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Exchangeable Soil Calcium May Not Reliably Predict In-season Calcium Requirements for Enhancing Potato Tuber Calcium Concentration

Christopher C. Gunter · Jiwan P. Palta

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Abstract Previous research has provided evidence that Ca is transported to the tuber along with water via the roots on stolons and tubers. Several studies have documented that in-season Ca application can increase tuber Ca concentration and reduce storage rot and internal defects such as hollow heart, brown center, and internal brown spot. The objective of the present study was to investigate the relationship between preplant soil test Ca levels and the tuber Ca concentration. Recommendation for Ca application in potato production guides are not necessarily geared towards tubers unique nutritional needs. In general, for potato production, Ca applications are recommended only if pre-plant soil exchangeable Ca is below 300 mg kg^{-1}. Studies were conducted in two soil types, namely loamy sand (Hancock location) and silt loam (Antigo location). The pre-plant soil Ca for the loamy sand tested at 285–563 mg kg^{-1} and the silt loam tested at 530–1,340 mg kg^{-1} of exchangeable Ca. Five cultivars were grown with or without in-season Ca applications of 168 kg ha^{-1}. At Hancock, 30 separate trials were conducted between the years 1999–2006, whereas at Antigo, 15 separate trials were conducted between the years 1995–1998. The tuber Ca concentration increased in 38 of the 45 total trials carried out in both locations. This increase in tuber Ca concentration varied among cultivars and seasons but had no relationship with soil Ca. This increase in tuber CA concentration occurred even when pre-season exchangeable Ca tested at over 1,000 mg kg^{-1}. These results suggest that testing for exchangeable Ca in these soils is not a good (or reliable) predictor of tuber Ca needs.

Resumen Investigaciones recientes han proporcionado evidencias que calcio es transportado a los tubérculos junto con el agua mediante las raíces de los estolones y de los tubérculos. Varios estudios han documentado que aplicando calcio durante el período de crecimiento puede incrementar la concentración de calcio en el tubérculo y reducir los problemas de pudrición durante el almacenamiento, así como los defectos internos conocidos como corazón hueco (hollow heart), centro pardo (brown center) y mancha parda (internal brown spot). El objetivo del presente estudio fue investigar la relación entre los niveles de calcio del suelo antes de plantar y la concentración de calcio en el tubérculo. Las recomendaciones para la aplicación de calcio, encontradas en las guías de producción de papa, no son necesariamente hechas de acuerdo a las necesidades nutricionales de los tubérculos. En general, para la producción de papa, la aplicación de calcio es recomendable solamente si el calcio con naturaleza química intercambiable presente en el suelo antes de plantar, es menor de 300 mg kg^{-1}. Se llevaron a cabo estudios en dos tipos de suelo, arenoso (Hancock) y sedimentario (Antigo). El análisis del suelo arenoso antes de plantar arrojó un valor de 285 mg kg^{-1} y, el suelo sedimentario de 530–1,340 mg kg^{-1} de calcio intercambiable. Cinco variedades fueron cultivadas con y sin la aplicación de 168 kg ha^{-1} de calcio durante su período de crecimiento. En Hancock, 30 ensayos diferentes se realizaron entre los años 1999–2006, mientras que en Antigo, 15 ensayos diferentes se realizaron

C. C. Gunter
Department of Horticultural Science,
North Carolina State University,
230 Kilgore Hall, P.O. Box 7609, Raleigh, NC 27695-7609, USA
e-mail: chris_gunter@ncsu.edu

J. P. Palta (✉)
Department of Horticulture, University of Wisconsin-Madison,
1575 Linden Drive,
Madison, WI 53706, USA
e-mail: ppalta@wisc.edu

entre los años 1995–1998. La concentración de calcio del tubérculo se incrementó en 38 de los 45 ensayos que se llevaron a cabo en los dos sitios. Este incremento en el contenido de calcio en el tubérculo fue variable entre los cultivares y los años, pero no tuvo ninguna relación con el contenido de calcio del suelo. Este incremento ocurrió aún cuando el análisis del contenido de calcio intercambiable, en el suelo antes de plantar, arrojó valores por encima de los 1,000 mg kg^{-1}. Estos resultados sugieren que los niveles de calcio intercambiable del suelo no son un buen indicador de las necesidades de calcio del tubérculo.

