Soil–Plant Nutrient Interactions on Manure-Enriched Calcareous Soils

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ABSTRACT

Growers working with manured soils often rely on soil test information when developing nutrient management for their crop, especially when manure application information is unavailable. Nutrient-enriched soils, like manured soils, can trigger nutrient deficiencies and toxicities due to plant–soil nutrient interactions. The goal of the study was to determine correlations between soil test and plant tissue nutrient concentrations for irrigated corn silage crops (*Zea mays* L. subsp. *mays*) with varying nutrient concentrations unique to dairy manure-enriched calcareous soils. Whole plant and soil samples were collected from 39 cooperator corn silage fields at harvest over a 2-yr period throughout the Snake River Plain region of southern Idaho. Soils were sampled to a depth of 30.5 cm and analyzed for plant available forms of P, K, Ca, Mg, Na, S, Zn, Fe, Mn, Cu, and B; whole plant tops were analyzed for total N, P, K, Ca, Mg, Na, S, Zn, Fe, Mn, and Cu. Significant positive correlations were detected between soil test K and tissue K (Spearman's rho correlation coefficient = 0.63), soil test K and tissue N (rho = 0.59), and soil test B and tissue N (rho = 0.53). A significant negative correlation was detected between soil test Fe and tissue Mn (rho = −0.59). Controlled studies are needed to corroborate the relationships observed in this survey study.

A major concern of intensive dairy manure applications to agricultural fields is the accumulation of nutrients and their impact on crop growth. For example, accumulations of P on fields receiving N-based applications of cattle (*Bos taurus*) manure are common (Eghball, 2002). A major concern with nutrient accumulations on heavily manured soils is the potential for nutrient imbalances triggered by nutrient interactions both in the soil and in the plant.

Many growers who field-apply cattle manure are concerned about Zn deficiencies caused by high levels of P. Phosphorus and Zn interactions have been extensively documented in relation to chemical sources of P. For example, Safaya (1976) showed that Zn tissue concentrations and Zn flux in corn decreased as plant-available P (i.e., Olsen P) increased from 4 to 37 mg kg^{-1}. Similarly, Adriano et al. (1971) found that growth was retarded more by Zn deficiency than any other deficiency in corn plants receiving high applications of P fertilizers. Similar P–Zn relationships have been found in other crops, including potato (*Solanum tuberosum* L.) (Christensen and Jackson, 1981) and wheat (*Triticum aestivum* L.) (Singh et al., 1986).

In contrast, P–Zn interactions have not been as apparent in relation to manure sources of P. In fact, many researchers have documented increased Zn tissue concentration and Zn uptake in relation to manure applications (Leytem et al., 2011; Pagliari et al., 2009; Raj and Gupta, 1986; Wong et al., 1999). Increased Zn has been attributed to (i) manures containing significant amounts of Zn and (ii) organic acids from manures that may serve as Zn-chelating agents for the plant (Stevenson and Ardkani, 1972; García-Mina et al., 2004).

While not as well documented, another rising issue is the potential for reduced Mn uptake on manure-treated soils. Warman and Cooper (2000) reported lower Mn forage tissue concentrations in compost treatments than fertilizer treatments. Leytem et al. (2011) also documented decreased Mn uptake for corn grown on manure and compost-treated soils in comparison to P fertilizer. Leytem et al. (2011) suggested that the decrease in Mn tissue concentration may have been attributed to Mn complexation by organic acids in the manure.

Another issue of concern in relation to manure applications and nutrient antagonism is the potential for cation competition, or ion antagonism, between K, Mg, and Ca cations in the soil.

Published in Agron. J. 106:73–80 (2014)
doi:10.2134/agronj2013.0345
Available freely online through the author-supported open access option.

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Abbreviations: ICP–OES, inductively coupled plasma–optical emission spectrometry; OPM, orbits per minute.

As there are a limited number of ion carrier sites on root plasma membranes, ions with similar diameters and ion strength can outcompete each other for space on these sites (Marschner, 2011). Potassium is known to be a strong competitor against Mg, Ca, and Na, and can restrict uptake of these nutrients when in abundant supply (Mengel, 2007). In addition to P, dairy manures also contain high quantities of K, which is a common dairy feed additive. In relation to fertilizer sources, excessive quantities of K has decreased Ca and Mg tissue concentrations in forage sorghum [*Sorghum bicolor* (L.) Moench] (Reneau et al., 1983) and in corn (Claassen and Wilcox, 1974), decreased Mg tissue concentrations in sorghum (Ologunde and Sorensen, 1982), and triggered Mg deficiencies in orange trees (*Citrus* spp.) (McColloch et al., 1957). Parsons et al. (2007) found significant reductions in Ca uptake by wheat receiving manure applications in comparison to fertilizer or an unamended control. The authors noted that Ca uptake may have been hindered by competition with K. Leytem et al. (2011) also found reduced Ca uptake in corn with increasing dairy manure application rates. In addition to cation competition, the authors suggested that the reduction in Ca uptake on manure-treated soils may also be related to the formation of Ca-phosphate precipitates.

