Potassium Availability Indices and Turfgrass Performance in a Calcareous Sand Putting Green

Micah S. Woods,* Quirine M. Ketterings, Frank S. Rossi, and A. Martin Petrovic

ABSTRACT

Turfgrass managers regularly apply K to creeping bentgrass [*Agrostis stolonifera* var. *palustris* (Huds.) Farw.] putting greens on the basis of soil test results or in some relation to annual N fertilizer rates. In the many putting greens that have sand rootzones, K is susceptible to leaching, and in calcareous sands, K availability is further limited by high Ca levels. The K requirements for calcareous sand putting greens are not clear. A 2-yr field study was conducted on an L-93 creeping bentgrass putting green grown on a calcareous sand rootzone at Ithaca, NY. Potassium fertilizer was applied with N in 167 mL H_2O m^{-2} at 0, 1, 2, 3, 5, and 6 g K m^{-2} 14 d^{-1} during the 2002 and 2003 growing seasons. Leaf tissue samples were collected monthly, and soil samples were collected every 56 d. Turfgrass performance characteristics such as color, quality, and ball roll were evaluated visually and quantitatively. Without K addition, soil test K indicators decreased over time, and low levels of soil K (<1.25 mmol 1 *M* NH_4OAc-K kg^{-1}) were prevalent in all plots receiving the lowest (<2 g K m^{-2} 14 d^{-1}) K rates. Potassium application had no beneficial effects on turfgrass performance. We conclude that acceptable creeping bentgrass performance can be achieved across a wide gradient of soil K levels and tissue K contents (255–639 mmol kg^{-1} dry weight) in calcareous sand rootzones. Recommended levels of soil and tissue K should be reevaluated to avoid gratuitous use of K fertilizers.

Sand rootzones are commonly used as a growing medium for intensively maintained turfgrass sites. Potassium (K) availability may be limited because of the low cation exchange capacity (CEC) of sands (Carrow et al., 2001b). Additionally, K mobility in sands is high compared with other nutrient cations such as calcium (Ca) and magnesium (Mg) (Spencer, 1954), and water movement through the rootzone can accelerate K leaching (Lodge and Lawson, 1993). For this reason, it is generally recommended to make multiple K applications per year to maximize turfgrass performance (Carrow et al., 2001b).

Calcareous soils cover about 8 × 10^8 ha of the earth's land area (FAO, 1999). The precise distribution of calcareous sands is not known, but calcareous sands are geographically ubiquitous and are in common use as rootzones for turfgrass sites (Christians, 1990; Lawson and Baker, 1987). Alkaline pH is not thought to influence K uptake; however, high Ca or Mg levels could inhibit K uptake (Stanford et al., 1941).

Rapid laboratory procedures are used to assess K availability. These tests involve the extraction of soil K, with each soil testing procedure extracting a different proportion of the total soil K. An evaluation of six soil 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 quantify extractable K showed that the methods differed in total extracted K but were equally effective in detecting K fertilization-induced changes in extractable soil K (Woods et al., 2005). Because methods differ in soil:solution ratio, pH, ionic composition, and shaking time, different testing methods extract different pools of soil K. Plant-available K and the pools from which soil K is extracted are discussed in detail in McClean and Watson (1985). Laboratories select a particular extraction method on the basis of convenience, cost, and effectiveness. A suitable testing method should be able to predict K uptake, tissue K content, or turfgrass performance. The relationship between extractable soil K and turfgrass tissue K content or turfgrass performance is distinguished by a general incoherence that limits the precision with which one can interpret soil tests for K (Carrow et al., 2001a; Fulton, 2002; Waddington et al., 1994; Woods et al., 2005).

The literature shows conflicting results with regard to the effect of K application on cool-season turfgrass performance in both calcareous and noncalcareous rootzones (Turner and Hummel, 1992). Some studies showed that K fertilizer applications improved turfgrass performance (Christians et al., 1981; Goss and Gould, 1968a); others found no effect of K applications (Dest and Guillard, 2001; Fulton, 2002; Johnson et al., 2003; Nikolai, 2002; Turner and Waddington, 1983); several studies have reported detrimental effects of K application (Bengston and Davis, 1939; Goss and Gould, 1968b; Hall, 1912; Lawson, 1999). Investigations by Holt and Davis (1948) and Reid (1933) showed that K deficiency inhibited bentgrass root growth. Markland and Roberts (1967) showed that K addition beyond the increment required to eliminate the deficiency caused decrease in root fresh weight. Turner and Hummel (1992), in reviewing the effect of K on turfgrass maintenance, concluded that results are conflicting for a number of development and quality parameters such as root growth, shoot growth, color, and disease intensity. Thus, additional research is needed to investigate the effects of K fertilizer on growth and performance of turfgrass grown specifically on calcareous sands, where K management could be complicated by inherent chemical factors.

We investigated the effects of K fertilizer application on creeping bentgrass performance and on soil and plant K availability indicators in a calcareous sand putting green. Our objectives were to: (i) describe the temporal variation in soil and plant K availability indicators as

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affected by K fertilizer application and (ii) determine if turfgrass performance was influenced by K-induced changes in the availability indices.

MATERIALS AND METHODS

A 2-yr study was conducted on a 30-cm calcareous sand rootzone (RMS Gravel, Groton, NY) seeded to L-93 creeping bentgrass at 4.5 g m^{-2} in 1997 at the Cornell University Turfgrass and Landscape Research and Education Center at Ithaca, NY. This site was maintained as a research putting green. Soil samples collected at the beginning of the study had a pH (1:1 H_2O) of 8.2 to 8.4, $CaCO_3$ equivalent of 320 g kg^{-1}, compulsive exchange CEC of 12 $mmol_c$ kg^{-1} (standard error = 0.07), nonexchangeable K of 4.4 mmol kg^{-1} (standard error = 0.145), and bulk density of 1.54 g cm^{-3} (standard error = 0.03); additional physical and chemical properties of this sand can be found in Woods et al. (2005). At the onset of the trial (Fig. 1), the site was classified as low in 1 *M* NH_4OAc and Morgan K, and medium in Mehlich 3 K (Carrow et al., 2004).

