Soil Calcium Status Unrelated to Tipburn of Romaine Lettuce

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Additional key words. soil testing, saturated paste, soil solution, fertigation, transpiration, *Lactuca sativa* L.

Abstract. Application of calcium (Ca) fertilizers is a common practice of California lettuce growers to minimize the occurrence and severity of tipburn, particularly in romaine lettuce (*Lactuca sativa* L. var. *longifolia* Lam.). An evaluation of the effect of soil Ca availability on the severity of tipburn in romaine lettuce was conducted in the Salinas Valley of central California in 2005 to 2006. Twenty representative soils from this region were evaluated for Ca availability by ammonium acetate extraction, saturated paste extraction, and extraction of soil solution through centrifugation of soil at field-capacity moisture content. Soil solution Ca in these soils was generally high, ranging from 5 to 80 mmol·L⁻¹, representing 44% to 71% of cations on a charge basis. Soil solution Ca was highly correlated with saturated paste Ca ($r^2 = 0.70$) but not with exchangeable Ca ($r^2 = 0.01$). However, saturated paste extraction significantly underestimated soil solution Ca concentration (regression slope = 0.19). A survey of 15 commercial romaine lettuce fields showed tipburn severity to be unrelated to either leaf Ca concentration or soil Ca availability. The most severe tipburn was observed in fields in which transpiration was reduced by foggy weather during the final 2 weeks of growth. Ca fertilizers (calcium nitrate, calcium thiosulfate, and calcium chloride) applied through drip irrigation during the final weeks of lettuce growth were ineffective in increasing romaine leaf Ca concentration in three field trials; tipburn was present in only one trial, and Ca fertigation had no effect on tipburn severity. We conclude that under typical field conditions in this region, tipburn severity is primarily a function of environmental conditions. Soil Ca availability plays no substantive role in tipburn severity, and Ca fertigation does not improve lettuce Ca uptake or reduce tipburn.

Tipburn of romaine lettuce is a serious quality defect, which causes significant economic loss to lettuce growers in the Salinas Valley of California. This defect is particularly problematic for the producers of fresh-cut salad mixes because the presence of even a few affected leaves in a consumer product is unacceptable. Tipburn is generally recognized as a localized calcium (Ca) deficiency that induces collapse and necrosis of the margins of actively expanding leaves (Collier and Tibbitts, 1982). Under field conditions, tipburn development is often related to factors other than soil Ca supply. Tipburn occurs primarily in the final weeks before harvest, when crop growth rate is most rapid. Environmental conditions such as high light intensity (Tibbitts and Rao, 1968) or warm temperatures (Rao, 1966) that encourage rapid growth also promote tipburn. Because Ca moves primarily by transpirational mass flow in the xylem (Clarkson, 1984), inner leaves that are enclosed within the develop-

ing head are particularly prone to the disorder because of their low transpiration rate.

Effective tipburn prevention measures have proven elusive. Cultivars vary considerably in tipburn susceptibility (Collier and Tibbitts, 1982; Ryder and Waycott, 1998), but no commercially acceptable romaine cultivar has been developed that is reliably tipburn-resistant. Under controlled conditions, Ca application to soil, foliage, or in nutrient solution has reduced tipburn (Ashkar and Ries, 1971; Sonneveld and van den Ende, 1975; Thibodeau and Minotti, 1969). Frantz et al. (2004) and Goto and Takakura (1992) reduced tipburn by blowing air onto the developing leaves, thereby increasing transpiration. However, under field conditions, success in reducing tipburn has been limited. Misaghi and Matyac (1981) found that soil Ca application at rates as high as 160 kg·ha⁻¹ reduced tipburn in only one of six fields. Bangerth (1979) and Collier and Tibbitts (1982) concluded that in soils normally used for lettuce production, soil Ca supply was not a significant factor in tipburn development.

Despite the generally poor success reported for soil Ca application, fertigation of products such as calcium nitrate or calcium thiosulfate remains a common practice in the

California lettuce industry. Ca fertigation is done without regard for soil test Ca level on the belief that in the high pH, alkaline soils typical of this region, the common soil test procedure (ammonium acetate extraction; Thomas, 1982) does not provide an accurate estimate of soil Ca availability. This study was undertaken to determine whether soil Ca availability played any substantive role in tipburn development in romaine lettuce under representative field conditions and whether Ca fertigation could improve lettuce Ca uptake and decrease tipburn severity.

