Chapter 2.

Effectiveness of standard soil tests for assessing potassium availability in sand rootzones*

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Abstract

Potassium (K) is the most abundant cation in the cytoplasm and large amounts are needed for optimum plant growth. In sand rootzones with low cation exchange capacity (CEC) commonly used for putting greens, K availability may be limited, especially when the sands are calcareous. Tools are needed to assess K availability and to direct K management for such calcareous sands. The objectives of this study were to: 1) evaluate six extraction methods (1 *M* NH_4OAc, Mehlich 3, Morgan, 0.01 *M* $CaCl_2$, 0.01 *M* $SrCl_2$, and water) for their effectiveness in quantifying soil extractable K following K fertilizer applications; and 2) to ascertain how the extractable K was related to tissue K concentrations. Potassium was applied as K_2SO_4 at 6 rates (0, 3, 6, 13, 19, and 25 g K m^{-2} 56 $days^{-1}$) to a creeping bentgrass [*Agrostis stolonifera* var. *palustris* (Huds.) Farw.] putting green grown on a calcareous sand rootzone. The potassium was applied at two week intervals (4 applications within the 56 day period) and repeated during two different irrigation regimes. Soils were sampled and analyzed after the 4th application. Each extraction method detected an increase in soil extractable K following K fertilizer application. The K concentrations were lowest in the water extracts and highest in the Mehlich 3 extracts irrespective of irrigation regime, but less K was recovered under higher irrigation intensity. Creeping bentgrass tissue K content increased with K application rate. However, maximum tissue K content was obtained at lower soil K levels under the high irrigation intensity than under the lower irrigation intensity. Our results show that each extraction method could be used to detect an increase in extractable K and to predict an increase in tissue K content. However, factors other than soil K concentration affected the tissue K content, which suggests that soil K concentrations may not be a reliable predictor of tissue K content in this sand rootzone.

Introduction

Sands are widely used as a well-drained growing medium for turfgrass sites (USGA Staff, 1993). A major disadvantage of both acidic and calcareous sands is the low cation exchange capacity (CEC). Low CEC rootzones are commonly associated with potassium (K) deficiencies (Carrow et al., 2001). The abundance of calcium (Ca) in calcareous sands can also complicate K management (Peech and Bradfield, 1943; Stanford et al., 1941).

Potassium is the most abundant cation in the cytoplasm (Marschner, 1995) and an important macronutrient for turfgrass (Carrow et al., 2001). Potassium makes up one to three percent of turfgrass leaf tissue on a dry weight basis; among the nutrients applied as fertilizer it is second only to nitrogen (N) in quantity (Carrow et al., 2001).

In order to ensure K availability in sands, turfgrass managers are directed to fertilize with equal amounts of K and N (Carrow et al., 2001), although in practice many turfgrass managers apply more K than N (Ervin et al., 2004; Snyder and Cisar, 2000). However, some recent research suggests that K fertilization of sands can have little influence on turfgrass quality (Dest and Guillard, 2001; Johnson et al., 2003; Nikolai, 2002). Published values for the K extracted by various methods in turfgrass sand rootzones are conspicuously absent. An investigation of the ability of different soil tests to predict tissue K concentrations could be the first step in a more effective and science-based approach to K nutrition of sand rootzones.

Different extractants have been used to assess the K status of soils. The method most often used is 1 *M* ammonium acetate (NH_4OAc) buffered at pH 7 (Haby et al., 1990). Common universal extractants used in soil testing include the Mehlich 3 extraction (Mehlich, 1984) and the Morgan extraction (Morgan, 1941). Less common methods used for K extraction are the 1:5 soil-water extraction (Soil and Plant

Analysis Council, 1999) and the 0.01 *M* calcium chloride ($CaCl_2$) extraction (Van Erp et al., 1998). Direct measurement of extractable Ca is complicated by the presence of Ca in the $CaCl_2$ solution. Because of chemical similarities between strontium (Sr) and Ca (Brescia et al., 1988), strontium chloride ($SrCl_2$) is expected to have an extraction efficiency equaling that of $CaCl_2$ while allowing for the determination of Ca in the extract.

Soil K consists of solution, exchangeable, fixed, and structural K (Sparks and Huang, 1985). The amounts of K extracted can be affected by the pH, ionic strength, and ionic composition of the extraction solution as well as soil to solution ratio and shaking time. Because the extraction methods mentioned above vary widely in these characteristics, it is to be expected that extractable K concentrations vary with extraction procedure. The 1:5 water procedure extracts soluble K (Bower and Wilcox, 1965). Although the amount of soluble K is known to vary with the soil:water ratio (Reitemeier, 1946) and extraction time, soluble K is highly correlated with soil solution K (Gillman and Bell, 1978). Extraction methods for the soil solution vary in the quantity of K extracted (Dahlgren, 1993), but a measurement of water soluble K is both highly correlated with soil solution K and simple to reproduce.

A solution containing $CaCl_2$ or $SrCl_2$ may extract the solution K and a portion of the adsorbed K, but should extract less of the adsorbed K than methods which attempt to measure exchangeable K (McLean and Watson, 1985). The NH_4OAc, Mehlich 3, and Morgan procedures extract all of the soluble K, most of the exchangeable K, and small but varying proportions of the fixed and structural K (Haby et al., 1990; McLean and Watson, 1985).

The objectives of this study were to: 1) evaluate six extraction methods (1 *M* NH_4OAc, Mehlich 3, Morgan, 0.01 *M* $CaCl_2$, 0.01 *M* $SrCl_2$, and water) for their ability to extract soil K in a calcareous sand; and 2) to investigate if soil extractable K could be used to manage tissue K concentrations of a creeping bentgrass putting green.

Materials and Methods

A field experiment was conducted on an L-93 creeping bentgrass putting green at the Cornell University Turfgrass and Landscape Center in Ithaca, New York. The putting green was established in 1997 with 4.54 g seed m^{-2} planted on a 30 cm deep rootzone using a calcareous sand (320 g $CaCO_3$ equivalent kg^{-1} soil) mined from glacial deposits at RMS Gravel (Dryden, New York). Sand properties are shown in Table 2.1.