Excess K application may also increase the potential for luxury K consumption by plants. When K supply is abundant, luxury K consumption is known to be an issue in many crop plants (Marschner, 2011). Unfortunately, dairy cows that consume forage tissue with K concentrations of 1.5% or greater are at risk of milk fever (Penn State University Extension, 2013), explaining why many animal producers are concerned with luxury consumption of K by forage crops. As described above, K is known to accumulate in manure-treated soils, and could therefore be a potential issue for growers who use their crop as an animal feed.

In Idaho, producers and growers often do not know the specific manure application history of a field in terms of application rates, timings of applications, number of applications, moisture content of manure, nutrient content of manure, etc. Regardless, growers are still very concerned about how the effects of these higher-nutrient fields impact their crops. Growers working with fields with a history of manure application depend on soil test results to predict both plant nutrient availability, as well as the potential for negative nutrient interactions described above.

The goal of this project was to determine soil and corn silage plant tissue nutrient interactions specific to southern Idaho soils in high nutrient status manured soils, based on soil test and tissue nutrient concentrations. To examine this question, soils and plant tissue collected from cooperator corn silage fields with reported dairy manure application histories were analyzed for most agronomic plant nutrients. Interactions between increasing soil test and tissue nutrient concentrations in silage corn were evaluated.

MATERIALS AND METHOD

Experimental Design and Sampling

As described in Hines et al. (2012), soil samples, whole plant tissues, and yields were collected from 18 southern Idaho irrigated silage corn fields in 2008 and 21 fields in 2009, for a total of 39 fields sampled over the 2-yr period. Fields were selected to represent predominant corn-growing areas in southern Idaho. The fields, all located within the Snake River Plain region of southern Idaho, ranged from approximately 716 to 1437 m in elevation. We sampled two fields in Canyon County, five fields in Cassia County, four fields in Franklin County, seven fields in Gooding County, seven fields in Jerome County, six fields in Lincoln County, and eight fields in Twin Falls County. Fields sampled in 2008 were not resampled in 2009. Among the 39 fields sampled, 5 had loam textured soils, 3 had loamy sand textured soils, 3 had sandy loam textured soils, 1 had a silt textured soil, and 18 had silt loam textured soils. Analyses were not conducted to accommodate for soil type, as groupings based on soil properties (silt content, clay content, or organic matter content, for example) did not contain a wide enough spread of soil nutrient levels for detecting plant–soil nutrient interactions.

Fields were selected to provide wide-ranging soil test P levels, based on information provided by growers and dairymen about manure application histories. As there were no fields with Olsen P concentrations between 100 and 200 mg kg^{-1} in 2008, fields with reported histories of more intensive dairy manure applications were targeted in 2009 to fill in this gap, allowing for improved analysis of nutrient interactions. Five of the 39 fields did not have a history of manure applications, allowing the inclusion of lower soil nutrient levels in comparison to higher nutrient levels commonly found in manured soils.

Soil samples, whole plants, and yield data were collected within a week of harvest. For consistency, fields were sampled once the kernels had reached the one-half to two-thirds milk line stage (approximately 65% whole plant moisture), which is the optimal dryness for southern Idaho silage storage systems. Each field was sampled at three random sampling areas throughout the field. Each sampling area was 3.05 m in length and two corn rows in width (corn row widths were recorded, and varied in width between 55.9 and 76.2 cm). Soils were sampled by compositing 10 soil cores at a depth of 0 to 30.5 cm at each transect. Three individual corn stalks were sampled from each transect at a height of 10.2 cm above the ground. Soil and tissue sampling area values for each field were averaged for data analysis. Silage yield, P uptake, and other agronomic findings are published in Hines et al. (2012). Yields were comparable to typical yields for corn silage grown in this region.

Soil Analysis

Soil samples were air-dried at 21°C for 7 d. The air-dried soil samples were further dried at 105°C for 4 h in a force draft oven. Soil samples were then ground using a Dynacrush grinder to pass through a no. 10 mesh screen (2.0 mm) and weighed for analysis. For analysis of K, Mg, and Ca, 3.0 g of soil were shaken with 12 mL of 1.0 M ammonium acetate for 15 min at 160 orbits per minute (OPM). Acetate extracts were analyzed for K, Mg, and Ca content using inductively coupled plasma–optical emission spectrometry (ICP–OES model 4300DV, PerkinElmer, Waltham, MA; Ellis and Brown, 1998). For analysis of Zn, Mn, Cu, and Fe, 3.0 g of soil were shaken with 12 mL of 0.005 M DTPA for 15 min at 160 OPM. The DTPA extracts were analyzed for Zn, Mn, Cu, and Fe content using ICP–OES (Ellis and Brown, 1998). For analysis of S, 3.0 g of soil was shaken with 12 mL of monocalcium phosphate extract (500 mg kg^{-1} P) for 15 min at 160 OPM. Extracts were analyzed for S content using

Table 1. Characterization of available nutrients in soil samples collected at harvest from 39 cooperator irrigated corn silage fields throughout the Snake River Plain region of southern Idaho in 2008 and 2009.