The green was mowed 6 d per week at 3.2 mm with clippings removed. Irrigation (pH from 5.1–7.7) was applied at the onset of drought stress through an automated irrigation system calibrated to deliver 1.8 cm water per irrigation event. The frequency of irrigation varied because no irrigation was applied until leaf wilting was observed. Monthly precipitation and irrigation are shown in Fig. 2. Curative fungicides and insecticides were applied when necessary to control black cutworm [*Agrotis ipsilon* (Hufnagel)] and dollar spot (caused by *Sclerotinia homoeocarpa* F.T. Bennett). Traffic was applied 6 d per week with a custom-fabricated pull-behind asynchronous double-cylinder roller with golf spikes (Softspike, Gaithersburg, MD) attached to each cylinder. This roller applied 257 spike imprints m^{-2} in one pass, and on an annual basis was used to produce traffic equivalent to that of 30c000 golfers, with each golfer taking 52 random paces on greens averaging 511 m^2 in shoes with 11 spikes attached to each sole. Topdressing sand (Cushion Sand, Hanson Aggregates, Poland, NY) was applied monthly from June through October at 1.9 kg m^{-2}. This calcareous topdressing sand had a pH of 8.5 and Mehlich 3 extractable K of 0.73 mmol kg^{-1}, resulting in a sand-applied K fertilization rate of 327 mg m^{-2} yr^{-1}. The rootzone sand had an initial Mehlich 3 extractable K of 2.2 mmol kg^{-1}, and the lowest Mehlich 3 K was 1.2 mmol kg^{-1} in March 2004. Because the K concentration of the topdressing sand never exceeded the K concentration of the rootzone material, the effect of topdressing

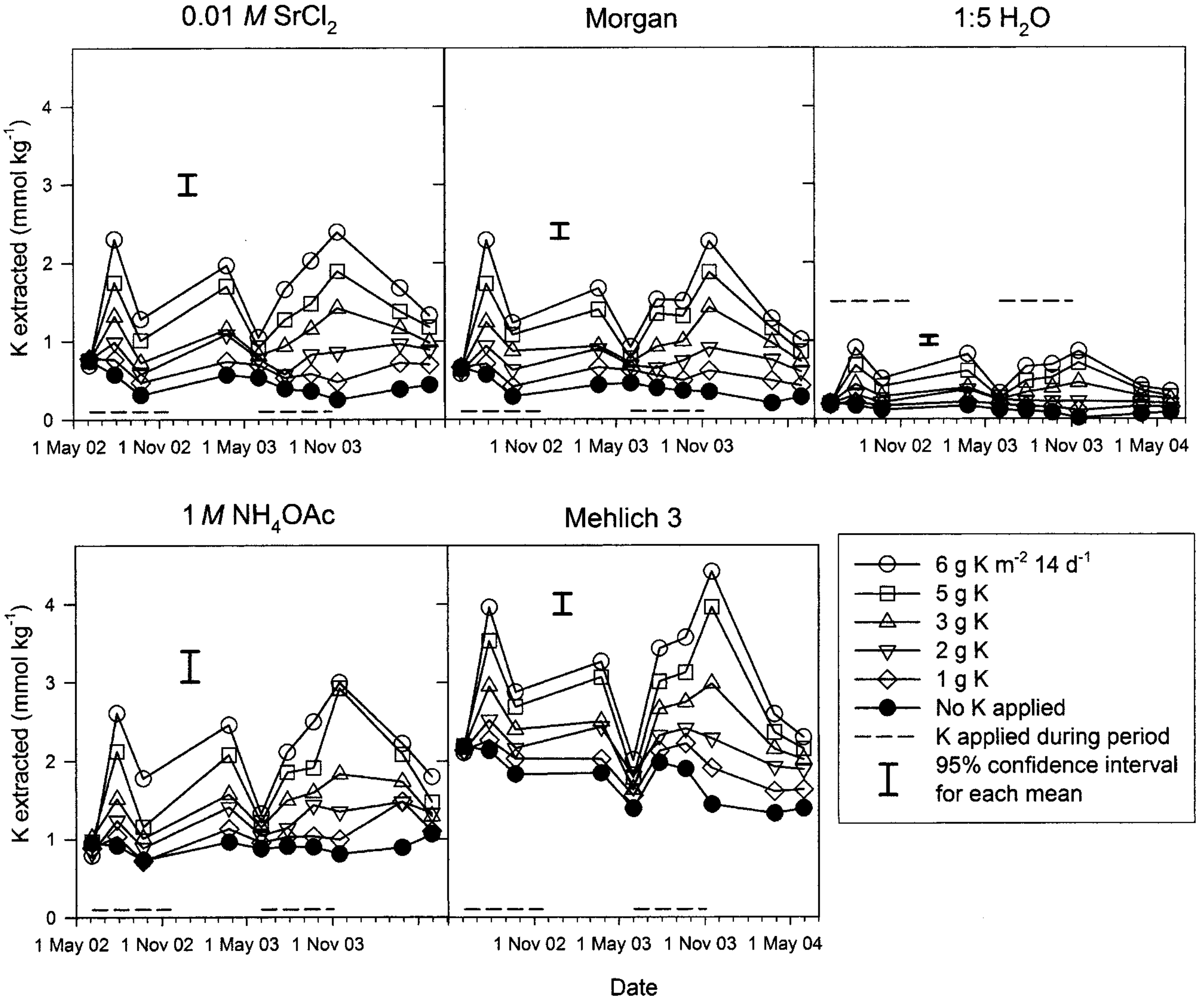

Fig. 1. Mean K extracted by 0.01 *M* $SrCl_2$, 1 *M* NH_4OAc, Mehlich 3, Morgan, and 1:5 H_2O, from a calcareous sand rootzone at Ithaca, NY, to which six rates of K fertilizer were applied from 2002 to 2004.

