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Chapter 9

The occurrence and correction of boron deficiency

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Abstract

Positive responses to B application, which provide clear evidence of B deficiency, have been reported in over 80 countries and on 132 crops over the last 60 years. It is estimated that about 15 million ha are annually treated with B. In a few regions in the world, B deficient soils exist over a wide area, as for example in eastern and southern China. Elsewhere B deficiency is restricted to particular soil types and crops. Acrisols and Podzols and to a much lesser extent Andosols, Luvisols and Ferralsols, appear to be the soil groups most likely to produce B deficient crops. Soil parent material and texture are considered to be the major soil factors associated with the occurrence of B deficiency. For many crops it is the B requirement for successful fertilisation that is of critical importance; even crops with a small B requirement, such as the cereals, can suffer impaired seed set due to B shortage at a critical time. Climate, particularly high light intensity and low temperature are factors that need to be considered in relation to the occurrence of B deficiency. Boron deficiency can be readily prevented and corrected by both soil and foliar applications. Most reliance is placed on refined sodium borates, but crushed ores are used both in the manufacture of boronated fertilisers and on their own. Depending on the ore, its particle size and method of application, B supply may be extended by using an ore which dissolves slowly.

Introduction

Unequivocal proof that B is an essential micronutrient was provided by Warington (1923) who showed not only that field bean (*Vicia faba*) died when B was not supplied in the nutrient solution but that B was needed for revival. However before Warington, there had been several studies – notably by Agulhon (1910a, 1910b) and Maze (1915) in France showing beneficial effects of B on plant growth. Agulhon (1910a, 1910b) provided the first documented evidence of the occurrence of B deficiency by demonstrating that B stimulated growth of oilseed rape (*Brassica napus* var. *oleifera*), turnip (*B. rapa*) and maize (*Zea mays*) in a field trial and of oat (*Avena sativa*), radish (*Raphanus sativus*), and wheat (*Triticum aestivum*) in a sand culture experiment but he did not prove that normal growth was impossible in the absence of B.

Maze (1915) presented data to show that B (together with aluminium, fluorine and iodine) was needed for the best growth of maize in nutrient solution but he did not prove essentiality. Indeed, none of the reports before Warington (1923), satisfied the conditions of essentiality that were subsequently laid down by Arnon and Stout (1939); even the Warington study did not show that the role of B could not be replaced by another element or that B was directly involved in plant metabolism.

Occurrence of boron deficiency

Boron deficiency in crops may be suspected on the basis of symptoms and by plant analysis, and anticipated by soil analysis (Bell, Chapter 10). In this review neither symptoms nor soil or plant analyses have been used as a basis in compiling the lists of crop/country situations in which B deficiency occurs. All the crops/countries listed in Tables 1, 2, 3 and 4 are based on reported positive responses to B application in the field over the last 50 years. References for the majority of the approximately 500 listed responses can be found in the abstract bulletins, Boron in Agriculture (first series 1948–1979, second series 1980-1989) and Micronutrient News and Information (1990–1996). The use of soil B analysis to assess soil B status

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Table 1. Europe: occurrence of boron deficiency based on responses

		Country*
Allium ampeloprasum	Leek	De
A. cepa	Onion	Fr
Apium graveolens var. *dulce*	Celery	Be, Ei, Fr, Gd, Ho, Uk
A. graveolens var. *rapaceum*	Celeriac	Ho
Avena sativa	Oats	Fi
Beta vulgaris	Sugar beet	Ab, As, Be, Bg, Cz, De, Ei, Fi, Fr, Gd, Gr, Ho, Hu, It, Po, Ru, Se, Sp, Si, Tk, Uk, Ur, Yu
B. vulgaris	Red beet	Gd, Fr, Uk, Ur
Betula spp.	Birch	No
Brassica napus	Oilseed rape	Cz, De, Ei, Fi, Fr, Gd, Hu, Po, Se, Uk
B. oleracea var. *botrytis*	Cauliflower	Be, Ei, Fi, Gd, No, Uk
B. oleracea var. *capitata*	Cabbage	Be, Cz, Fi, Gd, Ur, Uk
B. rapa	Turnip	Be, Ei, Gd, Uk
B. rutabaga	Swede	De, Ei, Fi, Gd, Ho, Se, Uk, Ur
Camellia sinensis	Tea	Ur
Chrysanthemum spp.	Chrysanthemum	Uk
Citrus spp.	Citrus	Sp, Ur
Cucumis sativus	Cucumber	Bg, Fi, Uk
Daucus carota var. *sativa*	Carrot	Be, De, Gd, Fi, Ho, Po, Uk, Ur
Dianthus caryophyllus	Carnation	Uk
Fragaria spp.	Strawberry	Be, Fr, Sp, Ur
Glycine max	Soybean	Ur
Gossypium hirsutum	Cotton	Bg, Sp, Ur
Helianthus annuus	Sunflower	Bg, Cz, Fr, Hu, Ru, Sp, Yu
Hordeum vulgare	Barley	Fi, Ur
Humulus lupulus	Hop	Be, Cz, It, Ur
Lactuca sativa	Lettuce	Fr, Uk
Lavandula spp.	Lavender	Bg
Linum usitatissimum	Flax	Ur
Lycopersicon esculentum	Tomato	Ei, Fr, Ho, No, Uk, Ur
Malus domestica	Apple	As, Be, Bg, Fi, Fr, Gd, Ho, Hu, It, No, Po, Pr, Sp, Uk, Ur, Yu
Medicago sativa	Lucerne	Be, Bg, Cz, Fr, Gd, Ho, Hu, Sa, Ur, Uk
Nicotiana tabaccum	Tobacco	Bg, Sp, Ur
Olea europaea	Olive	Gr, It, Pr, Sp, Tk, Yu
Onobrychis viciifolia	Sainfoin	Bg
Oryza sativa	Rice	Ur
Panicum miliaceum	Millet	Ur
Papava somniferum	Poppy	Cz, Gd, Po
Phaseolus vulgaris	Bean, french	Fr
Picea abies	Norway spruce	Fi, Gd, No, Se
Pinus spp.	Pines	Fi, No, Se, Tk, Ur
Pisum sativum	Pea	Ur
Prunus armeniaca	Apricot	Cz, Ur
P. cerasus	Cherry	Fr, Ur
P. domestica	Plum	Hu
Pyrus communis	Pear	As, Bg, Fr, Gd, Pr, Sp, Yu
Raphanus sativus	Radish	Fr, Po, Uk
Solanum tuberosum	Potato	Be, Cz, Fi, Gd, Hu, Se, Ur
Trifolium spp.	Clovers	Cz, Fi, No, Ru, Se, Ur
Triticum spp.	Wheat	Bg, Fi, Se, Ur, Yu
Tulipa spp.	Tulip	Ho
Vicia faba	Bean, field	Po, Sp, Uk
Vitis vinifera	Grape	As, Bg, Cz, Fr, Gd, Hu, It, Pr, Ru, Sp, Si, Ur, Yu
Zea mays	Maize	Bg, Fr, Ho, Po, Si, Ur, Yu

*Countries: Ab, Albania. As, Austria. Be, Belgium. Bg, Bulgaria. Cz, Czechoslovakia. De, Denmark. Ei, Ireland. Fi, Finland. Fr, France. Gd, Germany. Gr, Greece. Ho, Netherlands. Hu, Hungary. It, Italy. No, Norway. Po, Poland. Pr, Portugal. Ru, Romania. Sa, Saudi Arabia. Se, Sweden. Si, Switzerland. Sp, Spain. Tk, Turkey. Ur, USSR. Uk, United Kingdom. Yu, Yugoslavia.

Table 2. Australasia: occurrence of boron deficiency based on responses

		Country*
Allium cepa	Onion	In
A. sativum	Garlic	Id, In, Th
Ananas comosus	Pineapple	Au, Ch, Ta
Apium graveolens var. *dulce*	Celery	Ch, Jp, Nz
Arachis hypogaea	Groundnut	Ch, In, Ko, Th
Beta vulgaris	Sugar beet	Ch, Ir, Jp, Ko, In
B. vulgaris	Red beet	Au, Nz
Boehmeria nivea	Ramie	Ch
Brassica chinensis	Chinese cabbage	Ch, Jp, Ko, Ta
B. juncea	Mustard	In, Pk
B. napus	Oilseed rape	Au, Ch, In, Jp, Pk
B. oleracea var. *acephala*	Kale	Nz
B. oleracea var. *botrytis*	Cauliflower	In, Jp, Ko, Nz, Ta
B. oleracea var. *capitata*	Cabbage	Ch, In, Ko, Nz, Pg
B. rapa	Turnip	Au, Nz
B. rutabaga	Swede	Au, Nz
Cajanus cajan	Pigeon pea	In
Camellia sinensis	Tea	Ch, In, Pg, Sr
Carica papaya	Pawpaw	Au, In, Ms, Pg, Ta
Carthamus tinctorius	Safflower	In
Casuarina spp.	Casuarinas	Ch, Pg
Castanea spp.	Chestnut	Ko
Cicer arietinum	Chick pea	In
Citrullus lanatus	Water melon	In
Citrus spp.	Citrus	Ch, In, Jp, Ta
Cocos nucifera	Coconut	Id, In, Ph, Sr
Coffea spp.	Coffee	Ms, Pg
Cucumis melo	Melon	In
C. sativus	Cucumber	In
Dimocarpus longan	Longan	Ch
Elaeis guineensis	Oil palm	Id, Ms, Th
Eleusine coracana	Finger millet	In
Eucalyptus spp.	Eucalypt	Ch, Pg
Glycine max	Soybean	Ch, In, Ko, Th
Gossypium hirsutum	Cotton	Ch, In, Pk
Grevillea robusta	Grevillea	Sr
Helianthus annuus	Sunflower	Ch, In, Th
Hibiscus cannabinus	Kenaf	Ch
Hordeum vulgare	Barley	Ch, Ko
Humulus lupulus	Hop	Nz
Ipomoea batatas	Sweet potato	In, Pg
Lactuca sativa	Lettuce	Ko
Lens culinaris	Lentil	In
Linum usitatissimum	Flax	In
Litchi chinensis	Litchi	Ch, In
Lycopersicon esculentum	Tomato	Ch, In, Pg
Macadamia spp.	Macadamia	Au
Malus domestica	Apple	Au, Ch, In, Jp, Ko, Nz, Th, Ta
Mangifera indica	Mango	Au, Ch, In, Ta
Manihot esculenta	Cassava	In
Medicago sativa	Lucerne	Au, In, Ko, Nz
Mentha arvensis	Mint	In
Morus nigra	Mulberry	Ch, Ko
Musa spp.	Banana	Au, Ch
Nicotiana tabaccum	Tobacco	Ch, Id, Jp, Ko, Nz, Sr, Th

Table 2. Continued.

