Yield and Chemical Composition of Brussels Sprout (*Brassica oleracea* L. gemmifera) as Affected by Boron Management

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Abstract. Boron (B) deficiency is widespread in the Anatolia region of Turkey. This could impact production and quality of Brussels sprout (*Brassica oleracea* L. gemmifera). A 2-year field experiment was conducted to study yield and quality response of four cultivars (Star, Brilliant, Oliver, and Maximus) to B addition (0, 1, 3, and 9 kg·ha⁻¹ B). The optimum economic B rate (OEBR) ranged from 5.5 to 6.3 kg·ha⁻¹ B resulting in soil B levels of 0.94 to 1.13 mg·kg⁻¹. Independent of cultivar, B application decreased tissue nitrogen, calcium, and magnesium but increased tissue phosphorus, potassium, iron, manganese, zinc, and copper content. We conclude a B addition of 6 kg·ha⁻¹ is sufficient to elevate soil B levels to nondeficient levels. Similar studies with different soils and initial soil test B levels are needed to conclude if these critical soil test values and OEBR can be applied across the region.

Vegetable production continues to increase worldwide and Turkey is the fourth largest producer with 25.3 million tones annually (Anonymous, 2005). In terms of economic value, nutrition, consumer preference, general adaptability, and extent of cultivation, the most commonly grown vegetable crops in Turkey are tomato (*Lycopersicon esculentum* L.), watermelon [*Citrillus lanatus* (Thunb.) Mansf.], cucumber (*Cucumis sativus* L.), pepper (*Capsicum annuum* L.), eggplant (*Solanum melongena* L. var. *esculentum* Nees), squashes (*Cucurbita pepo* L., *C. maxima* L., and *C. moschata* L.), onion (*Allium cepa* L.), snap bean (*Phaseolus vulgaris* L.), melon (*Cucumis melo* L.), radish (*Raphanus sativus* L.), and salad vegetables, including lettuce (*Lactuca sativa* L. var.

longifolia) and crisp lettuce (*Lactuca sativa* L. var. *crispa*). Brussels sprout is not commonly grown, but there is an increasing interest in its production as a result of its high nutritional value.

Boron plays an important role in cell-wall synthesis, sugar transport, cell division, differentiation, membrane functioning, root elongation, regulation of plant hormone levels, and generative growth of plants (Marschner, 1995). Boron deficiency symptoms first become evident on the younger leaves, which change color and become hardened, malformed, and necrotic.

Boron (B) deficiency has been reported in 132 crops in 80 countries (Shorrocks, 1997) and is a major cause of crop yield loss in China, India, Nepal, and Bangladesh (Anantawiroon et al., 1997). In Turkey, B deficiency was identified through individual field trials (Gezgin et al., 2002; Gezgin and Hamurcu, 2006) and micronutrient availability studies (Gezgin et al., 1999). It is estimated that in the central southern and eastern Anatolia regions of Turkey, 27% to 34% of the soils are B-deficient (Angin et al., 2008; Gezgin et al., 2002; Gezgin and Hamurcu,

2006; Kacar and Fox, 1967; Kacar et al., 1979).

Boron management is challenging because the optimum B application range is narrow (Gupta, 1993), and optimum B application rates can differ from one soil to another (Gupta, 1993; Marschner, 1995).

Crop response to B application has been documented for wheat (*Triticum durum* Desf.) (Soylu et al., 2004), sunflower (*Helianthus annuus* L.) (Asad et al., 2002; Oyinlola, 2007), and chickpea (*Cicer arietinum* L.) (Ceyhan et al., 2007). However, little is known about the B requirements of Brussels sprout.

The objectives of this study were 1) to evaluate the yield response of four cultivars of Brussels sprout to B fertilizer; 2) to determine the effects of B addition on the mineral composition of Brussels sprout heads; and 3) to determine optimum soil test B levels for Brussels sprout cultivars under field conditions.

