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Boron Deficiency in Soils and Crops: A Review

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1. Introduction

Boron (B) is a unique non-metal micronutrient required for normal growth and development of plants. In 1923, it was first time reported that B is essential for cell structure of plants (Warington, 1923). The possible roles of B include sugar transport, cell wall synthesis, lignification, cell wall structure integrity, carbohydrate metabolism, ribose nucleic acid (RNA) metabolism, respiration, indole acetic acid (IAA) metabolism, phenol metabolism, and as part of the cell membranes (Parr & Loughman, 1983; Welch, 1995; Ahmad et al., 2009). In soils, concentration of total B is reported to be in the range of 20 to 200 mg B kg⁻¹ (Mengel & Kirkby, 1987), and its available concentrations also vary greatly from soil to soil.

Boron is absorbed by roots as undissociated boric acid [B (OH)₃ or H₃BO₃] (Mengel & Kirkby, 1982; Marschner, 1995) which has a strong ability to form complexes with diols and polyols, particularly with cis-diols inside the plant system (Loomis & Durst, 1992). Among the elements required by plants that are taken up from the soil, B is the only element that is taken up by plants not as an ion, but as an uncharged molecule (Marschner, 1995; Miwa & Fujiwara, 2010). The factors affecting B uptake include soil type (texture, alkalinity/calcareousness, pH, organic matter content), B concentration, moisture, and plant species (Welch et al., 1991). Boron absorption by plant roots is closely related to pH and B concentration in the soil solution; and is probably a non-metabolic process (Brown & Hu, 1998). The supplying mechanism of B to plant roots is primarily through mass flow, while its distribution in plants is governed by the transpiration stream through the xylem (Raven, 1980). Boron is relatively immobile in plant, and thus its availability is essential at all stages of growth, especially during fruit/seed development. However, recent physiological studies

have revealed the presence of channel-mediated facilitated diffusion and energy-dependent active transport against concentration gradients in B transport systems (Dannel et al., 2000, 2001; Stangoulis et al., 2001).

Boron deficiency is one of the major constraints to crop production (Sillanpaa, 1982), and has been reported in more than 80 countries and for 132 crops over the last 60 years (Shorrocks, 1997). Boron deficiency has been realized as the second most important micronutrient constraint in crops after that of zinc (Zn) on global scale. Boron deficiency has been reported to result considerable yield reduction in annual [fiber (cotton - *Gossypium hirsutum* L.), cereal (rice - *Oryza sativa* L., maize/corn *Zea mays* L., wheat - *Triticum aestivum* L.), legume/pulse (soybean - *Glycine max* L.), oilseed (groundnut - *Arachis hypogaea* L., oilseed rape/canola - *Brassica napus* or *B. rapa* L.)] and perennial [citrus fruit orchards, alfalfa - *Medicago sativa* L.] crops (Arora et al., 1985; Patil et al., 1987; Sakal et al., 1988; Ali & Monoranjan, 1989; Takkar et al., 1989; Dwivedi et al., 1990; Sinha et al., 1991; Borkakati & Takkar, 2000; Niaz et al., 2002, 2007; Rashid et al., 2005; Johnson, 2006; Zia et al., 2006). Rashid (2006) estimated a substantial potential net economic benefit from the use of B fertilizers in B-deficient crops.

Boron bioavailability decreases under drought condition because of reduced mobility of B from soil by mass flow to roots (Chiu & Chang, 1985; Chang et al., 1992; Chang, 1993; Barber, 1995). Boron can move relatively long distances by mass flow and diffusion to roots. Soil drying reduces B diffusion by reducing the mobility of soil solution and increasing the diffusion path length (Scott et al., 1975). The lack of moisture in soil reduces transpiration rate, thereby reducing B transport to shoots (Lovatt, 1985). Wetting and drying cycles and increasing soil temperature (25 to 45 °C) also increased B fixation by montmorillonite and kaolinite clays (Biggar & Fireman, 1960). Low temperature in spring and autumn season of temperate regions reduced availability of B to forage legumes while increased temperature enhanced B concentration for sugarcane (Gupta, 1993).

Boron deficiency has been commonly reported in soils which are highly leached and/or developed from calcareous, alluvial and loessial deposits (Takkar et al., 1989; Razzaq & Rafiq, 1996; Borkakati & Takkar, 2000). Several soil factors and conditions render soils deficient in B. For example, low soil organic matter content, coarse/sandy texture, high pH, liming, drought, intensive cultivation and more nutrient uptake than application, and the use of fertilizers poor in micronutrients are considered to be the major factors associated with the occurrence of B deficiency (Dregne & Powers, 1942; Elrashidi & O'Connor, 1982; Takkar et al., 1989; Goldberg & Forster, 1991; Rahmatullah et al., 1999; Eguchi & Yamada, 1997; Rashid et al., 1997, 2005; Mengel & Kirkby, 2001; Niaz et al., 2002, 2007; Rashid & Rayan, 2004). This paper reviews the roles of B in plant nutrition and the factors affecting B availability in soils in general, while focusing on a number of case studies related to diagnosis and correction of B deficiency in soils and crops.

2. Factors affecting boron availability in soils

Boron concentrations in soil vary from 2 to 200 mg B kg⁻¹, but generally less than 5-10% is in a form available to plants (Diana, 2006). Boron concentration and its bioavailability in soils is affected by several factors including parent material, texture, nature of clay minerals, pH, liming, organic matter content, sources of irrigation, interrelationship with other elements, and environmental conditions like moderate to heavy rainfall, dry

weather and high light intensity (Moraghan & Mascagni, 1991). Therefore, knowledge of these factors affecting B uptake is essential for the assessment of B deficiency and toxicity under different conditions.

Upon mineralization from organic matter or B addition to soils through irrigation or fertilization, a proportion of it remains in the soil solution while left of it is adsorbed by soil particles and other soil constituents. Tourmaline is a mineral which contains B in a very insoluble form while hydrated B minerals are the most soluble form of B minerals. These minerals do not usually determine the solubility of B in the soil solution (Goldberg, 1993), which is governed by B adsorption reactions mainly. The equilibrium exists between the soil solution and adsorbed B (Russell, 1973). Plants obtain B from the soil solution (Hatcher et al., 1959), and buffering against abrupt changes in the level of B in the soil solution is controlled by the adsorbed pool of B (Hatcher et al., 1962). Therefore, it is important to know the distribution of B between the solid and the liquid phases of the soil. Factors affecting the amount of B adsorbed by soils and the B bioavailability in soils include soil pH, texture, moisture, temperature, and management practices such as liming (Evans & Sparks, 1983).

2.1 Parent material

Parent material is considered a dominant factor affecting supply of B from the soil. Soils are quite variable in their B and clay forming minerals contents, and therefore have a fundamental effect on the availability of B. In general, soils derived from igneous rocks, and those in tropical and temperate regions of the world, have much lower B concentrations than soils derived from sedimentary rocks, and those in arid or semi arid regions (Ho, 2000). High B concentrations are usually found in the soils that have been formed from marine shale enriched parent material. Soils derived from acid granite and other igneous rocks, fresh-water sedimentary deposits, and in coarse textured soils low in organic matter have been reported with low B concentrations (Liu et al., 1983). Boron bioavailability is also reduced in soils derived from volcanic ash (Sillanpaa & Vlek, 1985) and in soils rich in aluminum (Al) oxides (Bingham et al., 1971). Soils along the sea shore as well as those derived from mudstone are usually B enriched. Conversely, lateritic soils, and soils derived from sandstone, slate or crystalline limestone do not contain much B. The levels of total B in common rocks are presented in Table 1.

Rock type	Minerals	B (mg B kg ⁻¹) ^z	B (mg B kg ⁻¹) ^y
Igneous	Basic: gabbro, basalt	5-20	5
	Intermediate: diorite	9-25	15
	Acid: granite, rhyolite	10-30	
Metamorphic	Gneiss	10-30	-
Sedimentary	Shale	120-130	100
	Sandstone	30	35
	Limestone dolomite	20-30	20

^zKabata-Pendias & Pendias, 1992; ^ySillanpaa & Vlek, 1985.

Table 1. Total B concentrations in major rock types

2.2 Soil reaction (pH)

Soil pH is one of the most important factors affecting the availability of B in soils. Its bioavailability becomes less at the higher solution pH. Consequently, application of lime to acid soils, in excessive amounts, can sometimes render plants deficient in B. There is a close association with the pH of the soil solution and the level of soluble B in soils (Elrashidi & O'Connor, 1982; Takkar et al., 1989; Rashid et al., 1994; Niaz et al., 2002, 2007). Boron uptake by plants growing in soil, with the same water soluble B concentration, was noticed to be higher where pH of the soil solution was lower (Wear & Patterson, 1962). The adsorption of B by soils is much dependent on pH of the soil solution. Boron adsorption by soils increased when the pH rose from 3 to 9 (Bingham et al., 1971; Mezuman & Keren, 1981; Keren & Bingham, 1985; Barrow, 1989), and it decreased when the pH was increased further in the range 10 to 11.5 (Goldberg & Glaubig, 1986). In several studies, highest levels of B adsorption by soil depicted close correlation with the pH of the soil solution (Okazaki & Chao, 1968; Evans, 1987; Shafiq et al., 2008).

