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Potassium-magnesium antagonism in high magnesium vineyard soils

Joseph Michael Hannan
Iowa State University

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Joseph Michael Hannan

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Program of Study Committee:
Paul A. Domoto, Major Professor
Gail R. Nonnecke
Thomas E. Loynachan

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ABSTRACT

The Iowa wine and grape industry underwent a rapid phase of growth at the turn of the 21st century that is continuing to evolve and develop today. Cultivar trials across the state found that 'Marquette' grapevines were performing poorly in eastern Iowa while other cultivars performed well. A preliminary investigation suggested a magnesium induced potassium deficiency and/or above optimum soil pH as the cause of poor growth of 'Marquette'. Soils in the upper Mississippi Valley are derived from limestone and dolomite bedrock resulting in their characteristically high pH and high magnesium properties, which often inhibits potassium uptake. Recommendations to amend these soil types for grape production do not exist but are essential for optimizing grapevine yield. This study was undertaken to determine how to amend vineyard soils with a low potassium/magnesium concentration and above optimum pH. The multi-year pot culture study included two cultivars, Marquette and St. Croix, and four soil amendment treatments. Soil amendment treatments compared all combinations of potassium/magnesium concentration (0.24 and amended to 0.50) and soil pH (7.2 and amended to 6.2) in a two-by-two factorial. Results indicated potassium additions increased the soil potassium/magnesium concentration as well as increased the petiole potassium concentration. Decreasing the pH alone decreased available soil magnesium but had no effect on the potassium/magnesium concentration. This suggests that it is only necessary to add potassium to increase the potassium/magnesium concentration in these soils.

CHAPTER 1

Introduction

The Iowa wine and grape industry has seen a rapid resurgence over the last decade with new vineyards and wineries emerging across the state. In 2003, through a grant from Iowa Department of Agriculture and Land Stewardship (IDALS), four Iowa State University (ISU) research vineyards were established to evaluate 20 wine grape cultivars for suitability and adaptability in Iowa under differing soil and climatic conditions. Vineyards were located at Horticulture Research Station (HORT), Ames, IA; Armstrong Research Farm (ARF), Lewis, IA; Northeast Research Farm (NERF), Nashua, IA; and Southeast Research Farm (SERF), Crawfordsville, IA. Fifteen cultivars evaluated in a grape cultivar by management system trial established in 2002 were included in the NERF and SERF plantings (Domoto et al., 2006; Domoto and Nonnecke, 2006).

Many of the cultivars in these trials were developed through breeding programs at Cornell University, the University of Minnesota, and by the late Elmer Swenson, a private breeder from Osceola, Wisconsin (Smiley et al., 2008). Cultivars such as Frontenac from Minnesota and St. Croix from Wisconsin were generally thriving at all four vineyards across the state except for the Minnesota cultivar, Marquette (tested as MN 1211) (Domoto et al., 2006; Domoto and Nonnecke, 2006). It grew and produced well at HORT, moderately well at ARF, but poorly at SERF and NERF (Fig. 1, 2). Soil and petiole analyses conducted in 2006 suggested an above optimum soil pH and/or a K-Mg interaction as possible causes for the poor performance of ‘Marquette’ at NERF and SERF.

Literature Review

Iowa soils developed over millions of years with most of this time as sea floor (Anderson, 1998). The earliest rock was formed during the Precambrian period and is largely comprised of granite, gneiss, quartzite, and other silicate-based minerals. Very little of this oldest rock is visually observable from the surface in Iowa. Younger bedrock formed 325 to 545 million years ago under water primarily by limestone and dolomite marine sedimentation. Except for Eastern Iowa, most of Iowa's soils have a deep layer of glacial till and/or loess covering this bedrock (Anderson and Langel, 2003). The last glaciation in Eastern Iowa left a thin layer of till and ground bedrock; however, most of the till eroded away leaving a thin soil based on underlying carbonate and dolomite bedrock. This bedrock is the primary influence for Mississippi Valley soils, giving them their characteristic high concentration of Ca and Mg (Anderson 1998).

Antagonism

Not all nutrient deficiencies are caused by insufficient nutrient availability (Grunes et al., 1968; Johansson and Hahlin, 1977; Omar and Kobbia, 1966; Prince et al., 1947). Antagonism, defined as the interactions between ions of similar size and valence, is often the cause for nutrient deficiencies because cellular binding sites cannot distinguish the difference between these ions (Marschner, 1995). The soil concentration difference influences the rate of absorption by the plant such that a greater availability of one competing ion will have a greater probability for absorption than other competing ions. Therefore the rate of absorption of competing ions is reduced (Cain, 1954; Sabet and Salem, 1966). The relationship between

K, Mg, and Ca has been studied across a wide variety of crops including *Dendranthema* x *grandiflorum* (Branson et al., 1968), *Gossypium* spp. (Pettiet, 1988), *Solanum lycopersicum* (Hartz et al., 1999; Kabu and Toop, 1970; Ward and Miller, 1969), *Spinacia oleracea* (Hohlt and Maynard, 1966), *Triticum aestivum* (Ohno and Grunes, 1985), and *Zea mays* (Bertic et al., 1989; Foy and Barber, 1958; Pathak and Kalra, 1971), and is a challenge in vineyards throughout the U.S. (Boynton, 1945; Cain, 1954).

Research has shown that an available soil K/Mg imbalance can be corrected by increasing the concentration of the deficient nutrient (Bertic et al., 1989; Pathak and Kalra, 1971; Pettiet, 1988; Rosen and Carlson, 1984; Tewari et al., 1971). Cain (1954) showed an increase in plant Mg and Ca when apples were grown in low K media. Pettiet (1988) reported that additions of K on cotton (*Gossypium* spp.) in soils with high available Mg and sufficient available K gave a positive growth response. He also noted that high K fertility in soils low in available Mg reduced Mg uptake in plants. Furthermore, Boynton (1945) from New York, working with *Vitis* spp. (grapes), which had deficient K and excessive Mg tissue content, also showed adding K to the soil increased plant K. He observed that grape leaves with a K/Mg concentration of 0.33 were severely scorched and dying while leaves with a concentration of 1.0 were only slightly scorched. Similar findings in other crops have been reported (Johansson and Hahlin, 1977; Kabu and Toop, 1970).