Keywords Fertility · Nutrition · Tuber quality · Internal defects · Bruising incidence · Hollow heart · Internal brown spot · Brown center

Abbreviations

Ca Calcium

Introduction

The role of Ca in plant structure and function is well documented (Clarkson and Hanson 1980; Marschner 1995; Palta 1996; White and Broadley 2003; Hirschi 2004). It is a non-toxic mineral nutrient and plant cells can tolerate very high concentrations of extracellular Ca (Palta and Lee-Stadelmann 1983). Ca contributes to the maintenance of cell membrane and cell wall structure by forming stable but reversible linkages between the polar head groups and in pectic acid fractions in the cell wall (Marschner 1995; Palta 1996).

A constant supply of Ca in the extracellular environment is also considered necessary for cell health. Ca in the extra cellular solution helps to maintain the selective permeability of the plasma membranes (Hanson 1984; Palta 1996; Hirschi 2004). This is accomplished, in part, by the bridging effect of divalent Ca ions on the phosphate and carboxylate groups of the phospholipid head groups at the membrane surface (Legge et al. 1982). Furthermore, it has been noted that the presence of Ca in the extracellular solution tends to increase the bonds between the cell wall and the outer face of the plasma membrane (Gomez-Lepe et al. 1979).

In potato (*Solanum tuberosum* L.) production, Ca in the soil is generally considered to be sufficient. Although commercial potato production guides recognize that Ca is essential for plant growth, most of these guides state that Ca is usually present in adequate amounts in calcareous and/or alkaline soils as well as in irrigation waters to supply plant demand (Stark and Westermann 2003). Others state that Ca is seldom a limiting factor in plant growth under field conditions (Lang et al. 1999). Potato production guides occasionally make recommendations for supplemental Ca based on measured exchangeable Ca concentrations. For example, in Idaho, if the exchangeable soil Ca concentration is less than 300 mg kg^{-1} a preplant application of 224 kg ha^{-1} of Ca is recommended (Stark and Westermann 2003). Similarly, in Wisconsin application of Ca has been found to improve potato yield and/or grade only in soils with a preplant Ca concentration less than 350 mg kg^{-1} (Simmons and Kelling 1987). In addition it has been recognized that to maintain Ca availability in the zone of tuber formation, the solubility and potential leaching of Ca fertilizers needs to be considered (Pan and Hiller 1992), which preplant fertilizer recommendations do not seem to take into account. However, all of these recommendations are for plant top growth and are not necessarily geared towards the tuber's unique nutritional needs or demands.

Potato tubers are generally considered a Ca deficient plant organ (Palta 1996). Ca moves with water in the xylem which means transpiration is the main driving force for Ca transport (Clarkson 1984). Being surrounded by moist soil, potato tubers have a very low transpiration rate compared with above ground plant parts, thus accumulating much less Ca per unit fresh weight than leaves (Palta 1996). Botanically, the potato tuber is a stem (Harris 1992), but Ca concentrations in aerial stems are typically two to four times greater than tuber flesh Ca concentrations (Cao and Tibbitts 1993). With this in mind, we can think of storage organs, like potato tubers, as naturally deficient in Ca (Palta 1996).