2.3 Soil texture and clay minerals

Coarse-textured soils often contain less available B than fine-textured soils (Takkar et al., 1989; Raza et al., 2002; Malhi et al., 2003). This might be one of the reasons that B deficiencies in crop plants have often been observed on sandy soils (Gupta, 1968; Fleming, 1980). Niaz et al. (2002) concluded from a study in Punjab, Pakistan that B concentrations of coarse- and medium-textured soils and plants grown in such soils were lower than their respective critical levels, because these soils were well drained and had good leaching. Besides aluminum and iron oxides, calcium carbonate and organic matter, clay minerals are considered to be amongst the primary B adsorbing surfaces in soils (Goldberg, 1997). The mechanism of B adsorption on these surfaces is considered to be ligand exchange with reactive surface hydroxyl groups leading to strong specific adsorption (Goldberg & Chunming, 2007). Boron adsorption in fine-textured soils is higher compared with the coarse- and medium-textured soils at the same equilibrium concentration (Table 2). The level of native B is also closely related to the clay content of the soil (Elrashidi & O'Connor, 1982; Raza et al., 2002). At the same time, water soluble B concentration and B uptake are reported to be higher in plants grown in coarse-textured soils (Wear & Patterson, 1962). The level of B adsorbed by the soil thus largely depends on soil texture in addition to pH of soil solution. It increases with an increase in clay content (Bhatnager et al., 1979; Wild & Mazaheri, 1979; Mezuman & Keren, 1981; Elrashidi & O'Connor, 1982).

More B adsorption is commonly found in illite as compared with kaolinite or montmorillonite clay types. . In fact, kaolinite adsorbs B the least (Hingston, 1964; Fleet, 1965). Frederickson & Reynolds (1959) proposed that most of the B in the clay mineral fraction of sedimentary rocks is contained in the illite fraction. Sims & Bingham (1967, 1968a, 1968b) found that B adsorption was greater for iron (Fe) and Al coated kaolinite or montmorillonite than for uncoated clays. It was concluded that hydroxyl of Fe and Al compounds present in the layer as silicates or as impurities dominate over clay mineral species per se in determining B adsorption characteristics. Bingham et al. (1971) and Schalscha et al. (1973) also inferred that B adsorption by certain soils was primarily due to their Al oxide content.

Sand dune		Sandy loam		Black clay	
Equilibrium conc.	B adsorbed	Equilibrium conc.	B adsorbed	Equilibrium conc.	B adsorbed
3.8	1.2	3.0	2.0	1.2	3.8
7.8	2.2	6.4	3.6	3.8	6.2
16.5	3.5	14.8	5.2	8.5	11.5
25.0	5.0	24.0	6.0	14.0	21.0
34.0	6.0	33.0	7.0	14.0	21.0
43.0	7.0	42.2	8.0	25.0	25.0

^zSource: Gupta, 1979a.

Table 2. Boron adsorption (mg B kg⁻¹) in soils as affected by texture^z

2.4 Organic matter

Organic matter (OM) is the storehouse for most nutrients in soil and is known to improve soil health and availability of plant nutrients. Many researchers have suggested that the level of soil organic matter (SOM) influences the nutrient bioavailability (Sarwar & Mubeen, 2009). Boron may bind with OM or with carbohydrates released during humification. Boron associated with humic colloids is the principal B pool for plant growth in most of the agricultural soils (Jones, 2003). However, there is limited information on the role of OM in B nutrition. The strongest evidence that OM affects the availability of soil B is derived from studies that show a positive correlation between levels of SOM and the amount of hot-water-soluble B (Kao & Juang, 1978; Chang et al., 1983; Takkar et al., 1989; Niaz et al., 2002; 2007; Raza et al., 2002; Shafiq et al., 2008).

The association between B and SOM is said to be caused by the assimilation of B by soil microbes (Gupta et al., 1985). Albeit, B present in SOM is not immediately available to plants, it seems to be a major source of available B when it is released through mineralization (Gupta et al., 1985). It is well documented, that the interaction of dissolved organic matter (DOM) with soil is affected by the presence of OM and hydroxides in the clay fraction particles (McDowell & Likens, 1988; Jardine et al., 1989; Donald et al., 1993). The role of DOM to affect B availability/adsorption has already been reported by Mackin (1986) from pore waters of marine sediments and recently by Communar & Keren (2008) for soil-plant system. Further the B solution concentration assessment may be driven through interaction of effluent DOM with native soil OM, B complexation with DOM, and adsorption of B and B-DOM complexes by soil. Correlations of total dissolved boron (TDB) and ratios of B to chloride with DOM, in organic-rich sediments, predispose that the fraction of dissolved boron (DB) that is complexed by OM is a function of dissolved organic matter concentration (Mackin, 1986). It can be inferred that DB concentrations equilibrium is highly related with organic-B complexes. Further, such potentially useful approximation should also be applied for determining concentrations of organic-B complexes in marine waters and sediments. Both deep understanding of the mechanisms of these relations and parameterization according to the local conditions permit to improve the model for B transport in soil (Communar et al., 2004; Communar & Keren, 2005, 2006). But all these investigations call for more extensive research on role of DOM pertaining to B desorption/release.

2.5 Sources of irrigation water

There are two common sources of water to irrigate crops, i.e., canal water and tube well water. The soil B status, and its availability and toxicity to plants also depend on the source of irrigation water. Underground water used for irrigation purpose has been reported to contain toxic amounts of B in many parts (Uttar Pradesh, Rajasthan, Haryana, Punjab, and Gujrat) (Chauhan & Asthana, 1981) of India. This toxicity reduces growth, particularly of shoots, and causes chlorosis starting at the leaf tip and margins of mature leaves (Nable et al., 1997; Reid et al., 2004; Reid & Fitzpatrick, 2009). Similarly, underground water for irrigation in the western desert of Egypt was also shown to be high in B (Elseewi, 1974). Boron toxicity has been reported in many crops irrigated with high-B water in Spain (Salinas et al., 1981), Arizona (Ryan et al., 1977), northern Greece (Sotiropoulos, 1997) and Philippines (Dobermann & Fairhurst, 2000). Ahmad et al. (2004) conducted a survey to determine the B concentrations in canal and ground waters used for irrigation in different villages of Faisalabad (Pakistan). The results showed that B in the tube well waters collected during February-March ranged from 0.14-0.65 mg B L⁻¹ [standard deviation (SD) = 0.16] with a mean of 0.38 mg B L⁻¹, and those collected in July-August ranged from 0.52 to 0.66 mg B L⁻¹ (SD = 0.28), with a mean 0.56 mg B L⁻¹. Boron in river water samples collected during February-March ranged from 0.11 to 0.43 mg B L⁻¹ (SD = 0.10), with a mean of 0.21 mg B L⁻¹. The authors concluded that tube well waters contain higher B concentrations compared to the canal waters, so farmers should get their water samples analyzed prior to irrigation and should consider these B concentrations in order to adjust B fertilizer doses to crops. This suggests that farmers using these waters for irrigation of their crops should pay attention to this potential source of B availability. This recommendation is of prime importance, because B is the unique element in the sense that there is a very narrow range between its deficient and toxic levels (< 0.5 mg B kg⁻¹ and > 5 mg B kg⁻¹, respectively). Farmers can calculate the amounts of B being added to their fields through irrigations of canal and tube well water. These results are also in line with those of Sillanpaa (1982) and Keren & Bingham (1985).

2.6 Interactions of boron with other nutrients

Some functions of B interrelate with those of nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca) in plants (US Borax, 2009). Its interaction (synergistic, antagonistic) with most of the nutrients (N, P, K, Ca, Mg [magnesium] Al [aluminum] and Zn) may be sometimes influential in regulating B availability to plants in soil. Application of B may improve the utilization of applied N in cotton plants by increasing the translocation of N compounds into the boll (Miley et al., 1969). Smithson and Heathcote (1976) found that when B deficiency occurred in cotton, the application of 250 kg N ha⁻¹ reduced the yield. However, when B was applied, crop biomass escalated with the same dose of N.

