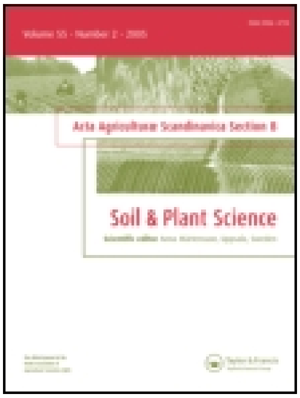

Acta Agriculturae Scandinavica, Section B - Soil & Plant Science
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/sagb20

Boron application improves on yield and chemical composition of strawberry

Aslihan Esringü [a] , Metin Turan [a] , Adem Gunes [a] , Ahmet Eşitken [b] & Paolo Sambo [c]

[a] Department of Soil Science, Faculty of Agriculture, Atatürk University, Erzurum, Turkey

[b] Department of Horticulture, Faculty of Agriculture, Atatürk University, Erzurum, Turkey

[c] Department of Environmental Agronomy and Crop Science, Padova University, (AGRIPOLIS), Viale dell'Università, Legnaro, PD, Italy

Available online: 09 Mar 2011

Acta Agriculturae Scandinavica Section B – Soil and Plant Science, 2011; 61: 245–252

Taylor & Francis
Taylor & Francis Group

ORIGINAL ARTICLE

Boron application improves on yield and chemical composition of strawberry

ASLIHAN ESRINGÜ[1], METIN TURAN[1], ADEM GUNES[1], AHMET EŞITKEN[2] & PAOLO SAMBO[3]

[1]*Department of Soil Science, Faculty of Agriculture, Atatürk University, Erzurum, Turkey,* [2]*Department of Horticulture, Faculty of Agriculture, Atatürk University, Erzurum, Turkey,* [3]*Department of Environmental Agronomy and Crop Science, Padova University, (AGRIPOLIS), Viale dell'Università, Legnaro (PD) Italy*

Abstract

Boron (B) is an essential micronutrient required for normal plant growth and development. Boron management is challenging because the optimum B application range is narrow and the application rates vary from one soil to another. Boron deficiency is widespread in the Anatolia region of Turkey. This may impact on yield and mineral contents of leaves and fruits of strawberry (*Fragaria × ananassa* cv. Fern) especially in B-deficient calcareous Aridisols in Eastern Anatolia, Turkey. A 2-year field experiment was conducted to study yield and quality response of strawberry to B application. Boron fertilizer application affected plant yield and chemical composition. B application decreased tissue nitrogen (N) and calcium (Ca) but increased tissue phosphorus (P), potassium (K), manganese (Mn), zinc (Zn) and copper (Cu) content. We conclude that a B addition of 5.5 kg ha^{-1} is sufficient to elevate soil B levels to non-deficient levels.

Keywords: *Aridisol, boron deficiency, macro and micro nutrient, optimum economic yield.*

Introduction

Strawberry (*Fragaria × ananassa*) is one of the most delicious fruits of the world. It is rich in vitamins and minerals, and has a good flavour and tantalizing aroma.

In Turkey, it was introduced in the early 1970s, but for several reasons, it is not yet considered as a staple food (Ercisli, 2004). However, in recent years, several day-neutral varieties have been introduced and different specific agro-techniques have been set for standardization at various research stations. Because of this research, during the last decade strawberry production has spread through almost all Turkey and has become a favourite fruit crop for both conventional and organic growers. Thus, strawberry production of Turkey is increasing steadily, reaching annually 250 000 tons (FAO, 2008). The country is now one of the biggest strawberry producers in Europe after Spain. Production in the Eastern Anatolia region starts in June and is harvested in November–December. Parallel to the increasing amount of strawberry production in Turkey, the problems faced by Turkish strawberry growers are also increasing. The major problems in strawberry production in Turkey are mainly connected with adverse soil conditions and plant protection (calcareous soils, salinity, diseases and pests). Soils in Turkey, especially in Mediterranean, Central, Western, Eastern and South Eastern Anatolia regions, usually have high levels of carbonate and so a high pH. Therefore, micro nutrient element such as B and Fe deficiency in these regions frequently have been shown in different fruit crops. Consequently, expansion of strawberry production in the region is limited if B deficiency of the soils will not be addressed economically.

Boron plays an important role in cell-wall synthesis, sugar transport, cell division and 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 colour and become harder, malformed and necrotic.

Correspondence: M. Turan, Department of Soil Science, Faculty of Agriculture, Atatürk University, 25240 Erzurum, Turkey. E-mail: m_turan25@hotmail.com

(Received 14 January 2010; revised 11 March 2010; accepted 14 March 2010)

ISSN 0906-4710 print/ISSN 1651-1913 online
DOI: 10.1080/09064711003776867

Boron deficiency has been reported in 132 crops in 80 countries (Shorrocks, 1997) and is a major cause of 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 & Hamurcu, 2006) and micronutrient availability studies (Gezgin et al., 1999). It is estimated that in the central southern and eastern Anatolia regions of Turkey 27–34% of the soils are B deficient (Kacar & Fox, 1967; Kacar et al., 1979; Gezgin et al., 2002; Gezgin & Hamurcu, 2006; Angın et al., 2008).

Boron management is challenging as 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). In semi-arid regions, the soils are light, having low organic content and B deficiency usually occurs during a growing season under low rainfall (Wojcik & Lewandowski, 2003). However, application of boron in soil, in some cases, causes phytotoxicity as there is a narrow range between B deficiency and toxicity for many fruit crops.