Localized deficiency in Ca has been associated with tissue necrosis such as brown center and internal brown spot (Bangerth 1979; Collier et al. 1980; Levitt 1942). Potato tubers can compensate for some of this Ca deficiency by uptake of Ca from the soil solution via roots on stolons and tubers (Kratzke and Palta 1985; Marschner 1995; Busse and Palta 2006). The discovery of the existence of functional roots on potato tubers (Kratzke and Palta 1985) led to a major breakthrough in the understanding of Ca nutrition of the potato tuber. These roots were shown to supply water (and thus Ca) to the tuber (Kratzke and Palta 1985). From these studies, Kratzke and Palta (1986) suggested that to enhance tuber Ca uptake the timing (when the tuber is developing and bulking) and placement (in the hill where tubers develop) of Ca fertilizer is critical. In support of this concept, it has been found that maximum increases in tuber Ca occur when Ca was mixed in to the soil where tubers were developing (Simmons and Kelling 1987; Simmons et al. 1988; Kratzke and Palta 1986).

Several studies have recently documented that in-season Ca application in Wisconsin soils can increase tuber Ca concentration and reduce internal defects such as internal brown spot and hollow heart (Kleinhenz et al. 1999; Ozgen et al. 2006) and black spot bruise incidence (Karlsson et al. 2006). This response of in-season Ca application has been found in soils that otherwise contain soil exchangeable Ca over 300 mg kg^{-1}, which is generally considered sufficient for potato production. These recommendations, as noted earlier, are for the above ground plant growth. Similarly, improvement in tuber quality by in-season application has been reported in sandy loam soils in Oregon (Clough 1994) and fine sandy soils in Florida (Locascio et al. 1992).

Over the last 10 years we have evaluated the response of various potato cultivars to in-season Ca application. These studies were conducted in central Wisconsin (commercial potato production area) and northern Wisconsin (potato seed production area). The soils in these two areas are loamy sand and silt loam, respectively, and the soil at our experimental sites tested at 285 to 563 and 530 to 1,340 mg kg^{-1} of exchangeable Ca, respectively. In spite of these high soil test values, we have been able to increase the tuber Ca concentration and reduce tuber internal defects as well as reduce black spot bruising by in-season application of 168 kg ha^{-1} Ca during the tuber bulking period (Kleinhenz et al. 1999; Ozgen et al. 2006; Karlsson et al. 2006). The objective of the present study was to determine the relationship between exchangeable soil Ca and tuber Ca, with and without in-season Ca fertilization.

Materials and Methods

In Antigo (silt loam soil type, Typic Glossoboralf), experimental plots were established in commercial seed production fields in Langlade County and in commercial production fields in Washara County at Hancock, Wisconsin (Plainfield loamy sand, Typic Udipsamment). Soil test and harvest information specific to the year, fields and cultivars used in the study are listed in Table 1. The cation exchange capacities for the Antigo soils were 15 to 20 meq·100 g^{-1} soil and the soil at the Hancock location had cation exchange capacities of 1 to 7 meq·100 g^{-1} (Hole 1976). Varieties in Antigo were planted in separate fields and potatoes were preceded in crop rotation by clover in all study years. All cultivars at Hancock were planted together in the same field and potatoes were preceded in crop rotation by either alfalfa or cucumber. Pre-plant ammonium acetate extractable Ca levels in these fields ranged from 530 to 1,340 mg kg^{-1} (silt loam, Antigo location) and 285 to 563 mg kg^{-1} (loamy sand, Hancock location). The experimental design used was a completely randomized design with between five and eight replications or a completely randomized block design with between five and ten replications depending on the location and year. Plots were 3.3 m long single rows and each contained ten to 14 plants, depending on the cultivar, at the Antigo site. Plant number per plot varied due to within row spacing for each cultivar. Whereas at Hancock each experimental plot consisted of four rows 6.6 m long and the middle two rows were used as the experimental rows. Each row contained 20 plants at this site. Cultivars used in the Hancock trials were Atlantic, Snowden, Russet Burbank, Superior, and Dark Red Norland. And in Antigo, the cultivars used were Atlantic, Snowden, Superior, and Dark Red Norland.

