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BORON DEFICIENCY IN RAINFED WHEAT IN PAKISTAN: INCIDENCE, SPATIAL VARIABILITY AND MANAGEMENT STRATEGIES

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□ *Boron (B) deficiency is potentially an important nutrient constraint in calcareous soils. We determined B deficiency incidence and spatial distribution in rainfed wheat (*Triticum aestivum *L.) in 1.82 Mha Pothohar plateau in Pakistan, its relationship with soil types, crop responses to B, and internal B requirement and B fertilizer use efficiency of wheat. Plant and soil analyses indicated deficiency in 64% of the 61 sampled fields; geostatistics-aided contour maps delineated B deficient areas. In rainfed field experiments, B use increased wheat yields up to 11%. Fertilizer requirement was 1.2 kg B ha^{-1}; critical B concentration (mg kg^{-1}) ranges were: young whole shoots, 4–6; flag leaves, 5–7. Boron uptake by wheat was 0.14–0.58% of applied dosage, leaving substantial residual impact. Highly cost-effective B use or B-efficient genotype adoption can enhance wheat productivity and grower-income. Such effective nutrient assessment and management approaches can be beneficially adopted elsewhere as well.*

Keywords: boron deficiency, wheat, calcareous soils, spatial variability, plant analysis, boron-use efficiency

INTRODUCTION

Boron (B) deficiency is a major micronutrient constraint for crop production worldwide (Alloway, 2008), being common in high-rainfall areas as well as in drier regions of the world (Gupta, 1993; Shorrocks, 1997). Boron is unique among micronutrients in that both deficiency and toxicity can occur (Yau and Ryan, 2008). The nutritional problem is common in

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alkaline–calcareous soils containing low organic matter (Havlin et al., 2005) because of high B adsorption despite relatively greater total B content in such soils. For example, B deficiency was observed to be the cause of almost complete crop failure in some 40,000 ha of wheat in Heilongjian Province in the north of China in 1972 and 1973 (Li et al., 1978). Consequently, B is applied routinely in many developed countries, especially for high value crops (Shorrocks, 1997). While information on micronutrients in the Mediterranean region has been scanty, there are indications that B deficiency is more common than previously thought, especially in Pakistan. (Rashid and Ryan, 2008; Rashid, 2006). Therefore, the potential significance of this nutritional disorder could not be ignored, especially for staple crops.

Wheat *(Triticum aestivum* L.), a staple cereal throughout the world, is among the most cultivated crops in Pakistan, where it is grown over >8 million ha annually. Wheat is generally considered to be insensitive to B deficiency (Shorrocks, 1997) presumably because of its low internal B requirement (Reuter et al., 1997) and low B removal (Shorrocks, 1992) compared with many other crops. However, the incidence of B deficiency in wheat has been attributed to its high plant-tissue B requirement for flower fertilization and seed set (Shorrocks, 1997; Rerkasem and Jamjod, 2004). For example, in Nepal, B deficiency was considered the main reason for panicle sterility in susceptible wheat genotypes because B application reduced sterility from 42.6% to 4.5% (Subedi et al., 1997).

Vegetative symptoms are not useful for diagnosing B deficiency in wheat as typical symptoms are not well established under field conditions. Male sterility with florets that stay open for many days at anthesis followed by grain-set failure, are the most common symptoms observed in B-deficient wheat plants (Li et al., 1978; Rerkasem and Loneragan, 1994).

In view of the likely importance of B deficiecy for wheat in Pakistan, the objectives of the present study were to: (1) determine the potential extent, and severity of B deficiency in a major rainfed wheat region of Pakistan where widespread occurrence of B deficiency was suspected, (2) examine the relationship of B deficiency with soil properties and soil types, (3) assess crop responses to B application, and (4) identify the internal B requirement of wheat plants.

MATERIALS AND METHODS

Nutrient Indexing of Boron in Rainfed Wheat

A nutrient indexing survey was carried out in the rainfed *Pothohar* Plateau, Pakistan (total area, 1.82 million ha; lat. 32° 2′–34° 0′ N, long. 71° 30′–73° 45′ E). At each field sampled, 25 young whole shoots (≤30 cm tall) of wheat (cv. Pak–81) at tillering stage 3–4 (Jones et al., 1991) were sampled and associated soil samples (0–15 and 30–45 cm) were collected within an area about 5 m^2. Samples were collected from 61 random fields. The soils of these fields represented 21 soil series belonging to three soil orders; 24 fields belonged to Inceptisol, 24 to Alfisol, and 13 to Entisol (Table 1). The soil samples were analyzed for pH, and percentages of calcium carbonate ($CaCO_3$), organic matter, clay, silt, and sand. Soil B was extracted by hot water following Berger and Truog, (1944) and measured colorimetrically using azomethine-H (Bingham, 1982). Plant tissues were dry-ashed at 600°C for 6 hr, digested in 0.36 *N* sulfuric acid (H_2SO_4) (Gaines and Mitchell, 1979), and B in the digests was determined colorimetrically using azomethine-H (Bingham, 1982).