Soil parameter (0– 25 cm)	Mean (n = 39)	SE	Lower and upper confidence interval (95%)		Minimum and maximum observed values	
P, mg kg^{-1}	78.2	(8.9)	60.1	96.2	8.3	258.3
K, mg kg^{-1}	512	(49)	412	611	143	1262
Mg, mg kg^{-1}	391	(17)	356	425	154	594
Ca, mg kg^{-1}	2727	(141)	2441	3013	997	4175
S, mg kg^{-1}	21.7	(1.7)	18.2	25.1	4.3	56.3
Zn, mg kg^{-1}	3.46	(0.27)	2.92	4.00	0.80	7.47
Mn, mg kg^{-1}	7.46	(0.40)	6.65	8.26	3.37	16.70
Cu, mg kg^{-1}	3.98	(0.63)	2.69	5.27	0.80	19.60
Fe, mg kg^{-1}	10.7	(0.73)	9.18	12.15	4.80	25.33
B , mg kg^{-1}	1.08	(0.06)	0.96	1.21	0.33	2.00
Na, mg kg^{-1}	91.0	(7.4)	76.0	106.0	12.7	219.3
pH	7.70	(0.04)	7.61	7.78	6.97	8.27
Electrical conductivity	0.48	(0.02)	0.42	0.53	0.15	1.13

Table 2. Nutrient characterization of corn silage whole plant top tissue collected at harvest from 39 cooperator irrigated corn silage fields throughout the Snake River Plain region of southern Idaho in 2008 and 2009.

Plant nutrient	Mean (n = 39)	SE	Lower and upper confidence interval (95%)		Minimum and maximum observed values	
N, g kg^{-1}	10.4	(0.3)	9.8	11.0	6.1	15.0
P, g kg^{-1}	2.0	(0.1)	1.9	2.1	1.4	2.9
K, g kg^{-1}	11.7	(0.3)	11.0	12.4	7.8	17.1
Mg, g kg^{-1}	1.5	(0.05)	1.4	1.6	1.1	2.3
Ca, g kg^{-1}	2.3	(0.1)	2.1	2.4	1.2	3.1
Na, g kg^{-1}	0.2	(0.01)	0.1	0.2	0.1	0.5
S, g kg^{-1}	0.8	(0.02)	0.8	0.8	0.6	1.0
Zn, mg kg^{-1}	20.4	(0.7)	19.1	21.8	12.8	28.2
Mn, mg kg^{-1}	26.1	(2.1)	21.9	30.4	7.9	54.7
Cu, mg kg^{-1}	14.6	(1.6)	11.4	17.8	5.0	53.2
Fe, mg kg^{-1}	57.1	(2.3)	52.3	61.8	34.7	110.0

ICP–OES (Ellis and Brown, 1998). Boron was extracted using the hot water extraction method, and analyzed using ICP–OES (Ellis and Brown, 1998). Soil pH was determined using a Fisher Scientific Accumet 50 pH meter with a lignin pH electrode on a mixture of approximately 10.0 g of soil and 10 mL deionized water (Ellis and Brown, 1998). Electrical conductivity (EC) was determined using the saturated paste method (Ellis and Brown, 1998). For analysis of Olsen P, 2.0 g of soil was extracted with 40 mL of 0.5 M sodium bicarbonate ($NaHCO_3$) and filtered through Schleicher and Schuell no. 605 filter paper (Gavlak et al., 2005). Extracts were analyzed for P at 882 nm using the ammonium molybdate colorimetric method with the Milton Roy Spectronic 301 Spectrometer (Gavlak et al., 2005).

Tissue Analysis

Corn stalk samples were weighed to determine fresh weight, dried at 60°C for 3 d, re-weighed, and then ground with a Wiley Mill to pass a 2-mm sieve. Plant nutrients were determined by weighing 0.350 g of plant tissue into 50-mL digestion tubes. Approximately 5.0 mL of concentrated HNO_3 was added to the tubes and heated for 30 min at 60°C under a fume hood. Approximately 3 mL of 30% H_2O_2 solution was added to the tubes and heated for an additional 90 min at 120°C. The digests were then cooled, diluted to a volume of 35 mL with 20% HCl, vortexed, and filtered through Ahlstrom 642 filter paper. Filtrates were analyzed for P, K, Mg, Ca, Na, S, Zn, Mn, Cu, and Fe using ICP–OES. Total Kjeldahl nitrogen (TKN) was determined by weighing 0.200 g tissue into 100 mL digestion tubes. Approximately 5.0 mL of concentrated H_2SO_4 and one Pro-Pac catalyst tablet (1.5 g K_2SO_4 and 0.125 g $CuSO_4$) were added. Samples were digested at 360°C for 1 h under a fume hood. Samples were then cooled to room temperature, diluted to a volume of 50 mL with deionized water, mixed, and transferred to test tubes for analysis of total N content on a Lachat Quik-Chem 8500 FIA.