Ca was applied in three equal split dosages starting at hilling with a total Ca application of 168 kg ha^{-1} for the season. Control plots received no in-season Ca. All plots received equal amounts of nitrogen with a season total of

Table 1 Soil test information for Hancock and Antigo sites

Preplant soil test	Location				
	Hancock	Antigo			
		Variety			
	All varieties	Atlantic	Dark Red Norland	Superior	Snowden
pH (in water)	5.9 to 7.0	5.5 to 6.2	5.4 to 5.9	5.2 to 6.1	5.7 to 5.9
Organic matter (%)	0.4 to 0.8	2.5 to 3.0	2.1 to 2.5	2.8 to 3.2	2.4 to 2.5
P (mg kg^{-1})	105 to 135	106 to 193	151 to 200	32 to 78	129 to 166
K (mg kg^{-1})	134 to 140	123 to 226	160 to 240	157 to 168	168 to 226
Ca (mg kg^{-1})	285 to 563	820 to 1,070	530 to 900	900 to 1,340	580 to 900

All fields used for tuber production were Antigo Silt Loam (Typic Glossoboralf) at Antigo location, and Plainfield sandy loamy (Typic Udipsamment) with at the Hancock location. All varieties (Atlantic, Dark Red Norland Russet Burbank, Snowden and Superior) at Hancock were planted in the same field together during a season. Hancock pre-plant K application was made with 0N–0P_2O_5–60K_2O at a rate of 134–140 kg ha^{-1} and Antigo preplant K Application 0N–0P_2O_5–50K_2O at a rate of 280 kg ha^{-1}. Starter fertilizer application at Hancock was made with 5N–10P_2O_5–30K_2O at a rate of 34N–67P_2O_5–202K_2O kg ha^{-1}.

224 kg ha^{-1}. All other chemical inputs and cultural practices were consistent with local production practices and were uniform for all plots within a cultivar field.

At the Antigo site the source of Ca was liquid Ca nitrate (9N-0P-0K-11Ca) (Yara North America Inc. Tampa, FL). All treatments were applied in the liquid form by mixing either the liquid Ca nitrate or granular ammonium nitrate in a watering can with 6 L of irrigation water per plot (3.3 m row). The resulting solution was then applied evenly to the top of the hill over the entire length of the experimental plot. Three split Ca applications of 56 kg ha^{-1} at hilling, 3 and 6 weeks after hilling were made. At the Hancock site the source of Ca was a mixture of Ca nitrate, urea and Ca chloride. In this mixture about 50% of the N was from Ca nitrate. Just like at the Antigo site, treatments were applied in the liquid form by mixing the chemicals in two watering cans with 6 L of irrigation water per can. A total of 12 L of mixed solution was applied to the top of the hill over the entire length of the plot (6.6 m per row). The control plots received split doses of nitrogen using the method described above. Both sources of Ca (calcium nitrate, and a mixture of calcium chloride and calcium nitrate) have been found to be effective in increasing tuber Ca concentration and improving tuber internal quality (Ozgen et al. 2006; Kleinhenz et al. 1999; Karlsson et al. 2006).

Harvest was completed after chemical vine desiccation according to cultivar maturity and commercial production schedule for all cultivars. At the Antigo site all tubers were removed by hand from each experimental row, placed in nylon mesh bags and stored in a cold room maintained at about 3°C, 80% relative humidity until evaluation. At the Hancock site all plots were machine harvested with a single-row Gallenberg harvester (Gallenberg Equipment, Inc., Antigo, WI). The tubers were washed, machine graded and tubers of 170 to 284 g were used for tuber Ca analysis.