Boron Spatial Variability

Semivariograms were used to examine the spatial dependence between measurements at pairs of location as a function of distance of separation (Bhatti et al., 1991). Semivariance γ(h) was computed using the expression:

$$\gamma(\mathrm{h}) = [1/2\mathrm{n}(\mathrm{h})] \sum_{i=1}^{n(h)} [\mathrm{z}(\mathrm{x_i}) - \mathrm{z}(\mathrm{x_{i+h}})]^2$$

Where γ(h) is the number of samples separated by a distance h, and z represents the measured value for a soil or crop B concentration. For quantitative description of the semivariograms, it is useful to fit standard models to the semivariance function. All the measured data were well described using a linear model given by:

$$\gamma(\mathrm{h}) = \mathrm{C_o} + \mathrm{Bh}$$

where h is the separation distance between observations, C_o is a model parameter known as the nugget, and B is the slope of the line.

After developing semivariogram models for the data, interpolation of B values at unsampled locations was made using kriging (Bhatti et al., 1991), which makes optimal, unbiased estimates of regionalized variables at unsampled locations using the structural properties of the semivariogram and the initial set of measured data. The basic equation for interpolation by kriging at an unsampled location x_o is:

$$\mathrm{zk}(\mathrm{x_o}) \sum_{i=1}^{n} \lambda \mathrm{i}\, \mathrm{z}(\mathrm{xi})$$

where *n* is the number of neighboring samples and λi are weighting factors for each of the z (xi). The weighting factors for neighboring measured points

TABLE 1 Hot water-extractable (HWE)-boron and soil properties according to soil series in the rainfed Pothohar Plateau, Pakistan

Soil series	Subgroup	Parent material	Site	Soil depth (cm)	pH (1:1)	$CaCO_3$ (%)	OM (%)	HWE- B (mg kg^{-1})	B deficient sites (%)
Argan (A)	Torrifluventic	Alluvium	1	0–15	8.1	3.60	0.10	0.24	100
	Ustochrept			30–45	8.1	6.80	0.10	0.24	100
Balkassar	Typic	Residuum	10	0–15	8.0	3.56	0.38	0.44	80
	Haplustalf			30–45	8.1	3.34	0.29	0.41	70
Balkassar (A)	Aridic	Residuum	5	0–15	8.0	8.44	0.46	0.41	60
	Haplustalf			30–45	8.2	6.90	0.40	0.29	80
Basal	Calcic	Loess	6	0–15	8.0	8.05	0.67	0.40	67
	Ustochreps			30–45	8.1	8.08	0.60	0.33	83
Basal (W)	Calcic Udic	Loess	2	0–15	8.0	4.50	0.76	0.68	50
	Ustochrept			30–45	8.0	4.40	0.59	0.44	50
Chakwal	Typic	Loess	2	0–15	8.0	2.60	0.14	0.09	100
	Haplustalf			30–45	8.1	2.40	0.11	0.27	100
Dhulian	Aridic	Residuum	2	0–15	8.1	9.30	0.65	0.65	50
	Ustochrept			30–45	8.1	9.10	0.37	0.31	100
Dhulian (A)	Aridic	Residuum	5	0–15	8.1	6.20	0.46	0.42	80
	Ustochrept			30–45	8.1	6.24	0.37	0.44	60
Dhumman	Typic	Alluvium	2	0–15	8.0	2.75	0.16	0.64	50
	Ustochrept			30–45	8.1	3.25	0.16	0.77	100
Guliana	Udic	Loess	6	0–15	7.9	5.58	0.82	0.51	83
	Haplustalf			30–45	8.0	7.95	0.65	0.30	83
Guliana (TU)	Typic	Loess	1	0–15	7.8	18.70	0.71	1.20	0
	Haplustalf			30–45	8.0	15.90	0.70	0.56	0
Missa (TU)	Calcic	Loess	1	0–15	7.9	1.90	0.64	0.33	100
	Ustochrept			30–45	7.9	1.60	0.58	0.22	100
Murat	Fluventic	Alluvium	2	0–15	8.0	8.60	0.52	0.23	50
	Ustochrept			30–45	8.1	9.55	0.41	0.35	100
Qazian	Lithic	Residuum	1	0–15	8.1	8.20	0.22	0.04	100
	Torripsamment			30–45	8.0	8.10	0.17	0.29	100
Qutbal	Typic	Loess	1	0–15	7.9	8.60	0.45	0.26	100
	Ustorthent			30–45	8.0	9.20	0.28	0.26	100
Qutbal (W)	Udic	Loess	2	0–15	8.1	8.70	0.73	0.34	100
	Ustorthent			30–45	8.2	10.25	0.43	1.15	100
Rajar	Udic	Loess	2	0–15	8.0	11.75	0.60	0.49	50
	Ustorthent			30–45	8.1	11.15	0.52	0.57	50
Rajar (TU)	Typic	Loess	4	0–15	7.9	7.28	0.43	0.57	50
	Ustorthent			30–45	8.0	6.98	0.36	0.32	75
Soan	Typic	Alluvium	3	0–15	8.0	3.17	0.51	0.33	100
	Ustorthent			30–45	8.0	3.50	0.29	0.34	100
Talagang	Typic	Alluvium	2	0–15	7.9	5.70	0.66	0.56	50
	Ustochrept			30–45	8.0	5.95	0.28	0.42	100
Therpal	Fluventic	Alluvium	1	0–15	7.8	1.50	0.40	1.01	100
	Ustochrept			30–45	8.1	3.00	0.49	0.56	100
	Total sites		61						