It has been reported that soil or foliar application of B increased fruit yield of apple (*Malus domestica* Borkh.) (Wojcik et al., 1999), cranberry (*Vaccinium macrocarpon*, Ait) (DeMoranville & Deubert, 1987), highbush blueberry (*Vaccinium corymbosum* L.) (Blevins et al., 1996), peach (*Prunus persica* L.) (Kamali & Childers, 1970), pear (*Pyrus communis* L.) (Wojcik & Wojcik, 2003), and prune (*Prunus domestica* L.) (Hanson & Breen, 1985). However, little is known about the response of strawberry to B fertilization.

The objectives of this study were (1) to evaluate the yield response of strawberry to B fertilizer; (2) to determine the effects of B addition on the mineral composition of strawberry; and (3) to determine optimum soil test B levels for strawberry under semi arid climate field conditions.

Materials and methods

Background information for the study site

This study was conducted at the Agricultural Research Station of Ataturk University located in Erzurum, Turkey (39° 55′ N and 41° 16′ E) during the summer periods (late May–late September) of 2005 and 2006. The elevation was 1835 m. The soil was classified as an Aridisol with parent materials mostly consisting of volcanic, marn and lacustrin transported material (Soil Survey Staff, 1992). The experimental region has a semi-arid climate. During the growing period, the mean maximum temperature was 29 °C in both years while 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–29 September), and 57.95%, 3.50 m s^{-1}, 10.07 h, 48.9 mm and 448 mm in 2006 (28 May–10 October), respectively.

Soil samples were taken over two depths (0–30 and 30–60 cm, 20 subsamples) to determine baseline soil properties. Soil samples were air-dried, crushed and passed through a 2-mm sieve prior to chemical analysis. Cation exchange capacity (CEC) 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 organic N while plant-available 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, 1982) was used to determine exchangeable cations. Micro elements in the soils were determined by Diethylene Triamine Pentaacetic Acid (DTPA) extraction methods (Lindsay & Norvell, 1978) (Table I).

Experimental design

The experiment was laid out in a randomized complete block design with a two growth model (not covered raised bed and covered with black plastic mulch raised bed) and four B application levels (0, 1, 3 and 9 kg B ha^{-1}) in four replicates. Each growth plot (not covered and covered with black plastic mulch) consisted of 25 plants. In the fall of 2004, farm manure at a rate of 20 tons ha^{-1} was distributed and ploughed to a depth of 40 cm. Strawberry plants with diameter of 15–22 mm were planted on the 5 May 2005 in a raised bed at a spacing of 0.30 × 0.35 m (50 000 plants per ha) on a loamy soil. A 2.0 m space was left between the plots to prevent water movement from one plot to another.

Plant cultivation and fertility management

Because of optimal concentrations of available K in the soil, this element was not applied during the experiment. In 2005 and 2006, P and B were broadcast applied in each plot at the rates of 90 kg P ha^{-1} (as triple superphosphate) and 0, 1, 3 and 9 kg B ha^{-1} (as $Na_2B_4O_7 \cdot 10H_2O$) respectively, N at the rate of 150 N kg ha^{-1} (as ammonium

Table I. Some chemical and physical properties of the experimental soils, prior to land preparation for boron response (mean ± SD, n = 20).

Soil properties	2005 SS (0–30 cm)	2005 SB (30–60 cm)	2006 SS (0–30 cm)	2006 SB (30–60 cm)
Clay, %	31.7 ± 1.30	28.50 ± 1.10	[a]ND	ND
Silt, %	44.5 ± 0.80	38.40 ± 0.90	ND	ND
Sand, %	23.9 ± 1.10	33.10 ± 1.60	ND	ND
Cation exchangeable capacity, $cmol_c\ kg^{-1}$	32.0 ± 2.40	27.50 ± 1.30	ND	ND
Total N, $g\ kg^{-1}$	0.5 ± 0.03	0.2 ± 0.06	0.8 ± 0.02	0.4 ± 0.06
pH (1:2 soil: water)	7.25 ± 0.2	11.00 ± 1.20	7.25 ± 0.17	11.00 ± 1.10
Organic matter, $g\ kg^{-1}$	19 ± 0.10	9 ± 1.70	11 ± 0.10	5 ± 1.90
$CaCO_3$, $g\ kg^{-1}$	130 ± 0.10	151 ± 0.30	120 ± 0.20	138 ± 0.20
Plant available P, $mg\ kg^{-1}$	7.3 ± 1.60	3.0 ± 0.40	8.2 ± 0.70	3.9 ± 0.30
Exchangeable Ca, $cmol_c\ kg^{-1}$	16.0 ± 2.20	22.1 ± 0.03	17.0 ± 1.10	20.2 ± 0.01
Exchangeable Mg, $cmol_c\ kg^{-1}$	4.40 ± 0.50	3.20 ± 0.11	3.1 ± 0.60	3.2 ± 0.15
Exchangeable K, $cmol_c\ kg^{-1}$	2.4 ± 0.80	1.6 ± 0.07	2.1 ± 0.50	1.2 ± 0.04
Exchangeable Na, $cmol_c\ kg^{-1}$	0.15 ± 0.05	0.11 ± 0.11	0.10 ± 0.07	0.09 ± 0.10
Available Fe, $mg\ kg^{-1}$	3.10 ± 0.30	1.55 ± 0.10	2.50 ± 0.20	1.23 ± 0.07
Available Mn, $mg\ kg^{-1}$	1.70 ± 0.09	1.35 ± 0.08	1.20 ± 0.08	1.11 ± 0.03
Available Zn, $mg\ kg^{-1}$	1.65 ± 0.15	1.28 ± 0.03	1.27 ± 0.15	1.13 ± 0.01
Available Cu, $mg\ kg^{-1}$	1.20 ± 0.13	0.75 ± 0.03	1.10 ± 0.13	0.70 ± 0.02
Available B, $mg\ kg^{-1}$	0.13 ± 0.06	0.07 ± 0.03	0.15 ± 0.07	0.09 ± 0.02
Electric conductivity, $dS\ m^{-1}$	1.05 ± 0.03	1.01 ± 0.02	1.35 ± 0.02	1.21 ± 0.03