For Ca analysis, tubers were washed with deionized water to remove any remaining soil and a longitudinal slice 5 to 10 mm thick was taken from the middle of each tuber. Each slice was trimmed to remove the tissue external to and including the cortical tissue ring. Trimmed slices were then diced, dried in a forced air oven, ground to pass a #40 mesh screen (0.42 mm opening size), and ashed in a muffle furnace at 500°C for 6 h. Individual tuber samples were prepared for atomic absorption measurements by digesting the ash with 2 N HCl and then brought to a standard volume with lanthanum chloride solution. The Ca concentration of each tuber sample was read using an atomic absorption flame spectrophotometer (Varian model Spectra AA20, Walnut Creek, CA). Details of this procedure are described by Kratzke and Palta (1986). Depending on the year, ten to 30 tubers per replication were used for Ca analysis for each treatment. Thus, each tuber calcium value reported in this study represents a composite sample of ten to 30 tubers obtained from a given plot.

Results and Discussion

At Hancock the soil pre-plant soil exchangeable Ca varied between 285 to 563 mg kg^{-1} for the years 1996 to 2006 (Tables 1 and 2). At this location, for the five cultivars during these years, a total of 30 separate trials were conducted on the response of tuber tissue Ca concentration to in-season Ca fertilization (Table 2). Of these 30 trials, tuber tissue Ca concentrations was significantly increased by in-season application of 168 kg ha^{-1} Ca in 25 trials (Table 2). In addition to Ca concentration, tubers from these trials were evaluated for hollow heart, internal brown spot and black spot bruise. The results from these evaluations were reported by Ozgen et al. (2006) and Karlsson et al. (2006). With an increase in tuber calcium concentration, a reduction in the incidences of these tuber defects was found Ozgen et al. 2006; Karlsson et al. 2006). Pre-plant soil exchangeable Ca at Hancock varied between 285–563 mg kg^{-1} (Table 2). As mentioned in the introduction, Ca application in potato production is recommended only when pre-plant exchangeable Ca is less than 300 mg kg^{-1} (Stark and Westermann 2003). Even though exchangeable soil Ca in a number of the trials at Hancock was over 300 mg kg^{-1}, tuber quality was improved with the addition of 168 kg ha^{-1} Ca at this location (Ozgen et al. 2006; Karlsson et al. 2006).

At the Antigo location, 15 trials were conducted during the four seasons (Table 2). At his site, the results were similar to the results obtained at the Hancock location (Table 2). Soil at Antigo is silt loam with much higher organic matter (2.5% to 3.0%) and cation exchange capacity (15 to 20 meq·100 g^{-1} soil) than the soil at the Hancock location (Table 1). In spite of twice the exchangeable Ca present in Antigo soil, there was a significant increase in tuber Ca concentration in 13 of the total 15 trials at this location (Table 2). For example, trials with cultivar Superior at Antigo were conducted in soil that tested at 900–1,340 mg kg^{-1} of pre-plant exchangeable Ca (Table 1). In all of these four trials, a significant increase in tuber Ca concentration resulted from in-season Ca application (Table 2). Specifically, for the year 1995, there was an increase of tuber Ca concentration from 168.5 to 202.7 mg kg^{-1} dry weight when the soil tested at 1,340 mg kg^{-1} exchangeable Ca (Table 2). This is remarkable since in-season application of only 168 kg ha^{-1} was made to this silt loam soil which tested over 1,000 mg kg^{-1} of exchangeable Ca.

In order to further explore any possible relationship between preplant soil exchangeable Ca and tuber Ca concentration, data in Table 2 were used to construct scatter

Table 2 Preplant soil test for exchangeable Ca and tuber internal tissue calcium concentration following harvest for 2 locations, Antigo and Hancock, WI for the years 1995 to 2006

