

Article

Effect of Foliar Boron Fertilization of Fine Textured Soils on Corn Yields

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Abstract: Boron (B) is an essential micronutrient needed for normal plant growth and development. To evaluate the response of corn to foliar B applications at V4–V6 (4–6 leaves with visible collars) and VT (tasseling) growth stages on fine textured soils, a field experiment was conducted at four sites from 2008 to 2010 in Northeast Missouri. The treatments included a non-treated control; V4–V6 applied B at 0.56, 1.12 and 2.24 kg·ha^{−1}; and VT applied B at 0.28, 0.56 and 1.12 kg·ha^{−1}. Foliar B, applied at V4–V6 at 2.24 kg·ha^{−1}, resulted in higher yields than VT applications. No significant differences in yield were found for B applications at different timings for concentrations of 0.56 and 1.12 kg·ha^{−1}. Boron applied at V4–V6 and 2.24 kg·ha^{−1} increased yield 0.29 Mg·ha^{−1} compared to the non-treated control. The B applications at VT increased ear leaf tissue B concentration compared to V4–V6 applications and non-treated control, but it had no significant effect on corn yields. No significant difference between B treatments was observed for grain oil, protein, starch or extractable starch concentration; severity of anthracnose stalk rot or common rust; and ear tip fill. The B application of 2.24 kg·ha^{−1} at V4–V6 decreased the severity of gray leaf spot, but increased the severity of northern leaf blight compared to the non-treated control. Boron applied at V4–V6 at 2.24 kg·ha^{−1} was the most beneficial timing and concentration evaluated in these fine textured soils.

Keywords: boron; corn; foliar fertilizer; V4–V6; VT

1. Introduction

Boron (B) is an essential micronutrient needed for normal plant growth and development. It is involved in many plant processes such as sugar transport, cell wall synthesis, lignification, meristematic tissue cell division, petal and leaf bud formation, cell wall structure integrity, sugar and hydrocarbon metabolism and their transport, ribose nucleic acid (RNA) metabolism, respiration, indole acetic acid (IAA) metabolism, cytokinin production and transfer, phenol metabolism, nitrogen fixation, pollen germination, pollen tube formation and seed formation [1–4]. Intensive cropping systems and the use of high yielding hybrids has resulted in depletion of soil micronutrients [5]. Globally, B deficiency has been recognized as the second most important micronutrient constraint in crops after zinc (Zn) [1]. In the USA, B deficiency was the most widespread among micronutrients [6,7]. In soil, concentrations of total B typically ranged from 20 to 200 mg·B·kg^{−1}, but generally the availability to plants is less than 5%–10% [8]. Boron requirements may vary by plant type, but the range for soil solution B concentration between deficiency and toxicity is smaller than other nutrient elements [9]. Corn has a low requirement for B, but can be very sensitive to excess B. Several factors affect B uptake by plants including soil type (texture, pH, organic matter content), B concentration, moisture, and plant species. The interaction of B with other nutrients (N, P, K, Ca, Mg, Al, and Zn) can be synergistic or antagonistic which can influence B availability to plants [2]. The bioavailability of B reduces as soil dries due to low rainfall or limited irrigation because of decreased B mobility in soil by mass flow to plant roots [1,9]. Boron is absorbed by plants as boric acid, which is easily leached in soils [10]. Boron is relatively immobile in a corn plant and its availability is essential at all growth stages, particularly during fruit and seed development [2]. Boron deficiency in corn was first observed during the 1960s in the United States [11] and B applications showed more than a 10% increase in yield on coarse textured soils [12]. The B sufficiency range for corn was from 4 to 25 ppm in the ear leaf [13]. In corn, B deficiency caused barren ears and blank stalks at concentrations below 0.05 ppm which resulted in lower yields [13]. Woodruff *et al.* reported that B interacted with N, K and lime while B fertilization at 2.24 kg·ha^{−1} was necessary for preventing a reduction in corn yields when higher K fertilizer rates were applied in South Carolina [12]. In B deficient soils, a B application increased plant B concentration which helped to improve the quality of corn fodder for animals without causing any significant increase in dry matter yield [14]. On a calcareous soil, B interacted with zinc (Zn) and antagonistically affected nutrient concentration and synergistically affected growth [15]. Minimum amounts of B accumulated in corn during initial growth stages and maximum accumulation was observed after 100 days of seedling emergence in two corn hybrids in Brazil while the total amount of B required to produce one ton of corn was 0.9 g [16]. However, B decreased P uptake and dry weight of corn genotypes [17], while a Ca application antagonized shoot B concentrations of four corn hybrids [18]. Boron applied with high Zn levels resulted in higher NPK concentrations in corn grains [19].

Foliar nutrient sprays may be an effective way to correct micronutrient deficiencies, which sometimes results in higher yields and crop quality [20,21]. Advantages of a foliar application compared to a soil

application included rapid plant response, increased convenience and effective placement [22]. The reported negative effects of foliar applications include leaf necrosis due to the direct effects of the foliar salts, which reduce effective leaf area and photosynthate production [23]. Boron can be soil applied (broadcast or banded) or foliar applied [5]. An in-row application of B has showed higher plant uptake compared to foliar application while both of these application methods were more effective than a broadcast soil application [24]. In some southeastern states, foliar spray applications increased tissue B concentration compared to a broadcast soil application [25]. In contrast, foliar applied B at high rates have caused severe toxicity to corn compared to soil applied rates [26]. In *Vigna radiata*, soil applied B had a greater impact on dry matter yield whereas a foliar application increased grain yield [5]. In Missouri, foliar applied B at $1.12 \text{ kg} \cdot \text{ha}^{-1}$ increased the number of soybean (*Glycine max*) branches per plant and the formation of pods on branches [27]. A pre-plant soil application of B, at $3 \text{ kg} \cdot \text{ha}^{-1}$, had a greater effect on corn growth and average dry matter accumulation, but had lower yields compare to the non-treated control [28]. In a greenhouse experiment, corn plants showed injury to soil solution B concentrations of $20 \text{ mg} \cdot \text{B} \cdot \text{L}^{-1}$ [29].