		Country*
Olea europaea	Olive	Ch
Oryza sativa	Rice	Ch, In, Jp
Pachyrhizus erosus	Yam bean	In
Papaver somniferum	Poppy	Au, In
Persea americana	Avocado	Au
Phaseolus vulgaris	Bean, french	In, Jp
Physalis peruviana	Cape gooseberry	Pg
Pinus spp.	Pines	Au, Ch, Nz, Pg, Ph, Vt
Pisum sativum	Pea	In
Prunus armeniaca	Apricot	Ch
P. cerasus	Cherry	Nz
P. domestica	Plum	Nz
P. persica	Peach	Ch, In, Ko, Nz
Punica granatum	Pomegranate	In
Pyrus communis	Pear	Ch, In, Ko, Nz
Psidium spp.	Guava	In, Jp, Sr
Raphanus sativus	Radish	In
R. sativus longipinnatus	Japanese radish	In, Jp
Ricinus communis	Castor oil	In
Rubus idaeus	Raspberry	Nz
Saccharum officinarum	Sugar cane	Ch, Id, In
Sesame indicum	Sesame	Ch, In
Sinapis alba	Mustard	In
Solanum melongena	Aubergine	In
S. tuberosum	Potato	Au, Ch, In
Sorghum vulgare	Sorghum	In, Pk
Trifolium spp.	Clovers	Au, Ch, In, Nz
T. subterraneum	Sub. clover	Au
Triticum spp.	Wheat	Bn, Ch, In, Ne, Pk, Th
Tulipa spp.	Tulip	Jp
Vicia faba	Bean, field	Ch
Vigna mungo	Gram, black	In, Th
V. radiata	Gram, green	In, Th, Ch
Vitis vinifera	Grape	Au, Ch, In, Jp, Ko, Nz
Zea mays	Maize	Ch, In, Ko, Pk
Zingiber officinale	Ginger	In
Ziziphus mauritiana	Ber	In

∗ Countries: Au, Australia. Bn, Bangladesh. Ch, China. Id, Indonesia. In, India. Ir, Iran. Jp, Japan. Ko, Korea. Ms, Malaysia. Np, Nepal. Nz, New Zealand. Pk, Pakistan. Ph, Philippines. Pg, Papua New Guinea. Sr, Sri Lanka. Ta, Taiwan. Th, Thailand. Vt, Vietnam.

and the linking of soil mapping units to the regional occurrence of B deficiency will be considered separately.

History of responses to boron application

The crops and countries where B deficiency was first identified by field experiments in the period 1920 to 1946 are listed in Table 5. Further details of the early work can be found in Anon. (1935, 1936), Dennis (1937, 1947/1948), Dennis and Dennis (1939,

Table 3. North and South America: occurrence of boron deficiency based on response

		Country*
Acer spp.	Maple	Cn
Aleurites spp.	Tung	Us
Allium ampeloprasum	Leek	Us
A. cepa	Onion	Bz
A. sativum	Garlic	Bz, Co
Ananas comosus	Pineapple	Us
Apium graveolens var. dulce	Celery	Us
Arachis hypogaea	Groundnut	Us
Asparagus officinalis	Aparagus	Cn, Us
Beta vulgaris	Sugar beet	Ci, Us
B. vulgaris	Red beet	Cn, Us
Brassica napus	Oilseed rape	Cn, Us
B. oleracea var. *botrytis*	Cauliflower	Bz, Cn, Us
B. oleracea var. *capitata*	Cabbage	Bz, Us
B. rutabaga	Swede	Cn, Us
Carica papaya	Pawpaw	Bz, Pe, Pu
Citrus spp.	Citrus	Bz, Co, Us
Citrullus lanatus	Water melon	Us
Cocos nucifera	Coconut	Mx
Coffea spp.	Coffee	Bz, Co, Cr, Ec, Pu
Coryllus spp.	Hazel	Us
Cucumis melo	Melon	Us
C. sativus	Cucumber	Bz, Us
Cynodon dactylon	Bermuda grass	Us
Daucus carota var. *sativa*	Carrot	Cn, Us
Elaeis guineensis	Oil palm	Co, Ec
Eucalyptus spp.	Eucalypt	Bz, Co, Ci
Fragaria spp.	Strawberry	Cn, Us
Ficus carica	Fig	Us
Glycine max	Soybean	Bz, Us, Ve
Gossypium hirsutum	Cotton	Bz, Us
Helianthus annuus	Sunflower	Ar, Bz
Hordeum vulgare	Barley	Cn
Ipomoea batatas	Sweet potato	Us
Juglans regia	Walnut	Us
Lactuca sativa	Lettuce	Us
Lycopersicon esculentum	Tomato	Bz, Co, Us
Malus domestica	Apple	Ci, Cn, Us
Manihot esculenta	Cassava	Bz
Medicago sativa	Lucerne	Ar, Ec, Cn, Co, Us
Musa spp.	Banana	Ec, Pu
Nicotiana tabaccum	Tobacco	Us
Olea europaea	Olive	Us
Oryza sativa	Rice	Bz, Co, Ec
Persea americana	Avocado	Us
Phaseolus vulgaris	Bean, French	Bz, Cn, Co, Us
Pinus spp.	Pines	Bz, Ci, Cn, Co
Pisum sativum	Pea	Cn, Us
Prunus amygdalus	Almond	Us

Table 3. Continued.

		Country*
P. armeniaca	Apricot	Cn, Us
P. cerasus	Cherry	Us
P. domestica	Plum	Us
P. persica	Peach	Us
Pseudotsuga menziensii	Douglas fir	Cn
Pyrus communis	Pear	Cn, Ci, Mx, Us
Raphanus sativus	Radish	Us
Rheum spp.	Rhubarb	Us
Rubus idaeus	Raspberry	Cn
Saccharum officinarum	Sugar cane	Bz, Co
Sesamum indicum	Sesame	Ve
Solanum melongena	Aubergine	Us
S. tuberosum	Potato	Bz, Co, Us
Sorghum vulgare	Sorghum	Bz, Co
Spinacia oleracea	Spinach	Us
Theobroma cacao	Cocoa	Bz, Co, Ec
Trifolium spp.	Clovers	Cn, Us
T. incarnatum	Crimson clover	Us
Triticum spp.	Wheat	Bz, Us
Vaccinium corymbosum	Blueberry	Us
Vitis vinifera	Grape	Bz, Ci, Co, Us
Vicia faba	Bean, field	Bz
Zea mays	Maize	Co, Us

* Countries: Ar, Argentina. Bz, Brazil. Cn, Canada. Ci, Chile. Co, Colombia. Cr, Costa Rica. Ec, Ecuador. Mx, Mexico. Pe, Peru. Pu, Puerto Rico. Us, United States. Ve, Venezuela.

1940/1941, 1943) and Dennis and O'Brien (1937). The first demonstration of a field response to the application of B in the USA came from experiments designed to assess crop tolerance to large amounts of borax, which were reported in the period 1920-1922, before it was known that B was essential. Although application of 2–10 kg borax ha^{-1} improved the yields of potato (*Solanum tuberosum*) and French bean (*Phaseolus vulgaris*), no attention was paid to the results as all interest was on toxicity. The toxicity studies were required because of the toxic effects of the borax-rich potash supplied to American farmers during the 1914-1918 war, when supplies of potash from the German beds were stopped. The potash, from the brine of Searles lake in California, could contain large and varying amounts (22–57%) of borax decahydrate. None of the borax-rich potash was shipped to Europe, and it is doubtful whether the American borax scare delayed the field studies on B nutrition outside the USA.

Beta vulgaris

Brandenburg (1931), in Germany, is usually credited with being the first to report on the occurrence and correction in the field of B deficiency but it is likely that experiments had been carried out earlier in Finland in 1928 even though they were reported much later (Kiviniemi, 1946). By 1935, several reports on the correction of heart rot in beet (*Beta vulgaris*) by soil application of borax had been presented in Germany and studies on beet in most European countries quickly followed. It is chastening to learn that the early workers quickly recognised that B deficiency was more likely to develop on limed land, that it was exacerbated by drought, and was worse on freely-draining sandy or gravelly soils.

Brassica rutabaga *and* B. rapa

The Brandenburg work stimulated studies on swede (*B. rutabaga*) and turnip in Canada, Finland and Wales over the period 1932–1934, which demonstrated that the brown heart symptoms that had been described

Table 4. Africa: occurrence of boron deficiency based on responses

		Country*
Acacia spp.	Wattle	Tz, Zi, Zm
Agave sisalana	Sisal	Tz
Apium graveolens var. *dulce*	Celery	Zi
Arachis hypogaea	Groundnut	Mg, Mw, Ng, Sf
Beta vulgaris	Sugar beet	Eg, Mo
Brassica rapa	Turnip	Zi
B. oleracea var. *botrytis*	Cauliflower	Mw, Zm
B. oleracea var. *capitata*	Cabbage	Zi
Camellia sinensis	Tea	Mw
Citrus spp.	Citrus	Sf, Zi
Cocos nucifera	Coconut	Iv, Mg
Coffea spp.	Coffee	Cg, Ke, Mg, Tz
Cola nitida	Kola	Ng
Cucumis melo	Melon	Sf
Elaeis guineensis	Oil palm	Ca, Cg, Iv, Mg, Ng, Za
Eucalyptus spp.	Eucalypt	Mw, Ng, Tz, Uv, Zm, Zi
Gossypium hirsutum	Cotton	An, Bb, Bt, Ca, Cd, Cr, Mg, Mw, Mz, Ng, Sg, Tz, Uv, Zi, Zm
Grevillea robusta	Grevillea	Ke
Helianthus annuus	Sunflower	Sf, Zm
Lycopersicon esculentum	Tomato	Eg
Malus domestica	Apple	Eg, Sf
Mangifera indica	Mango	Sf
Medicago sativa	Lucerne	Eg
Musa spp.	Banana	Iv, Sf
Nicotiana tabaccum	Tobacco	Mg, Mw, Sf, Tz, Zi, Zm
Parthenium argentatum	Guayule	Sf
Persea americana	Avocado	Sf
Pinus spp.	Pines	Ke, Mw, Tz, Zm
Prunus persica	Peach	Sf
Pyrus communis	Pear	Eg, Sf
Solanum tuberosum	Potato	Eg, Sf
Stylosanthes hamata	Stylosanthes	Ng
Theobroma cacao	Cocoa	Gh, Iv, Ng
Triticum spp.	Wheat	Mg, Sf, Tz, Zm
Vitis vinifera	Grape	Sf, Tu
Zea mays	Maize	Bt, Ng, Sf, Zi, Zm

*Countries: Al, Algeria. An, Angola. Bb, Benin. Bt, Botswana. Ca, Cameroon. Cd, Chad. Cg, Congo. Cr, Central African Republic. Eg, Egypt. Gh, Ghana. Iv, Ivory Coast. Ke, Kenya. Mg, Madagascar. Mw, Malawi. Mo, Morocco. Mz, Mozambique. Ng, Nigeria. Sg, Senegal. Sf, South Africa. Tu, Tunisia, Tz, Tanzania. Uv, Burkina Faso. Za, Zaire. Zm, Zambia. Zi, Zimbabwe.

some 20 years before were caused by a shortage of B. The same symptoms were also found, at about the same time in other countries, including New Zealand, Denmark and Ireland.