Materials and Methods

Background information for the study site. This study was conducted at the Agricultural Research Station of Atatürk University located in Erzurum, Turkey (long. 39°55' N, lat. 41°16' E) during the summer periods (late May to late September) of 2005 and 2006. Its altitude is 1835 m. The soil was classified as an Ardisol with parent materials mostly consisting of volcanic, marn, and lacustrine transported material (Soil Survey Staff, 1992). The experimental region has a semiarid climate. During the growing period, the mean maximum temperature was 29 °C in both years, whereas the minimum temperature was 10 °C in 2005 and 13 °C in 2006. The mean relative humidity, wind speed, daily sunshine, total precipitation, and total evaporation amounted to 54.58%, 2.72 m·s⁻¹, 11.23 h, 63.4 mm, and 388.7 mm in 2005 (20 May to 29 Sept.), and 57.95%, 3.50 m·s⁻¹, 10.07 h, 48.9 mm, and 448 mm in 2006 (28 May to 10 Oct.), respectively.

Before seedling, soil samples were taken over two depths (0 to 30 and 30 to 60 cm, 20 subsamples) to determine baseline soil properties. Soil samples were air-dried, crushed, and passed through a 2-mm sieve before chemical analysis. Cation exchange capacity was determined using sodium acetate (buffered at pH 8.2) and ammonium acetate (buffered at pH 7.0) according to Sumner and Miller (1996). The Kjeldahl method (Bremner, 1996) was used to determine total nitrogen (N), whereas plant-available phosphorus (P) was determined by using the sodium bicarbonate method of Olsen et al. (1954). Electrical conductivity (EC) was measured in saturation extracts according to Rhoades (1996). Soil pH was determined in 1:2 extracts, and calcium carbonate concentrations were determined according to McLean (1982). Soil organic matter was determined using the Smith-Weldon method according to Nelson and Sommers (1982). Ammonium acetate buffered at pH 7 (Thomas,

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Fig. 1. Brussels sprout cultivar yields as affected by boron (B) applications (2-year average) to a B-deficient calcareous Aridisol in eastern Turkey. Identified are optimum economic B rates for each of the 2 years and the 2-year average assuming U.S. \$0.65 kg⁻¹ B and a Brussels sprout value of U.S. \$2.08 kg⁻¹.

Table 1. Chemical properties of the experimental field soils before seedling (mean $\pm$ SD, n = 20).

Soil properties	Units	2005		2006	
		Soil depth		Soil depth	
		0–30 cm	30–60 cm	0–30 cm	30–60 cm
Clay	%	31.7 $\pm$ 1.30	28.50 $\pm$ 1.10	ND	ND
Silt	%	44.5 $\pm$ 0.80	38.40 $\pm$ 0.90	ND	ND
Sand	%	23.9 $\pm$ 1.10	33.10 $\pm$ 1.60	ND	ND
Cation exchangeable capacity ^a	cmol _c ·kg ⁻¹	32.0 $\pm$ 2.40	27.50 $\pm$ 1.30	ND	ND
Total N	g·kg ⁻¹	0.5 $\pm$ 0.03	0.2 $\pm$ 0.06	0.8 $\pm$ 0.02	0.4 $\pm$ 0.06
pH (1:2 soil:water)		7.25 $\pm$ 0.2	11.00 $\pm$ 1.20	7.25 $\pm$ 0.17	11.00 $\pm$ 1.10
Organic matter	g·kg ⁻¹	19 $\pm$ 0.10	9 $\pm$ 1.70	11 $\pm$ 0.10	5 $\pm$ 1.90
CaCO ₃	g·kg ⁻¹	130 $\pm$ 0.10	151 $\pm$ 0.30	120 $\pm$ 0.20	138 $\pm$ 0.20
Plant available P ^x	mg·kg ⁻¹	7.3 $\pm$ 1.60	3.0 $\pm$ 0.40	8.2 $\pm$ 0.70	3.9 $\pm$ 0.30
Exchangeable Ca ^w	cmol _c ·kg ⁻¹	16.0 $\pm$ 2.20	22.1 $\pm$ 0.03	17.0 $\pm$ 1.10	20.2 $\pm$ 0.01
Exchangeable Mg ^w	cmol _c ·kg ⁻¹	4.40 $\pm$ 0.50	3.20 $\pm$ 0.11	3.1 $\pm$ 0.60	3.2 $\pm$ 0.15
Exchangeable K ^w	cmol _c ·kg ⁻¹	2.4 $\pm$ 0.80	1.6 $\pm$ 0.07	2.1 $\pm$ 0.50	1.2 $\pm$ 0.04
Exchangeable Na ^w	cmol _c ·kg ⁻¹	0.15 $\pm$ 0.05	0.11 $\pm$ 0.11	0.10 $\pm$ 0.07	0.09 $\pm$ 0.10
Available Fe ^v	mg·kg ⁻¹	3.10 $\pm$ 0.30	1.55 $\pm$ 0.10	2.50 $\pm$ 0.20	1.23 $\pm$ 0.07
Available Mn ^v	mg·kg ⁻¹	1.70 $\pm$ 0.09	1.35 $\pm$ 0.08	1.20 $\pm$ 0.08	1.11 $\pm$ 0.03
Available Zn ^v	mg·kg ⁻¹	1.65 $\pm$ 0.15	1.28 $\pm$ 0.03	1.27 $\pm$ 0.15	1.13 $\pm$ 0.01
Available Cu ^v	mg·kg ⁻¹	1.20 $\pm$ 0.13	0.75 $\pm$ 0.03	1.10 $\pm$ 0.13	0.70 $\pm$ 0.02
Available B ^u	mg·kg ⁻¹	0.13 $\pm$ 0.06	0.07 $\pm$ 0.03	0.15 $\pm$ 0.07	0.09 $\pm$ 0.02
Electric conductivity	dS·m ⁻¹	1.05 $\pm$ 0.03	1.01 $\pm$ 0.02	1.35 $\pm$ 0.02	1.21 $\pm$ 0.03