Soil pH

The rate of K uptake is also influenced by soil pH, which further aggravates K-Mg antagonism in high pH soils (Brady and Weil, 1999; Epstein and Bloom, 2005). Liming will increase soil K fixation in very acidic soils (pH 2.0 – 5.5) by releasing tightly held H^+ ions from colloidal surfaces. As H^+ ions are released, K^+ ions move closer to colloidal surfaces, which increase the probability of release into soil solution (Brady and Weil, 1999). Liming also increases the cation exchange capacity (CEC) in soils where the negative charge is pH dependent. As the CEC increases, available soil K decreases by adsorbing to soil colloids. In slightly acidic to basic soils, additions of Ca and Mg from liming may also have a negative effect on K uptake by increasing competition at exchange sites. This problem is especially prevalent in calcareous soils where K availability is limited by high pH and high concentrations of Ca and Mg (Brady and Weil, 1999; Marschner 1995).

Cultivars

Vitis spp. ‘Marquette’ is a cold hardy, interspecific hybrid, red wine grape released from the University of Minnesota breeding program in 2006 (Hemstad and Luby, 2005). This hybrid has a complex heritage that includes ‘Pinot noir’ (*Vitis vinifera*) and *V. riparia* (Marquette Grape. University of Minnesota Cold Hardy Grapes; National Grape Registry). It can tolerate winter temperatures to -38° C and blooms moderately early (Marquette Grape. University of Minnesota Cold Hardy Grapes; Smiley et al., 2008). It has a clean, open canopy and has resistance to mildews and black rot (Hemstad and Luby, 2005). ‘Marquette’ has grown poorly at SERF and NERF but grew moderately well at ARF and well at HORT (Domoto et al., 2006).

Vitis spp. ‘St. Croix’, released in 1982 by Elmer Swenson, is a cold hardy, interspecific hybrid, red wine grape with a strong *V. labrusca* and *V. riparia* background (National Grape Registry; Swenson, 1982). It has a vigorous growth habit and is prone to multiple bud breaks, which require shoot thinning and lateral removal (Dami et al., 2005; Smiley et al., 2008). It is moderately susceptible to bunch rots and both downy and powdery mildews (Bordelon et al., 2008; Dami et al., 2005; Reisch et al., 2000; Smiley et al., 2008).

'St. Croix' can tolerate winter temperatures to -29° C or lower (Plocher and Parke, 2001; Smiley et al., 2008; Swenson, 1982). Unlike 'Marquette', it has performed well at all four ISU research vineyards (Domoto et al., 2006; Domoto and Nonnecke, 2006).

Preliminary Results

In 2006, at each of the four research vineyards across the state, soil and petiole samples were collected and analyzed at ISU Soil and Plant Analysis Laboratory (Table 1). Soil samples were collected at each site from 0-15 cm and 15-30 cm centered between rows. Each site represented different soil and climatic conditions; however, results showed "adequate" (> 125 $mg\cdot kg^{-1}$) to "high" concentration of available K and "very high" (> 150 $mg\cdot kg^{-1}$) concentration of available Mg at each site as classified by Rosen and Eliason (1996). There was a low and very low available K/Mg concentration at NERF and SERF, respectively, due to excessive available Mg.

Petiole samples collected in Aug. 2006 (Table 1) show "low" K (< 1.5%) and "excessive" Mg (> 0.8%) within plants at SERF (Table 1) (Dami et al., 2005). K concentration as well as the K/Mg concentration was lower in 'Marquette' than 'St. Croix' at all locations. SERF had the lowest petiole K/Mg concentration for both 'Marquette' and 'St. Croix'.

Soil pH at ARF, HORT, NERF, and SERF ranged from 6.07 to 6.94 at 0-15 cm and 5.87 to 6.82 at 15-30 cm (Table 1). Soils at NERF and SERF were above the recommended pH (6.0 to 6.5) guidelines while soils at HORT and ARF were within the recommended guidelines. Results of soil tests performed by the ISU Soil and Plant Analysis Laboratory on prospective and existing Iowa vineyard soils have shown available Mg concentrations ranging from as low as 100 $mg \cdot kg^{-1}$ to as high as 800 $mg \cdot kg^{-1}$ with a median of 380 $mg \cdot kg^{-1}$ and pH ranging from 5.00 to greater than 8.00 (well below to well above the recommended range) with a median of 6.60 at 0-15 cm depth indicating that this is a widespread problem (Domoto, unpublished data).

Objectives

Soils in the upper Mississippi river valley are derived from dolomite and typically have a pH above the recommended 6.5 for vineyards and extremely high concentration of available Mg. There are currently no guidelines in Iowa or the Midwest to amend soils with above optimum pH and low K/Mg concentration yet soil amendment guidelines are essential to optimize yield. The objectives of this project were to determine 1) if poor growth of 'Marquette' at SERF was due to above optimum soil pH and/or a Mg-induced K deficiency, and 2) if improved growth of 'Marquette' could be obtained by decreasing soil pH and/or increasing the soil K/Mg concentration.

Hypothesis

I hypothesize 'Marquette' grapevines do not tolerate soils with pH greater than the recommended guidelines of 6.0 to 6.5 and that 'Marquette' grapevines are susceptible to Mg-induced K deficiency on high Mg soils.

Materials and Methods

This was a multi-year pot culture study conducted from 2008 – 10 at Muscatine Island Research Farm (MIRF), Fruitland, IA (lat. 41° 21' 22" N, long. 91° 08' 13.4" W). Source soil collected from SERF, Crawfordsville, IA, (lat. 41° 12' 13.7" N, long. 91° 29' 10.0" W) in July 2008 was a Mahaska silty clay loam Mesic Aquertic Argiudoll soil that was cropped in wheat in 2007 (Table 2). Soil test results showed an available K/Mg concentration of 0.24 and a pH of 7.2. This soil had small amounts of free dolomitic limestone that needed to be neutralized in sulfur amendment treatments. After collection, soil was dried, separated into blocks, and blocks were thoroughly mixed to ensure uniformity.

Vineyard layout

A temporary trellis was constructed with three rows, 1.8 m apart, with wires located 0.9 and 1.8 m above the soil surface in a Fruitfield coarse sand. Sixteen containers (Nursery Supplies model C-2800, 23 L container with drainage holes, 35.6 cm dia. x 29.2 cm, BFG Supply Co, 27804 Fairground Rd., Adel, IA) per row were spaced 1.5 meters apart and buried to 2.5 cm from container lip in the field. A second container with soil amendment treatment was then placed into the previously buried field container forming a pot-in-pot (PIP) setup. Each PIP represented one soil amendment x cultivar treatment. Sand between containers ensured continuous soil contact from the inner container through the outer container to field soil for drainage. PIPs were used to deter grapevine roots from growing outside of the amended soil media and taking up additional nutrients from field soil. They were grouped so that each ½ row was arranged in a randomized complete block design

(RCBD) so that there were two blocks per row.