Potassium was applied as K_2SO_4 to 3 m^2 plots using a completely randomized design with 6 K application rates (0, 3, 6, 13, 19, and 25 g K m^{-2} 56 d^{-1} divided in 4 equal applications at 14 day intervals during June and July of 2002). Rates were selected to include a control, and to cover and exceed the range (5-10 g K m^{-2} 56 d^{-1}) frequently applied by turfgrass managers. Each treatment was replicated 4 times. The K was applied with a CO_2-powered backpack sprayer calibrated to deliver 167 ml solution m^{-2} at 345 kPa. Nitrogen (N) was applied at the rate of 2 g N m^{-2} on June 5, June 17, July 1 and September 9, 2001 while 1 g N m^{-2} was applied at 2 week intervals between July 15 and August 26. Phosphorus was applied to all plots at the rate of 1 g P_2O_5 m^{-2} on June 5, July 1, July 29 and August 26.

Sufficient irrigation was applied immediately after fertilization to wash the fertilizer solution from the leaves. Irrigation water contained 5.1×10^{-2} mmol K l^{-1}, and application of 370 mm irrigation in 2002 amounted to the addition of 4.1×10^{-2} mmol K kg^{-1} soil (an insignificant amount compared to the background level in the soil and the amount applied as fertilizer).

Table 2.1. Physical and chemical properties of 0-10 cm RMS sand based putting green soil prior to K application and irrigation treatments.

Parameter	Mean	N	Standard Error
pH (1:1 H_2O)	8.3	24	-
Sand (g kg^{-1})[†]	948	1	-
Silt (g kg^{-1})[†]	35	1	-
Clay (g kg^{-1})[†]	17	1	-
Organic matter (g kg^{-1})	4.0	24	0.01
Bulk density (g cm^{-3})	1.5	4	0.03
Total porosity (%)	43	4	1.0
Total Ca[‡] (mol kg^{-1})	2.39	8	0.057
Total Mg[‡] (mmol kg^{-1})	453	8	12.9
Total K[‡] (mmol kg^{-1})	262	8	5.2
Total Na[‡] (mmol kg^{-1})	176	8	2.8
Nonexchangeable K[§] (mmol kg^{-1})	4.40	3	0.145
Exchangeable K[¶] (mmol kg^{-1})	0.91	24	0.025
Water soluble K[‖] (mmol kg^{-1})	0.20	24	0.006
Cation exchange capacity[#] ($mmol_c$ kg^{-1})	12.0	24	0.07

[†] Particle size analysis by ASTM F-1632-03 (ASTM International, 2003) without destruction of organic matter or carbonates

[‡] Total digestion by EPA Method 3052 (US EPA, 1999)

[§] Nonexchangeable K by boiling HNO_3 (Pratt, 1965)

[¶] Exchangeable K by NH_4OAc (NCR-13, 1988)

[‖] Water soluble K by 1:5 H_2O extraction (Soil and Plant Analysis Council, 1999)

[#] Cation exchange capacity by $BaCl_2$ compulsive exchange (Gillman and Sumpter, 1986)

Soil samples (0-10 cm depth) were collected 13 days after the 4th fertilizer application. These samples are referred to as the July 28 samples. Verdure and thatch were removed from each sample. Soil samples were initially stored in a freezer at -12°C and were thawed, dried and ground to pass 2 mm prior to laboratory analyses.

The green was mowed 6 times weekly at a height of 3.2 mm and clippings were removed. Leaf tissue samples were collected on the same day that soil samples were taken. Tissue samples were analyzed for total K using the dry ash method of Greweling (1976) and tissue N was determined using a C/N analyzer (ThermoQuest Italia, Milan, Italy).

Potassium was extracted from the soil samples using 1 *M* NH_4OAc (NCR-13, 1988), Mehlich 3 (Wolf and Beegle, 1995), Morgan (Morgan, 1941), 1:5 H_2O (Soil and Plant Analysis Council, 1999), 0.01 *M* $SrCl_2$, and 0.01 *M* $CaCl_2$ (Houba et al., 2000). The Mehlich 3 extraction is an unbuffered dilute double acid extraction containing acetic acid, ammonium nitrate, ammonium flouride, nitric acid, and ethylinediaminetetraacetic acid (EDTA) with an initial pH of 2.5. The Morgan solution contains sodium acetate buffered at pH 4.8. Because NH_4OAc is the most commonly used extractant for exchangeable K (Haby et al., 1990), K extraction efficiencies for all other methods were correlated with the K extracted by NH_4OAc.

The 0.01 *M* $SrCl_2$ and 0.01 *M* $CaCl_2$ methods have a 1:10 soil-water ratio and a shaking time of 2 hours versus 30 minutes shaking for the 1:5 H_2O extraction method. To determine if differences between K extraction using the 1:5 H_2O method and the 0.01 *M* $CaCl_2$ method were due to the electrolyte or the soil:solution ratio and shaking time, all July 28 samples were also analyzed using a 1:10 H_2O extraction and a 2 hour shaking time. The pH of the 1:5 H_2O, 0.01 *M* $SrCl_2$, NH_4OAc, Morgan, and Mehlich 3 solutions were measured before mixing with soil and at the end of the extraction procedure (Table 2.2). This was done to determine the final pH of the extracting solution after shaking with the calcareous sand.

Table 2.2. Mean pH of extracting solutions prior to and after extraction of 0-10 cm RMS sand based putting green soil. Measurements were done in six replicates.

Extractant	pH before extraction	pH after extraction
1 *N* NH_4OAc	7.0	7.4
Mehlich 3	2.6	5.2
Morgan	5.0	5.5
1:5 H_2O	5.7	8.2
0.01 *M* $SrCl_2$	5.5	8.2

During June and July, the precipitation to evapotranspiration ratio (P:ET) was 1.2. The entire experiment was repeated on the same experimental units under a more intense irrigation scheme (P:ET = 2.0) in August and September of 2002. Soil samples were taken on September 22, 2002, 13 days after the 4th fertilizer application under more intense irrigation. These samples will be referred to as the September 22 samples.