A: relatively drier; TU: Typic Tempustic; W: relatively wetter.
Notations: $CaCO_3$ = calcium carbonate; OM = organic matter.

are constrained to sum of unity, i.e.,:

$$\sum_{i=1}^{n} \lambda i = 1$$

Thereafter, contour maps were developed for delineating areas of B deficiency and adequacy.

Crop Responses to Boron and Internal Boron Requirement of Wheat

Two field experiments were carried out on rainfed wheat (cv. 'Pak-81') tolerant or sensitive to B deficiency at Islamabad (lat. 33° 43′ N, long. 73° 5′ E) on a silty clay loam Gujranwala soil (coarse loamy mixed, hyperthermic Typic Hapludalf) by applying 0, 2, and 4 kg B ha^{-1} during 2001–2002 and 0, 1, 2, 4, 8, and 16 kg B ha^{-1} during 2002–2003. Soil characteristics were: pH (1:1), 8.2; $CaCO_3$, 4.6%; organic matter, 0.5%; sodium bicarbonate ($NaHCO_3$) phosphorus (P), 4.5 mg kg^{-1}; ammonium acetate (NH_4OAc) potassium (K), 55 mg kg^{-1}; diethylenetriaminepentaacetic acid (DTPA) zinc (Zn), 0.36 mg kg^{-1}; and hot water- extractable (HWE)-B, 0.3–0.4 mg kg^{-1}.

Boron, as borax, was applied by broadcasting and subsequent soil incorporation during normal cultivation. Uniform field broadcasting of the small amount of B was attained by pre-mixing with 4–5 times volume of well-pulverized soil. Basal fertilization was 110 kg nitrogen (N) ha^{-1} as urea, 36 kg P ha^{-1} as diammonium phosphate (DAP), 55 kg K ha^{-1} as potassium sulfate (K_2SO_4), and 5 kg Zn ha^{-1} as zinc sulfate ($ZnSO_4.7H_2O$).

The field experiments were laid out in randomized complete block design with three replications. Mean annual rainfall in Islamabad is 1,082 mm and rainfall during wheat season (Oct.–Apr.) was 277 mm in 2001–2002 and 244 mm in 2002–03 (Figure 1). Because of greater pre-crop season rains (i.e., July—Sept.) during 2002–2003, residual soil moisture was better for this crop season. Young whole shoots ($\leq$30 cm tall), flag leaves at 50% head emergence (Jones et al., 1991), and mature straw and grain were analyzed for B. Grain and straw yields were recorded at maturity.

RESULTS AND DISCUSSION

Boron Status of Soils and Wheat Plants

Of the 21 soil series, 13 exhibited mean HWE-B concentrations <0.5 mg kg^{-1} in the topsoils (0–15 cm), with a minimum of 0.04 mg kg^{-1} in Qazian series (Lithic Torrisamment, Table 1). As only 30% of the sampled soils had adequate plant-available B, deficiency most probably is a widespread nutrient disorder in rainfed wheat soils in the Pothohar plateau of Pakistan. This low

