l | | Desorption % of added B | | | | Residual in soil % of added B | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 | 5 | 2 | 3 | 4 | 5 | 2 | 3 | 5 |
| F-HCa | 0,81 | 0,29 | 15,4 | 8,0 | 6,1 | 7,2 | 43 | 35 | 22 |
| F-HCaL | 0,59 | 0,31 | 13,5 | 6,4 | 7,0 | 7,9 | 67 | 60 | 45 |
| F-HCb | 0,53 | 0,27 | 9,6 | 7,5 | 6,4 | 6,8 | 59 | 51 | 38 |
| F-LCa | 0,95 | 0,22 | 17,5 | 6,6 | 4,4 | 5,6 | 28 | 21 | 11 |
| F-LCaL | 0,79 | 0,30 | 17,5 | 7,4 | 7,6 | 7,4 | 53 | 45 | 30 |
| F-LCb | 0,81 | 0,24 | 16,0 | 8,2 | 5,2 | 6,0 | 40 | 31 | 20 |
| P3-SCa | 0,69 | 0,22 | 13,3 | 5,9 | 4,1 | 5,7 | 48 | 43 | 33 |
| P3-SCaL | 0,54 | 0,28 | 12,5 | 8,2 | 6,5 | 6,9 | 69 | 61 | 48 |
| F-La | 0,74 | 0,17 | 12,4 | 4,2 | 2,8 | 4,3 | 33 | 29 | 22 |
| F-LaL | 0,81 | 0,25 | 16,9 | 7,1 | 5,1 | 6,4 | 43 | 36 | 24 |
| F-Lb | 0,77 | 0,16 | 14,4 | 5,5 | 3,6 | 4,3 | 29 | 24 | 16 |
| F-FSa | 0,72 | 0,15 | 10,6 | 3,2 | 1,9 | 4,0 | 21 | 18 | 12 |
| F-FSb | 0,53 | 0,09 | 7,3 | 2,7 | 1,4 | 2,3 | 21 | 18 | 15 |
| P1-FSa | 0,61 | 0,15 | 9,0 | 2,8 | 1,7 | 4,0 | 27 | 24 | 19 |
| P1-Ma | 0,91 | 0,22 | 13,5 | 6,4 | 3,6 | 5,5 | 28 | 22 | 13 |
| P1-CPa | 0,98 | 0,16 | 12,2 | 2,6 | 3,4 | 3,8 | 22 | 19 | 12 |
| P1-CPaL | 0,60 | 0,25 | 10,9 | 7,3 | 6,3 | 6,1 | 60 | 53 | 41 |
| | ±(0,08 | 0,02 | 1,6 | 0,5 | 0,6 | 0,4 | 2,4 | 2,3 | 2,4) |

equal, especially in step 2. Only the weakest sorbing soils released boron markedly less than the others. Because more of the extracts remained in the more porous soils after being centrifuged, the extractions were somewhat weaker with organic soils than with mineral soils. The strong boron retaining power of limed peat was, however, unquestionably shown.

The values of the amounts of residual boron in the soils after the extractions are rather reliable according to the confidence limits obtained with the two replicates. In this case it should, however, be kept in mind that the reproducibility of the measurements was not equal to the accuracy, or correctness of the results. Only the differences between the soils but not the absolute level may be compared on the basis of the given confidence limits.

The large amounts of residual boron after the five extractions indicated a strong hysteresis in the desorption stage. In earlier studies, ELRASHIDI and O'CONNOR (1982) have found the hysteretic sorption pattern in some soils, but a complete reversibility in others.

When studying the kinetics of the desorption of boron, GRIFFIN and BURAU (1974) were able to show separate reactions. The fast reactions were speculated to have been desorption from the surfaces and the slow reaction a diffusion from the interior of the clay minerals. RHOADES et al. (1970 a) found that more boron was slowly released from soils than expected on the basis of the Langmuir equation. BIGGAR and FIREMAN (1960) found also another type of release which appeared similar to the formation of a saturated solution of a chemical compound, but no signs of this mechanism appeared in the present study.

## 2.3. Fixation in soils

The foregoing sorption studies indicated that there are different types of boron sorption in soils. Irreversible sorption is considered to be a result of the fixation of boron in soils. The term fixation will thus signify a special type of sorption, although it has earlier been used as synonym with sorption as well as with adsorption and retention. Because fixed boron is unavailable to plants, this reaction is important for plant nutrition. The HWB test was employed as a method to determine the extent of fixation.

Retention against the hot water extraction is thought to indicate fixation.

Applied boron when mixed with soils immediately before hot water extraction, has been found to be extracted almost completely in some studies (BERGER and TRUOG 1939, GUPTA 1967 b). However, the 5-min reflux extraction of the standard HWB method has been used in boron fixation studies as far back as the 1940's (OLSON and BERGER 1946). Significantly less than hundred percent of the added boron has sometimes been recovered in the soluble phase. OELSCHLÄGER (1958) obtained recoveries from 71 to 76 percent, and GUPTA and STEWART (1975) from 68 to 70 percent. SINGH and SINHA (1975) determined HWB from one hundred sandy soils in India 24 hours after boron application, and recovered 20 to 70 percent of the added boron.

In order to assess the fixation of boron, the soils which had been incubated for 100 days (Chapter 2.2.2.) were also analyzed for HWB. The previously described procedure with 0,01 M $CaCl_2$ was employed, except instead of volumetric measurement the soils were weighed to achieve better accuracy (25 g mineral soil, 10 g mull, 5 g peat). Fresh samples were analyzed for HWB similarly, except 5 mg B/l was added to the extractant (≈ 10 mg B per liter of soil).

The acid soils did not fix boron from the extractant during the 5-min boiling, except the slightly acid heavy clay subsoil (Table 19). All of the heavily limed mineral soils, however, did fix boron during the refluxing. The picture was somewhat different when the initial boron in the soils was taken into account. If the initial HWB was considered as unfixed, most of the soils fixed some boron. The previously discussed loss of water during boiling may also have decreased the apparent fixation by up to two percentage units.

After incubation the effect of the heavy liming on the hot water extractability of the boron which was initially contained by the soils was quite remarkable. The decreases in the HWB values of the five limed soils ranges from 29 to 47 percent with a mean of 38 percent (Table 19). This agreed with the results obtained with one soil by BISHOP and COOK (1958), and with 38 acid mineral soils by KLUGE et al. (1981).

Table 19. Fixation of added boron during hot water extraction and during a 100-d incubation into a form not released in hot water, in percent of added boron. Confidence limits of 0,95 below.

| | HWB | B added in extraction | | Incubated for 100 d | |
|---|---|---|---|---|---|
| Soil | | fixation | HWB* + fixation | fixation | HWB* + fixation |
| F-HCa | 1,20 | 1 | 13 | 18 | 30 |
| F-HCaL | 0,68 | 14 | 21 | 45 | 52 |
| F-HCb | 0,28 | 10 | 13 | 30 | 32 |
| F-LCa | 1,36 | 0 | 14 | 4 | 17 |
| F-LCaL | 0,88 | 8 | 17 | 26 | 35 |
| F-LCb | 0,28 | 2 | 5 | 13 | 16 |
| P3-SCa | 0,32 | — 3 | 0 | 29 | 32 |
| P3-SCaL | 0,20 | 22 | 24 | 50 | 52 |
| F-La | 0,60 | — 1 | 5 | 14 | 20 |
| F-LaL | 0,32 | 10 | 13 | 28 | 31 |
| F-Lb | 0,24 | 0 | 3 | 19 | 21 |
| F-FSa | 0,64 | — 3 | 3 | 3 | 9 |
| F-FSb | 0,30 | 0 | 3 | 4 | 7 |
| P1-FSa | 0,44 | — 2 | 2 | 3 | 7 |
| P1-Ma | 0,84 | — 1 | 8 | 1 | 9 |
| P1-CPa | 0,76 | 2 | 9 | 15 | 22 |
| P1-CPaL | 0,54 | 3 | 8 | 33 | 38 |
| | | ±(4,1 | 4,1 | 4,4 | 4,4) |

* as converted to percent of added B

The aerobic incubation of the soils with added boron caused a very considerable fixation of the boron from the ''unfixed'' HWB fraction in most of the soils (Table 19). The mull soil and the coarsest mineral soils, however, did not appear to fix much boron. High initial boron contents also seemed to have decreased the fixation. The absolute fixed amounts are rather large; as converted to kilograms per hectare (20 cm deep) the highest values equal more than ten kg per hectare.

The fixation of boron correlated positively with soil pH (r = 0,66 without and 0,79 with incubation) and clay percentage (r = 0,44 without and 0,47 with incubation). The fixations with and without the incubation correlated rather loosely (r = 0,73). The retentions against the cold and hot extractions after the incubation correlated more closely (r = 0,92). This was another indication of the importance of time for the reactions of boron in soils. The residual boron in the soils after the five cold extractions (Table 18) also closely correlated with the fixation against the hot water extraction (r = 0,92).

The fixation of applied boron in soils during one to two growing seasons was studied in the pot experiments P2 and P3 which were cropped with turnip rape as explained in Chapter 1.7. Different amounts of $CaCO_3$ (and other salts in P3) and boron ($H_3BO_3$) were mixed into the soils at the beginning of the experiments, as specified in Tables 20 and 21. After each season the soils were analyzed for pH and HWB. The leaves were not collected from P3 in the second year. Boron uptake was calculated assuming the ratio of boron uptake in leaves : boron uptake in straw to have been the same in both years. This estimated part was less than ten percent of the total uptake and thus did not significantly increase the errors.

The fixation, or change of the amount of fixed

Table 20. Effects of liming and boron application on boron uptake by turnip rape and changes of soil boron fractions in mg per liter of soil. 1 and 2 = first and second years. Results of pot experiment P2. Each soil tested separately (Duncan 0,05).

| $CaCO_3$ g/l | Soil pH ($CaCl_2$) | Boron application | Boron uptake | | Change in HWB | | Change in fixed B | |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 1 + 2 | 1 | 1 + 2 | 1 | 1 + 2 |
| | | | Loamy clay (HWB 0,95 mg/l) | | | | | |
| 0 | 5,0$^{a}$ | 0 | 0,37$^{ab}$ | 0,70$^{b}$ | —0,20$^{a}$ | —0,38$^{a}$ | —0,17$^{a}$ | —0,32$^{a}$ |
| 2,4 | 5,9$^{b}$ | 0 | 0,29$^{a}$ | 0,62$^{ab}$ | —0,20$^{a}$ | —0,42$^{a}$ | —0,09$^{a}$ | —0,20$^{a}$ |
| 4,8 | 6,7$^{c}$ | 0 | 0,26$^{a}$ | 0,51$^{a}$ | —0,14$^{a}$ | —0,42$^{a}$ | —0,12$^{a}$ | —0,09$^{a}$ |
| 0 | 5,0$^{a}$ | 2 | 0,61$^{d}$ | 1,22$^{c}$ | + 0,65$^{b}$ | + 0,12$^{b}$ | + 0,74$^{b}$ | + 0,66$^{b}$ |
| 2,4 | 5,9$^{b}$ | 2 | 0,50$^{cd}$ | 1,26$^{c}$ | + 0,76$^{b}$ | + 0,24$^{b}$ | + 0,74$^{b}$ | + 0,50$^{b}$ |
| 4,8 | 6,7$^{c}$ | 2 | 0,47$^{bc}$ | 1,25$^{c}$ | + 0,76$^{b}$ | + 0,18$^{b}$ | + 0,77$^{b}$ | + 0,57$^{b}$ |
| | | | Fine sandy till (HWB 0,49 mg/1) | | | | | |
| 0 | 4,4$^{a}$ | 0 | 0,10$^{a}$ | 0,18$^{a}$ | —0,16$^{a}$ | —0,15$^{a}$ | + 0,02$^{a}$ | —0,03$^{a}$ |
| 2,4 | 5,5$^{b}$ | 0 | 0,10$^{a}$ | 0,25$^{ab}$ | —0,22$^{a}$ | —0,21$^{a}$ | —0,12$^{ab}$ | —0,04$^{a}$ |
| 4,8 | 6,6$^{c}$ | 0 | 0,07$^{a}$ | 0,15$^{a}$ | —0,24$^{a}$ | —0,13$^{a}$ | + 0,17$^{b}$ | —0,02$^{ab}$ |
| 0 | 4,4$^{a}$ | 2 | 0,25$^{b}$ | 0,51$^{c}$ | + 0,98$^{b}$ | 0,71$^{c}$ | + 0,77$^{c}$ | + 0,78$^{b}$ |
| 2,4 | 5,5$^{b}$ | 2 | 0,25$^{b}$ | 0,39$^{bc}$ | + 0,88$^{b}$ | + 0,72$^{c}$ | + 0,87$^{c}$ | + 0,89$^{b}$ |
| 4,8 | 6,6$^{c}$ | 2 | 0,20$^{b}$ | 0,26$^{ab}$ | + 0,74$^{b}$ | + 0,53$^{b}$ | + 1,06$^{d}$ | + 1,21$^{c}$ |
| | | | Carex peat (HWB 0,42 mg/1) | | | | | |
| 0 | 4,8$^{a}$ | 0 | 0,20$^{a}$ | — | —0,04$^{a}$ | — | —0,16$^{a}$ | — |
| 2,4 | 5,7$^{b}$ | 0 | 0,14$^{a}$ | — | —0,11$^{a}$ | — | —0,03$^{a}$ | — |
| 4,8 | 6,5$^{c}$ | 0 | 0,10$^{a}$ | — | —0,13$^{a}$ | — | + 0,03$^{a}$ | — |
| 0 | 4,8$^{a}$ | 2 | 0,62$^{b}$ | — | + 1,24$^{c}$ | — | + 0,14$^{b}$ | — |
| 2,4 | 5,7$^{b}$ | 2 | 0,67$^{b}$ | — | + 0,89$^{b}$ | — | + 0,44$^{bc}$ | — |
| 4,8 | 6,5$^{c}$ | 2 | 0,60$^{b}$ | — | + 0,88$^{b}$ | — | + 0,52$^{c}$ | — |

Table 21. Effects of liming and boron application on boron uptake by turnip rape and changes of soil boron fractions in mg per liter of soil. Results of pot experiment P3 in the first year. HWB initially 0,52 mg/l. Statistical tests by Duncan 0,05.

| Added* compound | Soil pH ($CaCl_2$) | Boron application | Boron uptake | HWB | Change in HWB | Change in fixed B |
|---|---|---|---|---|---|---|
| — | 4,4$^{a}$ | 0 | 0,29$^{a}$ | 0,25$^{ab}$ | —0,27 | —0,02$^{a}$ |
| $CaCO_3$ | 5,3$^{c}$ | 0 | 0,26$^{a}$ | 0,30$^{abc}$ | —0,22 | —0,04$^{a}$ |
| $CaCO_3$ | 6,6$^{d}$ | 0 | 0,22$^{a}$ | 0,28$^{ab}$ | —0,24 | + 0,02$^{a}$ |
| $CaCO_3$ | 7,1$^{e}$ | 0 | 0,20$^{a}$ | 0,26$^{abc}$ | —0,26 | + 0,06$^{a}$ |
| $CaSO_4$ | 4,5$^{a}$ | 0 | 0,27$^{a}$ | 0,31$^{abc}$ | —0,21 | —0,06$^{a}$ |
| Mg-K-Na* | 4,9$^{b}$ | 0 | 0,28$^{a}$ | 0,24$^{a}$ | —0,28 | ±0,00$^{a}$ |
| — | 4,4$^{a}$ | 0,8 | 0,54$^{bcd}$ | 0,45$^{c}$ | —0,07 | + 0,33$^{b}$ |
| $CaCO_3$ | 5,3$^{c}$ | 0,8 | 0,57$^{cd}$ | 0,41$^{bc}$ | —0,11 | + 0,34$^{b}$ |
| $CaCO_3$ | 6,6$^{d}$ | 0,8 | 0,50$^{bc}$ | 0,36$^{abc}$ | —0,16 | + 0,46$^{b}$ |
| $CaCO_3$ | 7,1$^{e}$ | 0,8 | 0,47$^{b}$ | 0,40$^{abc}$ | —0,12 | + 0,45$^{b}$ |
| $CaSO_4$ | 4,5$^{a}$ | 0,8 | 0,51$^{bc}$ | 0,44$^{c}$ | —0,08 | + 0,37$^{b}$ |
| Mg-K-Na* | 4,9$^{b}$ | 0,8 | 0,59$^{d}$ | 0,32$^{abc}$ | —0,20 | + 0,41$^{b}$ |
| — | 4,4$^{a}$ | 3,2 | 0,80$^{fg}$ | 1,24$^{e}$ | + 0,72 | + 1,68$^{d}$ |
| $CaCO_3$ | 5,3$^{c}$ | 3,2 | 0,83$^{g}$ | 1,28$^{e}$ | + 0,76 | + 1,61$^{d}$ |
| $CaCO_3$ | 6,6$^{d}$ | 3,2 | 0,71$^{e}$ | 1,13$^{e}$ | + 0,61 | + 1,99$^{e}$ |
| $CaCO_3$ | 7,1$^{e}$ | 3,2 | 0,74$^{ef}$ | 0,85$^{d}$ | + 0,33 | + 2,13$^{f}$ |
| $CaSO_4$ | 4,5$^{a}$ | 3,2 | 0,75$^{ef}$ | 1,22$^{c}$ | + 0,70 | + 1,75$^{de}$ |
| Mg-K-Na* | 4,9$^{b}$ | 3,2 | 0,93$^{h}$ | 1,14$^{e}$ | + 0,62 | + 1,65$^{d}$ |

* For Mg-K-Na compounds and amounts see Table 32 (p. 241)

boron was calculated from the application, uptake, and change of HWB (Tables 20 and 21). When no boron was added, a minor amount of the initially fixed boron appeared to be released in most cases. The largest release was from the acid peat and the relatively high-boron loamy clay in P2. The initially acid, limed sandy till, however, seemed to have fixed a part of its original boron already in the first year. When the boron application exceeded the uptake, it is the balance was positive, both the HWB and the "fixed" fraction usually increased. The strongly-fixed sandy clay of P3, however, appear to have fixed all of the residual from the smaller rate already in the first year (Table 21).

The results of the fixation of boron in four soils in the pot experiments during two to three years are summarized in Table 22. In the second year, even the rather large residual (1,78 mg/l) from the higher rate was fixed entirely in the sandy clay of P3. The other two mineral soils also fixed the residuals to a great extent, but in the peat, the applied boron remained largely in the HWB fraction.

When compared, the results of the laboratory and the pot experiments were in agreement. The higher relative fixation values of the pot experiments were probably due to the smaller rate of added boron and longer contact times. The absolute rates of boron fixed per liter of soil were higher in the laboratory experiments than in the pot experiments. Biological fixation into the plant roots in significant amounts was possible in the pot experiments. The incubation experiments without a plant indicated the physico-chemical fixation much more reliably and accurately.

The results suggested that boron is rather strongly fixed in Finnish clay soils, even in acid clays. The long-term boron fixation in soils is a rather unknown subject area, but some published results were quite similar to those of the present study (SCHARRER et al. 1955, HADDAD and KALDOR 1984).

The results did not clarify the mechanisms involved in the fixation, but some possibilities may be speculated. The micaceous clays in Finnish soils have been shown to fix potassium (e.g. KAILA 1965, SIPPOLA 1974). The sites between the negatively charged layers in the clays are accessible to cations but not to anions. Small neutral molecules such as boric acid may perhaps also be diffused into the interlayer spaces. The diffusion may be retarded by partial adsorption on the internal surfaces causing the fixation to proceed very slowly. The fast fixation by the limed soils in the 5-min refluxing obviously was a totally different reaction, which perhaps took place on the external surfaces of the soil particles.

## 2.4. Movement in soil profiles

In the review on the occurrence of boron in soils (Chapter 2.1.1.) it was concluded that leaching is an important factor for the development of boron status. However, no experimental studies

Table 22. Boron balances in mg per liter of soil, and fixation of boron in percentages of changes in total boron in soils ((Balance — change in HWB)/Balance) during one and two years in pot experiments P2 and P3. Percent of B fixed with confidence limits of 0,95.

| Soil type | Soil pH ($CaCl_2$) | Boron applied | Balance 1st y | Balance 1+2 y | Percent of B fixed 1st y | Percent of B fixed 1+2 y |
|---|---|---|---|---|---|---|
| Loamy clay | 5,0 | 2 | 1,39 | 0,78 | 53±13 | 85±29 |
| | 6,7 | 2 | 1,53 | 0,75 | 50±13 | 76±29 |
| Fine sandy till | 4,4 | 2 | 1,75 | 1,49 | 44± 7 | 52±11 |
| | 6,6 | 2 | 1,80 | 1,74 | 59± 7 | 70±11 |
| Carex peat | 4,8 | 2 | 1,38 | — | 10±12 | — |
| | 5,7 | 2 | 1,40 | — | 37±12 | — |
| Sandy clay | 4,4 | 0,8 | 0,26 | — | 127±27 | — |
| | 7,1 | 0,8 | 0,33 | — | 136±27 | — |
| | 4,4 | 3,2 | 2,40 | 1,59 | 70±11 | 90±16 |
| | 7,1 | 3,2 | 2,46 | 1,78 | 87±11 | 102±16 |

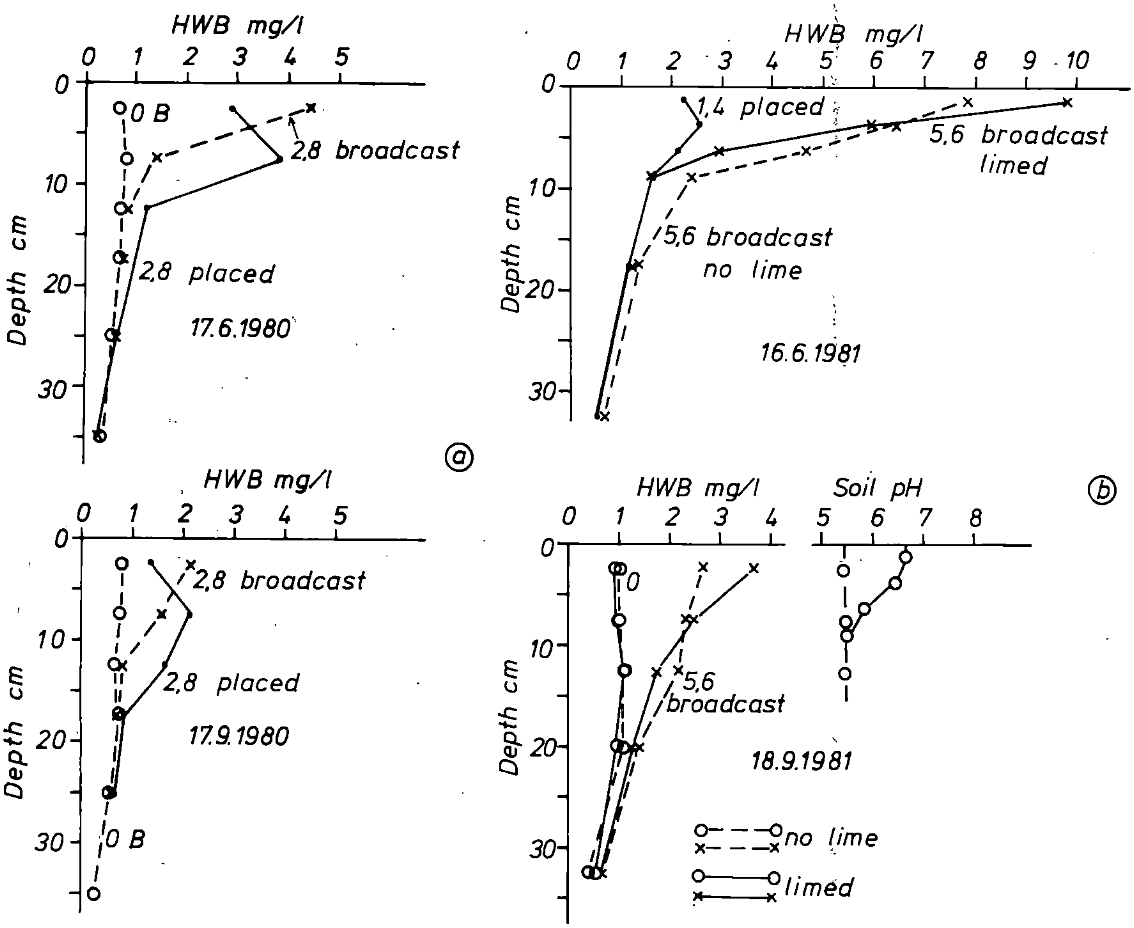

Fig. 4. Hot water extractable boron in soils by layers in the first experimental years. a. heavy clay, Jokioinen, b. loamy clay, Jokioinen, c. fine sand, Mietoinen, d. loam, Kokemäki. The numbers with lines indicate the amounts of applied boron in kg/ha. Soil pH by layers (b-d).

on the leaching process in Finnish soils have been reported. The leaching or movement of boron in soil is a function of the unsorbed content of boron and the flow of water in soil.