Boron has also helped to reduce disease severity in some crops because of the effect that B has on plant metabolism, cell membranes and cell wall structure [30–33]. Boron reduced the infection of pathogens by improving cell wall and membrane strength with cross-linked polymers and by strengthening the plant's vascular bundles [34]. Plant disease development and management were affected by the environment especially when nutrient deficiencies and toxicity occurred [33]. A B application of $0.5 \text{ kg} \cdot \text{ha}^{-1}$ along with a combination of nitrogen ($100 \text{ kg} \cdot \text{ha}^{-1}$) and Zn (0 and $1.0 \text{ kg} \cdot \text{ha}^{-1}$) resulted in reduced fungal mycotoxin production, which were responsible for rotting of corn ears [35]. On fine textured soils in Northeastern Missouri, B applied at VT (tasseling) with pyraclostrobin or pyraclostrobin alone reduced the disease severity most consistently [36]. There has been limited research on a suitable B application timing (early vs. late application) and concentration of foliar B on fine textured claypan soils in the Midwestern US. Therefore, the objective of this research was to evaluate the effects of foliar-applied B at different application concentrations and timings on corn yield, tissue B concentration, severity of diseases, grain oil, protein, starch, and extractable starch concentration.

2. Materials and Methods

Field experiments were conducted from 2008 to 2010 at four sites in Knox and Shelby counties in Northeastern Missouri. This research was conducted simultaneous to fungicide pyraclostrobin research at VT with foliar B applications at a single concentration [36]. The two sites in Knox County were at the University of Missouri's Greenley Research Center near Novelty ($40^{\circ}01' \text{ N}$, $92^{\circ}11' \text{ W}$) and a cooperator's farm nearby Bee Ridge ($40^{\circ}04' \text{ N}$, $92^{\circ}04' \text{ W}$). The locations in Shelby County were at the University of Missouri's Ross Jones Farm near Bethel ($39^{\circ}56' \text{ N}$, $92^{\circ}03' \text{ W}$) and a cooperator's farm nearby Leonard ($39^{\circ}54' \text{ N}$, $92^{\circ}16' \text{ W}$). Different sites were selected each year for each experiment at individual locations. All locations had a silt loam soil texture and were planted with corn (Table 1). The experiment was randomized complete block design with five replications and had seven B treatments including a non-treated control. Treatments included foliar applied B (Solubor, US Borax Inc., Valencia, CA, USA) at different timings and concentrations (Table 2). Boron was applied at V4–V6 (4–6 leaves with visible collars) [37] growth stage at 0.56 , 1.12 and $2.24 \text{ kg} \cdot \text{B} \cdot \text{ha}^{-1}$ as well as VT at 0.28 , 0.56 and

1.12 kg·B·ha⁻¹. Foliar B was applied using a CO₂ propelled backpack sprayer with 8002 flat fan nozzles (TeeJet Technologies, Wheaton, IL, USA) at 140 L·ha⁻¹ and no surfactant was used. The B concentrations used in this study were in the range recommended for foliar applications in corn [38,39]. Plants were 18 to 36 cm tall at V4–V6 and 183 to 305 cm tall at VT. The individual plot size was 3 by 15.2 m. All plots were planted in 0.76 m wide rows. Field information about the four sites, selected management practices and details about foliar B application are shown in Tables 1 and 2 [36]. These sites had different tillage operations (conventional vs. no-till), previous crops, hybrids and seeding rates, which varied from 70,400 to 86,500 seeds ha⁻¹ (Table 1). Fertilizer was applied based on recommendations from the University of Missouri soil test lab at Novelty and Bethel and by private labs at Bee Ridge and Leonard. Supplemental irrigation was scheduled using the Woodruff chart at the Novelty site [40].

Initial soil samples before planting and fertilizer application were collected from each replication from 15-cm deep soil cores (20 cores per replication). The soil samples were dried at approximately 50 °C, ground, and analyzed using standard methods by Clemson University Agricultural Service Laboratory (Clemson, SC, USA). Soil test information at all 12 site-years are presented in Table 3.

Before the V4–V6 B application and 10 days after application (DAA), 10 plants per plot from treatments with only foliar applied B at V4–V6 and the non-treated control were harvested, oven dried at 60 °C for 48 h, ground, weighed and tissue analyzed for B concentration. Ear leaf tissue was collected at VT and again 10 days after the VT B application, oven dried at 60 °C, weighed and analyzed for tissue B concentration. Plant stand counts were determined in order to calculate the plant population hectare⁻¹, while ear tip fill and barren stand counts were also recorded prior to harvest. A digital caliper (Performance Tool, Tukwila, WA, USA) was used for measuring the ear tip that remained with no kernels from 20 plants row⁻¹ at each site-year. Foliar injury due to B applications was visually rated on a scale of 0 (no crop injury) to 100% (complete plant death). Corn plants were rated for diseases severity including gray leaf spot (*Cercospora zea-maydis*) and common rust (*Puccinia sorghi*) at all site-years. There was no apparent disease in 2008 (data not presented). The severity of diseased plants in each plot was assessed 42 days after VT based on a percentage of the plants (0%–100%) showing symptoms of gray leaf spot, common rust, northern corn leaf blight (*Exserohilum turcicum*), or anthracnose stalk rot (*Colletotrichum graminicola*). The percentage of leaf area with lesions over the entire canopy (0 = no lesions to 100 = complete plant coverage) was used for rating gray leaf spot, common rust, and northern corn leaf blight. The grey leaf spot measurements were taken at all sites in 2009 and at Bethel and Bee Ridge in 2010. The northern corn leaf blight measurements were taken only at Leonard in 2010. The percentage of the stalk with lesions was rated for anthracnose stalk rot (0 = no lesions to 100 = complete stalk coverage). The centermost two rows in each plot were harvested using a small plot combine (Wintersteiger Delta, Salt Lake City, UT, USA) and weighed for grain yields and test weights were determined. The seed moisture was measured at harvest and adjusted to 150 g·kg⁻¹ before analyzing data. Ten subsamples from collected grain samples were analyzed for oil, protein, starch, and extractable starch (Foss Infratec 1241, Eden Prairie, MN, USA).