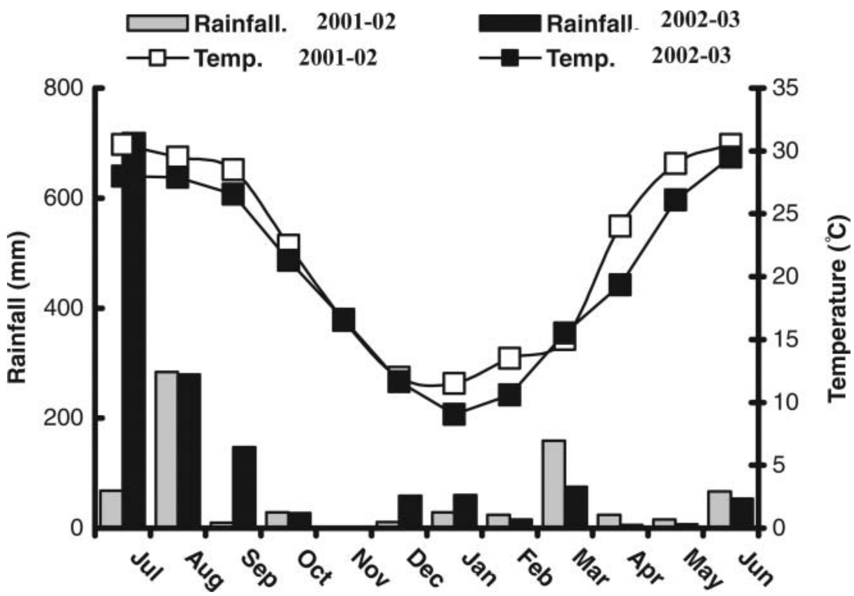

FIGURE 1 Monthly rainfall and mean temperature in 2001–2002 and 2002–2003 (Muhammad Khan, personal communication).

B availability in these soils is probably the outcome of a number of adverse soil factors (Table 2) that affect B, i.e., coarse–texture (mean sand content 62%) (Shorrocks, 1997), alkaline pH, calcareousness (Goldberg, 1993) and low organic matter (Halvin et al., 2005).

The extent of B deficiency was somewhat related to soil types. On an average, the soils belonging to the Entisol order had much lower mean HWE-B. Thus, there could be more widespread B deficiency in this soil

TABLE 2 Soil properties of wheat fields in the rainfed Pothohar Plateau, Pakistan

		Attock district		Chakwal district	
Soil properties	Soil depth (cm)	Range	Mean ± SD	Range	Mean ± SD
pH (1:1)	0–15	7.7–8.2	8.0 ± 0.1	7.6–8.1	7.9 ± 0.1
	30–45	7.8–8.4	8.1 ± 0.1	7.6–8.3	8.1 ± 0.1
Calcium carbonate (%)	0–15	0.8–16.6	7.8 ± 4.1	0.9–18.7	5.0 ± 4.1
	30–45	1.3–18.4	8.3 ± 4.9	1.2–15.9	4.8 ± 3.6
Organic matter (%)	0–15	0.19–1.1	0.66 ± 0.2	0.07–0.97	0.40 ± 0.3
	30–45	0.05–1.0	0.50 ± 0.2	0.05–0.81	0.32 ± 0.2
Clay (%)	0–15	11–34	22 ± 6.5	12–29	19 ± 5
	30–45	12–36	22 ± 5.8	12–31	20 ± 6
Silt (%)	0–15	7–38	21 ± 9.8	3–44	17 ± 11
	30–45	3–35	22 ± 10.0	6–37	17 ± 10
Sand (%)	0–15	35–82	57 ± 14.8	28–84	65 ± 15
	30–45	36–81	56 ± 13.5	34–82	64 ± 15

TABLE 3 Boron contents in young whole shoots of wheat and in associated soils in the rainfed Pothohar Plateau, Pakistan

District	Soil depth (cm)	Range	Mean ± S.D.	Category based on B level Low	Adequate	High
		---------(mg kg^{-1})---------				
Whole shoot B						
Attock (27 sites)				< 6[a]	6–10	> 10
		4.20–13.70	6.86 ± 2.58	16 (59%)[b]	8 (30%)	3 (11%)
		3.20–7.50	5.49 ± 0.98	23 (68%)	11 (32%)	—
Chakwal (34 sites)						
HWE-soil B				< 0.5[c]	> 0.5	
Attock (27 sites)	0–15	0.18–1.08	0.47 ± 0.28	19 (70%)	8 (30%)	
	30–45	0.04–0.70	0.35 ± 0.16	21 (78%)	6 (22%)	
Chakwal (34 sites)	0–15	0.04–1.20	0.44 ± 0.39	25 (74%)	9 (26%)	
	30–45	0.04–1.01	0.38 ± 0.23	25 (74%)	9 (26%)	

a Critical B concentration (mg kg^{-1}) in whole shoots (Jones et al., 1991; results of this investigation).
b Number and percentage of samples falling in that range.
c Critical level of HWE-soil B (Tiwari et al., 1988; Rashid et al., 1997b).

order than the soils belonging to the Inceptisol order (Table 1). Mean B content of the Balkassar soil series (Typic Haplustalf and Aridic Haplustalf) was 0.43 mg kg^{-1}. The soils belonging to eight other series were adequate in B as their mean B content was >0.50 mg B kg^{-1} (Table 1).