Year	Location	Cultivar	Preplant soil exchangeable Ca (mg kg^{-1})	Internal tuber tissue Ca (mg kg^{-1} dry weight)		Increase in tuber Ca by in-season Ca application %
				Control	Ca treated	
1995	Antigo	Atlantic	1,070	101.7 b	122.3 a	20.3*
1996	Antigo	Atlantic	820	235.3 b	249.5 a	6.0*
1997	Antigo	Atlantic	910	109.2 a	116.3 a	6.5
1998	Antigo	Atlantic	900	185.7 a	200.9 a	8.2
1995	Antigo	Dark Red Norland	770	128.2 b	156.3 a	21.9*
1996	Antigo	Dark Red Norland	870	187.3 b	199.1 a	6.3*
1997	Antigo	Dark Red Norland	530	98.2 b	130.1 a	32.5*
1998	Antigo	Dark Red Norland	900	124.8 b	152.1 a	21.9*
1996	Antigo	Snowden	820	221.5 b	246.6 a	11.3*
1997	Antigo	Snowden	580	179.6 b	203.8 a	13.5*
1998	Antigo	Snowden	900	196.3 b	216.7 a	10.4*
1995	Antigo	Superior	1,340	168.5 b	202.7 a	20.3*
1996	Antigo	Superior	1,070	303.9 b	323.9 a	6.6*
1997	Antigo	Superior	970	172.9 b	201.5 a	16.5*
1998	Antigo	Superior	900	182.5 b	217.9 a	19.4*
1999	Hancock	Atlantic	380	119.2 b	142.9 a	19.9*
2000	Hancock	Atlantic	285	131.6 b	160.5 a	22.0*
2001	Hancock	Atlantic	400	143.6 b	176.9 a	23.2*
2003	Hancock	Atlantic	520	159.4 a	174.2 a	9.3
2004	Hancock	Atlantic	340	179.2 b	206.0 a	15.0*
2005	Hancock	Atlantic	563	139.3 b	174.7 a	25.4*
2006	Hancock	Atlantic	334	124.6 b	167.2 a	34.2*
1999	Hancock	Dark Red Norland	380	215.3 b	288.7 a	34.1*
2000	Hancock	Dark Red Norland	285	162.4 b	214.0 a	31.8*
2001	Hancock	Dark Red Norland	400	256.3 b	322.7 a	25.9*
2003	Hancock	Dark Red Norland	520	213.8 b	264.6 a	23.8*
1999	Hancock	Snowden	380	137.7 a	153.3 a	11.3
2000	Hancock	Snowden	285	127.7 b	162.1 a	26.9*
2001	Hancock	Snowden	400	151.0 b	190.7 a	26.3*
2003	Hancock	Snowden	520	183.8 a	199.4 a	8.5
2004	Hancock	Snowden	340	185.0 a	206.4 a	11.6
2005	Hancock	Snowden	501	148.3 b	179.9 a	21.3*
2006	Hancock	Snowden	363	140.2 b	185.5 a	32.3*
1999	Hancock	Superior	380	212.0 b	263.3 a	24.2*
2000	Hancock	Superior	285	188.5 b	234.3 a	24.3*
2001	Hancock	Superior	400	295.1 b	338.4 a	14.7*
2003	Hancock	Superior	520	228.8 b	250.1 a	10.9*
1997	Hancock	Russet Burbank	380	175.0 b	219.1 a	25.2*
1999	Hancock	Russet Burbank	380	203.3 b	233.4 a	14.8*
2000	Hancock	Russet Burbank	285	178.6 b	223.7 a	25.3*
2001	Hancock	Russet Burbank	400	176.3 b	246.5 a	39.8*
2003	Hancock	Russet Burbank	520	230.7 b	255.9 a	10.9*
2004	Hancock	Russet Burbank	340	200.0 b	242.0 a	21.0*
2005	Hancock	Russet Burbank	354	204.6 b	235.7 a	15.2*
2006	Hancock	Russet Burbank	538	183.3 a	201.3 a	9.8

Calcium treated plots were given 168 kg ha^{-1} of calcium in-season. Values for tuber Ca concentration represent mean of 5–10 replications per treatment. Treatment mean separation (between column) is by LSD. Calcium values having the same letter within a row are not considered statistically different at $p<0.05$.