Table 1. Field information and selected management practices at 12 site-years [36].

Field	Novelty			Bethel			Leonard			Bee Ridge			
Information [†]	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010	
Previous crop	Soybean	Corn	Corn	Corn	Soybean	Soybean	Soybean	Soybean	Soybean	Soybean	Soybean	Soybean	
Tillage	Conv.	Conv.	Conv.	NT	NT	NT	NT	NT	NT	Conv.	Conv.	Conv.	
Planting date	19 May	11 May	26 May	14 June	19 May	28 May	21 May	23 May	29 May	21 May	22 May	28 May	
Hybrid	DKC63–42VT3	DKC63–42VT3	DKC63–42VT3	Burrus 795t	DKC63–42 VT3	DKC63–42 VT3	Crow’s 4835	Mycogen 2D653	Mycogen 2K594	Pioneer 33D13	Pioneer 33D13	Pioneer 33T57	
Seeding rate, (seeds ha ^{−1})	86,500	79,000	84,000		74,000	74,000	73,400	74,000	74,000	74,000	70,400	75,300	76,600
Fertilizer applications (N–P ₂ O ₅ –K ₂ O, kg·ha ^{−1})													
Fall date	15 December 2008					21 November 2009			21 November 2007				
Rates	34–90–135					66–170–252			34–90–180				
Source(s)	DAP					DAP			DAP				
Preplant date	19 May	4 May	12 April	14 June	8 April	20 May	25 April	20 May	19 May	25 April	15 April		
Rates	224–0–0	202–0–0	280–90–170	202–100–135	202–0–0	56–0–0	44–112–135	56–0–0	163–0–0	40–103–0	44–112–112		
Source(s)	AN	AN	AN + DAP	AN + DAP	AA	UAN	DAP	UAN	AA	DAP	DAP		
Preemergence date	4 May						1 June			21 May			15 April
Rates	90–67–22						34–0–0			190–0–0			179–0–0
source(s)	AN + DAP						UAN			AA			AA
Top-dress date	17 June	11 June					14 June	20 June	23 & 28 June				
Rates	90–0–0	202–0–0					112–0–0	112–0–0	135–0–0 & 370–0–0				
source(s)	AA	UAN					UAN	UAN	UAN				

[†] Abbreviations: AA, anhydrous ammonia; AN, ammonium nitrate; Conv., Conventional; DAP, diammonium phosphate; NT, no-till; and UAN, 32% urea ammonium nitrate.

Table 2. Foliar B application information at V4–V6 and VT at the 12 site-years [36].

B Application Information	Novelty			Bethel			Leonard			Bee Ridge		
	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
V4–V6 [†]												
Application date	16 June	12 June	17 June	16 July	15 June	19 June	15 June	17 June	20 June	15 June	10 June	
Air temperature (°C)	21	22	23	33	24	27	26	33	38	19	27	
Relative humidity, %	61	90	92	56	82	65	83	71	45	95	69	
Height, cm	25	25	30	36	28	36	27	25	36	33	18	
VT												
Application date	23 July	20 July	23 July	15 August	27 July	28 July	27 July	23 July	28 July	27 July	23 July	
Air temperature (°C)	25	23	28	27	29	34	31	37	34	29	33	
Relative humidity, %	52	77	33	75	60	60	61	33	60	61	33	
Height, cm	183	183	244	305	183	183	183	213	183	183	213	
Harvest date	5	2	27	13	24	28	13	4	19	7	20	
Soil type	November	November	September	November	November	October	November	October	November	December	October	
		Kilwinning			Putnam		Arbela		Wabash	Chariton	Wabash	

[†] As described by Abendroth *et al.* [37].

Table 3. Initial soil test information at Novelty, Bethel, Leonard, and Bee Ridge in 2008, 2009, and 2010 [36].