Crops

Boron deficiency has been reported in the field on at least 132 crops, and in 80 countries (Tables 1, 2, 3 and 4). Crop species undoubtedly plays a major part in determining whether B deficiency is a problem or not, even to the extent of obscuring soil differences in B supplying capacity. For example, beet suffers from B

Table 5. First reports of the field occurrence of boron deficiency. Based on positive responses to application of B

	Country*	
1910	Fr	Oilseed rape (*Brassica napus*), turnip (*B. rapa*), maize (*Zea mays*)
1920-1922	Us	Potato (*Solanum tuberosum*), French bean, (*Phaseolus vulgaris)*
1930	Id	Tobacco (*Nicotiana tabaccum*)
1931-1932	Gd	Fodder and sugar beet (*Beta vulgaris*)
1933-1938	Be, Cz, De, Ei, Fr, Gd, Ho, Hu, Po, Se, Si, Us, Uk	Mainly sugar beet (*B. vulgaris*)
1935-1937	Cn, De, Ei, Fi, No, Nz, Uk	Swede (*Brassica rutabaga*), turnip (*B. rapa*)
	Au, Cn, Fi, Nz, Us	Apple (*Malus domestica*)
	Us	Red beet (*Beta vulgaris*), cauliflower (*Brassica oleracea* var. *botrytis*), cabbage (*B. oleracea* v. *capitata*), carrot (*Daucus carota*), cotton (*Gossypium hirsutum*), tobacco (*Nicotiana tabaccum*)
	Zi	Orange (*Citrus* spp.)
	Ur	Flax (*Linum usitatissimum*)
	Cn, Nz	Apricot (*Prunus armeniaca*)
	Jp	Grape (*Vitis vinifera*)
	Fr, Gd, Uk	Potato (*Solanum tuberosum*)
	Cn, Us	Lucerne (*Medicago sativa*)
	Ho, Us	Celery (*Apium graveolens* var. *dulce*)
1939-1946	Us	Strawberry (*Fragaria* spp.), walnut (*Juglans regia*), olive (*Olea europaea*), red clover (*Trifolium pratense*)
	No	Barley (*Hordeum vulgare*)
	Cn	Cherry (*Prunus cerasus*)
	Au	Pear (*Pyrus communis*)
	Zi	Wheat (*Triticum* spp.)

*Countries: Au, Australia. Be, Belgium. Cn, Canada. Cz, Czechoslovakia. De, Denmark. Ei, Ireland. Fi, Finland. Fr, France. Gd, Germany. Ho, Netherlands. Hu, Hungary. Id, Indonesia. Jp, Japan. No, Norway. Nz, New Zealand. Po, Poland. Se, Sweden. Si, Switzerland. Uk, United Kingdom. Ur, USSR. Us, United States. Zi, Zimbabwe.

deficiency in nearly all countries in which it is grown, likewise lucerne (*Medicago sativa*) responds to B in over 40 states in the USA; neither crop is thus a good indicator of regional or soil differences that might be linked to B deficiency.

Crops can be rated, albeit somewhat subjectively, according to the likelihood with which they are expected to suffer from B deficiency; the crops which are most susceptible to B deficiency and which are those most responsive to B application are listed in Table 6. The validity of such a table can be questioned in view of the likely, but as yet largely unexamined, genotypic variation in the ability of cultivars of a given species to obtain and utilise B (Rerkasem and Jamjod, Chapter 11). However, the rating of crops on a sensitivity scale has been of benefit, for example in helping to set priorities for crops to study. At the practical level, a B response on a crop in the tolerant group would suggest that B responses and symptoms would be expected on crops in the sensitive group.

Plant families

Except perhaps for the Rosidae, consideration of the likely incidence of B deficiency amongst flowering plants according to taxonomic relationships reveals nothing significant. Six subclasses, 13 orders and 14 families are represented by the 16 crops in Table 6. The large subclass Rosidae is represented by seven crops in Table 6, however, no single subclass or order of plants is distinguishable as being either sensitive or tolerant to B deficiency. However, at the family level and below some differences with respect to B appear.

Among the monocotyledons, the Gramineae appear to have the lowest B requirement, due to the fact that primary cell walls of this family contain very little of the B-complexing pectin (Matoh, Chapter 5). Onion (*Allium cepa*) and asparagus (*Asparagus officinalis*) of the Liliaceae, however are pectin-rich and have high B requirements similar to, if not higher than, some of the dicotyledons. It is thus important not to think that all monocots have low B requirements as is also evidenced

Table 6. Species most sensitive to boron deficiency and most responsive to B application

Apium graveolens var. *dulce*	Celery	*Eucalyptus* spp.	Eucalypts
Arachis hypogaea	Groundnut	*Gossypium* spp.	Cotton
Beta vulgaris	Sugar beet	*Helianthus annuus*	Sunflower
Brassica spp.	Brassica	*Malus domestica*	Apple
B. rutabaga	Swede	*Medicago sativa*	Lucerne
Coffea spp.	Coffee	*Olea europaea*	Olive
Daucus carota	Carrot	*Pinus* spp.	Pines
Elaeis guineensis	Oil palm	*Vitis vinifera*	Grape

by two members of the Palmae, namely coconut (*Cocos nucifera*) and oil palm (*Elaeis guineensi*).

Amongst the dicotyledons, only two families are notable with respect to sensitivity to B deficiency, namely the Cruciferae and Chenopodiaceae. The common occurrence of B deficiency on members of the Cruciferae (*Brassica* spp. and *Raphanus* spp.) and on *Beta* spp. of the Chenopodiaceae has been recognised for over 60 years. It is likely, in the case of the Chenopodiaceae that it was the evolution of the wild sea beet (*Beta vulgaris*) under saline, B rich conditions, that resulted in the selected derivatives (sugar beet, fodder beet) having relatively high B requirements. Unfortunately, there is little opportunity to extend this hypothesis to other crop plants, as only two other members of the family are grown for human consumption, namely spinach (*Spinacia oleracea*) and quinoa (*Chenopodium quinoa*).

Soils

Soil B analysis has frequently been used to assess the B supplying capacity of soils for particular crops but there are only a few instances where sufficient data has been collected to permit soil B maps to be drawn; notable exceptions are the maps prepared by Liu Zheng et al. (1980, 1989) in China, by Bergmann et al. (1968) in the former East Germany and by Kurki (1982) in Finland.

Considerable, but locally limited data, is available to allow associations to be made between soil conditions, soil B analysis and the occurrence of B deficiency. In this section links will be attempted, using the FAO/UNESCO (1978) mapping units as being the only ones for which global maps are available.

Soil analysis and crop responses

A useful global assessment was made by Sillanpaa (1982) of soil micronutrient status by means of centralised analysis (a) of soils from 30 countries and (b) of wheat grown on these soils under identical conditions in Finland. Eight years later Sillanpaa (1990) reported on field experiments in 14 participating countries designed to assess the need for micronutrients on the main food crops [rice (*Oryza sativa*), wheat and maize].

Even though the crops used are not particularly responsive to B, responses were shown in 11 of the 14 countries (Table 7) where field trials were carried out (Sillanpaa, 1990). Acute B deficiency was rated in 10% of all trials and a latent B deficiency in a further 21%. The fact that B responses were found in trials in countries where the national mean B concentrations are undoubtedly high, is a further indication of the danger of attempting to generalise on a country or regional basis from a limited database.

Inevitably in a study of this kind, there is the problem of obtaining sufficient samples to typify any given country, but with this limitation in mind it is possible to rate countries according to the average national soil B concentrations (hot water soluble); the values extracted in Table 7 should be viewed as indications of the likely average situation on the selected cultivated soils and should be modified in the light of local field knowledge on the occurrence of B deficiency.

Sillanpaa (1982) concluded that B deficiency would be possible on crops at some locations in almost every country but the likelihood of deficiency was greater in several countries in the Far East notably, India, Korea, Nepal, Philippines and Thailand and also in Africa particularly Malawi, Nigeria, Sierra Leone and Zambia. On the other hand, B toxicity was most likely in Iraq, Mexico, Pakistan and Turkey particularly at irrigated

Table 7. National mean boron concentrations (Sillanpaa, 1982)

Country	Response to B	Sample size	Hot water soluble B (mg L^{-1})
Nepal	+	35	0.19
Zambia	–	44	0.25
Nigeria		153	0.27
Philippines	+	194	0.28
Malawi	+	97	0.29
Sri Lanka	+	18	0.32
Korea		90	0.37
Sierre Leone	–	48	0.39
Thailand	–	150	0.42
India		128	0.42
Belgium		36	0.52
Lebanon		16	0.54
Ethiopia	+	125	0.54
Finland	+	90	0.55
Ghana		93	0.57
Brazil		158	0.63
Peru		68	0.65
Pakistan	+	237	0.68
Tanzania	+	163	0.78
Argentina		208	0.74
New Zealand		35	0.76
Italy		170	0.82
Egypt		198	0.93
Hungary		201	1.02
Syria		38	1.08
Turkey	+	298	1.10
Malta		25	1.14
Mexico	+	142	1.26
Iraq	+	150	1.51

+ Positive responses to B application.
– No response to B (Sillanpaa, 1990).

sites. These are not comprehensive lists as the majority of countries did not participate in the study.

Soil groups

The limited data presented by Sillanpaa (1982) permits an initial examination of the link between soil B levels and soil groups. In Table 8 the soil groups have been listed in ascending order of soil B concentration. A few features emerge.

Soils with low B concentrations include: strongly weathered soils (Acrisols, Podzols, Ferralsols); coarse textured soils (Arenosols); shallow soils (Lithosols); thin soils over calcareous material (Rendzinas); and volcanic ash soils (Andosols).

Not unexpectedly it was the strongly weathered and coarse textured soils that contained the least available B. Whether B deficiency can be linked to any one soil unit is discussed below.

Global assessment of boron deficient areas

There are only a few regions in the world where B deficiency occurs sufficiently frequently on crops to permit relatively large areas to be mapped on a world scale. These areas are roughly identified in Figure 1 and listed in Table 9, together with the principle soil groups. Elsewhere, B deficiency exists on relatively small areas and is more dependent on local conditions and crops; this makes it impossible in the absence of

Table 8. Mean hot water soluble boron concentration (corrected for variation in CEC) for FAO/UNESCO soil groups (Sillanpaa, 1982). USDA Soil Taxonomy equivalents are shown in parentheses.

Mean hot water soluble B (mg L^{-1})	Sample size	Soil group
0.5–0.6	48	Rendzina (Rendoll)
	73	Acrisol (Ultisol)*
	22	Arenosol (Psamment)*
	8	Andosol (Andept)
	31	Gleysol (Aquic)**
	27	Podzol (Spodosol)
	135	Vertisol (Vertisol)
	23	Lithosol (Lithic)***
	127	Ferralsol (Oxisol)
0.6–1.0	106	Nitosol (some Ultisols and Alfisols)
	217	Luvisol (Alfisol)*
	246	Cambisol (Inceptisol)
	7	Histosol (Histosol)
	307	Phaeozem (Udoll)
	64	Kastanozem (Ustoll)
	48	Chernozem (Boroll)
	11	Planosol (−)
	470	Fluvisol (Fluvent)
1.0–2.0	42	Regosol (Orthent, Psamment)
	101	Xerosol (Aridisol)*
	92	Yermosol (Aridisol)*
	60	Halosol (−)

*partial correspondence; **corresponds to aquic subgroups of various Great groups; ***corresponds to lithic subgroups of various Great groups.