[a]ND, Not done; SS, surface soil; SB, subsurface soil.

nitrate) was applied in two equal parts, the first was applied 2 weeks after strawberry transplant and the second 6 weeks later. The crop was manually weeded with a hoe and weeding was repeated as needed. No pesticide was applied.

Irrigation water applications

Good quality underground water with an electrical conductivity of 0.28 $dS\ m^{-1}$, Na adsorption ratio of 0.40 and pH of 7.4 was used for drip irrigation. The moisture content (0–60 cm soil depth) was increased to field capacity after planting and soil moisture contents at 0–30 cm and 30–60 cm soil depths were determined daily by a time domain reflectometer (TDR 300, Spectrum Technologies, East Plainfield, IL, USA). When the moisture content fell below 20.65% (Pw), a total of 16.4 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 0–30 cm when strawberry started first harvest and last harvest. The samples were air-dried, crushed and passed through a 2 mm sieve prior to undergoing B analysis using the azomethine-H extraction as described in Wolf (1974) and an Aqumat UV/VIS spectrophotometer (Thermo Electron Spectroscopy Ltd, Cambridge, UK).

Of the 25 plants per plot, eight plants were sampled at first harvest time to determine the mineral contents on fruit and leaf while another eight plants were harvested on 25 September 2005 and 10 October 2006 to determine yields. Samples were oven-dried at 68 °C for 48 h and ground to pass 1 mm sieve. The Kjeldahl method and a Vapodest 10 Rapid Kjeldahl Distillation Unit (Gerhardt, Konigswinter, Germany) were used to determine total N (Bremner, 1996). Macro (P, S, K, Ca and Mg) and micro elements (Fe, Mn, Zn, Cu and B) were determined after wet digestion of dried and ground sub-samples using a HNO_3-H_2O_2 acid mixture (2:3 v/v) with three step (first step; 145 °C, 75% RF, 5 min; second step; 180 °C, 90% RF, 10 min and third step; 100 °C, 40% RF, 10 min) in a microwave (Bergof Speedwave Microwave Digestion Equipment MWS-2) (Mertens, 2005a). Tissue P, K, S, Ca, Mg, Fe, Mn, Zn, Cu and B were determined using an Inductively Couple Plasma spectrophotometer (Perkin-Elmer, Optima 2100 DV, ICP/OES, Shelton, CT, USA) (Mertens, 2005b).

Statistical analysis

The experiment was laid out in a randomized complete block design with four B application levels (0, 1, 3 and 9 kg B ha^{-1}) in four replicates. All data were subjected to analysis of variance (ANOVA) and means separation was performed by means of Duncan's multiple range test method, performed using SPSS 13.0 (SPSS Inc., 2004). Mean

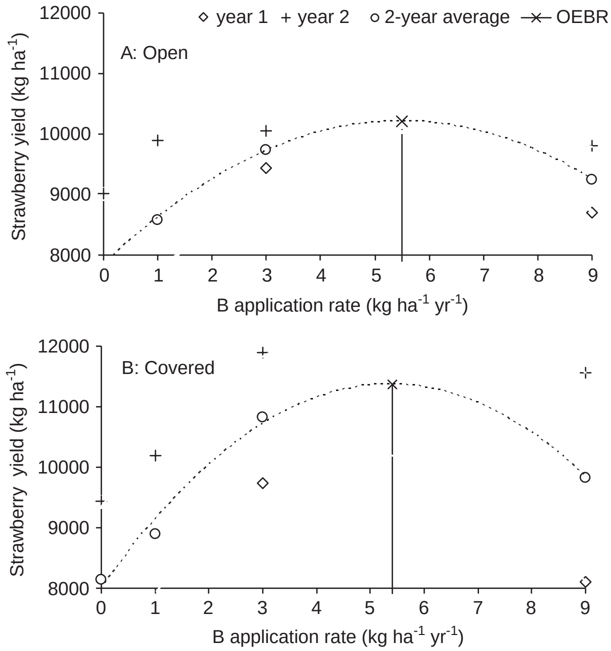

Figure 1. Strawberry yields as affected by boron (B) applications (2-year average) in open (A) and covered (B) growth condition.

differences were considered significant when $p \leq 0.05$. The optimum economic B rate (OEBR) was defined as the B rate at which the highest return to B fertilizer was obtained assuming a quadratic-plus-plateau model, a strawberry value of US$ 1.93 kg^{-1} and a fertilizer cost of US$ 0.65 kg^{-1} B. For return per ha calculations, an annual (fixed) cost of production of US$ 3550.20 ha^{-1} for not covered raised bed and US$ 4000.00 ha^{-1} for covered black plastic mulch raised bed were assumed. For each B application rate, the apparent B recovery (ABR) was calculated as the B removal in harvest per kg of B applied:

$$\text{Apparent B recovery (\%)} = (\text{B at Brate} - \text{B at control})/(\text{B applied}) \times 100 \quad (1)$$

Results and discussion

Boron fertilizer application affected plant yield in both open and covered growth conditions, and there were statistically significant differences in strawberry production between years (Figure 1). There were significant interactions between growth condition (open-covered) and B treatment for any of the response variables. Based upon the average yield of 2 years, the highest yield was obtained from covered growth conditions (Table II) at OEBRs that ranged from 5.1 kg B ha^{-1} to 5.8 kg B ha^{-1} (Table II).