All statistical analyses were performed using the REG procedure in SAS/STAT software, version 8.02 (SAS Institute, Cary, NC).

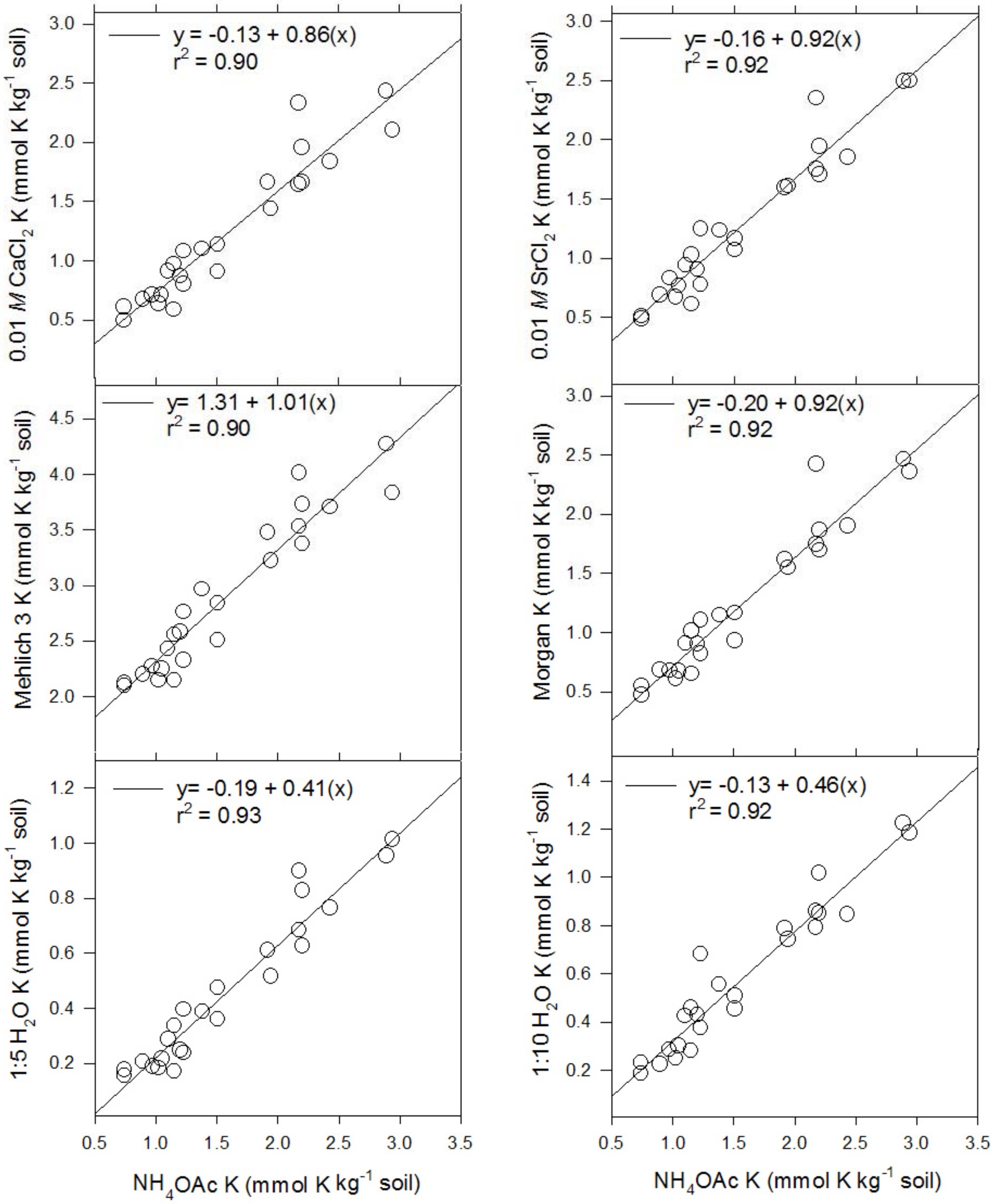


Figure 2.1. Correlation of K extracted by 0.01 *M* $CaCl_2$, 0.01 *M* $SrCl_2$, Mehlich 3, Morgan, 1:5 H_2O, and 1:10 H_2O, with the K extracted by 1 *M* NH_4OAc from 24 soil samples from a calcareous sand putting green.

Results and Discussion

Extraction Methods for Potassium

Under both P:ET regimes, all soil extraction methods gave results that were correlated with the NH_4OAc extractable K. The correlations for the July 28 samples are shown in Fig. 2.1. However, the absolute quantities of K extracted were method and time dependent (Fig. 2.2 and Table 2.3). For the July 28 samples, the Mehlich 3 extraction method removed 1.3 mmol nonexchangeable and structural K kg^{-1} soil in addition to the soluble and NH_4OAc extractable K. Morgan extracted 0.3 mmol K kg^{-1} less than the NH_4OAc.

The relationship between 0.01 *M* $SrCl_2$ and 0.01 *M* $CaCl_2$ extractable K was nearly 1:1 (data not shown). This indicates that 0.01 *M* $SrCl_2$ is a suitable analog for 0.01 *M* $CaCl_2$ in K extraction of the RMS sand. As mentioned in the introduction, the 0.01 *M* $SrCl_2$ has an advantage in that Ca can be easily measured in the extract. The 0.01 *M* $SrCl_2$ and 0.01 *M* $CaCl_2$ extracted 0.3 mmol K kg^{-1} soil less than the NH_4OAc extraction method. Averaged across all K treatments, 0.01 *M* $SrCl_2$ extracted 82% of the K that was extracted by NH_4OAc. These results compare well with those of Vogeler et al. (1997) who found that only 85% of exchange sites as measured by NH_4OAc were actively exchangeable after leaching with $MgCl_2$ for 13 days. Schneider (1997) suggested that the K extracted by NH_4OAc but not by 0.01 *M* $CaCl_2$ was not readily exchangeable with ions in the soil solution and hence largely unavailable to plants. Given the 2 hour shaking time, unbuffered solution and an ionic strength similar to the soil solution ionic strength, our results suggest that the 0.01 *M* $SrCl_2$ and 0.01 *M* $CaCl_2$ extractable K pools may better represent actively exchangeable K, while the 1 *M* NH_4OAc method also extracts part of a less readily exchangeable K pool.