Graham et al. (1987) found that B uptake by barley (*Hordeum vulgare* L.) was lower when Zn was applied compared to in its absence. Further, they also showed that rate of B accumulation in plants is increased even at low levels of Zn and high levels of P. Therefore, Zn fertilization may reduce B accumulation, and lessen the risk of toxicity in plants (Ahmed et al., 2008). A significant relationship has been found between K and B fertilizers regarding their assimilation/uptake by crop plants as well as crop produce (Hill & Morrill, 1975). At heavy applications of K and other intensive production practices B may need to be applied to prevent reduction in corn yield (Woodruff et al., 1987). , Yang & Gu (2004) studied the

effect of B on Al toxicity on seedlings of two soybean cultivars. The results showed that high B was found to ameliorate Al toxicity by significantly increasing the growth characters including root length under 2 mM Al stress, and epicotyl length and fresh weight under 5 mM Al stress of the two cultivars. Similar kind of study was conducted by Hossain and Hossain (2004) which confirmed the relationship of B with Al. The ratio between Ca and B in the plant is sometimes used to identify B deficiency. In a recent study, application of the both Ca and B to four cultivars of maize significantly enhanced shoot dry matter production (Kanwal et al., 2008). Nevertheless, B concentration in the shoot of maize cultivars was antagonized with Ca application. A curvilinear relation was exhibited between Ca/B ratio in shoot and relative shoot dry matter. In this regard, further work is warranted on Ca/B utilizing association for ameliorating B deficient calcareous soils (Rashid et al., 1997).

3. Sensitivity of crop species/cultivars to boron deficiency

Crop species differ in their capacity to take up B, even when they are grown in the same growth medium. These differences generally reflect different B requirements for growth. In general, dicots (cotton and leguminous plants) have 4-7 times higher B requirement (20-70 mg B kg⁻¹) than monocots (graminae family), 5-10 mg B kg⁻¹ (Bergmann, 1988, 1992; Marschner, 1995). As the most important functions of B in plants are thought to be its structural role in cell wall development and stimulation or inhibition of specific metabolism pathways (Gupta, 1979a, 1979b, 1993; Ahmad et al., 2009), thereby, differences in the B demand of graminaceous and dicotyledonous species are probably related to the differences in their cell wall composition, and cis-diol configuration in the cell walls, such as pectic substances. A meager amount of pectic material is constituted in the cell walls of graminaceous species (wheat and rice). Such species also have much lower Ca requirements. In fact, these two plant categories also differ in their capacity for silicon (Si) uptake, which is usually inversely related to B and Ca requirements (Loomis & Durst, 1992). All the three elements are located mainly in the cell walls. Brown & Shelp (1997) and Brown & Hu (1998) concluded that knowledge of the relative mobility of B within a particular species determines the optimum fertilization strategy and the same can also be used in partial understanding of the causes and consequences of B deficiency.

In summary, B deficiency is commonly induced under the following soil conditions; 1) soils which are inherently low in B, such as those derived from the parent material made from acid granite and other igneous rocks, and freshwater sedimentary deposits, 2) leaching impacted naturally acid soils from which native B has been removed, 3) light-textured sandy soils and gravelly soils, 4) alkaline and calcareous soils, 5) irrigated soils having low B concentration in irrigation water, and where salt or carbonate has been deposited, and 6) soils low in OM.

4. Diagnosis and correction of boron deficiency

4.1 Identification of boron deficiency

Boron is very vulnerable to leaching, so its deficiency can temporarily be expected in countries like Pakistan and India during and after monsoon rains, especially in coarse-textured soils. However, its major source mineral (i.e., tourmaline) is highly insoluble. In Pakistan, Alfisols appear to be the soil group most likely to produce B-deficient crops (Zia et

al., 2006). Singh (2001) explored that out of 36,825 soil samples collected throughout India, 33% were deficient in B. In India, laterite and lateritic soils (Ferralsols and Dystric Nitisols) have been widely reported for the deficiency of B. Boron deficiencies are also more pronounced during drought periods when root activity is restricted. Once B has accumulated in a particular organ, it has restricted mobility in most plant species but not all. Boron is immobile in plants, so its deficiency symptoms develop firstly, and are more severe, on young leaves with marginal, dull yellow chlorosis at the tip of young leaves. Because B plays an important role in the elongation of stems and leaves, stems of B deficient plants are short and stout. If B deficiency is severe, many tillers can die before maturity, or whole plant may die before producing heads. Boron deficiency also manifests itself in poorly developed stamens, blast of pear blossoms, inadequate fruit set, bark necrosis of apple, corking in the fruit, and cracking of fruit. When leaf B levels are in the range of 20 to 25 mg B kg⁻¹ (desired is 35 mg B kg⁻¹) on a dry-weight basis, supplemental B is needed. Boron is taken up from the soil only at higher soil temperatures than are other elements. Most values of the critical concentration for B deficiency range from 0.15 to 0.50 mg kg⁻¹ soil (HWE – hot water extractable). However, in highly sensitive crops and alkaline clay soils, these values can double. This is because, B sorption increases to a maximum between pH 7.5-9.5. Hence, the critical range of extractable B is generally higher in alkaline soils. For example Bell (1997) reported that for wheat grown on alkaline clay soils in northern China, a critical range of 0.32-0.38 mg B kg⁻¹ (HWE) was proposed, whereas on loams in northern Thailand the figure was 0.12-0.15 mg B kg⁻¹. The critical concentration of B (HWE) in soils which is considered deficient to most crops in Pakistan was 0.45-0.50 mg B kg⁻¹ until revised recently to 0.65 mg B kg⁻¹ (Rashid et al., 1994; Rashid, 2006). Singh (1994) concluded that depending upon groundnut genotypes and soil, the critical limits of B may vary from 0.2-0.4 mg B kg⁻¹.

4.2 Sources, rates, methods and timing of boron application

There are eight different sources of B [borax (Na₂B₄O₇·10H₂O with 11% B), solubor - Na₂B₈O₁₃·4H₂O (20% B), sodium borate (Na₂B₄O₇·5H₂O with 20% B), sodium tetraborate (Na₂B₄O₇·5H₂O with 14% B), boric acid (H₃BO₃ with 17% B), Colemanite (Ca₂B₆O₁₁·5H₂O with 10% B), B frits containing 2-6% B, and boronated superphosphate being used to prevent/correct B deficiency in crops. Borax, solubor, sodium borate and sodium tetraborate have been most commonly used for soil application. Boric acid, colemanite and B frits are considered to be more promising on highly leached sandy soils as well as for long duration field crops including perennial forages and fruit plants owing to their low solubility and slow release of B. Boronated superphosphate has also been tried to correct B deficiency in crops (Patil et al., 1987).

Among these B fertilizer sources, borax is the most commonly used B fertilizer to prevent and/or correct B deficiencies in crops. Because of the narrow margin between B sufficiency and toxicity, an excess dose can easily occur and harm plant growth (Gupta, 1972; Marschner, 1995). Therefore, extreme care is needed to apply the correct dose of B fertilizer and to distribute it uniformly. Boron application rates generally range from 0.25 to 3.0 kg B ha⁻¹, depending on crop requirement and the method of application (Arora et al., 1985; Nuttall et al., 1987; Patil et al., 1987; Sakal et al., 1988; Ali & Monoranjan, 1989; Dwivedi et al., 1990; Sinha et al., 1991; Mortvedt & Woodruff, 1993). Higher rates are

required for broadcast applications than for banded soil applications or foliar sprays. Because B is immobile in plants, B deficiency in crops growing in soils with marginal B levels can occur during peak growing periods (vegetative, flowering, and seed development stages), so a steady supply of B throughout the growing season is essential for optimum growth and seed yield. Foliar fertilization is also an effective way to supply B to plants, especially when root activity is restricted and B deficiency in crop appears under dry soil conditions in the growing season (Mortvedt, 1994). Experiments regarding the effect of B on yield, mobility and stress tolerance in different crop species revealed that B significantly enhanced yield and it was attributed to the significant increase in the panicle fertility. In extreme cases, crops on low B soils grow well until flowering when floral abortion or seed set failure can result in severe yield losses. Boron deficiency at critical stages of reproductive development has been shown to cause pod abortion with poor seed setting in wheat in Western Australia (Wong, 2003). Boron application at the onset of reproductive phase was found to be more effective, most likely due to its immobile nature in the plants depending upon the photosynthetic efficiency of the plants (Anonymous, 2007a). These findings are in agreement with the recent work of Ahmad et al. (2009).

Relatively small amounts of B that are normally required to make significant improvements in B status of annual crops, 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 (Shorrocks, 1997). Application of 10 kg of boric acid ha⁻¹ (1.7 kg B ha⁻¹) or 18 kg of borax ha⁻¹ (2.0 kg B ha⁻¹) proved to be effective for 4–5 years in order to cure B deficiency in rice, wheat and cotton soils. It was found that in case of cotton, 0.1% solution of B would be economical if used with insecticides foliar sprays. Value cost ratios (VCR) for B use in these crops have been very good, particularly in the case of cotton, where it ranged from 5:1 to 13:1 by soil application and 20:1 by foliar application of B. It was revealed that application of B significantly boosted rice yield, mainly because of increase in the panicle fertility (Anonymous, 2007b). Application of B fertilizers up to 2.5 kg B ha⁻¹ is recommended for major crops like cotton, rice and wheat in Pakistan (Anonymous, 1998). Boron may safely be applied to orchard crops at a rate of 0.56 kg B ha⁻¹ as a maintenance dose and at a rate of 1.12 kg B ha⁻¹ as a deficiency dose (Zia et al., 2006) and its residual effect has generally been reported for at least two years. In the case of borax, application rates should not exceed 90 g borax per orchard tree (Zia et al., 2006).