Statistical Analysis

All data analysis for this paper was generated using SAS 9.3 software (SAS Institute, 2011). Means, standard errors, and confidence intervals for soil (Table 1) and plant nutrient (Table 2) concentrations were determined using the Proc SURVEYMEANS procedure. Correlations among soil nutrients and between soil and tissue nutrients were determined using Spearman's rank correlation (Proc CORR, Spearman) procedure. Correlation values >0.50 in magnitude (positive or negative) were determined to be relevant for further consideration using linear regression analyses. Silage yield was not correlated with any of the soil or plant nutrient components included in this study. For this reason, yield was not included in the correlation analysis.

Before regression analysis, a preliminary ANOVA was conducted using the GLM procedure to assess for significant

Table 3. Spearman's correlation rho coefficients, detecting correlations between increasing soil test P and other soil test nutrient levels for 39 soils with varying manure application histories, collected from corn silage fields throughout southern Idaho. Values approaching 1 indicate a positive correlation between the two parameters; values approaching –1 indicate a negative correlation; values approaching 0 indicate no correlation.

Soil	Olsen P	
	rho	*p* value
K	0.53	0.0006
Mg	–0.06	0.7007
Ca	–0.24	0.1349
S	0.22	0.1769
Zn	0.78	<0.0001
Mn	0.09	0.5762
Fe	0.50	0.0017
B	0.53	0.0009
Na	0.26	0.1025
Cu	0.45	0.0036

year effects potentially arising from higher rates of dairy manure application in 2009 than 2008. Given those results, a mixed model random effects regression analysis was performed assuming a random intercept effect due to years (Proc MIXED). In some cases where nonlinear relationships were evident, for example, soil test Fe and tissue Mn, an inverse transformation of the independent variable was used before analysis to linearize the relationship. Confidence intervals for each model were determined using $\alpha = 0.10$.

RESULTS AND DISCUSSION

Soil Nutrient Interaction

Correlations between increasing dairy manure application rate and increasing Olsen P soil concentration are well supported (Sharpley et al., 1996; Eghball et al., 1996). Based on this fact, correlations between Olsen P and other soil test nutrients were seen as an indication of nutrient accumulations in response to