The HWE-B concentration of the topsoils ranged from 0.04 to 1.20 mg kg^{-1} with an average of 0.4 mg kg^{-1} (Table 3). Average B values of the topsoils were greater than in the subsoils (30–45 cm), presumably because of their slightly higher organic matter content, lower $CaCO_3$ content (Attock district) and possibly lower pH (Table 2).

Considering 6 mg kg^{-1} as the deficiency critical concentration in young wheat whole shoots (Jones et al., 1991) B deficiency critical range determined in this investigation), wheat plants were B deficient in 64% of the sampled fields of both the geographical districts (Table 3). Boron concentration in young wheat plants ranged from 3.2 to 13.7 mg kg^{-1} and averaged 6.1 mg kg^{-1}. A low correlation existed between plant-tissue B concentration and surface soil B concentration ($r = 0.35$; $P < 0.01$). Plant B concentration was also positively related with soil organic matter.

In our previous studies in the rainfed Pothohar Plateau, B deficiency was observed in about 50% of the fields growing peanut and sorghum (Rashid et al., 1997a, 1997b). Thus, despite similar soils and agro-climatic conditions, the magnitude of B deficiency was relatively greater in rainfed wheat (64% sites) than peanut and sorghum. Also, results of this field investigation do not seem to support reports indicating lower B-deficiency sensitivity of wheat than of peanut (Keren and Bingham, 1985). Moreover, the possible disparity between the extent of B deficiency indicated by B concentration of wheat plants and associated soils was less (Table 3) compared with our finding for sorghum plants and associated soils (Rashid et al., 1997b). Thus, despite discrepancies between crop species, soil testing for B appears to be a more reliable approach for predicting B fertilizer needs of wheat crop.

Spatial Variability of Boron

The contour maps showing spatial variability of B concentration in soils and in wheat plants for the Attock district are shown in Figure 2. The localized areas of adequate soil B fertility (i.e.,$\geq$ 0.5 mg B kg^{-1}) appeared in the southern, eastern and western parts of the district. Thus, B-deficient soils appear to be widespread in the north, central and south-western parts of this district. Spatial variability of B in wheat plants indicated that B deficiency (i.e., $<$ 6 mg B kg^{-1}) would be less widespread than indicated by the soil test, occurring mainly in the north, central and south-western parts of the district. Similar patterns in spatial variability of B were observed in the Chakwal district.

Despite the finding that B deficiency is widespread in the *Pothohar* Plateau based on soil and plant tissue analyses, a more comprehensive survey is needed to establish severity of the deficiency. This survey should be carried out during and after flowering since wheat plants have a high plant tissue B requirement for flower fertilization and seed set, and severe B deficiency is known to lead to head sterility (Shorrocks, 1997; Rerkasem and Jamjod, 2004; Subedi et al., 1997).

Wheat Responses to Boron

Wheat grain yield increased with B fertilization up to 2 kg B ha^{-1} in 2001–2002 and up to 4 kg B ha^{-1} in 2002–03 ($P \leq 0.05$; Figure 3a). The straw yield increase with B fertilization was even greater than that of grain in 2002–03 ($P \leq 0.05$; Figure 3b), coinciding with other reports (e.g., Rerkasem and Jamjod, 2004) that B deficiency in wheat causes relatively more reduction of straw yield than grain yield.

While B deficiency in crops is often associated with dry weather and low soil moisture conditions (Havlin et al., 2005), the magnitude of grain yield increase following B application was greater during the relatively drier year, i.e., 2001–2002, than the more favorable year, i.e., 2002–2003. The differential crop responses found in this study could be attributed to the different rainfall distribution patterns of the two years, particularly during the pre-sowing months (Figure 1). More rainfall during the months of July, September, December, and January of 2002–2003 resulted in better moisture availability during the early phase of the crop, leading to better crop establishment and substantially greater biomass production than in 2001–2002. As soil B accessibility to plant roots is dependent on B mass flow as well as diffusion (Havlin et al., 2005), better soil moisture led to improved B