In India, soil application of B at 20 kg sodium tetraborate to supply 2.8 kg B ha⁻¹ as well as two foliar sprays with 0.2% solution of this salt proved equally effective in increasing soybean grain yield and the residual effect of soil applied B on subsequent wheat crop was significantly higher as compared with direct foliar B application (Table 3). Since B undergoes less leaching in fine-textured soils, single application may produce residual effect. In view of very sharp and narrow difference between optimum and toxic levels of B, more precaution is needed in its repeat application, particularly in medium- to fine-textured soils. Boron deficiency is also invariably corrected by its soil application depending upon soil type (Arora et al., 1985; Sakal et al., 1988; Ali & Monoranjan, 1989). In calcareous soils of Bihar, the rate varying between 1.0 to 2.5 kg B ha⁻¹ has been found to be optimum for different crops (Sakal et al., 1988; Sinha et al., 1991).

Treatment	Grain yield (Mg ha ⁻¹)	
	Soybean	Wheat
Soil Application (20 kg sodium tetraborate ha ⁻¹)	1.41	1.46
Foliar application (0.2% sodium tetraborate soil)	1.33	1.35
Control	0.89	0.66
LSD (p=0.05)	0.1	0.11

^zSource: Dwivedi et al., 1990.

Table 3. Effect of mode of B application on grain yield of soybean and wheat^z

5. Yield response of selected crops to boron fertilization

5.1 Cotton

Cotton (*Gossypium hirsutum* L.) is an important fiber crop grown in many countries of the world. There are several factors responsible for low yields of cotton, and micronutrient deficiency is one of them. Boron has been recognized as the most important micronutrient for cotton production in some countries. Its deficiency inhibits petiole and peduncle cell development and reduces growth of cotton (De Oliveira et al., 2006). In a number of studies, application of B fertilizer has been shown to increase cotton yield (Murphy & Lancaster, 1971; Rashid, 1995, 1996; Anonymous, 1998). Research has shown that as little as 1.1 kg of B ha⁻¹ can increase cotton seed yield by more than 560 kg ha⁻¹ (US Borax, 2002). In Pakistan, 50% cotton fields have been reported to be deficient in B (Anonymous, 1998). Cotton is very responsive to B fertilization on B deficient soils. For example, in a study in Pakistan with 30 field experiments, B application has been reported to increase cotton yield in the range of 2 to 30%, with an average value of 14%, over the zero-B control (Malik et al., 1992; Rashid, 1995, 1996; Anonymous, 1998). The value cost ratio (VCR) data indicated that by spending one rupee on B fertilizer, crop yield increase was worth Rs. 5 to 20 (average Rs. 16) in cotton (Anonymous, 1998). Use of B and Zn fertilizers proved highly profitable, benefit cost ratio being 15:1 for soil application and 30:1 for foliar spray (Rashid & Akhtar, 2006). Niaz et al. (2002) conducted field experiments on cotton at 13 different sites in Punjab, Pakistan; five were medium-textured (clay loam), two were silty clay, one was loam, and five were coarse-textured (sandy loam or loamy sand). Of the 13 soils, 12 were found deficient in B (less than 0.5 mg B kg⁻¹ 0.05M HCl extractable). Boron concentration in younger leaves, at flowering stage and harvest, ranged from 7.8 to 23.8 mg B kg⁻¹ with an average of 11.4 mg B kg⁻¹, whereas only one of the 13 samples had adequate B concentration (15 mg B kg⁻¹). Similar results have also been reported from Australia (Reuter & Robinson, 1986; Shorrocks, 1997), Egypt (Ibrahim et al., 2009), Turkey (Gormus, 2005) and USA (Zhao & Oosterhuis, 2003). In Taiwan, Smithson & Heathcote (1976) found that when B deficiency occurred in cotton, the application of 250 kg N ha⁻¹ reduced the yield. However, if B was applied, the same application of N increased the crop yield. In pot experiments, application of 0.06 g of borax to 40 kg soil, deficient in B, was sufficient to overcome B deficiency problem in cotton. In field experiments, 10 to 30 kg ha⁻¹ of applied borax (to supply 1.1 to 3.3 kg B ha⁻¹) was enough to prevent B deficiency. Since B is essential for the transfer and assimilation of sugars and N into complex carbohydrates (fiber) and protein, demand for this element is the greatest during lint and seed development (Lancaster et al., 1962).

5.2 Rice

Rice (*Oryza sativa* L.) is grown worldwide, but it is one of the most important cereal grains especially in Asia. Severe B deficiency has been reported in 10-45% rice fields in Pakistan (Tahir et al., 1990; Zia, 1993) and 1-69% (average 33%) rice fields in India (Singh, 2001). Average increase in rice paddy yield with B application in 22 field experiments was 14% over the zero-B control (Anonymous, 1998). Results of recent research have shown 15-25% increase in seed yield over N, P and Zn, coupled with appreciable improvement in grain/cooking quality (more recovery and less breakage of kernels during milling, greater grain elongation, less bursting and less stickness upon cooking) with application of B (Rashid et al., 2009). The authors also found that the B use in rice was highly profitable. Similarly, Mehmood et al. (2009) worked on three rice cultivars [viz., KS-282 (salt-tolerant), BG-402-4 (mixed behavior) and IR-28 (salt-sensitive)] to investigate the ameliorative nutritional aspects of B. Boron was applied at 25, 50, 100, 200, 400 and 800 ng B mL⁻¹ in the presence (80 mol m⁻³) and absence (0 mol m⁻³) of NaCl salinity, whereas in solution culture B was applied at 1.5, 3.0 and 6.0 kg B ha⁻¹ to saline [electrical conductivity of saturated paste extract (ECe) 9.0 dS m⁻¹, sodium adsorption ratio (SAR) 5.46, and pH 7.8), and saline-sodic soils (ECe 9.0 dS m⁻¹, SAR 28.2, pH 8.2]. Application of B improved all growth parameters, i.e., tillering capacity, shoot and root length, and shoot and root weight at external B application rates of 200-400 ng B mL⁻¹ in solution culture in the presence and absence of NaCl salinity. Moreover, rice cultivars have shown differential response to B application (Table 4). In contrast, a marked increase in the paddy rice yield with the application of B was also reported in a non-saline soil (Chaudhry et al., 1976). Increasing supply of B increased the accumulation of B in roots and shoots (Nable et al., 1990; Akram et al., 2006). Vasil (1987) reported that the stigma, style and ovary often contain high concentration of B, and this B occurs in pollen at about 0.7 mg B kg⁻¹ dry weight.

B concentration (mg B kg ⁻¹) in leaves				
SN.	Cultivar	Control (no B)	B applied	Remarks
1	Super Basmati	7.58	11.24	B concentration in leaves of different cultivars increased with B application
2	Basmati-6129	9.36	16.19	
3	DR-83	9.07	14.70	
4	KS-282	9.86	16.67	
5	Basmati-385	7.14	8.42	
6	Pakhal	9.29	11.56	
7	Basmati-370	7.43	9.79	
8	IR-6	8.62	11.31	

^zAdapted from Rashid et al., 2005.

Table 4. Response of B concentration in leaves of different rice cultivars to B application^z

5.3 Wheat

Wheat (*Triticum aestivum* L.) is amongst the major cereal crops grown in almost every part of the world. Boron deficiency in wheat field was first observed almost concurrently on different sides of the world following the spread of semi-dwarf wheat in the 1960s (Rerkasem & Jamjod, 2004). Its deficiency has been reported to cause grain set failure and considerable yield losses in the

wheat belt of the world's wheat growing countries (Rerkasem & Jamjod, 2004; Rerkasem et al., 2004). Since introduction of green revolution cases of severe B deficiency have been reported from several wheat growing countries of the world (Li et al., 1978; da Silva & de Andrade, 1980; Misra et al., 1992). Bangladesh, Brazil, Bulgaria, China, Finland, India, Madagascar, Nepal, Pakistan, South Africa, Sweden, Tanzania, Thailand, USA, USSR, Yugoslavia and Zambia are amongst the countries where B fertilization response based B deficiency, in wheat has been reported (Shorrocks, 1997). The B deficiency prone regions are believed to be in adjoining areas of eastern Nepal, northeastern India and northwestern Bangladesh, through to southwestern China (Rerkasem & Jamjod, 2004; Bhatta & Ferrara, 2005). Boron application on such fields (B-deficient soils) can make profound contributions to grain yield in wheat (Chakraborti & Barman, 2003; Soylyu & Topal, 2004). In Pakistan, Chaudhry et al. (2007) conducted a study to identify the wheat response to micronutrients (B, Fe, Zn) in rainfed areas. The authors observed an increase in the yield of wheat and other crops (rice, maize and cotton) in a number of field experiments in response to B application. Summary of 16 field experiments revealed that application of B contributed 16% increase in grain yield, and also increase in value to cost ratio (VCR) over the zero-B control (Table 5; Anonymous, 1998). Further, genotypic differences were observed among wheat cultivars for their response to B application (Table 6).