Boron application reduced the ABR (Figure 2). The ABR at the OEBR varied for leaves from 3.2–3.5% for open and covered growth conditions, respectively, and to slightly lower than 1% for fruit (Figure 2).

Without B addition, the average (2-year) soil B content at harvest time was 0.072 and 0.080 mg kg^{-1} for open and covered growth conditions, respectively. These values increased to 1.27 and 1.26 mg B kg^{-1}, respectively, when B fertilizer was applied at the OEBR (Figure 3). Boron application decreased leaf tissue N and Ca and increased P, K, Zn, Mn and Cu content in both growing conditions, but increased only P and K contents in fruit (Tables III and IV).

The 2-year average tissue B content in the control treatments was 2.36, 3.30 and 0, 46, 0.71 mg kg^{-1} DW for open and covered growth condition strawberry leaf and fruit, respectively. This increased up to 25.0, 29.0, 10.8 and 13.9 mg B kg^{-1}, respectively, when B fertilizer was applied at the OEBR (Table IV).

Table II. Yields, optimum economic B rates, and R^2 values for strawberry plants grown in open and covered conditions on a calcareous Aridisol.

		Boron application rate						
		0	1	3	9	OEBR[a]	Yield at OEBR	R^2
Year	Strawberry growth condition	kg ha^{-1}						
2005	Open	6720 d	7248 c	9440 a	8708 b	5.6	10029	0.950
	Covered	6840 d	7584 c	9744 a	8100 b	5.1	10200	0.965
2006	Open	9020 c	9900 b	10050 a	9800 b	5.3	10402	0.793
	Covered	9440 c	10200 b	11900 a	11560 a	5.8	12573	0.989
Average	Open	7870 d	8574 c	9745 b	9254 a	5.5	10214	0.998
	Covered	8140 c	8892 b	10822 a	9830 a	5.4	11373	0.977

[a]OEBR, optimum economic B rate.

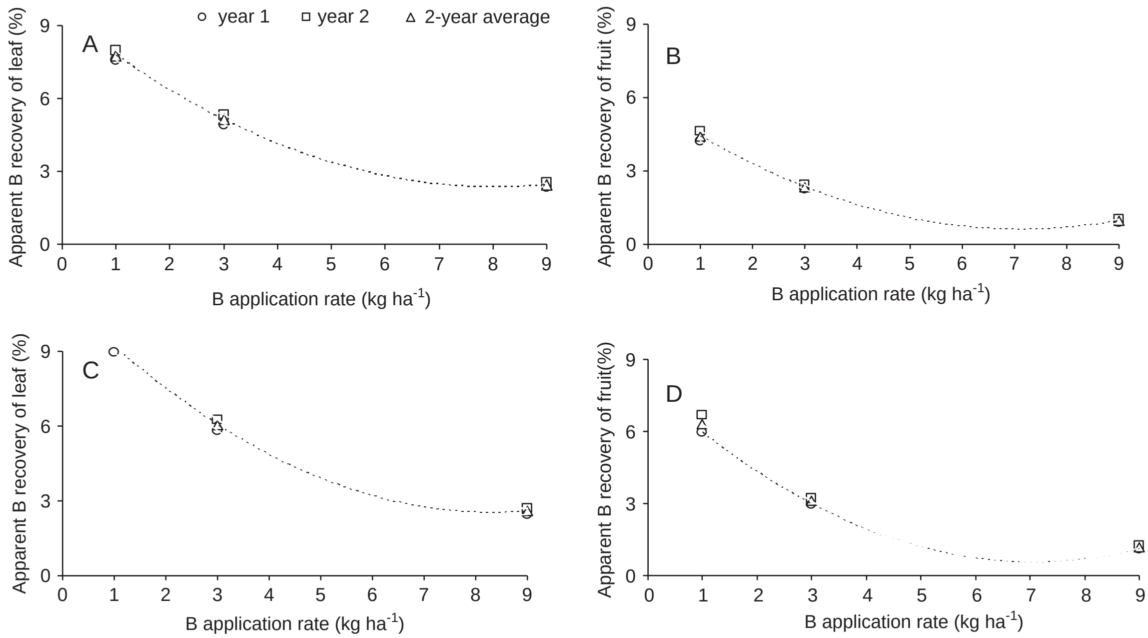

Figure 2. Relationship between boron application and apparent B recovery for leaf and fruits of strawberry grown on a calcareous Aridisol at open (A: leaf; B: fruit), and covered (C: leaf; D: fruit) conditions.