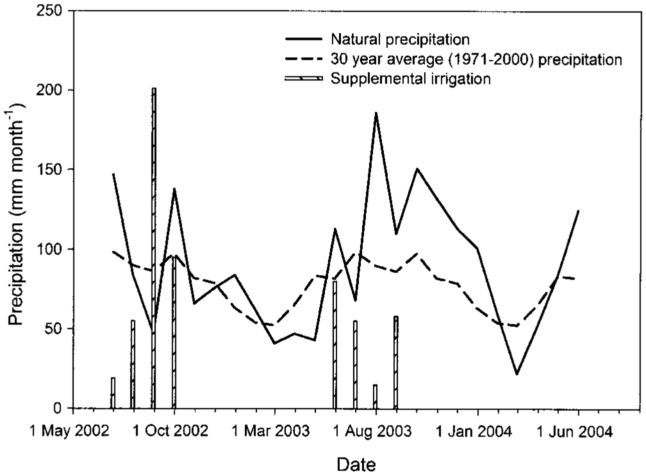

Fig. 2. Precipitation and irrigation from June 2002 through May 2004 at the test site in Ithaca, NY. Thirty-year precipitation averages (1971–2000) are shown for comparison.

was to slightly dilute the soil K concentration as expressed on a mmol kg^{-1} basis.

Experimental units were laid out as 3-m^2 rectangular plots on the putting green. There were four replications of each K treatment arranged in a completely randomized design. All applications were made with a CO_2–pressurized sprayer (R&D Sprayers, Opelousas, LA) calibrated to deliver 167 mL solution m^{-2} at 345 kPa. Potassium fertilizer was applied to the plots as K_2SO_4 at 6 rates (0, 1, 2, 3, 5, and 6 g K m^{-2}) at 14-d intervals during the 2002 and 2003 growing seasons. Thirteen applications were made in 2002 from 5 June to 19 November; 12 applications in 2003 were sprayed from 2 June to 1 November. Nitrogen was applied as urea and monoammonium phosphate. The N was applied equally to each plot and in conjunction with the K. In 2002, 19 g N m^{-2} were applied, and 13.5 g N m^{-2} were applied in 2003. Phosphorus was applied as monoammonium phosphate once every 28 d. In both years 3 g P m^{-2} yr^{-1} were applied. Morgan extractable P at the beginning of the study was 6 mg P kg^{-1} (standard error = 0.1). This is classified as below the medium sufficiency range (Carrow et al., 2004), and we followed the spoon-feeding approach recommended by Carrow et al. (2001b) to ensure P availability. No other fertilizers were applied over the course of the study. Leaf nutrient content of all essential plant nutrients was evaluated monthly during the growing season to ensure that no deficiencies required correction. Irrigation and rain water contained negligible concentrations of fertilizer nutrients.

Leaf tissue samples were collected before the first fertilizer application and on 14 subsequent occasions from 2002 to 2004. During the growing season, tissue samples were collected every 28 d; each tissue sampling was made 13 d after the most recent fertilization event. A Toro 1000 walking greensmower was used to collect clippings from the plots. Clippings were dried and analyzed for nonacid cation content using the dry ash method (Greweling, 1976) with determination of nonacid cations in solution by ICP (Thermo Jarrell-Ash Model 975, Waltham, MA). The N content of each clipping sample was measured with a C/N analyzer (ThermoQuest Italia, Milan, Italy). Leaf chlorophyll, used as a quantitative indicator of turfgrass color (Johnson, 1974), was determined on a fresh weight basis by acetone extraction and light absorbance measurements at 645 and 663 nm. Visual ratings of turfgrass color and quality were made at tissue collection using the National Turfgrass Evaluation Program (NTEP) rating scale of 1 to 9, with 1 representing dead turf, 6 implying acceptable quality and/or color, and 9 reserved for perfect turf.

Soil samples were collected before the first fertilizer application and on nine subsequent occasions. Samples were collected every 56 d during the 2002 and 2003 growing seasons, and additional samples were collected in March of each year to measure soil K levels at the end of winter. The samples collected in July, September, and November were collected 13 d after the previous fertilizer application; the samples collected in March, May, and June were collected 4, 6, and 6 mo after the previous fertilizer application. At each sampling date, 5 cores m^{-2} were collected to a depth of 10 cm with a 1.9-cm-diam. core sampler. Verdure and thatch were removed from each sample. The soil samples were stored at −14°C until they were prepared for nutrient analysis. Potassium was extracted from each sample using Mehlich 3 (Wolf and Beegle, 1995), Morgan (Morgan, 1941), 1 *M* NH_4OAc (Brown and Warncke, 1988), 1:5 H_2O (Soil and Plant Analysis Council, 1999), and 0.01 *M* $SrCl_2$ [substituted for 0.01 *M* $CaCl_2$ in the method of Houba et al. (2000)]. Mehlich 3, Morgan, and NH_4OAc are soil testing methods that are commonly used to derive K recommendations in the turfgrass industry (Carrow et al., 2004), and the 1:5 H_2O and 0.01 *M* $SrCl_2$ show potential as more sensitive indicators of K availability (Woods et al., 2005).

Disease damage from dollar spot and gray snow mold (*Typhula* spp.) was visually evaluated as percentage of plot area affected when the damage was observed. Laboratory confirmations of the disease organisms were not conducted.

Ball roll was measured in triplicate and in two directions using a stimpmeter (USGA, Far Hills, NJ). The stimpmeter reading was taken as the average of distance rolled in the first and second directions. The difference in roll between the two directions never exceeded 457 mm.

Ash-free root weight was determined for samples collected on 24 Aug. 2003, 16 Nov. 2003, and 30 May 2004. One 1.9-cm diam core plot^{-1} was taken to a depth of 20 cm and the sample was divided into a 0- to 10-cm section and a 10- to 20-cm section. These samples were stored at −14°C until roots were separated from soil using the screen method described in Böhm (1979). Roots were ashed at 500°C for 2 h to obtain the ash-free root weights (Willard and McClure, 1932).