Soil amendment treatments

Soil amendment treatments compared all combinations of soil pH (7.2 and amended to 6.2) and available K/Mg concentration (0.24 and amended to 0.50) and in a two-by-two factorial for each cultivar. Soil amendment treatments were 1) control: no amendments added (pH 7.2, K/Mg concentration 0.24); 2) S only (pH 6.2, K/Mg concentration 0.24); 3) K only (pH 7.2, K/Mg concentration 0.50); and 4) S+K (pH 6.2, K/Mg concentration 0.50). In August 2008, powdered elemental S was added to all S treatments at a rate of 1.39 g S / 19 L soil (98.3 $kg{\cdot}ha^{-1}$) while KCl was added to all K treatments at a rate of 3.04 g K / 19 L soil (334 $kg{\cdot}ha^{-1}$). Soil amendment treatments were combined with dry soil, mixed in a plastic drum, and placed into an empty Nursery Supplies model C-2800 container. Containers were inserted into buried field liner to form a PIP and were rested from Aug. 2008 to 30 Apr. 2009 to allow time for bacterial conversion of elemental S to SO_4^- required for soil pH reduction.

Plant materials

One-year-old cuttings of ‘Marquette’ and ‘St. Croix’ grapevines were collected from HORT in Spring 2008 and were rooted at MIRF in a Fruitfield coarse sand mixed Mesic Entic Hapludoll. Plants were mulched with straw through winter. On 30 Apr. 2009, plants were dug, graded by bud damage so that selected plants had > 75% alive primary buds, grouped according to weight so that plants in each block were the same weight (± 1g), and transplanted into soil amendment treatments.

Vineyard management

Plants were grown using best management practices (Bordelon et al., 2008) with the exception that weeds inside pots were hand-pulled to reduce the amount of nutrients removed from each treatment. An automatic drip irrigation system maintained tensiometer readings of 10 – 50 centibars. Three Watermark 30 KTCD Soil Moisture Meters with temperature compensation (Irrometer Company, Inc. Riverside, CA) were used to calculate soil moisture. Vines were trained to a fan system and tied to trellis wires as needed. Each PIP was fertilized with 16.8 g nitrogen (as 32% ammonium nitrate) in 2009 and 2010. Nitrogen was applied weekly in four equal split applications in July of each year. Each fall after canes hardened off, the base of each plant was straw mulched. Snow cover held the straw on the ground and provided extra protection. Mulch was removed in early spring each year at bud swell and used as a weed barrier between rows.

Data collection

In Aug. 2009 and 2010, five and seven soil cores, respectively, with diameter of 1.9 cm were taken to depth (29.2 cm) of container from each soil amendment treatment. For each plot, cores were oven-dried, ground, and sent to A&L Analytical Laboratories, Inc. (2790 Whitten Road Memphis, TN 38133). Samples were analyzed for pH, K, Mg, and Ca. Soil samples collected August 2009 indicated the pH in all soil amendment treatments and those receiving no soil amendment decreased; however, treatments receiving S decreased more than treatments not receiving S (Table 3). Furthermore, the available K/Mg concentration did not increase to 0.5 as anticipated. Additional S as aluminum sulfate was added to all S soil amendment treatments at a rate of 1.39 g S / 19 L soil (98.3 $kg \cdot ha^{-1}$) and additional K as KCl to all K treatments at a rate of 6.08 g K / 19 L soil (668 $kg \cdot ha^{-1}$) in Nov. 2009. Additional soil amendments were mixed throughout each container with care taken to not disturb existing roots.

Dormant one-year-old canes for each plant were pruned to 20 buds in Mar. 2010.

Prunings were air-dried and weighed. Through Aug. and Sept. 2009, 52 petioles from fully expanded mature leaves were collected from each plot over the duration of four weeks (13 petioles per plot per week) due to low vigor of each plant. To ensure adequate sample volume for analysis, petioles from blocks one, two, and three were combined and petioles from blocks four, five, and six were combined. Through Aug. and Sept. 2010, 250 petioles from fully expanded mature leaves were collected from each plot over the course of four weeks. Unlike 2009, all petioles from a block were collected on the same day in 2010 such that blocks one and two were collected in the first week; block three in the second week; blocks four and five in the third week; and block six in the fourth week. With adequate sample material available for analysis, blocks were not combined in 2010. Each year, samples were oven-dried, ground, and sent to A&L Analytical Laboratories, Inc. for analysis. Foliar analysis for both years included K, Mg, Ca, Zn, Mn, Fe, Cu, B, and Al. After petiole samples were collected in Sept. 2010, canes were removed, dried, and weighed. Trunks and roots were then removed from containers, gently washed to remove all traces of soil, air-dried, and weighed.

Experimental design and analysis

Plot design was a randomized complete block with six replications of four soil amendment treatments x two cultivars over two years. Treatment variables were analyzed using the PROC GLM procedure in SAS software, (Version 9.2 SAS Institute Inc., Cary, NC) for multiple comparisons of least significant differences tests among treatments. Soil samples of similar treatments were pooled for each block.

Results

Weather

The 2009 and 2010 growing seasons were cooler and wetter than normal; they were the third and second wettest, respectively, on record at MIRF (Lawson, 2010 and 2011). On 18 Apr. 2010, a low of 2.3° C (measured at 1.2 m above the soil surface at an on-site weather station) for approximately 3 hours resulted in death of all buds between growth stages scale crack and bud burst. However, no dormant or expanded shoots were injured.

Soil samples

Soil samples collected from each plot in Aug. 2009 show soil pH decreased in all soil amendment treatments and control (Table 3). There was no significant change in soil pH from 2009 to 2010 across all treatments. Additional K applied Nov. 2009 did not change the available soil K concentration in 2010; however, there was more available K in soil amendment treatments receiving K than treatments receiving no K for both years. Available Mg decreased in S treatments from 2009 to 2010 and there was less available Mg in S treatments than the control in both years. Available Ca decreased in all treatments from 2009 to 2010. The available K/Mg concentration was greater in soil amendment treatments receiving K than treatments receiving S only or no treatments each year.