Discussion

Boron application increased strawberry yield, indicating B deficiency. Averaged over the 2 years, the maximum return for B fertilizer was obtained for the covered grown strawberry plants at an OEBR of 5.5 kg B ha^{-1}. The OEBRs in our study were higher than the 1.5 to 4.4 kg B ha^{-1} rates measured in mustard (*Brassica juncea* L.) by Stangoulis et al. (2000) and bentgrass (*Agrostis palustris* Huds.) by Guertal (2004) but lower than the 8.0 kg B ha^{-1} obtained for sunflower (*Helianthus annuus* L.) by Oyinlola (2007). Oyinlola (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 0.13–0.15 mg kg^{-1} in our study). The higher OEBR may also be related to soil type (Alfisol) and sunflower sensitivity to B deficiency (Tisdale et al., 1985).

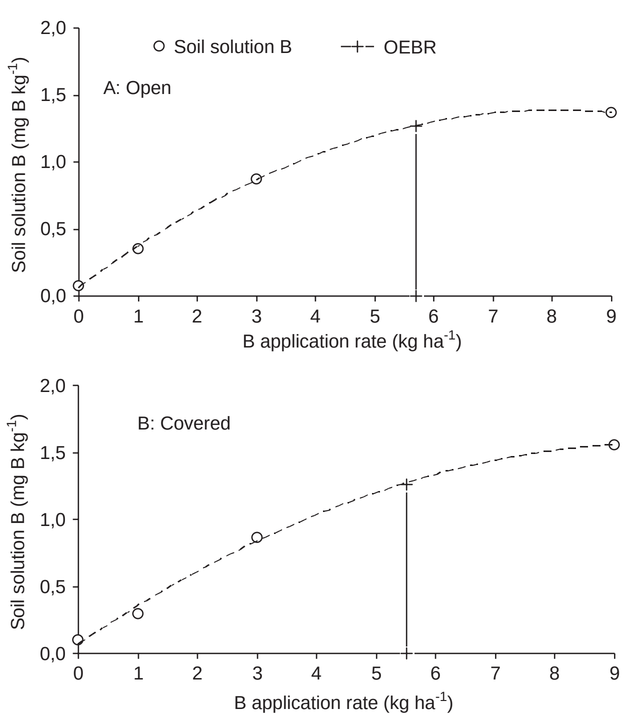

Figure 3. Relationship between boron application and soil solution B concentration (2-yr average) for open and covered growth conditions grown on a calcareous Aridisol.

The ABR at the OEBR varied for leaves from 3.2–3.5% for open and covered growth conditions, respectively. The ABRs in our study were also higher than those obtained by Byju et al. (2007) for sweet potato, who showed 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 where the ABR decreased from 48% upon application of 0.25 kg B ha^{-1} to 10% when 2.0 kg B ha^{-1} was applied. These differences most likely reflect the very low initial soil B concentration (0.025 mg B kg^{-1}) in the study by Santos et al. (2004).

Independent from growth condition, B application increased leaf tissue P, K, Fe, Mn, Zn and Cu content but decreased tissue N and Ca, while only increased P and K contents of fruit in each of the growth conditions. Boron is related to many physiological and biochemical processes likely to affect the utilization of other plant nutrients, but no clear physiological and chemical mechanisms are proposed in the literature (Tariq & Mott, 2007). However, B interactions, either synergism or an

Table III. Effects of B application on macro element contents of leaf and fruit of strawberry plants under open and covered growth conditions on a calcareous Aridisol.

Boron application doses kg ha^{-1}	Leaf Open	Leaf Covered	Fruit Open	Fruit Covered
	% of DM			
	N			
0	3.24 a	3.83 a	2.56 a	3.07 a
1	3.29 a	3.78 a	2.20 b	2.62 b
3	2.97 b	3.39 b	1.72 c	1.99 c
9	2.81 b	3.12 c	1.42 d	1.57 d
LSD	*0.094*	*0.106*	*0.071*	*0.081*
	P			
0	0.39	0.49	0.31 b	0.37 b
1	0.57	0.68	0.36 b	0.43 b
3	0.64	0.71	0.40 b	0.46 b
9	0.69	0.77	0.52 a	0.60 a
LSD	*0.116*	*0.132*	*0.045*	*0.052*
	Ca			
0	1.84 a	2.24 a	1.55 a	1.65
1	1.68 ab	2.19 a	1.29 b	1.47
3	1.48 bc	1.73 b	1.23 b	1.28
9	1.37 c	1.56 b	0.77 c	0.85
LSD	*0.108*	*0.128*	*0.107*	*0.335*
	K			
0	2.56 c	2.92	2.17 c	2.55
1	2.65 b	3.37	2.24 bc	2.58
3	2.76 a	3.03	2.34 ab	2.68
9	2.76 a	3.32	2.42 a	2.68
LSD	*0.024*	*0.319*	*0.070*	*0.086*
	Mg			
0	1.35 c	1.56 a	1.00	1.19 b
1	1.38 b	1.52 b	1.04	1.19 b
3	1.38 ab	1.56 a	1.06	1.25 ab
9	1.40 a	1.57 a	1.10	1.32 a
LSD	*0.009*	*0.010*	*0.030*	*0.036*

Table IV. Effects of B application on micro element contents of leaf and fruit of strawberry plants under open and covered growth conditions on a calcareous Aridisol.