Soil Test Information	Novelty	Bethel	Leonard	Bee Ridge
2008				
pH (1:1 water)	5.8 ± 0.3 [†]	6.1 ± 0.1	6.2 ± 0.1	6.3 ± 0.2
Mehlich-1				
P, kg·ha ⁻¹	30 ± 8	76 ± 21	62 ± 9	89 ± 4
K, kg·ha ⁻¹	220 ± 43	173 ± 13	176 ± 12	220 ± 4
Ca, kg·ha ⁻¹	3660 ± 310	3920 ± 140	4110 ± 200	3720 ± 110
Mg, kg·ha ⁻¹	509 ± 48	336 ± 15	298 ± 24	246 ± 8
B, kg·ha ⁻¹	0.67 ± 0.08	0.58 ± 0.04	0.47 ± 0.04	0.96 ± 0.09
CEC [‡] , cmol _c kg ⁻¹	14.2 ± 0.9	12.8 ± 0.3	13.4 ± 0.6	11.8 ± 0.4
2009				
pH (1:1 water)	6.3 ± 0.1	6.3 ± 0.2	7.2 ± 0	7.0 ± 0.2
Mehlich-1				
P, kg·ha ⁻¹	71 ± 10	37 ± 1	75 ± 8	100 ± 16
K, kg·ha ⁻¹	387 ± 74	181 ± 10	136 ± 4	163 ± 13
Ca, kg·ha ⁻¹	4260 ± 140	3610 ± 360	4800 ± 420	4790 ± 620
Mg, kg·ha ⁻¹	538 ± 24	360 ± 36	286 ± 47	361 ± 6
B, kg·ha ⁻¹	1.05 ± 0.06	1.03 ± 0.04	1.01 ± 0.13	0.81 ± 0.09
CEC, cmol _c kg ⁻¹	16.0 ± 0.5	12.9 ± 0.9	14.1 ± 1.4	14.3 ± 1.2
2010				
pH (1:1 water)	5.7 ± 0.3	7.3 ± 0.2	6.4 ± 0.1	6.7 ± 0.2
Mehlich-1				
P, kg·ha ⁻¹	28 ± 4	34 ± 2	48 ± 4	92 ± 27
K, kg·ha ⁻¹	166 ± 16	101 ± 9	137 ± 27	186 ± 47
Ca, kg·ha ⁻¹	3010 ± 380	4870 ± 340	4870 ± 210	3990 ± 490
Mg, kg·ha ⁻¹	377 ± 34	367 ± 24	343 ± 27	341 ± 50
B, kg·ha ⁻¹	0.47 ± 0.27	0.76 ± 0.27	0.43 ± 0.27	0.54 ± 0.27
CEC, cmol _c kg ⁻¹	12.3 ± 0.6	14.4 ± 0.8	15.4 ± 0.6	12.8 ± 1.1

[†] Standard deviation of the five replications; [‡] CEC, cation exchange capacity.

All the collected data were analyzed using analysis of variance (ANOVA) in PROC GLM with the SAS statistical computer program [41]. If the overall F was significant, Fisher's Protected Least Significant Difference (LSD) at $p = 0.1$ was used for mean separation. In absence of a significant interaction between B treatments and site-years, data were averaged over the 12 site-years. Pearson correlation analysis (PROC CORR procedure of SAS) was used to determine the relationship between corn yield and other plant measurements.

3. Results and Discussion

The initial soil B concentration ranged from 0.43 kg·ha⁻¹ at Leonard in 2010 to 1.05 kg·ha⁻¹ at Novelty in 2009 (Table 3). All sites had acidic to neutral pH soils. The soils at all site-years were high in potassium concentration (101 to 387 kg·ha⁻¹). The monthly precipitation at Novelty and Bee Ridge in Knox County was higher than the 10-year average precipitation for northeast Missouri except in the

month of August in 2010. In 2010, there was 62% and 63% lower monthly precipitation in August at all sites compare to the 10-year average precipitation (Table 4) which made it drier compare to other years. In Shelby County during 2008 and 2010, the average monthly precipitation was 19% and 33% lower in May compared to the 10-year average precipitation. Since rainfall early in the season and during pollination was generally high, the overall availability of B to corn plants should have been readily available during critical portions of plant development. In general, overall corn yields were high for the period this research was conducted.

Table 4. Monthly precipitation average (10-year) for Northeast Missouri during the growing season and at Novelty, Bee Ridge, Bethel, and Leonard in 2008, 2009, and 2010. Novelty and Bee Ridge are in Knox County, and Bethel and Leonard are in Shelby County [36].

Month	Northeast Missouri 10-Year Average [†]	Knox County (Novelty and Bee Ridge) (mm)			Shelby County (Bethel and Leonard) (mm)		
		2008	2009	2010	2008	2009	2010
April	100	116	121	146	116	120	135
May	113	112	170	160	92	170	76
June	124	257	145	163	133	148	168
July	93	272	108	326	195	79	93
August	122	108	167	45	206	141	46
September	85	201	86	242	315	96	250
Total	637	1066	797	1082	1057	754	768

[†] Averaged from 2000 to 2009.

The mean corn yield averaged over the 12 site-years and B treatments was $11.7 \text{ Mg} \cdot \text{ha}^{-1}$. A significant effect of B treatments, site-years and B treatment \times site-year interaction was found for corn yields (Table 5). Boron applied at V4–V6 at $2.24 \text{ kg} \cdot \text{ha}^{-1}$ was the highest yielding treatment in five of the 12 site-years, and had the highest average yield of $11.96 \text{ Mg} \cdot \text{ha}^{-1}$ compared to all other treatments (Figure 1). The V4–V6 B application at $2.24 \text{ kg} \cdot \text{ha}^{-1}$ increased yield $0.29 \text{ Mg} \cdot \text{ha}^{-1}$ compared to the non-treated control. None of the other B treatments affected yield when averaged over the 12 site-years in this research. The V4–V6 B application at 0.56 and $1.12 \text{ kg} \cdot \text{ha}^{-1}$ had higher yields than VT B application at the same concentrations, but they were not significantly different. Corn yields from B applications at VT ranged from 11.56 to $11.58 \text{ Mg} \cdot \text{ha}^{-1}$. Foliar B applications at VT resulted in $0.24 \text{ Mg} \cdot \text{ha}^{-1}$ lower yields than V4–V6 B applications. Higher yields due to an early application of B compared to late B application were reported for rice in Missouri [42]. Woodruff *et al.* [12] also reported an increase in corn yields due to B at $2.24 \text{ kg} \cdot \text{ha}^{-1}$ for soils receiving higher K fertilization (131 – $317 \text{ kg} \cdot \text{ha}^{-1}$). A beneficial effect of early applications of B for grain yields were also reported for wheat, rice and cotton [43]. In contrast to this, no differences in soybean yields were observed due to early or late B applications in Northeast Arkansas [44]. There were no differences in yield due to B application in 2010 at all sites except Bee Ridge (Table 5). At Leonard, greater corn yields were obtained with a V4–V6 B application at $0.56 \text{ kg} \cdot \text{ha}^{-1}$, which was significantly different from the lowest yields obtained with a VT application at 0.28 and $0.56 \text{ kg} \cdot \text{ha}^{-1}$ in 2009 only. The higher total rainfall received in Knox County compared to Shelby County may have resulted in greater B solubility and availability to corn plants [9]. The maximum corn yield obtained was $15.32 \text{ Mg} \cdot \text{ha}^{-1}$ at Novelty in 2009, which had

the highest initial B concentration, of $1.05 \text{ kg} \cdot \text{ha}^{-1}$, among all site-years and had sufficient rainfall along with supplemental irrigation (Table 5). However, the lowest yield obtained was $6.46 \text{ Mg} \cdot \text{ha}^{-1}$ in 2008 at Leonard, which had only $0.47 \text{ kg} \cdot \text{ha}^{-1}$ of initial B in the soil.