Plant growth

Spring pruning weight from 2009 vegetative growth was significantly less than 2010 vegetative growth (Table 4). 'Marquette' accumulated more vegetative growth in 2010 than 'St. Croix'. Within cultivars, additions of K and S alone or in combination did not affect the 2010 spring pruning weight, vegetative, root and trunk, or total dry weight (Table 4).

Petiole samples

In 2009, across all treatments, 'St. Croix' grapevines accumulated more petiole K than 'Marquette' (Table 5). However, in 2010 only 'St. Croix' vines treated with K accumulated more petiole K than 'Marquette'. In 2010, all 'Marquette' and 'St. Croix' vines treated with K accumulated more petiole K than those treated with S only or no soil amendments. There was a decrease in petiole K accumulation across all treatments from 2009 to 2010.

In 2009, across all treatments, except for vines treated with S alone, 'St. Croix' accumulated more petiole Mg than 'Marquette' (Table 5). In 2009 there was no difference in Mg accumulation between treatments for 'St. Croix'; however, in 2010, 'St. Croix' vines treated with K accumulated less petiole Mg than those receiving S alone or no soil amendment treatment. In 2010 all 'Marquette' vines receiving a soil amendment treatment accumulated less petiole Mg than vines receiving no soil amendment.

There was a decrease in petiole Ca accumulation across all treatments from 2009 to 2010 (Table 5). In 2009 and 2010, there was no difference in petiole Ca between treatments for 'St. Croix'. 'Marquette' petioles treated with only S accumulated more petiole Ca than the control in 2009, but in 2010 there was no difference between soil amendment treatments and control.

'Marquette' grapevines treated with S accumulated more Zn than vines treated with K only or no soil amendment treatment in 2009 but there was no difference between treatments and control in 2010 (Table 6). 'Marquette' grapevines receiving soil amendment treatments accumulated more Zn in 2009 than in 2010. For 'St. Croix' there was no difference in petiole Zn between treatments or between years.

‘Marquette’ grapevines treated with only S accumulated more Mn in 2009 and 2010 than vines not treated with S (Table 6). There were no differences between years for ‘Marquette’ vines. For ‘St. Croix’ vines, treatments did not affect petiole Mn in 2009 while in 2010, vines treated with S accumulated more Mn than vines receiving no soil amendment treatment. ‘St. Croix’ vines treated with S accumulated more petiole Mn in 2010 than in 2009.

In 2009, ‘Marquette’ vines treated with S alone had a greater concentration of petiole B than the control, but neither treatment was different from vines treated with K (Table 6). Treatments had no effect on petiole B concentration in 2010. For ‘St. Croix’ vines, treatments had no effect on petiole B in 2009. In 2010, vines treated with K alone accumulated less B than vines treated with S alone but was not different from vines treated with S+K or no soil amendment treatments.

Discussion

The upper Mississippi Valley soils are derived from limestone and dolomite bedrock, which gives them their characteristically high pH, low to sufficient available K, and high available Mg concentrations for crop production. These soils will often cause Mg-induced K deficiencies as observed in our preliminary data. ‘Marquette’ appears to be especially sensitive to these soil extremes while ‘St. Croix’ appears to tolerate them. Currently, there are no guidelines for amending these types of soils for wine grape production in the upper Mississippi Valley. A pot culture study with two cultivars, Marquette and St. Croix, and all combinations of two soil amendment treatments was conducted from 2008 – 10 at MIRF to determine how best to amend soils with a low available K/Mg concentration and above optimum pH. It was determined that adding K achieved greatest increase in the available soil K/Mg concentration. Additions of K to the soil increased petiole K in both 'St. Croix' and 'Marquette' grapevines yet fertility recommendations on these types of soils remain difficult.

Applications of K increased the available soil K/Mg concentration in 2009 and were again associated with the greatest K/Mg concentration in 2010. Adding K, assuming it would remain available, to increase the K/Mg concentration to 0.5 only increased it slightly in 2009. Additional K applied Nov. 2009 to soil amendment treatments receiving K did not increase available soil K concentration when tested in 2010. While the addition of K increased available soil K, the addition of S decreased available Mg in 2009. Additional S applied to soil amendment treatments receiving S again decreased available Mg when tested in 2010. While there were no differences in available soil K concentration or the K/Mg concentration between treatments receiving K only or treatments receiving S+K, there was more available Mg in treatments receiving K only than treatments receiving S+K (Table 3). In vineyard soils with above optimum pH and a low available K/Mg concentration, there seemed to be an added benefit of using S to decrease soil pH. Not only did S decrease the soil pH, which typically increases micronutrient availability, it decreased available Mg as previously reported by Williams and Donald (1957). However, a decrease in Mg in S treatments had no effect on the overall available K/Mg concentration nor was the targeted K/Mg concentration obtained in any treatment in 2009 or 2010. Additional soil samples were collected in Sept. 2009 to determine why the desired available K/Mg concentration was not achieved; however, results from a microwave digestion were inconclusive in determining if available K was leached or fixed in soil colloids. K applied in 2008 and 2009 was most likely leached from excessive rainfall (Paul et al., 1998), fixed (Zeng and Brown, 2000), and/or utilized by grapevines (Dami et al., 2005).

Sulfur was added to reduce the soil pH from 7.2 to 6.2 from 2008 to 2009, yet treatments not receiving S also had a reduction in pH from 7.2 to 6.7 from 2008 to 2009 (Table 3). As reported by Paul et al. (1998), this decrease in pH was most likely caused by high rainfall in 2009 leaching cations from the soil. Additional S was applied Nov. 2009 to increase the difference between soil amendment treatments receiving S and treatments receiving no S. However, additional S did not decrease the soil pH from 2009 to 2010 even though there was sufficient time for a chemical change to occur. Again, excessive rainfall during the 2010 season is the most likely possibility for no change in pH from 2009 to 2010 as suggested by Jang and Townsend (2001).

In Iowa, a decrease in soil pH typically corresponds to a decrease in available cations, yet results show an increase in available Ca, Mg, and K from 2008 to 2009 (Tables 2, 3). An increase in available Ca and Mg may have been caused by the dissolution of free dolomitic lime in the source soil. Alternatively, above normal rainfall throughout the growing season, as well as trickle irrigation, maintained the containers at near optimal moisture conditions. Release of K, Ca, and Mg from continuously wet soil clays could have caused an increase in cation availability as shown by Fletcher et al. (1984). Differences in soil moisture, temperature, as well as bulk density, from moving source soil from field to containers, from 2008 to 2009 may also account for the increase in available cations as suggested by Fletcher et al. (1984) and Inoue (1983). Furthermore, the primary clay in Mahaska soil is montmorillonite. Montmorillonite is a 2:1 clay known for releasing and fixing K as soil moisture increases and decreases (Shaulis, 1961; Shaulis and Kimball, 1956). Excessive moisture during the 2009 season would further increase available K by releasing it from the clay structure.