B application doses kg ha^{-1}	Leaf Open	Leaf Covered	Fruit Open	Fruit Covered
	mg kg^{-1} DM			
	Fe			
0	63.65	54.74	9.92	9.42
1	63.40	50.72	10.20	9.59
3	62.63	57.62	11.62	10.46
9	65.06	58.72	13.03	12.25
LSD	*6.096*	*4.873*	*1.472*	*1.377*
	Zn			
0	30.26	35.10	10.46	13.07
1	37.08	40.79	10.75	12.80
3	39.75	44.92	11.39	14.50
9	36.19	40.54	11.09	14.42
LSD	*4.190*	*4.624*	*1.246*	*1.604*
	Mn			
0	29.63	26.66	4.92	6.40
1	28.75	25.58	4.88	5.81
3	35.60	39.87	5.04	5.75
9	29.04	32.85	5.33	5.97
LSD	*5.005*	*2.492*	*0.741*	*0.838*
	Cu			
0	12.35	10.62	2.01	2.34
1	13.62	10.89	2.00	2.56
3	17.58	13.11	2.03	2.47
9	15.83	13.93	2.05	2.63
LSD	*4.537*	*4.785*	*0.133*	*0.168*
	B			
0	2.36 d	3.30 d	0.46 d	0.71 c
1	10.13 c	12.49 c	4.88 c	7.03 b
3	17.18 b	21.47 b	7.49 b	10.01 a
9	24.37 a	26.60 a	9.11 a	11.19 a
LSD	*0.816*	*0.816*	*0.632*	*0.712*

antagonism, can affect plant nutrition under both deficiency and toxicity conditions. Applied B had an antagonistic effect on the uptake of some nutrients and this could be due to the toxic effects of B on root cells, resulting in an impaired nutrient absorption process. There are clear differences observed and contradictions in plant nutrient response with regard to B supply, which must be due to the use of different growth media, crop species and varieties, plant parts analysed, various growth stages and environmental conditions. The evidence suggests that the deficiency or excess of B not only affects the relative values of individual elements, but it also affects the balance among certain nutrient elements within plants, causing either an increase or decrease of dry matter production.

The average (2-year) soil B content at harvest time was 0.072, and 0.080 mg kg^{-1} for open and covered growth conditions, respectively. These values increased to 1.27 and 1.26 mg B kg^{-1}, respectively, when B fertilizer was applied at the OEBR. Soil B content at the optimum yield in our study was higher than the 0.28 mg B kg^{-1} 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.

Tissue B content increased from 3.30 mg kg^{-1} DW in the control treatment to 29.0 mg B kg^{-1} when B was applied at the OEBR. In both plant growth conditions, soil B levels ranged from 1.26–1.27 mg kg^{-1} at OEBRs that ranged from 5.4 to 5.5 kg B ha^{-1}. The range in tissue B content at the OEBR in our study (25–29 mg B kg^{-1}) suggests similar critical tissue B contents for strawberry plants. The concentrations of all plant nutrients measured

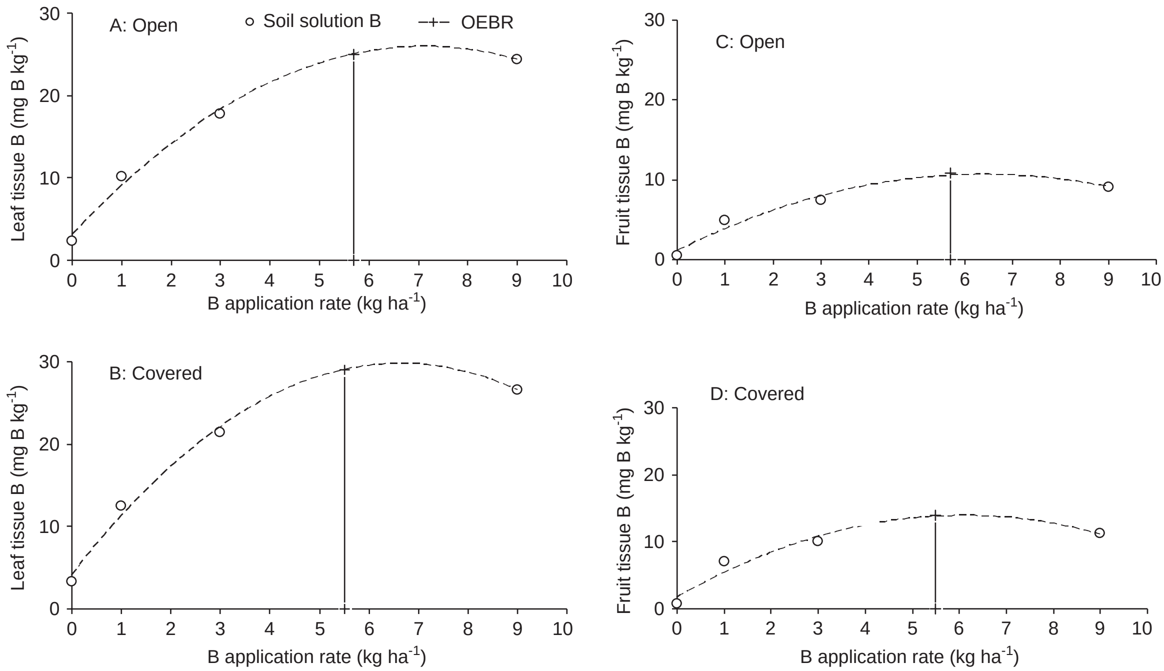

Figure 4. Effects of boron application on soil solution B content and strawberry leaf and fruit tissue B content (2-yr average) for open (A, C) and covered (B, D) growth conditions grown on a calcareous Aridisol.