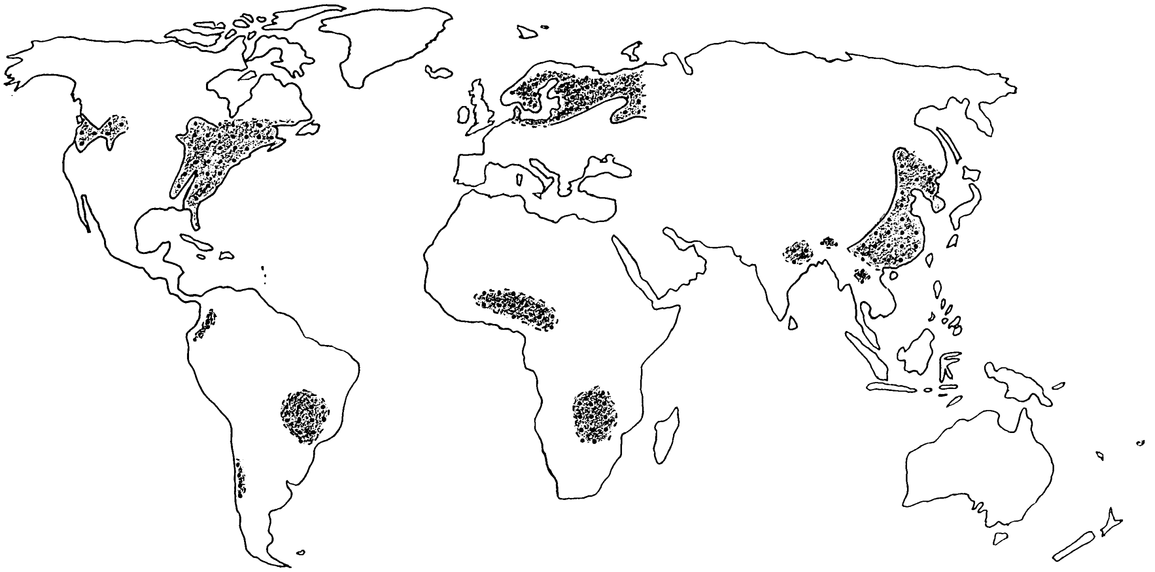

Figure 1. Boron deficient areas. Areas identified on the basis of crop responses to boron and by soil B analysis. Solid lines indicate that boundaries have a firmer basis.

Table 9. Main FAO/UNESCO soil groups in principal boron deficiency areas. USDA Soil Taxonomy equivalents are shown in parentheses

		Soil group
Asia	China, south of Yangtze	Acrisols (Ultisols*)
	China, north of Yangtze	Lithosols/Cambisols (Lithic Inceptisols)
	China, north east	Lithosols/Luvisols (Lithic Fluvents)
	Korea	Lithosols/Cambisols (Lithic Inceptisols)
		Acrisols (Ultisols*)
		Cambisols (Inceptisols)
	Thailand, north west	Acrisols (Ultisols*)
	India, north east	Acrisols (Ultisols*)
		Luvisols (Alfisols*)
West Africa	Nigeria and Benin	Arenosols (Psamments*)
		Luvisols (Alfisols*)
	Ivory Coast	Acrisols (Ultisols*)
	Chad	Arenosols (Psamments*)
Central Africa	Zambia, Zimbabwe, Malawi	Luvisols (Alfisols*)
		Ferralsols (Oxisols)
Scandinavia and North Europe	Denmark, Germany, Norway, Sweden	Podzols (Spodosols)
	Finland, USSR	Luvisols (Alfisols*)
		Podzoluvisols (Alfisols*)
North America	USA, Atlantic SE coastal plain	Acrisols (Ultisols*)
	USA, Pacific Northwest	Podzols (Spodosols)
		Luvisols (Alfisols*)
		Acrisols (Ultisols*)
	USA, Great Lakes area	Podzols (Spodosols)
		Luvisols (Alfisols*)
	Canada, Atlantic	Podzols (Spodosols)
	Canada, north west	Podzols (Spodosols)
South America	Brazil	Ferralsols (Oxisols)
		Acrisols (Ultisols)
	Chile	Andosols (Andepts)

* Partial correspondence.

detailed soil studies to link B deficiency and soil B levels to soil groups. The situations discussed here are those where sufficient data is available.

Asia. China: Cultivated soils in south and east China, south of the Yangtze and many of the soils in northeast China are known, on the basis of B responses as well as soil analysis, to constitute the single largest contiguous area of B deficiency in the world (Liu Zheng et al., 1980, 1982a, 1982b, 1983). The soil B maps of China (Liu Zheng et al., 1980, 1989), show large areas of soils containing very low levels of hot water soluble B (<0.25 mg kg^{-1}). Acrisols predominate south of the Yangtze, many of which are formed on acid igneous and metamorphic rocks and on fluviatile deposits in the valleys, giving soils locally described as red earths and laterites. North of the Yangtze, B deficiency is common on soils derived from loess and calcareous alluvium of the Yellow river (Liu Zheng et al., 1980). In contrast the soils in the arid regions of western China, mostly classified as Lithic Kastanozems and Lithic Yermosols, are rich in B.

India: Soil B analyses (over 13,000 mostly from just four states) and crop responses (Table 2) show that B deficiency occurs quite commonly in several states. Links with soil groups have not been reported. Sakal and Singh (1995) highlighted northern Bihar, part of Assam, West Bengal, Meghalaya and northern Orissa, all in northeast India together with Karnataka and Gujarat as areas where B deficiency was most common. Granites and gneisses are the predominant parent material in these states, with the exception of

Gujarat. In Maharashtra, where most soils are formed from the basalts of the Deccan Trap, soil B levels seldom indicate B deficiency.

Acrisols are widespread in Assam whereas, in the other listed states Luvisols predominate. Luvisols and Acrisols are common in all but northern Karnataka. Luvisols are also prevalent in Tamil Nadu and Kerala (Acrisols also) but little soil B data is available for these states.

Sri Lanka: Boron deficiency has long been recognised on high grown tea (*Camellia sinensis*) on the Acrisols in the wetter central and south-western parts of Sri Lanka; most of these soils are derived from acid metamorphic rocks.

Africa. Cameroon, Chad, Benin, Ivory Coast, Nigeria: The occurrence of B deficiency on cotton (*Gossypium hirsutum*) has been known for many years in these countries where metamorphic and acid igneous rocks are fairly common and on which have formed Acrisols, notably in Ivory Coast, and Luvisols and Arenosols in Nigeria and Benin. Limited soil B data is available; in Nigeria Lombin (1985) reported low B levels and Odunze et al. (1992) found 0.32–0.49 mg B kg^{-1} in Luvisols from the Nigerian savannah.

Malawi, Zimbabwe, Zambia: As in west Africa recent interest has centred on cotton but tobacco (*Nicotiana tabacum*) has long been treated with boronated fertilisers in these countries. In Zimbabwe, where over 60% of the soils are derived from granitic and metamorphosed igneous rocks, Luvisols are very common in the eastern half of the country. A similar geological situation prevails in Zambia where Ferralsols have formed on the ancient acidic parent materials.

Europe. Scandinavia and Northern Europe: Podzols and Luvisols (also some Cambisols) cover much of the B responsive areas in Finland, Sweden, Denmark, Germany and Poland. In Finland and Sweden, the soil parent materials are almost exclusively acid igneous and metamorphic rocks.

Belarus, Estonia, Latvia, Lithuania and Russia: To the east in the former USSR, the soils with the lowest B levels are the Podzoluvisols and Luvisols (mainly formed on Devonian and Carboniferous sediments), whereas the Chernozems and Kastanozems to the south, formed on more recent sediments, are better supplied with B (V Ivchenko pers. comm., 1993); Pieve (1959) quoted water soluble B values (mg kg^{-1}) of 0.08–0.38 in Podzoluvisols, 0.38–1.58 in Chernozems and 0.30–0.90 in Kastanozems. About 35% of soils in the European part of the former USSR are rated as having a low B status.

Germany: As in the former USSR, many of the soils in the south of eastern Germany are Cambisols which Bergmann et al. (1968) found contained more B than the Podzols and Luvisols to the north.

Poland: Over 50% of the soils (mostly Podzols) in 11 provinces in central and eastern Poland were rated as low in B by Gembarzewski (1987).

Latvia: 40% of soils, mainly Podzoluvisols were found to be B deficient (Anspoks and Liepins, 1987).

Finland: The Podzols that cover most of southern Finland are likely to contain, on average, <0.5 mg hot water soluble B L^{-1} (Kurki, 1982); soil B levels were greater in soils with higher base exchange capacity and higher pH.

Americas. Brazil: Many of the B responsive soils in the state of Sao Paulo are known locally as various latosols (Ferralsols) and podzolic soils (Luvisols and Acrisols) (Sobrinho and Freire, 1980). Soluble B concentrations are usually <0.5 mg kg^{-1}; with the Ferralsols containing less B than the Luvisols; many of the soils are derived from basaltic parent material. Boron responsive soils also occur throughout the "Cerrado" region, which covers much of Minas Gerais, Mato Grosso and Goias (Lopes, 1984) and where 56% of soils are Ferralsols, 20% Arenosols and 10% Acrisols.

Chile: Many soils in central Chile carry B deficient crops (Tollenaar, 1970), including beet, pine (*Pinus radiata*) and grape (*Vitis vinifera*). Most are Andosols formed from basaltic-andesitic ashes, but a few are Cambisols derived from granitic and metamorphic rocks (Etchevers et al., 1983; Schlatter and Gerding, 1985).

USA: Although B deficiency has been reported in over 40 states (in most of which lucerne predominates) three areas have traditionally been cited (Anon., 1977; Berger, 1962) as being B deficient, namely the states along the Atlantic and Gulf of Mexico, the Pacific Northwest and the Great Lakes region; the occurrence of Podzols (Great Lakes and northeast), Acrisols (southeast) and Andosols and Acrisols (northwest) is noteworthy.

Canada: Boron deficiency occurs in the northwest in British Columbia on various soils, including Podzols derived from glacial till as well as some Luvisols and Kastanozems in the Okanagan valley; in the eastern Atlantic states on Podzols (Gupta, 1983, 1984).

Soil groups closely associated with boron deficiency

Boron deficiency seems to occur more frequently on certain soil groups than on others. Identification of problem areas will be facilitated if these associations are confirmed by future work. The Acrisols and Podzols are prominent as often carrying B deficient crops, less noteworthy are the Andosols and Luvisols.