Crop	Field experiments	Control yield (Mg ha ⁻¹)	Yield increase (%)	VCR
Wheat	16	3.286	14	4:1
Rice	19	3.081	14	5:1
Maize	9	2.512	20	7:1
Cotton				
Soil	30	2.377	14	16:1
Foliar	13	2.156	12	33:1

^zSource: Anonymous, 1998.

Table 5. Yield responses and crop value to cost ratios (VCR) of four major crops to B fertilizer application in field experiments, Pakistan^z

B concentration (mg B kg ⁻¹) in leaves				
SN.	Cultivar	Control (no B)	B added	Remarks
1	Rohtas-90	5.2	11.0	All cultivars showed a positive response to B application as depicted from the increase in B contents of the leaves
2	Sindh-81	9.0	17.0	
3	Faisalabad-85	8.0	10.3	
4	Rawal-87	9.3	18.0	
5	Pak-81	8.7	15.8	
6	Sariab-92	10.0	19.5	
7	Inqalab-91	7.2	20.7	
8	Bakhtawar	11.0	21.0	

^zAdapted from Rashid et al., 2005.

Table 6. Response of B concentration in leaves of different wheat cultivars to B application^z

5.4 Oilseed *Brassica* spp.

Canola or oilseed rape (*Brassica* spp. L.) is one of the major oilseed crops grown worldwide. Canola is considered to have high requirements for B. In addition, a steady supply of B during the peak vegetative, flowering, pod production and seed development stages is needed for optimum seed yield of canola. Deficiency of B at any growth stage in canola can severely affect its seed yield (US Borax, 1996). Research has shown that application of B fertilizers can be most effective if incorporated into the soil, seed and band placement may have toxic effects, and foliar application may be very effective to supply B to plants when deficiency is noted in the growing season. Foliar fertilization is an effective way to supply B to plants, especially when root activity is restricted by dry soil (Mortvedt, 1994). In a field study comparing rapeseed (*Brassica campestris* L.), barley (*Hordeum vulgare* L.) and potato (*Solanum tuberosum* L.) test crops, rapeseed showed the largest response to B fertilization (Wooding, 1985). In that study, symptoms of B deficiency on rapeseed plants did not appear until upper parts of the plants formed pods, with seed development limited to only those pods located on the lower parts of the plant. Also, B deficiency delayed maturity and kept the plants in an indeterminate stage of growth with flowers forming up to the time of the first killing frost. In other study in Alberta, Canada, B-deficient oilseed rape appeared normal in early growth stages, showed red margins and/or inter-veinal mottling at bloom stage and had reduced seed set (Nyborg & Hoyt, 1970).

In China, on a clayey soil with 0.7 mg B kg⁻¹, application of B fertilizer to *Brassica napus* L. improved plant height, pod-bearing branches and pod number per plant, seed number per pod, seed yield and oil content (Hu et al., 1994). Recently, Shi & Wang (2009) reported decrease in seed yield in oilseed rape (*Brassica napus* L.) with B deficiency. In Pakistan, based on various nutrient indexing field experiments on rapeseed-mustard, Rashid (1993, 1994) reported that 65% of the tested sites were deficient in B under the agro-ecological conditions. Oilseed crops responded well to B application for the reported B-deficient sites in Pakistan (Anonymous, 1998). In other studies, canola yield was not affected by B fertilization, although B concentration in plants was significantly increased and 20-30 mg B kg⁻¹ in plant tissue was considered adequate for optimum yield (Bullock & Sawyer, 1991). In the Parkland region of western Canada, canola grown on Gray Luvisol soils has sometimes shown failure of flower bud development and poor seed set, more often on sandy soils. Deficiency of B was suspected to be responsible for these conditions because the symptoms match B deficiency symptoms (Grant & Bailey, 1993). In an earlier study on the Parkland region soils of Saskatchewan, B fertilization was observed to enhance rapeseed yield in a greenhouse experiment but its effect was not consistent in field experiments (Nuttall et al., 1987). In another field study in Saskatchewan, Canada, application of B fertilizer did not have any consistent influence on seed yield increase of canola, grown on soils ranging between 0.11 to 0.82 mg plant-available B kg⁻¹ (Malhi et al., 2003).

5.5 Maize/corn

Maize (*Zea mays* L.) belongs to Graminae family. It ranks second (after wheat) in the world cereal production. Contribution to world corn/maize production is 2% from India, while it is 10% from China, and U.S. contribution to the total maize production of the world is

known to be 43%. Approximately 80% of the maize production in Pakistan is concentrated in North West Frontier Province and Northern and Central Punjab. Maize in Pakistan is cultivated as a multipurpose food and forage crop, therefore the economic potential of this important crop is overwhelming (Khan et al., 2008). According to National Fertilizer Development Centre, (NFDC), forty percent (40%) maize fields in Pakistan, surveyed for fertility status, have been reported to be deficient in B (Anonymous, 1998). Boron application on nine fields exhibiting B deficiency in maize has shown to be very effective for yield increases, ranging from 12% to 35%, with an average increase of 20% over zero-B control. Maize yield increases worth of 5-15 Rs. (mean Rs. 7) have been documented after spending one rupee on B fertilizer (Anonymous, 1998). In a study in India, Mishra & Shukla (1986) reported considerable increase in plant height, metabolic rate, content of photosynthetic pigment and all dry weight fractions measured after the application of B containing amendment to maize.

5.6 Groundnut/peanut

Groundnut (*Arachis hypogaea* L.) belongs to Leguminosae family and is known as arachide in France, mani or cacahuete in Spain, pistachio di terra in Italy, erdnuss in Germany and amendoim in Portugal. Farmers in Asia and Africa grow 90% of the world's total groundnut production. The leading groundnut growing countries include India, China and USA. Groundnut is also one of the important cash crops of the Potohar plateau in the Punjab province of Pakistan. The crop is grown under rainfed conditions on relatively poorly fertile alkaline-calcareous soils with no adequate fertilization history (Rashid et al., 1997). Its average yield in Pakistan is reported to be 921 kg ha⁻¹ (Anonymous, 2009) and is much less as compared with the average yields of some other countries, e.g., in China, 2180 kg ha⁻¹ (Luo et al., 1990). As in alkaline and calcareous soils B is deficient (Tisdale et al., 1993), its deficiency is suspected in a highly sensitive crop species like groundnut (Katyal & Randhawa, 1983; Luo et al., 1990) when grown over such a soils. Application of B on such soils has shown positive results throughout the world.

In Pakistan, 50% B-deficient test sites have been reported in farm fields with groundnut, based on multi-locations field trials by Rashid & Qayyum (1991) and Rashid (1993, 1994). The value cost ratio (VCR) data of NFDC (Anonymous, 1998) indicated that by spending one rupee on B fertilizer, crop yield increase was worth Rs. 11 in groundnut. Seed yield increases in groundnut have been reported from 9 to 12% by borax application in B deficient Chinese soil (0.3-0.5 mg B kg⁻¹) by Zhang et al. (1986). A 10% increase in pod yield of groundnut after B fertilization over the control) was obtained with 1 kg B ha⁻¹ (Rashid et al., 1997) in Pakistan. Encouraging responses of groundnut to B application have also been recorded in India, with average pod yield increase of 180 kg ha⁻¹ (Takkar & Nayyar, 1984). In China, Zhang et al. (1986) and Luo et al. (1990) indicated that 1 kg B ha⁻¹ (borax) can be the optimal B fertilizer requirement of groundnut. Foliar application of B is also very effective and it can be used with herbicides for groundnut. Nonetheless, B use in Pakistan is not a promising practice in groundnut as it is a low-input high-risk rainfed crop. Since internal B requirements of various groundnut genotypes vary greatly; a viable and practical solution of managing B deficiency in groundnut could be the screening of the available germplasm with respect to its sensitivity to B deficiency (Rashid et al., 1997).

5.7 Alfalfa

Alfalfa (*Medicago sativa* L.; also called lucerne) is one of the most important forage crops globally. It is well adapted to a wide range of growing conditions on soils of varied fertility. Boron deficiency caused nutritional disorders are quite common (Shorrocks, 1997; Dell & Huang, 1997). Its deficiency in alfalfa is causative of leaf yellowing, reddening of the upper leaves, shorten internodes and rosette appearance of the plant. At this stage the growing point becomes dormant or dies, flowering is reduced and the flower falls before setting seed (Bell, 1997; Shorrocks, 1997). Boron and other micronutrients applications on Indian soils for alfalfa have shown positive results in the form of increase in forage and seed yield (Kormilitsyn, 1992; Hazra & Tripathi, 1998; Patel & Patel, 2003). In a study on Chinese soils, B application along with other micronutrients increased yield and crude protein content in alfalfa (Wang & Chen, 2003; Liu & Zhang, 2005). Rammah & Khedr (1984) reported positive response of alfalfa to B application in some Egyptian soils.