^aND = not done.

^xSodium acetate at pH 8.2 according to Sumner and Miller (1996).

^wSodium bicarbonate according to Olsen et al. (1954).

^vAmmonium acetate at pH 7.0 according to Thomas (1982).

^vDiethylene triamine pentaacetic acid extraction according to Lindsay and Norvell (1978).

^uAzomethine-H extraction according to Wolf (1974).

1982) was used to determine exchangeable cations. Microelements in the soils were determined by diethylene triamine pentaacetic acid extraction methods (Lindsay and Norvell, 1978). Some physical and chemical properties of soil were given in Table 1.

Trial design. The experiment was laid out in a split plot design with four Brussels sprout

cultivars (Star, Brilliant, Oliver, and Maximus) as the main plot and four B application levels (0, 1, 3, and 9 kg·ha⁻¹ B) as the subplot in four replicates. Individual plots (3 $\times$ 3 m) consisted of raised beds (3.0 m long and 3.0 m wide). A 2.0-m space was left between the plots to prevent water movement from one plot to another. Twenty-four Brussels sprout plants

were planted in each plot on 24 May 2005 and 1 June 2006. Row distance was 70 cm and plants were spaced 40 cm apart within rows.

Plant cultivation and fertility management. Before planting, N, P, potassium (K), and B were broadcast-applied in each plot at the rates of 350 N kg·ha⁻¹ (as ammonium sulfate), 92 kg·ha⁻¹ P (as triple superphosphate), 166

Table 2. Yields, optimum economic boron (B) rates (assuming U.S. \$0.65 kg⁻¹ B and a Brussels sprout value of U.S. \$2.08 kg⁻¹), and R² of the quadratic fit for the yield response data for Brussels sprout cultivars grown on a calcareous Aridisol in eastern Turkey in 2005 and 2006.

