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Soil and Broccoli Head Sulfur Levels but not Yields are Improved by the Application of Gypsum to a Light Textured Soil

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Light textured soils in semi-arid areas can be deficient in sulfur (S). Broccoli was used in the present study to evaluate the effects of genotype (open pollinated vs. hybrid), minimum (strip) vs. conventional (bedded) tillage, and gypsum application rates between 0 and 2000 kg/ha on soil properties and mineral nutrients, particularly S, and on yield and head (floret) mineral nutrient concentrations, particularly tissue S. Field-grown broccoli, *Brassica oleracea* Italica group (L.), cultivars Waltham 29 and Gypsy, were direct seeded into raised beds and into stripped tilled sudex residue at a site near Weslaco, TX (Lat. 26° 08'). Gypsum (23% Ca and 16.5% S) at rates of 0, 500, 1000, and 2000 kg/ha were applied and incorporated in order to determine the effects of added soil sulfur (S) on soil properties and broccoli head mineral nutrients. Results indicate that the open-pollinated 'Waltham' is more nutrient dense than the hybrid 'Gypsy'; that tillage method does not affect broccoli head nutrients or yield, but does influence plant establishment (stand) and head size. Increased gypsum rates improved head S concentrations (linearly), but did not affect plant stand or yield. Soil that was on raised beds tested higher in soil organic matter, extractable K, Mn, B, and Zn compared to strip-tilled soil. Gypsum application increased the soil cation exchange capacity, soil Ca and S, but linearly decreased soil Mn, B and pH and organic matter (quadratically). Initial soil penetration force was greater in strip-tilled vs. bedded plantings but these differences declined after 80 days. At the end of the study there was both a linear and quadratic reduction in penetration force to 15 cm depth resulting from increased gypsum application.

Additional Index Words: Brassica oleracea, soil compaction, strip-tillage, conservation tillage

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Broccoli is an excellent source of fiber, mineral nutrients and vitamins for the human diet (U. S. Dept. Agriculture, 2011) and human health compounds containing sulfur (Jez and Fukagawa, 2008). Glutathione levels, for example, were found to be highest in broccoli stem and head (floret) tissues (dry wt. basis) compared to 30 other vegetables tested (Mills, et al., 1997). Brassicaceae also have the capacity to store excess inorganic S in the form of glucosinolates (Marschner, 1995).

Soils used in vegetable production in south Texas vary greatly in chemical nutrients and physical properties. The range in soil sulfur can be 20 fold, from ca. 10 to 200 kg/ha (Makus and Lester, 2002). Annual rain-fall and cultural practices all can affect soil sulfur concentrations in soils in addition to plant productivity. Semi-arid climates generally receive S as SO_4^{2-} aerosols in the form of precipitation (Franzen and Grant, 2008), which has been declining in south Texas and elsewhere since 1981 (Nilles and Conley, 2001; Lehmann, et al., 2007). Sulfur deficiencies in crops have been reported worldwide, especially in Western European countries, and particularly in Brassicaceae (Scherer, 2009).

Gypsum, as calcium sulfate, is an inexpensive and fairly rapid sulfur delivery system, which can provide sulfur and calcium to soils depleted in these nutrients (Hickman and Whitney, 2004). Gypsum can also improve soil properties by reducing soil compaction and salinity, and improving water infiltration and storage (Baumhardt, et al., 1992; Hamza and Anderson, 2003).

The lack of nutrient density of the newer broccoli cultivars, specifically hybrid types, verses the older open-pollinated cultivars, has been recently debated (Farnham, et al., 2011; Davis, 2009).

Tillage systems which allow vegetable seeds to be planted directly into plant residue are being evaluated for their potential to conserve water, reduce wind-blown soil and improve soil organic matter. In southern latitudes (in North America) manipulating black oat residue management at 26º N Lat. was found to reduce both upper soil surface temperatures and soil moisture loss, and reduced microbial biomass and organic matter decomposition rates (Zibilske and Makus, 2009).

The objective of the present study was to evaluate the effects of cultivar type (open pollinated vs. hybrid), minimum (strip-tillage) vs. conventional (bedded), and gypsum rate (0, 500, 1000 and 2000 kg/ha) on soil properties and mineral nutrients, particularly S, and on broccoli yield and head mineral nutrient concentrations, particularly tissue S.