Figure 2.2. Extractable K by 5 soil extraction methods following 4 consecutive K fertilizer applications to a calcareous sand creeping bentgrass putting green. Samples were taken 13 days after the last of the 4 applications.

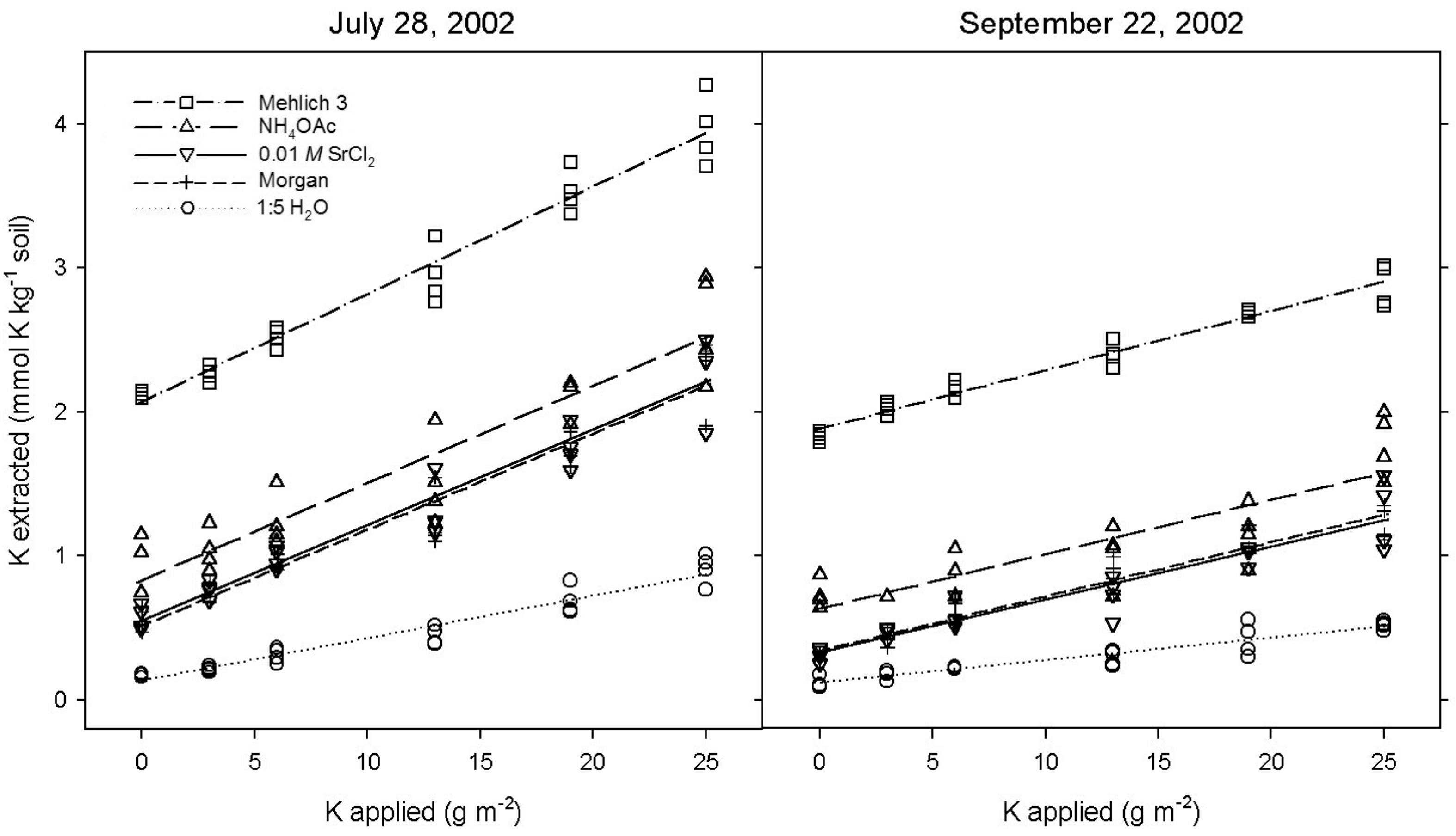

July 28, 2002
September 22, 2002
Mehlich 3
NH_4OAc
0.01 *M* $SrCl_2$
Morgan
1:5 H_2O
K extracted (mmol K kg^{-1} soil)
0
1
2
3
4
0
5
10
15
20
25
K applied (g m^{-2})
K applied (g m^{-2})

Table 2.3. Intercepts (β_o), slopes (β_1), and coefficients of determination (r^2) for K extracted from the surface 0-10 cm of a RMS sand based putting green on July 28 (precipitation to evapotranspiration ratio = 1.2) and September 22 (precipitation to evapotranspiration ratio = 2.0) following previous K applications of 0, 3, 6, 13, 19, and 25 g K m^{-2} 56 days^{-1}.

Extractant	β_o	β_1	r^2	P value
		July 28 samples		
0.01 *M* $SrCl_2$	0.55	0.066	0.93	< 0.0001
1 *N* NH_4OAc	0.83	0.067	0.87	< 0.0001
Mehlich 3	2.07	0.075	0.95	< 0.0001
Morgan	0.51	0.067	0.93	< 0.0001
1:5 H_2O	0.13	0.029	0.93	< 0.0001
		September 22 samples		
0.01 *M* $SrCl_2$	0.33	0.037	0.88	< 0.0001
1 *N* NH_4OAc	0.63	0.038	0.75	< 0.0001
Mehlich 3	1.88	0.041	0.96	< 0.0001
Morgan	0.34	0.038	0.93	< 0.0001
1:5 H_2O	0.11	0.016	0.87	< 0.0001

The 1:5 H_2O method extracted the least K of any of the methods tested. The 1:10 H_2O method with a 2 hour shaking time extracted slightly more K than the 1:5 H_2O method with a 30 minute shaking time. There was also more Ca and Mg extracted by the 1:10 H_2O and 2 hour shaking time than the 1:5 H_2O extraction with the 30 minute shaking time. Similar results were obtained by Reitemeier (1946), who attributed the differences to an increased dissolution of carbonates upon dilution prompting a small amount of ion exchange of Mg and/or Ca for K, thus increasing the

K concentration of the 1:10 H_2O extract as compared to the 1:5 H_2O extract. Since both extraction ratio and shaking time differed between the methods, we cannot attribute the differences to either one.