Year	Brussels sprout cultivar	B application rate				OEBR	Yield at OEBR	R ²
		0	1	3	9			
		kg·ha ⁻¹						
2005	Oliver	10,113 d	11,924 c	13,024 a	12,754 b	5.7	14,010	0.953
	Star	9,484 d	11,361 c	12,317 b	13,000 a	6.4	13,617	0.918
	Maximus	9,292 d	9,896 c	11,382 a	10,373 b	5.2	11,761	0.977
	Brilliant	8,627 c	9,092 b	10,173 a	9,982 a	5.8	10,601	0.988
2006	Oliver	9,547 d	12,062 c	13,067 a	12,693 b	5.6	14,302	0.902
	Star	9,036 d	10,942 c	11,404 b	11,964 a	6.3	12,351	0.876
	Maximus	8,409 c	9,556 b	10,942 a	10,756 a	5.8	11,744	0.998
	Brilliant	8,114 c	9,360 b	9,957 a	9,840 a	5.7	10,614	0.927
Average	Oliver	9,830 d	11,993 c	13,045 a	12,724 b	5.6	14,156	0.927
	Star	9,260 d	11,152 c	11,860 b	12,482 a	6.3	13,074	0.919
	Maximus	8,850 d	9,726 c	11,162 a	10,564 b	5.5	11,744	0.998
	Brilliant	8,370 c	9,226 b	10,065 a	9,911 a	5.7	10,608	0.990

OEBR = optimum economic B rate.

Different letters within the rows indicate mean differences at $P < 0.05$ significance level.

kg·ha⁻¹ K (as potassium sulfate), and 0, 1, 3, and 9 kg·ha⁻¹ B (as Na₂B₄O₇·10H₂O), respectively (Booij, 2000; Turan and Sevimli, 2005). The crop was weeded manually with a hoe and weeding was repeated as required. No pesticide was applied.

Irrigation water applications. Good-quality underground water with an EC of 0.28 dS·m⁻¹, sodium adsorption ratio of 0.40, and pH of 7.4 was used for surface irrigation. The moisture content (0- to 60-cm soil depth) was increased to field capacity after planting and soil moisture contents at 0- to 30-cm and 30- to 60-cm soil depths were determined daily by time domain reflectometer (TDR 300; Spectrum Technologies, East Plainfield, IL). When the moisture

content fell below 23.5% (Pw), a total of 32.4 mm irrigation water was applied to the soil based on an effective root depth of 60 cm (Allen et al., 1998). The total amount of irrigation water was 388.8 mm in 2005 and 453.6 mm in 2006.

Soil boron and plant sampling and analytical methods. Three soil samples from each plot were taken from 0 to 30 cm when Brussels sprouts started heading. The samples were air-dried, crushed, and passed through a 2-mm sieve before B analysis using the azomethine-H extraction as described in Wolf (1974) and an Aquamat ultraviolet/VIS spectrophotometer (Thermo Electron Spectroscopy Ltd., Cambridge, U.K.).

Of the 24 plants per plot, eight plants were sampled at heading time to determine the mineral contents of the heads, whereas another eight plants were harvested on 28 Sept. 2005 and 6 Oct. 2006 to determine season yields. Three heads per plant were taken at heading time for a total of 24 heads per treatment. Samples were oven-dried at 68 °C for 48 h and ground to pass 1 mm. The Kjeldahl method and a Vapodest 10 Rapid Kjeldahl Distillation Unit (Gerhardt, Königswinter, Germany) were used to determine total N (Bremner, 1996). Macro- [P, K, calcium (Ca), and magnesium (Mg)] and microelements [iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu)] were determined after wet digestion of dried and ground subsamples using a H₂SO₄-HClO₄ acid mixture (4:1 v/v) (AOAC922.02 2005; Mertens, 2005a). Phosphorus in the extraction solution was measured spectrophotometrically using the indophenol-blue and ascorbic acid method (AOAC931.01 2005; Mertens, 2005b) and an Aquamat ultraviolet/VIS spectrophotometer (Thermo Electron Spectroscopy Ltd.). Tissue K, Ca, and Mg, Fe, Mn, Zn, and Cu were determined after wet digestion using a H₂SO₄-HClO₄ acid mixture (4:1 v/v) and a Perkin-Elmer 360 atomic absorption spectrophotometer (Perkin-Elmer, Waltham, MA) (AOAC975.03 2005; Mertens, 2005c). Boron analysis was done using the azomethine-H procedure and an Aquamat ultraviolet/VIS spectrophotometer (Thermo Electron Spectroscopy Ltd.) (AOAC958.03 2005; Mertens, 2005d).