The sorption of boron was studied in Chapter 2.2. The velocity of water percolating in soil increases with an increase in the infiltration rate, and with a decrease in the water holding capacity of the soil. Within the rooted soil depth, the water flow diminishes from the surface as the water is absorbed by the plants. The amount of water discharged through the drainage pipes varied from 65 to 225 mm per year (mean 145 mm) in another clay field in Jokioinen during 1976—1982 (JAAKKOLA 1984).

There are two alternative ways to investigate nutrient movements: field conditions may be simulated in the laboratory, or the movements may be assessed in situ. Because of the questionable reliability of the laboratory methods (see SCHARRER et al. 1955), soil profile sampling and analysis were employed in the present study. An assessment of boron movement was the primary purpose of the large store dressings in the field experiments (Chapter 1.6.). Some other treatments were also sampled for comparison. Soil pH was determined by layers.

In the first experimental years, the soil profiles were sampled in several layers. 4—6 subsamples per plot were taken systematically to represent

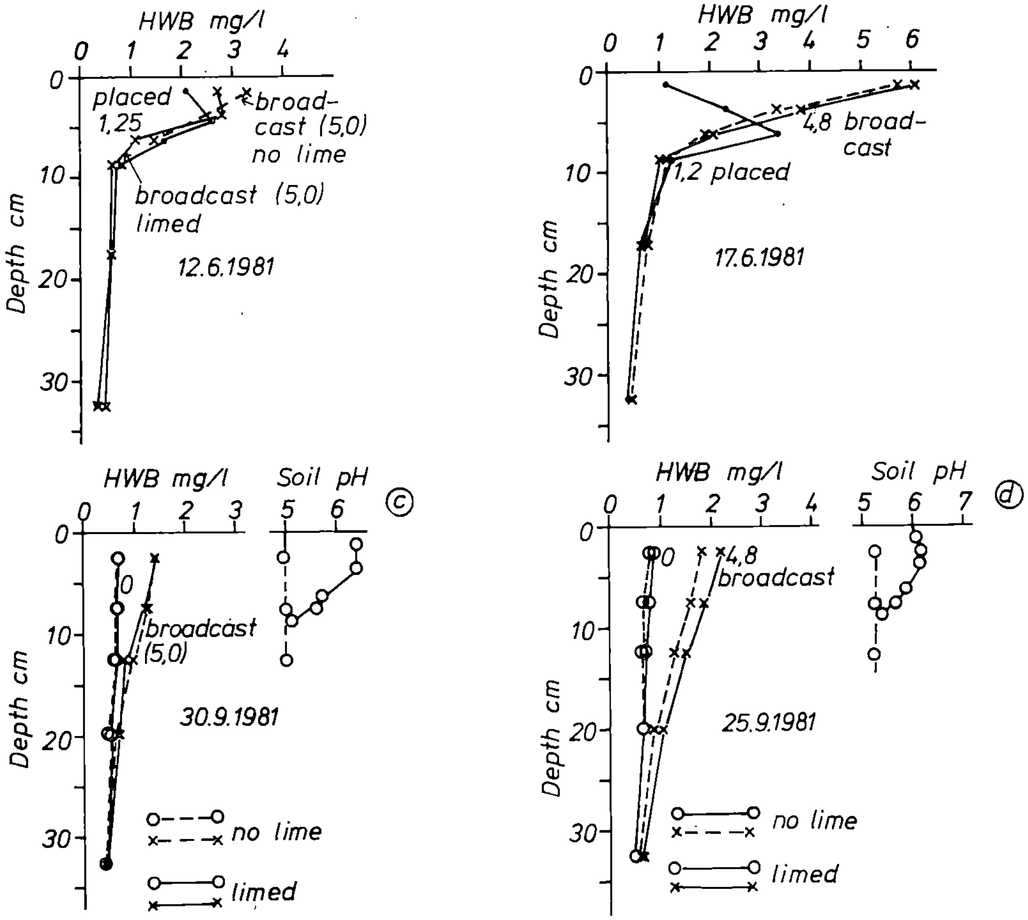

Fig. 4. Continued.

the average also with the placement. The first samples were collected in early summer when the plants were about 10 cm high and the second samples were obtained in the autumn after the harvest.

The contents of hot water extractable boron (HWB) in the layers of the four fields are shown graphically in Fig. 4. The points of the broken lines indicate the mean depths of each layer. The HWB values include only a part of the applied boron, but as rather constant proportions of the additions were probably extracted, they show the movements quite reliably. The final conditions were not affected if the applied boron had exchanged for the boron initially in the soils.

The downward movement was slowest in the heavy clay (Fig. 4 a). The boron that was applied in the spring did not descend more than about five centimeters during the summer. The major part of the applied amount stayed in the same layer where it was placed. The applied boron moved faster in the coarser soils, the faster the coarser the texture. Liming retarded movement most efficiently in the loamy clay (Fig. 4 b). This effect was statistically very significant in the relative values of the different layers (slope), although it was not significant in any individual layer. In the fine sand and loam soils, boron did not descend much faster than in the unlimed loamy clay, but the liming was less effective in these coarse soils (Fig. 4 c and d). No increase in the HWB was found in the subsurfaces after the first season.

The HWB values from the treatments without applied boron did not indicate significant leaching, but this result may have been affected for example by the boron released from the turnip rape plants on the soil surface. Some treatments were sampled in thin layers also in the spring of 1982 before tillage. If boron had leached from a shallow surface layer before sowing, the supply of boron to the small seedlings would have become poorer, although the values at the whole plow layer would have remained almost unchanged. However, only a weak leaching from the uppermost 2,5 cm layer of the coarser soils was detected (SAARELA 1984, p. 47—48).

At the end of the experiments the fields were sampled in three 25 cm deep layers. Significant effects of boron applications were found in the HWB values at each of the four sites (Table 23). In the plow layer, the greatest effects were found in the clays, but in the subsurface layer (25 to 50 cm), the differences were significant only in the coarser soils. The amount that was recovered in the HWB fraction from the annually applied boron varied from 25 to 40 percent. A smaller proportion was recovered of the store dressing in the fine sand and loam. Liming appeared to have increased the HWB values with large rates of applied boron, but these differences were statistically insignificant.

The measurements of the slow boron movement in clay soils agreed with other studies (KUBOTA et al. 1948, WILSON et al. 1951). Even in coarse-textured soils, the leaching of boron may be controlled by the clay fraction (PINYARD et al. 1984). The role of organic matter is obviously important in the retention of this nutrient in coarse soils (e.g. ERIKSSON et al. 1981). The retarding effect of liming has also

Table 23. Hot water extractable boron in the field soils by depth at the end of the experiments, in mg/l. $Ca_0$ = no lime, $Ca_1$ = with liming (for amounts see Chapter 1.6., for boron in the lime used in Kokemäki see Chapter 3.2.1.). Each soil and layer tested separately (Duncan 0,05).

| Boron applied total in 3 years kg/ha | method | Plow layer 0—25 cm $Ca_0$ | Plow layer 0—25 cm $Ca_1$ | Subsurface 25—50 cm $Ca_0$ | Subsurface 25—50 cm $Ca_1$ | Subsoil 50—75 cm $Ca_0$ | Subsoil 50—75 cm $Ca_1$ |
|---|---|---|---|---|---|---|---|
| | | Heavy clay, Jokioinen | | | | | |
| pH(H$_2$0) | | 6,3 | | 6,2 | | 6,5 | |
| 0,1 | placement | 0,69$^{a}$ | | 0,27$^{a}$ | | 0,12$^{a}$ | |
| 0,7 | ,, | 0,83$^{ab}$ | | 0,28$^{a}$ | | 0,11$^{a}$ | |
| 2,8 | ,, | 0,97$^{b}$ | | 0,32$^{a}$ | | 0,12$^{a}$ | |
| 2,8 | store dressing | 0,99$^{b}$ | | 0,27$^{a}$ | | 0,10$^{a}$ | |
| 5,6 | placement | 1,33$^{c}$ | | 0,32$^{a}$ | | 0,18$^{a}$ | |
| 8,4 | store + placement | 1,61$^{d}$ | | 0,32$^{a}$ | | 0,14$^{a}$ | |
| | | Loamy clay, Jokioinen | | | | | |
| pH(H$_2$0) | | 6,0 | 6,4 | 6,6 | 6,6 | 6,8 | 6,8 |
| 0,2 | placement | 1,02$^{a}$ | 0,98$^{a}$ | 0,45$^{a}$ | 0,53$^{a}$ | 0,29$^{a}$ | 0,40$^{a}$ |
| 1,1 | ,, | 1,15$^{a}$ | 1,10$^{a}$ | 0,49$^{a}$ | 0,55$^{a}$ | 0,34$^{a}$ | 0,35$^{a}$ |
| 4,2 | ,, | 1,57$^{bc}$ | 1,73$^{c}$ | 0,48$^{a}$ | 0,52$^{a}$ | 0,34$^{a}$ | 0,40$^{a}$ |
| 5,6 | store dressing | 1,49$^{bc}$ | 1,41$^{b}$ | 0,64$^{a}$ | 0,63$^{a}$ | 0,45$^{a}$ | 0,38$^{a}$ |
| | | Fine sand, Mietoinen | | | | | |
| pH(H$_2$0) | | 5,5 | 6,0 | 5,4 | 5,5 | 5,4 | 5,5 |
| 0,2 | placement | 0,76$^{a}$ | 0,80$^{a}$ | 0,46$^{ab}$ | 0,37$^{ac}$ | 0,54$^{a}$ | 0,43$^{a}$ |
| 0,9 | ,, | 0,87$^{ab}$ | 0,91$^{ab}$ | 0,38$^{ad}$ | 0,42$^{ab}$ | 0,49$^{a}$ | 0,57$^{a}$ |
| 3,8 | ,, | 1,03$^{bc}$ | 1,21$^{c}$ | 0,51$^{bc}$ | 0,54$^{bd}$ | 0,53$^{a}$ | 0,53$^{a}$ |
| (15.0) | broadcast | 1,95$^{d}$ | 2,12$^{d}$ | 0,60$^{bc}$ | 0,51$^{bd}$ | 0,55$^{a}$ | 0,53$^{a}$ |
| | | Loam, Kokemäki | | | | | |
| pH(H$_2$0) | | 6,0 | 6,3 | 6,8 | 6,8 | 7,0 | 7,1 |
| 0,2 | placement | 0,54$^{a}$ | 0,59$^{a}$ | 0,21$^{a}$ | 0,27$^{ab}$ | 0,21$^{a}$ | 0,23$^{a}$ |
| 0,9 | ,, | 0,59$^{a}$ | 0,67$^{ab}$ | 0,23$^{ab}$ | 0,25$^{ab}$ | 0,18$^{a}$ | 0,21$^{a}$ |
| 3,6 | ,, | 0,90$^{de}$ | 1,04$^{e}$ | 0,35$^{b}$ | 0,33$^{ab}$ | 0,27$^{a}$ | 0,21$^{a}$ |
| 4,8 | store dressing | 0,72$^{bc}$ | 0,84$^{cd}$ | 0,30$^{ab}$ | 0,32$^{ab}$ | 0,25$^{a}$ | 0,27$^{a}$ |

been found earlier (SCHARRER et al. 1955, JENSEN 1964, BAKER and MORTENSEN 1966).

Results of earlier studies concerning the mobility of boron in coarse-textured soils have been contradictory. SCHARRER et al. (1955), who observed slow movements even in coarse soils, found serious methodological deficiencies in earlier studies. Some simple laboratory experiments have led to estimates of leaching rates that were too high.

In Finland, large boron dressings have partly been recovered in the HWB fraction in the plow layer even after six years (TÄHTINEN 1970). Normal rates have been detected after three years (ERVIÖ 1975, TARES and SIPPOLA 1978). The residual effect of soluble boron in a fine sand soil was found in red clover seed production six years after the application (SALMINEN 1959).

The results of the present work provided an explanation and confirmed the reliabilities of these occasional observations of a long persistence of soluble boron in Finnish soils and agreed with the earlier mentioned general increase in the HWB values. It is possible that a small amount of boron is retained against leaching fairly well even in those soils which sorbed only a small part of the large rates. In relation to the amounts required by crops, about 0,01 to 0,1 mg boron per liter of surface soil, the storing capacities appeared to be quite large. As the relatively high content of organic matter contributes to the retention, extremely weak storing capacities of boron do probably not occur in Finnish soils.

### 2.5. Estimation of availability to plants

The supply of boron from soils to plants is an essential parameter in estimating the requirement for boron fertilization. After the analytical studies (Chapter 1.2.) the hot water method (HWB) and the cold water method (CWB) were compared in estimating the amounts of boron which were taken up from soils by turnip rape.

The dependencies of the boron uptake on the chemical soil test values were studied in the pot experiment P1 with 30 soils (Chapter 1.7). The studies were based on the total uptake of boron by the shoots over the first two seasons, and on the initial soil test values. The dependencies are shown in Fig. 5.

The uptakes rather closely correlated with the HWB values ($r^2 = 0,82$). The relationships of the uptakes and the soil test values were similar in all soil types (Fig. 5 a). When the pH values of the soils were entered in the regression equation in addition to the HWB values, the soil analyses determined the uptakes still more accurately (Fig. 5 b). The coefficient of multiple determination ($R^2$) was 0,89.

The "cold water extractable boron" (CWB) did not indicate the amount of boron used by the turnip rape so closely as the HWB values did (Fig. 5 c). The obtained coefficient of determination ($r^2 = 0,61$), can not be considered satisfactory for such an exhaustively cropped pot experiment as the present.

The CWB values appeared to have overestimated the availability of boron in organic soils, but entering the soil pH values into the regression equation as another independent variable, corrected that bias and improved the $R^2$ value to a satisfactory level of 0,79 (Fig. 5 d). This was almost the same as that reached by the HWB values without the pH.

The inferiority of the CWB method in estimating the supply of boron from soils to plants was partly a result of the analytical difficulties of this test. In addition to the inaccurate determination due to excessively dilute extracts (Chapter 1.4.), pretreatment of the soil samples (grounding and drying) may have affected the results more using this weak-extraction test than with the HWB test. The CWB values were also much lower than the amounts of boron absorbed by the plants. The regression coefficient, which relates the increases in the boron uptakes to the increases in the soil test values, was 2,03 by CWB (Fig. 5 c) and 0,70 by HWB (Fig. 5 a).

The amounts of boron taken up per liter of soil are much smaller in the field than in the pots. The "optimum extraction power" may therefore be weaker in estimating the supply of boron by soils under field conditions. The possible advantages of the weaker and more sensitive CWB method could not be examined

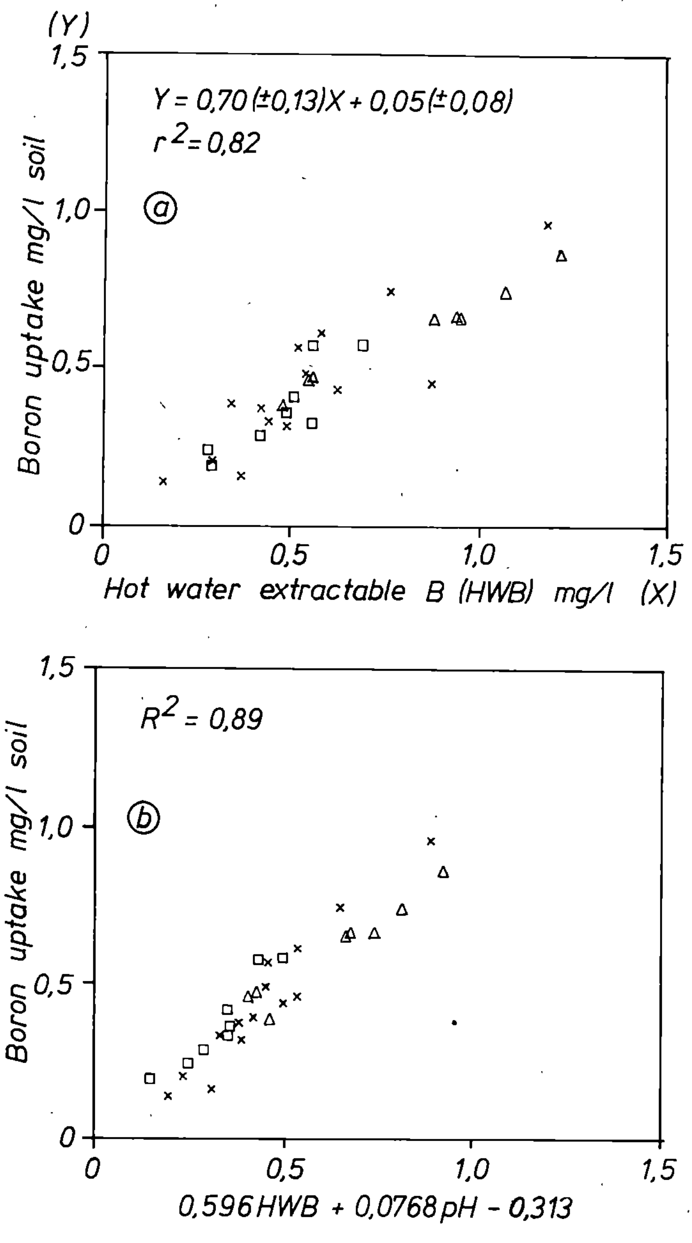

Fig. 5. Dependence of boron uptake by turnip rape on soil test values.
Δ = clay soil
× = coarse mineral soil
□ = organic soil

on the basis of the four field experiments, for the ratio CWB/HWB was almost equal in each soil (0,32—0,38). The correlation between the test values of the two methods from the 30 soils (P1) were quite loose ($R^2$ = 0,61).

The HWB values significantly correlated with the extractable content of calcium in soil (r = 0,55), the clay percentage (r = 0,52), pH (r = 0,45) and the organic carbon percentage (r = —0,33). The correlation coefficient between the HWB and the uptake, however, decreased only from 0,91 to 0,87 when the effects of these

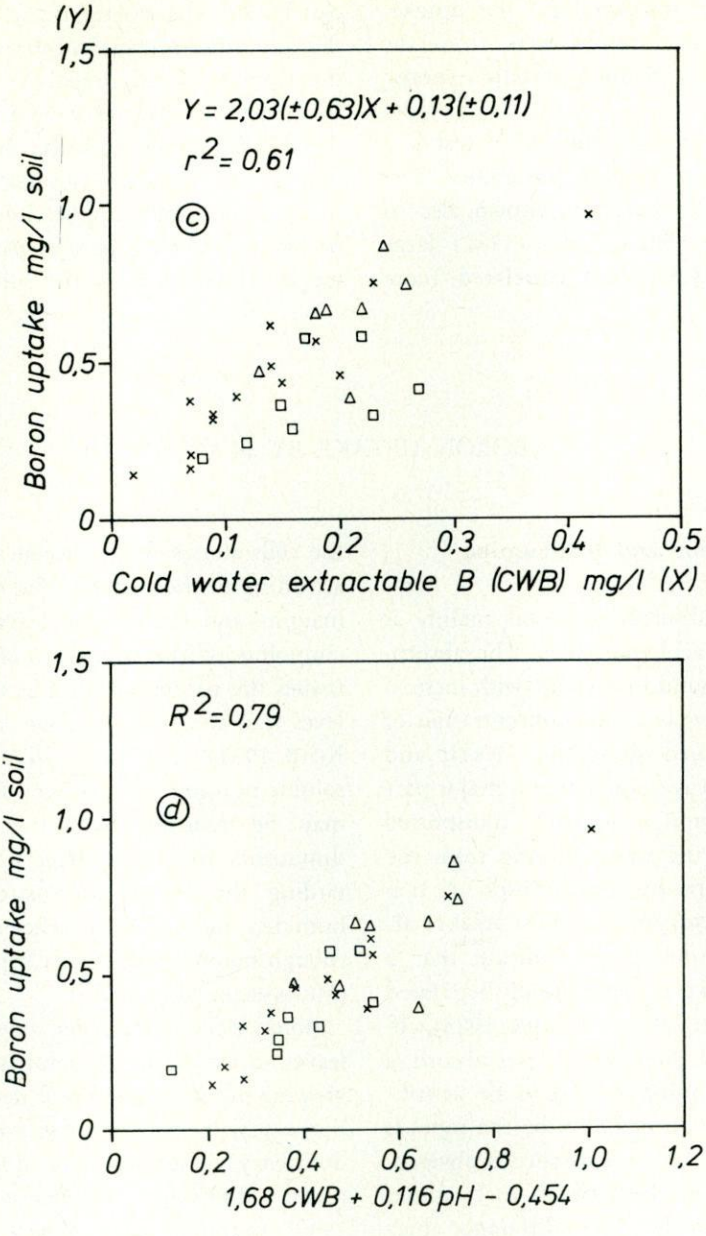

Fig. 5. Continued.

variables were eliminated by partial correlation. In the multiple regression (Fig. 5 b and d) the other soil variables were excluded as being non-significant at the five percent level. The calcium values could effectively be substituted for the pH values.

When the dependencies were calculated separately from each harvest, it was found that the correlation became closer the longer the soils were depleted (SAARELA 1984, p. 39). This was an indicator of the quantitative character of the HWB values in Finnish soils. The boron content in plants could be substituted for the uptake. The closest correlations found were from the boron content of straw ($R^2$ for quadratic response = 0,87).

According to the results, the HWB test is a useful indicator of soil boron availability. The usefulness of this test has been shown also in previous studies. In SILLANPÄÄ's (1982) large assessment, the HWB values correlated more closely with the uptake of boron in plants than did any other soil micronutrient test values with the uptake of the respective nutrient. Highly significant correlations were also found between the HWB values and the boron contents in field-grown timothy (PAASIKALLIO 1978), although the small applications of boron have probably masked a part of the variation in the supply of boron from the soils.