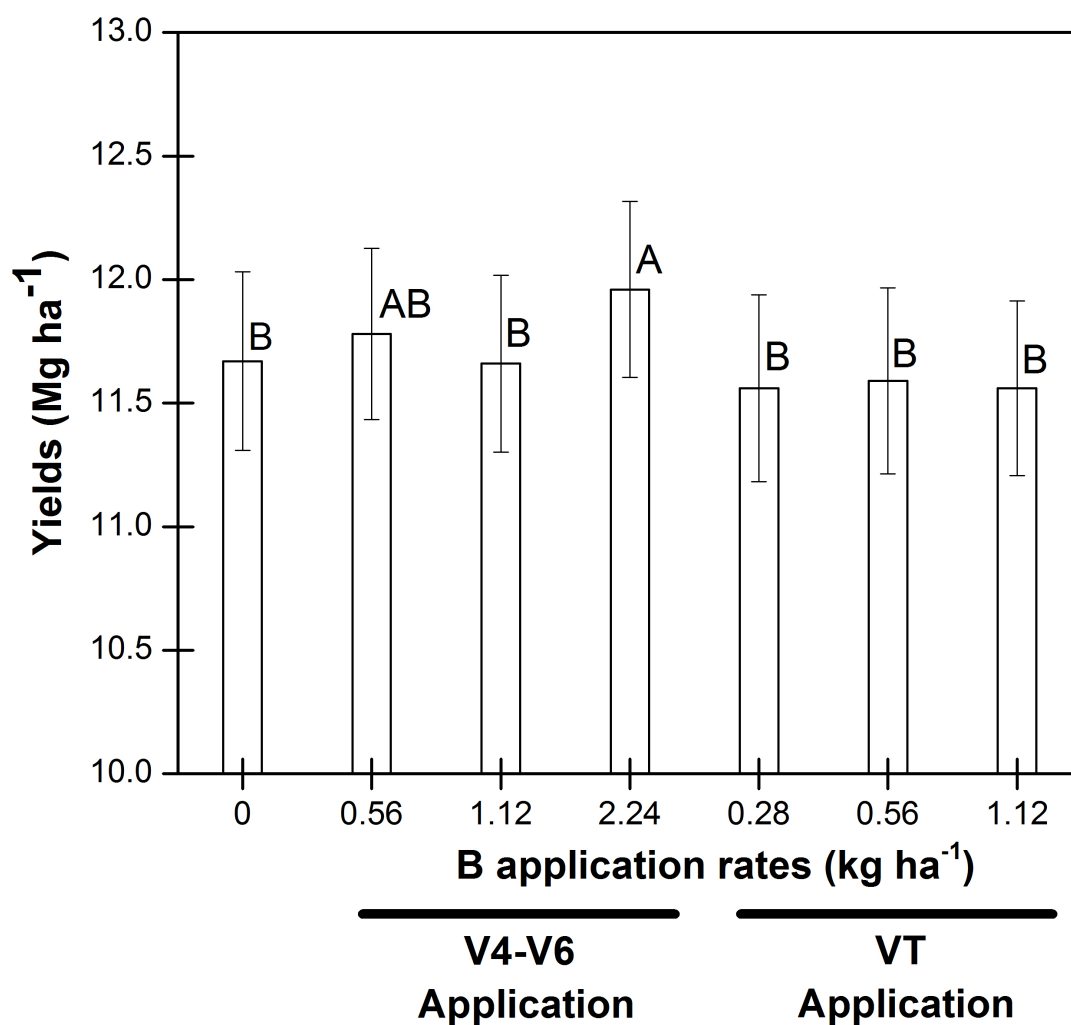


Figure 1. Corn grain yield in response to V4–V6(4–6 leaves with visible collars) and VT (tasseling) foliar B applications at different concentrations. Data were averaged over 12 site-years and the LSD ($p = 0.1$) was $0.24 \text{ Mg} \cdot \text{ha}^{-1}$. Similar letters on bars indicate no significant differences between treatments. Error bars represents standard error.

Table 5. Corn grain yields at 12 site-years for V4–V6 and VT foliar B applications at different concentrations.

Application Timing	Application Concentration (kg·ha ⁻¹)	Novelty (mg·ha ⁻¹)			Bethel (mg·ha ⁻¹)			Bee Ridge (mg·ha ⁻¹)			Leonard (mg·ha ⁻¹)		
		2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
Non-treated	0	8.6	14.9	9.3	11.6	10.8	14.1	14.3	14.3	9.4	6.5	12.3	14.0
V4–V6	0.56	8.9	14.6	8.6	11.4	11.3	14.1	13.7	14.3	10.8	6.7	13.0	14.1
V4–V6	1.12	8.8	15.0	8.3	10.6	11.3	14.2	14.0	14.4	9.7	6.9	12.6	14.1
V4–V6	2.24	9.2	15.3	9.7	11.9	11.1	14.2	13.9	14.5	9.7	6.8	12.7	14.4
VT	0.28	8.9	14.9	9.6	11.6	10.6	14.4	14.0	14.0	7.7	6.5	12.1	14.3
VT	0.56	8.7	14.7	7.8	11.7	11.3	14.4	13.7	14.4	9.1	6.9	11.9	14.4
VT	1.12	9.0	14.0	8.2	11.2	10.8	14.6	13.6	14.3	9.1	7.0	12.6	14.4
LSD ($p = 0.1$)		0.5	0.9	ns [†]	1.2	ns	ns	ns	0.5	1.8	ns	0.9	ns

[†] ns: not significant.**Table 6.** Whole plant tissue B concentrations 10 days after V4–V6 B application at different concentrations.