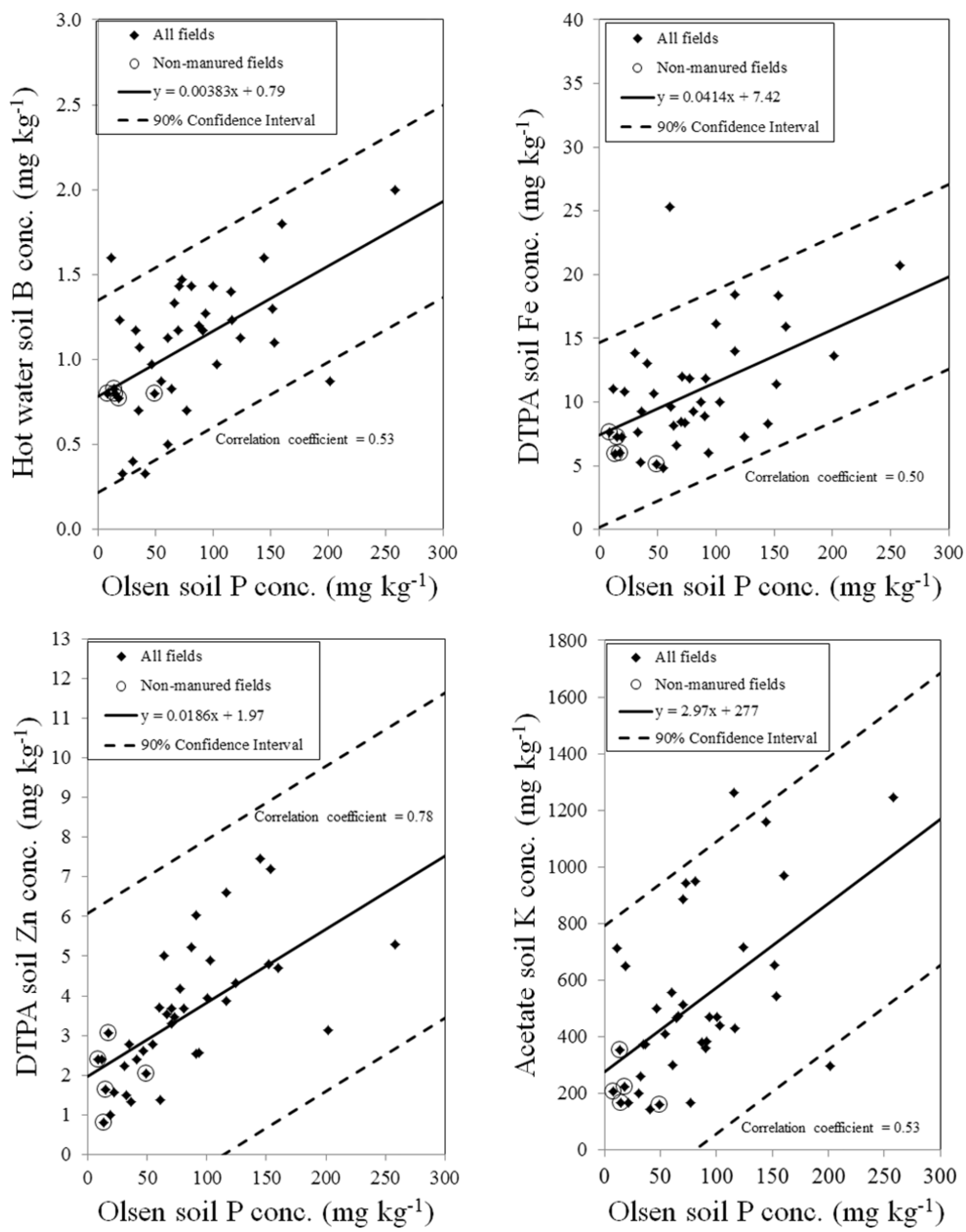

Fig. 1. Increasing K, Zn, Fe, and B soil concentrations with increasing soil Olsen P concentrations (0–30.5-cm depth) from 39 cooperator irrigated silage corn fields with various dairy manure application histories (five of the fields did not have dairy manure applied). The fields were located throughout the Snake River Plain region of Idaho and were sampled at or near silage harvest in 2008 and 2009. A mixed linear regression model was applied with "year" as a fixed effect.

Table 4. Spearman's correlation rho coefficients, detecting correlations between increasing soil test nutrients and tissue nutrient concentration 39 corn silage fields with varying manure application histories, collected from corn silage fields throughout southern Idaho. Values approaching 1 indicate a positive correlation between the two parameters; values approaching –1 indicate a negative correlation; values approaching 0 indicate no correlation.

Soil test nutrient concentration, 0- to 30.5-cm depth	Whole top tissue concentration at harvest.									
	rho	*p*	rho	*p*	rho	*p*	rho	*p*	rho	*p*
	N		P		K		Mg		Ca	
P	0.50	0.0010	–0.11	0.4780	0.37	0.0197	–0.19	0.2463	–0.25	0.1242
K	0.59	<0.0001	–0.07	0.6511	0.63	<0.0001	–0.43	0.0068	–0.20	0.2336
Zn	0.50	0.0012	–0.10	0.5329	0.40	0.0129	–0.41	0.0096	–0.41	0.0108
Fe	0.33	0.0405	0.19	0.2622	0.42	0.0085	–0.20	0.2264	–0.31	0.0570
B	0.53	0.0006	–0.18	0.2661	0.39	0.0155	–0.27	0.1041	–0.26	0.1188
	S		Zn		Mn		Cu		B	
P	0.08	0.6162	–0.12	0.4570	–0.44	0.0038	–0.09	0.5566	–0.04	0.8083
K	0.17	0.2995	–0.28	0.0915	–0.04	0.8306	–0.27	0.0924	0.09	0.5576
Zn	0.01	0.9279	–0.08	0.6261	–0.50	0.0014	–0.45	0.0047	–0.13	0.4153
Fe	0.21	0.2014	–0.40	0.0138	–0.59	0.0001	–0.34	0.0337	–0.06	0.7020
B	0.14	0.3745	–0.34	0.0351	–0.05	0.7673	–0.13	0.4230	0.09	0.5925

increasing manure applications. As information on manure application practices was not included in this study, it is difficult to know for certain whether these trends are related to manure applications or other agricultural practices (such as fertilizer applications). More research is needed to further evaluate nutrient accumulations on calcareous soils receiving dairy manure applications.