## 3. BORON UPTAKE BY PLANTS

### 3.1. Absorption and translocation

Boron is probably absorbed by roots mainly as undissociated boric acid molecules. The absorption rate has been found to decrease with increasing pH about as steeply as the concentration of the undissociated acid decreases (OERTLI and GRGUREVIC 1975). It is evident that a major part of the absorbed boron is passively transported into the plants via the water flowing from the soil through the plant into the atmosphere, it is in the transpiration stream (e.g. BINGHAM et al. 1970). However, some results indicate that a fraction of the uptake is metabolically regulated (BOWEN and NISSEN 1977, DUGGER 1983). If metabolic energy is directly used to absorb a substance, the absorption is said to be active.

The active absorption of boron by the rapes is an unstudied action, but its existence is obvious. The boron content in the rapes is many times greater than in cereals. This difference may probably not be explained in any other way than by supposing a metabolic regulation system. More water is transpired by the rapes, but not so much more as the ratios of the boron contents would require. As boron is absorbed in the soluble form, the sorbed forms are not (immediately) available to the plants (HATCHER et al. 1959, KEREN et al. 1985).

Boron flows from the roots to the shoots probably in the transpiration stream through the xylem. According to BUSSLER and DÖRING (1979) the cells alongside the stream absorb this boron according to their needs. The excess flows to the margins and tips of the leaves, which are the endpoints of the transpiration stream. In these tissues the concentration may rise to such a high level that the cells are soon killed (OERTLI and KOHL 1961). The excess in the leaves remains soluble in water (BUSSLER and DÖRING 1979) and may be reduced by guttation, which thus diminishes the toxic effect (OERTLI 1962). Retarding the transpiration stream by high air humidity may cause a deficiency symptom, although boron is sufficiently supplied to the roots (MICHAEL et al. 1969).

Boron does not readily move from the older leaves to the stems, and further, to the current growing points. Therefore it may be possible that boron toxicity may occur in young plants, while deficiency symptoms may appear in the same plants afterwards (HOBBS and BERTRAMSON 1949). In some studies, however, boron has been found to be rather mobile (CHANDLER 1941, van GOOR and van LUNE 1980). According to OERTLI and RICHARDSON (1970) immobility is due to free diffusion of boron between the phloem and the xylem parts of a vascular bundle. A substance which is in equilibrium, does not move against the transpiration stream. Reversing the stream has also reversed the direction of boron flow (OERTLI and AHMED 1971).

The retranslocation of boron from the leaves of turnip rape was studied in one part of the pot experiment P4 (Chapter 1.7.) comparing the effects of different application methods on the contents of boron in various parts of plants. Foliar sprayings (1 or 4 mg B in 4 ml of water) were compared to the common soil application (= mixed before seeding).

The contents of boron in the leaves and in the straws of the turnip rape indicated a very low retranslocation rate (Table 24). When boron was sprayed onto the plants, almost all of it remained in the leaves. The minor amounts which were recovered from the straw and seeds may have been dropped directly on the stems or moved via the soil. In reality, the results did not assure any retranslocation of the applied boron from the leaves.

Table 24. Effects of application methods on boron distribution in turnip rape. Statistical tests by Duncan 0,05.

| Boron application |  | Boron content in dry matter |  |  |  |
|---|---|---|---|---|---|
| mg/pot | method | Seedlings ppm | Straw ppm | Leaves ppm | Straw/leaves % |
| 0 | — | $9^{a}$ | $13^{a}$ | $22^{a}$ | 56 |
| 1 | to soil | $25^{b}$ | $16^{ab}$ | $46^{b}$ | 34 |
| 4 | ,, | $34^{c}$ | $32^{d}$ | $95^{d}$ | 34 |
| 16 | ,, | $59^{d}$ | $63^{e}$ | $216^{f}$ | 29 |
| 1 | on seedlings | $9^{a}$ | $13^{a}$ | $64^{c}$ | 20 |
| 4 | ,, | $10^{a}$ | $21^{bc}$ | $141^{e}$ | 15 |
| 1 | on lower leaves* | $9^{a}$ | $14^{a}$ | $67^{c}$ | 20 |
| 4 | ,, | $9^{a}$ | $23^{c}$ | $188^{f}$ | 12 |
| 1 | on upper leaves* | $8^{a}$ | $13^{a}$ | $50^{bc}$ | 26 |
| 4 | ,, | $8^{a}$ | $16^{ab}$ | $118^{de}$ | 13 |

* in full bloom

## 3.2. Availability of original and applied boron in soils as indicated by contents in plants

At the beginning of this study, before the results presented in Chapter 2.5. were obtained, we did not know if soil tests were reliable as a basis for estimating the requirement of boron fertilization in Finland. SIMOJOKI (1972) had concluded that plant analysis is more reliable compared to the soil HWB test. The primary purpose of the large number of plant analyses was initially to develop a routine test for boron assessment. Another objective of plant analysis was to study the soil-plant relationships of this micronutrient. This became the most discussed topic when the soil HWB test appeared to be the preferable method for the former purpose.

The contents in plants indicate the relative amounts of nutrients taken up from soils if the plants compared have the same amount of matter. Because vegetative growth is significantly affected only by very severe deficiencies, the boron contents in plants indicate its availability in soils quite well. However, the less variable contents in seeds are not suitable for this purpose. Preliminary studies have also shown that the differences in boron uptake could not be measured from ripened turnip rape straw grown in a field. A large part of the boron seemed to have been washed back to the soil, in addition to the loss via fallen leaves.

For the present purpose, the field experiments had thus to be sampled at an early stage of development. The rainless conditions of the pot experiments allowed the use of ripened straw. These samples included also the emptied seed pods. The analyzed seedlings had been cut when about 10 cm high.

### 3.2.1. Effects of liming and boron application in pot experiments

The occurrence of the heart rot diseases in beets had been found to be connected with basic soil reactions even before they were known to be symptoms of boron deficiency. The alkalinity of the soil, indicated by a high pH value, had been suspected to be the actual cause of the growth disturbances, until BRANDENBURG (1931) discovered the essential role of boron. Now it is well assured that boron supply to plants is retarded when soil is made more alkaline by liming, and that the resulting disturbance in growth is often a symptom of boron deficiency (e.g. TRUNINGER 1944, JAMALAINEN 1949, GUPTA and CUTCLIFFE 1972, PRASAD and BYRNE 1975, PETERSON and NEWMAN 1976, PUUSTJÄRVI 1980, NILSSON 1982).

According to the foregoing, liming exerts a significant influence on boron nutrition of crops.

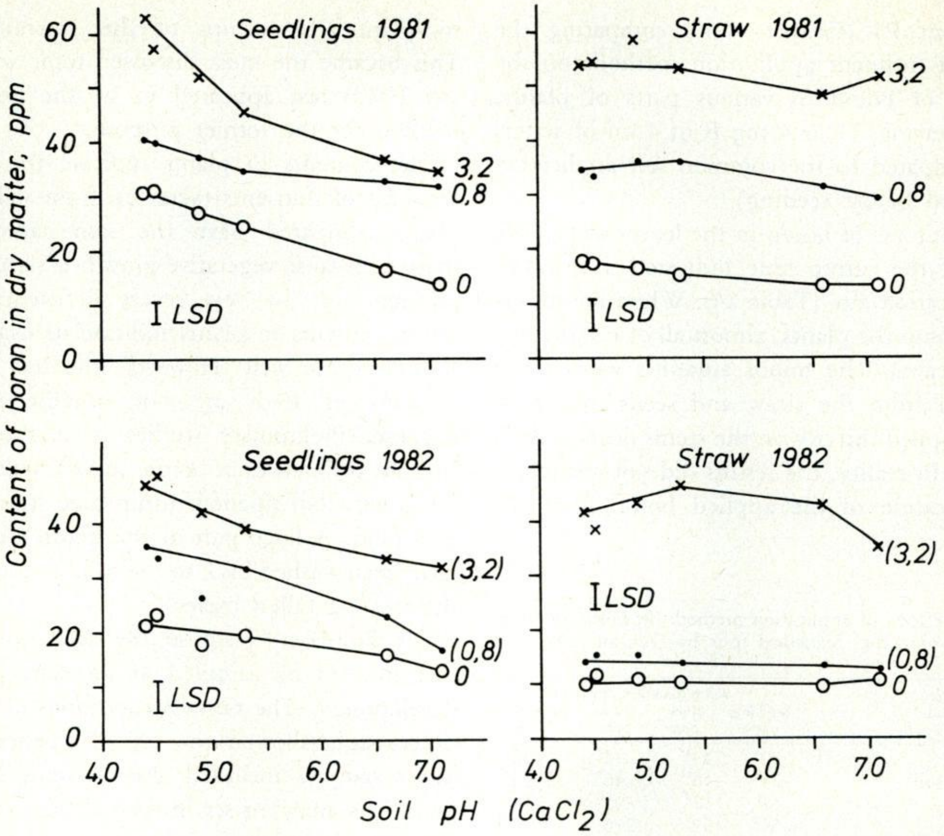

Fig. 6. Effect of lime conditions and boron application on boron content in turnip rape grown in sandy clay. Numbers with broken lines indicate amounts of applied boron in mg/l soil (residuals in brackets). The points at pH 4,5 and 4,9 show the effects of calcium sulphate and Mg-K-Na treatments, respectively.

The previously discussed increase in the sorption by soils with an increase in soil pH provides an obvious explanation for this being probably the most important mechanism involved in the retarding effect.

The effects of increasing amounts of lime and applied boron on the contents of boron in turnip rape were studied in several pot experiments (Chapter 1.7). These studies were continued over several years, because the first results (P2 and P3) indicated strong effects of liming, but were too inconsistent for generalization. The pot experiment P5 with five soils was aimed at testing the effects in several soils, and the pot experiment P6 with various liming treatments in three soils was an enlargement of P3 for different soil types. The compared treatments were formed by mixing different amounts of boron and liming materials in the soils at the beginning of the experiments, as specified for P2 in Table 20 (p. 216), for P3 in Table 21 (p. 216) and for P5 and P6 together with results (Figs. 7 and 8).

The boron contents in turnip rape of pot experiment P2 were published in the preliminary report (SAARELA 1984, p. 54) and are partly listed in Table 29. Results of the pot experiment P3 with acid and rather low-boron sandy clay, which fixed boron strongly in the incubation test, are presented in Fig. 6.

The effect of boron application was very pronounced, as usual in pot experiments. The effect of liming was marked in the seedling stage. The

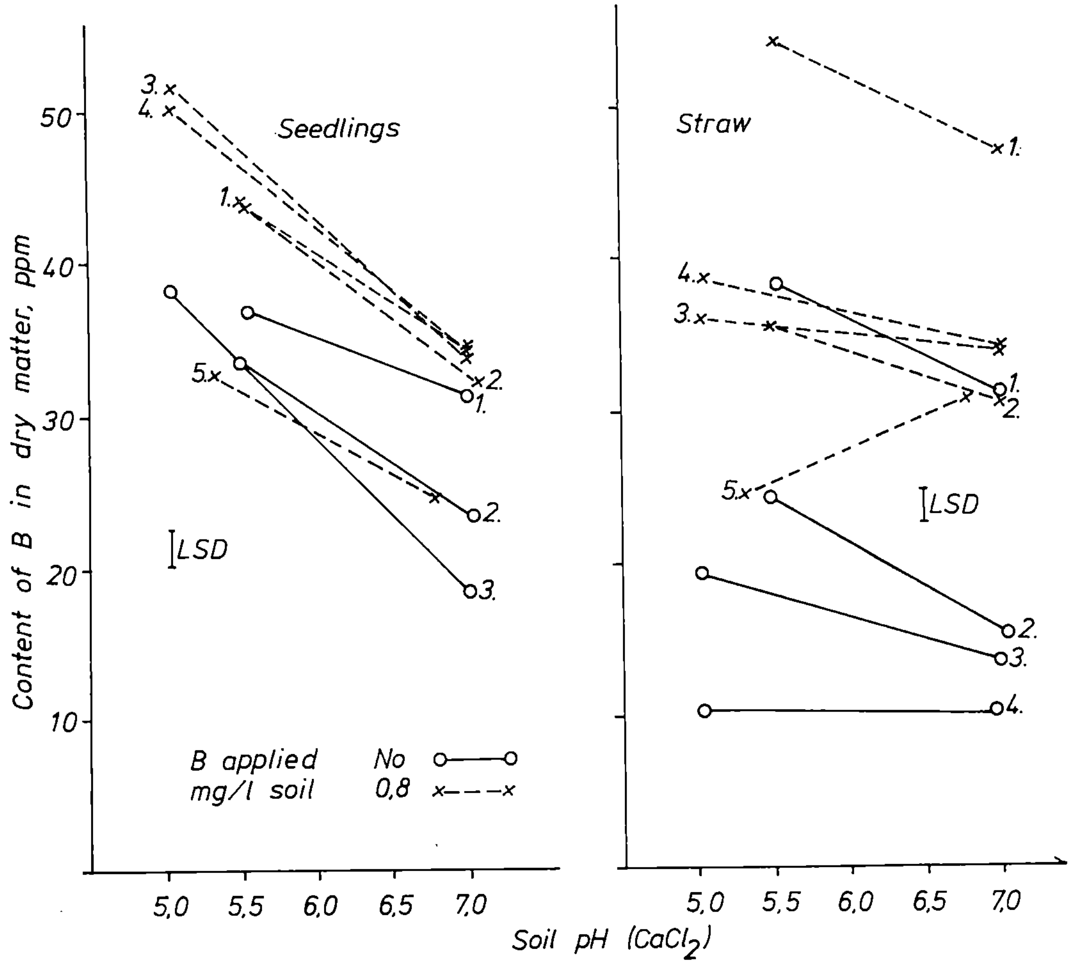

Figure 7. Effects of liming and boron application on boron content in turnip rape. The lower pH values are without liming, the higher with 7,2 g $CaCO_3$/l soil.

1. Loamy clay
2. Loam
3. Fine sand F
4. Fine sand
5. Carex peat

boron content in the turnip rape seedlings greatly decreased with increasing soil pH. The effects of lime were connected with the changes of soil pH. Calcium sulphate was inefficient and the effects of the Mg-K-Na-treatment appeared to be quite similar as those of calcium carbonate when the changes in the pH were equal.

The content of boron in the straw of the turnip rape was rather independent of the liming compared to the strong effects on the seedlings in each of the two years (Fig. 6), while intermediate effects were recorded in the leaves (SAARELA 1984, p. 56).

In 1981, there was a highly significant interaction between the liming and the amount of applied boron in effecting the contents of boron in the seedlings (Fig. 6). Liming decreased the contents much less with the smaller amount of applied boron than with the larger amount or without applied boron. This somewhat peculiar result possibly indicated some kind of active striving by the plants to obtain a sufficient boron

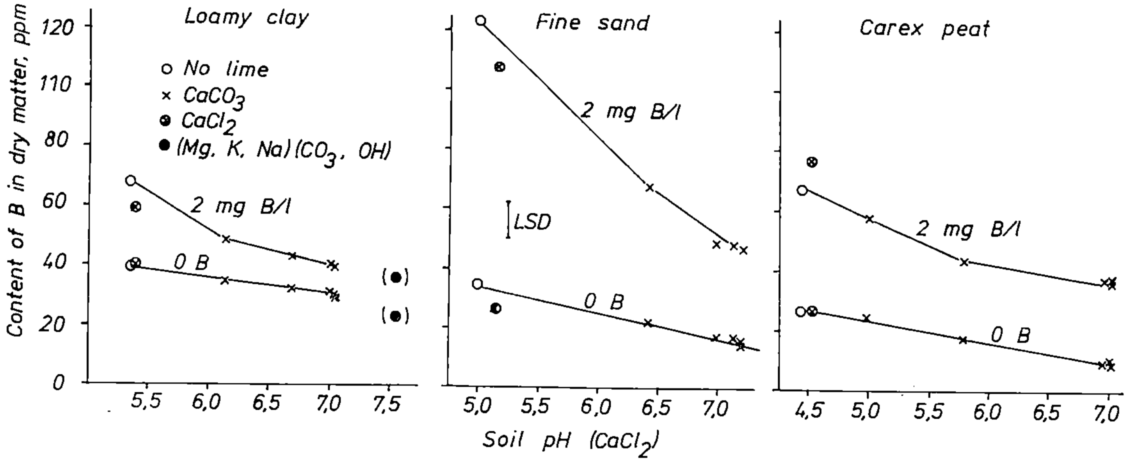

Fig. 8. Effects of liming on boron content in turnip rape shoots at the budding stage. Results of the pot experiment P6 with small (0,5 l) pots. $CaCO_3$ rates 40, 100, 200, 300 and 400 me/l soil. $CaCl_2$ and sum of Mg, K and Na compounds 400 me/l soil. Cl from $CaCl_2$ washed with two soil volumes of water.

level, which was about 30 ppm, because it probably may not be explained by any physicochemical process.

In the second year when the residual effects were studied, the same interaction was to the opposite direction than that of the first year (Fig. 6), but if the lower level of the boron in the soils is taken into account, the results become quite similar. The lines 0,8 in 1981 and 3,2 in 1982 correspond each other, and the lines 0 in 1981 and (0,8) in 1982 are in correspondence.

Very distinct effects of boron application and liming were also obtained in the pot experiment P5 with five soils (Fig. 7). In each of the four non-clay soils, the boron contents of seedlings decreased steeply with increasing soil pH, but again the effect was much less in the straw. In peat soil, the effect was even to the opposite direction. This was a result of poorer growth from heavy liming, which obviously caused a deficiency of some micronutrient(s) other(s) than boron (Mn and/or Zn).

The effects of the increasing rates of lime on the boron contents of the turnip rape shoots at the budding stage in P6 (Fig. 8) were quite similar to the corresponding effects on the seedlings. The contents decreased linearly with increasing soil pH in each of the three soils when no boron was applied. With boron application, the decrease in the plant boron appeared somewhat steeper in the more acid end of the range. Neutral calcium salt did not effect the contents, but when the clay was made basic by adding Mg, K and Na compounds, boron contents strongly decreased. The latter treatment caused poor growth even in clay, and in the other two soils it was lethal. The excess calcium carbonate which did not alter pH, also did not change the boron content. The boron application 2 mg B per liter soil was about ten times more efficient in acid sand than in neutral clay.

The results obtained (Figs. 6 and 8) showed that it is the change in soil pH, and not the added calcium, which is the principal cause of the retarding effect of liming on the supply of boron from soils to plants. This finding agreed with earlier results obtained with other plants on other continents (WOLF 1940, BLAMEY and CHAPMAN 1979, GUPTA and MACLEOD 1981). However, the high activity of calcium ions has also been found to retard boron absorption in certain conditions in connection with high pH (FOX 1968).

Usually the growth of the test plant did not significantly depend on the liming. Despite this, the contents of boron did not exactly show the relative absorption rates, for different amounts of boron may have been retained by the roots or passed through the analyzed parts. An increase in the retention by the roots of the seedlings and by the stems of the older plants with increasing pH would contribute to the obtained boron contents. However, the main cause of the observed differences was probably the variable absorption rate.

The effects of liming on the contents of boron in plants were remarkably regular, although the absorption of other pH-dependent nutrients has been found to be influenced largely by the rhizosphere pH, which may differ from the pH in the bulk soil (NYE 1981, SARKAR and WYN JONES 1982).

The effects of soil pH on the contents of boron in the turnip rape seedlings appeared relatively small in clay soils with a sufficient boron level. The less sensitivity to liming of boron supply in the clay soils compared to other soils agreed with earlier results by WEAR and PATTERSON (1962). The smaller effect of liming in clay may be a result of the stronger but (relatively) less pH-dependent sorption of boron by clays.

In the sandy till of the pot experiment P2, the contents of boron in the flowering turnip rape decreased almost as much by the smaller lime rate as by the double rate (Table 29, p.234), but only in the first year, for the usual linear response was obtained in the later years (SAARELA 1984. p. 54). A possible reason for this exceptional behavior of boron in the initially very acid soil was exchangeable aluminum, but further investigation is necessary for a proper explanation of these reactions.

As the dependence between the contents of boron in the plants and the soil pH was usually linear, there seems not to be any critical pH level, in which the supply of boron would change particularly sharply. According to PUUSTJÄRVI (1980) the pH of the press extract from peat exerts a strong effect on the boron supply, and a deficiency often appears if the pH is higher than 6,3. However, this critical limit did not appear in the present study. PETERSON and NEWMAN (1976) found that the supply of boron decreased by liming only when the pH exceeded 6,3, but they had limed the soils in the field six years earlier, and only one treatment (to pH 7,4) was limed at the establishment of the pot experiment.

The results agreed with the previously known fact that plants are not able to regulate the flow of excessive boron from the soil to the plant. The capacity of soils to sorb boron appeared to efficiently regulate the rate of absorption of the applied boron by plants. This was probably the reason why the same application of boron increased the boron contents of plants grown in acid fine sand so much more than plants grown in neutral clay soil.

According to the obtained results, an optimal supply of boron to plants may be maintained at any possible pH level, but the reduced availability should be taken into account by increasing the applied rates with rising pH values. The increase in the requirement for boron fertilization because of liming is probably temporary, because the reduced uptakes, and reduced leaching rates under field conditions, result in increases in the amounts of soil boron.

### 3.2.2. Availability of boron in ground limestone

The boron contained in the liming materials is an addition to the soil reserves, and may be significant under certain conditions (e.g. TRUNINGER 1944). It should be taken into account as a possible "mechanism" in the effects of liming.

The availability to plants of the boron in liming materials was the particular objective of pot experiment P9 (Chapter 1.7.). In this experiment, two of the ground limestones used in the field experiments (Chapter 1.6.) were compared to analytical grade calcium carbonate and to an unlimed control with four combinations of fresh and residual amounts of applied boron, as specified in Table 25.