Application Rate (kg·ha ⁻¹)	Tissue B Concentration [‡]	Novelty (mg·kg ⁻¹)			Bethel (mg·kg ⁻¹)			Bee Ridge (mg·kg ⁻¹)			Leonard (mg·kg ⁻¹)		
		2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
Non treated	5.0	5.4	5.2	5.2	6.0	4.8	4.8	6.0	4.0	5.2	4.6	5.0	4.0
0.56	5.5	5.4	5.4	5.4	8.2	5.0	5.0	5.6	4.2	6.8	5.2	5.4	4.2
1.12	5.8	6.2	5.2	5.5	9.6	5.8	4.8	5.8	4.2	6.4	5.8	5.4	5.2
2.24	7.3	6.6	6.2	5.6	14.4	7.4	5.4	10.2	4.4	7.6	8.4	5.6	5.2
LSD ($p = 0.1$)	0.4	0.4	0.8	ns [†]	2.0	2.2	ns	4.1	ns	1.8	1.2	ns	0.7

[†] ns: not significant; [‡] Tissue B concentrations were averaged over 12 site-years.

The initial B concentration in plant tissue ranged from 3.8 to 6.8 mg·kg⁻¹. There were no significant differences in tissue B concentration between B treatments from plant samples taken before the V4–V6 application of B among all site-years except at Bee Ridge in 2008 and Leonard in 2009 (data not presented). This might be due to higher initial soil B concentration at Bee Ridge in 2008 and Leonard in 2009, which was 0.96 and 1.01 kg·ha⁻¹, respectively. At Bee Ridge in 2008, treatments containing B applied at V4–V6 at 0.56 kg·ha⁻¹ had 0.8 mg·kg⁻¹ greater B concentration than treatments having B applied at 2.24 kg·ha⁻¹. In 2009 at Leonard, both of these treatments showed no differences in tissue B concentration, but a V4–V6 B application at 0.56 kg·ha⁻¹ had 0.8 mg·kg⁻¹ lower tissue B concentration than B application at 1.12 kg·ha⁻¹ (data not presented). Tissue B concentration from samples taken 10 days after B application at V4–V6 showed differences among treatments and an interaction between treatments and site-years was observed (Table 6). Foliar B applied at V4–V6 at 2.24 kg·ha⁻¹ had 2.3 mg·kg⁻¹ higher tissue B concentration when averaged over the 12 site-years compared to the non-treated control. A V4–V6 B application at 0.56 and 1.12 kg·ha⁻¹ had 0.5 to 0.8 mg·kg⁻¹ greater tissue B concentration than the non-treated control, but 1.5 to 1.8 mg·kg⁻¹ lower tissue B concentration than the treatment having a V4–V6 B application at 2.24 kg·ha⁻¹. No differences were observed between treatments at Novelty and Bethel in 2010 and at Bee Ridge and Leonard in 2009. In the remaining site-years, a V4–V6 B application at 2.24 kg·ha⁻¹ had higher B concentrations compared to the non-treated control. A V4–V6 application of B increased B concentration in the plant tissue among all site-years as the rate of B increased.

Boron concentration in plant tissue samples taken at VT before VT B application did not show any differences at the 12 site-years (data not presented). The ear leaf B concentration averaged over site-years ranged from 3.71 to 8.42 mg·kg⁻¹ among treatments from plant samples taken 10 days after a foliar VT application (Figure 2). The treatments having a V4–V6 application at 0.56 and 1.12 kg·ha⁻¹ had similar ear leaf B concentrations as the non-treated control plots; while V4–V6 applied B at 2.24 kg·ha⁻¹ had a 0.37 mg·kg⁻¹ higher ear leaf B concentration compared to other B application concentrations at V4–V6. All VT B application treatments resulted in significantly higher ear leaf B concentration (5.2 to 8.41 mg·kg⁻¹) compared to non-treated (3.7 mg·kg⁻¹) and V4–V6 treatments. Ear leaf B concentration increased with increasing concentrations of foliar B application from 0.28 kg·ha⁻¹ to 1.12 kg·ha⁻¹ at VT. A foliar VT B application at 1.12 kg·ha⁻¹ had 4.7 mg·kg⁻¹ greater ear leaf B concentration compared to the non-treated control. A significant interaction was observed between ear leaf B concentration and site-years (Table 7). Among all site-years, a VT B application at 1.12 kg·ha⁻¹ had higher ear leaf B concentrations compared to the other B treatments including the non-treated control. An increase in leaf B concentration with increasing B application concentrations were also reported in soybean in Northeast Arkansas [45].