'Marquette' vines grew more vigorously than 'St. Croix' vines as reflected by 2010 vegetative and total weights (Table 3). This was contrary to fruit yield (Fig. 1) and pruning weight data (Fig. 2) collected from HORT, ARF, NERF, and SERF from 2006 – 10. Marquette vines were not more vigorous than St. Croix vines because of low winter temperatures or late spring frosts as both cultivars are capable of equally withstanding minimum winter temperatures encountered as reported by Hemstad and Luby (2005) and Swenson (1982) and both were equally damaged by the 18 Apr. 2010 spring frost. 'St. Croix' roots tend to be slightly less hardy than the rest of the plant (Plocher and Parke, 2001), but soil temperatures (measured at 10 cm below the soil surface at a weather station located on site) in 2009 and 2010 never dropped below -3.9° C. Furthermore, vines were covered with straw mulch and snow providing them with extra layers of protection (Dami et al., 2005). The only nutrient in either year to show a difference between cultivars was Zn (Table 6). In 2010, data show 'St. Croix' Zn uptake was "above normal" while 'Marquette' Zn uptake was "normal" as classified by Rosen and Eliason (1996). As Yang et al. (2011) has shown, excessive total Zn (> 915 $mg \cdot L^{-1}$) can limit grape growth, which may be the cause for greater 'Marquette' vigor in this trial.

Within cultivars, there were no growth differences between soil amendment treatments; however, neither cultivar was under nutrient stress in 2009 (Tables 4, 5, 6). In 2010, grapevines treated with K were "low" in petiole K while grapevines not treated with K were "deficient" in K as classified by Rosen and Eliason (1996). No differences in any growth data suggest that nutrition was not a limiting growth factor in this study.

Results indicated addition of K to soils increased grapevine K, which is consistent with previous findings with grapes (Boynton, 1945) as well as in other crops (Johansson and Hahlin, 1977) (Tables 3, 5). For both ‘St. Croix’ and ‘Marquette’, additions of K to soil were associated with increased grapevine K uptake and decreased Mg uptake in 2010 (Table 5). There were no differences in ‘St. Croix’ macronutrient or micronutrient uptake between the K and S+K soil amendment treatments in 2009 or 2010 (Tables 5, 6). There were also no differences in ‘Marquette’ micronutrient uptake between the S and S+K soil amendment treatments.

In soils with optimal pH and a low available K/Mg concentration, it appears that it is only necessary to add K to increase the K/Mg concentration as results from this study show no significant differences in petiole K, spring pruning weight, vegetative growth, roots and trunks weight, or total weight between soil amendment treatments receiving K only and treatments receiving S+K (Tables 4, 5). Furthermore, there were no significant differences in petiole Zn, Mn, or B between soil amendments receiving K only or treatments receiving S+K either year for both cultivars (Table 6). Results from this study indicate that a Mg-induced K deficiency can occur in soils with an available K/Mg concentration below 0.30. In conjunction with preliminary data, an available soil K/Mg concentration between 0.40 and 0.50 is suggested to avoid a Mg-induced K deficiency.

Unfortunately, increasing available soil K is not a simple task on montmorillonite soils. In somewhat poorly drained soils containing considerable quantities of montmorillonite, the available K, Mg, and Ca concentration can change drastically from year to year depending on soil moisture (Shaulis, 1961; Shaulis and Kimball, 1956) and bulk density (Fletcher et al., 1984) as evidenced in our trial. Because of the ability of montmorillonite to absorb and release K, it has been suggested that a build up of K in these soils is not feasible and that K fertility should be managed on an annual basis (OMAFRA Staff, 2010). This is a practical solution for annual crops where K applications can be tilled into the soil but is much more difficult for perennial crops, particularly in dry years when K will not easily leach into and through the soil profile. Ontario Ministry of Agriculture Food and Rural Affairs recommend annual banded applications of K tilled into the soil on high clay content vineyards to reduce fixation (OMAFRA Staff, 2010). However, tilled vineyard rows are not recommended in the Midwest due to high erosion potential (Dami et al., 2005). In lieu of soil K application, foliar application of K, as potassium nitrate ($KN0_3$) or potassium sulfate (K_2S0_4), has been shown as a viable alternative fertility management tactic in perennial crops experiencing Mg-induced K deficiency (Dami et. al., 2005; Mimoun et al., 2004; Weir, 1998). However, Kasimatis and Christensen (1976) report that grapes do not actively uptake foliar applications of $KN0_3$.

As always, it is suggested to choose a different site or use adapted cultivars when site properties are not ideal. When no alternate site or cultivars are feasible, it is suggested to monitor available soil and petiole K yearly as montmorillonite clays readily fix and release K according to soil conditions. Additional research is required to determine the amount of K removed from the soil yearly by hybrid grapevine prunings and fruit. This information would be beneficial to growers and to individuals making fertility recommendations because yearly applications of K could be applied to the soil to replace what is removed in vine prunings and fruit each year.

We were unable to determine if ‘Marquette’ grapevines tolerate soils with pH greater than the recommended guidelines from this study, due to an observed decrease in soil pH in all treatments. Furthermore, we were unable to discern any differences in grapevine micronutrient concentration between treatments. However, ‘Marquette’ and ‘St. Croix’ seem to be susceptible to Mg-induced K deficiency on high Mg soils. It was determined from this trial that adding K or adding K in combination with decreasing the soil pH achieved greatest increase in the soil available K/Mg concentration and additions of K to the soil increased petiole K in both ‘St. Croix’ and ‘Marquette’ grapevine.

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Table 1. Percentage dry weight of petiole K and Mg and available soil K, Mg, and pH tests taken in 2006 at ARF, HORT, NERF, and SERF for 'Marquette' and 'St. Croix' grapevines.