The experiment consisted of treatments and observations made on experimental units arranged in a completely randomized design between treatments and with repeated measures over time within treatments. Data analysis was performed with SAS version 8.2 (SAS Institute, Cary, NC). Treatment effects on the various response variables were evaluated using linear mixed models in PROC MIXED. Appropriate covariance structures for the correlation between repeated measures on the same experimental unit were selected as described by Littell et al. (2002) and Wolfinger (1993). Simple regressions between quantitative variables at individual dates were performed using PROC REG. Regression analysis of replicated data was conducted with the mean instead of all replicate values (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Soil K Dynamics Over Time

Application of less than 2 g K m^{-2} 14 d^{-1} was insufficient to maintain soil K concentrations at their pretreatment levels. Potassium application rates greater than 2 g K m^{-2} 14 d^{-1} tended to increase soil K concentrations above the levels measured at the beginning of the experiment (Fig. 1). Although extracting solutions

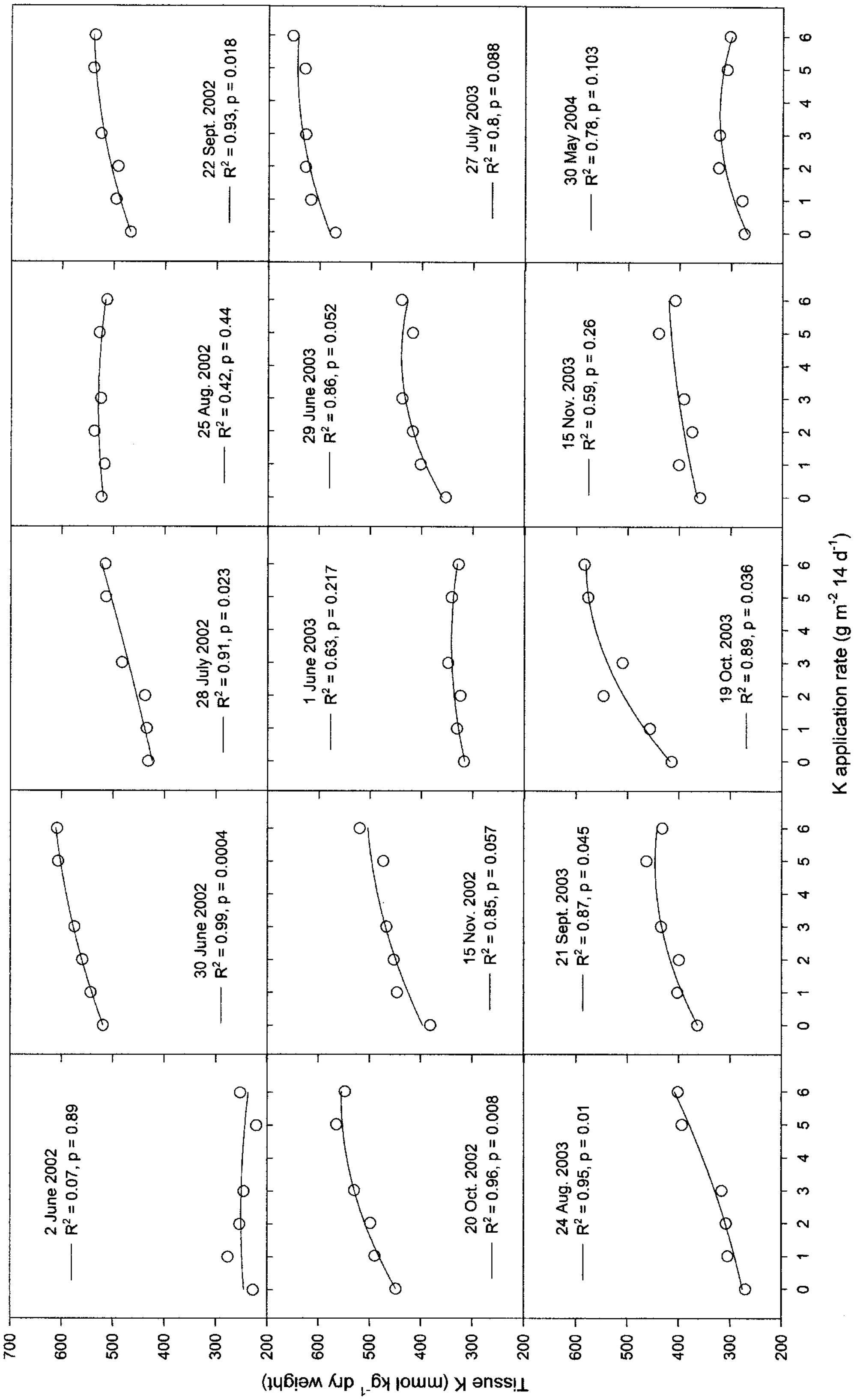

Fig. 3. Relationship between K application rate to a calcareous sand putting green at Ithaca, NY, and the associated creeping bentgrass leaf tissue K content at 15 sampling events from 2002 to 2004.

differed in extractable K concentrations, each extractant adequately detected changes in soil K.

Surprisingly, differences in soil K concentration established by K fertilization persisted for more than 7 mo after K fertilizer applications ceased in spite of the highly leachable character of the sand (Fig. 1). This result was unexpected, as K is known to be susceptible to leaching from sand rootzones (Carrow et al., 2001b; Lodge and Lawson, 1993; Sheard et al., 1985; Spencer, 1954). Particularly in this calcareous sand rootzone, with a relatively low CEC and an infiltration rate of 50.8 cm h^{-1}, it seemed improbable that the adsorbed K would remain in the 0–10 cm profile of the rootzone for up to 7 mo. We speculate that nonexchangeable K was increased in plots receiving the higher rates of K and that this pool served to resupply K to exchangeable and soluble forms when solution K^+ activity decreased after leaching. When less than 2 g K m^{-2} 14 d^{-1} were applied, extractable K increased from March to June even though no K treatments were made. This also suggests that nonexchangeable K was being released to exchangeable and soluble pools but less so than in plots which received the higher rates of K fertilizer in the preceding year.