Because the ionic strengths of the 1:5 and 1:10 H_2O solutions are below that of the soil solution, an overestimation of monovalent cations and an underestimation of divalent cations is expected due to the concentration charge effect (McBride, 1994). The 0.01 *M* $SrCl_2$ solution, with an ionic strength approximating that of soil solution, appeared to be unaffected by this shift between monovalent and divalent cations.

Most soil test extractants used for measurement of sand rootzone K status do not adjust to the pH of the sand (Table 2.2). Because the pH-dependent charge of organic matter is the source of most cation exchange sites in sand rootzones, unbuffered extracting solutions may provide a more accurate measurement of the exchangeable K (Sumner and Miller, 1996). While Morgan extractable K was very similar to that of 0.01 *M* $SrCl_2$ (Figure 2.2 and Table 2.3) the pH of the Morgan solution after shaking with the RMS sand was well below the soil pH (Table 2.2). The ionic strength of the Morgan extractant is also well above that of the soil solution, which may increase the dissociation of organic acids at a given pH (McBride, 1994). Both the pH and ionic strength effects of the NH_4OAc, Morgan and Mehlich 3 extraction methods make it difficult to both predict and interpret the source of the K extracted from sand rootzones with pH-dependent charge.

Effect of Potassium Application on Extractable Potassium

The four sequential K applications increased extractable K for each method under both irrigation regimes (Fig. 2.2). Figure 2.2 and Table 2.3 show that while the NH_4OAc, Mehlich 3, Morgan, and 0.01 *M* $SrCl_2$ methods all extracted roughly the same amount of K with increase in K application in the July 28 samples (slopes varying from 0.066 to 0.075 mmol K kg^{-1} soil per gram of K applied per m^2), the 1:5 H_2O method extracted proportionally less K as the K application rate was increased (slope equaled 0.029 mmol K kg^{-1} soil per gram of K applied per m^2). These results suggest that K application increased the exchangeable K (in addition to soluble K), and that the 1:5 H_2O does not extract K from this exchangeable pool.

Similar results were obtained for the September 22 samples (Fig. 2.2 and Table 2.3). However, there was a net loss in extractable K for all methods under a more intensive irrigation regime (Fig. 2.3), most likely due to K leaching from the rootzone's upper 10 cm. In Fig. 2.3, the dashed line represents the amount of K we would expect to extract on each date if all the applied K was extracted, which for comparison purposes has been calculated for even dispersion of K through the rootzone's 30 cm depth, with no leaching and no plant uptake of K. The K extracted by the various methods, shown on the Y-axis of each plot, was determined by taking the K extracted after 4 fertilizer applications and subtracting the amount of K measured by the same extractant in that plot prior to the first of the 4 fertilizer applications. The result is the net change in K from the beginning to the end of the experimental period for each of the 24 experimental plots. Extractable soil K increased in June and July under the low irrigation regime (Fig. 2.2), so the soil K concentrations were higher at the beginning of the high irrigation regime than they were at the beginning of the low irrigation regime. However, net extractable K decreased with K application under high irrigation (Fig. 2.3), regardless of the method used to extract K from the soil and despite the fact that the same amount of K was added under both irrigation regimes. These results are similar to the decrease in extractable soil K observed under conditions of increased irrigation by Lodge and Lawson (1993). If extractable soil K can be readily influenced by regular turfgrass management practices such as irrigation, it may be difficult to rely upon infrequent