Alfalfa is sometimes grown on the Coastal Plain of southern United States, but poor soil fertility status is one of the production problems in these areas. Field-scale demonstrations have shown a considerable increase in alfalfa forage yields (3.9 Mg ha⁻¹ or 159%) with B application. The sustainable economic production is possible under rainfed conditions on selected, limed Coastal Plain soils of US with improved methods of site selection, adequate fertility and management guidelines (Haby & Leonard, 2000, 2005).

In a field study (Greece), foliar B application helped to increase the percentage of pods formed per inflorescence up to 52% as compared with the control. However, no significant difference between the different rates of B application was observed. The seed yield was increased by an average of 37% compared with the zero-B control during the second year at both locations. Moreover, foliar application of B improved seed germination and increased seed vigor which was increased by 27% in 2003 and up to 19% in 2004 as compared with the control (Dordas, 2006). Recently in a field study on calcareous soils in eastern Turkey, Turan et al. (2010) have also reported positive responses to B application. The authors concluded that lucerne production requires B addition to alleviate natural B deficiency problem in soils. This study warrants further studies with different soils and initial soil test B levels needed to conclude critical soil and tissue values for wider application across the region.

5.8 Soybean

Soybean (*Glycine max* L.) belongs to Leguminosae family. China, India and Indonesia are the leading soybean growing countries after USA. The occurrence of B deficiency based on responses at farmers fields have been reported for many countries like Australasia (China, India, Korea, Thailand), Europe (USSR) and in South America (Shorrocks, 1997). Generally, B deficiency is a common problem for this crop, especially when grown on alkaline calcareous soils of the world. The alkaline, silt, and sandy loam soils in Northeast Arkansas are also known to suffer from B deficiency (Anonymous, 2007a). Soybean is known to respond positively to B application on deficient sites of the world (Wu, 1986; Kirk & Loneragan, 1988). The increase in oil content and other quality parameters in soybean with combined application of B and sulfur in India have been noticed by Dinesh & Sudkep (2009), and Kumar & Sidhu (2009). In another study, Eguchi (2000) found a depressing effect of B deficiency on growth, yield, and protein and fat contents in the grains of soybean.

Boron application was also found to ameliorate Al toxicity by increasing growth characters (Yang & Gu, 2004). Furthermore, the genotypic variations in responses to B and other micronutrients (Zn, Mn) deficiencies have been observed by Graham & Heavner (1993) at the cellular level. In other field experiments the susceptibility of soybean cultivars to B deficiency was examined on "Typic Tropaqualf soils" in Northern Thailand, where B deficiency depressed seed yield by 60% in different cultivars. Sometimes, B deficiency also induced a localized depression on the internal surface of cotyledons in soybean seeds resembling to the symptom of 'hollow heart' in peanut. However, addition of B either decreased or eliminated such symptoms. In a comparative study of 19 soybean cultivars, the incidence of hollow heart symptoms in seeds at control (zero-B) appeared to be 75% but by the addition of only 1% B it reduced from none to 36%. The results suggested that susceptibility to B deficiency is sufficiently important and variable among soybean genotypes to warrant its inclusion as a selection criterion when breeding cultivars for areas with low soil B (Rerkasem et al., 1993).

5.9 Potato

Potato (*Solanum tuberosum* L.) belongs to Solanaceae family. Potatoes were probably brought to the Indian sub-continent hundred years ago by the Portuguese, and its cultivation expanded under British colonial rule in the 19th century (Geddes et al., 1989). The occurrence of B deficiency in potato based on responses at farmers fields have been reported in Australasia (Australia, China, India, Pakistan), Europe (Belgium, Czechoslovakia, Finland, Germany, Hungary, Sweden, USSR), and USA (Shorrocks, 1997). Despite favorable diversity of soils, climate and agricultural practices for potato cultivation, the average yield of potato has been reported to be 20.3 Mg ha⁻¹ in Pakistan (Anonymous, 2008). Imbalanced use of fertilizers is one of the main reasons for this low yield (Nazli, 2010). Thus, the balanced use of micro and macronutrients (B, Zn, N, P and K) can considerably increase the yield. Lora (1978) obtained B responses in potato crop on Andosols soils in Colombia. Boron has also been identified to play a key role in forming abscission layers such as scar tissues at the stem end of potato at maturity that seals the tuber and thereby preventing it from diseases and bacterial infection on its storage. In a study, the growth of potatoes in sand cultures with zero-B resulted in poor vigour, yield and quality of tuber. Application of even 1 µg mL⁻¹ B resulted in normal growth (Hill, 1936). Potatoes have shown positive response to B application if drilled in the row with fertilizer (Midgley & Dunklee, 1947). Higher rates of B were suggested if it was broadcasted and worked into the soil. In Pakistan, application of B fertilizer on three fields exhibiting B deficiency in potato has shown to be very effective for yield increases, ranging from 15% to 30%, with an average increase of 21% over zero-B control (Anonymous, 1998). Potato yield increases worth of Rs. 9 to Rs. 40 have been documented after spending one rupee on B fertilizer.

5.10 Citrus fruits

Citrus production is one of the world's largest agricultural industries. It is sown in more than 125 countries in the belt within 35° latitude north and south of equator (Duncan and Cohn, 1990). In addition to other factors, micronutrient deficiency (including B) is also considered among constraints that are currently hampering citrus yield (Johnson, 2006). In Pakistan, B deficiencies have been exhibited in citrus and other deciduous fruits (Tariq et al.,

2004; Zia et al., 2006). Its deficiency decreases growth and photosynthesis, and increases starch and hexoses in leaves of citrus seedlings (Han and Chen, 2008). Soil and plant analysis showed that > 50% of the cultivated soils of Pakistan were unable to supply sufficient B to meet the needs of many crops (Khattak, 1995) including citrus. Keeping in view the export potential for this crop, in a survey, 1250 citrus orchard growers were interviewed and soil samples were selected from their respective orchards in district Sargodha of Punjab to investigate B application trend and its suspected deficiency. The results revealed that out of the 1250 citrus growers majority (58.8%) never used the B since the establishment of their orchards, 18.4% farmers were in a practice of using recommended doses of macro and micronutrients depending upon their current financial position, while 11.6% citrus growers seasonally applied B (Table 7). Only 140 (11.2%) farmers were in a habit to use recommended doses of B. This percentage of the growers (11.2%) is the main contributor to the foreign exchange while exporting citrus.

In Pakistan (citrus belt, Sargodha), soil samples from varied depths (0-22.5 and 22.5-45 cm) were analyzed for B concentrations by Azomethine-H method (Ponnamperuma et al., 1981). Forty eight percent (600) orchards (samples) were found to be deficient in B. Since, in the past, farmers used to fertilize their citrus orchards without any soil testing, nutrient problem were common. Other reasons for B deficiency in the orchards might be due to the effect of sampling time. As the samples were taken during the monsoon season, this sampling time could be one of the reasons to affect B concentrations. These results are in agreement with the findings of Zia et al. (2006).

Growers category	Number of citrus growers	Percentage	Remarks
Never used	735	58.8	Low income, low education
Seasonal users	145	11.6	Lack of interest
Conditional users	230	18.4	Low income from the other sources of livelihood
Regular users	140	11.2	Education level, accessible extension and advisory services, good income

^zSource: Ahmad et al., unpublished data.

Table 7. Boron use matrix in Bhalwal, Sillanwali and Sahiwal tehsil of district Sargodha^z

As far as B concentrations in leaves and fruits of citrus are concerned, 38% of the samples were also found to be B deficient. At the appearance of B deficiency symptoms during drought year , B concentration was below 10 mg B kg⁻¹ in fruit peel and leaves, but at abundant precipitation B was 20 mg B kg⁻¹ in leaves and 14 mg B kg⁻¹ in peel, and no B deficiency symptoms were observed. In an orchard where fruit had deficiency symptoms, 0.5 M HCl-extractable-B concentrations were 0.15 mg B kg⁻¹ in surface soil (0-22.5 cm) and 0.10 mg B kg⁻¹ in the subsoil (22.5-45 cm). The reasons for this deficiency could be, low B status in soils of the orchards, less than recommended use of B containing fertilizers and moisture stress during the drought periods. This aspect of B deficiency induced by drought might be due to the restricted mineralization of organically bound soil B (Evans & Sparks, 1983; Flannery, 1985). Research has also shown B deficiency to be responsible for diseases and/or application of B fertilizers to correct those diseases in vegetables such as brown heart of turnips, heart rot of beets, browning of cauliflower (Hill, 1936; Greenhill, 1938), and

fruits such as corky-core, blotchy cork and drought spot of apple (Hill, 1936; Greenhill, 1938; McLarty, 1940; Fritzsche, 1955), die-back of apricot (Fitzpatrick & Woodbridge, 1941) and deformed mandarin fruits of citrus (Chiu & Chang, 1985, 1986).