Acrisols. These strongly weathered, and frequently coarse-textured soils with low base exchange capacity are, together with the Podzols, the soils on which B deficiency most often occurs; they are the soils that typically develop under humid conditions. Apart from the countries listed in Table 9, over 50% of the soils in southeast Asia are classified as Acrisols. The occurrence of B deficiency on Acrisols in Indonesia, Malaysia, Thailand, Laos and Vietnam is recognised and in Burma low soil B levels (0.1–0.7 mg kg^{-1}) have been reported (Gyul'akhmedov and Mamedov, 1984); however, in the absence of sufficient soil B data it is not possible to consider these countries as one contiguous B deficient zone.

Acrisols are found in other countries, apart from China, USA and Brazil, all of which have more than 100 million ha of Acrisols (FAO/UNESCO, 1978): 30–100 million ha (Burma, Indonesia, Tanzania and Thailand); 10–30 million ha (Australia, Bolivia, Cambodia, Colombia, India, Ivory Coast, Laos, Malaysia, Peru, Venezuela and Vietnam); and 4–10 million ha (Central African Republic, Ghana, Guinea, Japan, Mexico, Nicaragua, Nigeria, Papua New Guinea, Paraguay, Philippines and Suriname).

A small (200,000 ha) area of Acrisols in the north of South Island New Zealand is particularly noteworthy as it is the area on which Askew et al. (1936) discovered B deficiency on apple (*Malus domestica*) in 1935 and on which Rigg et al. (1937) reported wide-scale B deficiency on swede and turnip. Boron deficiency has since been found on other crops in the area including hop (*Humulus lupulus*) (Askew and Monk, 1953), raspberry (*Rubus idaeus*) (Askew et al., 1951) and pine (*Pinus radiata*) (Stone and Will, 1965). These Acrisols are formed on alluvium from metamorphic rocks and greywackes.

Sillanpaa and Vlek (1985) highlighted three countries in the tropics as B deficient zones namely Colombia, Nigeria and Zambia, the first two of which are notable for their Acrisols.

Podzols. Podzols commonly develop under coniferous forest in climates often unsuitable for agriculture but their occurrence in such regions as Scandinavia, Europe and North America appears relevant to the B situation. Elsewhere, for example in Australia (Tasmania and NSW) podzolic soils were some of the first to show B deficiency on apple, swede and turnip (Savage and Broadfoot, 1937). In northeast (Atlantic) Canada, B deficiency occurs on cabbage (*Brassica oleracea*), carrot (*Daucus carota*), lucerne and radish on podzolic soils (Gupta, 1983, 1984; Gupta and Cutliffe, 1975, 1985).

Andosols. The strong adsorption of B by allophane in soils derived from volcanic ash (Bingham et al., 1971) would appear to be the common factor in relation to the occurrence of B deficiency in such countries as Chile, Colombia, Ecuador, Japan, New Zealand and USA. The Andosols in central-southern Chile can adsorb massive amounts of B (Schalscha et al., 1973). However it may be dangerous to extrapolate to all Andosols, as demonstrated by a survey of parts of southern Chile by Rodriguez and Tomic (1984); they found wide (0.3–1.5 mg kg^{-1}) variation in hot water soluble B concentrations in Andosols in a region, where 70% were rated to be deficient for a sensitive crop such as beet. Lora (1978) obtained B responses on Andosols in Colombia on crops not normally rated as sensitive, such as potato and garlic (*Allium sativum*). Boron deficiency occurs in *Pinus radiata* (Will, 1971) on Andosols (coarse-textured pumice soils) in north island of New Zealand.

Arenosols and Lithosols. Sandy soils that have been well leached and thin rocky soils are prime candidates for B deficiency as indicated by Tables 8 and 9. However, the variable nature of Arenosols and Lithosols, particularly with regard to parent material, means that as groups they can not be classified as B deficient.

Luvisols. Luvisols, which together with the Acrisols are characterised by illuviation of clay, commonly occur throughout the world. Although in several countries they carry B deficient crops, they are not closely linked with B deficiency, probably due to varying parent materials and the fact that these soils normally have a high base exchange capacity. For example, the Luvisols in northeast India are B deficient most probably because they are formed from B poor parent materials.

Table 10. Estimated areas ('000 ha) and main crops treated annually with boron. Based on 1 kg B ha^{-1}

	'000 ha	
Europe	3000–4000	Beet (*Beta vulgaris*), oilseed rape (*Brassica napus*), grape (*Vitis vinifera*), sunflower (*Helianthus annuus*), fruit, vegetables
Australasia	3700–5000	Cotton (*Gossypium* spp.), oil palm (*Elaeis guineensis*), oilseed rape, groundnut (*Arachis hypogaea*)
Africa	600–1000	Cotton
Americas	6000–8000	Lucerne (*Medicago sativa*), coffee (*Coffea* spp.), cotton, fruit, vegetables

Extent of boron deficiency

There have been very few published statistics on the use of agricultural borates (either in terms of tonnes of products or areas treated), which makes it very difficult to assess the actual areas of different crops given B on a regular basis. Experience in the global agricultural borate market, combined with information published by the US Bureau of Mines on the use of B has permitted an estimate of the likely current use (Table 10) on a continental basis. In the USA, 5–7% of all B has historically been used in agriculture, in the rest of the world the percentage is smaller. The estimates in Table 10 are consistent with an annual global consumption for all end uses of B of 350–400,000 tonnes B, of which 6% USA and 3–4% in the rest of the world is for agricultural use. No allowance has been made, in Table 10, for B use in the former USSR.

The estimates of areas treated annually are based on a uniform application rate of 1 kg B ha^{-1} throughout the world; it is likely that in USA and Europe B rates are higher, and in the rest of the world lower, than 1 kg ha^{-1}. In the absence of survey data it is not possible to achieve greater precision.

Factors associated with the occurrence of boron deficiency

Within the few large, contiguous areas where the soils are of low B status, responses to B can be expected on many crops. However, even in such areas, local conditions of soil, climate and crop species will influence the incidence of B deficiency. In most countries in the rest of the world, it is these local conditions that play the major role and result in B deficiency occurring on particular crops and soils.

The occurrence of B deficiency at the local level can be related to several factors, including: the ability of the soil to provide sufficient available B during the growing season; the crop requirement and the removal of B; nature of the crop and of the harvested portion; climate; and management. Many of these factors, particularly those relating to soils, are discussed in detail elsewhere in this book. In this section the operation of these factors in the field will be considered, particularly their significance to the occurrence of B deficiency.

Supply of boron from soil

Boron can be considered as existing in five categories in the soil: in primary minerals such as tourmaline and B rich micas (1); in secondary minerals, particularly within the clay mineral lattice (2); adsorbed on clays, hydrous oxide surfaces and organic matter (3); in solution usually as boric acid but also as borate anions (4); and in organic matter and the microbial biomass (5).

Parent material, soil texture, pH, liming and leaching can be viewed as variously influencing B in one or more of these categories; parent material and soil texture are considered to be the dominant factors.

Parent material

Soil parent materials differ widely in their B content (Table 11), thereby having a fundamental effect on B in categories 1 and 2; they also differ in their content of clay-forming minerals which ultimately dictate how much of the B released from 1 will be held in the soil.

These differences are commonly reflected in the B contents of soils as well as in the regional occurrence of B deficiency. For example, granite-derived soils often carry B deficient crops, as in Korea where upland soils on granite were found to contain on average 0.07–0.15 mg hot water soluble B kg^{-1} (Park and Park, 1966) compared to 0.25–0.35 in soils derived from basalt and up to 0.50 mg kg^{-1} in soils from sedimentary rocks.

Table 11. Boron concentrations (mg kg^{-1}) in major rock types

		B (mg kg^{-1})[1]	B (mg kg^{-1})[2]
Igneous	Basic: gabbro, basalt	5–20	5
	Intermediate: diorite	9–25	
	Acid: granite, rhyolite	10–30	15
Metamorphic	Gneiss	10–30	
Sedimentary	Shale	120–130	100
	Sandstone	30	35
	Limestone, dolomite	20–30	20

[1] Data from Kabata-Pendias and Pendias (1992).
[2] Data from Sillanpaa and Vlek (1985).

Table 12. Total and water soluble boron contents (mg kg^{-1}) of Chinese soils[1]

Region	Soil group	Parent material	Total B (mg kg^{-1})	Water Soluble B (mg kg^{-1})
South of Yangtze	Acrisols	Granite	4-16	0.06–0.29
	Acrisols	Rhyolite	13–19	0.21–0.24
	Acrisols	Phyllite	15–40	0.02–0.19
	Acrisols	Red Sandstone	25–28	0.0–0.11
	Acrisols	Gneiss	13–22	0.0–0.13
North of Yangtze	Various	Loess	55–87	0.14–0.70
Central China just north of Yangtze	Various	Quaternary red clay	48–96	0.08–0.37
–	–	Limestone	49–145	0.14–0.34

[1] Liu Zheng et al. (1980). B deficiencies occur in all soil regions but particularly on the Acrisols.

Studies in China have linked the low B soils with parent material. For example, Liu Zheng et al. (1980, 1982a, 1982b, 1983) found that soils derived from granite and other igneous rocks, gneiss and sandstone were particularly low in both total and water soluble B (Table 12), whereas soil derived from loess contained more B. In the northeast of China, where many soils are derived from loess and calcareous alluvial deposits of the Yellow river, B deficiency is not so serious. Despite the clear links between B deficiency in China and parent material, it is not possible to assess the extent to which the current low soil B status is due to parent material, to soil age, to the intensity of weathering or to the extensive exploitation of the soil for food production.

Granitic and metamorphic rocks frequently give rise to B deficient soils and their importance as a common factor, regardless of soil group, cannot be underestimated. Boron is lost during metamorphism, some contributing to tourmaline formation, but most is released into the environment (Harder, 1961). In contrast, young soils derived from fine grained marine sediments will be B rich. The factor of greatest importance in determining the B supplying capacity of soils derived from sedimentary rocks is undoubtedly the clay content and possibly the type of clay. Marine clays and shales can accumulate much B particularly if they contain illite, which incorporates B into the clay lattice. Sediments in which glauconite forms will contain much B, as it is incorporated as the mineral forms in the presence of sea water (Harder, 1970). Leakage of B from illite and glauconite as they weather could be relevant to the soil buffering capacity for B.

Soil texture

Soil texture, which itself is very dependent on parent material and on the weathering and the illuviation of clay from the top soil, has a major influence on B in categories 3 and 4. Coarse-textured soils contain less total and water soluble B, and as a result, B deficiency commonly occurs more frequently on these soils than on fine-textured, less freely drained soils. Boron held in categories 2 and 3 comprise very important soil reserves in fine-textured soils which as a result seldom carry B deficient crops.

It seems likely that the occurrence of B deficiency in the highly weathered Acrisols and Podzols is basically a function of the loss of B reserves held with clay minerals. In the similarly weathered Luvisols, with generally higher clay contents (base exchange capacity), B deficiency is not as likely to occur.