Tissue K Content

Tissue K content when no K was applied varied over time from less than 255 mmol K kg^{-1} at the onset of the trial to over 500 mmol K kg^{-1} in June 2002 and July 2003 (Fig. 3). Tissue K contents were below the 383 to 767 mmol K kg^{-1} (15 to 30 g K kg^{-1}) sufficiency range identified in Carrow et al. (2001b) on eight of the 15 sampling days and below the 255 to 639 mmol K kg^{-1} (10–25 g K kg^{-1}) range suggested by Jones (1980) on just one of the sampling days. Potassium application increased leaf K content on most sampling dates (Fig. 3) and leaf tissue K content was positively correlated with tissue N content (Fig. 4).

The leaf tissue K content in the plots receiving the highest K application rate (6 g K m^{-2} 14 d^{-1}) was noticeably lower (Fig. 3) than the upper limits of the sufficiency ranges reported by both Carrow et al. (2001b) and Jones (1980). Calcium activity in the soil solution is known to affect K uptake (Beckett, 1972), and the leaf tissue K content of creeping bentgrass grown in acid sands (pH 5.4) has been found to be greater than in calcareous sands (pH 7.3) (Sheard et al., 1985). We suspect that high Ca^{2+} activity in this calcareous sand may have depressed K uptake. Calcium extracted by 1:5 H_2O ranged from 0.8 to 1.7 mmol kg^{-1} over the course of this experiment; by comparison, the mean water extractable Ca in a selection of 26 noncalcareous sands was 0.25 mmol kg^{-1} (standard error = 0.05) (Woods, unpublished data, 2005). It is expected that similarly high K application rates in sands with lower Ca^{2+} activity would result in higher tissue K content.

Soil K Effect on Tissue K

There was an inconsistent relationship between soil and tissue K levels throughout the study (Table 1). For example, all soil test levels implied the need for additional K according to interpretations reported in Carrow et al. (2004), but the mean tissue K content in the plots receiving no K in this study was within the sufficiency ranges for K on 45 and 90% of the 15 sampling days according to classifications by Carrow et al. (2001b) and Jones (1980), respectively. This supports the findings of Dest and Guillard (2001) and Colby and Bredakis (1966) who suggested that the ability of bentgrass species to utilize K from nonexchangeable forms in the soil may diminish the value of a standard soil test in prediction of K availability to bentgrass roots.

In the absence of predictive relationships between soil test K and turfgrass performance (Carrow et al., 2001b; Fulton, 2002; Johnson et al., 2003; Nikolai, 2002) or leaf tissue K content (Woods et al., 2005), we find it difficult to interpret routine soil tests for K in sand rootzones. The variability in tissue K content between sampling dates limits the usefulness of standard soil nutrient analyses (Mehlich 3, Morgan and NH_4OAc methods) for assessment of K status in creeping bentgrass putting greens (Fig. 5). Soil testing seems a better tool for predicting tissue K status when tissue K status is expressed

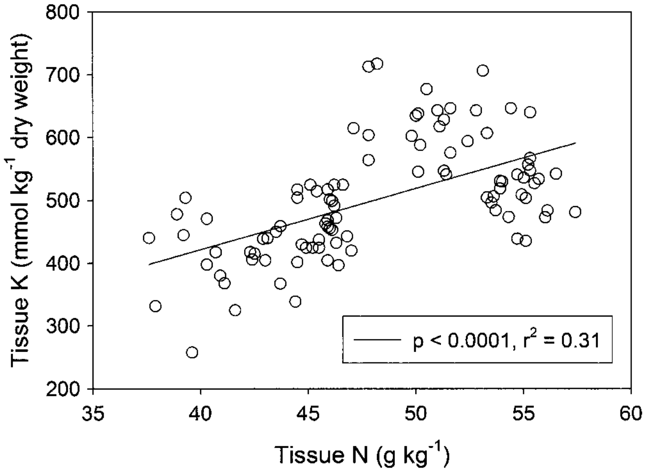

Fig. 4. The effect of creeping bentgrass leaf N content on corresponding leaf K content. Data shown are from a calcareous sand putting green at Ithaca, NY, with leaf samples collected on 28 July and 22 Sept. 2002 and 27 July and 16 Nov. 2003.

Table 1. Coefficient of determination for the simple linear regression between extractable soil K (mmol kg^{-1}) and tissue K content (mmol kg^{-1} dry weight) for five extraction methods and five sampling dates. Data are from creeping bentgrass grown at Ithaca, NY.

Soil K extraction method	Date 28 July 2002	22 Sept. 2002	27 July 2003	21 Sept. 2003	16 Nov. 2003
1 *M* NH_4OAc	0.71***	0.23*	0.15	0.37**	0.10
Mehlich 3	0.78***	0.48**	0.14	0.48***	0.06
Morgan	0.72***	0.46**	0.12	0.47***	0.08
1:5 H_2O	0.72***	0.39**	0.07	0.44***	0.05
0.01 *M* $SrCl_2$	0.73***	0.38**	0.19*	0.39**	0.02

* Regression significant at 0.05 level.
** Regression significant at 0.01 level.
*** Regression significant at 0.001 level.