6. Boron deficiency and crop diseases

As discussed earlier, B deficiency is widespread in Pakistan (Rashid et al., 2009), India (Gupta, 1983, 1984; Sillanpaa & Vlek, 1985; Sakal & Singh, 1995), China (Liu Zheng et al., 1980, 1982a, 1982b, 1983, 1989) and Western Australia (Wong, 2003) and many other countries (Sillanpaa, 1982). Boron deficiency has been reported to be associated with internal tissue breakdown in root crops, groundnut/peanut, and some bean cultivars. Warncke (2005) observed the amelioration of internal black spot in cranberry bean seed with B application. Boron nutrition of cereal crops in connection to chilling tolerance has also been demonstrated by Huang & Ye (2005). Problems like stunning of cotton growth, wilting of the plants and reddening of cotton leaves have been observed in the major cotton growing areas of Sindh province in Pakistan. At present, integrated plant nutrient management including B with the best management practices seems to be the only solution of this lethal problem (Abid Niaz - personal communication). However, no clear relationships have been established between above mentioned symptoms and B nutrition. Similar relation of B application in curing the problem of rust in wheat has also been reported by Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad, Pakistan. Application of B also minimized the adverse effects of drought stress in crop plants during dry spell. Severe attack of rust was observed on B-deficient wheat plants exposed to drought stress, whereas no incidence of disease was found in B treated plants (Anonymous, 2007a).

7. Boron extractants and their comparative efficiency

Several extractants used for soil B extraction have been employed over time for example, hot water for plant-available B (Berger & Truog, 1939; Parker & Gardner, 1981; Mahler et al., 1984; Rahmatullah et al., 1999), 0.05 M HCl for plant-available B (Ponnamperuma et al., 1981), 0.018 M CaCl₂ for non-specifically adsorbed/readily soluble B on soil surfaces (Iyenger et al., 1981; Aitken & McCallum, 1988; Spouncer et al., 1992; Hou et al., 1996; Rahmatullah et al., 1999), 1 M NH₄OAc for multi-element extraction (Gupta & Stewart, 1975; Chaudhary & Shukla, 2004), 0.25 M sorbitol-DTPA for bioavailable B (Goldberg, 1997; Miller et al., 2000; Goldberg et al., 2002; Shiffler et al., 2005), 0.05 M mannitol prepared in 0.01 M CaCl₂ for B in soil solution and its nonspecifically adsorbed forms to assess regenerative power of soil for B (Cartwright et al., 1983; Aitken et al., 1987; Jin et al., 1988; Rahmatullah et al., 1999; Vaughan & Howe, 1994), and 0.005 M AB-DTPA for multi-element extraction (Gestring & Soltanpour, 1984, 1987; Matsi et al., 2000).

There are a number of methods for extracting available B from soils. The colorimetric and other methods of determining B in the soil extract remain the same for testing on acid and alkaline soils (Bingham, 1982; Gupta, 2006). The most common extractant is hot water (Berger & Truog, 1939) because soil solution B is most important with regard to plant uptake. Li and Gupta (1991) compared hot water, 0.05 M HCl, and hot 0.01 M CaCl₂ solutions as B extractants in relation to B accumulation by soybean, red clover, alfalfa, and rutabaga. The authors concluded that 0.05 M HCl was the best extractant ($r=0.82$) followed

by hot water, and hot 0.01 M CaCl_2 . Tsadilas et al. (1994) in a study using diverse soils concluded that HWS-B was a valuable measure of available soil B and it correlated strongly with 0.05 M mannitol in 0.1 M CaCl_2 extractable, 0.05 M HCl-soluble B. Another extractant, ammonium bicarbonate-diethylenetriaminepentaacetic acid (AB-DTPA) has been suggested for effective B determination in alkaline soils (Gestring & Soltanpour, 1984, 1987, Gupta, 2006). Studies involving 31 US soils (Kaplan et al., 1990) and 100 Dutch soils (Novozamsky et al., 1990) have also confirmed that B values of cold extraction using 0.01 M CaCl_2 were highly associated with those of hot extraction (hot 0.01 M CaCl_2). However, for hot water B extraction method, several researchers have marked some problems of significance such as problematic comparability of the basic soil parameters determined routinely, precision, time consumption etc. (Shiffler et al., 2005).

Using irrigated rice soils ($n=53$, pH 3.5-8.0) Ponnampuruma et al. (1981) recommended 0.05 M HCl as equally good extractant as HWS-B method ($r=0.96$) of Berger and Truog (1939). Cartwright et al. (1983) in a study concluded that extraction of wide range of soils (pH 5.4-10.1, CaCO_3 0-85%) with 0.01 M CaCl_2 , + 0.05 M mannitol was found to be a more convenient soil test for plant-available B than the standard HWS-B method, and to be as good in predicting the response in B uptake by plants. With a cold 0.01 M CaCl_2 extraction ($n=100$, pH 3.9-6.5) equally valuable soil B values can be obtained as with the more difficult to standardize hot water extraction procedure (Novozamsky et al., 1990). Vaughan and Howe (1994) suggested sorbitol (prepared in a buffered solution of 1 N ammonium acetate and 0.1 M triethanolamine) as an alternate for HWS-B test in determining available soil B. The amounts of B recovered by HWS, 0.05 M mannitol in 0.01 M CaCl_2 extractable B, 0.05 M HCl soluble B methods were strongly correlated with each other, the highest correlation obtained being between HWS-B and HCl-B. Plant B was highly correlated to the B recovered ($n=50$, pH 6.1-8.2, CaCO_3 0-9.2%) by all the three extractants (Tsadilas et al., 1997). Amounts of extractable B with AB-DTPA and with hot water were similar ($r=0.84$) for ten soils (pH 5.8-7.8, CaCO_3 0-61 g/kg) studied by Matsi et al. (2000). There were highly significant positive correlations between the amounts of B extracted through hot water-soluble, 1:1 soil: distilled water and 1:2 soil:distilled water, ammonium acetate, calcium chloride - mannitol, and DTPA - sorbitol extractants (Goldberg et al., 2002). Latter, Chaudhary & Shukla (2004) also accentuated the advantageous features of sorbitol + NH_4OAc + TEA and mannitol + NH_4OAc + TEA extractants. Further, the simplicity of these extractants has also been compared to hot water and hot 0.01 M CaCl_2 methods. These extractants have the tendency to demarcate the available B status of arid soils on a routine basis where a large number of samples are to analyze. DTPA-Sorbitol has been recommended as a replacement to these cumbersome hot water extraction procedures (Shiffler et al., 2005).

8. Advances in boron analysis

The spectrophotometric technique using a colorimetric reaction with azomethine-H has been the most extensively tested B determination method for soil and plant samples (Ogner, 1980; Parker & Gardner, 1981; Porter et al., 1981; Lohse, 1982; Garcia et al., 1985; Lee et al., 1987; Chen et al., 1989; Kaplan et al., 1990; Banuelos et al., 1992; Campana et al., 1992; Nogueira et al., 1993). In this type of determination, hot water and 0.5 M HCl have commonly been used as extractants, both for acidic and alkaline soils. The use of these extractants is attributed with certain merits and demerits. For example, the HWE procedure

embodies several potential sources of error like difficulty to standardize (Novozamsky et al., 1990), time consuming and tedious for routine and reproducible usage (Deabreu et al., 1994). Further, the amount of B extracted is affected by the reflux time (McGeehan et al. 1989), extraction time and temperature (Spouncer et al., 1992). The coloured hot water extracts in some soils may affect B determination. The HWE method has limitations for some soils and B extracted by this method did not correlate with crop responses under some management conditions (Gestring & Soltanpour, 1987; Offiah & Axley, 1988; Mustafa et al., 1993). The use of 0.05 M HCL has eliminated the problems of extraction with hot water. Overall, the colorimetric methods, in general, suffer several interferences, such as sample pH in the range of 6.4 to 7.0 (Carrero et al., 1993), sample colour (McGeehan et al., 1989; Evans & Krahenbuhl, 1994a), nitrate complexes in the wet HNO₃ acid digests of plants (Gestring & Soltanpour, 1981a) and the presence Fe, Al, Cu, Zn and Mo (Arruda & Zagatto, 1987). These interferences and lack of sensitivity limit the application of these methods for the samples with low B concentrations and complex matrices.

The reliability of B measurements has improved in the last decade with better instrumentation and analytical methodology (Sah & Brown, 1997). After spectrophotometry, B has been determined utilizing potentiometer, chromatography, flame atomic emission and absorption spectrometry, inductively coupled plasma (ICP) optical emission (OES) and mass spectrometry (MS), and neutron activation analysis using neutron radiography and prompt-activation analysis. The extraction with 0.05 M HCl is concerned; it has also worked well for predicting B availability to crop plants in acid soils (Ponnemperuma et al., 1981; Renan & Gupta, 1991). However, Fe extracted with the acid extractant often interferes in B determination by spectrophotometric and ICP-OES methods (Evans & Krahenbuhl, 1994a; Pougnet & Orren, 1986a, 1986b).