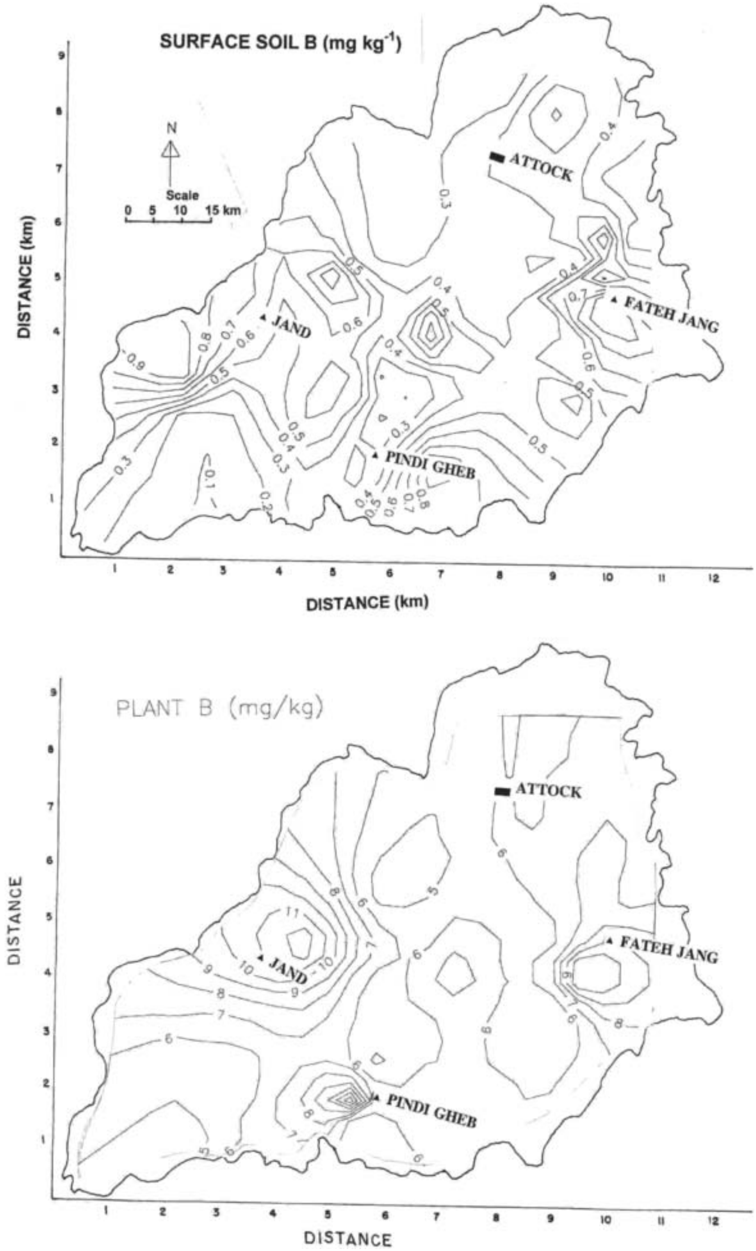

FIGURE 2 Spatial variability of B in surface soils and associated wheat plants within Attock District, Punjab Province, Pakistan.

nutrition of wheat plants. Thus, despite a dilution effect (consequent to greater biomass production), B concentration in wheat plant tissues was greater during 2002–2003, revealing a substantial improvement of fertilizer and/or soil B availability to plants.

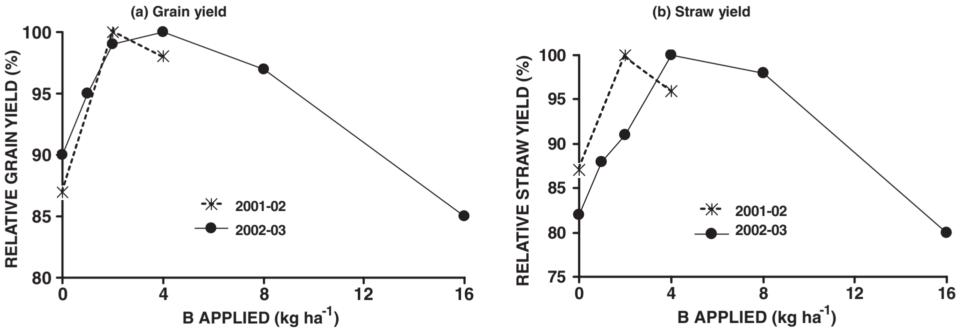

FIGURE 3 Relationship between B application rate and relative grain and straw yield of rainfed wheat (maximum grain yield: 2001–2002, 2.67 t ha^{-1}; 2002–2003, 3.14 t ha^{-1}; maximum straw yield: 2001–02, 4.47 t ha^{-1}; 2002–03, 5.38 t ha^{-1}).