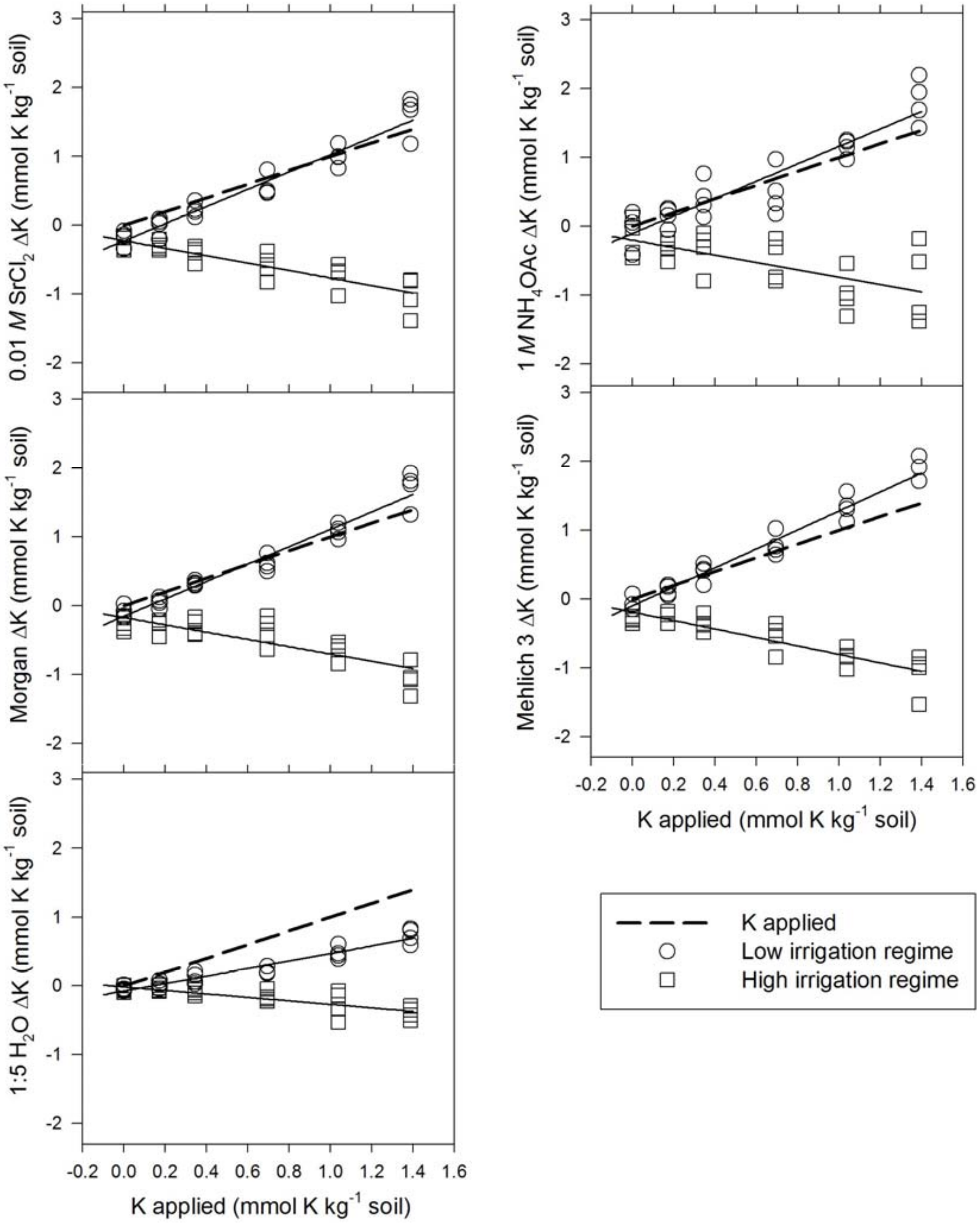


Figure 2.3. Net change in 0.01 *M* $SrCl_2$, NH_4OAc, Morgan, Mehlich 3, and 1:5 H_2O extractable K under low irrigation (○) and high irrigation (□) following 4 fertilizer K applications to a calcareous sand creeping bentgrass putting green. The precipitation to evapotranspiration ratio for the low and high irrigation rates were 1.2 and 2.0, respectively.

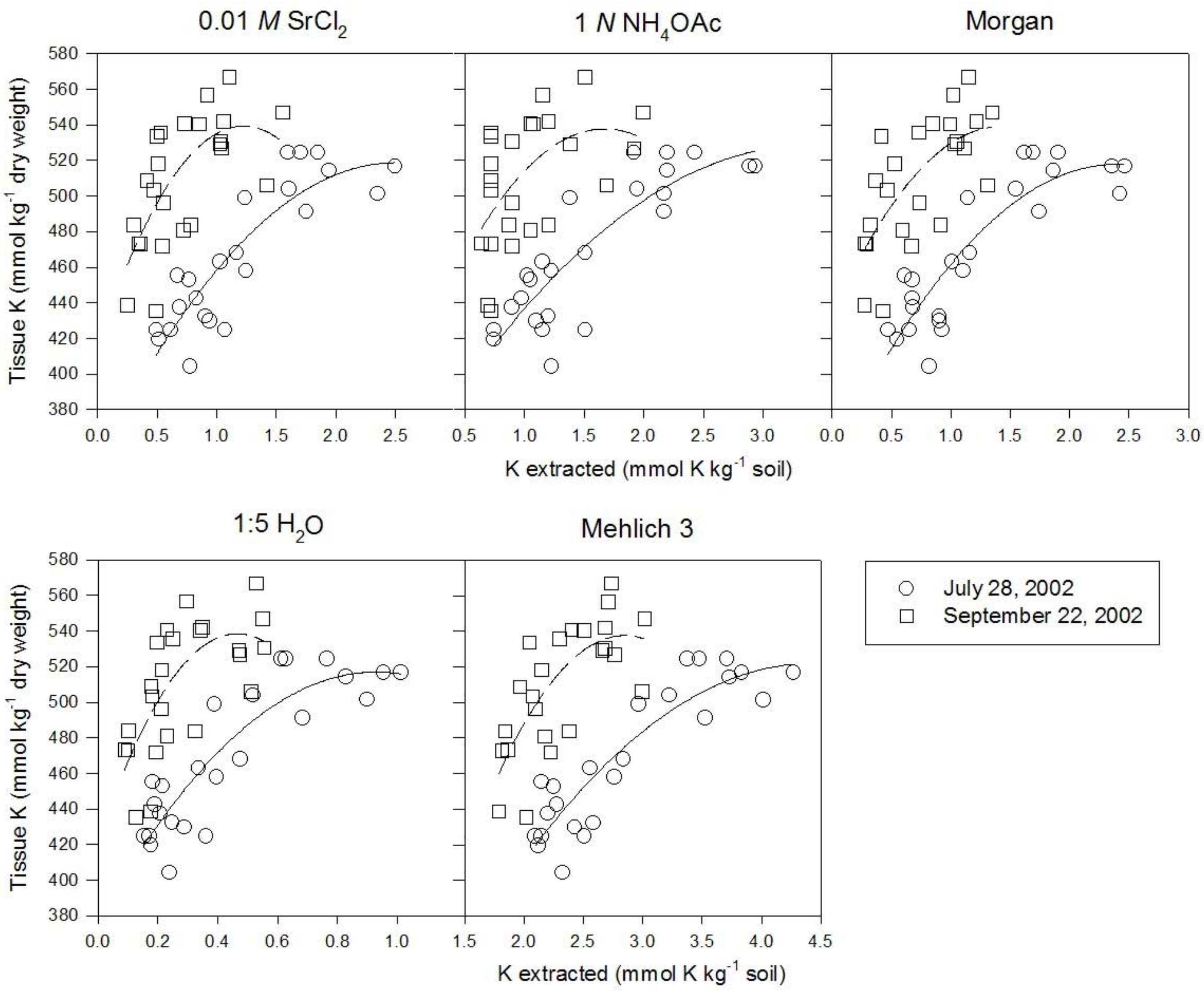
assessment of extractable soil K as the only means of monitoring K availability in sand rootzones.