There are reports on the use of plasma-source OES for assaying B (Pritchard & Lee, 1984; Nilsson & Jennische, 1986; Lee et al., 1987; Jeffrey & McCallum, 1988; Novozamsky et al., 1990; Goto et al., 1992; Spouncer et al., 1992; Ferrando et al., 1993; Evans & Krahenbuhl, 1994a). Reported detection limits for B are 10 to 15 mg B L⁻¹ in soil solutions and plant digests (Spiers et al., 1990). Boron determination by ICP-OES is also affected by other interfering species, for example, Si (Owens et al., 1982; Din, 1984), Ni, Cr, Al, V, Mn, Ti, Mo and high concentrations of Na (Pougnet & Orren, 1986b; Kavipurapu et al., 1993). Nevertheless, recently, Mehlich-3 has been promoted as a "universal" extractant in a wide variety of soils. But ICP analysis of B following extraction with Mehlich-3 chemicals has proven difficult because of B contamination within the ICP unit. Secondly, the effects of distilled water, nitric acid and sorbitol solutions used between samples for correcting B contamination has also been diagnosed by Allen et al. (2005). Sorbitol solution is found as the most effective solution to rectify the contamination problem. The contamination problem unique to Mehlich-3 has the tendency to limit the development of Mehlich-3 as the widely accepted extractant. However, no such problem was observed with ICP analysis of B with hot water, pressurized hot water or DTPA-Sorbitol extractions. (Allen et al., 2005). Consequently, pressurized hot water or DTPA-Sorbitol extractions have been proposed as replacement.

Overall, mostly all the above mentioned soil B extractants, provide good correlaton with plant B contents under controlled conditions. However, the efficacy of these extractants should also be tested under field conditions (Goldberg & Chunming, 2007). Historically, B

soil tests have been developed to predict B deficient soils and have not generally been evaluated for their ability to predict soil conditions that produce B toxicity effects in plants. The work reported by Goldberg et al. (2002, 2003) for using shallow groundwater to apply for crops could predict improvement in irrigation efficiency. Such sort of attributes must be incorporated in B investigation techniques/methodologies to take into loop B content of both field grown and crops grown under controlled conditions of potential B toxicity. Boron determination by ICP-MS suffers no spectroscopic interferences, and is considered the most practical and convenient technique for B isotope determination. Among the present technologies, ICP-MS has emerged as the method of choice for determining B concentration and a convenient method for B isotope determination (Sah & Brown, 1997). With the increased use of inductively coupled plasma atomic emission spectrophotometry (ICP) (especially instruments with simultaneous detection capability) soil test laboratories would welcome the need for different extractions for many element analyses. Boron is readily measured with ICP instrumentation. However, the predictions of B deficiencies by soil testing needs to be based on local data and not from broad generalizations from other areas.

9. Summary

Boron (B) is a unique micro mineral nutrient required for normal plant growth and optimum yield of crops. Its deficiency is widespread in alkaline/calcareous, coarse-textured and low organic matter soils in many countries of the world. Annual [fiber (cotton), cereal (rice, maize/corn, wheat), legume/pulse (soybean), oilseed (groundnut/peanut, oilseed rape/canola)], vegetable (potato), and perennial [citrus fruit orchards, alfalfa] crops grown on such soils usually suffer from B deficiency. This paper discusses factors affecting B availability in soils, including parent material, soil pH, texture, clay minerals and organic matter, irrigation sources, nutrient interactions, and plant species. The paper also documents the diagnosis and correction of B deficiency in several important crops in a wide range of soils. Crop yield increases up to 14% each in cotton and wheat, 14-30% in rice, 20% in maize, 58% in soybean, 10% in groundnut, 45% in oilseed rape, 30% in potato, 37% in alfalfa seed and 159% in alfalfa forage are reported with application of B by using appropriate rates, methods (soil or foliar) and sources (such as borax) on B-deficient soils. Application of B fertilizers up to 2.5 kg B ha⁻¹ is recommended to prevent/correct B deficiency in major crops depending on the placement method. The paper also reviews comparative efficiency of various boron extracts under different soil conditions in addition to advances in boron analysis. Among the present technologies, ICP-MS has emerged as the method of choice for determining B concentration and a convenient method for B isotope determination.

Prevention and/or correction of B deficiency in crops on B-deficient soils can have a dramatic effect on yield and produce quality of many crops including fibers, cereals, pulses, oilseeds, vegetables, citrus fruits and alfalfa. Source, rate, formulation, time and method of B application and proper balancing of B with other nutrients in soil all affect crop yield on B-deficient soils. Both soil and foliar application methods of B are effective in improving crop yield, produce quality, concentration and uptake of B, and economic returns. Soil applied B leaves residual effect for years on succeeding crops grown on B-deficient soils in the same fields. The actual fraction of B fertilizer removed by the crops is only 1-2% of the total applied fertilizer through soil. However, it is very important that research for improving

crop yields must move beyond applications of B based on general recommendations, and that deriving methods to predict site-specific deficiencies (e.g., soil or plant tests) are essential since the potential for B toxicity is large and the difference between deficiency and toxicity is very narrow. This could be especially important if B is applied sequentially to fields over a series of years without knowing the residual effects.

10. Conclusions and future research needs

Prevention and/or correction of B deficiency in crops on B-deficient soils can have a dramatic effect on yield and produce quality of many crops including fibers, cereals, pulses, oilseeds, vegetables, citrus fruits and alfalfa. An increase in yield of 14% each in cotton and wheat, 14-30% in rice, 20% in maize/corn, 58% in soybean, 10% in groundnut/peanut, 45% in oilseed rape, 30% in potato, 37% in alfalfa seed and 159% in alfalfa forage was observed with B fertilization. Source, rate, formulation, time and method of B fertilizer application, and proper balancing of B with other nutrients in soil all affect crop yield on B-deficient soils. Both soil and foliar application methods of B are effective in improving crop yield, produce quality, concentration and uptake of B, and economic returns. Application of B to rice on B-deficient soils also enhanced milling recovery and head rice recovery, and improved kernels quality traits like stickiness and cooking quality. Zinc application has been found to neutralize toxic effect of B in some crop plants and produced increase in crop yield.

Soil applied B leaves residual effect for years on succeeding crops grown on B-deficient soils in the same fields. The actual fraction of B fertilizer removed by the crops is only 1-2% of the total applied fertilizer through soil. Research on recycling of crops from rotation system rather than mono-cropping culture can generate useful information for B management. Moreover, adaptive research is also a pre-requisite for B management under efficient irrigation systems, e.g., drip, sprinkler and others. Impact of B nutrient use on product quality is needed, especially for high B requirement crops. Moreover, B efficient genotypes for different crops need to be identified and developed for commercial use.

Effect of B fertilizer use in high input system should also be given priority as a futuristic option for the sustainability of crop production, soil quality and environment. Further, management decisions for use of B fertilizers should consider both immediate and long-term effects of B fertilizer on crop yield, produce quality and economic returns. Research is also required, in different agro-ecological zones, to determine the long-term effects of different sources of B on accumulation and distribution of B and its balanced application with other nutrients to investigate its relationship with disease and insect resistance in different crops. However, it is very important that research for improving crop yields must move beyond applications of B based on general recommendations, and that deriving methods to predict site-specific deficiencies (e.g., soil or plant tests) are essential since the potential for B toxicity is large and the difference between deficiency and toxicity is very narrow. This could be especially important if B is applied sequentially to fields over a series of years without knowing the residual effects. It could become a serious problem if B was applied for several years for a tolerant crop and then change to B sensitive crop. Soil test could potentially determine potential problems of excessive accumulations of B in the soil.

11. References

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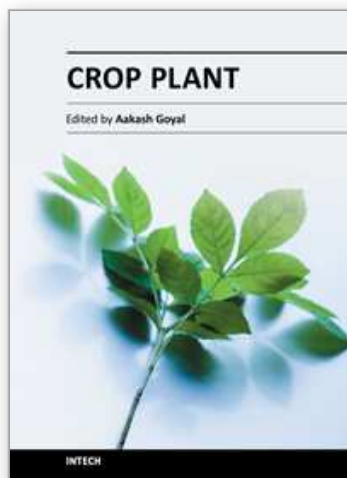
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This book provides us a thorough overview of Crop Plant with current advance in research. Divided into two section based on the chapters contents. Chapter 1 provides information about markers and next generation sequencing technology and its use. Chapter 2 is about how we can use Silicon for Drought tolerance. Chapter 3 is to deal with the major problem of rising CO₂ and O₃ causing environmental pollution. Chapter 4 covers the phenomena of RNAi and its use, application in crop science. Chapter 5 is a review for boron deficiency in soils and how to deal with it for better crops. Chapter 6-10 provide some information regarding recent works going on in crop science.

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