Somewhat paradoxically, less B is required to correct B deficiency on coarse-textured soils than on fine-textured soils due to the stronger adsorption of B by the latter. An understanding of the nature of this phenomenon was provided by Wear and Patterson (1962) who showed that absorption of B by lucerne was greater from a coarse- than from a fine-textured soil containing the same concentration of hot water soluble B. Liming had a much greater impact in reducing B absorption in the coarse-textured than in the fine-textured soil. Furthermore, B losses by leaching will be greater on freely drained coarse-textured than on impervious, fine-textured soils. Coarse-textured soils will quickly dry out during droughts, making crops more reliant on deep roots growing in the lower, B poor soil horizons. In England and Wales soils which contain <0.2 mg hot water soluble B L^{-1} are almost invariably sandy in texture (Archer and Hodgson, 1987). Boron deficiency frequently occurs in England on beet and swede on soils derived from Triassic and Devonian sandstones as well as post-glacial sands (Farrer, 1976). In France the risk of B deficiency on sunflower (*Helianthus annuus*) is highest on soils containing more than 15% fine and coarse sand, on thin soils and soils with pH > 7.0 (Merrien, 1993).

Soil pH, clay minerals and hydrous oxides of iron and aluminium

It is frequently stated that soil pH is one of the most important factors affecting availability of soil B. However, except in the case of the adverse effects of liming on B availability, soil pH *per se* appears to have little practical bearing, via its effect on adsorption by clay minerals and aluminium and iron oxides. The strong adsorption of B at both high and low pH levels has not been held responsible for causing B deficiency. Despite adsorption of B by soils, clay minerals and hydrous oxides being maximal at about pH 8–10, B deficiency does not occur on soils with a naturally high pH such as the desert soils of North Africa and Saudi Arabia, or on soils with very high calcium carbonate levels. At low pH levels it will be factors associated with low fertility (e.g. leached, coarse-textured soils) that will be more relevant than any tendency for adsorption to increase.

The many adsorption studies reported in the literature have not had a major impact on the understanding of the non-toxic behaviour of either indigenous or applied B despite the large differences between adsorbents and the marked pH effects. The understanding of the toxic effects of B rich irrigation water has, however, been considerably helped by adsorption studies. It remains to be seen whether the strong adsorption (and weak desorption) by humic acid and by the "short-range" clay minerals, imogolite and ferrihydrite plays a significant part in determining B availability and deficiency in any soils. Boron can be adsorbed by calcium carbonate (Goldberg and Forster, 1991) and some workers report positive correlations between amounts of adsorbed B and calcium carbonate. However, there is little, if any evidence, to indicate that such adsorption is responsible for B deficiency anywhere in the world.

It is the increased adsorption by raising the pH within the range pH 4-7 (at which B adsorption by phylosilicate clay minerals is usually minimal) that is in practice of greatest significance in inducing B deficiency. It is important to distinguish between situations where liming has recently been carried out and where "equilibration" may not be complete, and those where the pH of a soil has been raised a considerable time before. Peterson and Newman (1976), for example, showed on the same soil that neither indigenous B uptake nor recovery of applied B by *Festuca arundinacea* was affected over a pH range of 4.7–6.3 when soils had been limed 11 years previously. However, when the pH was raised to 7.4 by liming 4 months before the experiment, B uptake and recovery were markedly reduced. Likewise Wear and Patterson (1962) found that liming just before B treatment reduced uptake of B by lucerne and that the effect was more marked on a coarse-textured soil than on a silty clay soil.

Liming

Liming of soil with marginal B content frequently induces B deficiency. The idea that freshly precipitated aluminium hydroxide is responsible for scavenging soluble B has been widely accepted for many years (Hatcher et al., 1967; Sims and Bingham, 1968a, 1968b). The fact that the ability of aluminium hydroxide to adsorb B diminishes with time, is in accord not only with the soil situation mentioned above, but it fits with the idea that it is the recent effects of liming rather than a general pH rise which markedly affects B availability.

Organic matter

Many workers (e.g. Elrashidi and O'Connor, 1982) have shown strong correlations between B and organic carbon contents of soil. Mineralisation of organic matter releases some B. The risk of B deficiency increases when organic matter contents decline. On the other hand, organic matter has the ability to complex large amounts of B (usually more than mineral soil constituents e.g. Yermiyaho et al., 1988), a feature which has sometimes (e.g. Liu Zheng et al., 1989) been held responsible for B deficiency. However there is no suggestion that Histosols or Chernozems can be considered as being basically deficient in B.

Leaching

Data is available to support the logical view that leaching losses of B will be maximal on the coarse-textured soils e.g. Kubota et al. (1948), Ouellette (1958) and Wilson et al. (1951). There have, however, been few attempts to build models that can be used to predict the vertical (and lateral) movement of B in soils (the work of Wild and Mazaheri (1979) with soil columns is an exception); the lack of information is unfortunate in view of the importance of leaching not only in the short term during agricultural use of the soil, but also during the millennia of soil formation. More is known about the behaviour of potentially toxic amounts of B supplied in irrigation water than about indigenous and corrective B applications.

Distance from sea

Significant amounts of B can be supplied in rainfall in coastal regions, for example Wikner (1983) reported that soils near the west coast of Sweden received 25–40 g B ha^{-1} annually compared to <2 g B ha^{-1} in northern Sweden far from the sea. Sea water normally contains 4.5 mg B kg^{-1}. Similar data is available for Western Australia (Hingston, 1986).

Crop requirement and crop removal of boron

Data (Shorrocks, 1991) on crop B requirements and removals as given in Table 13 should be used to indicate little more than the general order of magnitude of the amounts involved. The values must be linked to a yield level as well as to B concentrations. It is only possible to contrast these amounts with the B supplying capacity of the soil in a roughly qualitative manner. It is likely that most crops remove less than 100 g B ha^{-1} and that it is only crops such as lucerne and beet that often remove more than 300 g B ha^{-1}. Despite the small amounts of B removed by cereals in grain, B deficiencies do occur because of the particular B requirement for fertilisation and seed set.

Nature of the crop and of the harvested portion

The relative sensitivity of different crops to B deficiency was discussed in "Crops". Here the particular features of crops that are relevant to the effects of impaired B supply are considered. It is extremely rare for B deficiency to result in crop death in the field, although cases are known (e.g. *Pinus radiata* in Chile and oilseed rape in China). The economic consequences of an inadequate supply of B have to be considered in relation to whether damage is caused to a particular part of the plant, or whether overall growth is impaired. The symptoms that have the greatest impact on the performance of the crops which are most sensitive to B deficiency, are shown in Table 14. Impairment or death of the apical meristem has serious consequences for crops such as beet, *Eucalyptus* spp., *Pinus* spp. and oil palm. For the vegetable brassicas and carrot, it is essential that damage to root and stem tissues does not reduce quality.

For virtually all crops, not only cotton, sunflower, apple and grape, included in Tables 6 and 14, it is the B requirement for pollen tube growth and pollen viability, and thereby for seed and fruit development, that is of vital importance. For example, many clovers (*Trifolium* spp.) produce more seed when given B, but will seldom show increased dry matter production. Boron deficient wheat and other small grained cereals exhibit sterility without exhibiting any other symptoms (Rerkasem, 1996). Unfertilised fruit will fall and partially fertilised fruit will be misshapen [e.g. papaya (*Carica papaya*), apple and pear (*Pyrus communis*)]. The optimal concentrations of boric acid in culture media for pollen germination and growth are high for many species – for some such as chick pea (*Cicer arietinum*), coconut, eucalypts, *Hibiscus esculentis*, olive (*Olea europaea*) and almond (*Prunus amygdalus*), 100 mg B L^{-1} is required (Anon., 1996).

Table 13. Boron requirement for growth and removal in harvested crop (g B ha^{-1})

		Yield t ha^{-1}	B requirement for growth (g ha^{-1})	B removal in crop (g ha^{-1})
Beta vulgaris	Sugarbeet	50	480	300
Brassica napus	Oilseed rape	4	320	80
Gossypium hirsutum	Cotton	3	225	150
Helianthus annuus	Sunflower	3.5	400	100
Malus domestica	Apple	40	380	250
Medicago sativa	Lucerne	7		350
Triticum spp.	Wheat	3	60	25
Vitis vinifera	Grape	6	240	120
Zea mays	Maize	6	150	30

Table 14. Agronomically significant symptoms on crops most sensitive to boron deficiency

	Symptoms	Species
Impaired meristem activity	Dieback	Beet (*Beta vulgaris*) Eucalypt (*Eucalyptus* spp.) Pine (*Pinus* spp.)
	Malformed leaves	Oil palm (*Elaeis guineensis*) Coffee (*Coffea* spp.)
Impaired cell wall development	Cracking of stems and petioles	Celery (*Apium graveolens* var. *dulce*) Chinese cabbage (*Brassica chinensis*) Beet
Protection against phenols	Damaged tissue	Swede (*Brassica rutabaga*) Carrot (*Daucus carota*)
Pollen tube growth	Reduced seed set	Sunflower (*Helianthus annuus*) Coffee Oilseed rape (*Brassica napus*) Olive (*Olea europaea*) Clover (*Trifolium* spp.)
	Fruit fall	Cotton (*Gossypium hirsutum*) Apple (*Malus domestica*)
	Deformed fruit	Apple Grape (*Vitis vinifera*) Olive

Climate

Climate can have an impact on B deficiency, both in the short and long term. The more extreme the conditions of rainfall and temperature, and the longer the weathering of the soil, the greater the loss of soil B. Both rainfall and temperature can also play a part in the short term. Heavy rainfall, particularly on freely drained soils, can not only exacerbate B deficiency, but minimise residual effects of B application. Application of B should be timed to avoid leaching by heavy rain.

The onset of B deficiency symptoms on many crops has long been associated with hot, dry weather. Until recently, the only explanation of this association has been that as the topsoil dries out, less B can be absorbed from the relatively B rich topsoil (e.g. as demonstrated by Hobbs and Bertramson (1949) with tomatoes (*Lycopersicon esculentum*) in a split root experiment). When root growth recommences in the topsoil with the improving soil moisture conditions and more B becomes available, the symptoms disappear.

There were anecdotal cases of B deficiency developing in hot weather on irrigated crops, e.g. beet in France, but these were unfortunately ignored. Also ignored was the finding by Tanaka (1966), albeit with duck weed (*Lemna pausicostata*), that B deficiency was exacerbated and the critical B concentration increased as the light intensity was raised from 1000 to 5500 lux.

A major advance was made by Merrien (1993) on sunflower in France; he observed that the somewhat unusual necrotic symptoms on midstem/upper leaves on otherwise reasonably well grown sunflower, developed a few days after hot, dry conditions, particularly on thin and gravelly soils. Careful observation of climatic conditions allowed Merrien to specify that if the maximum temperature exceeded 35 °C and daily evapotranspiration exceeded 6 mm for several days, then the necrotic symptoms could be expected within 15 days.

Cakmak et al. (1995) reported that B deficiency symptoms develop more quickly on sunflower seedlings (at the first leaf stage) when they are grown under high (580 μmol $m^{-2}s^{-1}$) rather than low light intensity in a growth chamber. Noppakoonwong et al. (1993) showed in glasshouse trials that high light intensity increased the requirement for B in shading experiments with black gram (*Vigna mungo*). Possible involvement of B in protecting leaves against the damaging consequence of elevated phenol levels caused by high light, is discussed by Cakmak and Römheld (Chapter 6).