Fig. 2. Relationship between boron (B) application and apparent B recovery for four Brussels sprout cultivars grown on a calcareous Aridisol in eastern Turkey. At the economic optimum B rates of 5.6, 6.3, 5.5, and 5.7 kg·ha⁻¹·year⁻¹ B (averaged over the 2 years) for 'Oliver', 'Star', 'Maximus', and 'Brilliant', the apparent B recovery was 4%, 4%, 6%, and 23%, respectively.

Fig. 3. Relationship between boron (B) application and soil solution B concentration (2-year average) for four Brussels sprouts cultivars (Star, Brilliant, Oliver, and Maximus) grown on a calcareous Aridisol in eastern Turkey. At the optimum economic B rate (OEBR), soil solution B ranged from 0.94 to 1.13 mg·kg⁻¹ B.

Table 3. Leaf macroelement concentration of Brussels sprout cultivars when grown in 2 consecutive years under four different boron (B) application treatments on a calcareous Aridisol in eastern Turkey in 2005 and 2006.

B application doses kg·ha ⁻¹	Brussels sprout cultivars			
	Oliver	Star	Maximus	Brilliant
N				
0	2.47 a	2.32 b	2.28 a	2.31 a
1	2.46 a	2.44 a	2.09 b	2.22 a
3	2.35 b	2.34 b	1.99 c	2.09 b
9	2.22 c	2.20 c	1.85 d	1.88 c
Adjusted R ²	0.683	0.711	0.767	0.631
LSD	0.050	0.033	0.050	0.058
P				
0	0.67 c	0.70 d	0.62 d	0.65 d
1	0.77 b	0.97 c	0.81 c	0.74 c
3	0.87 a	1.14 b	0.86 b	0.81 b
9	0.83 a	1.28 a	0.89 a	0.88 a
Adjusted R ²	0.670	0.841	0.920	0.907
LSD	0.025	0.049	0.015	0.013
Ca				
0	3.92 a	3.95 a	4.05 a	4.03 a
1	3.58 b	3.73 b	3.52 b	3.77 b
3	3.27 c	3.62 b	3.43 b	3.42 b
9	2.57 d	3.27 c	3.17 c	3.23 c
Adjusted R ²	0.902	0.635	0.897	0.696
LSD	0.077	0.091	0.057	0.093
K				
0	1.32 d	1.19 d	1.53 c	1.63 d
1	1.63 c	1.28 c	1.78 b	1.82 c
3	1.93 b	1.83 b	2.02 a	1.97 b
9	2.08 a	1.93 a	2.13 a	2.08 a
Adjusted R ²	0.841	0.964	0.894	0.977
LSD	0.064	0.031	0.062	0.033
Mg				
0	2.27 c	2.47 a	2.32 a	2.11 a
1	2.73 a	2.48 a	2.12 b	1.75 b
3	2.28 b	2.28 b	1.97 b	2.03 a
9	2.47 c	1.85 c	1.76 c	1.79 b
Adjusted R ²	0.829	0.761	0.670	0.410
LSD	0.085	0.071	0.079	0.075

LSD = least significant difference.

Different letters within the columns indicate mean differences at $P < 0.05$ significance level.

Statistical analysis. The experiment was laid out in a split plot design with four Brussels sprout cultivars (Star, Brilliant, Oliver, and Maximus) in a randomized block design as main plots and four B application levels (0, 1, 3, and 9 kg·ha⁻¹ B) as the subplot in four replicates. All data were subjected to analysis of variance and significant means were compared by Duncan's multiple range test method performed using SPSS 13.0 (SPSS Inc., 2004). Mean differences were considered significant if $P \leq 0.05$. The optimum economic B rate (OEBR) was defined as the B rate at which the highest returns to B fertilizer were obtained assuming a quadratic-plus-plateau model, a Brussels sprout value of U.S. \$2.08 kg⁻¹, and a fertilizer cost of U.S. \$0.65 kg⁻¹ B. For return per ha calculations, an annual (fixed) cost of production of \$833.53/ha⁻¹ was assumed. For each B application rate, the apparent B recovery (ABR) was calculated as the B removal in harvest per kilogram B applied:

$$\text{Apparent B recovery (\%)} = \frac{(\text{B at } B_{\text{rate}} - \text{B at control})}{(\text{B applied})} \times 100 \quad [1]$$

Results

Boron fertilizer application affected the yield of all Brussels sprout cultivars in each of the 2 years and there were no statistically significant differences between the mean yields of the 2 years (Fig. 1). There were no significant interactions between cultivar selection and B treatment for any of the response variables. The highest yields were obtained with the Oliver cv. (Table 2)

Table 4. Leaf microelement concentration of Brussels sprout cultivars when grown in 2 consecutive years under four different boron (B) application treatments on a calcareous Aridisol in eastern Turkey in 2005 and 2006.