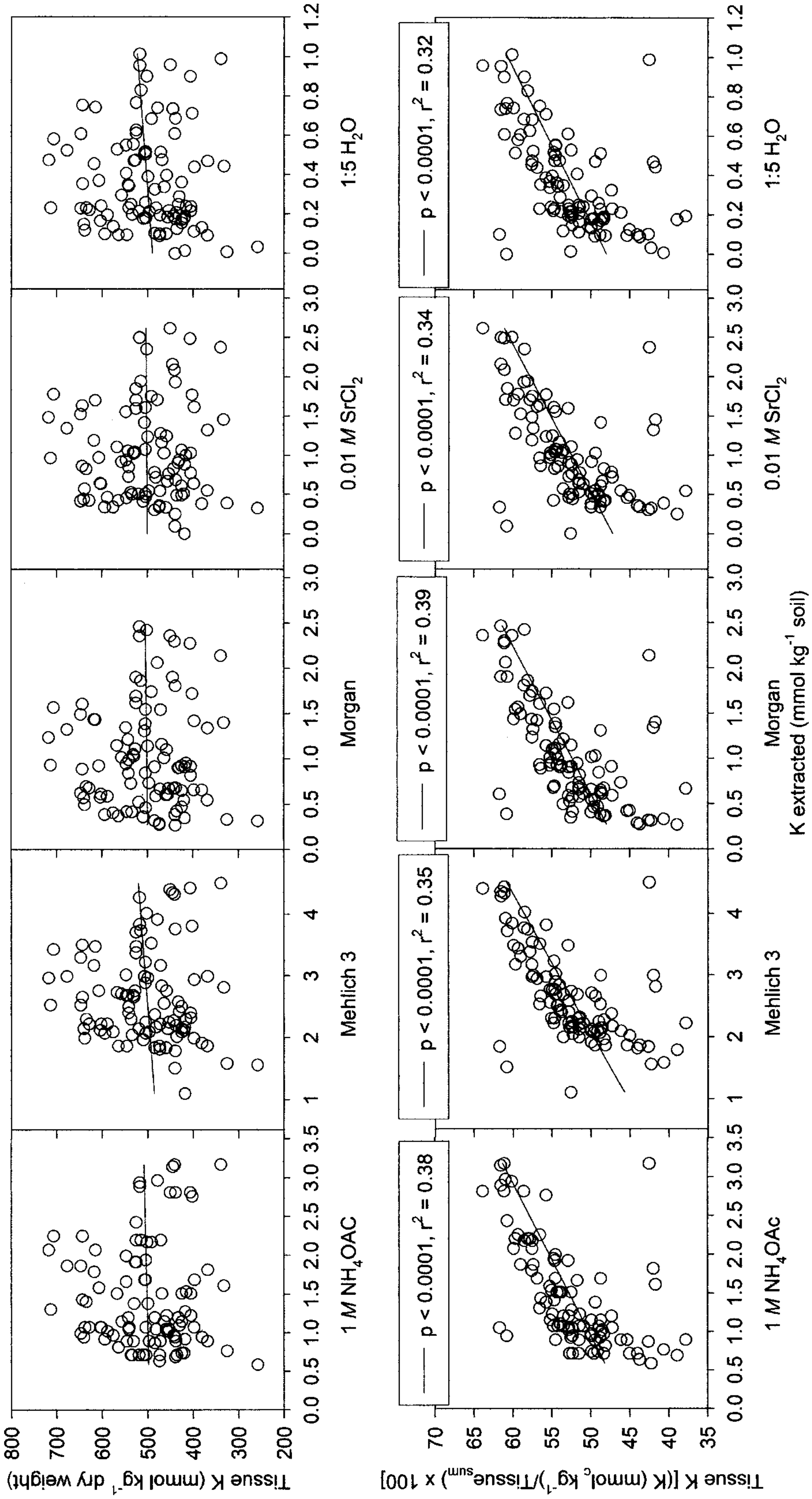

Fig. 5. Relationship between K extracted from a calcareous sand putting at Ithaca, NY, and corresponding creeping bentgrass leaf K content. Data are from soil and leaf samples collected on 28 July and 22 Sept. 2002 and 27 July and 16 Nov. 2003. Results for five different soil extraction procedures are shown. Upper plots show the relationship between extracted soil K and leaf tissue dry weight K content. The lower plots keep extracted soil K the same, but express the leaf tissue K as a percentage of the sum of positive charge from leaf nonacid cations.

as a ratio of K and the other nonacid cations Ca, Mg, and Na:

$$K\% = \text{Tissue K } (\text{mmol}_c\ \text{kg}^{-1}) \div \text{Tissue}_{\text{sum}} \times 100 \quad [1]$$

where $\text{Tissue}_{\text{sum}}$ is the sum of the positive charge of tissue Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} in $\text{mmol}_c\ \text{kg}^{-1}$ tissue dry weight. Figure 5 shows that soil K levels, even across different sampling dates, show a positive relationship with tissue K expressed according to Eq. [1]. More work remains to be done in evaluating the relationships between extractable soil K and tissue K content in a wide range of sand rootzones; it is not clear whether this relationship between soil K and tissue K% would hold on a larger dataset encompassing sands of varying mineralogy.

Turfgrass Performance

Others have observed spring chlorosis in plots receiving no K (Waddington et al., 1978), but under our conditions, with soil K levels as shown in Fig. 1 and tissue K content as shown in Fig. 3, the color ratings were not influenced by K addition. The mean color at 15 rating events from 2002 to 2004 was 6.2 (standard error = 0.05) with the lowest rating a 4 on 4 June 2002 and the highest rating a 7.5 on 21 Sept. 2003. Leaf chlorophyll content, which averaged 2.2 mg g^{-1} fresh weight (standard error = 0.03), was not influenced by K application rate or K availability indicators on any of the dates when tissue was collected.

The roll of a ball across the putting surface is perhaps the most important quality parameter of a putting green (Nikolai, 2005). Ball roll is affected by shoot growth (Nikolai, 2005), and a study by Reid (1933) showed that K application increased shoot growth of creeping bentgrass grown in sand culture. In our study, with dry matter clipping yield ranging from 0.18 to 1.46 g m^{-2} d^{-1} at 7 measurements of clipping yield from 2002 to 2004, there were no effects of K application, soil K concentration, or leaf tissue K content on clipping yield. Ball roll measurements in the summer of 2002 exceeded 3 m at all measurement dates and could not be used for treatment comparisons because the roll in at least one direction extended the complete length of each experimental unit; ball roll on six measurement dates from 21 July to 6 Sept. 2003 ranged from 2.7 to 3.0 m and was affected by measurement date but not by K application.

Dollar spot infection was not affected by K application. However, gray snow mold damage observed in the springs of 2003 and 2004 was increased ($p < 0.01$) in plots receiving higher rates of K fertilizer (Fig. 6). There was also more rapid spring growth in 2003 in plots which received no K fertilizer in the previous year. Similar effects of K addition on spring green-up were seen by Waddington et al. (1972).