Further evidence of the involvement of climatic factors in B nutrition comes from the several studies on the causes of sterility in wheat (Rawson and Subedi, 1996). Rawson (1996) hypothesises that the primary cause of sterility is due to inadequate B reaching the flowers in the critical 6–10 days of pollen formation. Climatic factors that reduce transpiration such as low vapour pressure deficit and low radiation as well as inadequate B availability in the soil will be important. High temperatures, which have been reported to increase the incidence of sterility, are believed to operate by reducing the number of days available for the critical B supply to the flowers.

Boron nutrition also appears to play a part at low temperatures, insofar as frost damage can be exacerbated by B deficiency and minimised by B application. Anecdotal evidence was followed by field experiments, mostly in Yugoslavia but also in Germany and Austria, on ash (*Fraxinus*), apple, *Pinus*, poplar (*Populus*), plum (*Prunus domestic*), peach (*Prunus persica*) and grape (Anon., 1958; Beltram, 1958) which showed definite protective effects of B application against frost damage. It is not possible to assess whether the experiments, which mostly used a 0.5% w/v solution of borax decahydrate as the B treatment, were on B deficient soils on which growth/yield responses could be expected or not. In some cases rapid, almost immediate effects of spraying borax were claimed by Beltram. In the absence of proof under controlled conditions (which was attempted in Germany on vines in the 1960’s) this early work has tended to be discounted.

Probably the best evidence of an involvement of B in helping to protect plants against low temperature damage was provided by work on eucalypts in field studies in Zambia (Cooling, 1967; Cooling and Jones, 1970); frost damage, which caused a dieback very similar to B deficiency, was minimised by B application in a dose-related manner.

Braekke (1979, 1983) working with birch (*Betula*), Scots pine (*Pinus sylvestris*), *P. contorta* and Norway spruce (*Picea abies*) on peat soils in Norway found that young plantations were frequently damaged not only by winter frosts, but also by radiation frosts in the growing season and that the damage could be reduced by B application. Moller (1983) in Sweden and Veijalainen (1983) in Finland both provided circumstantial evidence on conifers that the shoot dieback and "growth disturbances" that had always been attributed to frost damage, were in fact, caused by B deficiency. Hanson and Breen (1985) reported that prunes responded positively to autumn B sprays which increased fruit set only when the flowering period in the following spring was "cool" (mean 8 °C without any frost) and not when it was "warm" (mean 12 °C), when fruit set was higher. Borax application was found by Ryu et al. (1986) to increase frost tolerance of *Morus* in South Korea. Other recent examples of B benefits in relation to frost include Milovankic et al. (1990) with apple and pear in Yugoslavia, Svagzdys (1995) with apple in Lithuania and Blevins et al. (1996) with blueberry (*Vaccinium corymbosum*) in USA.

Observations indicating an involvement of B nutrition in frost resistance have continued for almost 40 years, but the basic question as to whether the protective effects of B applications only operate under deficient conditions remains unanswered. In other words, is it just a matter of B deficiency symptoms being accentuated by the low temperature stress?

Management

In a few cases, crop management may have a bearing on the occurrence of, and significance attached to, B deficiency. For example, the cutting of lucerne for consumption away from the field of production means that relatively large amounts of B will be removed (Table 13). The combination of high productivity and cutting led to lucerne being the principle crop treated with B in the USA. In contrast, in Argentina, where lucerne has been mostly grazed, there has been relatively little B deficiency; not only do the Argentinian soils contain more B than many in the USA, but B is recycled via urine and faeces.

Boron deficient leaves and petioles are often brittle due to impaired cell wall development (Table 14). Beet has traditionally been harvested in Ireland by equipment that grabs the petioles and leaves to lift the roots out of the ground. The risk of crop losses due to brittle petioles is minimised by applying B.

Correction of boron deficiency

History

Two B products, namely borax (sodium pentaborate decahydrate) and boric acid, were available to the workers in the 1930's and virtually all the early literature on B use relates to them. The easy use of boric acid in solution made it the preferred compound for spray application but there was in fact very little interest in B sprays until the 1950's, which indicates that most found soil applications to be perfectly satisfactory.

Because the first B problems in the USA were due to toxicity (see "History of responses to boron application") work continued there until the 1950's on the use of borates with low solubility, particularly colemanite and borosilicate, glassy frits (fritted trace elements) but neither have found a permanent place in the agricultural market. Fritted trace elements formed by the fusion and quenching process became popular in horticulture in several countries as a means of providing season-long and toxicity-free supply not only of B but also of other micronutrients; although similar named products are still available not all are fused glassy materials.

With the increase in use of B, after 1945, upgraded sodium borate ores (essentially anhydrous and pentahydrate borax) were offered (in 1952) as cheaper alternatives to the refined borax decahydrate and boric acid for soil application. Although partially processed, these upgraded ores contained some insoluble gangue and were accordingly not suitable for spray application. The big increase in cost of production of anhydrous sodium tetraborate following the rise in fuel prices in the 1970's effectively removed this product from the agricultural market and helped again to stimulate interest in the cheaper ores, particularly colemanite and ulexite. The upgraded pentahydrate sodium tetraborate has been replaced by a completely refined grade for economic reasons of large-scale production. The spray grade product Solubor was introduced in 1954.

The bulk blending of similar sized fertiliser granules in the USA resulted in the development, in the late 1970's, of granular formulations of borax pentahydrate; from the viewpoint of uniform application they are to be welcomed but too little seems to be known about the agronomic efficacy of such materials. A relatively small number of the 1.4–4.0 mm granules are normally applied; an application rate of 1–2 kg B ha^{-1} would involve about 80 to 160 granules m^{-2} and would seem to indicate reliance on lateral movement of B in the soil.

The expanding use of B in agriculture has resulted, in the last 20 years, in a proliferation of different formulations designed to facilitate use; a dry flowable formulation of Solubor was introduced in 1994 and there are many liquid formulations of borates, some apparently simple aqueous solutions with performance-enhancing additives and others utilising the relatively high solubility of boric acid in monoethanolamine to increase the strength of the B concentrate and so reduce handling costs.

Sources of boron

The main B products that are used as primary sources of B are listed in Table 15. Basically there are two types, firstly the refined, completely soluble materials which can be conveniently applied either in solution or as solids, and secondly the crushed ores that contain insoluble gangue and which have variable chemical and physical properties. Aspects of the solubility of different borates are discussed by Power and Woods (Chapter 1). Borax and boric acid are easily dissolved in soils and are quickly available for uptake, but at the same time the B that is not adsorbed can be leached. Pentahydrate borax dissolves more slowly than decahydrate borax and faster than anhydrous borax but there has been no indication that these differences are agronomically significant. Once in solution there are no chemical differences. In order to facilitate dissolu-

Table 15. Commonly used agricultural borates

			B (%)
Refined products	$Na_2B_4O_7{\cdot}5H_2O$	Sodium tetraborate pentahydrate	14.9
	$Na_2B_8O_{13}{\cdot}4H_2O$	Solubor	20.8
	$Na_2B_4O_7{\cdot}10H_2O$	Sodium tetraborate decahydrate	11.3
	$Na_2B_4O_7$	Sodium tetraborate	21.4
	$B(OH)_3$	Boric acid	17.5
Crushed ores	$2CaO{\cdot}3B_2O_3{\cdot}5H_2O$	Colemanite	variable
	$Na_2O{\cdot}2CaO{\cdot}5B_2O_3\ 16H_2O$	Ulexite	variable
	$2CaO{\cdot}B_2O_3{\cdot}2SiO_2{\cdot}H_2O$	Datolite	variable
	$CaO{\cdot}MgO{\cdot}3B_2O_3{\cdot}6H_2O$	Hydroboracite	variable
	$2MgO{\cdot}B_2O_3{\cdot}H_2O$	Ascharite	variable

tion in cold water, the product Solubor, which in many respects can be considered a hybrid between borax and boric acid, was developed. Solubor dissolves more quickly than borax and boric acid, results in solutions with high saturated B concentrations and readily forms super-saturated solutions, which are all valuable properties for a spray-grade product.

The two crushed ores ulexite and colemanite are only used for soil application, usually after inclusion in a boronated NPK or PK fertiliser, but also sometimes on their own; there have been attempts to promote a colemanite suspension as a foliar spray product. When such ores are incorporated during the manufacture of compound boronated fertilisers they will react with any free acid, and boric acid will be formed so converting a slowly soluble borate into a quickly soluble form.

In the former USSR and eastern Europe datolite (a calcium borosilicate), ascharite (a magnesium borate) and hydroboracite (a calcium magnesium borate) have all been used for making boronated fertilisers but data on solubility of B in the finished fertiliser is not available. Pot tests with white clover (*Trifolium repens*) by M Ewens and S P McGrath (pers. comm.) showed that hydroboracite was a satisfactory and quickly available source of B when applied on its own. Muller and McSweeney (1976) found, in pot tests, that massive applications of datolite had little effect on either the B content or growth of *Brassica campestris*. In contrast, Sherrell (1983) concluded that finely-divided datolite could be an adequate source of B for lucerne and red clover (*Trifolium pratense*). Calcining has been found, in the Ukraine, to increase the solubility (in citric acid) of datolite (Polyak and Boronkova, 1958). Magnesium borate made by reacting boric acid with magnesium hydroxide has been proposed/used in the former USSR (Katalimov and Churbanov, 1959) as a slow release borate source.

Very few B rich waste products have been used as B fertilisers. The boric acid/gypsum mud, a waste from the manufacture of boric acid is an obvious candidate, but would appear to have been used only in the former east Germany (Bergmann and Buechel, 1963).

Where a long acting borate is required for application on its own, as for example in forestry, there may be a case for using a crushed ore with a large particle size. However apart from any questions about chemical and physical variability, the efficacy of the actual ore to be used needs to be assured; particle size, physical condition and whether it needs to be incorporated into the topsoil must be considered. Uncertainties about the speed of action of a borate with slow release properties are clearly of greater concern for annual than for perennial crops.

The results of comparative studies on the efficacy of different crushed ores to supply B are not apparently consistent. Currently, for example, ulexite is used as a slow acting borate in New Zealand whereas in Brazil it is viewed as being more or less identical to borax decahydrate. The overall picture that emerges is that fine particles of ulexite behave similarly to borax both when incorporated into the soil or left on the surface. On the other hand large particles of non-incorporated ulexite will be long lasting – and will also take longer to provide B initially. The situation with regard to colemanite is similar but differs insofar as colemanite is generally less reactive than ulexite, with the result that non-incorporated colemanite, especially granular, is of much less benefit as a B source – at least for annual crops. Unfortunately very few field comparative studies on borate ores have been reported; most studies on ores have been carried out in pots often with toxicity and leaching in mind rather than crop responses.