Soil Test Potassium as a Predictor of Creeping Bentgrass Tissue K Content

The increase in soil test K for all tests was reflected in an increase in creeping bentgrass tissue K content (Fig. 2.4). Thus, on individual sampling dates, soil test K levels were predictive of tissue K content. However, maximum tissue K content was obtained at a lower soil test K level on September 22 as compared to the samples taken on July 28 (Table 2.4). These results indicate that tissue K content could be related to soil test K on individual sampling dates, but factors other than extractable soil K can also influence tissue K concentrations. Such factors could include N fertilization, variations in root activity, seasonal variations in plant requirements for K, changes in soil activity of Ca and Mg, plant growth rate, age of the sampled leaves, and varied soil moisture levels. In our study, the mean N content of tissue samples collected July 28, 2002, was 46 g kg^{-1}; the September 22 samples had a mean N content of 54 g kg^{-1}. It is possible that higher nitrogen fertilization prior to the September 22 sample collection caused this increase in overall tissue K content.

Tissue K contents represent the actual K status of a plant, while soil analysis is used to assess potential availability of K to the plant roots (Marschner, 1995). Waddington et al. (1994) stated that the nutrient status of a turfgrass stand grown in a sand rootzone can be better assessed using tissue nutrient analyses than soil nutrient analyses. Barraclough and Leigh (1993a, 1993b) have demonstrated that variability in tissue K content can be caused by factors other than soil K concentration. Our results support this finding; soil extractable K levels were not consistently predictive of tissue K from July to September, 2002. Where no K was added, standard soil test K results suggested K deficiency while tissue contents were in the reported sufficiency ranges.

Figure 2.4. Relationships between extractable soil K and creeping bentgrass tissue K on July 28 (precipitation to evapotranspiration ratio = 1.2) and September 22 (precipitation to evapotranspiration ratio = 2.0) as determined by the 0.01 *M* $SrCl_2$, NH_4OAc, Mehlich 3, Morgan, and 1:5 H_2O extraction methods.


0.01 M $SrCl_2$
1 N NH_4OAc
Morgan
1:5 H_2O
Mehlich 3
Tissue K (mmol kg^{-1} dry weight)
K extracted (mmol K kg^{-1} soil)
580
560
540
520
500
480
460
440
420
400
380
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.2
0.4
0.6
0.8
3.5
4.0
4.5
July 28, 2002
September 22, 2002

These results suggest that current soil K interpretations for sand putting greens may need to be adjusted, and they indicate limited usefulness of one-time soil sampling for predicting K needs.

Table 2.4. Maximum predicted tissue K content (quadratic model) with associated soil K, coefficient of determination (R^2), and P-value for creeping bentgrass tissue K concentration as predicted by extractable soil K from five different soil extraction methods on July 28 (precipitation to evapotranspiration ratio = 1.2) and September 22 (precipitation to evapotranspiration ratio = 2.0) in 2002.

Soil K extraction method	R^2	P value	Maximum predicted tissue K mmol K kg^{-1} dry matter	Soil test K at maximum predicted tissue K mmol K kg^{-1} soil
		July 28 samples		
0.01 *M* $SrCl_2$	0.78	< 0.0001	519	2.5
1 *N* NH_4OAc	0.73	< 0.0001	525	2.9
Mehlich 3	0.81	< 0.0001	521	4.3
Morgan	0.78	< 0.0001	518	2.4
1:5 H_2O	0.78	< 0.0001	516	1.0
		September 22 samples		
0.01 *M* $SrCl_2$	0.47	0.0012	538	1.1
1 *N* NH_4OAc	0.28	0.0309	532	2.0
Mehlich 3	0.54	0.0003	536	3.0
Morgan	0.48	0.0010	539	1.3
1:5 H_2O	0.45	0.0017	535	0.6

Summary and Conclusion

Application of K fertilizer caused an increase in extractable K from a calcareous sand rootzone for all extraction methods evaluated in this study. All extraction methods exhibited a positive correlation with NH_4OAc for extractable K. Methods differed in the absolute amounts of K extracted, possibly due to differences in extraction pH, ionic strength, and saturating ion. The 1:5 H_2O method did not appear to extract K from the exchangeable pool, indicating that this method may underestimate plant available K. The Morgan and $SrCl_2$ procedures extracted equal amounts of K. Averaged across all K treatments, 0.01 *M* $SrCl_2$ extracted 82% of the K that was extracted by NH_4OAc. Under high irrigation intensity, extractable K decreased when the extractable K at the onset of the high irrigation regime was accounted for. More K was lost from the soil which contained a higher amount of extractable K at the beginning of the high irrigation regime. Furthermore, maximum tissue K concentrations were reached at lower soil test K levels (for all methods) for the samples collected on September 22 as compared to those collected on July 28. We conclude that each of the methods investigated in this study can identify an increase in extractable K after K application, but that extractable K cannot consistently predict tissue K content, indicating that it may be difficult to diagnose K deficiencies in sand rootzones solely with soil tests.

References

ASTM International. 2003. ASTM F-1632-03, standard test method for particle size analysis and sand shape grading of golf course putting green and sports field rootzone mixes. West Conshohocken, PA.

Barraclough, P.B. and R.A. Leigh. 1993a. Critical plant K concentration for growth and problems in the diagnosis of nutrient deficiencies by plant analysis. Plant Soil 155/156:219-222.

Barraclough, P.B. and R.A. Leigh. 1993b. Grass yield in relation to potassium supply and the concentration of cations in tissue water. J. Agric. Sci. 121:157-168.

Brescia, F., J. Arents, H. Meislich, and A. Turk. 1988. General Chemistry. Harcourt Brace Jovanovich, Publishers, Orlando.

Bower, C.A. and L.V. Wilcox. 1965. Soluble salts. *In* C.A. Black (ed.). Methods of Soil Analysis. Part 2. ASA, Madison, WI. pp. 933-951.