The boron in the ground dolomite from Siikainen was well available to the turnip rape when the lime was thoroughly mixed with the acid peat. The availability of the small amount in the calcite from Lohja, on the other hand, remained uncertain. This lime did promote

Table 25. Effects of boron contents of liming materials, and soluble boron on turnip rape in pot experiment P9 (in 1984). Statistical tests by Duncan 0,05.

| B application, mg/l soil | | | B content, ppm in dry matter | | B uptake in straw mg/l soil | Yields g/pot | |
|---|---|---|---|---|---|---|---|
| As boric acid 1982—83** | As boric acid 1984 | As lime* 1984 | Seedlings | Straw | | Straw | Seeds |
| 0 | 0 | 0 | $14^{b}$ | $6^{a}$ | $0,10^{b}$ | $91,6^{e}$ | $3,6^{b}$ |
| 0 | 0 | <0,01 | — | $4^{a}$ | $0,01^{a}$ | $7,8^{a}$ | $0^{a}$ |
| 0 | 0 | 0,07 | — | $6^{ab}$ | $0,02^{a}$ | $23,8^{b}$ | $0,3^{a}$ |
| 0 | 0 | 0,81 | $28^{ef}$ | $23^{e}$ | $0,30^{d}$ | $74,4^{cd}$ | $32,5^{d}$ |
| 0 | 0,2 | 0 | $31^{f}$ | $9^{c}$ | $0,13^{b}$ | $83,1^{cde}$ | $41,9^{f}$ |
| 0 | 0,2 | <0,01 | $11^{a}$ | $8^{bc}$ | $0,10^{b}$ | $72,2^{cd}$ | $23,7^{c}$ |
| 0 | 0,2 | 0,07 | $17^{c}$ | $7^{bc}$ | $0,10^{b}$ | $82,2^{cde}$ | $27,0^{c}$ |
| 0 | 0,2 | 0,81 | $25^{ef}$ | $29^{ef}$ | $0,32^{d}$ | $68,5^{c}$ | $40,2^{ef}$ |
| 0,8 | 0 | 0 | $35^{g}$ | $12^{d}$ | $0,19^{c}$ | $84,3^{de}$ | $43,8^{f}$ |
| 0,8 | 0 | <0,01 | $14^{b}$ | $9^{c}$ | $0,12^{b}$ | $73,7^{cd}$ | $38,6^{ef}$ |
| 0,8 | 0 | 0,07 | $21^{d}$ | $9^{c}$ | $0,13^{b}$ | $74,6^{cd}$ | $39,1^{ef}$ |
| 0,8 | 0 | 0,81 | $30^{ef}$ | $29^{g}$ | $0,38^{e}$ | $71,3^{cd}$ | $36,4^{de}$ |
| 0,8 | 0,8 | 0 | $41^{h}$ | $34^{h}$ | $0,49^{g}$ | $76,9^{cde}$ | $44,2^{f}$ |
| 0,8 | 0,8 | <0,01 | $28^{e}$ | $30^{g}$ | $0,43^{f}$ | $78,6^{cde}$ | $42,2^{f}$ |
| 0,8 | 0,8 | 0,07 | $30^{e}$ | $26^{f}$ | $0,39^{e}$ | $81,3^{cde}$ | $42,8^{f}$ |
| 0,8 | 0,8 | 0,81 | $34^{g}$ | $42^{i}$ | $0,62^{h}$ | $79,7^{cde}$ | $43,7^{f}$ |

* 0 = no lime, soil pH($CaCl_2$) 4,3
<0,01 = 7,2 g/l soil analytical grade $CaCO_3$, soil pH 6,6
0,07 = 8,0 g/l soil calcite from Lohja (9 ppm B), soil pH 6,3
0,81 = 8,0 g/l soil dolomite from Siikainen (102 ppm B), soil pH 6,4
** = Residuals of these treatments from pot experiment P7 (see Chapters 1.7. and 3.3)

better growth and higher boron contents in the seedlings than did the purified chemical, but this was partly due to the slower and smaller increase in pH with the ground stone. The boron content in the seedlings decreased greatly with an increase in the soil pH. The greatest effect was with the smaller amounts of applied boron. The boron-containing dolomite diminished the differences between boron application rates; it even decreased the contents with the higher boron levels (Table 25). In this case the boron in the liming material did not entirely compensate the retarding effect of the increased pH.

The boron input in the dolomite from Siikainen used in the loam field at Kokemäki was 0,7 kg/ha. According to the foregoing experiments, a major part of it was released from the lime in an available form and should be taken into account in interpreting the results.

### 3.2.3. Effects of different rates and methods of boron application in field experiments

Because placement is today by far the most frequently used method of boron distribution in this country, the field studies were concentrated on it (Chapter 1.6). The effects of different rates of placed boron were tested with this method. Different application methods were compared in the heavy clay field at Jokioinen. The large broadcasted rates in the other experiments also provided some possibilities to compare the application methods.

In order to investigate the availability to plants of original and applied boron, leaf samples were collected from the field experiments at the early flowering stage. Mature leaves from the upper middle height of the turnip rape plants were picked (about 30 per plot).

The contents of boron in these leaves varied widely from year to year, even with the same treatments (Table 26). The highest variation coinsided with the highest levels of boron. This perhaps indicated the sensitivity of the excess boron to the outer conditions. The level of boron appeared to increase when there was high transpiration rate and slow growth. It may have been possible that some boron was washed from the leaves by rain.

The boron applied by the placement method quite efficiently increased the content of boron

Table 26. Boron contents of turnip rape leaves in field experiments (in ppm of dry matter). Liming and boron fertilization treatments explained in details in Chapter 1.6. Each column tested separately (Duncan 0,05).

| Liming (1981) | Boron application | | Jokioinen | | | Mietoinen | | | Kokemäki | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Method* | Rate, kg/ha | 1981 27.6. | 1982 13.7. | 1983 22.6. | 1981 30.6. | 1982 15.7. | 1983 4.7. | 1981 6.7. | 1982 18.7. | 1983 6.7. |
| None | Traces | <0,1 | $30^{a}$ | $38^{a}$ | $30^{a}$ | $42^{ab}$ | $(58^{a})$ | $28^{a}$ | $31^{a}$ | $40^{a}$ | $33^{a}$ |
| ,, | Placement | 0,3—0,35 | $33^{a}$ | $53^{c}$ | $34^{b}$ | $49^{bc}$ | $58^{a}$ | $31^{a}$ | $35^{a}$ | $64^{b}$ | $44^{b}$ |
| ,, | Placement | 1,2—1,4 | $61^{b}$ | $130^{d}$ | $54^{c}$ | $64^{d}$ | $95^{b}$ | $(39^{a})$ | $63^{b}$ | $155^{c}$ | $88^{d}$ |
| ,, | Broadcast | 4,8—5,6 | $76^{c}$ | $41^{ab}$ | $30^{a}$ | $92^{e}$ | $95^{b}$ | $81^{b}$ | $93^{cd}$ | $51^{a}$ | $32^{a}$ |
| 7—10 t/ha | Traces | <0,1 | $31^{a}$ | $36^{a}$ | $30^{a}$ | $36^{a}$ | $(51^{a})$ | $28^{a}$ | $29^{a}$ | $40^{a}$ | $30^{a}$ |
| ,, | Placement | 0,3—0,35 | $34^{a}$ | $50^{bc}$ | $35^{b}$ | $42^{ab}$ | $52^{a}$ | $29^{a}$ | $37^{a}$ | $70^{b}$ | $42^{b}$ |
| ,, | Placement | 1,2—1,4 | $65^{b}$ | $123^{d}$ | $52^{c}$ | $53^{c}$ | $84^{b}$ | $(37^{a})$ | $76^{bc}$ | $156^{c}$ | $78^{c}$ |
| ,, | Broadcast | 4,8—5,6 | $71^{bc}$ | $39^{a}$ | $28^{a}$ | $57^{cd}$ | $73^{ab}$ | $72^{b}$ | $97^{d}$ | $52^{a}$ | $32^{a}$ |

* Broadcasting as store dressing in 1981 (annually at Mietoinen)

in the turnip rape leaves (Table 26). The NPK fertilizer that contained 0,2 % B (1,2—1,4 kg/ha) on average doubled the level of boron in the leaves, compared to the ''boronless'' control. The increase caused by the ''normal'' NPK fertilizer with 0,05 % B was quite regularly about a fourth of the increase caused by the quadrupled boronation of the same basic fertilizer. The effect thus increased linearly with increasing rates of boron, and may so be interpolated for intermediate rates. According to this calculation, the traces of boron in the unboronated control (about 60 g/ha) had increased the contents of boron in the leaves by about seven percent.

The boron which was broadcasted on the soil surfaces and incorporated in a shallow layer increased the contents of boron in the leaves less efficiently than the placed boron (Table 26). The large broadcasted rates increased boron levels in the plants not much more than the four times smaller placed rates, even in the application year. The residual effects of the store dressings were small and statistically insignificant, although the HWB values of the soils at the end of the experiments had increased (Table 23, p. 220). The contents of boron in the seeds were also analyzed, but the differences were not more than ten percent.

In the heavy clay field at Jokioinen, the uneven growth (Chapter 1.6.) affected the precision of the measurements. However, the importance of the placement of boron could be demonstrated. Boron sprayed onto the soil surface before the combined seed and fertilizer drilling did not, according to the analyses, increase boron contents in the plants (Table 27). Boron that was sprayed onto the canopy, efficiently increased the level of boron in the leaves.

Table 27. Effects of rates and methods of boron application on boron contents of turnip rape grown on heavy clay field in Jokioinen (in ppm of dry matter). Statistical tests by Duncan 0,05.

| Boron rate, kg/ha/a | Placement | Broadcast | Foliar |
|---|---|---|---|
| | Whole shoots 24.6.1980 (at budding) | | |
| 0,07 | $18^{a}$ | — | — |
| 0,35 | $19^{a}$ | — | $29^{cd\ 1)}$ |
| 0,7 | $22^{abc}$ | — | $32^{d\ 1)}$ |
| 1,4 | $21^{ab}$ | $18^{a}$ | — |
| 2,8 | $27^{bcd}$ | $18^{a}$ | — |
| | Leaves 14.7.1981 (in full bloom) | | |
| 0,07 | $44^{a}$ | — | — |
| 0.35 | $50^{b}$ | — | $152^{c\ 2)}$ |
| 0,7 | $50^{b}$ | — | $248^{f\ 3)}$ |
| 1,4 | $61^{c}$ | $(43^{a})$ | — |
| 2,8 | $99^{d}$ | $(41^{a})$ | — |

( ) B applied 1980 only
1) 19.6. 1,7 kg/ha Solubor in 350 l water (0,49 % B)
2) 9.7. 1,7 kg/ha Solubor in 350 l water (0,49 % B)
3) 9.7. 3,4 kg/ha Solubor in 350 l water (0,98 % B)

### 3.3. Boron contents in several species and varieties grown in pots side by side

The large variation in boron contents of different plant species is generally known. The three oilseed crop plants, turnip rape (Ante), rape (Topas), and poppy (Soma) were compared in one part of pot experiment P4. (The same results from turnip rape were also compared to other application methods.) The low-boron Carex peat

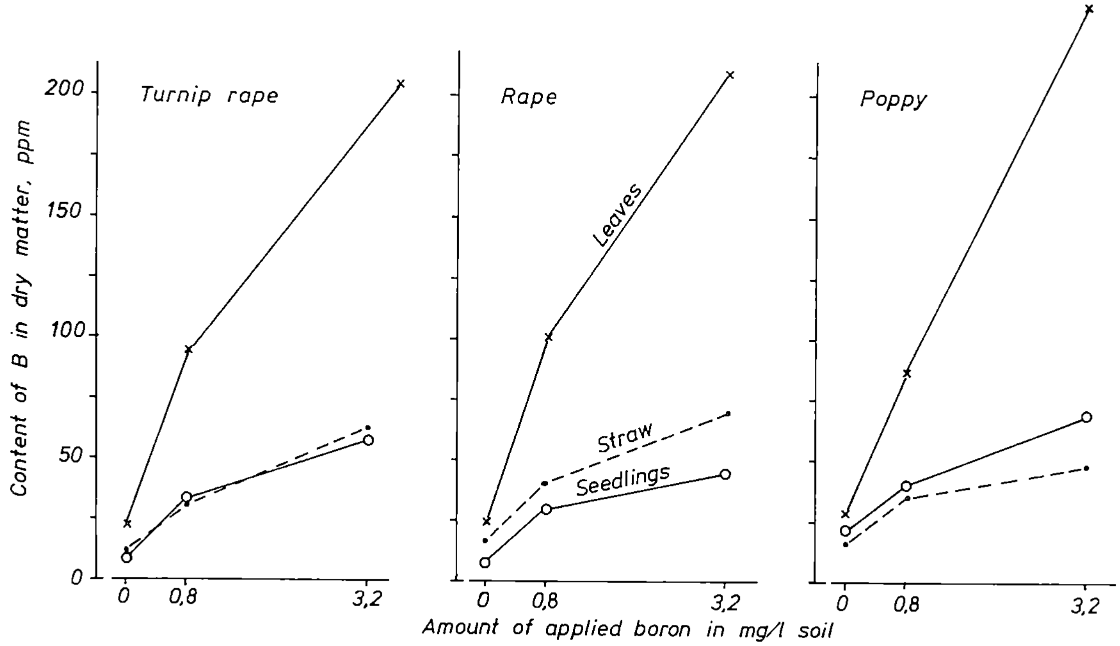

Fig. 9. Effect of applied boron on boron contents in oilseed plants grown in pots in low-boron peat.

was limed with 1,2 g $CaCO_3$ per liter and 0, 0,8 and 3,2 mg boron per liter was added to form the treatments studied. Several species and varieties were compared in pot experiment P7 as specified in Table 28. The experiments were cropped as described in Chapter 1.7.

In the low-boron Carex peat, the contents of boron in each of the three oilseed crop plants increased steeply with increasing rates of applied boron (Fig. 9). In each of these species the highest level of boron as well as its increase was in the leaves. Only minor differences between the species appeared, and even these were possibly caused by different developing rates of the plants.

In the other experiment which included two spring rape and four spring turnip rape varieties, there were no major differences in the level of boron between these species and varieties (Table 28). The differences in the second year straw were probably caused by variable dilutions due to the different straw yields. In the first year with a sufficient initial amount of boron in the soil, the application did not significantly increase the contents in the rapeseeds, but it nearly doubled in the seedlings, and more than doubled in the straw. During the second year the contents of boron decreased also in the seeds if no boron was applied, because the depleted soils became moderately deficient.

Only a few studies on the contents of boron in the rape plants have been reported (HOLMES 1980), but the level of contents have been rather equal to the results of this work (e.g. SZUKALSKI and SIKORA 1981). The smaller turnip rape seeds had higher contents than the rape seeds (Table 28). The lower level of rape is similar as earlier found in winter rape (GERATH et al. 1975). Even lower contents have been obtained in the seeds of winter turnip rape (YADAV and MANCHANDA 1982).

Highly differing contents of boron were measured in the other crop plants (Table 28). The lowest level occurred in barley grains, and the highest level was in the tops of the sugar beet. In the leguminous species, especially in the broad bean plant, the contents in the seeds also strongly responded to the boron supply.

Table 28. Boron contents (in ppm of dry matter) of varieties of spring oilseed rapes and other crop plants in pot experiment P7. Boron applied annually. Primary yields are seeds, roots or tubers. Secondary yields are straw, tops or haulms. Each column tested separately (Duncan 0,05). Barley seeds tested alone.

| Variety | B applied mg/l soil | Seedlings | | Primary yield | | Secondary yield | |
|---|---|---|---|---|---|---|---|
| | | 1982 | 1983 | 1982 | 1983 | 1982 | 1983 |
| | | Carex peat (HWB 0,85 mg/l) | | | | | |
| Topas | 0 | $22^{c}$ | $10^{a}$ | $11^{hi}$ | $6^{bc}$ | $13^{b}$ | $8^{a}$ |
| Rape | 0,8 | $38^{g}$ | $34^{e}$ | $11^{hi}$ | $10^{de}$ | $27^{e}$ | $30^{cde}$ |
| Lergo | 0 | $21^{c}$ | $11^{ab}$ | $11^{hi}$ | $7^{c}$ | $13^{b}$ | $8^{a}$ |
| Rape | 0,8 | $37^{g}$ | $30^{cd}$ | $11^{hi}$ | $10^{de}$ | $27^{e}$ | $30^{cde}$ |
| Ante | 0 | $28^{ef}$ | $13^{b}$ | $12^{ij}$ | $7^{c}$ | $13^{b}$ | $10^{ab}$ |
| Turnip rape | 0,8 | $36^{g}$ | $33^{de}$ | $13^{j}$ | $12^{f}$ | $31^{g}$ | $41^{f}$ |
| Emma | 0 | $28^{ef}$ | $11^{ab}$ | $12^{ij}$ | $7^{c}$ | $12^{b}$ | $10^{ab}$ |
| Turnip rape | 0,8 | $37^{g}$ | $30^{cd}$ | $13^{j}$ | $12^{f}$ | $26^{e}$ | $34^{e}$ |
| Span | 0 | $27^{de}$ | $13^{b}$ | $11^{hi}$ | $6^{bc}$ | $12^{b}$ | $9^{ab}$ |
| Turnip rape | 0,8 | $38^{g}$ | $32^{de}$ | $13^{j}$ | $12^{f}$ | $27^{e}$ | $28^{cde}$ |
| Vankka | 0 | $28^{ef}$ | $13^{b}$ | $11^{hi}$ | $6^{bc}$ | $13^{b}$ | $10^{ab}$ |
| Turnip rape | 0,8 | $36^{g}$ | $29^{c}$ | $11^{hi}$ | $11^{ef}$ | $27^{e}$ | $33^{de}$ |
| Salohill | 0 | $22^{c}$ | — | $9^{g}$ | $11^{ef}$ | $21^{cd}$ | $7^{a}$ |
| Sugar beet | 0,8 | $53^{h}$ | — | $13^{j}$ | 14 | $52^{j}$ | $71^{h}$ |
| Pito/Record | 0 | — | — | $4^{d}$ | $4^{a}$ | $34^{h}$ | $28^{cd}$ |
| Potato | 0,8 | — | — | $5^{de}$ | $6^{bc}$ | $45^{i}$ | $66^{h}$ |
| Mikko | 0 | — | — | $6^{ef}$ | $4^{a}$ | $20^{c}$ | $8^{a}$ |
| Broad bean | 0,8 | — | — | $12^{ij}$ | $12^{f}$ | $30^{f}$ | $27^{c}$ |
| Heikka/Proco | 0 | $27^{de}$ | — | $7^{f}$ | $5^{ab}$ | $23^{d}$ | $14^{b}$ |
| Pea | 0,8 | $31^{f}$ | — | $10^{gh}$ | $9^{d}$ | $50^{j}$ | $56^{g}$ |
| Pomo | 0 | $7^{b}$ | — | $1{,}9^{b}$ | — | $14^{b}$ | — |
| Barley | 0,4 | $9^{c}$ | — | $2{,}2^{c}$ | — | $19^{c}$ | — |
| | | Limed peat (HWB 0,21 mg/l) | | | | | |
| Ante | 0 | — | — | — | — | — | — |
| Turnip rape | 0,8 | $25^{d}$ | — | — | — | $32^{fg}$ | — |
| Pomo | 0 | $4^{a}$ | — | $1{,}8^{ab}$ | — | $6^{a}$ | — |
| Barley | 0,4 | $7^{b}$ | — | $1{,}7^{a}$ | — | $12^{b}$ | — |

# 4. EFFECTS OF BORON ON PLANTS

## 4.1. Role of boron in plants, a review

When boron is insufficiently supplied to a plant, the disturbances begin in the fastest growing tissues, as in the stem apices (WARINGTON 1923), and in the youngest leaves (BRANDENBURG 1931, JAMALAINEN 1936 b, 1949). In *Brassica* species, the growth of the roots was restricted more by the deficiency of boron than the growth of the shoots, and the root tips died before the shoot tips (CHANDLER 1941).

Because floral and fruiting organs are especially sensitive to deficiency, more boron is required by the generative than by the vegetative growth (HEWITT 1983). Pollen germination and pollen tube growth are easily affected (DUGGER 1983). Therefore seed formation may be very poor, even if the vegetative growth is almost normal. This has also been shown with cruciferous plants (HASLER and MAURIZIO 1949, KOSKINEN 1952).

Boron is essential for normal cell division and differentiation. As a result of its deficiency, cell division may be excessive in the cambial tissues but arrested in the root tips. The cell wall thickness and fine structure are altered. As the cells do not differentiate normally, the formation of specialized tissues such as the vascular system is affected (DUGGER 1983, HEWITT 1983, PILBEAM and KIRKBY 1983).

Boron facilitates sugar transport (GAUCH and DUGGER 1953) and controls carbohydrate metabolism (LEE and ARONOFF 1967). If it is lacking, phenolic compounds accumulate and the biosynthesis of lignin may be disturbed (e.g. LEWIS 1980). Other alterations which have been found in an early stage of the deficiency are disorders in hormonal regulation systems (BOHNSACK and ALBERT 1977), and in nucleic acid metabolism (JOHNSON and ALBERT 1967).

Although many diverse effects of boron deficiency on plants have been repeatedly and carefully recorded, the primary function(s) of this nutrient is (are) still unknown. One new, and strongly supported hypothesis suggests that boron is indispensible for plant cell membranes. Growth disorders may result because the transport of nutrient ions and metabolites are altered in deficient plants (ROTH-BEJERANO and ITAI 1981, PARR and LOUGHMAN 1983, DUGGER 1983).

## 4.2. Effects on other nutrients in plants

If boron was required in the cell membranes for efficient nutrient absorption by the cells, its deficiency would also cause deficiencies of other nutrients. There is both theoretical and experimental evidence for this (e.g. PARR and LOUGHMAN 1981). However, several long-term experiments to prove this have failed (MILLER and SMITH 1977, TOUCHTON et al. 1980). Toxic amounts of boron have decreased the contents of calcium in plants, and the more calcium supplied to the plants, the more boron the plants have tolerated (JONES and SCARSETH 1944).

The effects of boron on the contents of other nutrients in plants were studied in pot experiment P2 (Chapter 1.7., soil pH and HWB

Table 29. Effect of liming and boron application on the yields and nutrient contents in dry matter of turnip rape shoots in full bloom in pot experiment P2. Each soil and crop tested separately (Duncan 0,05).

| B applied mg/l | $CaCO_3$ g/pot | Yield g/pot | B ppm | P g/kg | Ca g/kg | Mg g/kg | K g/kg | N g/kg |
|---|---|---|---|---|---|---|---|---|
| | | | 1st crop on loamy clay | | | | | |
| 0 | 0 | $34^{a}$ | $36^{b}$ | $4,5^{cd}$ | $18^{a}$ | $2,8^{b}$ | $61^{ab}$ | $39^{a}$ |
| 0 | 2,4 | $36^{a}$ | $29^{a}$ | $4,0^{b}$ | $23^{b}$ | $2,4^{a}$ | $56^{a}$ | $37^{a}$ |
| 0 | 4,8 | $34^{a}$ | $25^{a}$ | $3,5^{a}$ | $24^{b}$ | $2,3^{a}$ | $57^{ab}$ | $39^{a}$ |
| 2 | 0 | $33^{a}$ | $53^{d}$ | $4,6^{d}$ | $19^{a}$ | $2,8^{b}$ | $63^{b}$ | $41^{a}$ |
| 2 | 2,4 | $35^{a}$ | $42^{c}$ | $4,1^{bc}$ | $23^{b}$ | $2,5^{a}$ | $60^{ab}$ | $37^{a}$ |
| 2 | 4,8 | $34^{a}$ | $40^{bc}$ | $3,8^{ab}$ | $24^{b}$ | $2,4^{a}$ | $57^{a}$ | $39^{a}$ |
| | | | 2nd crop on loamy clay | | | | | |
| 0 | 0 | $23^{a}$ | $27^{c}$ | $4,6^{ab}$ | $20^{ab}$ | $3,0^{b}$ | $75^{a}$ | $42^{a}$ |
| 0 | 2,4 | $17^{a}$ | $24^{b}$ | $4,7^{b}$ | $26^{b}$ | $3,0^{b}$ | $69^{a}$ | $38^{a}$ |
| 0 | 4,8 | $21^{a}$ | $20^{a}$ | $4,4^{ab}$ | $25^{ab}$ | $2,3^{ab}$ | $73^{a}$ | $42^{a}$ |
| 2 | 0 | $27^{a}$ | $48^{f}$ | $4,4^{ab}$ | $16^{a}$ | $2,9^{ab}$ | $72^{a}$ | $42^{a}$ |
| 2 | 2,4 | $25^{a}$ | $42^{e}$ | $4,4^{ab}$ | $23^{ab}$ | $2,5^{ab}$ | $74^{a}$ | $41^{a}$ |
| 2 | 4,8 | $27^{a}$ | $37^{d}$ | $4,1^{a}$ | $21^{ab}$ | $2,2^{a}$ | $68^{a}$ | $40^{a}$ |
| | | | 1st crop on fine sandy till | | | | | |
| 0 | 0 | $16^{ab}$ | $24^{b}$ | $2,4^{ab}$ | $17^{a}$ | $4,1^{c}$ | $47^{ab}$ | $44^{a}$ |
| 0 | 2,4 | $22^{b}$ | $18^{a}$ | $3,0^{b}$ | $27^{b}$ | $2,4^{b}$ | $49^{b}$ | $41^{a}$ |
| 0 | 4,8 | $15^{a}$ | $16^{a}$ | $3,4^{b}$ | $32^{c}$ | $2,0^{a}$ | $52^{b}$ | $43^{a}$ |
| 2 | 0 | $13^{a}$ | $68^{d}$ | $1,7^{a}$ | $14^{a}$ | $4,0^{a}$ | $33^{a}$ | $40^{a}$ |
| 2 | 2,4 | $18^{b}$ | $46^{c}$ | $2,6^{ab}$ | $25^{b}$ | $2,2^{ab}$ | $41^{ab}$ | $41^{a}$ |
| 2 | 4,8 | $18^{b}$ | $42^{c}$ | $2,5^{ab}$ | $29^{bc}$ | $1,9^{a}$ | $40^{ab}$ | $39^{a}$ |
| | | | 2nd crop on fine sandy till | | | | | |
| 0 | 0 | $6^{a}$ | $20^{ab}$ | $1,5^{a}$ | $13^{a}$ | $4,2^{b}$ | $49^{a}$ | $34^{a}$ |
| 0 | 2,4 | $11^{ab}$ | $11^{a}$ | $2,4^{b}$ | $25^{b}$ | $2,2^{a}$ | $47^{a}$ | $35^{a}$ |
| 0 | 4,8 | $8^{a}$ | $12^{a}$ | $2,2^{b}$ | $28^{b}$ | $1,8^{a}$ | $51^{a}$ | $34^{a}$ |
| 2 | 0 | $6^{a}$ | $71^{c}$ | $1,9^{ab}$ | $18^{a}$ | $5,5^{c}$ | $54^{a}$ | $36^{a}$ |
| 2 | 2,4 | $14^{b}$ | $28^{b}$ | $2,3^{b}$ | $23^{b}$ | $2,2^{a}$ | $49^{a}$ | $32^{a}$ |
| 2 | 4,8 | $9^{ab}$ | $24^{b}$ | $2,5^{b}$ | $28^{b}$ | $1,8^{a}$ | $48^{a}$ | $36^{a}$ |

in Table 20, p. 216). The flowering turnip rape shoots from two soils were analyzed for P, Ca, Mg, K, and N in additon to B. According to the obtained contents (Table 29), the supply of boron did not effect the uptakes of other nutrients.