MATERIALS AND METHODS

Broccoli seeds of the open pollinated cultivar 'Waltham 29' and the hybrid 'Gypsy' were planted with a Stanhay Model S870 planter at a rate of 6.6 kg/ha into light (sandy loam) textured soil on 20 Oct. 2010. Seeding was on raised beds and strip-tilled rows. Both tillage methods were made in a field which had been spring-planted in Sudex, sickle-mowed three times, and sprayed with glyphosate prior to field cultivation. The Sudex residues were never removed prior to field operations. The raised beds were approx. 35 cm wide, and both beds and strip-tilled rows were on 1 m centers with experimental row lengths of 7.6 m. Strip-tillage involved rotovating a 25 cm wide strip to a depth of 10 cm. Five days prior to seeding, gypsum (23 % Ca and 16.5% S) was broadcast at rates of 0, 500, 1000, and 2000 kg/ha as a 30 cm band centered in the row before bed formation / shaping or strip-tillage. Soil penetrometer (Eijkelkamp, Giesbeek, Netherlands) readings, using a No. 2 16 mm tip, were made at 5 and 15 cm depths on 6 Dec. 2010 and 24 Feb. 2011, 52 and 132 days, respectfully, after gypsum application. Soil water content was measured gravimetrically on these same dates. Leaf greenness was measured with a Minolta SPAD meter (Minolta Corp., Ramsay, NJ) on 27 Jan. 2011. On 23 and 24 Mar. 2011 all 64 plots were sampled for soil analysis at the 0 – 15 cm depth and dried at 105 ºC.

Rainfall was supplemented by surface trickle irrigation to planted beds when soil moisture was depleted to approximately -40 kPa at 15 cm. A total of 130 kg $N \cdot ha^{-1}$ (as 20-20-20; Scotts, Marysville, OH) were added by trickle irrigation in four equal amounts on 21 Oct., 18 Nov., 12 Dec. 2010, and 7 Jan. 2011. Ammonium nitrate was the N form. Temperature (°C) and solar radiation (400 – 1100 nm, in $kW \cdot m^{-2}$) were recorded hourly (Campbell Scientific, CR-10) with a thermister (Vasiala HMP-35) and a pyranometer (LI-200SA), respectively, by a weather station located within 100 m of the experimental plots.

Stand counts were made on 1 Nov 2010. 'Waltham' was harvested on 25 Jan., 1 Feb and 18 Feb. 2011 and 'Gypsy' was harvested on 31 Jan., 15 Feb. and 18 Feb. 2011. Plot yield (in kg fresh wt.) and head number per 6 m of row were determined at each harvest date, then pulled for season totals. Ten broccoli head sub-samples per plot at the first harvest of each cultivar were collected for head nutrient analysis. After removing a vertical 10 cm x 1 cm dia. core from the center of each head, samples were frozen, freeze-dried, and passed through a 40 mesh (0.36 mm^2) screen and stored at -20 ºC until analysis. Leaf mineral nutrients (K, P, Ca, Mg, S, Na, Fe, Mn, Zn, B, and Cu) were determined, after HNO_3 digest, by ICP spectroscopy (Plank, 1992) (Midwest Laboratories, Omaha, NE). Leaf total-N was determined by dry combustion (Elementar Vario Max, Mt. Laurel, NJ).

The experiment design was a split-split plot, where tillage method (bedded and strip-tilled) were main plots, cultivars were sub-plots, and gypsum rates were sub-subplots in a randomized complete block design (N = 4). Gypsum rate was fitted to a polynomial regression model to determine any linear, quadratic, or cubic relationships. Differences between response means were tested using the PDIFF option of the LSMEANS statement of PROC GLM of SAS Version 9.1 (SAS Institute, Cary, N.C.).

RESULTS AND DISCUSSION

Environment

Rainfall of 63 mm was supplemented with 146 mm of water (ha-mm basis) by surface trickle irrigation with water testing ca. 0.35 dS/m during the 121 day growing season. All treatments received the same amount of water. Average mean season temperature was 17.7 °C and cumulative total solar radiation over the 126 day growing period (sowing to final harvest) was 1563 MJ/m^2. Soil water content at the time of early and late season penetrometer readings was 11.2 and 7.7 %, respectively.

Plant Responses

Cultivar

Leaves of 'Gypsy' were greener than those of 'Waltham' on 27 Jan. 2011 (Table 1.). Plant stand of 'Gypsy', compared with 'Waltham', was significantly higher by 12 % (Table 2.). Season yield and average head weight was also greater in 'Gypsy'. Plants were not thinned to a set plant density and seeds of 'Gypsy' were about 41 % larger in weight than were

Table 1. Broccoli SPAD (greenness) values taken on 27 Jan. 2011. There were no tillage x cultivar interactions.