Potassium, Zn, Fe, and B soil test concentrations were positively correlated with increasing soil Olsen P concentrations (Spearman rho coefficient = 0.52, 0.77, 0.51, and 0.52, respectively) (Table 3, Fig. 1). On average, for every 25 mg kg^{-1} increase in Olsen P from 0 to 250 mg kg^{-1}, soil test K concentrations increased by 77 mg kg^{-1}, soil test Zn concentrations increased by 0.5 mg kg^{-1}, soil test Fe concentrations increased by 1.0 mg kg^{-1}, and soil test B concentrations increased by 0.09 mg kg^{-1} (Fig. 1). Edmeades (2003) showed a consistent trend of increasing K accumulations in association with fields having extensive histories of manure applications, based on information collected from 14 different long-term field trials on cattle manure applications. Accumulations of Zn from cattle manure applications are also well documented (Chang et al., 1991; Brock et al., 2006; Benke et al., 2008). Although we did not measure manure application rates, our soil test B accumulations findings contrast with Benke et al. (2008), who found no significant increase in soil test B levels in fields that had received up to 180 Mg ha^{-1} cattle manure each year for a period of 25 yr. This finding could be encouraging for fields that suffer from Zn and Fe deficiencies, which are common under alkaline soil pH conditions as found in southern Idaho (Table 1).

Magnesium, Ca, S, Na, Cu, and Mn concentrations in the soil did not appear to be correlated with increasing Olsen P concentrations (Table 3). Lund and Doss (1980) found increasing Mg levels in the soil with manure applications, although the rates that were used in those trials (up to 270 Mg ha^{-1} annually for a 3-yr period) greatly exceed manure application rates used by producers in southern Idaho. Magnesium and Ca are naturally abundant under the alkaline and calcareous conditions that are typical of southern Idaho soils, making it difficult to observe significant correlations between soil Ca and Mg concentrations and soil P concentrations.

Nutrient Interactions between Soil and Silage Tissue

Positive correlations were detected between soil test K and tissue N (0.59), soil test B and tissue N (0.53), and soil test K and tissue K (0.63) (Table 4). To explore these correlations, mixed model regression analyses between the two components for each of these three correlations were performed. Soil test Ca, Mg, Na, S, Mn, and Cu was not included in the correlation analysis, as it appeared that nutrient interactions would potentially be less related to manure application history and more related other external factors due to their lack of correlation with Olsen P concentrations.

Soil Test Potassium and Tissue Nitrogen

Between soil test K concentrations of 100 and 1300 mg kg^{-1}, the relationship between soil test K concentration and tissue N concentration was linear ($y = 0.000371x + 0.85$; Fig. 2). Potassium is needed by the plant for activation of enzymes required for N metabolism (Havlin et al., 2005), and has been shown to increase yields and N uptake when applied in conjunction with N fertilizers (MacLeod, 1969). Because soil ammonium and nitrate levels were not tested, it is also possible that there was increased N in the soil similar to increases in K, which would have also increased N uptake. According to Brown et al. (2010), it is suggested that silage corn grown in southern Idaho will not respond to additional K above 150 mg kg^{-1} for Olsen-extracted K or 180 mg kg^{-1} for acetate-extracted K. While this was the case for yield (data not shown), it appears possible that the increasing K levels in the soil may improve the ability of corn to take up more N. In one sense, this could be a positive finding, suggesting that corn grown on K enriched fields (>1000 mg kg^{-1} soil test K) can take up more N compared to corn grown on soils with comparably lower K concentrations (<500 mg kg^{-1} soil test K), which could help to reduce nitrate-leaching losses. On the other hand, increased N concentration in corn also increases the potential for excessive nitrate levels in corn silage that may be toxic to cows. However, because the nitrate form of N was not analyzed in the plant tissue, it is difficult to make this conclusion based solely on our findings.