The maximum mean grain yield increase with B application was 11% over the control, and fertilizer requirement associated with near-maximum (95% of maximum) grain yield was 1.2 kg B ha^{-1} (Figure 3a). Similarly, in Turkey, Soylu et al. (2004) showed that application of 1–3 kg B ha^{-1} increased grain yield of six durum wheat (*Triticum durum Desf*.) genotypes by 9–11% over the control on a calcareous soil having 0.19 mg B kg^{-1}. Unlike grain yield, fertilizer B requirement for straw yield was highly moisture-dependent. The B-fertilizer requirement associated with near-maximum straw yield was 1.1 kg ha^{-1} in 2001–2002 and 2.9 kg ha^{-1} in 2002–2003. As grain yield is the main concern with wheat, overall fertilizer B requirement for the crop is considered to be 1.2 kg B ha^{-1}. Despite not having a more impressive grain yield increase with B application (i.e., 11% over control), the economics of B use in wheat was attractive with a value: cost ratio (i.e., the ratio between value of increased grain yield to the cost of B fertilizer) of 5:1 for both crop years.

Excessive B application led to lower crop yields as more than 2 and 4 kg B ha^{-1} depressed crop productivity in 2001–2002 and 2002–2003, respectively (Figure 3). In 2002–2003, 16 kg B ha^{-1} caused 15% grain yield reduction, relative to the maximum yield. Straw yield was slightly depressed by applying 8 kg B ha^{-1} but 19% yield reduction occurred with an application of 16 kg B ha^{-1}. In the durum wheat study by Soylu et al. (2004), 9 kg B ha^{-1} proved toxic resulting in 7% grain yield reduction over the maximum. As some wheat cultivars are sensitive to B toxicity (Yau and Ryan, 2008) and Pak-81 is probably one of them, great care is warranted for attaining uniform field broadcast of a small quantity of fertilizer B.

Results of the B fertilization experiment show that B deficiency in the *Pothohar* plateau is not as severe as reported elsewhere, where seed yield is minimum without B fertilization (Li et al., 1978; Rerkasem and Loneragan, 1994). A wide range of genotypic variation in the response to low B has been observed (Rerkasem and Jamjod, 1997). Therefore, under such a sub-critical

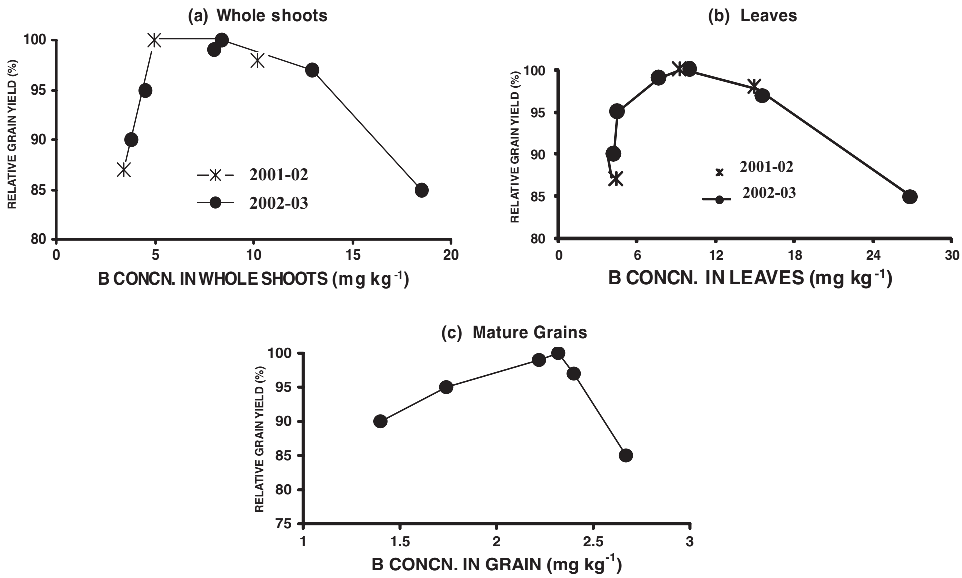

FIGURE 4 Relationship between B concentration in diagnostic plant parts and relative grain yield of rainfed wheat.

deficiency condition, the use of more soil B-efficient cultivars is suggested, as it will save the cost of applying B fertilizers and avoid the chance of having B toxicity.