Ash-free root weights at 0- to 10-cm depth were not affected by K application rate. At the 10- to 20-cm depth, the mean ash-free root weight was 6.9 mg sample^{-1} in plots receiving K rates of 0, 1, and 2 g m^{-2} 14 d^{-1}, and the mean ash-free root weight was 4.5 mg sample^{-1} in the plots receiving 3, 5, and 6 g K m^{-2} 14 d^{-1}. The probability of observing such a difference if the true

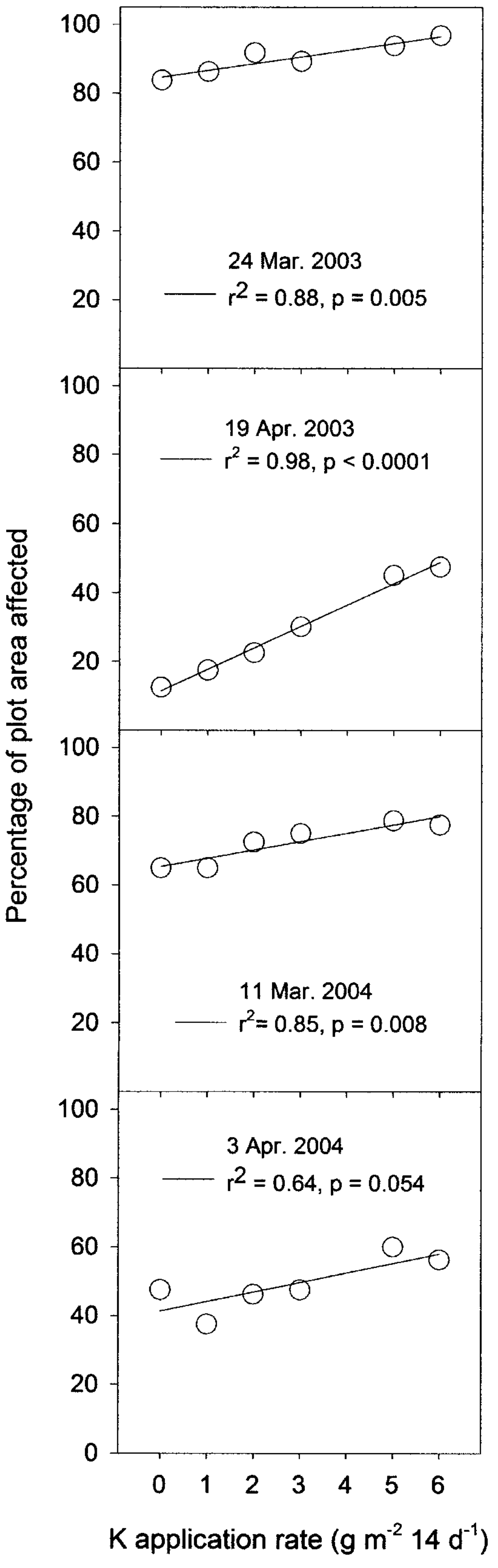

Fig. 6. Visual ratings of gray snow mold (*Typhula* spp.) damage as percentage of plot area affected following snow melt at Ithaca, NY, in 2003 and 2004.

difference was zero is 0.0023. We did not measure soil K levels below 10 cm, so we cannot directly associate soil K with ash-free root weight. However, Cherney et al. (2004) found 21% more root production in reed canarygrass (*Phalaris arundinacea* L.) when N was applied without K. The difference we observed in ash-free root weight may have been a growth response as the bentgrass roots explored the rootzone for K.

CONCLUSIONS

Tissue K content was increased by all K application rates but remained within recommended sufficiency ranges. Extractable soil K was also increased by K application rate, and treatment differences persisted in the 0- to 10-cm depth 7 mo after the last K treatment. However, we were not able to detect any effects of K application on turfgrass performance parameters such as ball roll and visual quality. The stability of extractable soil K, even when no K was applied, suggests that release of K from nonexchangeable forms in the rootzone was sufficient to meet plant requirements at this site.

We conclude that the leaf tissue K concentrations observed in this study (Fig. 3) can be classified as sufficient for L-93 creeping bentgrass putting green performance in this calcareous sand green. The increase in gray snow mold damage, combined with reduced 10- to 20-cm ash-free root weight, in the plots receiving the highest rates of K, suggest that K addition is not needed at the study site.

The extractable soil K concentration ranges established in this study (Fig. 1) are greater than the critical soil test levels required for optimum performance. The current target ranges of extractable K in sand rootzones promote K fertilizer applications that may be detrimental to turfgrass performance. More research is needed to understand the supply of nonexchangeable K in sand rootzones.

The "conflicting results" of K fertilizer application, as described by Turner and Hummel (1992), may be better understood by evaluating combinations of extractable soil K and tissue K content to predict actual turfgrass performance on different sand types.

REFERENCES

Beckett, P. 1972. Critical cation activity ratios. Adv. Agron. 24:379–412.

Bengston, J.W., and F.F. Davis. 1939. Experiments with fertilizers on bent turf. USGA Green Section Rec. Dec.:192–213.

Böhm, W. 1979. Methods of studying root systems. Springer-Verlag, New York.

Brown, J.R., and D. Warncke. 1988. Recommended cation tests and measures of cation exchange capacity. *In* Recommended chemical soil test procedures. North Central Regional Publication No. 221 (revised). North Dakota Agric. Exp. Sta., Fargo, ND.

Carrow, R.N., L.J. Stowell, S.D. Davis, M.A. Fidanza, J.B. Unruh, and W. Wells. 2001a. Developing regional soil and water baseline information for golf course turf. *In* Agronomy abstracts. ASA, Madison, WI.

Carrow, R.N., D.V. Waddington, and P.E. Rieke. 2001b. Turfgrass soil fertility and chemical problems. John Wiley & Sons, New York.

Carrow, R.N., L. Stowell, W. Gelernter, S. Davis, R.R. Duncan, and J. Skorulski. 2004. Clarifying soil testing: III. SLAN sufficiency ranges and recommendations. Golf Course Manage. 72(1):194–198.