Sample		Petiole		Soil				
		K	Mg	K ($mg \cdot kg^{-1}$)	Mg ($mg \cdot kg^{-1}$)	K/Mg	pH 0-15 cm	pH 15-30 cm
ARF	Marquette	1.41	0.56	226	398	0.57	6.27	5.87
ARF	St. Croix	2.41	0.84					
HORT	Marquette	1.61	0.34	183	350	0.46	6.07	6.69
HORT	St. Croix	1.88	0.46					
NERF	Marquette	1.55	0.45	141	362	0.39	6.94	6.73
NERF	St. Croix	1.87	0.57					
SERF	Marquette	0.87	0.88	166	639	0.26	6.70	6.82
SERF	St. Croix	1.25	0.88					

(Domoto, 2007 – unpublished data)

Table 2. Properties of source soil collected from Southeast Research Farm in Mar. 2008.

Soil pH	Potassium	Magnesium	Calcium	Phosphorus	Organic Matter	CEC
7.2	126 ($mg \cdot kg^{-1}$)	533 ($mg \cdot kg^{-1}$)	2310 ($mg \cdot kg^{-1}$)	44 ($mg \cdot kg^{-1}$)	1.90%	13.5 meq/100 g

Table 3. Average soil test results in 2009 and 2010 for pH, K, Mg, Ca, and K/Mg in four soil treatments.

Treatment [z]	pH^{zy}	K ($mg \cdot kg^{-1}$)	Mg ($mg \cdot kg^{-1}$)	Ca ($mg \cdot kg^{-1}$)	K/Mg
2009					
S+K	6.2 b	172 a	610 c	2444 bc	0.28 a
K	6.7 a	187 a	681 ab	2736 a	0.27 a
S	6.3 b	139 b	621 bc	2578 ab	0.22 b
Control	6.7 a	147 b	707 a	2743 a	0.21 b
2010					
S+K	6.0 b	170 a	506 d	2113 d	0.34 a
K	6.6 a	182 a	627 bc	2315 cd	0.29 a
S	6.1 b	98 c	514 d	2110 d	0.19 c
Control	6.4 a	108 c	645 abc	2445 bc	0.17 cd

[z]Values represent the mean of 12 samples per year.

[y]Means within columns followed by the same lowercase letter are not different at $p \leq 0.05$ according to Fisher's least significant difference test.

Table 4. Spring pruning weight, 2010 vegetative growth, roots and trunk, and total weight of 'Marquette' and 'St. Croix' grape growth.

Treatment	Spring Pruning^{zy} (g)	2010 vegetative (g)	Roots and Trunk (g)	Total Weight (g)
Marquette				
S+K	19 a	1368 a	282 a	1669 a
K	20 a	1013 ab	237 a	1270 ab
S	13 ab	1104 a	257 a	1373 ab
Control	17 a	1004 ab	215 a	1236 abc
St. Croix				
S+K	6 b	510 c	282 a	798 c
K	13 ab	599 bc	279 a	892 bc
S	11 ab	520 c	275 a	806 c
Control	13 ab	577 bc	251 a	841 c

^{z}Values represent the mean of 12 samples per year.

^{y}Means within columns followed by the same lowercase letter are not different at $p \leq 0.05$ according to Fisher's least significant difference test.

Table 5. Percentage dry weight of K, Mg, and Ca in petioles of ‘Marquette’ and ‘St. Croix’ grape collected in August 2009 and August 2010 from vines in four soil treatments.

	2009			2010		
Soil treatment	K^{zyx}	Mg	Ca	K	Mg	Ca
Marquette						
$S+K^{w}$	1.91 cA	0.47 bA	1.89 abA	1.19 bB	0.43 cA	1.11 abB
K	1.84 cdA	0.41 bA	1.80 abA	1.22 bB	0.33 dA	1.11 abB
S	1.73 cdA	0.76 aA	1.99 aA	0.80 cB	0.47 cB	1.11 abB
Control	1.44 dA	0.43 bB	1.62 bA	0.73 cB	0.59 bA	1.15 aB
St. Croix						
S+K	2.37 abA	0.83 aA	1.61 bA	1.77 aB	0.50 cB	0.98 bB
K	2.50 aA	0.90 aA	1.75 abA	1.60 aB	0.48 cB	1.02 abB
S	1.96 bcA	0.88 aA	1.57 bA	0.81 cB	0.99 aA	1.04 abB
Control	2.05 abA	0.80 aA	1.56 bA	0.85 cB	0.91 aA	0.99 bB

^{z}250 petioles per plant.

^{y}Values represent the mean of six plants.

^{x}Means within columns followed by the same lowercase letter are not different at $p \leq 0.05$ according to Fisher’s least significant difference test.

^{w}Means across rows for each individual nutrient followed by the same upper case letter are not different at $p \leq 0.05$ according to pair wise difference tests.

Table 6. Milligrams per kilogram Zn, Mn, and B in petioles of 'Marquette' and 'St. Croix' grape collected in Aug. 2009 and 2010 from vines in four soil treatments.

	2009			2010		
Soil treatment	Zn[zvx]	Mn	B	Zn	Mn	B
Marquette						
S+K[x]	73 abA	132 bA	47.6 abA	41 bB	207 abA	17.0 cdB
K	55 bcA	99 bcA	44.0 abA	31 bB	165 bA	16.2 dB
S	87 aA	170 aA	52.0 aA	34 bB	256 aA	15.8 dB
Control	48 cA	99 bcA	42.0 bA	33 bA	168 bA	16.3 cdB
St. Croix						
S+K	76 abA	95 cdB	43.0 abA	76 aA	254 aA	19.7 abB
K	83 aA	77 cdA	48.0 abA	60 aA	206 abA	17.5 bcdB
S	74 abA	76 cdB	41.0 bA	71 aA	259 aA	20.0 aB
Control	75 abA	60 dA	38.5 bA	61 aA	173 bA	18.5 abcB

[z]250 petioles per plant.

[y]Values represent the mean of six plants.

[x]Means within columns followed by the same lower case letter are not different at $p \leq 0.05$ according to Fisher's least significant difference test.

[w]Means across rows for each nutrient followed by the same upper case letter are not different at $p \leq 0.05$ according to pair wise difference tests.

Figure Captions

Fig. 1. Average five year yield (2006 to 2010) in kg / vine for ‘St. Croix’ and ‘Marquette’ grapevines at HORT, ARF, NERF, and SERF (Domoto et al., 2007ab; Domoto et al., 2008ab; Domoto et al., 2009ab; Domoto et al., 2010ab; Domoto et al., 2011ab).

Fig. 2. Average five-year pruning weight (2006 to 2010) in kg / vine for ‘St. Croix’ and ‘Marquette’ grapevines at HORT, ARF, NERF, and SERF (Domoto et al., 2007ab; Domoto et al., 2008ab; Domoto et al., 2009ab; Domoto et al., 2010ab; Domoto et al., 2011ab).