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 3.10–4.50% for N, 60–150 mg kg^{-1} for Fe and 25–200 mg kg^{-1} for Mn, suggesting N, Fe and Mn addition might increase yields beyond those obtained in our study. Compiling results from the greenhouse and field experiments published during 10 years, Guertal (2004), Santos et al. (2004), Ross et al. (2006) and Turan et al. (2009, 2010) suggested 10 mg kg^{-1}, 66 mg kg^{-1}, 44.1 mg kg^{-1} and 51 mg kg^{-1} in plant tissue to be the critical level for boron in bentgrass (*Agrostis palustris* Huds.), alfalfa (*Medicago sativa* cv. Crioula), soybean (*Glycine max* (Merr.) L.), Brussels sprout (*Brassica oleracea* L. gemmifera) and lucerne (*Medicago sativa* L.) respectively.

We conclude that addition of B at rate of 5.5 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 non-deficient levels of 1.26–1.27 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.

Acknowledgements

We are very grateful to the National Boron Research Institute of Turkey for their generous financial support for this study (Project Number AR-GE/8).

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No 56*. Rome: FAO.

Angin, I., Turan, M., Ketterings, Q. M., & CakIcI, A. (2008). Humic acid addition enhances B and Pb phytoextraction by Vetiver grass (*Vetiveria zizanioides* (L.) Nash). *Water Air Soil Pollution*, *188*, 335–343.

Anantawiroon, P., Subedi, K. D., & Rerkasem, B. (1997). Screening wheat for boron efficiency. In R. W. Bell & B. Rerkasem (eds.) *Boron in soil and plants*, pp. 101–104. Dordrecht: Kluwer Academic Publishers.

Asad, A., Bell, R. W., Dell, B., & Huang, L. (1997). External boron requirements for canola (*Brassica nopus* L.) in boron buffered solution culture. *Annals of Botany*, *80*, 65–73.

Blevins, D. G., Scrivner, C. L., & Reibott, T. M. (1996). Foliar boron increases berry number and yield of two highbush blueberry cultivars in Missouri. *Journal of Plant Nutrition*, *19*, 99–113.

Bremner, J. M. (1996). Nitrogen-total. In J. M. Bartels & J. M. Bigham (eds.) *Methods of soil analysis part 3: chemical methods*, pp. 1085–1121. Madison: The Soil Science Society of America and the American Society of Agronomy.

Byju, G., Nedunchezhiyan, M., & Naskar, S. K. (2007). Sweet potato response to boron application on an alfisols in the sub humid tropical climate of India. *Communication Soil Science and Plant Analysis*, *38*, 2347–2356.

DeMoranville, C. J. & Deubert, K. H. (1987). Effect of commercial calcium boron and manganese-zinc formulations on fruit set of cranberries. *Journal of Horticultural Science*, *62*, 163–169.

Ercisli, S. (2004). A short review of the fruit germplasm resources of Turkey. *Genetic Resources and Crop Evaluation*, *51*, 419–435.

FAO (2008). www.fao.org.

Gezgin, S., Dursun, N., Hamurcu, M., & Ayasli, Y. (1999). Konya ovasInda şekerpancarI bitkisinin beslenme sorunlarInIn toprak ve bitki analizleri ile belirlenmesi. Konya Pancar Ekicileri Kooperatifi Eğitim ve SağlIk Vakfi YayInlari.

Gezgin, S., Dursun, N., Hamurcu, M., Harmankaya, M., Önder, M., Sade, B., Topal, A., Soylu, S., Akgün, N., Yorgancilar, M., Ceyhan, E., Çiftçi, N., Acar, B., Gültekin, I., Işik, Y., Şeker, C., & Babaoğlu, M. (2002). Determination of boron contents of soils in central Anatolian cultivated lands and its relations between soil and water characteristics. In H. E. Goldbach, B. Rerkasem, M. A. Wimmer, P. H. Brown, M. Thellier, & R. W. Bell (eds.) *Boron in plant and animal nutrition*, pp. 391–400. New York: Kluwer Academic/Plenum Publishers.

Gezgin, S. & Hamurcu, M. (2006). *The importance of the nutrient elements interaction and the interactions between boron with the other nutrient elements in plant nutrition*. Dergisi: Selçuk Universitesi, Ziraat Fakültesi.

Goldberg, S., Shouse, P. J., Lesch, S. M., Grieve, C. M., Poss, J. A., Forster, H. S., & Suarez, D. L. (2003). Effect of high boron application on boron content and growth of melons. *Plant and Soil*, *256*, 403–411.

Guertal, E. A. (2004). Boron fertilization of bentgrass. *Crop Science*, *44*, 204–208.

Gupta, U. C. (1993). Factors affecting boron uptake by plants. In U. C. Gupta (ed.) *Boron and its role in crop production*, pp. 87–104. Boca Raton: CRC Press.

Hanson, E. J. & Breen, P. J. (1985). Effects of fall boron sprays and environmental factors on fruit set and boron accumulation in 'Italian' prune flowers. *Journal of American Society for Horticultural Science*, *110*, 389–392.

Kacar, B. & Fox, R. L. (1967). *Boron status of some Turkish soils*. University of Ankara, Yearbook of the Faculty of Agriculture, pp. 9–11.

Kacar, B., Prezeemek, E., Özgümüş, A., Turan, C., Katkat, A. V., & Kayıkçıoğlu. I. (1979). Türkiye'de çay tarımı yapılan toprakların ve çay bitkisinin mikroelement gereksinimleri üzerinde bir araştIrma. S.1-67, TÜBITAK, Tarım ve Ormancılık Araştırma Grubu, Kesin Rapor Proje No 321 Ankara.