Carrow, R.N., D.V. Waddington, and P.E. Rieke. 2001. Turfgrass Soil Fertility and Chemical Problems. John Wiley & Sons, New York.

Dahlgren, R.A. 1993. Comparison of soil solution extraction procedures: effect on solute chemistry. Commun. Soil Sci. Plant Anal. 24(15&16): 1783-1794.

Dest, W.M. and K. Guillard. 2001. Bentgrass response to K fertilization and K release rates from eight sand rootzone sources used in putting green construction. Intl. Turfgrass Soc. Res. J. 9:375-381.

Ervin, E.H., Goatley, J.M. Jr., Richardson, M.D., and G. Munshaw. 2004. Late-season bermudagrass nutrition and cold tolerance: time for a paradigm shift? Golf Course Management. 73(9):81-85.

Gillman, G.P. and L.C. Bell. 1978. Soil solution studies on weathered soils from tropical north Queensland. Aust. J. Soil Res. 16:67-77.

Gillman, G.P. and E.A. Sumpter. 1986. Modification to the compulsive exchange method for measuring exchange characteristics of soils. Aust. J. Soil Res. 24:61-66.

Greweling, T. 1976. Dry ashing. Cornell University Ag. Exp. Sta. Res. Bull. 6(8):4.

Haby, V.A., M.P. Russelle, and E.O. Skogley. 1990. Testing soils for potassium, calcium, and magnesium. *In* R.L. Westerman (ed.). Soil Testing and Plant Analysis, 3rd Ed. SSSA, Madison, WI, pp. 181-227.

Houba, V.J.G., E.J.M. Temminghoff, G.A. Gaikhorst, and W. van Vark. 2000. Soil analysis procedures using 0.01 *M* calcium chloride as extraction reagent. Commun. Soil Sci. Plant Anal. 31:1299-1396.

Johnson, P.G., R.T. Koenig, and K.L. Kopp. 2003. Nitrogen, phosphorus, and potassium responses and requirements in calcareous sand greens. Agron. J. 95:697-702.

Lodge, T.A., and D.M. Lawson. 1993. The construction, irrigation, and fertilizer nutrition of golf greens. Botanical and soil chemical measurements over 3 years of differential treatment. J. Sports Turf Res. Inst. 69:59-73.

Marschner, H. 1995. Mineral Nutrition of Higher Plants. 2nd Ed. Academic Press, San Diego.

McBride, M.B. 1994. Environmental Chemistry of Soils. Oxford University Press, New York.

McClean, E.O. and M.E. Watson. 1985. Soil measurements of plant-available potassium. *In* R.D. Munson, ed. Potassium in Agriculture. ASA, Madison, WI.

Mehlich, A. 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Morgan, M.F. 1941. Chemical soil diagnosis by the universal soil testing system. Conn. Agric. Exp. Sta. Bull. 450.

NCR-13. 1988. Recommended Chemical Soil Test Procedures. North Central Regional Publication No. 221.

Nikolai, T. 2002. Effects of Rolling and Fertility on Putting Green Root Zone Mixes. PhD. dissertation, Michigan State University.

Peech, M. and R. Bradfield. 1943. The effect of lime and magnesia on the soil potassium and on the absorption of potassium by plants. Soil Sci. 55:37-48.

Pratt, P.F. 1965. Potassium. *In* C.A. Black (ed.). Methods of Soil Analysis. Part 2. ASA, Madison, WI. pp. 1022-1030.

Reitemeier, R.F. 1946. Effect of moisture content on the dissolved and exchangeable ions of soils of arid regions. Soil Sci. 61:195-214.

Schneider, A. 1997. Release and fixation of potassium by a loamy soil as affected by initial water content and potassium status of soil samples. Euro. J. Soil Sci. 48:263-271.

Snyder, G.H. and J.L. Cisar. 2000. Nitrogen/potassium fertilization ratios for bermudagrass. Crop Sci. 40:1719-1723.

Soil and Plant Analysis Council. 1999. Major cations (potassium, calcium, magnesium, and sodium). *In* Soil Analysis: Handbook of Reference Methods. CRC Press, Boca Raton, FL. pp. 93-115.

Sparks, D.L. and P.M. Huang. 1985. Physical chemistry of soil potassium. *In* R.D. Munson, ed. Potassium in Agriculture. ASA, Madison, WI.

Stanford, G., J.B. Kelly, and W.H. Pierre. 1941. Cation balance in corn grown on high-lime soils in relation to potassium deficiency. Soil Sci. Soc. Am. Proc. 6:335-341.

Sumner, M.E. and W.P. Miller. 1996. Cation exchange capacity and exchange coefficients. *In* D.L. Sparks (ed.). Methods of Soil Analysis. Part 3. Chemical Methods. SSSA, Madison, WI. pp. 1201-1229.

US EPA. 1999. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods. EPA Publication SW-846. (Available on-line with updates at http://www.epa.gov/epaoswer/hazwaste/test/pdfs/3052.pdf).

USGA Staff. 1993. USGA recommendations for a method of putting green construction. USGA Green Section Record. 31:(2)1-3.

Van Erp, P.J., V.J.G. Houba, and M.L. van Beusichem. 1998. One hundredth molar calcium chloride extraction procedure. Part I: a review of soil chemical, analytical, and plant nutritional aspects. Commun. Soil Sci. Plant Anal. 29:1603-1623.

Vogeler, I., D.R. Scotter, B.E. Clothier, and R.W. Tillman. 1997. Cation transport during unsaturated flow through two intact soils. Euro. J. Soil Sci. 48:401-410.

Waddington, D.V., Gover, A.E., and D.B. Beegle. 1994. Nutrient concentrations of turfgrass and soil test levels as affected by soil media and fertilizer rate and placement. Commun. Soil Sci. Plant Anal. 25(11&12):1957-1990.

Wolf, A. and D. Beegle. 1995. Recommended soil tests for macronutrients: phosphorus, potassium, calcium, and magnesium. *In* Recommended Soil Testing Procedures for the Northeastern United States. 2nd Ed. University of Delaware Agricultural Experiment Station, Newark, DE.