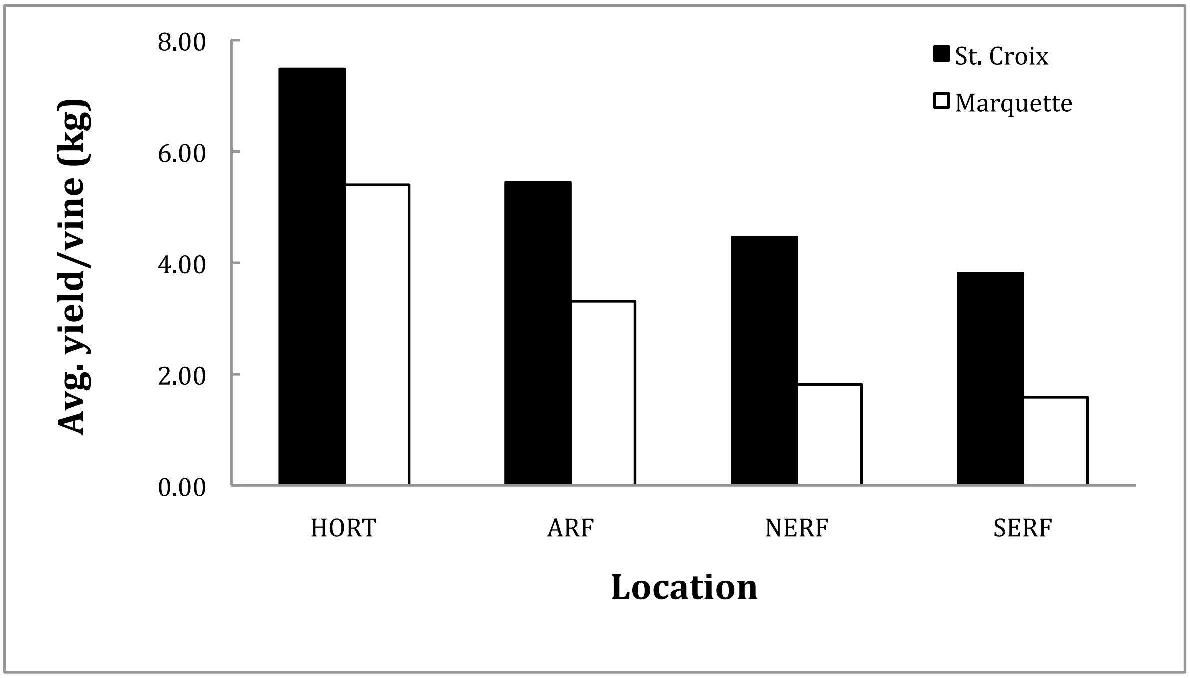
8.00
6.00
4.00
2.00
0.00
Avg. yield/vine (kg)
St. Croix
Marquette
HORT
ARF
NERF
SERF
Location

Fig. 1.

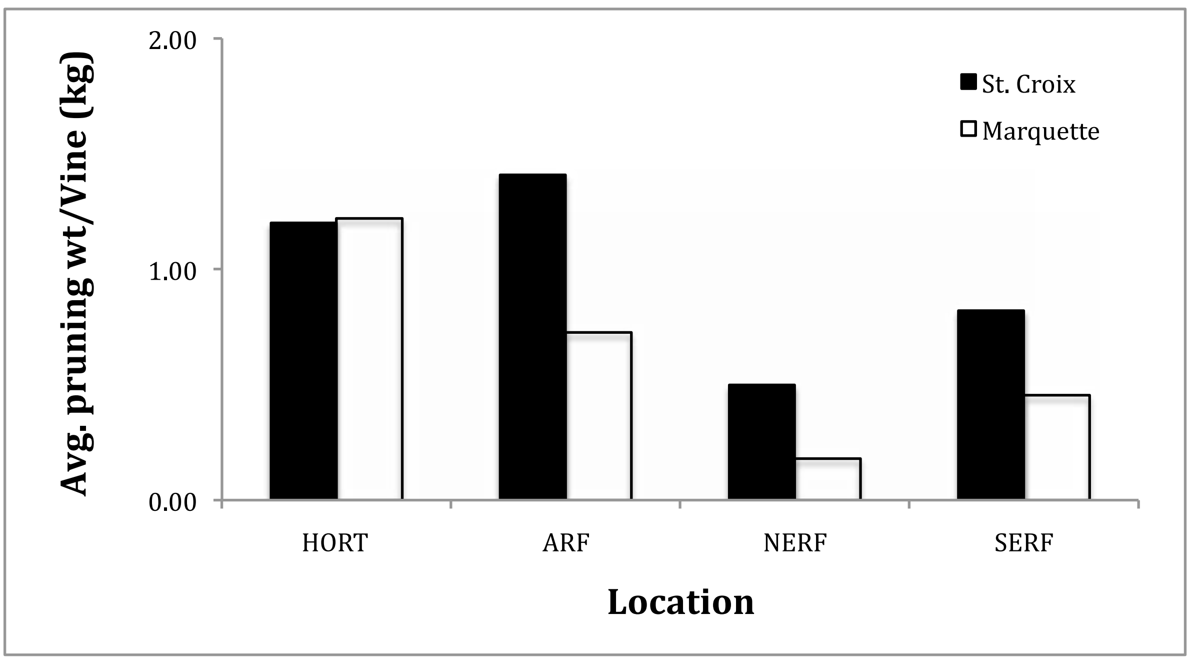
2.00
1.00
0.00
Avg. pruning wt/Vine (kg)
St. Croix
Marquette
HORT
ARF
NERF
SERF
Location

Fig. 2.

APPENDIX

Appendix Tables and Figures

Table 1. Irrigation water sample from 2008 for pH, K, Mg, Ca, Na, P, B, Cl, conductivity, total dissolved solids (TDS), sulfate, nitrate, carbonate, and bicarbonate .