Cherney, J.H., Q.M. Ketterings, and J.L. Orloski. 2004. Plant and soil elemental status as influenced by multi-year nitrogen and potassium fertilization. J. Plant Nutr. 27(6):991–1014.

Christians, N. 1990. Dealing with calcareous soils. Golf Course Manage. 58(6):60–66.

Christians, N.E., D.P. Martin, and K.J. Karnok. 1981. The interrelationship among nutrient elements applied to calcareous sand greens. Agron. J. 73:929–933.

Colby, W.G., and E.J. Bredakis. 1966. The feeding power of four turf species for exchangeable and non-exchangeable potassium. p. 35 *In* Agronomy abstracts. ASA, Madison, WI.

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. Int. Turfgrass Soc. Res. J. 9:375–381.

FAO. 1999. http://www.fao.org/WAICENT/FaoInfo/Agricult/agl/agll/prosoil/calc.htm (verified 14 September 2005).

Fulton, M. 2002. Creeping bentgrass responses to long-term applications of nutrients. Golf Course Manage. 70(2):62–65.

Gomez, K.I., and A.A. Gomez. 1984. Statistical procedures for agricultural research. 2nd ed. John Wiley & Sons, New York.

Goss, R.L., and C.J. Gould. 1968a. Turfgrass diseases: The relationship of potassium. USGA Green Section Rec. 5(5):10–13.

Goss, R.L., and C.J. Gould. 1968b. Some inter-relationships between fertility levels and fusarium patch disease of turfgrasses. J. Sports Turf Res. Inst. 44:19–26.

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

Hall, A.D. 1912. The manuring of golf greens and courses. p. 31–45. *In* M.H.F. Sutton (ed.) The book of the links. W.H. Smith & Son, London.

Holt, E.C., and R.L. Davis. 1948. Differential responses of Arlington and Norbeck bent grasses to kinds and rates of fertilizers. Agron. J. 40:282–284.

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, G.V. 1974. Simple procedure for quantitative analysis of turfgrass color. Agron. J. 66(3):457–459.

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.

Jones, J.B., Jr. 1980. Turf analysis. Golf Course Manage. 48(1):29–32.

Lawson, D.M. 1999. Phosphate and potassium nutrition of *Agrostis* spp. and *Festuca* spp. turf growing on sandy loam soil. I. Turf ground cover and *Poa annua* ingress. J. Turfgrass Sci. 75:45–54.

Lawson, D.M., and S.W. Baker. 1987. The nutrient content of sands used for turf culture in the United Kingdom. J. Sports Turf Res. Inst. 63:49–56.

Littell, R.C., W.W. Stroup, and R.J. Freund. 2002. SAS for linear models. 4th ed. SAS Institute, Inc. Cary, NC.

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.

Markland, F.E., and E.C. Roberts. 1967. Influence of varying nitrogen and potassium levels on growth and mineral composition of *Agrostis palustris* Huds. p. 53. *In* Agronomy abstracts. ASA, Madison, WI.

McClean, E.O., and M.E. Watson. 1985. Soil measurements of plant-available potassium. p. 277–308. *In* R.D. Munson (ed.) Potassium in agriculture. ASA, CSSA, and SSSA, Madison, WI.

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

Nikolai, T.A. 2002. Effects of rolling and fertility on putting green root zone mixes. PhD. diss., Michigan State Univ., East Lansing (Diss. Abstr. AAI3064284).

Nikolai, T.A. 2005. The superintendent's guide to controlling putting green speed. John Wiley & Sons, Hoboken, NJ.

Reid, M.R. 1933. Effect of variations in concentration of mineral nutrients upon the growth of several types of turf grasses. USGA Green Section Rec. 13(5):122–131.

Sheard, R.W., M.A. Haw, G.B. Johnson, and J.A. Ferguson. 1985. Mineral nutrition of bentgrass on sand rooting systems. Int. Turfgrass Soc. Res. J. 5:469–485.

Soil and Plant Analysis Council. 1999. Major cations (potassium, calcium, magnesium, and sodium). p. 93–115. *In* Soil analysis: Handbook of reference methods. CRC Press, Boca Raton, FL.

Spencer, W.F. 1954. Influence of cation-exchange reactions on retention and availability of cations in sandy soils. Soil Sci. 77(2): 129–136.

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.

Turner, T.R., and D.V. Waddington. 1983. Soil test calibration for establishment of turfgrass monostands. Soil Sci. Soc. Am. J. 47: 1161–1166.

Turner, T.R., and N.W. Hummel, Jr. 1992. Nutritional requirements and fertilization. p. 385–439. *In* D.V. Waddington et al (ed.) Turfgrass. Agron. Monogr. 32, ASA, CSSA, and SSSA, Madison, WI.

Waddington, D.V., A.E. Gover, 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.

Waddington, D.V., E.L. Moberg, and J.M. Duich. 1972. Effect of N source, K source, and K rate on soil nutrient levels and the growth and elemental composition of Penncross creeping bentgrass, Agrostis palustris Huds. Agron. J. 64(5):562–566.

Waddington, D.V., T.R. Turner, J.M. Duich, and E.L. Moberg. 1978. Effect of fertilization on Penncross creeping bentgrass. Agron. J. 70(5):713–718.

Willard, C.J., and G.M. McClure. 1932. The quantitative development of tops and roots in bluegrass with an improved method of obtaining root yields. J. Am. Soc. Agron. 24(7):509–514.

Wolf, A., and D. Beegle. 1995. Recommended soil tests for macronutrients: Phosphorus, potassium, calcium, and magnesium. p. 30–38. *In* Recommended soil testing procedures for the northeastern United States. 2nd ed. University of Delaware Agricultural Experiment Station, Newark, DE.

Wolfinger, R. 1993. Covariance structure selection in general mixed models. Comm. Statist. Simul. 22(4):1079–1106.

Woods, M.S., Q.M. Ketterings, and F.S. Rossi. 2005. Effectiveness of standard soil tests for assessing potassium availability in sand rootzones. Soil Sci. 170(2):110–119.