The plant population varied from 69,500 to 71,500 plants·ha⁻¹ over the 12 site-years. There was no effect of B treatments on plant population, but there were differences in plant population among site-years (Table 8). Similar results were obtained by Nelson *et al.* [36] for B applications with fungicides in corn. The highest plant population of 86,064 plants·ha⁻¹ was found at Leonard in 2010 and lowest population of 61,132 plants·ha⁻¹ was found at Novelty in 2009 (Table 8). Woodruff *et al.* [12] reported increased corn yields with B with plant populations more than 50,000 plants·ha⁻¹. Oil, protein, starch and extractable starch content of grains were not affected by the B treatments and no significant interaction of B treatments and site-years were found. Grain protein, oil, starch and extractable starch

concentrations varied by site-years (Table 8). The differences between site-years might be because of different environmental conditions, management systems, soil properties and hybrid differences. No differences in protein and oil concentration in corn grains due to B at 0.28, 0.56 and 1.12 kg·ha⁻¹ were also observed in Georgia [46]; however, B at 0.45 kg·ha⁻¹ increased seed oil and protein concentration in soybean [47]. Boron alone increased corn grain protein and starch concentration by 0.7% and 3.7%, respectively, in wheat [48]. Corn yields were negatively correlated with ear leaf B concentration, plant population, grain starch and extractable starch concentration (Table 9). There was positive correlation of corn yields with grain protein concentration. However, a highly positive correlation was reported for seed yield and leaf B content of *Vigna radiata* [5].

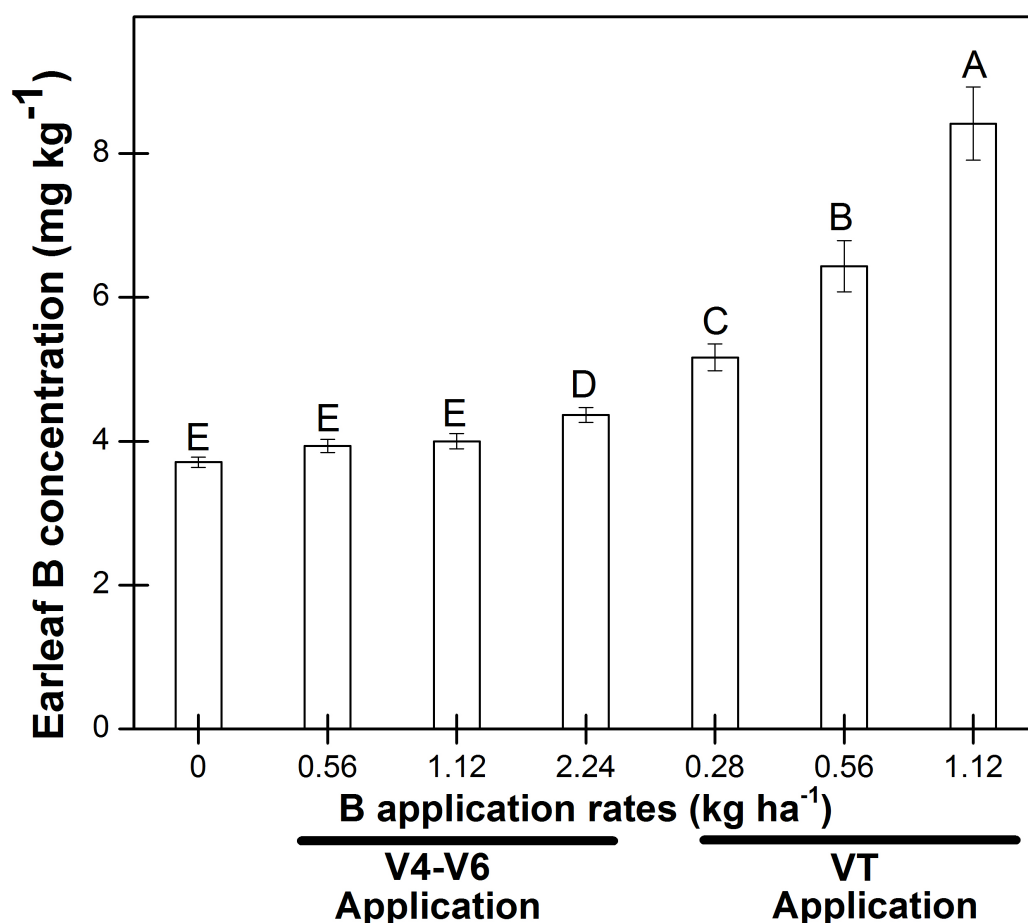


Figure 2. Ear leaf B concentration in response to V4–V6 (4–6 leaves with visible collars) and VT (tasseling) foliar B application 10 days after VT application. Data were averaged over 12 site-years and the LSD ($p = 0.1$) was 0.3 mg·kg⁻¹. Similar letters on bars indicate no significant differences between treatments. Error bars represents standard error.

Table 7. Ear leaf B concentration ten days after VT at the 12 site-years for V4–V6 and VT foliar B applications.

Application Timing	Application Concentration (kg·ha ⁻¹)	Novelty (mg·kg ⁻¹)			Bethel (mg·kg ⁻¹)			Bee Ridge (mg·kg ⁻¹)			Leonard (mg·kg ⁻¹)		
		2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
Non-treated	0	3.8	3.8	4.2	3.6	4.0	4.4	3.8	3.2	3.0	3.0	3.9	3.8
V4–V6	0.56	3.8	4.2	4.4	4.0	4.4	4.6	4.0	3.8	3.0	3.6	3.6	3.8
V4–V6	1.12	4.0	3.8	4.0	4.2	4.6	5.0	3.8	3.8	3.0	3.8	3.8	4.0
V4–V6	2.24	4.2	4.2	4.8	4.4	5.4	5.0	4.2	3.8	3.2	4.4	4.6	4.4
VT	0.28	4.8	4.8	6.2	4.4	6.2	4.6	4.2	5.0	3.4	6.2	8.0	4.2
VT	0.56	5.8	5.8	5.2	5.8	7.8	4.8	5.4	6.8	3.2	12.2	10.4	4.0
VT	1.12	8.2	7.2	6.0	8.2	10.4	5.6	8.0	7.4	4.0	14.0	16.4	5.6
LSD (<i>p</i> = 0.1)		1.3	0.9	1.1	1.6	1.5	0.9	1.4	0.9	0.5	1.9	2.1	0.7

Table 8. Oil, protein, starch and extractable starch concentration in corn grains, ear tip fill, and common rust severity at 12 site-years. Data were averaged over treatments at each site-year.