Kamali, A. & Childers, N. F. (1970). Growth and fruiting of peach in sand culture as affected by boron and a fritted form of trace elements. *Journal of American Society for Horticultural Science*, *95*, 652–656.

Lindsay, W. L. & Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil Science Society of American Journal*, *42*, 421–428.

Marschner, H. (1995). *Mineral nutrition of higher plants*. San Diego: Academic Press.

McLean, E. O. (1982). Soil pH and lime requirement. In A.L. Page, R. H. Miller, & D. R. Keeney (eds.) *Methods of soil analysis. Part II. Chemical and microbiological properties* (2nd edn), pp. 199–224. Madison: ASA SSSA.

Mertens, D. (2005a). AOAC Official Method 922.02. Plants preparation of laboratory sample. In W. Horwitz & G. W. Latimer (eds.) *Official Methods of Analysis* (18th edn), Chapter 3, pp. 1–2. Gaitherburg: AOAC-International.

Mertens, D. (2005b). AOAC Official Method 975.03. Metal in plants and pet foods. In W. Horwitz & G. W. Latimer (eds.) *Official Methods of Analysis* (18th edn), Chapter 3, pp. 3–4. Gaitherburg: AOAC-International.

Mills, H. A. & Jones, J. B. (1996). *Plant analysis handbook II*. Athens, GA: Micromacro Publishing.

Nelson, D. W. & Sommers, L. E. (1982). Organic matter. In A.L. Page, R. H. Miller, & D. R. Keeney (eds.) *Methods of soil analysis. Part II. Chemical and microbiological properties* (2nd edn), pp. 74–79. Madison: ASA SSSA.

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. Circ. 939. Washington, DC: USDA.

Oyinlola, E. Y. (2007). Effect of boron fertilizer on yield and oil content of three sunflower cultivars in the Nigerian Savanna. *Journal of Agronomy*, *6*, 421–426.

Rhoades, J. D. (1996). Salinity: Electrical conductivity and total dissolved solids. In J. M. Bartels & J. M. Bingham (eds.) *Methods of soil analysis. Part III. Chemical methods* (2nd edn), pp. 417–436. Madison: ASA SSSA.

Ross, J. R., Slaton, N. A., Brye, K. R., & Delong, R. E. (2006). Boron fertilization influence on soybean yield and leaf and seed boron concentrations. *Agronomy Journal*, *98*, 198–205.

Santos, A. R., Matttos, W. T., Almeida, A. S., Monteiro, F. A., Correa, B. D., & Gupta, U. C. (2004). Boron nutrition and yield of alfalfa cultivar crioula in relation to boron supply. *Scientia Agricola*, *61*, 496–500.

Shorrocks, V. M. (1997). The occurrence and correction of boron deficiency. *Plant and Soil*, *193*, 121–148.

Soil Survey Staff (1992). *Keys to soil taxonomy* (5th edition). SMSS Technical monograph No. 19 Blacksburg: Pocahontas Press Inc.

SPSS Inc. (2004). *SPSS Inc. SPSS® 13.0*. Base User's Guide. Prentice Hall.

Stangoulis, J. C. R., Harsharn, S. G., Richard, W. B., & Robin, D. G. (2000). Boron efficiency in oilseed rape: I. Genotypic variation demonstrated in field and pot grown Brassica napus L. and Brassica juncea L. *Plant and Soil*, *225*, 243–251.

Sumner, M. E. & Miller, W. P. (1996). Cation exchange capacity and exchange coefficients. In J. M. Bartels & J. M. Bingham (eds.) *Methods of soil analysis. Part III. Chemical methods* (2nd edn), pp. 1201–1230. Madison: ASA SSSA.

Tariq, M. & Mott, C. J. B. (2007). Effect of boron on the behavior on nutrients in soil-plant systems. A review. *Asian Journal of Plant Science*, *6*, 195–202.

Tisdale, S. L., Nelson, W. L., & Beaton, J. J. (1985). *Soil fertility and fertilizers* (4th edn). New York: Macmillan.

Thomas, G. W. (1982). Exchangeable cations. In *Chemical and microbiological properties* (2nd edn), pp. 159–165. Madison: ASA SSSA.

Turan, M., Ataoğlu, N., Güneş, A., Oztaş, T., Dursun, A., Ekinci, M., Ketterings, Q. M., & Huang, Y. M. (2009). Yield and chemical composition of brussels sprout (*Brassica oleracea* L. *gemmifera*) as affected by boron management. *Hortscience*, *44*, 176–182.

Turan, M., Ketterings, Q. M., Güneş, A., Ataoğlu, N., Esringü, A., Bilgili, A.V., & Huang, Y.M. (2010). Boron fertilization of Mediterranean aridisols improves lucerne (*Medicago sativa* L.) yields and quality. *Acta Agriculturae Scandinavica B* (in press).

Wolf, B. (1974). Improvements in the azomethine-H method for the determining of boron. *Communication Soil Science and Plant Analysis*, *5*, 39–44.

Wojcik, P., Cieslinski, G., & Mika, A. (1999). Apple yield and fruit quality as influenced by boron applications. *Journal of Plant Nutrition*, *9*, 1365–1378.

Wojcik, P. & Lewandowski, M. (2003). Effect of spray of calcium and boron on yield and quality of 'Elsanta' strawberry. *Journal of Plant Nutrition*, *3*, 671–682.

Wojcik, P. & Wojcik, M. (2003). Effect of boron fertilization on 'Conference' pear tree vigor, nutrition, and fruit yield and storability. *Plant and Soil*, *256*, 413–421.