Critical Tissue Boron Concentrations

Plant tissue B concentration increased progressively with increasing B application rates: 3.7 to 18.5 mg kg^{-1} in young whole shoots, 4.2 to 27.0 mg kg^{-1} in flag leaves, 3.2 to 12.1 mg kg^{-1} in mature straw, and 1.4 to 2.7 mg kg^{-1} in grain (Figure 4). Similar results were reported by Soylu et al. (2004) in a field study on a B deficient soil in Turkey, in which B concentration in flag leaves increased from 11.1 mg kg^{-1} to 24.3 mg kg^{-1} after applying 0−9 kg B ha^{-1} to six durum wheat genotypes. In our study, the internal B requirement for near–maximum grain yield, determined by the boundary-line technique (Webb, 1972), was 4.0 mg kg^{-1} in whole shoots (Figure 4a). The literature, however, suggests slightly higher values. The sufficiency ranges reported for wheat whole shoots, for example, are 6–12 mg B kg^{-1} at Feekes' Growth Stage 5–6, 5–10 mg kg^{-1} at Stage 7–8 (Bergmann, 1992), and 6–10 mg kg^{-1} at Stage 10 or when the head emerges from the boot (Jones et al., 1991).

The plant's internal nutrient element requirement may vary because of the interaction of plant growth with the supply of other nutrients (Munson and Nelson, 1990) and with environmental factors such as temperature, CO_2 concentration, disease organisms, and errors involved in derivations (Munson and Nelson, 1990; Smith and Loneragan, 1997). Smith and

Loneragan (1997), therefore, believed that the critical concentration is not a single value but a narrow range of nutrient concentration above which a plant is adequately supplied with the nutrient and below which the plant is 'deficient'. Such a range would cover the different critical values derived under different physical, environmental, and biological conditions that influence plant nutrition element levels. Interpreting the presently observed critical concentration in whole shoots (i.e., 4 mg B kg^{-1}) and the values reported in literature (e.g., Bergmann, 1992; Jones et al., 1991), critical B range in young wheat whole shoots appears to be 4–6 mg kg^{-1}.

The internal B requirement for near–maximum grain yield in our study, determined by the boundary line technique (Webb, 1972), was 5.1 mg kg^{-1} in flag leaves, and 2.0 mg kg^{-1} in mature grain (Figure 4). The reported B sufficiency range in most recently matured leaves is 5–10 mg kg^{-1} at the beginning of heading (Weir, 1983) and 7–24 mg kg^{-1} at booting (Rerkasem and Loneragan, 1994). Therefore, in consideration of our result and the values suggested in the literature, critical B range in in wheat leaves appears to be 5–7 mg kg^{-1}. The present study indicated the same critical B concentration in wheat grain, i.e., 2.0 mg kg^{-1}, as suggested earlier by Holloway and Alston (1992).

Boron-Use Efficiency of Wheat

Total B uptake by the wheat crop ranged from 13.3 to 18.8 g ha^{-1} in 2001–2002 and 18 to 60 g ha^{-1} in 2002−03 (Table 4). Much less B uptake during 2001–02 is attributed to lower crop yield coupled with lower plant tissue B concentration (Figure 4). Boron fertilizer use efficiency by the crop (i.e., fraction of the B dose taken up by above ground plant parts) was very low, ranging from 0.14% to 0.58%. Since only a very small fraction of the applied B is taken up by the current wheat crop, an appreciable amount is expected to be left behind for succeeding crop(s). However, agronomic

TABLE 4 Total B uptake, B-use efficiency, and agronomic efficiency of B applied to rainfed wheat in a Typic Hapludalf

B applied (kg ha^{-1})	Total B uptake (g ha^{-1})		B use efficiency[1] (%)		Agronomic efficiency (kg grain kg^{-1} B)	
	2001–02	2002–03	2001–02	2002–03	2001–02	2002–03
0	13.3	18.0	—	—	—	—
1		21.8		0.39		155
2	17.3	29.5	0.20	0.58	172	140
4	18.8	32.6	0.14	0.37	75	78
8		57.0		0.49		29
16		60.0		0.26		—

[1] The fraction of fertilizer B taken up by wheat crop in above-ground parts.

efficiency of B use by wheat crop was high, ranging from 75 to 155 kg grain kg^{-1} B fertilizer. This high agronomic efficiency translates into attractive economics of B fertilizer use in wheat.

CONCLUSIONS

Based on various lines of evidence, from soil tests and nutrient indexing to plant tissue content and crop responses, B deficiency appears to prevail in almost two-thirds of rainfed wheat fields in Pothohar Plateau of Pakistan. Spatial variability contour maps can delineate areas of B deficiency using the nutrient indexing data derived from simple and reliable soil B testing. The plant analysis approach indicated that critical B concentration range/concentration in wheat plant parts is: young whole shoots, 4–6 mg kg^{-1}; flag leaves, 5–7 mg kg^{-1}; and mature grains, 2 mg kg^{-1}. As maximum crop yield improvement with B use was 11% over the control, this nutritional disorder does not cause drastic yield losses, but a low application of about 1.0–1.5 kg B ha^{-1} can effectively ameliorate the deficiency. Thus, a nominal investment on fertilizer B, in deficient situations, can improve crop productivity and enhance grower income.

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