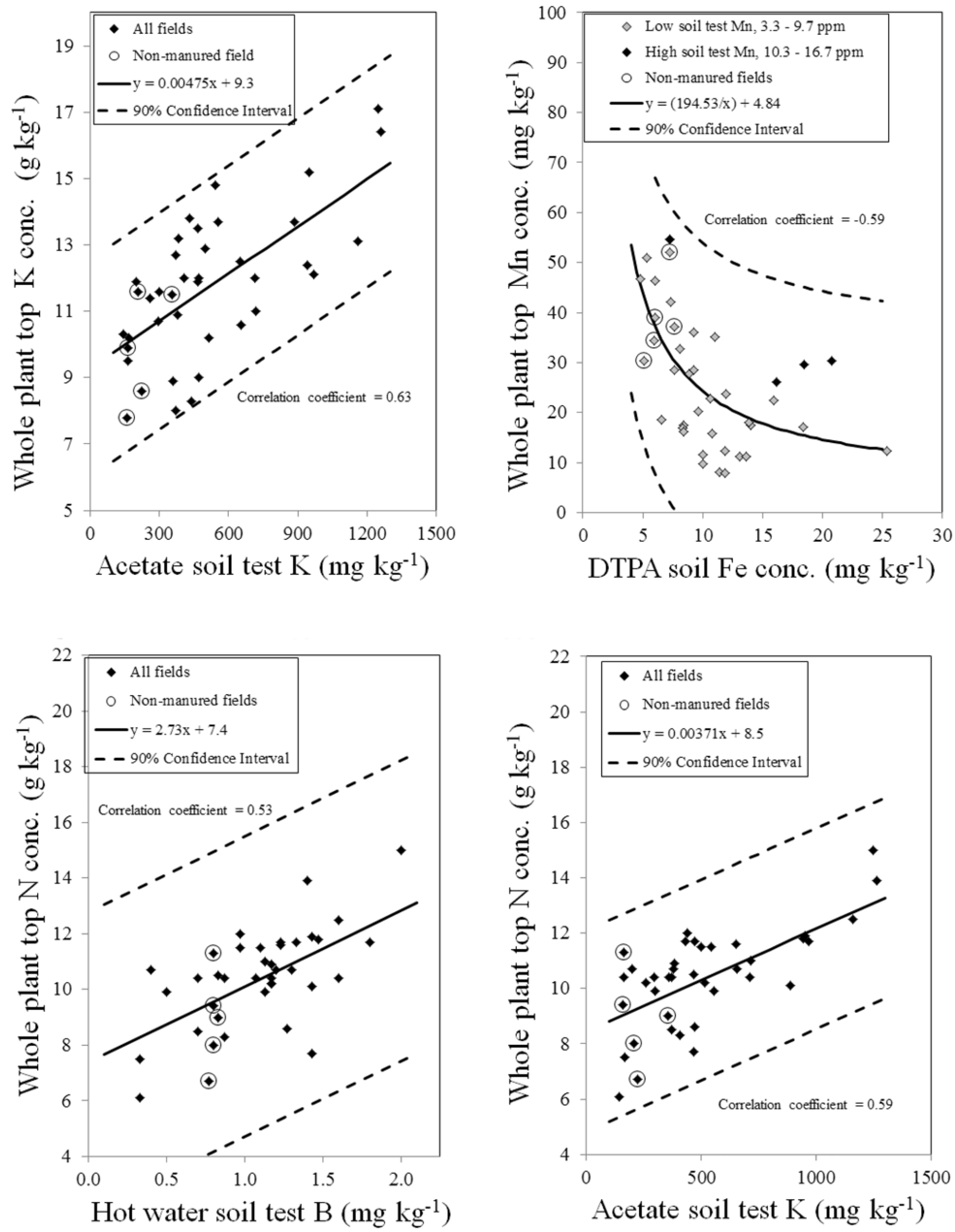

Fig. 2. Correlated relationships between specific soil nutrient concentration (0– 30.5-cm depth) and whole plant top nutrient concentration for 39 cooperator irrigated silage corn fields with various dairy manure application histories (five of the fields did not have dairy manure applied). The fields were located throughout the Snake River Plain region of Idaho and were sampled at or near silage harvest in 2008 and 2009. A mixed linear regression model was applied with "year" as a fixed effect.

Soil Test Boron and Tissue Nitrogen

In addition to soil test K, we also found a significant positive correlation between soil test B and tissue N concentrations (Table 4). The relationship between soil test B and tissue N was linear ($y = 0.273x + 0.74$; Fig. 2). Boron is required by plants for important processes related to N, including protein synthesis, amino acid synthesis, and nitrate metabolism (Marschner, 2011). Research relating soil B to tissue N levels is minimal. Camacho-Cristóbal and González-Fontes (1999) showed a decrease in tissue nitrate content at deficient soil test B concentrations, suggesting that sufficient amounts of B in the soil are needed to facilitate N uptake in the plant. Our finding suggests that N uptake on manured soils may be improved by the addition of B from the manure, which again could help improve N uptake and potentially reduce N leaching on these soils. Further research is needed to support this finding.

Soil Test Potassium and Tissue Potassium

One of the strongest correlations detected was between soil test K and tissue K. Tissue K increased linearly with increasing soil test K concentrations ($y = 0.000475x + 0.93$; Fig. 2). This finding illustrates that corn silage appears to be a luxury consumer of K. Reneau et al. (1983) also showed increasing tissue K concentrations with increasing K fertilizer applications. Increasing K concentrations in corn silage tissue could trigger milk fever in dairy cattle, a common illness in cattle caused by hypocalcemia (low blood Ca). Penn State University Extension (2013) recommends K tissue levels of 0.8 to 1.0% for forage feeds, suggesting that milk fever becomes a concern for forages with K levels above 1.5%. On the highest soil test K soils in this study (>1200 mg kg^{-1}), whole plant top K content was approximately 1.5%. According to the linear regression model, tissue K% would exceed 1.5% at soil test K concentrations above soil test K concentrations of 1178 mg kg^{-1}. Three of the 39 fields in this study exceeded 1178 mg kg^{-1} for soil test K. This finding suggests that a small number of fields may be producing corn silage with K levels that could lead to milk fever if consumed by cattle.