Borates can be applied alone, incorporated in or mixed with a fertiliser. For mixed fertilisers, the major concern is normally one of particle size and density in order to achieve uniform mixing and distribution. Normally the pentahydrate borax is used. Borate ores can also be used with due consideration being given to their properties. In compound fertilisers the temperature of the granulation process, and particularly of drying (which can exceed 200 °C), may also dictate the use of a borate with a higher melting temperature than pentahydrate borax, which starts to melt at 200 °C; agglomeration (balling) of granules occurs if the borate on the granule surface melts. Anhydrous borax which starts to melt at 742 °C does not give these problems, likewise colemanite which starts to disintegrate at around 400 °C. In a fertiliser such as boronated fused magnesium phosphate, popular in Japan and Brazil, the high (1300–1400 °C) fusing temperature necessitates the use of an anhydrous borate or at least one that does not disrupt production by the violent release of water.

Procedures have been developed (e.g. Mortvedt, 1991) for coating granular fertilisers with finely divided sodium borates using oil (<1.0%) as a sticker; although this system offers considerable flexibility in production, it has not, somewhat surprisingly, attracted much attention. For liquid and suspension fertiliser, the more rapidly soluble and small particle size sodium borates are preferred.

Soil application

Boron can be satisfactorily applied to the soil to provide season-long elevation of the B status of a crop. Regardless of the chemical form of the borate applied, it is likely, after dissolution in most agricultural soils, that B is absorbed as boric acid, the B species that predominates at pH <7.0.

There is very little data on the recovery of broadcast B by annual crops. M Ewens and S P McGrath (pers. comm.) measured recoveries of 20–30% of incorporated B (non-toxic rates of application) by white clover in a pot test over a 9 month period. Jin et al. (1988) reported B (applied as $B(OH)_3$) recoveries, over 5 weeks, by maize of 0.4–13.5% in 14 soils (several Acrisols). Recovery under field conditions in the year of application is likely to be in the range 5–15%. The relatively small amounts of B that are normally required to effect a significant improvement in B status of an annual crop, namely 1–2 kg B ha^{-1}, are in broad accord with such recovery rates. For many crops, absorption of 100–200 g B ha^{-1} of applied B could be expected to be sufficient.

Boron is readily absorbed by roots and is rapidly translocated to the growing points and actively transpiring tissues, and as a result becomes well distributed throughout the plant. There is very little evidence of significant transport to the roots, either from other roots or from the shoot, which emphasises the importance for all roots to obtain B from the soil they are growing in – in a way analogous to that of the pollen tube in the style. Good root growth depends on there being sufficient B in the rooting zone.

It is important, in order to minimise the risk of B toxicity hot-spots in the field, that borates are uniformly distributed. Historically this was achieved by mixing the borate with soil or sand before application. Boronated fertilisers (solid, liquid and suspension) enable good distribution as does application of a soluble (and compatible) borate with a herbicide. Application via nutrient feed and irrigation systems also affords good distribution.

Timing of soil application

Because of the over-riding importance of local seasons and climates, only the basic principles can be considered. Soluble borates should be thought of as being very similar to nitrate fertilisers, although they do not leach as readily; they should be applied early enough before growth starts in the spring to allow for the boric acid to move into the rooting zone, but they must not be applied too early in order to minimise leaching losses, especially on coarse-textured soils.

Residual effects of soil applied boron

The length of any residual effect of soil applied B will clearly depend on many soil factors, notably those that influence adsorption/desorption and leaching. It is not therefore possible to specify length of residual effects except after precise local experiments e.g. Gupta and Cutcliffe (1982, 1984) who were concerned about toxic residual affects. Mathematical modelling of the behaviour of both indigenous and applied B is required in order to improve our understanding and to facilitate predictions. The different rates of dissolution of borates and the method of application, especially whether they are incorporated or not, will also have a marked influence on the length of any residual effect, as shown for example by Wilson et al. (1951). Because B deficient soils are very often coarse-textured it is customary to think of soluble borates as being readily leached with applications of 1–2 kg B ha^{-1} being effective for only one crop with little carry-over to a second year. Where B is needed by only a single crop in the rotation this means that the each such crop should be given B. However the adsorption of B by fine-textured soils can result in significant carry-over (see "Leaching").

Foliar application

Foliar application of B provides not only a means to apply B at a particular stage in the growth cycle, but it also permits rapidly-acting remedial action to be taken soon after diagnosis of a deficiency; soil applied B would not be as quick acting. Until the recent work in the USA by Hanson (1985, 1991) and Brown and Hu (1996) there had been considerable doubt as to the mode of action of foliar applied B, and although much has been revealed, the picture is not entirely clear. The fact that root absorbed B appeared to be more or less immobile in the phloem, after it reaches the leaves, had led to the widely held conclusion that foliar applied B would be similarly immobile. Boron deficiency symptoms invariably occur in the young tissues and apical meristems.

It is still accepted that once B has been incorporated into cell walls in leaves it is effectively removed from circulation and is not available to support new growth. The rethinking concerning foliar applied B originates from the work of Hanson (1985) who showed that spray application of Solubor, in the autumn just before leaf fall, to prunes resulted in much improved fruit set in the following year indicating significant phloem mobility of B to flowering meristems from either senescing leaves and/or bark. Hanson (1991) demonstrated the rapid – within a few days – export of sprayed B from the leaves of apple, plum and pear; export was much slower in cherry, indicating that it will be difficult to generalise. Similar results were obtained by Gu et al. (1995) with *Malus prunifolia*.

An explanation of what seemed the anomalous results of Hanson with foliar applied B has been provided by the work of Brown and Hu (1996). There seems to be no impediment to the phloem movement of foliar absorbed B in the woody Rosaceae e.g. apple, *Prunus* spp. and pear, most probably because these species translocate the B-complexing sugar alcohol, sorbitol (Brown and Shelp, Chapter 7). Very few species, apart from the woody Rosaceae, use sorbitol, so it remains to be seen whether other sugar alcohols such as mannitol assist in B transport. Delgado et al. (1994) showed that B was phloem-mobile in olive and time will tell whether this can be positively linked to the fact that this species transports mannitol in the phloem.

These results have a direct bearing on the question of timing of B applications. For the woody Rosaceae the opportunity is now afforded to apply B sprays in the autumn before leaf fall as an alternative to spring application at and around the time of flowering; comparison of the efficacy of autumn and spring sprays on fruit set and B utilisation by these species is now required. Autumn sprays depend on B absorption by leaves followed by mobilisation, whereas spring sprays rely on the floral tissues receiving the B directly. Questions about the capacity of leaves to retain B sprays, which Picchioni et al. (1995) found to be the major determinant of the amount of B absorbed, and therefore exported, will need to be asked not only of species but also of genotypes. There will be little merit in a genotype having an inherent capacity to transport B out of leaves unless it exhibits good spray retention.

For annual crops and perennials, belonging to families other than the woody Rosaceae, the position is unchanged with regard to timing. For example Brown and Hu (1996) showed that there was no evidence of significant phloem transport from leaves of three species that do not use sorbitol, namely fig (*Ficus carica*), walnut (*Juglans regia*) and pistachio (*Pistacia vera*). There is a strong physiological case for applying B before, and just after, flowering as a means of ensuring that the floral tissues receive B at the time of peak demand. The poor phloem mobility of spray applied B to all but the woody Rosaceae, means that a single foliar application of B is often not sufficient; repeated sprays on cotton are particularly effective in maintaining a satisfactory B supply over the prolonged flowering period. In the case of annual crops, some of the spray applied B, which is intended for the leaves, inevitably reaches the soil surface thereby benefiting the crop via root absorption.

Solubor is applied to some crops at concentrations up to 5% w/v e.g.beet, but in the absence of tests, it is recommended that spray concentrations do not exceed 1% w/v. The main reason for using low concentrations of Solubor is to minimise the risk of applying too much B if high spray volumes are mistakenly employed, rather than to limit phytotoxic damage to the leaves; it is the amount of B applied, and absorbed, not the concentration which is important. In a Solubor spray trial in the UK (A D Scaife, pers. comm.) with several crops, red beet (*Beta vulgaris*), Chinese cabbage

(*Brassica chinensis*), cauliflower (*Brassica oleracea* var. *botrytis*), rape, swede, carrot and field bean, it was found that the extent of necrotic patches that develop where B accumulates in the leaf was related to the total amount of Solubor applied and not to the concentration of spray solution: Solubor was applied at concentrations from 0.17–8% and at rates of 1.6 to 22 kg Solubor ha^{-1} (0.3–4.8 kg B ha^{-1}). Similar results were obtained for sugar beet (*Beta vulgaris*), Chinese cabbage, rape, swede, carrot, sunflower, tomato, French bean, pea (*Pisum sativum*), radish and potato, by M Hoppe and S P McGrath (pers. comm.) and for apple (var. Cox) by M J Marks (pers. comm.).

Aerial application

There has been limited application of borates from the air. A notable exception is the application to *Pinus radiata* in New Zealand where large particle size pieces of ulexite are now preferred to the dusty colemanite and to the shorter-acting borax pentahydrate.

Suspensions of Solubor have been applied from the air in South Africa to sunflower. Sunflower in Spain is often sprayed with Solubor (2.1 kg ha^{-1} at 1.4–1.7% w/v) using ground equipment or at 3.5% w/v from aircraft.

Applications to seeds

Application of B to seeds or even application in close proximity to the seed is not advisable; root damage (albeit often ephemeral) can readily occur, as for example when boronated sugar beet fertilisers are mistakenly drilled with cereal seed. Likewise application of boronated fertilisers close to potato tubers can be extremely damaging. Soaking of seeds in dilute solutions (2 to 20 m*M*) of boric acid (e.g. 100–1000 mg L^{-1}) has been used as a research tool, almost exclusively in the former USSR, in mainly short term physiological and biochemical studies. Experiments have been carried out on a large number of crops including, beet, turnip, soybean (*Glycine max*), sunflower, barley (*Hordeum vulgare*), lucerne, and wheat. Both beneficial and harmful effects (mostly on germination) have been reported. Despite the beneficial effects there are no reports of the practical use of B as a seed treatment in the USSR – or elsewhere. Very few experiments have been carried out in which seed has been dusted, coated or pelleted with a borate, none of which practices can be recommended.

Rates of application

The current and generally recommended rates of B application given in the review "Boron Deficiency its Prevention and Cure" (Shorrocks, 1989) are based on the rates determined by trials around the world as well as those that had become official recommendations in different countries. The rates had their origin in the early trials on beet etc. (Table 5) and have been refined with time. Inevitably more data is available to substantiate soil application rates than spray-applied rates. For annual crops, similar rates of B application (1–2 kg B ha^{-1}) are recommended regardless of method of application. This is in line with the view that efficacy of foliar applications during the early growth of annual crops is likely to depend both on absorption via the roots as well as via the leaves; the poor phloem mobility of B in annual crops adds credence to this view. For perennial crops, where the target tissues are the flowers and the newly developing fruit, low concentrations, aimed at avoiding phytotoxicity, have been successfully employed; although several applications are usually needed, the total amounts of B applied are, on an area basis, normally lower than for annual crops. Local conditions dictate the severity of the deficiency and accordingly it is not possible to do more in a general review, such as Shorrocks (1989), than indicate a range of rates. On the one hand it is important to apply sufficient B to make a significant improvement in the uptake of B and on the other hand not to be wasteful or run the risk of toxicity.

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