In 1982 the turnip rape seedlings in seven soils from the pot experiments were analyzed for calcium, but the nontoxic boron applications caused no differences from the control. The seedlings of the rape and turnip rape varieties in pot experiment P7 in 1983 (B contents listed in Table 28, p. 00) were also analyzed for P, K, Ca and Mg, but no sign of an impaired nutrient uptake was found, despite a moderate deficiency of boron. Similar results were also obtained from pot experiment P9. These results also included the contents of Fe, Mn, Zn and Cu.

The effects caused by liming on nutrients other than boron were beyond the scope of the present work, but it may be relevant to compare the effects of liming on boron with its effects on other nutrients. The results in Table 29 show that boron is not the only nutrient which is greatly affected by liming.

A part of the leaf samples collected from the field experiments to assess boron were also analyzed for other nutrients. The B contents are listed in Table 26 (p. 231). The nutrient contents in turnip rape leaves differed slightly with the boron fertilization treatments, but these effects were quite inconsistent (Table 30).

Table 30. Nutrient contents of turnip rape leaves in field experiments (g/kg dry matter). Each experiment and year tested separately (Duncan 0,05).

| Liming 1981 | B application kg/ha* | | 1982 | 1983 | | | |
|---|---|---|---|---|---|---|---|
| | | | Ca | Ca | Mg | K | P |
| | | | Jokioinen | | | | |
| — | 0,07/a | Tr | 23$^{a}$ | 26$^{ab}$ | 3,9$^{a}$ | 44$^{a}$ | 5,6$^{a}$ |
| — | 0,35/a | Pl | 21$^{a}$ | 26$^{ab}$ | 3,8$^{a}$ | 43$^{a}$ | 5,6$^{a}$ |
| — | 1,4/a | Pl | 22$^{a}$ | 24$^{a}$ | 3,5$^{a}$ | 42$^{a}$ | 5,8$^{a}$ |
| — | 5,6 -81 | St | 22$^{a}$ | 28$^{ab}$ | 3,8$^{a}$ | 43$^{a}$ | 5,6$^{a}$ |
| 10 t/ha | 0,07/a | Tr | 23$^{a}$ | 29$^{b}$ | 3,8$^{a}$ | 40$^{a}$ | 5,6$^{a}$ |
| ,, | 0,35/a | Pl | 23$^{a}$ | 28$^{ab}$ | 3,7$^{a}$ | 40$^{a}$ | 5,2$^{a}$ |
| ,, | 1,4/a | Pl | 22$^{a}$ | 27$^{ab}$ | 3,7$^{a}$ | 43$^{a}$ | 5,6$^{a}$ |
| ,, | 5,6 -81 | St | 23$^{a}$ | 29$^{b}$ | 3,9$^{a}$ | 42$^{a}$ | 5,2$^{a}$ |
| | | | Mietoinen | | | | |
| — | 0,06/a | Tr | 17$^{a}$ | 18$^{a}$ | 2,6$^{a}$ | 39$^{a}$ | 6,3$^{a}$ |
| — | 0,31/a | Pl | 17$^{a}$ | 20$^{ab}$ | 2,8$^{a}$ | 44$^{a}$ | 6,7$^{a}$ |
| — | 1,25/a | Pl | 17$^{a}$ | 20$^{ab}$ | 2,8$^{a}$ | 41$^{a}$ | 6,6$^{a}$ |
| — | 5,0/a | Br | 16$^{a}$ | 19$^{ab}$ | 2,3$^{a}$ | 37$^{a}$ | 6,7$^{a}$ |
| 8 t/ha | 0,06/a | Tr | 19$^{a}$ | 22$^{ab}$ | 2,6$^{a}$ | 37$^{a}$ | 6,3$^{a}$ |
| ,, | 0,31/a | Pl | 19$^{a}$ | 23$^{b}$ | 2,8$^{a}$ | 39$^{a}$ | 6,2$^{2}$ |
| ,, | 1,25/a | Pl | 20$^{a}$ | 23$^{b}$ | 2,7$^{a}$ | 39$^{a}$ | 6,2$^{a}$ |
| ,, | 5,0/a | Br | 18$^{a}$ | 23$^{b}$ | 2,2$^{a}$ | 36$^{a}$ | 6,6$^{a}$ |
| | | | Kokemäki | | | | |
| — | 0,06/a | Tr | 27$^{a}$ | 26$^{b}$ | 4,1$^{ab}$ | 57$^{a}$ | 8,7$^{ab}$ |
| — | 0,3/a | Pl | 25$^{a}$ | 24$^{ab}$ | 3,8$^{ab}$ | 54$^{a}$ | 8,7$^{ab}$ |
| — | 1,2/a | Pl | 26$^{a}$ | 21$^{a}$ | 3,6$^{a}$ | 54$^{a}$ | 9,6$^{b}$ |
| — | 4,8 -81 | St | 27$^{a}$ | 25$^{ab}$ | 4,1$^{ab}$ | 56$^{a}$ | 8,5$^{ab}$ |
| 7 t/ha | 0,06/a | Tr | 28$^{a}$ | 29$^{b}$ | 4,7$^{b}$ | 54$^{a}$ | 8,3$^{a}$ |
| ,, | 0,3/a | Pl | 28$^{a}$ | 27$^{b}$ | 4,5$^{ab}$ | 55$^{a}$ | 9,0$^{ab}$ |
| ,, | 1,2/a | Pl | 26$^{a}$ | 23$^{a}$ | 3,7$^{a}$ | 58$^{a}$ | 9,3$^{ab}$ |
| ,, | 4,8 -81 | St | 28$^{a}$ | 26$^{b}$ | 3,9$^{ab}$ | 53$^{a}$ | 8,7$^{ab}$ |

* Tr = traces in NPK fertilizer, Pl = placement, St = store dressing, Br = broadcasting.
For more details see Chapter 1.6.

However, the analyses of variance showed significant factorial effects of boron fertilization on the calcium contents in 1983 in Jokioinen (F = 6,6**) and in Kokemäki (F = 4,5*). In the latter case, the phosphorus contents also differed significantly (F = 5,5*). The deviating results were with the NPK fertilizer with 0,2 % B (1,2—1,4 kg/ha), which caused lower contents of calcium but a higher content of phosphorus than the other treatments. The latter effect was a single case without much general meaning. The decrease in the content of calcium in the turnip rape leaves appeared to be a more typical effect when boron was applied in a high rate by the placement method. These decreases were often followed by decreases in the seed yields, which suggested that the decreased calcium contents in the plant was a symptom of boron toxicity.

## 4.3. Visible symptoms of deficiency and toxicity

Visible symptoms in plants are considered useful means for boron diagnosis despite the development of chemical tests (e.g. SHORROCKS 1982). Although the symptoms do not reveal concealed deficiencies and toxicities and thus do not replace chemical tests in ensuring optimal boron supply, the ability to identify these symptoms will help in recognizing the reason for some occasional growth disturbances. Most of the observations presented in this chapter were recorded from the experiments dealt with in the previous chapters (pot experiment P8 will be presented in Chapter 4.4.1.). One photograph on boron toxicity (Fig. 21) was taken from an additional demonstrative pot experiment.

In the low-boron limed peats in pot experiments P5 and P9, the growth of the turnip rape seedlings ceased before the cotyledons were mature (Figs. 10 and 11). The seedlings in P5 did not grow any more but died. On the other hand, the weakest in P9 partly recovered. When the peats were not limed, the stems and leaves of the turnip rapes grew almost to normal size, but no seeds were formed without applied boron.

With the extremely severe boron deficiencies, the root systems of the turnip rapes developed even more poorly than the shoots. The primary roots died soon after germination (Fig. 12). The stunted lateral roots were abnormally thick, this was similar to the earlier studies with the *Brassica* species (CHANDLER 1941) and other plants (KORONOWSKI 1961).

In the low-boron fine sand in pot experiment P5, early growth was not much faster than in the low-boron peats, but the development of the lateral roots, shown in Fig. 13, enabled the seedlings to recover somewhat better. The death of the growing points in the tap roots naturally resulted in abnormal root systems.

Fig. 10. Effects of limes with different boron contents on early growth of turnip rape on low-boron peat. From the left: no lime, purified $CaCO_3$, calcite from Lohja (9 g B/t), dolomite from Siikainen (102 g B/t). Boron applied to the back row.

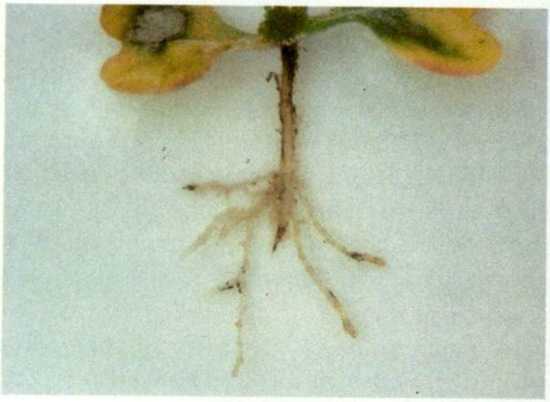

Fig. 12. Due to severe boron deficiency the primary root of a turnip rape has died and its lateral roots are short and abnormally thick.

Fig. 11. Turnip rape seedlings dying of severe boron deficiency in pot experiment P5. Above right normally growing seedlings of the same age.

Fig. 13. Seedling of turnip rape grown on low-boron fine sand. Boron applied to the two middle specimens of four plants of the same age.

Fig. 14. Stunted stem elongation caused by boron deficiency has caused rosetting. Boron applied to plants on the left.

Fig. 15. Effect of boron on early growth of poppy on peat (HWB 0,28 mg/l). No-boron control in middle front.

Fig. 16. Yellowing of leaves of turnip rape due to boron deficiency.

Fig. 17. Reddening and late flowering of rape due to boron deficiency.

Fig. 18. Effects of boron deficiency (left) on bud development of turnip rape.

Fig. 19. Boron deficiency in rape (left) poppy and turnip rape. Boron applied to the pots on the right side of each species.

On the very low-boron heavy clay in pot experiment P8, the cotyledons of the turnip rape matured, and other leaves began to grow, but then the seedlings completely yellowed, and started to die. This soil was taken from below the plow layer from the heavy clay field experiment in Jokioinen.

In 1981 in pot experiment P1, the leaves of the young turnip rape plants were entirely green despite the severe boron deficiency which retarded the elongation of the stems (Fig. 14) and caused a very poor seed set. These symptoms were equal to the "Sitzenbleiben" symptom in rape (BERGMANN and NEUBERT 1976). The stunted stems usually cracked and had dark corky lesions. In the year 1982 the symptoms appeared earlier, and were in the seedling stage stronger than in the other years with an equally poor boron supply. An apparent reason for this was the exceptionally cold period in June of 1982, which particularly seemed to strengthen the color changes.

The poppy seedlings in the pot experiment P4 were very stunted, although the peat in this experiment was acid (Fig. 15). The seedlings, however, retained their green color and recovered. Afterwards a large part of the leaves turned light gray, as earlier shown by SHORROCKS (1982). The rapes were much less stunted in this experiment. Their seedlings (10 cm high) weighed only 30 % more with than in the absence of applied boron.

Some yellowing of the leaves of the turnip rape plants was already visible in Figs. 10, 11 and 12. A clearer example of these symptoms is seen in Fig. 16. When the deficiency was slight, only the uppermost leaves turned yellow and not before the late flowering stage. In these cases the color change caused by a boron deficiency, and the normal maturing could not easily be distinguished. If the yellowing began in the uppermost leaves, the reason probably was a boron deficiency.

Some leaves of a few individual boron-deficient plants of the turnip rape varieties became reddish. Reddening (purplish) was the typical color change in the leaves of boron-deficient rape (Fig. 17). The appearance of the red color agreed with previous photos (BERGMANN and NEUBERT 1976). However, the color changes were less striking in the rapes than in the turnip rapes.

The effects of boron deficiency on the development of the pods of the turnip rape is seen in Fig. 18. The poor development of the seed pods has been found earlier in Finland in the winter turnip rape (TAINIO 1957), and in Australia in the spring rape (MYERS et al. 1983).

With a severe boron deficiency, when even the vegetative growth was restricted, the branching and flowering of the rapes continued longer than normal, right up to the beginning of harvest. Then the lower leaves also remained green longer than usual (Fig. 19). These changes, however, were not very suitable to diagnose the sufficient level of boron, for the seed yield could have decreased by almost fifty percent without any late flowering. No late flowering occurred in the poppy, although the boron deficiency decreased the seed yield to zero.

Although the whole plants grew very poorly in the extremely deficient soils, the observations strongly substantiated the localization of the growth disturbances in certain sensitive parts of a plant. The plants did not seem to be able to adjust their growth to the boron supply by means of decreasing the growth rate, which is possible if the supply of nitrogen or phosphorus is low. The supply of boron has obviously not been such an essential growth factor in nature that the adaption to its shortage would have been ecologically important.

Foliar application of boron in the field experiment (heavy clay, Jokioinen) did not cause any symptoms in the first year, but in the second year the aqueous solution of Solubor caused yellow lesions and margins in the leaves (Fig. 20). The marginal chlorosis indicated that the applied boron had been absorbed into the leaves and transported through the inner tissues. These toxic effects were visible on the second day, and were most distinct three to four days after the spraying.

Another disturbance in the turnip rape caused by foliar application of boron was an increased sensitivity to lodging. (This effect was observed

Fig. 20. Effects of sprayed Solubor (350 l/ha) on leaves of turnip rape. No-boron control on the left, 0,5 % (0,1 % B) in the middle and 1,0 % on the right, B applied 3 d before photographing.

Fig. 21. Toxicity of boron on turnip rape and barley on fine sand (left) and clay soils. Rates of boron applied in mg/l soil from the front 20, 6 and 2 in fine sand and 60, 20 and 6 in clay.

in Mietoinen, where the foliar spraying was an additional treatment.) In the preliminary pot experiments (in 1980) excessive amounts of boron applied in the soil caused curved stems inside the supporting frames. The same primary effect was possibly involved in both of these symptoms, which appeared as a weakness of the stems. The literature reviewed for this work did not include these symptoms.

The heavy store dressings in the field experiments showed slight or moderate toxicity symptoms during the application year. In the loam soil in Kokemäki the early growth was restricted, but the plants recovered later, and there was no significant decrease in the yield. The dressing caused a slight dirty yellow tint also in the loamy clay at Jokioinen. In the last year at this site, a weak color change was observed with the placed boron rate of 1,4 kg/ha, and the root depth at budding also appeared lower with this (55 cm) than with the other treatments (59 cm). However, the values obtained by digging the roots out from a small area did not differ significantly (Duncan 0,05).

The toxicity of soil-applied boron to plants was demonstrated in a complementary pot experiment in 1983. Unexpectedly, the growth of the small seedlings of the turnip rape were affected more than the growth of barley sprouts (Fig. 21). The stunted growth of the seedlings was the first visible symptom of excess boron in the turnip rape. The tint of the leaves changed to a dirty yellowish green, but these weak and irregular symptoms probably could not have been detected if there had not been a healthy control.

In the later stage, the excess of boron in the turnip rape plants appeared as chlorosis and necrosis in the leaf margins; similarly it appeared in roundish leaves of other plants (BERGMANN and NEUBERT 1976). When the leaf-margins died prematurely while the middle of the leaf-blade was still elongating, regular shaped cups were sometimes formed, as already found in the 1930's by EATON (1935).

The observations indicated that the turnip rape is more sensitive to an excess of boron than would be expected on the basis of earlier experiments and generalized knowledge about the *Brassica* species (e.g. JAMALAINEN 1936 b, GUPTA 1979 b, BERGMANN and NEUBERT 1976, HOLMES 1980). The highest sensitivity was found at the early seedling stage. Slight toxicity symptoms often disappeared, and even rather badly injured seedlings could partly recover. Because of this recovery excess boron reduces the seed yields less in the turnip rape than in barley. This agreed with the earlier studies reviewed above (JAMALAINEN 1936 b et al.).

## 4.4. Effects of boron on yields

### 4.4.1. Quantity of yields

The importance of a sufficient supply of boron in the oilseed rapes has clearly been shown in pot experiments (e.g. HASLER and MAURIZIO 1949, NYBORG and HOYT 1970) and also in field experiments (e.g. SALMINEN 1952, TAINIO 1957, JOHANSSON 1970, JOHANSSON and NILSSON 1973, GERATH et al. 1975, TEUTEBERG 1978, JUEL 1980, MYERS et al. 1983). The initial boron in soil has been almost or wholly sufficient in several studies (e.g. LARPES 1980, HOVELAND et al. 1981, YADAV and MANCHANDA 1982, CEDELL 1983). In a fine sand soil in South Savo (Central Finland), the seed production of the white mustard *(Sinapis alpa)* has almost completely failed without applied boron (KOSKINEN 1952).

The observations presented in the foregoing Chapter (4.3.) already strikingly indicated the effects of boron on growth in pot experiments. The seed yields of the pot experiments will be dealt with later in determining the sufficient levels of boron in soils and plants. Yields of some representative pot experiments are presented also in this chapter. The seed yields of the field experiments are listed in these pages. The field experiments have been dealt with in Chapters 1.6. (soils, treatments), 2.4. (soil pH and HWB), and 3.2.3. (plant B).

The differences in yields between the liming and boron application treatments were usually rather small (Table 31). The only significant positive effect of applied boron in the seed and oil yields was found in the three year average in Mietoinen. The harmful effects of boron appeared more clearly than the beneficial effects. In 1983 in Jokioinen and Kokemäki, the boronated

Table 31. Seed and oil yields of turnip rape in field experiments, kg/ha. Each experiment and year tested separately (Duncan 0,05).

| Liming 1981 | B application kg/ha* | Seed yield 1981 | 1982 | 1983 | Average | Oil yield Average |
|---|---|---|---|---|---|---|
| | | Jokioinen | | | | |
| — | 0,07/a Tr | $1980^a$ | $2330^a$ | $2560^{ab}$ | $2290^a$ | $940^a$ |
| — | 0,35/a Pl | $1990^a$ | $2360^a$ | $2600^b$ | $2320^a$ | $950^a$ |
| — | 1,4/a Pl | $1980^a$ | $2360^a$ | $2420^a$ | $2260^a$ | $930^a$ |
| | 5,6 -81 St | $1930^a$ | $2380^a$ | $2670^b$ | $2330^a$ | $950^a$ |
| 10 t/ha | 0,07/a Tr | $1970^a$ | $2400^a$ | $2820^b$ | $2390^a$ | $980^a$ |
| ,, | 0,35/a Pl | $2060^a$ | $2390^a$ | $2840^b$ | $2430^a$ | $990^a$ |
| ,, | 1,4/a Pl | $2140^a$ | $2420^a$ | $2690^{ab}$ | $2420^a$ | $990^a$ |
| ,, | 5,6 -81 St | $1960^a$ | $2440^a$ | $2820^b$ | $2410^a$ | $980^a$ |
| | | Mietoinen | | | | |
| — | 0,06/a Tr | $1560^a$ | $2230^a$ | $2160^a$ | $1980^a$ | $810^a$ |
| — | 0,31/a Pl | $1640^a$ | $2370^a$ | $2250^a$ | $2090^b$ | $860^b$ |
| — | 1,25/a Pl | $1540^a$ | $2350^a$ | $2180^a$ | $2020^{ab}$ | $830^{ab}$ |
| — | 5,0/a Br | $1560^a$ | $2350^a$ | $2210^a$ | $2040^{ab}$ | $830^{ab}$ |
| 8 t/ha | 0,06/a Tr | $1610^a$ | $2450^a$ | $2290^a$ | $2120^b$ | $850^b$ |
| ,, | 0,31/a Pl | $1620^a$ | $2360^a$ | $2310^a$ | $2090^b$ | $850^b$ |
| ,, | 1,25/$a^a$ Pl | $1570^a$ | $2360^a$ | $2240^a$ | $2060^{ab}$ | $840^{ab}$ |
| ,, | 5,0/a Br | $1580^a$ | $2370^a$ | $2290^a$ | $2080^b$ | $840^{ab}$ |
| | | Kokemäki | | | | |
| — | 0,06/a Tr | $1700^a$ | $1570^a$ | $2500^b$ | $1920^b$ | $760^b$ |
| — | 0,3/a Pl | $1660^a$ | $1640^a$ | $2550^b$ | $1950^b$ | $770^b$ |
| — | 1,2/a Pl | $1460^a$ | $1630^a$ | $2180^a$ | $1760^a$ | $710^a$ |
| — | 4,8 -81 St | $1420^a$ | $1580^a$ | $2510^b$ | $1840^{ab}$ | $730^{ab}$ |
| 7 t/ha | 0,06/a Tr | $1690^a$ | $1490^a$ | $2560^b$ | $1910^{ab}$ | $770^b$ |
| ,, | 0,3/a Pl | $1680^a$ | $1580^a$ | $2460^{ab}$ | $1910^{ab}$ | $760^{ab}$ |
| ,, | 1,2/a Pl | $1800^a$ | $1550^a$ | $2490^{ab}$ | $1950^{ab}$ | $780^b$ |
| ,, | 4,8 -81 St | $1540^a$ | $1450^a$ | $2630^b$ | $1870^{ab}$ | $750^{ab}$ |

* Tr = traces in NPK fertilizer, Pl = placement, St = store dressing, Br = broadcasting.
For more details see Chapter 1.6.