Materials and Methods

Characterization of soil calcium availability. Soil samples were collected from 20 representative vegetable fields in central California in 2005. The fields were chosen to cover the range of soil texture and pH commonly used for lettuce production. Samples (top 30 cm) were air-dried, sieved through a 2-mm screen, and subjected to ammonium acetate extraction (Thomas, 1982) and saturated paste extraction (Rhoades, 1982). Additionally, a centrifugation method similar to that of Thibault and Sheppard (1992) was used to extract soil solution. In brief, 30-g samples of air-dried soil were placed in polyethylene cylinders and wetted with deionized water to field capacity (defined as the gravimetric water content at a soil moisture tension of 0.02 MPa). The samples were allowed to equilibrate overnight and then centrifuged for 40 min at 2000 rpm, equivalent to a force of $\approx 800 g$. The filtered soil solutions collected were analyzed for Ca, magnesium (Mg), potassium (K), and sodium (Na) concentration by atomic emission spectrometry.

Lettuce tipburn survey. Fifteen fields of romaine lettuce were sampled in 2005 to 2006 to document the relationships among soil Ca status, weather conditions, leaf Ca concentration, and tipburn severity. Fields were distributed throughout the Salinas Valley; harvest dates ranged from April through September. Soil samples (top 30 cm) were collected and analyzed for Ca, Mg, K and Na in saturated paste extracts. At commercial maturity, 24 randomly selected plants per field were evaluated for tipburn. Each plant was split longitudinally, and the number of leaves per plant exhibiting tipburn was recorded. From each field, a composite sample comprised of inner leaves (those ≈ 10 to 15 cm long from within the “heart” of the plant) from all 24 plants were oven-dried, ground, and analyzed for Ca concentration by inductively coupled plasma atomic emission spectrometry (Meyer and Keliher, 1992) after microwave digestion with nitric acid and hydrogen peroxide (Sah and Miller, 1992).

For each field, daily air temperature and reference evapotranspiration (ET₀; Goldhamer and Snyder, 1989) data were obtained from weather stations of the California Irrigation Management Information System (CIMIS) for the final 2 weeks of growth, the period when tipburn typically develops. Given the

Received for publication 22 Mar. 2007. Accepted for publication 24 June 2007.

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importance of transpiration on Ca movement to developing leaves (Collier and Tibbitts, 1982), and plant growth rate on tipburn susceptibility (Cox et al., 1976), a daily transpiration index was calculated by dividing daily ET_0 (mm) by the number of degree days (DD). DD were calculated by the formula:

$$[(\text{max. air temp.} + \text{min. air temp.})/2] - 5 = \text{DD}$$

using 5 °C and 30 °C as lower and upper temperature thresholds, respectively. This index provided an estimate of crop transpiration per unit growth potential; lower values indicated greater potential for tipburn.

Calcium fertigation effects on lettuce. Two field trials were conducted in the Salinas Valley in 2005 and another in 2006 to evaluate the effects of soluble Ca applied through drip irrigation on romaine lettuce growth, inner leaf Ca concentration, and tipburn severity. Soil characteristics and cultural details are given in Table 1. In the 2005 trials, three Ca fertilizers [calcium nitrate (CN), calcium thiosulfate (CTS), and calcium chloride] were injected into the drip systems twice, the first application ≈ 3 weeks preharvest and the second ≈ 1 week preharvest. Ca fertigation was applied during this timeframe because this is the part of the season in which tipburn most commonly occurs. Injections of 17 kg·ha⁻¹ Ca were made over 4 h at a concentration of ≈ 15 mmolc·L⁻¹ Ca. In the 2006 trial, two Ca fertilizers (CN and CTS) were injected at 28 kg·ha⁻¹ Ca (at ≈ 22 mmolc·L⁻¹ Ca) in a single application 1 week before harvest. These Ca applications simulated common commercial rates and timing. In all trials, the Ca fertigation treatments were compared with a control treatment receiving no Ca fertigation. Irrigation water Ca ranged among trials from 2 to 5 mmolc·L⁻¹. A randomized complete block experimental design was used in all trials with five single-bed replicates 120 m long. In the 2005 trials, soil beds were 2 m wide with six plant rows and three drip irrigation lines; in 2006, the beds were 1 m wide with two plant rows and one drip line. The daily transpiration index in the last 2 weeks of growth averaged 0.43, 0.32, and 0.28 mm ET_0 /DD in trials 1, 2, and 3, respectively.