Effects	SPAD Value
Tillage:	
Bedded	59.3 a
Strip-tilled	59.0 a
Prob. > 'F' value	NS[z]
Cultivar:	
Gypsy	61.8 a
Waltham	56.5 b
Prob. > 'F' value	**
Tillage X Gypsum:	
Bedded – 0 lbs/Ac	59.9 ab
Bedded – 500 lbs/Ac	57.9 bc
Bedded – 1000 lbs/Ac	60.0 ab
Bedded – 2000 lbs/Ac	59.6 ab
Strip-tilled – 0 lbs/Ac	58.0 bc
Strip-tilled – 500 lbs/Ac	61.0 a
Strip-tilled – 1000 lbs/Ac	57.3 c
Strip-tilled – 2000 lbs/Ac	59.6 ab
Prob. > 'F' value	*

[Z] NS, *, ** = not significant and significant at *P*=0.05 and *P*=0.01, respectively. LSMEAN separation at the probability level shown.

'Waltham' seed (6.22 mg vs. 3.67 mg, respectively). These factors, in addition to the inherent hybrid vigor associated with 'Gypsy', contributed to the head size and yield differences between cultivars. In another study, head weights of 'Gypsy' were 2.2 X larger compared to 'Waltham 29' head weights (Farnham, et al. 2011). In the current study, there were no interactions between cultivar, tillage system, and gypsum rate (Table 2.).

Head total N (*P*=0.09), Ca, Mg, Zn, and B (*P*=0.06) nutrients (µg/g dry wt.) were higher in 'Waltham', the non-hybrid. Nutrient differences between 'Waltham 29' (the same open pollinated cultivar used in the current study) and 13 hybrid broccoli cultivars introduced between 1975 and 2004, were numerically higher in head Mg, P, Cu, Fe, Zn and Mn (fresh wt. basis) than were hybrid heads with the exception of Ca and Na (Farnham, et al., 2011). They reported head weights of 'Waltham' to be typically one-half those of almost all the 13 hybrids evaluated, and Waltham "bead" size, the largest among all cultivars. Both observations were significant (P=0.05).

Leaf greenness, usually attributed to greater leaf N, was significantly higher in Gypsy (Table 1) but tissue N concn. (head, not leaf) was actually lower in Gypsy compared to Waltham (Table 3.). The greenness differences between cultivars may be attributed to other factors perhaps related to leaf morphology (thickness) or leaf waxes (bloom) or genotype carotenoids / chlorophyll differences (Farnham and Kopsell, 2009).

Tillage

Tillage method had no effect on broccoli leaf greenness (Table 1.). Planting into strip-tilled rows improved stand compared to bedding, had no affect on final season yield, but resulted in smaller head weights (Table 2.). Sodium levels were higher in strip-tilled broccoli compared to bedded broccoli, perhaps due to better Na leaching from the beds (Table 3.). Strip-tilled 'Waltham' tended to accumulate the highest

Table 2. Broccoli plant stand on 1 Nov. 2010 and season average head weights and yield. Season totals are based on the first two harvest dates. There were no gypsum effects or interactions in these responses.

Main effects	Plant stand[z] (No.)	Season yield[y] (Kg)	Season avg. head yield[y] (g)
Tillage:			
Bedded	40.7 b	4.67 a	200 a
Strip-tilled	44.8 a	4.72 a	176 b
Prob. > 'F' value	*[x]	NS	*
Cultivar:			
Gypsy	45.3 a	7.35 a	251 a
Waltham	40.3 b	2.04 b	125 b
Prob. > 'F' value	*	**	**

[Z] Based on 6.1 m of row.
[Y] Based on 7.6 m of row.
[X] NS, *, ** = not significant or significant at *P*= 0.05 and *P*=0.01, respectively. LSMEAN separation at the probability level shown.

Table 3. Effect of tillage type, cultivar, and gypsum rate on broccoli head nutrients harvested in 2011.[z]