*$p<0.05$

plots of soil Ca versus tuber Ca concentration. Results are shown in Figs. 1 and 2. No systematic relationship between preplant soil Ca and tuber tissue Ca concentration was found at either Hancock (Fig. 1a) or Antigo (Fig. 2a). This was true for both the in-season Ca treated plots (filled symbols) as well as the untreated control plots (open symbols). However at both of these locations an increase in tuber Ca concentration resulted from the in-season application of Ca (Figs. 1b and 2b). This increase in tuber Ca concentration ranged from 8% to 35% over untreated control tubers at Hancock (Fig. 1b) and 7% to 33% over untreated control tubers at Antigo (Fig. 2b). This increase in tuber Ca concentration varied among cultivars and among seasons at both locations but appears to have no relationship with soil Ca.

Our recent studies have shown that in-season application of Ca can increase tuber Ca concentration and improve tuber quality (Palta 1996; Kleinhenz et al. 1999; Ozgen et al. 2006; Karlsson et al. 2006). Frequently asked questions

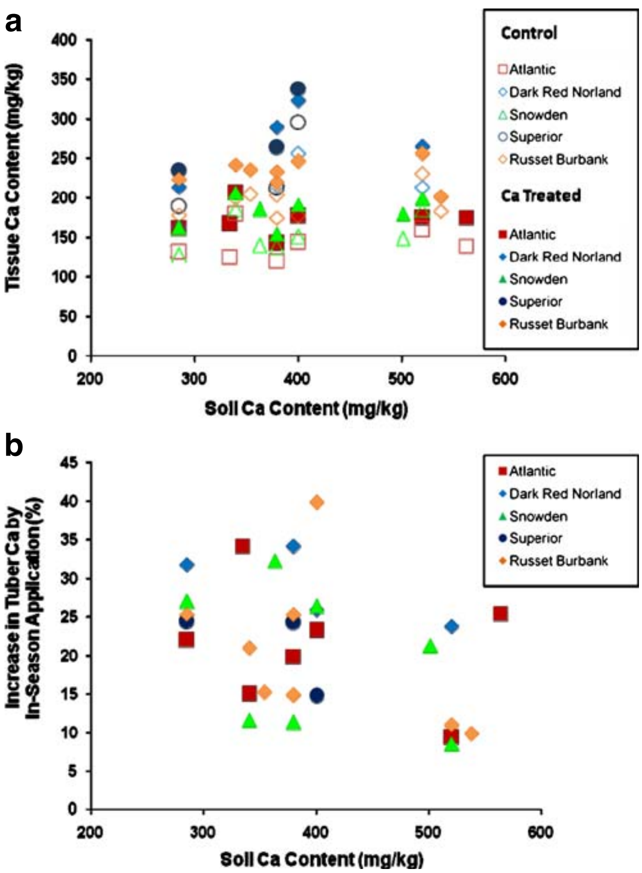

Fig. 1 Tuber tissue calcium concentration (**a**) and increase in tuber calcium concentration by in-season application of 168 kg ha^{-1} Ca (**b**), in relation to pre-plant soil Ca test at the Hancock location. **a** Data presented are average tissue Ca concentration for both control and Ca-treated plots. **b** An increase in tuber calcium concentration resulting from in-season application of calcium