In each trial, the percentage of marketable plants was determined by taking plant counts before and after the commercial harvest. Before commercial harvest, 32 random plants

per plot were evaluated for total fresh weight. Sixteen plants per plot were evaluated for tipburn as previously described. A composite sample of inner leaves was collected from each plot, oven-dried, ground, and analyzed for Ca concentration.

Results

Characterization of soil calcium availability. The soils tested ranged in soil solution Ca from 5 to 80 mmolc·L⁻¹, representing 44% to 71% of cations in soil solution on a charge basis; the soils averaged 34 mmolc·L⁻¹ Ca, representing 57% of cation charges. Soil solution Ca was highly correlated with saturated paste Ca ($r^2 = 0.70$) but not exchangeable Ca ($r^2 = 0.01$; Fig. 1). Saturated paste extraction yielded significantly lower Ca concentrations than in soil solution (regression slope = 0.19). Even after adjusting for the disparity in soil water content (preparation of saturated paste extracts required between 160% and 200% of field capacity moisture content), saturated paste Ca averaged only 35% of soil solution Ca.

Lettuce tipburn survey. The percentage of romaine plants showing tipburn ranged among fields from 0% to 88%, whereas tipburn severity, defined as the mean number of affected leaves per plant, varied among fields from 0 to 2.8. There were no apparent relationships (no significant linear or quadratic trends) among soil Ca availability, inner leaf Ca concentration, or tipburn severity (Fig. 2A–C); in fact, the field with the most severe tipburn had both the highest saturated paste soil Ca and the highest leaf

Ca concentration, suggesting that factors other than soil Ca availability governed tipburn development. Limited transpiration may have been such a factor. Two of the three fields with significant tipburn had the lowest transpiration indices over the final 2 weeks of growth (Fig. 2D). These two fields, both harvested 27 July 2005, were located in the coastal region near Castroville. Persistent marine fog from 9 to 6 d before harvest resulted in the low transpiration index over that period (Fig. 3).

Calcium fertigation effects on lettuce. Applying Ca fertilizers through drip irrigation had no significant effect on romaine yield or inner leaf Ca concentration in any trial (Table 2). Inner leaf Ca was consistent across trials despite substantial differences in soil Ca availability. No tipburn was observed in two of the trials; in one trial, a low level of tipburn was present, but Ca fertigation did not reduce its incidence.

Discussion

Soil Ca availability appeared to play no substantive role in the development of tipburn in romaine lettuce grown under field conditions representative of the Salinas Valley. This confirmed prior observations that tipburn severity was generally unrelated to soil Ca status and could not be reduced through soil Ca application (Bangerth, 1979; Collier and Tibbitts, 1982; Misaghi and Matyac, 1981). The lack of correlation between soil Ca availability and tipburn incidence, and the lack of crop response to Ca fertigation, can be attributed to two main factors: generally high soil Ca availability in the soils of this region and the confounding effects of environmental factors on plant Ca uptake.

Ca dominates the base exchange in central California soils. Saturated paste extracts from the soils used in the laboratory extraction methods comparison averaged 6.9 mmolc·L⁻¹ Ca, whereas those from the tipburn field survey averaged 7.7 mmolc·L⁻¹. Given the fivefold difference between saturated paste Ca and soil solution Ca, soil Ca availability was very high across the soils tested. Soil solution Ca in the extraction methods comparison averaged 34 mmolc·L⁻¹, representing 57% of cation charges. By comparison, hydroponic nutrient solutions used in greenhouse vegetable production, formulated to provide optimum nutrient balance, typically range between 5 and 10 mmolc·L⁻¹ Ca, representing 30% to 50% of cations in the solution (Hanna, 1998; Jones, 1997).

At the modest application rates used, which reflected current industry practices, Ca fertigation had no measurable effect on crop Ca status, undoubtedly in part because the application represented an insignificant increase in soil Ca availability. Fertigation trial 1 had the lowest soil Ca availability (19 mmolc·L⁻¹ in soil solution). At field capacity moisture content (21% by weight) and typical field bulk density (1.3 g cm⁻³), this soil had

Fig. 1. Relationship between soil calcium (Ca) extracted by the ammonium acetate or saturated paste methods and Ca in soil solution obtained by centrifugation. Regression between ammonium acetate and soil solution nonsignificant at $P < 0.05$; regression between saturated paste and soil solution significant at $P < 0.01$.

Table 1. Summary of soil characteristics and crop management practices for the 2005 and 2006 calcium (Ca) fertigation trials.