Table 32. Effects of boron application on yields of turnip rape with different lime conditions in pot experiment P3. Soil pH values given in Table 21, p. 216. Each year and yield component tested separately (Duncan 0,05).

| Treatment me/l soil | Boron applied mg/l soil |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  | 0 | 0,8 | 3,2 | 0 | 0,8 | 3,2 |
|  | Seeds, g/pot |  |  | Straw, g/pot |  |  |
|  | 1981 (application year) |  |  |  |  |  |
| — | 16,9$^{bc}$ | 17,5$^{bc}$ | 16,6$^{bc}$ | 43,2$^{ab}$ | 45,4$^{a-c}$ | 43,4$^{ab}$ |
| 48 CaCO$_3$ | 18,4$^{c}$ | 18,2$^{bc}$ | 19,2$^{c}$ | 47,9$^{a-e}$ | 47,4$^{a-e}$ | 48,4$^{b-e}$ |
| 144 ,, | 15,1$^{b}$ | 19,6$^{c}$ | 19,5$^{c}$ | 47,6$^{a-e}$ | 48,0$^{a-c}$ | 47,7$^{b-e}$ |
| 432 ,, | 10,4$^{a}$ | 17,1$^{bc}$ | 18,1$^{bc}$ | 44,0$^{a-d}$ | 48,2$^{b-e}$ | 47,4$^{a-e}$ |
| 48 CaSO$_4$ | 17,9$^{bc}$ | 19,6$^{c}$ | 18,8$^{c}$ | 47,8$^{a-e}$ | 49,1$^{de}$ | 45,9$^{a-e}$ |
| 144 ,, | 16,8$^{bc}$ | 17,0$^{bc}$ | 17,6$^{bc}$ | 43,6$^{abc}$ | 42,8$^{a}$ | 42,8$^{a}$ |
| 48 Mg-K-Na* | 19,9$^{c}$ | 19,5$^{c}$ | 18,5$^{c}$ | 48,4$^{b-e}$ | 50,3$^{e}$ | 48,9$^{cde}$ |
|  | 1982 (residual effect) |  |  |  |  |  |
| — | 7,3$^{b}$ | 23,8$^{de}$ | 23,6$^{de}$ | 64,6$^{b}$ | 55,1$^{ab}$ | 58,3$^{ab}$ |
| 48 CaCO$_3$ | 8,4$^{b}$ | 23,7$^{de}$ | 24,1$^{de}$ | 61,8$^{b}$ | 56,0$^{ab}$ | 55,8$^{ab}$ |
| 144 ,, | 7,2$^{b}$ | 19,7$^{cd}$ | 24,6$^{e}$ | 56,9$^{ab}$ | 63,9$^{b}$ | 51,6$^{ab}$ |
| 432 ,, | 2,2$^{a}$ | 18,6$^{c}$ | 22,6$^{cde}$ | 49,8$^{ab}$ | 63,9$^{b}$ | 64,6$^{b}$ |
| 48 CaSO$_4$ | 6,7$^{b}$ | 18,5$^{c}$ | 21,4$^{cde}$ | 58,1$^{ab}$ | 53,6$^{ab}$ | 53,0$^{ab}$ |
| 144 ,, | 9,0$^{b}$ | 20,5$^{cde}$ | 20,5$^{cde}$ | 51,2$^{ab}$ | 45,1$^{a}$ | 52,5$^{ab}$ |
| 48 Mg-K-Na* | 8,1$^{b}$ | 24,5$^{e}$ | 24,0$^{de}$ | 58,5$^{ab}$ | 52,6$^{ab}$ | 59,0$^{ab}$ |

* 24 me MgCO$_3$, 12 me K$_2$CO$_3$ and 12 me NaOH per liter soil

NPK (0,2 % B, 1,2—1,4 kg/ha) produced about 100—350 kg/ha (5—14 %) less seeds than the other fertilizers. In the unlimed plots of the three experiments, the average yield loss was 110 kg/ha. However, no differences were found in the averages of the limed plots.

In the pot experiment P3 in the acid medium-boron sandy clay (see Chapter 1.7. for cropping, 2.3. for soil pH and HWB, and 3.2.1. for plant B), the application of boron did not cause any yield difference in the first year if the clay was not limed heavily (Table 32). When the soil pH was increased to 6,6 by adding 7,2 g of CaCO$_3$ per liter of soil, the absence of applied boron reduced the seed yield by 23 %. The largest lime addition with the resulting soil pH 7,1 decreased the yield by almost fifty percent.

In the residual year, the seed set was very poor with each liming treatment if no boron was applied in the first year. The poorest yield, which resulted from the excessive liming, was only ten percent of the normal level (Table 32). The "normal" amount for one year (0,8 mg B per liter of soil) was sufficient even in the first residual year if the soil was strongly acid. The heavier limings reduced the seed yields at this boron level almost as much as they did in the no-boron control in the application year. Because the treatments caused only minor differences in the straw yields, the ratio of the seeds to the whole yield (harvest index) drastically dropped by a deficiency of boron.

In the pot experiment P4 for comparing the three oilseed crop species in low-boron peat (see Chapter 1.7. for cropping and 3.3. for varieties and plant B), the poppy formed no seeds in the absence of applied boron (Table 33). The seed yields of the rapes in the same experiment were without applied boron ten percent of that obtained with a sufficient application. The greater boron requirement of the poppy, compared to the oilseed rapes, thus appeared in the growth of the seedlings as well as in the seed yields, although a deficiency of this nutrient prevented the seed set completely also in the turnip rape, which was planted in extremely low-boron peat, fine sand, and heavy clay soils, as seen in Tables 25 (p. 230) and 34, and shown later.

Table 33. Effects of boron on yields of oilseed crops grown in low-boron (HWB = 0,28 mg/l) Carex peat in pot experiment P4. Each species tested separately (Duncan 0,05).

| Boron applied mg/l soil | Turnip rape |  | Rape |  | Poppy |  |
|---|---|---|---|---|---|---|
|  | Seeds | Straw | Seeds | Straw | Seeds | Straw |
| 0 | 2,5$^{a}$ | 47,9$^{a}$ | 2,5$^{a}$ | 69,0$^{b}$ | 0$^{a}$ | 14,2$^{a}$ |
| 0,8 | 25,9$^{b}$ | 63,5$^{b}$ | 24,0$^{b}$ | 62,0$^{a}$ | 15,4$^{b}$ | 42,7$^{b}$ |
| 3,2 | 23,0$^{b}$ | 57,3$^{b}$ | 26,1$^{b}$ | 64,9$^{ab}$ | 14,5$^{b}$ | 44,9$^{b}$ |

In the pot experiment P7 for comparing several species and varieties (Chapter 1.7.), all the six oilseed rape varieties produced rather equal relative yields (Table 34). This results could be expected on the basis of the equal boron contents in plants (Chapter 3.3.). The differences between the relative yields were statistically insignificant, because the occurrence of damping-off in the seedlings caused slightly uneven growth in the second year, and there were only three replicates. These results, however, showed that the possible differences between the varieties are not important in estimating the required fertilization. This did not exclude even a close genetic control of boron nutrition, which has been found with inbred lines of sunflower (BLAMEY et al. 1984).

The requirement of boron varied greatly among the other compared crops. Barley, peas and potatoes suffered much less from the poor supply than did the rapes. Sugar beets did not appear to require more boron than the oilseed plants. The greatest requirement of this nutrient was found in the broad bean. The deficiency of boron caused an increase in the straw yields in the broad bean and barley, but not much in the rapes. This agreed with the visual observations that the excessive late vegetative growth, caused by a deficiency of boron, was fairly weak in the oilseed rapes.

The obtained results concerning the requirement of boron by the oilseed rapes agreed with earlier studies (e.g. HASLER and MAURIZIO 1949, GERATH et al. 1975, TEUTEBERG 1978, JUEL 1980). The high toxicity to the turnip rape of the boron applied by the placement method, on the contrary, was a new finding. A rather good tolerance to excess boron has been found in rutabaga (JAMALAINEN 1935 b), big-leafed turnip (TÄHTINEN 1970), turnip (MULLER and MCSWEENEY 1976) and cabbage (GUPTA and CUTCLIFFE 1984). These are close relative species of the turnip rape. The winter rape has also shown a high tolerance (JOHANSSON 1970, GERATH et al. 1975). In some cases, the usually applied rates have caused small decreases in the yield, but the differences have been statistically insignificant (JOHANSSON and NILSSON 1973, LARPES 1980, HOVELAND et al. 1981).

The high toxicity of the boron applied by the placement method was certainly a result of a good availability of this nutrient in the fertilizer rows. According to the leaf analyses, this method improved the usage of the boron from the

Table 34. Relative yields of varieties obtained without applied boron in pot experiment P7 as percent of the yields with sufficient boron. Primary yields are seeds, roots and tubers; secondary yields are straw, tops and haulms.

| | | Relative yields without applied boron* | | | |
|---|---|---|---|---|---|
| | | Primary | | Secondary | |
| Crop | Variety | 1982 | 1983 | 1982 | 1983 |
| | | Carex peat | | | |
| Rape | Topas | 97 | 53*** | 97 | 104 |
| Rape | Lergo | 102 | 66*** | 101 | 120 |
| Turnip rape | Ante | 102 | 72** | 102 | 101 |
| Turnip rape | Emma | 88* | 78** | 106 | 115 |
| Turnip rape | Span | 95 | 55** | 104 | 110 |
| Turnip rape | Vankka | 95 | 73** | 99 | 112 |
| Sugar beet | Salohill | 90 | 70* | 92 | 85 |
| Potato | Pito/Record | 103 | 95 | 94 | 108 |
| Broad bean | Mikko | 91 | 26*** | 98 | 211*** |
| Pea | Heikka/Proco | 102 | 96 | 97 | 100 |
| Barley | Pomo | 98 | — | 101 | — |
| | | Limed peat | | | |
| Turnip rape | Ante | 0*** | — | 0*** | — |
| Barley | Pomo | 37*** | — | 142*** | — |

* Values followed by asterisks differ significantly from 100
* P = 0,05
** P = 0,01
*** P = 0,001

fertilizer markedly, compared to the broadcasting method. Earlier comparisons between the effects of these methods have produced similar results (PETERSON and MACGREGOR 1966, GUPTA and CUTLIFFE 1978). The improved availability of the placed boron is probably a result of two factors: First, the sorption by soils is evidently reduced. Second, the coincidence with root activity is obviously increased.

It is unlikely that the disturbances in the leaves, as indicated by the weak color changes, could alone cause the yield decreases of several percent. A high concentration of boron in the vicinity of the fertilizer grains has been found to hamper the growth of the roots of oats and alfalfa (MORTVEDT and OSBORN 1965). Thus the measured insignificant reduction of the rooting depth provides a clue about the negative action of an excess amount of boron. As the root systems of the plants normally grow densest along the fertilizer rows (KÄHÄRI and ELONEN 1969), possible avoidance of these rows by the roots because of the boron would be very detrimental for the use of the other nutrients from the placed fertilizer.

### 4.4.2. Quality of rapeseeds

The extremely detrimental effect of a boron deficiency on the quality of the edible roots of *Brassica* species is well known (e.g. JAMALAINEN 1935 a). In turnips, the contents of glucosinolates have increased due to a deficiency of this nutrient (JU et al. 1982), and in radishes, other toxic compounds have increased (BIBLE et al. 1981). The quality of the rapeseeds has not been affected much by an insufficient boron supply, but the harmful substance chlorophyll

Table 35. Contents of protein, chlorophyll and oil in dry matter as well as weight of thousand seeds and moisture at harvest of rapeseeds from field experiments. Each experiments and column tested separately (Duncan 0,05).

| Liming 1981 | B application kg/ha* | In 1981 Protein % | In 1981 Chlorophyll ppm | Average in 1981—1983 Oil % | Average in 1981—1983 1000 seeds g | Average in 1981—1983 Moisture % |
|---|---|---|---|---|---|---|
| | | Jokioinen | | | | |
| — | 0,7/a Tr | $20,9^{a}$ | $10^{ab}$ | $45,2^{a}$ | $2,31^{a}$ | $16,9^{a}$ |
| — | 0,35/a Pl | $20,9^{a}$ | $8^{ab}$ | $45,1^{a}$ | $2,29^{a}$ | $16,8^{a}$ |
| — | 1,4/a Pl | $21,2^{a}$ | $11^{ab}$ | $45,2^{a}$ | $2,32^{a}$ | $16,8^{a}$ |
| — | 5,6 -81 St | $21,1^{a}$ | $10^{ab}$ | $44,8^{a}$ | $2,30^{a}$ | $17,1^{a}$ |
| 10 t/ha | 0,07/a Tr | $21,0^{a}$ | $9^{b}$ | $44,8^{a}$ | $2,30^{a}$ | $16,5^{a}$ |
| ,, | 0,35/a Pl | $21,0^{a}$ | $6^{a}$ | $44,9^{a}$ | $2,31^{a}$ | $16,6^{a}$ |
| ,, | 1,4/a Pl | $21,1^{a}$ | $9^{b}$ | $44,9^{a}$ | $2,27^{a}$ | $16,8^{a}$ |
| ,, | 5,6 -81 St | $21,3^{a}$ | $8^{ab}$ | $44,7^{a}$ | $2,29^{a}$ | $17,0^{a}$ |
| | | Mietoinen | | | | |
| — | 0,06/a Tr | $22,9^{a}$ | $7^{a}$ | $44,8^{ab}$ | $2,35^{a}$ | |
| — | 0,31/a Pl | $23,2^{a}$ | $6^{a}$ | $45,0^{ab}$ | $2,40^{a}$ | |
| — | 1,25/a Pl | $23,2^{a}$ | $7^{a}$ | $44,8^{ab}$ | $2,38^{a}$ | |
| — | 5,0/a Br | $23,2^{a}$ | $7^{a}$ | $44,9^{ab}$ | $2,40^{a}$ | |
| 8 t/ha | 0,06/a Tr | $23,7^{a}$ | $10^{a}$ | $44,3^{a}$ | $2,41^{a}$ | |
| ,, | 0,31/a Pl | $23,4^{a}$ | $7^{a}$ | $44,8^{b}$ | $2,37^{a}$ | |
| ,, | 1,25/a Pl | $23,3^{a}$ | $8^{a}$ | $44,6^{b}$ | $2,35^{a}$ | |
| ,, | 5,0/a Br | $23,2^{a}$ | $10^{a}$ | $44,2^{a}$ | $2,33^{a}$ | |
| | | Kokemäki | | | | |
| — | 0,06/a Tr | $23,7^{a}$ | $28^{a}$ | $43,2^{a}$ | $2,50^{a}$ | |
| — | 0,3/a Pl | $23,7^{a}$ | $32^{a}$ | $43,3^{a}$ | $2,52^{a}$ | |
| — | 1,2/a Pl | $23,5^{a}$ | $55^{b}$ | $44,0^{b}$ | $2,49^{a}$ | |
| — | 4,8 -81 St | $24,2^{a}$ | $55^{b}$ | $43,2^{a}$ | $2,53^{a}$ | |
| 7 t/ha | 0,06/a Tr | $23,0^{a}$ | $33^{ab}$ | $44,0^{ab}$ | $2,49^{a}$ | |
| ,, | 0,3/a Pl | $23,6^{a}$ | $38^{ab}$ | $43,4^{ab}$ | $2,52^{a}$ | |
| ,, | 1,2/a Pl | $22,2^{a}$ | $31^{ab}$ | $43,8^{ab}$ | $2,50^{a}$ | |
| ,, | 4,8 -81 St | $23,7^{a}$ | $43^{ab}$ | $43,5^{ab}$ | $2,52^{a}$ | |

* Tr = traces in NPK fertilizer, Pl = placement, St = store dressing, Br = broadcasting.
For more details see Chapter 1.6.

has slightly increased in the deficient plants (TEUTEBERG 1978). The contents of oil in the rapeseeds have been remarkably independent of boron applications (e.g. GERATH et al. 1975, TEUTEBERG 1978, JUEL 1980, LARPES 1980, CEDELL 1983). Several other chemical constituents have also been unaffected (TEUTEBERG and TRAUTSCHOLD 1978).

In order to study the possible effects of boron on the quality of rapeseeds, some physical, chemical, and biological determinations were performed on the yields from the experiments dealt with in the foregoing chapter (4.4.1.).

In the field experiments, the oil contents of the rapeseeds varied only slightly between the treatments (Table 35), which agreed with the reviewed studies. The maximum oil contents usually appeared with the highest yields, but when yields decreased due to an excess of boron, the oil contents remained the same. Chlorophyll contents were somewhat reduced by applied boron, but increased with an excessive application. The protein contents, weights of 1000 seeds, and moisture percentages at harvest were unaffected (Table 35).

In pot experiment P7, the application of boron had no effect on the 1000-seed weights of the six oilseed crop varieties in the first year when the initial soil boron was sufficient. In the second year, the weights of the seeds were higher without than with applied boron (Table 36). Thus, the moderate deficiency had increased the seed size. The greatest difference, about 50 %, occurred with the rape. With the turnip rapes, excluding 'Vankka', the effect was 10 to 25 %. The increased seed size, caused by a boron deficiency, has also been found in the field with the winter rape (TEUTEBERG 1978), but an opposite effect has also been observed in winter oilseed rapes (JOHANSSON and NILSSON 1973).

Table 36. Effects of boron application on thousand seed weight and germination percentage of seeds of rape and turnip rape varieties in pot experiment P7.

| Variety | B applied* mg/l soil | 1000-seed weight, g 1982 | 1983 | Germinativity, % 1983 |
|---|---|---|---|---|
| Rapes | | | | |
| Topas | 0 | 4,1 | 4,5** | 21** |
| | 0,8 | 4,0 | 3,1 | 70 |
| Lergo | 0 | 4,0 | 4,2** | 31** |
| | 0,8 | 4,0 | 2,8 | 67 |
| Turnip rapes | | | | |
| Ante | 0 | 2,6 | 2,5** | 85* |
| | 0,8 | 2,5 | 2,0 | 98 |
| Emma | 0 | 2,4 | 2,2* | 88** |
| | 0,8 | 2,3 | 2,0 | 99 |
| Span | 0 | 2,5 | 2,4 | 79 |
| | 0,8 | 2,3 | 2,0 | 97 |
| Vankka | 0 | 2,5 | 2,5 | 76 |
| | 0,8 | 2,6 | 2,4 | 75 |

* Asterisks indicate significant effect of applied B
* P = 0,05
** P = 0,01

The primary reason for the abnormally large seeds caused by a boron deficiency was probably a disorder in the development of the seed primordia so that a reduced number of seeds began to grow. The few seeds were then abundantly supplied with metabolites and therefore were able to grow larger than the more numerous seeds of the healthy plants.

The large seeds of the boron-deficient rapes were not entirely healthy. As seen in Table 36, the germination percentages were lower without applied boron. As no disinfectants were used, fungal growth was quite vigorous, especially on the rapes. This possibly decreased the percentages and increased the deviation of the results. In spite of this the three replicates showed significant effects on five of the six varieties. These results suggested that a sufficient supply of boron to the crops is particularly important in producing sowing seed, because even a rather slight deficiency seems to weaken the vitality of the seeds.

# 5. BORON REQUIREMENT OF SPRING OILSEED RAPES

## 5.1. Sufficient levels in soils and plants

### 5.1.1. Sufficient contents in plants

Because the indispensable functions of boron in the plants take place within the plant tissues, the sufficiency of boron is probably well indicated by the contents of this nutrient in the tissues shelf. Although the total content does not possibly always show the physiological activity, the level is usually estimated on the basis of the total content in dry matter. The ratio of calcium to boron has earlier been applied (e.g. JONES and SCARSETS 1944), but the simple content has been considered a better indicator for the inner status in the plants (e.g. GUPTA 1979 b). Because the calcium contents did not appear useful in preliminary calculations of the present results, the interpretation of the plant analyses was based on the contents of boron only.

To develop and calibrate a routine plant boron test was one objective of the pot experiment P1 with 30 soils (Chaptrers 1.7. and 2.5.). The yields and their boron contents from each of these soils were listed in the preliminary report (SAARELA 1984, p. 121—122). The requirements of boron in the plants were also attempted to determine using the combined results from other pot experiments (Chapter 1.7.).

The seed yields from the 30 soils in the pot experiment P1 correlated positively with the contents of boron in each of the analyzed part of the plant. In 1981 the coefficient of determination ($r^2$) was 0,37 with the seedlings and 0,53 with the seed shelf. The coefficient of multiple determination ($R^2$) according to the quadratic equations were 0,38 with the straw, and 0,55 with the leaves.

The growth of the seedlings was very sensitive to the physical conditions of the soils in the pots. This was one reason for the looseness of the correlation between the seed yields and the contents of boron in the seedlings. The "active" regulation of the contents by the plants (discussed in Chapter 3.1.) also most distinctly appeared at the seedling stage. Because the strong retarding effect of high soil pH levels on the absorption of boron decreased with time, lower contents in the seedlings were sufficient with the heavy limings than in the more acid soils. In the seedlings, the lowest level of boron sufficient for maximum seed yield was from 18 to 32 ppm (SAARELA 1984, p. 83—84).

Although the multiple determination in the regression equation with the contents of boron in the straw was so low, a graphical plotting of the results (Fig. 22) revealed a close dependence of the seed yields on these contents in the lower end of the range. The relative yields with the no-boron controls from other pot experiments gave a very similar picture (Fig. 23). On average, the relative seed yield increased from zero to 100 % when the contents of boron in the straw increased from 10 to 15 ppm. The individual means did not deviate by more than ±2 ppm. Thus the range for the minimum sufficient content of boron in the turnip rape straw was from 13 to 17 ppm. However, in the pot experiment P9 (Table 25, p.230), the boron-containing lime caused a boron content of 23 ppm in turnip rape straw but a significantly smaller seed yield than did a sufficient amount of soluble boron. This deviating result probably indicated that the lime supplied boron too slowly to meet the requirement at the early seedling stage.

In spite of the closer correlation, the critical level of the content of boron in the leaves could not be determined as precisely as that of the straw. When the content was less than 20 ppm, the seed set was very poor. 30 ppm was usually sufficient, but in some cases more was required. The variation of the minimum sufficient contents of boron in the turnip rape leaves ranged from 22 to 38 ppm. The seeds from the boron-deficient turnip rape plants contained about 10 ppm B, while the seeds produced with sufficient boron contained at least 10 ppm of the nutrient (SAARELA 1984, p. 86—87).

According to the variety comparison dealt with previously (Chapters 1.7., 3.3. and 4.4.), all rape

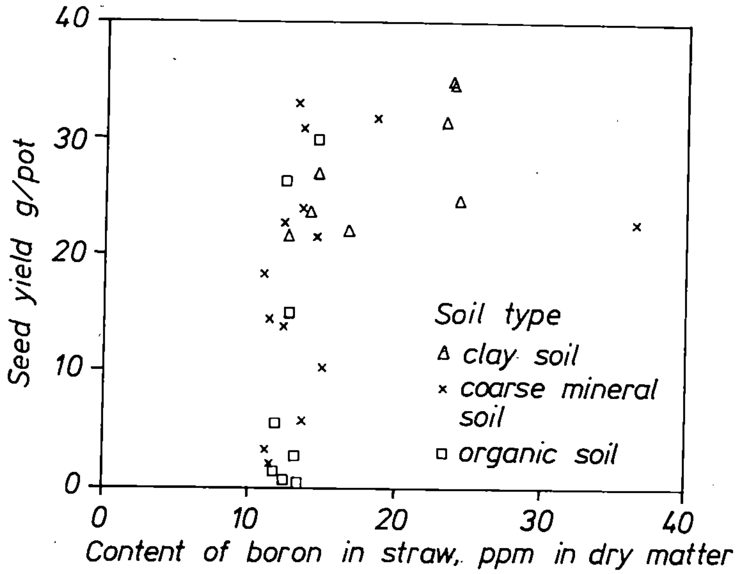

Fig. 22. Seed yield of turnip rape on boron content in straw from pot experiment P1.

and turnip rape varieties appear to require rather similar contents of boron in their tissues. The obtained sufficient contents agreed with some earlier results from rape (GERATH et al. 1975, BERGMANN and NEUBERT 1976, SZUKALSKI and SIKORA 1981). The spring turnip rape has been a crop plant quite unstudied in relation to boron nutrition.