Effect	N	S	Ca	Mg	Na	Fe	Zn	B
	……………………(%)………………..				……………..…..(ug/g)………………….			
Tillage:								
Bedded	3.85 a	0.86 a	0.38 b	0.17 a	58 b	59 a	25 a	21 a
Strip-tilled	3.92 a	0.87 a	0.40 a	0.18 a	65 a	56 a	24 b	21 a
Prob. > ‘F’ value:	NS	NS	0.07	NS	*	NS	0.07	NS
Cultivar:								
Gypsy	3.77 b	0.86 a	0.37 b	0.17 b	62 a	57 a	23 b	20 b
Waltham	3.99 a	0.86 a	0.41 a	0.18 a	61 a	58 a	26 a	22 a
Prob. > ‘F’ value:	0.09	NS	*	**	NS	NS	*	0.06
Gypsum:								
0 kg/ha	3.89 a	0.81 b	0.38 a	0.18 a	69 a	56 a	24 a	21 a
500 kg/ha	3.90 a	0.86 a	0.39 a	0.18 a	57 b	58 a	24 a	21 a
1000 kg/ha	3.87 a	0.88 a	0.39 a	0.18 a	59 b	58 a	25 a	22 a
2000 kg/ha	3.87 a	0.90 a	0.40 a	0.18 a	61 b	58 a	24 a	20 a
Prob. > ‘F” value:	NS	**	NS	NS	**	NS	NS	NS
Polynomial fit:	—	L**	—	—	L**,Q**, C*	—	—	—
Tillage x Cultivar:								
Bedded-Gypsy	3.96 ab	0.87 ab	0.39 b	0.18 b	61 ab	62 a	25 a	21 ab
Bedded-Waltham	3.73 bc	0.84 c	0.38 b	0.17 b	55 b	56 b	24 a	21 ab
Strip-tilled - Gypsy	3.59 c	0.85 bc	0.36 b	0.17 b	64 a	51 b	21 b	20 b
Strip-tilled –Waltham	4.25 a	0.88 a	0.44 a	0.20 a	66 a	62 a	27 a	23 a
Prob. > ‘F” value:	**	**	**	**	0.11	**	**	0.04

[Z] NS, *, ** = not significant or significant at *P*=0.05 and *P*=0.01, respectively. Column mean separation at *P*=0.05 or at the Prob. > ‘F’ value given. L, Q, C = linear, quadratic, or cubic, respectively.

Table 4. Soil penetrometer readings were taken 52 and 132 days (on 6 Dec. 2010 and 4 Feb. 2011, respecively) after initial gypsum application on 15 Oct. 2010.[Z]

Effect	Penetrometer force 5 cm depth	15 cm depth
	..........(kg/cm^2)	....
Date:		
Pre-plant	113 a	510 a
Post-harvest	116 a	473 b
Prob. > 'F' value:	NS	**
Tillage:		
Bedded	92 b	430 b
Strip-tilled	137 a	554 a
Prob. > 'F' value:	**	**
Gypsum		
0 kg/ha	106 a	546 a
500 kg/ha	118 a	446 b
1000 kg/ha	118 a	440 b
2000 kg/ha	116 a	536 a
Prob. > 'F' value:	NS	**
Polynomial fit:	—	L**, Q**
Date X Tillage		
Pre-plant - bedded	98 c	439 c
Pre-plant - strip-tilled	128 b	583 a
Post-harvest - bedded	85 c	421 c
Post-harvest - strip-tilled	146 a	525 b
Prob. > 'F' value:	**	*

[Z] NS, *, ** = not significant and significant at *P*=0.05 and *P*=0.01, respectively. LSMEANS separation at the probability level shown.
L, Q = linear and quadratic, respectively.

levels of head nutrients compared to other tillage x cultivar combinations, particularly strip-tilled 'Gypsy'.

Gypsum rate

Leaf greenness was not affected by gypsum rate (Table 1.), nor was plant stand, season yield or average head weight (Table 2.). Head S concentration was increased linearly and Na levels decreased cubically by increasing gypsum application (Table 3.). Other head nutrients were not influenced by gypsum rates. In another study, supplemental gypsum rates of 0, 23 and 92 kg S/ha improved head S levels in three broccoli cultivar grown under field conditions (Rangkadilok, et al., 2004). These authors also found that glucoraphanin, (an aliphatic glucosinolate which is a precursor to the chemoprotective compound sulforaphane), levels were increased as gypsum application rates increased.

Correlations

Head S concentrations were highly correlated ($P \leq 0.01$) with tissue total N (0.6089), Ca (0.8852), Mg (0.9096). P (0.6380), Zn (0.4868), Mn (0.3878), Fe (0.5710), B (0.4767) and negatively correlated with K (-0.4675).

Soil responses

Tillage.

Early and late season penetrometer readings were similar at the shallow 5 cm depth, but penetration force to 15 cm depth was reduced late in the season (after 132 days) due to gypsum application (Table 4.). Though not measured, the higher rates of gypsum probably improved soil porosity and aggregate size, thus accounting for the lower penetrometer values late in the season. Soil density was higher in strip-tilled beds compared to bedded broccoli, both early and late in the growing season. Increasing gypsum application levels did not affect shallow 5 cm penetration force but decreased 15 cm force linearly and quadratically over time. The interaction illustrates that the differences in penetration force between the two tillage methods decreased more late in the season. An attempt to take penetrometer readings at similar soil water content levels (Bradford, 1986) was not successful and the late season readings taken in drier soil (11.2 vs. 7.7 % SWC) probably resulted in higher penetrometer values and therefore reduced the perceived benefits from gypsum application over time.