Test	Value
pH	7.06
K ($mg \cdot L^{-1}$)	4.49
Mg ($mg \cdot L^{-1}$)	6.38
Ca ($mg \cdot L^{-1}$)	26.60
Na ($mg \cdot L^{-1}$)	3.33
P ($mg \cdot L^{-1}$)	0.12
B ($mg \cdot L^{-1}$)	0.03
Cl ($mg \cdot L^{-1}$)	10.00
conductivity ($ds \cdot L^{-1}$)	0.21
TDS ($mg \cdot L^{-1}$)	130.00
Sulfate ($mg \cdot L^{-1}$)	26.60
Nitrate ($mg \cdot L^{-1}$)	9.00
Carbonate ($mg \cdot L^{-1}$)	0.00
Bicarbonate ($mg \cdot L^{-1}$)	36.60

Appendix Figure Captions

Fig. 1. Soil potassium-magnesium ratio (K/Mg) for HORT, ARF, NERF, and SERF from samples taken in 2006.

Fig. 2. Petiole potassium (percentage dry weight) concentration for ‘St. Croix’ and ‘Marquette’ grapevines for HORT, ARF, NERF, and SERF from samples taken in 2006.

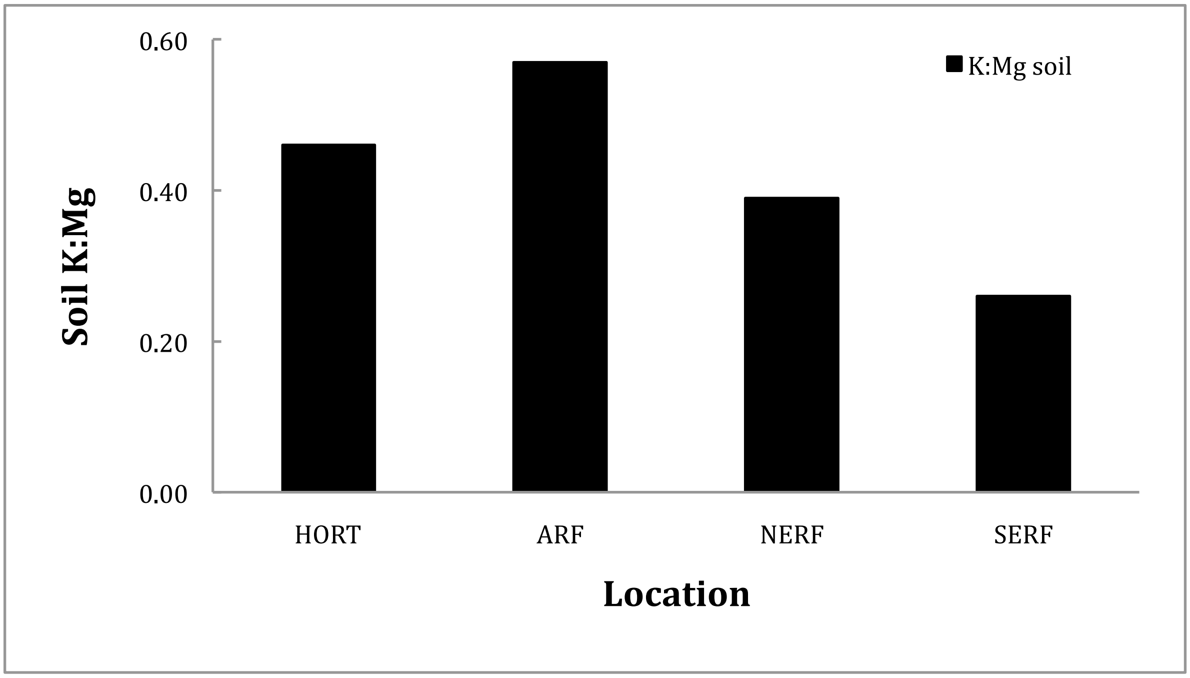
0.60
0.40
0.20
0.00
Soil K:Mg
K:Mg soil
HORT
ARF
NERF
SERF
Location

Fig. 1.

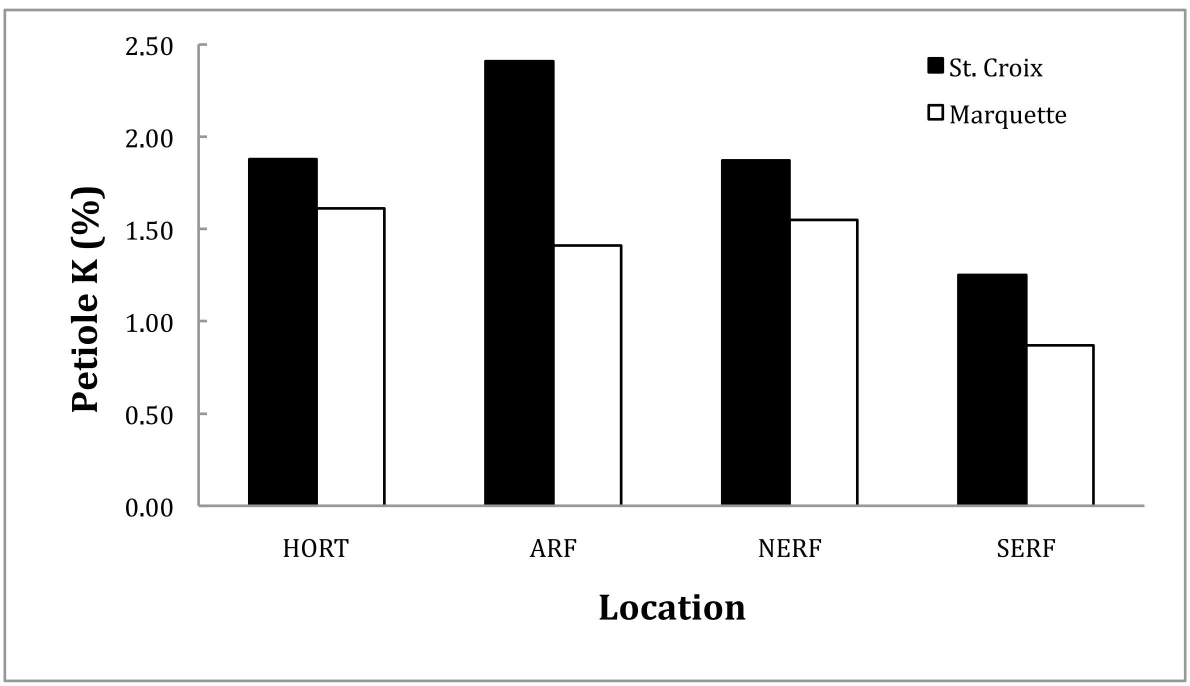
2.50
2.00
1.50
1.00
0.50
0.00
Petiole K (%)
St. Croix
Marquette
HORT
ARF
NERF
SERF
Location

Fig. 2.

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