Although the deficiency limit varied less in the straw than in the leaves, leaf analysis is perhaps more applicable in practice. Leaves are easy to sample during a late budding or early flowering stage. Leaching of boron from the plant tissues in different intensities probably affects the results less during active early growth than later. The

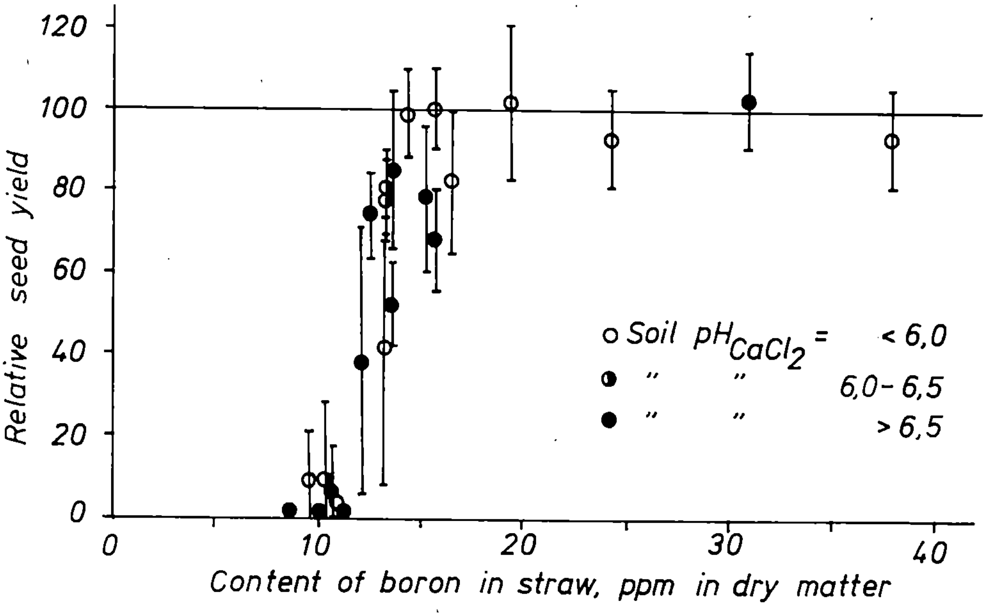

Fig. 23. Relative seed yield of no-boron control on boron content in turnip rape straw. Yield with sufficient boron application = 100. Results combined from several pot experiments.

range of the minimum sufficient level of boron in the leaves according to the pot experiments, from 22 to 38 ppm, appeared suitable also in the field experiments. In the young leaves of a fast-growing plant the requirement seemed to be at the lower end of the range, and conversely in the slowly-growing and old leaves.

The quantitative requirement of boron in a plant is the product of the minimum sufficient content and the weight. It may be calculated as the sum of the different parts of the plant. As the contents are only seldom at the exactly required level, a somewhat higher content must be aimed at if deficiencies are to be avoided. The content of boron in the seeds varied from 12 to 16 ppm in the field experiments. In the pot experiments, the yield ratio straw/seeds was about 2, and the yield ratio leaves/seeds was about 0,5. If the required contents in the straw and in the seed were 20 and 40 ppm, respectively, the requirement in the whole shoots was about 75 g per ton of seeds. At the average yield level in Finland, about 1 500 kg/ha, the sufficient boron uptake is about 110 g/ha.

As well as in the shoots, boron is also necessary in the roots. On the other hand, the oldest leaves start to drop off before the seed development begins. As the boron in the fallen leaves may partly be re-utilized via the roots, the sum of the amounts in the parts of the plant is not an exact measure of the quantitative requirement of boron.

### 5.1.2. Sufficient status of soils

Compared to the amounts sufficient in the plants, the amounts of boron in soils are usually rather large even if an available fraction is considered. However, the boron in soil does not satisfy the inner plant's requirement of boron until it is transported into the plant, and the rate of this transport is not sufficient if the level of available boron in the soil is not sufficiently high.

The same experiments dealt with in the foregoing chapter were also used to determine the requirement of available boron in soils. In the pot experiment P1 with 30 soils, fairly close dependencies of the seed yields on the HWB values of soils were found. The multiple determination ($R^2$) according to the quadratic responses varied from 0,54 to 0,65. When the soil pH values and clay percentages were taken into account, the $R^2$ values increased up to 0,83 (Table 37).

The coefficients of determination for the dependence of the yields and the initial HWB values tended to become higher with time. The initial values also appeared to predict the seed yields closer than the values determined prior to the sowing of the crops in question. The real dependencies, however, were closest with the latest HWB values, for the variation range of these values decreased. The standard deviation of the initial HWB values was 0,27 mg/l, and that

Table 37. Dependence of turnip rape seed yields on soil test values in pot experiment P1.

| Dependent variable | | Independent variables and their coefficients with confidence limits (5 %) | | | | Coefficient of determination |
|---|---|---|---|---|---|---|
| Yield 1981<br>g/pot | = | 94,5 B1<br>± 52,0 | — 43,8 $(B1)^2$<br>± 36,3 | —18,5<br>±16,5 | | $R^2$ = 0,63 |
| ,, | = | 95,2 B1<br>± 40,0 | — 50,8 $(B1)^2$<br>± 28,1 | + 6,9 pH<br>± 3,2 | —53,9<br>±20,6 | $R^2$ = 0,79 |
| ,, | = | 195,4 B2<br>±129,1 | —132,5 $(B2)^2$<br>±115,5 | —39,9<br>±33,0 | | $R^2$ = 0,54 |
| ,, | = | 208,3 B2<br>±100,6 | —159,4 $(B2)^2$<br>± 90,6 | + 7,6 pH<br>± 3,6 | —81,2<br>±32,2 | $R^2$ = 0,73 |
| Yield 1982<br>g/pot | = | 10,6 $(B1)^2$<br>± 4,3 | + 4,8 pH<br>± 2,0 | + 0,078 clay<br>± 0,075 | —22,3<br>±10,4 | $R^2$ = 0,83 |

B1 = initial HWB, mg/l
B2 = HWB in autumn 1980, mg/l
clay = clay-% (0,002 mm)

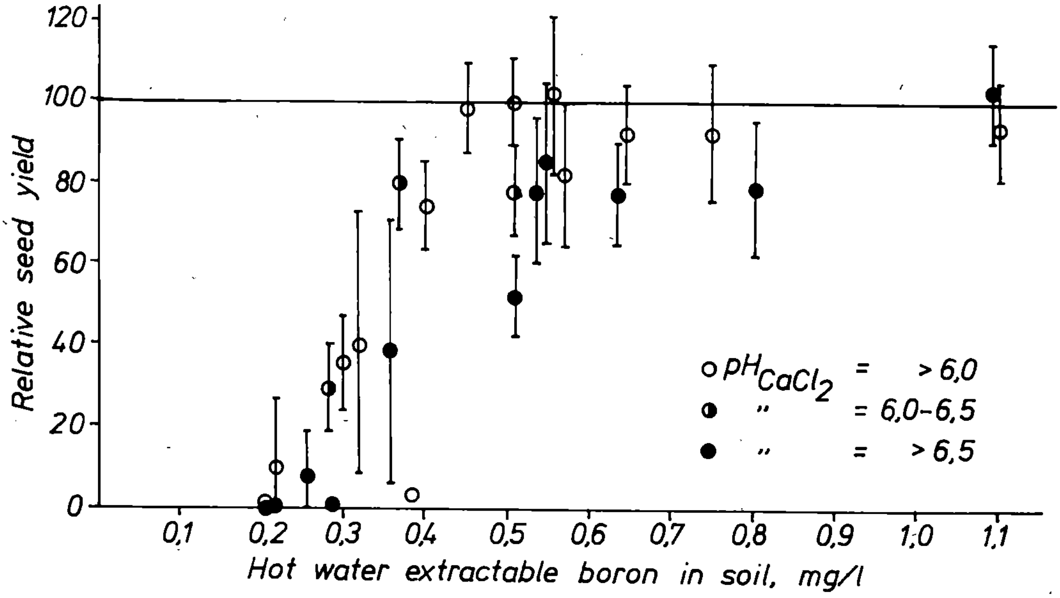

Fig. 24. Relative seed yield of no-boron control on soil HWB value. Yield with sufficient boron application = 100. Results combined from several pot experiments.

of the values determined prior to the sowing in 1981 was 0,17 mg/l. The deviation of the initial values was similar to those obtained in Finnish soils earlier, 0,29 mg/l by SIPPOLA and TARES (1978) and 0,28 mg/l by SILLANPÄÄ (1982).

The phrase correlation is no causation should always be kept in mind when results of correlation and regression analyses are interpreted. In the pot experiment P1, the possible effects of other soil properties on the seed yields were assessed in the third year by applying boron to one of the two replicates. The dependencies of the seed yield on the HWB values disappeared completely, and so the effects of the estimated availability of boron in the soils on the seed yields was assured (SAARELA 1984, p. 91).

The sufficient HWB value was quite equal in all types of soils. The most important other soil property was soil pH. In the pot experiment P1, the seed yields increased with increasing soil pH. When plotted, these results formed a similar graph (SAARELA 1984, p. 90) to that of the relative yields from the other acid soils (Fig. 24). No seeds were formed when the soil HWB was less than 0,2 to 0,4 mg/l. The minimum HWB values sufficient for the maximum seed yield of the turnip rape varied from 0,45 to 0,65 mg/l in the acid soils, and from 0,6 to 0,9 mg/l in the heavily limed soils.

This decrease of the relative seed yields, when the soil pH was increased by liming, was to the opposite direction than the effect of the initial soil pH in pot experiment P1. The results undoubtedly seem contradictory, but can be explained. The primary effect in each case was probably the increased sorption and fixation of boron in the soils with increasing pH. The boron fixed by liming obviously released slowly from the previously limed soils during the exhaustive cropping in pot experiment P1. The increase of the sufficient soil HWB level with liming, which was shown convincingly in the relative yields, is easily understood as a direct result of the enhanced sorption of boron from the soil solution, which is the immediate source for the plants.

The rate of the depletion of nutrients from soils is much higher in pot experiments than under field conditions, and thus the effects of the capacity predominate over the initial boron intensity. The increase of the seed yields with the increasing soil pH in the pot experiment P1 must not be unconditionally generalized to field conditions. However, one result of the same kind was also obtained in the field experiment in Mietoinen. The increase of the sufficient HWB level may even be greater under field conditions than in the pots because it appeared to be the rate of absorption and not the available amount which was most efficiently reduced by liming.

The initial HWB values in the soils in the field experiments were at the level which was sufficient in the pot experiment. Both the coarse-textured soils, however, were recorded at the higher end of the critical range. In the pot experiment P5 testing the soils from the field experiments (Chapters 1.7. and 3.2.1.), boron application increased the seed yield only in the limed loam from Kokemäki. These results using the same soils show that rather equal soil HWB levels are required in both systems. Similar results have also been obtained with sugar beets (SMILDE 1970). According to the plant analyses of the present work, a somewhat higher HWB level is required in the field during prolonged drought periods than was sufficient in the same soil in the pot experiments.

The traces of boron in the unboronated fertilizer and in the liming materials may have covered the possible requirements for boron fertilization. It was shown that the 60 g of boron in the fertilizer did increase the contents of boron in the turnip rape leaves. In the pot experiment P4, one mg of boron mixed into the low-boron peat, increased the seed yield of the turnip rape by 18,8 g. The 60 g of B would produce a yield increase of 1 130 kg if the efficiency was the same! This same rate, when it was applied repeatedly over some years in Norway, distinctly reduced the brown heart of rutabaga (ØDELIEN 1963).

In the pot experiments the sufficient HWB level was very similar in all the soil types classified by texture and content of organic matter. In other countries, the threshold value has often been higher in heavy-textured soils than in light-textured soils (e.g. OUELLETTE and LACHANCE 1954, JUEL 1980, SHORROCKS 1982). The high content of organic matter in Finnish mineral soils obviously equalizes the chemical properties in the soils to a considerable degree. In the field experiments, however, the contents of boron in the plants compared to the HWB values of the surface soils were lower in the clay soils than in the coarser soils.

One reason for the higher sufficient HWB value in the clay soils is the stronger sorption of boron by clays. This decreases the intensity of boron in soil in the same way as do high pH values. Another obvious reason for the difference was the extremely low extractable amounts in the deeper layers in the clay fields. In the heavy clay subsoil tested in pot experiment P8, (Chapter 1.7.), turnip rape produced the following yields (g/pot):

| | Unlimed | | Limed | |
|---|---|---|---|---|
| | Seeds | Straw | Seeds | Straw |
| No boron applied | $0^a$ | $24^b$ | $0^a$ | $5^a$ |
| 2 mg B/l soil | $18^c$ | $37^c$ | $14^b$ | $29^b$ |

For liming, 4,8 g of CaCO3 was added per liter of soil. The two yield components were tested separately (Duncan 0,05). More soils should be assessed for generalization of this finding, but it is easily understood on the basis of the low level of native boron and the slow downward movement of the applied boron.

No other soil characteristics, besides textural soil type, and pH, have been important in estimating the requirement of boron. Nitrogen fertilizers may have an effect on the boron nutrition of plants, but this effect occurs indirectly through the acidifying property of ammonium ions (JAMALAINEN 1949, MAURUA et al. 1977, SCHNUG 1982).

The minimum sufficient levels of the soil HWB values obtained in the present work with the spring turnip rape were approximately the same as earlier obtained with the rape in Germany (TEUTEBERG 1978) and in Denmark (JUEL 1980). In another German study, a somewhat lower value was sufficient for the winter rape, for the application of boron has only been considered important if the HWB was less than 0,25 ppm (GERATH et al. 1975). For the winter turnip rape in India, 0,43 ppm was sufficient (YADAV and MANCHANDA 1982). A rather low HWB value has often been sufficient in Sweden also (CEDELL 1983), but a somewhat higher level has been required for winter rapes in dry years (JOHANSSON and NILSSON 1973).

### 5.2. Recommendations for boron fertilization of spring oilseed rapes in Finland

Plant analysis, which takes into account all the effective edaphic, climatic, and biological factors, seemed to allow a slightly more precise estimate of the supply of boron from soils than the soil tests. The obtained knowledge about the inner plant's requirement of boron allows the possibility to use plant analysis for the diagnosis of boron. The content of boron in a plant is particularly suitable for use in research as a sensitive measure of the utilization of boron by the plants.

Some researchers have found that the plant analysis is more reliable than the soil HWB test, e.g. SIMOJOKI (1972) with barley. However, the same test may be more reliable in the higher level of boron in soil required for the rapes. Further, the accuracy of the soil test can be improved by taking other soil properties into account (e.g. OUELLETTE and LACHANCE 1954). By means of the soil tests, the available boron and the requirements for fertilization can be estimated prior to the sowing of the crop. This is necessary for the application of the boron to the soil in the usual way.

As the results of the present work are inadequate for proper fertilization recommendations, appropriate earlier studies must also be considered. Unfortunately, many of the earlier Finnish studies have only shown the existence of a boron requirement, but not the minimum sufficient application rate. For white mustard in an extremely deficient fine sand, 0,8 kg B per hectare was enough to almost reach the maximum yield (KOSKINEN 1952). For sugar beets, a boron rate of 2,1 kg/ha has prevented heart rot in some cases (BRUMMER 1965), but 1,4 to 2,1 kg B/ha, when incorporated into the soil prior to sowing, has not prevented this rotting-disease in soils limed heavily (JAMALAINEN 1968).

Because of the differences between the application methods in the utilization of applied boron, the earlier results appear to be largely out-of-date for the Finnish placement system. In North America, the higher efficiency of banded boron has led to a reduction in the recommended rates so that they were only a third of the broadcasted rates (MORTVEDT 1974). The results of the present work agreed with these relative doses.

The apparent recovery of the applied boron was quite high in the pot experiments; the maximum was more than fifty percent. Hence the amount of boron which equals the inner plant's requirements was always sufficient for the maximum seed yield in the application year, for the soil was never free of original boron. Even with the placement method, the utilized percentages are much lower in field conditions. The results, however, support the observations from the field experiments that boron when introduced into the densely rooted zone of soil, as by placement, is used efficiently.

More field experiments will be conducted, but the rates required for spring oilseed rapes under Finnish conditions, when boron is applied by the placement method, can already be estimated. A current hypothesis of the requirement is:

$$R = 0{,}6 - 0{,}67\ \mathrm{HWB}_a,$$

where R = required rate kg B per hectare and
$\mathrm{HWB}_a$ = pH-texture-corrected HWB value of the soil.

The $\mathrm{HWB}_a$ is derived from the HWB by reducing 0,1 unit of it per 0,3 $\mathrm{pH}_{\mathrm{CaCl_2}}$ units in excess to 6,0 ($\mathrm{pH}_{\mathrm{H_2O}}$ to 6,6). With clay soils, the pH-corrected value is further multiplied by 0,75. If the pH of the soil is in the general acid level of Finnish soils, the estimate decreases to zero when the HWB value increases to 0,9 in non-clay soil, and to 1,2 in clay soil. The most frequent values of the estimate range from 0,2 to 0,4 kg/ha.

When boron is applied as a boronated compound fertilizer, it is not usually possible to exactly distribute it at the estimated rate. Therefore, a range of the optimum rates with each level of soil boron should be known. Although excess placed boron appeared highly toxic, an excess of 0,5 kg B/ha over the estimated requirements is probably nontoxic. The range according to these criteria can be followed by using the boronated NPK fertilizers which are available in Finland (in April 1985). The specially boronated fertilizer with 0,12 % B is suitable in low-to-medium-boron soils, and the "common" fertilizers with a B addition of 0,05 % are suitable for soils with medium or higher boron levels.

According to the results, a positive response of the rapeseed yield to applied boron can be generally expected only when the $HWB_a$ value of the soil is less than about 0,5 mg/l. Because the recommendations are estimated on the basis of maximum certainty of an optimum boron supply, they are higher than averagely required. Precautions are necessary for exceptionally dry seasons (HOBBS and BERTRAMSON 1949) and for variations of the nutrient levels within the tested fields (JOKINEN 1983). The cost of the small doses are so low that the application may on average become profitable even if a weak positive effect occurs as seldom as in every tenth case.

When boron is broadcasted and incorporated into the soil, the doses should be about two to three times those recommended for the placement application. This means that the earlier recommendations (e.g. KURKI 1981) still are applicable for the earlier methods. The application method is apparently most important for crops which are sensitive early in the growing season, such as the turnip rape.

When broadcasted and incorporated into the soil, boron is affected by the sorption in the soil much more than when the placement method is used. Therefore, the required rate increases with an increase in the soil pH and fineness much more with broadcasting than with placement applications. In clay soils, where the uppermost (about 5 cm deep) layer is unrooted during the dry periods of early summer, an increased amount may not always compensate for the poor and uncertain availability of the broadcasted nutrient.

The Finnish spring rape fields are usually sprayed for pest control in the budding stage. It would be practical to apply boron in the same operation. However, foliar application has sometimes been inferior to soil application, which has been concluded to be a result of the immobility of boron in plants (e.g. FLEMING 1980).

The restricted retranslocation of boron from the leaves of the turnip rape in the pot experiment P4 (Chapters 1.7 and 3.1) also caused a very poor seed set (Fig. 25). These results suggested that a significant amount of the boron sprayed onto the leaves can only be transported into the boron-sensitive fruiting organs via the soil and roots. The conditions in Finland during early summer are not favorable for transport via the soil, as rather long dry periods are common, and the time from the spraying to the boron-sensitive flowering stage is short. An additional restriction is the high toxicity of boron by the foliar application. According to the observations (Fig. 20, p. 239) the highest safe concentration of boron in the solution sprayed onto the canopy is about 0,1 % (200 g B per 200 l water).

According to the results of the present work, the foliar application of boron can be recommended for the spring oilseed rapes in Finland only, when the estimated requirement is very small, or as a complement to soil application. The effect of the foliar spray, or actually, a late dressing onto the soil, is obviously most efficient in acid coarse-textured soils, and is the least efficient in clay soils with high pH values.

Because a normal interval of the chemical fertility tests in Finnish agricultural soils is as long as five years, the estimation of the required fertilization also includes the possible changes in the test values after the last testing. When the ordinary compound fertilizers with 0,05 % B are used, the changes are usually insignificant during the five-year period, although a slow increase is common. Large amounts of applied boron and heavy liming, on the other hand, may cause significant predictable changes.

When boron is applied, the calculated increase in the total content in a 25 cm deep layer is 0,4 mg/l per one kg B/ha. In the field experiments (Table 23), the increase in the HWB values averaged about one fourth of this, but the variation, because of variable fixation and leaching rates, was wide. The results with the usual

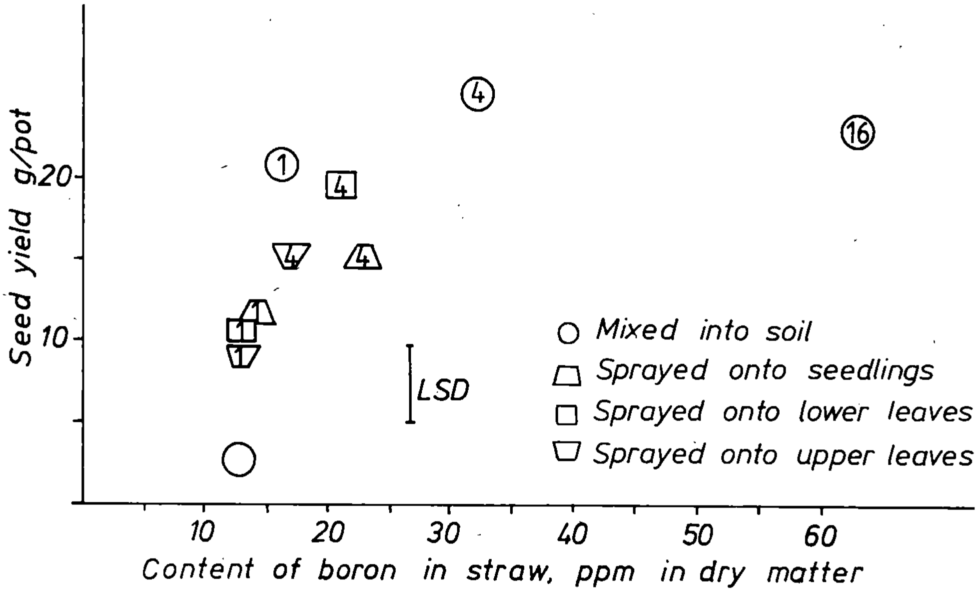

Fig. 25. Seed yield of turnip rape on boron content in straw with different rates and methods of boron application. Enclosed numbers indicate amounts of applied boron in mg per pot. Leaves sprayed at full bloom.

rates agreed with the earlier recommendations that boron should be applied annually (JAAKKOLA 1978, JOKINEN and LARPES 1978). Large doses, on the other hand, appeared to be sufficient over several years.