B application doses kg·ha ⁻¹	Brussels sprout cultivars			
	Oliver	Star	Maximus	Brilliant
	mg·kg ⁻¹ dry matter			
	Fe			
0	10.50 d	9.67 d	8.83 c	7.33 d
1	16.67 c	15.83 c	13.33 b	10.83 c
3	29.17 b	25.50 b	18.83 a	18.50 b
9	37.33 a	30.17 a	20.17 a	21.33 a
Adjusted R ²	0.986	0.985	0.910	0.971
LSD	0.607	0.476	0.678	0.465
	Zn			
0	26.50 c	23.83 c	20.33 d	17.50 d
1	30.50 b	30.50 b	23.17 c	21.17 c
3	33.00 a	34.50 a	26.17 b	31.17 b
9	34.33 a	33.67 a	31.50 a	38.83 a
Adjusted R ²	0.819	0.914	0.917	0.976
LSD	0.688	0.685	0.615	0.638
	Mn			
0	10.00 c	9.83 c	10.67 d	11.33 c
1	14.83 b	16.67 b	12.00 c	13.50 b
3	19.33 a	17.17 b	13.83 b	16.67 a
9	19.83 a	19.50 a	15.17 a	16.67 a
Adjusted R ²	0.945	0.929	0.803	0.846
LSD	0.465	0.478	0.581	0.456
	Cu			
0	7.00 d	7.83 b	5.00 c	6.50 c
1	10.00 c	11.33 a	4.50 c	9.83 b
3	12.17 a	11.50 a	6.33 b	9.67 b
9	11.33 b	10.83 a	8.33 a	10.83 a
Adjusted R ²	0.935	0.706	0.823	0.922
LSD	0.281	0.473	0.333	0.252
	B			
0	6.62 d	6.90 d	7.38 d	7.54d
1	24.29 c	23.11 c	19.70 c	22.06c
3	35.88 b	35.18 b	35.21 b	29.75b
9	47.84 a	48.07 a	44.27 a	45.06a
Adjusted R ²	0.991	0.994	0.986	0.994
LSD	0.701	0.578	0.814	0.512

LSD = least significant difference.

Different letters within the columns indicate mean differences at $P < 0.05$ significance level.

at OEBRs that ranged from 5.5 kg·ha⁻¹ B to 6.3 kg·ha⁻¹ B (Table 2).

Boron application reduced the ABR (Fig. 2). The ABR at the OEBR varied from ≈4% for Oliver and Star to slightly more than 6% for Maximus and almost 23% for Brilliant (Fig. 2).

Without B addition, the average (2-year) soil B contents at heading time were 0.072, 0.072, 0.055, and 0.053 mg·kg⁻¹ for Oliver, Star, Maximus, and Brilliant cultivars, respectively. This increased to 1.08, 1.02, 1.13, and 0.94 mg·kg⁻¹ B for 'Oliver', 'Star', 'Maximus', and 'Brilliant', respectively, when B fertilizer was applied at the OEBR (Fig. 3).

Boron fertilizer application decreased tissue N, Ca, and Mg and increased P, K, Fe, Zn, Mn, and Cu content of all four cultivars (Tables 3 and 4). The 2-year average tissue B content in the control treatments was 6.62, 6.90, 7.38, and 7.35 mg·kg⁻¹ dry weight for 'Oliver', 'Star', 'Maximus', and 'Brilliant', respectively. This increased to 49.7, 50.2, 46.8, and 42.5 mg·kg⁻¹ B, respectively, when B fertilizer was applied at the OEBR (Figure 4).