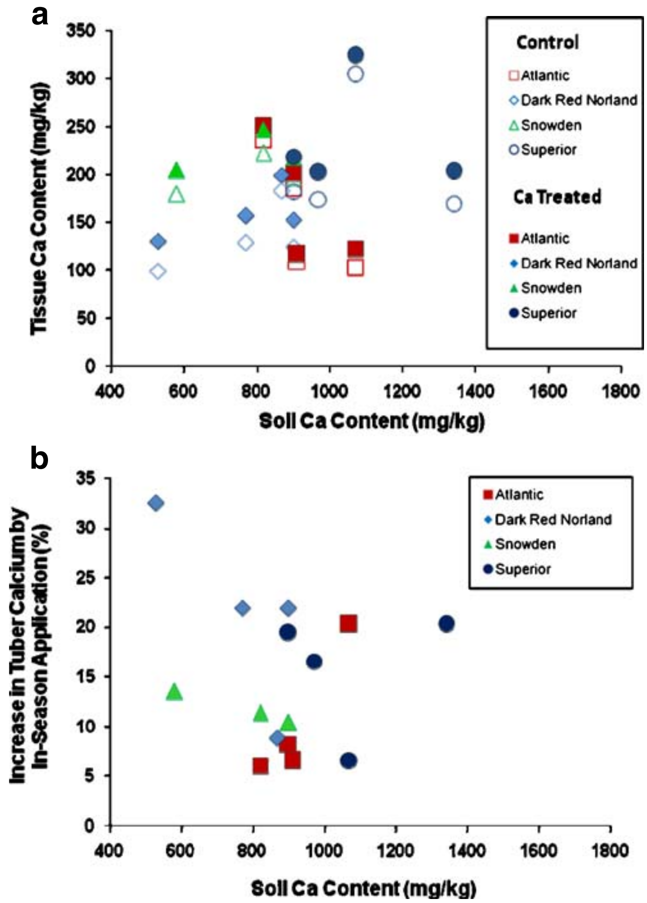

Fig. 2 Tuber tissue calcium concentration (**a**) and increase in tuber calcium concentration by in-season application of 168 kg ha^{-1} Ca (**b**), in relation to pre-plant soil Ca test at the Antigo location. **a** Data presented are average tissue Ca concentration for both control and Ca-treated plots. **b** An increase in tuber calcium concentration resulting from in-season application of calcium

include: when should supplemental Ca be applied and at what soil test Ca level should these applications be made to provide adequate Ca for tuber quality? The results reported in the present study suggest that a preplant test of exchangeable Ca in soil may not provide guidance for Ca fertility recommendation for Wisconsin soils. Potato production guides make recommendations based on soil exchangeable Ca. For example a preplant application of 224 kg ha^{-1} of Ca is recommended if the soil exchangeable Ca is less than 300 mg kg^{-1} (Stark and Westermann 2003). However, this recommendation is for above ground plant growth and not necessarily appropriate for the unique Ca needs of the tuber. Similarly, in Wisconsin application of Ca has been found to improve potato yield and/or grade only in soils with a preplant Ca concentration less than 350 mg kg^{-1} (Simmons and Kelling 1987). Clearly, in our study it was possible to improve tuber Ca concentration in soils that tested over 500 mg kg^{-1} exchangeable Ca (Table 2). Furthermore, as mentioned above, in our studies it was possible to improve tuber quality with a modest (168 kg ha^{-1}) application of in-season Ca (Kleinhenz et al. 1999; Ozgen et al. 2006; Karlsson et al. 2006). In the studies by Simmons and Kelling (1987), Ca was either applied as preplant band in the row (Gypsum) or two equal split sidedress applications (Ca nitrate at emergence and tuber initiation). However, in our studies, water-soluble forms of Ca were applied during the tuber bulking period. Thus, the lack of response to Ca fertilization in high Ca soils reported by Simmons and Kelling (1987) could be due to the difference in timing and source of Ca fertilization.

The reason for the response of tuber Ca to in-season Ca application is because potato tubers are generally deficient in Ca (Palta 1996). The Ca in plants moves with water in the xylem and very little water moves into tubers which are surrounded by moist soil. Furthermore it has been shown that Ca is transported to the tuber by the roots on the tuber as well as on the stolons closely associated with the tuber (Kratzke and Palta 1985 and 1986; Busse and Palta 2006). These studies provided the evidence that tuber Ca concentration can be enhanced by in-season Ca application by placing the Ca in the tuber area during the tuber bulking period even on soils that otherwise tested sufficient for exchangeable Ca. Results of the present study suggest that in our soils exchangeable soil Ca may not reliably predict in-season Ca requirement for enhancing potato tuber Ca concentration and tuber quality. These studies further suggest that an alternative test, yet to be developed, is needed to ascertain tuber Ca needs.

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