Particular precautions should be taken when the soil is treated with large rates of lime. As the soil HWB value may decrease because of liming, the previous test is not quite valid after liming. The increase of the sufficient HWB level in higher pH levels may also increase the requirement for boron fertilization. Special attention is needed when prevention of fungal diseases (club root) is attempted by dressing large rates of lime. The common doses of ground limestone for correcting toxic soil acidity (about 5 t/ha) do not appear to significantly increase the requirements for boron fertilization. Over a longer time period, the available amounts of boron in soils may even be increased by liming as a result of decreased leaching. The positive effect is obvious in soils which retain boron weakly, such as in acid coarse-textured soils.

## APPLICATION OF RESULTS AND NEED FOR FURTHER STUDIES

The behavior and function of boron in the soil-plant system is an infinitely complicated network of reactions. Detailed research on the different reactions within this system is necessary for a deeper understanding. However, for practical nutrition control, the field and the crop should be examined as one unit, and soils and plants ought to be studied jointly for applicable results.

The results published in the preliminary report (SAARELA 1984) have led to a reduction of the rates of boron applied to the oilseed rapes in Finland. The boron content of the boronated NPK (16—7—13) fertilizer, which is marketed for the oilseed rapes, has been reduced from 0,20 to 0,12 %. The use of low-boron (0,05 %) compound fertilizers with more economical NPK ratios is also becoming easier, for complementary boron application is no longer needed in many cases. More field experiments are planned for further studies on the rates of boron which are needed when using the placement method under various soil and weather conditions.

The average rate of boron currently being applied to Finnish agricultural soil is about ten times higher than that removed by the crops. The sorption of boron by the soils is therefore important for the development of the available amounts of boron in the soils. The average increase of the HWB fraction is about 18 % of the calculated boron accumulation since the early 1970s (KURKI 1982, TAKAMÄKI 1984, KÄHÄRI 1985). The remaining 82 % of the residue is either fixed into a form inextractable into hot water or leached deeper into the soil. As estimated according to the results of the sorption, fixation and movement experiments of the present work, the fixed amount is on average larger than the leached amount.

The rather weak boron sorption capacity of coarse-textured mineral soils and organic soils would still require further research for a reliable prediction of retention. Additional sorption and leaching experiments would particularly be required in organic soils. The behavior of boron in organic soils, especially under field conditions, seems to be a rather unstudied area even globally.

The slow process of boron sorption and fixation by soils, observed in the present study and earlier by SCHARRER et al. (1955) affects the validity of short-term sorption and leaching experiments. The sorption coefficients obtained without precautions for the slow reaction are not applicable to such sorption and leaching models as that by JAME et al. (1982). Under Finnish weather conditions, the boron which is applied in spring has usually a three to four months' period to be sorbed before it is subjected to any stronger leaching as deep as the bottom of the plow layer. The rate of leaching of boron in Finnish soils has apparently been overestimated (e.g. HOVI 1947, SILLANPÄÄ 1972, TARES and SIPPOLA 1978).

Earlier studies on the boron in Finnish agricultural soils have been concentrated on the HWB in the plow layer. In the present work, some preliminary analyses for the total amounts of boron in soils and their fractionating by extraction with strong acids were done, but the results are not published because of the obvious errors due to analytical difficulties. However the overall level of the total amounts of boron in a few samples appeared to be quite high, from 50 to 300 ppm. The highest values were obtained in heavy clay. The HWB fraction in these soils were not greater than one percent of the total amount. Less than ten percent of the total boron in mineral soils was extracted by a 1 M strong acid in one hour.

On the basis of the low amounts of available native boron in Finnish soils and the slow release of boron from soils in the pot experiments, the fractions of soil boron which are inextractable in hot water can be presumed to be rather unimportant for the supply of boron to plants and for the requirement of fertilization. However, the significance of total boron and other sparingly soluble fractions of soil boron for the nutrition of crops would be a relevant objective of future research. The reverse reaction, the fixation of available boron into an unavailable form, seemed to be more important and would need additional investigation.

The boron sorption and fixation capacities of soils were closely related to soil pH, texture, and content of organic matter. Awareness of these dependencies may help in controlling the supply of boron to crops. However, the statistical dependencies did not tell us very much about the mechanisms of the reactions. The roles, e.g. of active aluminum and iron compounds and different saturating cations would require additional experimental work. Fractionation of the boron which became fixed during the incubation is a particularly interesting topic for chemical as well as biological studies.

# SUMMARY

The main objective of the present work was to estimate the requirements of boron fertilization in growing spring oilseed rapes under Finnish conditions. Determining the inner plant's requirement of boron and estimating the availability to plants of boron in soils were the most important aims. Explaining and predicting the behavior of boron in soils was another object. Boron application methods were also compared. Four field experiments, a series of pot experiments, and some laboratory studies were carried out. The procedures for determining boron in soils and plants by the colorimetric azomethine-H method were also tested and improved.

The coloring agent azomethine-H forms the measurable complex with boric acid in aqueous solutions, and so allows safe and convenient procedures. This method appeared liable to errors caused by turbidity and the yellowish color in the hot water extracts from soils, and the iron in acid extracts from soils. The formation of the measurable complex did not seem to be disturbed, but the interfering substances absorbed light. Thus it was possible to correct the errors by measuring the background absorbances separately, and subtracting them from the total absorbances.

The background absorbances of the hot water extracts from soils decreased by about fifty percent when 0,01 M $CaCl_2$ was substituted for the extractant. This dilute salt solution extracted essentially the same amounts of boron as did the pure water. The background-corrected HWB values appeared reliable when testing mineral soils. However, with organic soils containing low levels of boron the corrections tended to be larger than the residual absorbances from which the test values were calculated, thus the results were less accurate. An evaporating — dry ashing — redissolving procedure was applied for organic soils, and also for the cold extracts which were too dilute for the direct measurement.

No major problems were encountered in determining the concentration of boron from the acid extracts of the dry-ashed plant tissue samples. All vegetative tissues and rapeseeds could be ashed without any base additions, but a significant loss of boron by evaporation was found when cereal grains were ashed without an added base.

The sorption of applied boron was weak by acid coarse-textured soils but increased with increasing pH and fineness of soils. Clay soil sorbed boron rather efficiently even in acid mediums. The sorption increased remarkably with time. The proportions of applied boron (10 mg/l) sorbed against a cold extraction (0,01 M $CaCl_2$ 1:2,5), with 17 soils, ranged from 8 to 48 % after a 20 h contact time, and from 28 to 82 % after an aerobic incubation of 100 d.

The fixation of applied boron in soils was studied by using the standard hot water extraction. During the 5-min refluxing, a significant fixation occurred only in heavily-limed soils but the 100 d incubation caused fixation to also occur in acid soils. The fixation percentages of applied boron in the 17 incubated soils, increased with increasing soil pH and fineness and varied from 1 to 50 %. Still higher percentages were fixed by the soils in long-term pot experiments with smaller rates of applied boron. The hot water extractability of the initial boron in the soils also decreased when the soils were incubated with lime.

Under field conditions, the movement of applied boron varied in different soil types. In heavy clay, it was so slow that even after three years no leaching from the plow layer to the deeper layers was analytically detected. In coarser soils, movement was faster but was retarded by liming. In loamy clay after three years, a considerable part of the large store-dressing but a minor part of the annually applied boron appeared to have leached into the subsurface layer. Even in the fine sand and loam soils, the annually applied boron mainly remained in the plow layer until the autumn of the third experimental year.

In the pot experiment with 30 soils, the uptakes of boron by the turnip rape (in two years) fairly closely correlated with the hot water

extractable boron (HWB) in the soils ($r^2$ = 0,82). When the soil pH values were also entered into the regression equation, a multiple determination ($R^2$) of 0,89 was obtained. The ''cold water method'' (0,01 M $CaCl_2$, 1:5) was less dependent, but together with the pH values it appeared to be quite satisfactory ($R^2$ = 0,79).

The absorption of boron by the turnip rapes grown in pots was drastically retarded by heavy liming, particularly in the seedling stage. The contents of boron in plants usually decreased linearly with increasing soil pH, but less in clay soils than in coarse soils. Similar applications increased the contents of boron in the plants even ten times more in acid sand than in neutral clay. Most of the absorbed boron appeared to have passively flown into the plants via the transpiration stream, and excessive amounts accumulated in the margins or tips of the leaves which are the terminal points of the stream. In pot-grown turnip rape, boron did not move downward from the leaves to the stem. Under field conditions, the boron applied by the placement method increased the contents of boron in the plants much more efficiently than did the broadcast boron.

A moderate deficiency of boron did not appear to affect the uptake of other nutrients by the rape and turnip rape varieties. In some cases the placed boron decreased the content of calcium in the turnip rape leaves. Growth of the oilseed plants was sometimes stunted by a boron deficiency already in the seedling stage. By a severe deficiency with a heavy liming, the plants even died before the cotyledons matured. With a lethal boron deficiency, the tips of the primary roots died first.

Other observed visible symptoms of boron deficiency were: stunted stem elongation; cracking and corky lesions in the stems; yellowing of young leaves by the turnip rape and reddish coloring of leaves by the rape; poor flower and pod development, and prolonged flowering. The symptoms of excess boron were stunted growth and dirty yellowish tint of seedlings, chlorosis and necrosis in margins of older leaves, curved stems and lodging.

Seed set was effectively prevented by an inadequate supply of boron in the pot experiments. When the HWB value of the soil was less than 0,2 to 0,4 mg/l, no seeds developed, although the stems and leaves usually reached almost normal size. The lowest soil HWB values which were, without boron application, sufficient for the maximum seed yields of the turnip rape ranged from 0,45 to 0,65 mg/l in acid soils, and from 0,60 to 0,90 mg/l in heavily-limed soils. The required contents in the turnip rape tissues (in dry matter) were from 18 to 32 ppm in the seedlings, 13 to 17 ppm in the straw, and 22 to 38 ppm in the leaves. The requirements appeared similar in several spring rape and spring turnip rape varieties.

No distinct requirement of boron fertilization was found in the four three-year field experiments, in which the level of soil HWB was 0,62 to 0,97 mg/l. Compared to the less-boronated fertilizers, the NPK fertilizer with 0,2 % B (600—700 kg/ha = 1,2—1,4 kg B/ha) in some cases significantly decreases the seed yields of the turnip rape. The average yield decrease because of this excess of boron was 110 kg/ha or 5 % in the unlimed soils, but absent in the limed soils.

Under field conditions, excessively high rates of boron increased the chlorophyll contents in the rapeseeds. No major effect of boron in the oil content of the rapeseeds was found, and the seed size, protein content, and moisture percentage at harvest were unaffected. In a pot experiment, the seeds of the rape and the turnip rape varieties grew larger in a moderate deficiency state than by a sufficient application of boron. However, the germination percentages of the abnormally large seeds were lower than those with sufficient application.

The common soil boron test, hot water extractable boron, seemed to be the most useful means in estimating the requirements of boron fertilization for the spring oilseed rapes grown under Finnish conditions. Plant analysis appeared to give a slightly more precise estimates on the supply of boron than the soil tests, but too late to apply the required rates into the soil prior to sowing, as is usually done in Finland.

In estimating the requirements for boron fertilization, soil texture and pH as well as the method of application were also taken into account. When boron is applied by the placement method, the most frequent values of the estimate range from 0,2 to 0,4 kg/ha. An excess of 0,5 kg B/ha over the estimate is probably nontoxic. When boron is broadcasted and incorporated into the soils, about two to three times the rates recommended for placement should be applied.

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Into Saarela
Agricultural Research Centre
Department of Agricultural
Chemistry and Physics
SF-31600 Jokioinen, Finland

## SELOSTUS

# Kasveille käyttökelpoinen maan boori ja kevätrypsin ja -rapsin boorin tarve

INTO SAARELA

Maatalouden tutkimuskeskus

Tutkimuksessa selvitettiin kevätrypsin ja -rapsin boorilannoitustarvetta ja sen arviointia maa- ja kasvianalyysien avulla. Tärkeimpinä tavoitteina olivat kasvien riittävien booripitoisuuksien määrittäminen ja kasveille käyttökelpoisen boorin arvioiminen maasta. Maan booritilan kehityksen ennakoimiseksi tutkittiin lisätyn boorin pidättymistä maahan ja liikkumista maaprofiileissa. Tutkimusaineisto käsitti neljä kolmivuotista kenttäkoetta, sarjan astiakokeita ja joitakin laboratoriokokeita. Maa- ja kasvinäytteiden boorimäärityksen eri vaiheita testattiin ja parannettiin.

Boorimäärityksissä käytettiin kolorimetristä azometiini-H-menetelmää, jossa mitattava värillinen boorikompleksi muodostuu vesiliuoksessa ja määritys on siten helppoa ja turvallista. Menetelmä osoittautui alttiiksi maan vesiuutteiden sameuden ja värillisyyden ja maan happouutteiden raudan aiheuttamille virheille. Nämä häiritsevät aineet absorboivat valoa ja aiheuttavat siten liian suuria pitoisuuslukuja. Mitattavan kompleksin muodostuminen ei näyttänyt häiriytyvän, mutta häiritsevät aineet sellaisenaan absorboivat valoa. Positiivinen virhe voidaan siten korjata mittaamalla tausta-absorbanssi erikseen.

Maan kuumavesiuutteiden tausta-absorbanssi väheni suunnilleen puoleen käytettäessä uuttonesteenä 0,01 M $CaCl_2$:a puhtaan veden sijasta. Tämä laimea suolaliuos uutti jokseenkin yhtä paljon booria kuin pelkkä vesi. Vegetatiiviset kasvinäytteet ja öljykasvien siemenet voitiin polttaa boorimääritystä varten sähköuunissa ilman emäslisäystä, mutta viljan jyvistä hävisi poltossa booria ellei emästä lisätty.

Lisätty boori pidättyi happamiin, karkeisiin maihin heikosti, mutta pidättyminen voimistui maan hienouden ja nousevan pH-luvun myötä. Savet pidättivät booria melko tehokkaasti myös happamassa ympäristössä. Pidättyminen eteni hitaasti ajan mukana. Pidättynyt osuus lisätystä boorista (10 mg/l) vaihteli 17 maanäytteellä 8:sta 48:aan %:iin 20 tunnissa ja 28:sta 82:een %:iin sadassa vuorokaudessa. Kuumaan veteen uuttumattomaksi pidättyi sadassa vuorokaudessa 1—50 % lisätystä boorista. Monivuotisissa astiakokeissa pienemmistä boorilisäyksistä pidättyi kuumaan veteen uuttumattomaksi vielä suurempi osuus.

Lisätty boori liikkui aitosavessa niin hitaasti, ettei huuhtoutumista kyntökerroksesta jankkoon kolmen vuoden aikana voitu analyyttisesti osoittaa. Karkeissa maissa boori vajosi veden mukana nopeammin, mutta kalkitus hidasti tätä huuhtoutumista. Suuresta kerta-annoksesta huuhtoutui kolmessa vuodessa suurempi osuus kuin toistuvista vuotuislannoituksista. Suurin osa vuotuislannoituksena annetusta boorista näytti olleen kolmannen koevuoden syksyllä kyntökerroksessa myös hieta- ja hiuemaassa.

Kaksivuotisessa astiakokeessa 30 maalla maan kuumavesiliukoinen boori osoitti rypsin boorin saantia maasta tyydyttävästi (selvitysaste $r^2$ = 0,82). Kun maan booritilan regressioyhtälöön otettiin toiseksi selittäväksi muuttujaksi maan pH-luku, selvitysasteeksi ($R^2$) saatiin 0,89. Laimealla kalsiumkloridilla uuttuva eli "kylmävesiliukoinen" boori ei osoittanut boorin saantia yhtä tarkasti, mutta yhdessä pH-luvun kanssa kuitenkin melko tyydyttävästi ($R^2$ = 0,79).

Boori näyttää kulkeutuvan maasta kasviin pääasiassa passiivisesti haihtumisvirtauksen mukaan. Kasvit eivät voi rajoittaa ylimääräisen boorin kerääntymistä haihtumisvirtauksen päätepisteisiin myrkyllisiksi pitoisuuksiksi. Boori ei juuri siirry lehdistä takaisin varteen. Astiakokeissa kalkitus hidasti rypsin boorinottoa voimakkaasti varsinkin taimivaiheessa. Kalkituksen aiheuttama taimien booripitoisuuden pieneneminen oli lineaarinen maan pH-luvun suurenemisen suhteen. Boorilannoitus suurensi rypsin booripitoisuutta happamalla hiedalla jopa kymmenen kertaa tehokkaammin kuin neutraalilla savella. Kenttäolosuhteissa sijoitettu boori suurensi kasvin booripitoisuutta paljon tehokkaammin kuin hajalevitetty boori.

Boorin puutos hidasti kasvua taimivaiheesta alkaen. Ankarassa puutteessa runsaan kalkituksen yhteydessä astiakokeissa rypsin taimet kuolivat jopa ennen sirkkalehtien kehittymistä täysikokoisiksi. Letaalissa rypsin boorinpuutostaudissa kuoli ensin juuren kärki. Muita havaittuja boorinpuutosoireita olivat hidastunut varsien pituuskasvu, varsien halkeilu ja korkkiutuminen, lehtien kellastuminen rypsillä ja punertuminen rapsilla, kukkien ja litujen heikko kehitys sekä jälkikukinta. Liiallinen boori näkyi taimissa hidastuneena kasvuna ja likaisenkellertävänä värisävynä, vanhemmissa lehdissä reunojen kellastumisena ja kuivettumisena, varsissa rentoutena ja mutkaisuutena sekä lakoontumisena.

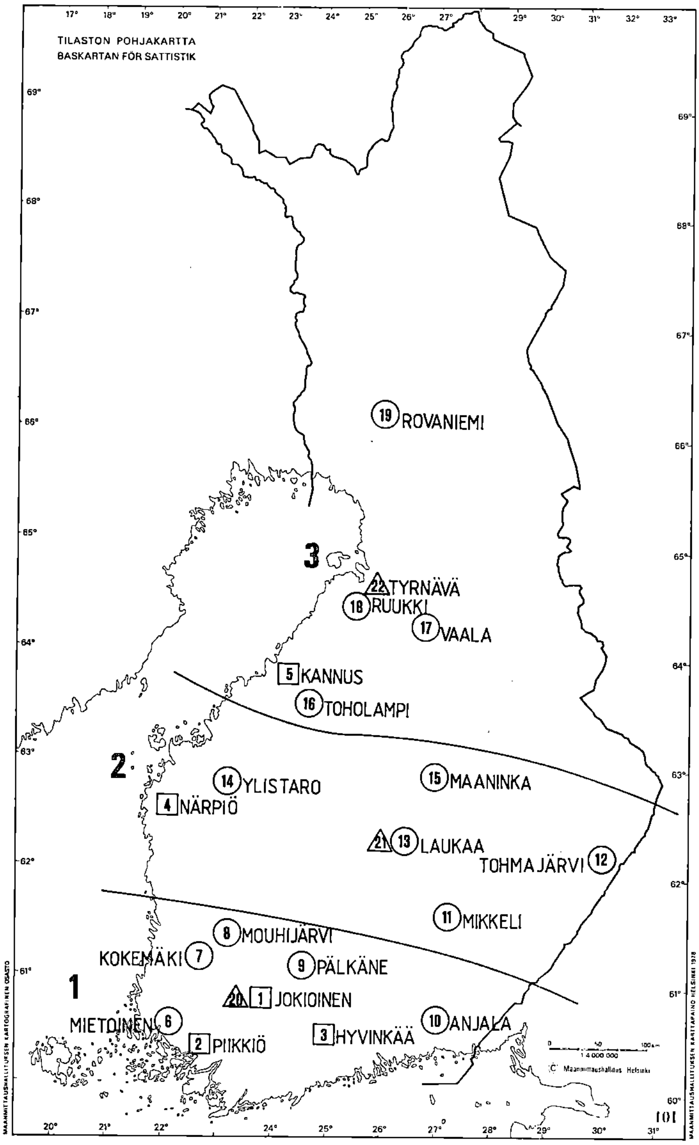
Riittämätön boorin saanti esti siementen muodostumista astiakokeissa voimakkaasti. Maan kuumavesiliukoisen boorin pitoisuuden ollessa alle 0,2—0,4 mg/l, rypsi ei muodostanut siemeniä lainkaan, vaikka varret ja lehdet kasvoivat tavallisesti lähes normaalin kokoisiksi. Täyteen siemensatoon ilman boorilannoitusta tarvittava maan kuumavesiliukoinen boori vaihteli astiakokeissa happamilla mailla välillä 0,45—0,65 mg/l, mutta runsaasti kalkituilla mailla tämä ''puutosraja'' oli korkeammalla, välillä 0,6—0,9 mg/l. Rypsin sisäinen boorintarve milligrammoina kilossa kuiva-ainetta oli taimissa 18—32, varsissa 13—17 ja lehdissä 22—38.

Neljässä kolmivuotisessa kenttäkokeessa, joissa maan kuumavesiliukoinen boori oli välillä 0,62—0,97 mg/l, ei todettu selvää boorilannoitustarvetta. Booripitoinen Y-lannos (0,2 % B, 600—700 kg/ha = 1,2—1,4 kg B/ha) pienensi joissakin tapauksissa rypsin siemensatoa verrattuna vähemmän booria sisältäviin lannoitteisiin. Liiallisen boorin aiheuttama sadonvähennys oli keskimäärin ilman kalkitusta 110 kg/ha eli 5 %, mutta kalkituksen yhteydessä nolla.

Ylimääräinen boori suurensi kenttäkokeissa rypsin siementen klorofyllipitoisuutta. Boorilannoitus ei vaikuttanut kenttäkokeissa merkittävästi siementen öljypitoisuuteen, valkuaispitoisuuteen, kokoon eikä puintikosteuteen. Astiakokeissa rypsi- ja rapsilajikkeiden siemenet kasvoivat kohtalaisessa boorin puutteessa suuremmiksi kuin riittävällä boorilannoituksella kasvatetut siemenet, mutta näiden epänormaalin suurten siementen itävyys oli heikompi.

Boorilannoitustarpeen arvioinnin perustaksi näyttää soveltuvan Suomen olosuhteissa parhaiten maa-analyysi, jonka tulos on käytettävissä ennen kylvöä. Tulosten perusteella arvioitu kevätrypsin ja -rapsin boorin tarve sijoituslannoituksessa kiloina hehtaarille on happamilla mailla 0,6 vähennettynä, savimailla 0,5 kertaa ja muilla mailla 0,67 kertaa maan kuumavesiliukoisen boorin luvulla (mg/l). Maan pH-luvun ($CaCl_2$) ylittäessä 6,0 ($pH_{H_2O}$ 6,6) kuumavesiliukoisesta boorista tulisi vähentää 0,1 yksikköä 0,3 ylittävää pH-yksikköä kohti. Yleisimmällä Suomen peltojen nykyisellä booritasolla kevätöljykasvien boorilannoitustarve on sijoituslannoituksessa tämän arvion mukaan 0,2—0,4 kg/ha. Arvioitu tarve voitaneen haitatta ylittää noin puolella kilolla hehtaaria kohti. Kun boori levitetään ja mullataan äestäen, sitä tarvittaneen noin 2—3 kertaa niin paljon kuin sijoituslannoituksessa.

# CONTENTS



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