Soil Test Iron and Tissue Manganese

An antagonistic relationship between soil test Fe and tissue Mn was observed (Spearman's correlation = −0.59; Table 4), as described by a nonlinear inverse relationship ($y = 194.53x^{-1} + 4.84$; Fig. 2). Reduced Mn uptake and Mn deficiencies induced by Fe additions on calcareous soils have been well documented for soybean [*Glycine max* (L.) Merr.], chickpea (*Cicer arietinum* L.), and small grains (Ghasemi-Fasaei et al., 2003; Moraghan, 1985, 1992; Alam et al., 2000; Ghasemi-Fasaei et al., 2005; Heenan and Campbell, 1983; Ghasemi-Fasaei and Ronaghi, 2008). The mechanism that causes this antagonistic effect between soil Fe and plant Mn uptake is not well understood. Increased soil Fe concentrations appear to inhibit Mn translocation from root to shoot (Alam et al., 2000; Ghasemi-Fasaei et al., 2005; Heenan and Campbell, 1983). The critical value for Mn deficiency in corn ear leaf tissue at tassel is 15 mg kg^{-1} (Melsted et al., 1969). Assuming that ear leaf Mn concentrations at tasseling are closely related to whole shoot Mn concentrations at harvest, then our logarithmic model would suggest that growing corn silage on manured fields with soil DTPA Fe content >18 mg kg^{-1} may result in a Mn deficiency. In our survey fields, 21% of the corn silage tissue samples had Mn concentrations below 15 mg kg^{-1}. These findings suggest that growers with corn silage on manured fields should consider monitoring Mn in the ear leaf tissue at tasseling to determine if Mn deficiencies are an issue. Taking into account soil test Fe content should also be considered if Mn is of concern.

Three fields appeared not to follow this antagonistic relationship (Fig. 2). Between the soil test Fe concentrations of 15 and 20 mg kg^{-1}, tissue Mn concentrations for these three fields ranged between 25 and 35 mg kg^{-1}. Upon closer evaluation, these select fields were found to also have the highest soil test Mn concentrations of all the fields included in the study (between 10.3 and 16.7 mg kg^{-1}). This finding suggests that Mn deficiencies on high soil test Fe soils (>10 mg kg^{-1} DTPA Fe) may be avoided if there are adequate soil test Mn concentrations (>10 mg kg^{-1} DTPA Mn).

Soil Test Phosphorus and Tissue Zinc

Spearman's correlation was −0.12 between soil test P and tissue Zn (Table 4), illustrating no correlation between these two parameters in the 39 fields studied. Although Zn uptake has been found to decrease with increasing soil test P levels (Safaya, 1976; Adriano et al., 1971; Christensen and Jackson, 1981; Singh et al., 1986), it appears that the increasing soil test Zn associated with manure applications (Fig. 1) likely added enough additional Zn to the soil to resolve any potential P–Zn antagonism. Increased Zn uptake with manure applications have been well documented (Leytem et al., 2011; Pagliari et al., 2009; Raj and Gupta, 1986; Wong et al., 1999). Based on our finding, it seems likely that the addition of Zn with manure applications will likely negate the potential for Zn deficiencies on P-rich soils that have received manure.

Cation Competition between Potassium, Calcium, and Magnesium

Correlation analyses between soil and plant K, Ca, and Mg concentrations suggested that cation competition for plant membrane ion carrier sites was not affecting the concentrations of these cations in the plant tissue. The rho coefficient between soil test K and tissue Ca was −0.20; rho coefficient between soil test K and tissue Mg was −0.43. While there may be a slight antagonistic relationship between soil test K and Mg tissue concentration, it was difficult to confirm with the level of variability in the dataset. It is possible that factors, such as naturally high levels of Mg and Ca in these alkaline soils, may preclude finding significant cation competition effects.

CONCLUSION

From this research, we found correlations between soil nutrient levels and tissue nutrient levels for corn silage grown on nutrient-enriched calcareous soils with reported dairy manure application histories. Specifically, we found positive linear correlations between soil test K and tissue N, soil test B and tissue N, and soil test K and tissue K concentrations, and found a significant negative inverse relationship between soil test Fe and tissue Mn concentration. These findings suggest that growers producing corn silage on alkaline soils receiving dairy manure applications should consider monitoring plant tissue for N, K, and Mn concentrations to avoid reaching toxic (N or K) or deficient (Mn) levels. Our findings also suggest that interactions such as P–Zn and cation competition between K, Ca, and Mg may not be a major issue on nutrient-enriched alkaline and calcareous soils with dairy manure application histories. Finally, there were significant soil accumulations of K, Fe, Zn, and B associated with increasing Olsen P accumulations, suggesting that dairy manures are significant sources of these five nutrients in the Snake River Region of southern Idaho. Controlled studies are needed to further validate the interactions found in our study.

ACKNOWLEDGMENTS

We would like to acknowledge the support of William Price, statistician with the University of Idaho College of Agricultural and Life Sciences, who helped us to discover critical relationships in our dataset that we may never have discovered otherwise. We would also like to acknowledge the University of Idaho Extension Topic Team funding program, which provided the necessary funds needed for our research efforts.

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