Discussion

The OEBRs in our study were higher than the 1.5 to 4.4 kg·ha⁻¹ B rates obtained for mustard [*Brassica juncea* (L.)] by Stangoulis et al. (2000) and for bentgrass (*Agrostis palustris* Huds.) by Guertal (2004) but lower than the 8.0 kg·ha⁻¹ B obtained for sunflower by Oyindola (2007). Oyindola (2007) emphasized that the high OEBR might be related to low initial soil B level in the study (0.09 mg·kg⁻¹ as compared with 0.13 to 0.15 mg·kg⁻¹ in our study). The higher OEBR

Fig. 4. Relationship between boron (B) application and Brussels sprout tissue B content (2-year average) for four Brussels sprouts cultivars (Star, Brilliant, Oliver, and Maximus) grown on a calcareous Aridisol in eastern Turkey. At the optimum economic B rate (OEBR), plant tissue B ranged from 42.5 to 50.2 mg·kg⁻¹ B.

may also be related to soil type (Alfisol) and sunflower sensitivity to B deficiency (Tisdale et al., 1985).

The ABRs in our study were higher than those obtained by Byju et al. (2007) for sweetpotato, in which the highest ABR was 0.4% at a B application rate of 1.0 kg-ha⁻¹, but lower than those obtained by Santos et al. (2004) for alfalfa in which the ABR decreased from 48% on application of 0.25 kg-ha⁻¹ B to 10% when 2.0 kg-ha⁻¹ B was applied. These differences most likely reflect the very low initial soil B concentration (0.025 mg·kg⁻¹ B) in the study by Santos et al. (2004).

Soil B content at the optimum yield in our study was higher than the 0.28 mg·kg⁻¹ B reported by Asad et al. (1997) for canola (*Brassica napus* L.) grown under greenhouse conditions. On the other hand, our study showed lower optimum soil B levels than the 2 mg·kg⁻¹ reported for muskmelon (*Cucumis melo* L.) grown in field conditions (Goldberg et al., 2003), possibly reflecting species-specific differences in optimum soil B content as well as soil and greenhouse to field differences.

Compiling results from the greenhouse and field experiments published during 10 years, Guertal (2004), Santos et al. (2004), and Ross et al. (2006) suggested 10 mg·kg⁻¹, 66 mg·kg⁻¹, 44.1 mg·kg⁻¹ in plant tissue to be the critical level for boron in bentgrass (*Agrostis palustris* Huds.), alfalfa (*Medicago sativa* cv. Crioula), and soybean [*Glycine max* (Merr.) L.], respectively. The range in tissue B content at the OEBr in our study (42.5 to 50.2 mg·kg⁻¹ B) suggests similar critical tissue B contents for Brussels sprouts as for soybeans.

The concentrations of all plant nutrients measured were within agronomic critical levels defined in Mills and Jones (1996) except for N, Fe, and Mn. Mills and Jones (1996) defined critical ranges of 3.10% to 4.50% for N, 60 to 150 mg·kg⁻¹ for Fe, and 25 to 200 mg·kg⁻¹ for Mn, suggesting N, Fe, and Mn addition might increase yields beyond those obtained in our study.

Conclusion

Boron application increased Brussels sprout yield, indicating B deficiency. Averaged over the 2 years, the maximum return to B fertilizer was obtained for the Oliver cv. at an OEBr of 5.6 kg-ha⁻¹ B. Tissue B content increased from 6.62 mg·kg⁻¹ dry weight in the control treatment to 37.81 mg·kg⁻¹ B when B was applied at the OEBr. Across all cultivars, soil B levels ranged from 0.94 to 1.13 mg·kg⁻¹ at OEBr that ranged from 5.5 to 6.3 kg-ha⁻¹ B. Independent of cultivar, B application increased tissue P, K, Fe, Mn, Zn, and Cu content but decreased tissue N, Ca, and Mg for each of the cultivars. We conclude B addition of 6 kg-ha⁻¹ is sufficient to elevate soil B levels of this soil with an initial B content of 0.13 mg·kg⁻¹ to nondeficient levels of 0.94 to 1.13 mg·kg⁻¹. Similar studies

with different soils and initial soil test B levels are needed to conclude if these B application rates and critical soil test values can be applied across the region.

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