	Trial 1	Trial 2	Trial 3
Soil characteristics			
Texture	Sandy clay loam	Sandy loam	Sandy loam
pH	7.0	6.8	6.9
Saturated paste Ca (mmolc·L ⁻¹)	4.4	8.9	8.6
(% of cations, charge basis)	54	52	59
Cultivar	Harvest Gold	Harvest Gold	Sunbelt
Seasonal N total (kg·ha ⁻¹)	360	370	170
Ca fertigation date(s)	22 July, 2 Aug.	22 Aug., 6 Sept.	14 Aug.
Harvest date	9 Aug., 2005	15 Sept., 2005	21 Aug., 2006

Fig. 2. Relationships among saturated paste soil calcium (Ca), inner leaf Ca, transpiration index, and tipburn rating in the tipburn survey fields. Tipburn rating is mean number of affected leaves per plant; transpiration index is the mean daily value over the final 2 weeks before harvest.

greater than 300 kg·ha⁻¹ Ca in the top 30 cm. By comparison, each fertigation of 17 kg·ha⁻¹ Ca represented less than 6% of the Ca in soil solution. The failure of Ca fertigation to increase lettuce Ca concentration supported the observations of Misaghi and Matyac (1981); working in California and Arizona,

they found that soil Ca applications up to 160 kg·ha⁻¹ increased lettuce Ca uptake in only one of six field trials.

The importance of environmental factors on tipburn development has been widely recognized. Tipburn is enhanced by environmental conditions that promote rapid growth (Cox et al., 1976; Tibbitts and Rao, 1968) or that limit transpirational flow (Collier and Tibbitts, 1982; Wien and de Villiers, 2005). The transpiration index used to characterize the environmental conditions of the survey fields attempted to integrate these influences into a single parameter. All three survey fields with significant tipburn were grown in the summer (the season of most rapid growth), and two of these fields near the coast encountered weather conditions that severely limited transpiration.

Although greenhouse lettuce growers can manipulate the environment to minimize tipburn (Ashkar and Ries, 1971; Cresswell, 1991; Frantz et al., 2004; Goto and Takakura, 1992), under field conditions, practical tipburn

Fig. 3. Transpiration index (mm ET₀/degree day) for Castroville, CA, site of two 2005 survey fields with significant tipburn; data represent the final 14 d before harvest.

Table 2. Effects of calcium fertigation on romaine lettuce yield, inner leaf calcium (Ca) concentration, and tipburn severity.

Trial	Ca Treatment ^a	Mean plant mass (kg)	Marketable plants (%)	Tipburn rating ^b	Leaf Ca (g·kg ⁻¹)
1	No Ca	0.76	97	0	4.3
	CN	0.79	98	0	4.7
	CTS	0.79	97	0	4.6
	CC	0.80	98	0	4.4
	NS	NS	NS	NS	NS
2	No Ca	0.84	98	0.3	3.7
	CN	0.85	98	0.4	4.1
	CTS	0.83	97	0.2	3.9
	CC	0.83	98	0.2	3.9
	NS	NS	NS	NS	NS
3	No Ca	0.72	97	0	4.2
	CN	0.70	98	0	3.9
	CTS	0.69	95	0	4.3
	NS	NS	NS	NS	NS

^aCN = calcium nitrate; CTS = calcium thiosulfate; CC = calcium chloride.

^bMean number of leaves per plant showing tipburn.

NS = Ca treatments not significantly different at $P < 0.05$.

control measures are limited. Salinas Valley growers currently attempt to minimize tipburn incidence by growing less tipburn-susceptible cultivars during the summer and by concentrating summer production away from the coastal area, practices supported by our results and those of Ryder and Waycott (1998). However, the application of Ca fertilizers is clearly an ineffective practice.

These findings have relevance for other production areas and for Ca disorders affecting other horticultural crops. The Ca characteristics of the soils evaluated in this study are not unique to California. Throughout the western United States, alkaline, mineral soils containing free lime are common. In such soils, at normal application rates, the application of Ca fertilizer is unlikely to substantively increase crop Ca uptake or reduce the incidence or severity of Ca-related disorders. In addition to liming acid soil for pH adjustment, there are several valid uses for soil applied Ca: improving infiltration of rain or irrigation water of low electrical conductivity and reclaiming sodic soil (Shainberg et al., 1989). However, for these uses, the relatively high application rates required for efficacy favor the use of an inexpensive Ca source such as lime or gypsum rather than the more expensive Ca fertilizer products evaluated here.

In summary, soils used for lettuce production in central California have high Ca availability. Tipburn severity is unrelated to soil Ca availability and therefore is unlikely to be reduced by soil Ca fertilization.

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