Grain Components	Novelty			Bethel			Bee Ridge			Leonard			LSD (<i>p</i> = 0.1)
	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010	
Oil (g·kg ⁻¹)	46	42	44	43	43	42	42	37	34	42	55	45	3
Protein (g·kg ⁻¹)	66	85	67	71	90	75	85	84	74	62	84	89	1
Starch (g·kg ⁻¹)	739	720	739	714	719	723	740	734	734	745	702	716	2
Extractable starch (g·kg ⁻¹)	702	675	679	693	649	690	688	687	703	709	653	639	2
Ear tip fill (mm)	10	4	29	2	2	28	1	7	25	7	24	18	2
Common rust	- ‡	3	10	-	12	11	-	6	33	-	5	27	1
Plant population (plants·ha ⁻¹)	76,041	61,132	64,958	69,679	65,758	65,745	66,708	72,221	69,654	69,782	77,822	86,063	2169

‡ Common rust measurements were not taken at all sites in 2008.

Table 9. Correlation analysis between corn grain yields and corn response measurements.

Measurement	Yield
Plant population	−0.13
$p > r $	0.0059
Grain protein	0.74
$p > r $	<0.0001
Grain starch content	−0.47
$p > r $	<0.0001
Grain extractable starch	−0.44
$p > r $	<0.0001
TipFill	−0.13
$p > r $	0.0075
Common Rust	−0.21394
$p > r $	0.0003

No toxicity symptoms and barren stalks were observed due to foliar B treatments at all 12 site-years (data not presented). Production of barren ears in corn was reported for B levels less than 0.05 ppm [49]. Ear tip fill was used to evaluate the effect of B treatments on ear filling. A higher number for ear tip fill indicated a greater amount of ear was barren. Although ear tip fill did not show differences between B treatments, it varied by site-years (Table 8). The ear tip fill was greater in 2010 than in 2008 and 2009.

The severity of disease varied by sites and years, and the impact of B applications were generally subtle. The occurrence of common rust was not significantly different between B treatments, but it varied by site-year. Common rust severity was 22% higher at Bee Ridge in 2010 compared to Leonard. Ear tip fill and common rust were negatively correlated with the corn yields (Table 9). In 2010, corn was rated for the severity of anthracnose stalk rot at Bethel and Leonard. Severity of anthracnose stalk rot at Bethel and Leonard in 2010 was not affected by B treatments (data not presented). At Leonard in 2010, severity of northern corn leaf blight was affected by the timing of foliar B application, but not by the amount of B applied (Table 10). A reduction in the severity of common rust, gray leaf spot, and northern corn leaf blight in corn due to pyraclostrobin, not B was found by some other researchers [36,50]. The V4–V6 B application at 2.24 kg·ha^{−1} and all VT applications increased the severity of northern corn leaf blight compared to the non-treated control. The severity of gray leaf spot was 6% and 12% lower with V4–V6 applied B at 1.12 and 2.24 kg·ha^{−1} and VT applied B at 0.56 kg·ha^{−1}, respectively, compared to other B treatments including non-treated control (Table 10). Boron applied at V4–V6 at 2.24 kg·ha^{−1} decreased gray leaf spot severity, but the severity of northern leaf blight increased compared to non-treated control. Reductions in disease severity due to B have been reported by other researchers [35,36], but may be inconsistent depending on the disease, environmental conditions, and hybrids. Frequent rains along with cool and cloudy weather has favored fungal disease development, in addition to nutrient deficiencies and toxicities [32].

Table 10. Effect of B application timing and concentrations on severity of grey leaf spot and northern corn leaf blight. Data were averaged over 6 site-years for grey leaf spot. Severity of northern corn leaf spot was measured in 2010 at Leonard.

Application Timing	Application Concentration (kg·ha ⁻¹)	Grey Leaf Spot (%)	Northern Corn Leaf Blight (%)
Non-treated	0	16	7
V4–V6	0.56	16	8
V4–V6	1.12	15	8
V4–V6	2.24	15	9
VT	0.28	16	11
VT	0.56	14	9
VT	1.12	16	9
LSD (<i>p</i> = 0.1)		1	2

4. Conclusions

A B application along with recommended NPK fertilizers affected corn grain yields and severity of diseases. Boron applied at V4–V6 and 2.24 kg·ha⁻¹ was more beneficial than VT applications at 0.28, 0.56 and 1.12 kg·ha⁻¹ for high yield production systems even though VT B applications resulted in higher tissue B concentrations in the ear leaf. The ear leaf B concentrations were not positively correlated with corn yield. No significant differences in yield were found for B applications at different timings for same concentration of 0.56 and 1.12 kg·ha⁻¹. A V4–V6 application of B at 2.24 kg·ha⁻¹ had the greatest average corn yields. The V4–V6 foliar B application concentrations up to 2.24 kg·ha⁻¹ were not toxic to corn plants and increased corn yields. A higher concentration of B for VT application was not included in this study. Since B is needed by corn plants throughout the growing period, foliar application of B at earlier growth stages (V4–V6) was more beneficial for high yields. Boron showed no significant effect on plant populations, grain oil, protein, starch, or extractable starch concentration. Boron application concentrations up to 2.24 kg·ha⁻¹ did not cause any visual injury to crop plants. The B applications at V4–V6 had a slight decrease severity of diseases including gray leaf spot and leaf blight compared to foliar VT applications. The V4–V6 B application at 2.24 kg·ha⁻¹ was the best option for B fertilization in corn on fine-textured soils with low soil test B.

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Author Contributions

Gurpreet Kaur was responsible for the interpretation of results and manuscript preparation. Kelly Nelson was responsible for planning, design, site selection, coordination of the field research, data collection, interpretation of results, and editing of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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