Soil organic matter (OM), K, Mn, B, and Zn were higher in bedded soil (Table 5.). The 40% difference in soil S concentration between tillage methods was not significant (*P*=0.17; C.V. =107 %). The OM in the strip-tilled treatments were probably stratified on the soil surface and not mixed into the 0- 15 cm sampling profile during bed preparation, resulting in lower OM values for the strip-tilled planting method.

Gypsum rate

Increasing the gypsum application rate had a linear effect on decreasing soil pH, Mn, and Zn, but linearly increased C.E.C. and soil Ca (Table 5.). Soil OM decreased quadratically while soil S increased linearly and quadratically due to increasing gypsum

Table 5. Effect of tillage type and gypsum rate on soil pH, C.E.C., organic matter (%) and mineral nutrients, 159 days after gypsum application.[Z]

Main Effects	pH	C.E.C.	OM (%)	Ca	K	S	Mn	B	Zn
				……..…………………(ug/g)……..……………..……..…					
Tillage:									
Bedded	8.30 a	13.4 a	0.68 a	2323 a	310 a	21.7 a	5.69 a	1.21 a	1.01 a
Strip-tilled	8.29 a	13.5 a	0.57 b	2364 a	275 b	36.2 a	4.28 b	1.19 b	0.67 b
Prob. > 'F' value:	NSY	NS	*	NS	**	0.17	**	*	0.06
Gypsum rate:									
0 kg / ha	8.38 a	13.3 b	0.69 a	2287 c	305 a	11.6 b	5.62 a	1.21 a	1.08 a
500 kg / ha	8.33 ab	13.3 b	0.68 a	2322 bc	315 a	15.6 b	5.75 a	1.20 a	0.95 a
1000 kg / ha	8.29 b	13.6 ab	0.56 a	2361 ab	270 a	18.2 b	4.31 a	1.18 a	0.71 a
2000 kg / ha	8.20 c	13.7 a	0.58 a	2404 a	280 a	70.5 a	4.25 a	1.20 a	0.63 a
Prob. > 'F' value:	**	*	NS[Y]	**	NS[Y]	**	NS[Y]	NS[Y]	NS[Y]
Polynomial fit:									
Gypsum rate	L**	L**	Q*	L**	—	L**,Q*	L*	—	L*

[Y] NS, *, ** = not significant and significant at *P*=0.05 and *P*=0.01, respectively. LSMEANS separation the probability level shown. L, Q = linear and quadratic, respectively. Mineral nutrients P, Mg, Fe and Cu levels were not affected by treatments.

rate. Soil K and Mg, often negatively influenced by gypsum application, were not statistically reduced, but soil pH dropped by 0.18 units at the highest rate of gypsum. Sanderson (2003) reported typically 8-fold increases in leaf S levels from broccoli planted at four locations (over 2 years), that were supplemented with 670 kg S/ha (as gypsum) compared to plants receiving no gypsum. Soil pH was reduced typically by 0.3 units from gypsum application averaged over all sites.

Tillage X gypsum rate.

There was a tillage x gypsum interaction for soil test S (P=0.03). Increasing the gypsum rate in strip-tilled treatments resulted in a greater accumulation of soil S at the higher rates (L**, Q*), whereas increasing gypsum application to bedded treatments resulted in less dramatic soil S increases overall and a linear response to gypsum rates (data not shown).

CONCLUSIONS

Gypsum application had no effect of broccoli yield, but decreased the soil penetration force at 15 cm depth between 52 and 132 days after application. The decrease was both linear (L) and quadratic (Q) with increasing application rate. Soil sulfur levels were increased (L, Q) as was Ca (L) and cation exchange capacity (L), whereas pH was reduced (L). Broccoli head S was increased by gypsum addition (L). 'Waltham' heads were higher in total N, Ca, Mg, Zn and B compared to 'Gypsy' (dry wt. basis), but the agronomic performance (yield and average head size) of the open-pollinated cultivar was inferior to 'Gypsy'. Tillage method had no effect on yield or on head nutrients, but strip-tillage reduced head weight and resulted in lower soil organic matter and soil test K, Mn, B and Zn values in the 0 – 15 cm sampling profile than did the bedding method.

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