INORGANIC AMENDMENTS AS PUTTING GREEN CONSTRUCTION MATERIALS

by

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (continued)

ABSTRACT

Recently, interest has arisen in the use of inorganic materials as amendments to sand-matrix golf course putting greens because of their ability to hold water and nutrients. This study was conducted to determine the agronomic, environmental, and economic advantages and disadvantages of using AgriBoost (phillipsitic zeolite), Profile (calcined clay), or GSA ZK406H (clinoptilolitic zeolite) in place of Canadian sphagnum peat moss in sand-matrix putting greens. A pure sand control was also included in the study. An experimental putting green was built in Verona, WI in the fall of 2001 and seeded with creeping bentgrass (*Agrostis palustris* **Huds**.) in the spring of 2002. Root zone mixes had their relevant physical and chemical properties characterized in the laboratory. Several agronomic responses to the root zone mixes were recorded in the field. Leachate was collected periodically from each plot and analyzed for N, P, and K concentration. An economic analysis was conducted paying attention to root zone mix cost and differences in water, pesticide, or fertilizer use among mixes. During the establishment period, the GSA ZK406H treatment significantly reduced NO_3-N leaching compared to the peat treatment. The AgriBoost treatment significantly reduced P leaching compared to all other treatments over the course of the study. The AgriBoost and peat treatments improved bentgrass establishment compared to all other treatments. The Profile and GSA ZK406H treatments improved bentgrass establishment compared to pure sand. After establishment, few agronomic differences between treatments existed. An economic analysis revealed that the use of inorganic amendments in place of peat is not justified based on agronomic responses alone. The initial cost of the root zone mixes was too high. However, the use of inorganic amendments in place of peat is warranted in a situation where a reduction in N or P leaching is necessary.

LITERATURE REVIEW

In 1999, 12.3 million rounds of golf were played on 454 golf courses in Wisconsin for an average yearly play volume of over 27,000 rounds per course (University of Wisconsin – Extension, 1999). It is not uncommon for a busy municipal golf course to incur foot traffic from over 40,000 rounds per year. Theoretically, over 75% of the shots taken in a round of golf are either played on or to the putting green surface. A typical 18-hole golf course has a par of 72. Two putts on each green are assumed in calculating par. Adding the 36 putts to the 18 shots required to reach each of the greens makes for at total of 54 shots out of 72 that are played on or to the green. Thus, a large portion of the play volume is concentrated on the putting greens, which typically make up less than 2% of the total golf course area (Beard, 2002). This large volume of play on a relatively small total area establishes the need for a growth medium that fosters maintenance of high quality turf on a heavily trafficked area.

The United States Golf Association (USGA) recognized the need for compaction resistant putting greens over 40 years ago and, in 1960, (USGA, 1960) published specifications for constructing putting greens that could withstand heavy traffic and support healthy turfgrass. These specifications were largely based upon the research of Dr. Marvin H. Ferguson of Texas A & M College. Several revisions to the original 1960 specifications have been made over the years, the most recent being in 1993 (USGA, 1993).

The USGA-style putting green consists of a sub-grade, subsurface drainage system, a gravel blanket, intermediate coarse sand layer, and root zone mix. The sub-grade is thoroughly compacted and graded to conform to the contours of the finished putting green. A 10-cm deep pea gravel blanket with embedded drainage pipe overlays the sub-grade. Depending on the particle size distribution of the gravel, a 5- to 10-cm intermediate coarse sand layer may or may not be needed between the gravel layer and the root zone mix to prevent downward migration of the mix. The root zone mix is 30 cm in depth and should fall within the particle size limits listed in Table 1 and the physical properties in Table 2. The purpose of these specifications is to create putting greens with high drainage rates, compaction resistance, and porosity favorable for turfgrass growth.

By layering the finer textured root zone mix over the coarse intermediate sand and gravel layer, a differential in matric potential is created and an accumulation of water occurs at the root zone mix/gravel layer interface until saturation and drainage occur. The effectiveness of such textural discontinuities in increasing the moisture retention in the root zone mix has been demonstrated. Taylor and others (1993) set up 30 cm of a uniform root zone mix overlaying three different coarse-textured sublayers and a control consisting of the root zone mix over subsoil alone. The coarse-textured sublayers were 5 cm of sand over 10 cm of gravel, 15 cm of gravel, and 15 cm of sand. Tensiometers were used to measure soil water matric potential at 2- and 28-cm depths below the surface. The root zones were saturated and after 48 hours of drainage, the matric potential of the root zone mix at the 28-cm depth over gravel only, sand + gravel, sand only, and subsoil were -11, -17, -25, and -29 cm, respectively. At the 2-cm depth the matric potentials for the corresponding root zone mixes were -3.68, -3.99, -4.78, and -5.20 kPa. This research clearly demonstrates the effectiveness of the gravel or coarse sand + gravel layer

Table 1. Recommended particle size distribution of a USGA root zone mix.

Name	Particle diameter	Recommendation	
	mm		
Fine Gravel	2.0 - 3.4	Not more than 10% of the total particles > 1.0 mm, including a maximum of 3% fine gravel (preferably none)	
Very Coarse Sand	1.0 - 2.0		
Coarse Sand	0.5 - 1.0	Minimum of 60% of the particles must fall in the 0.25 to 1.0 mm range	
Medium Sand	0.25 - 0.5		
Fine Sand	0.15 - 0.25	Not more than 20% of the particles may be fine sand	
Very Fine Sand	0.05 - 0.15	Not more than 5%	Not more than a total of 10% of the particles may fall within the < 0.002 to 0.15 mm range
Silt	0.002 - 0.05	Not more than 5%	
Clay	< 0.002	Not more than 3%	

Table 2. Recommended physical properties of a USGA root zone mix.

Physical Properties	Recommended Range
Total porosity, %	35 - 55
Air-filled porosity, %	15 - 30
Capillary porosity, %	15 - 25
Saturated conductivity:	
Normal range, cm hr^{-1}	15 - 30
Accelerated range, cm hr^{-1}	30 - 61
Organic matter content (weight basis)†, %	1 - 5

† Recommendation dropped in 1997 (USGA, 1997)

used in putting green construction in increasing moisture retention of the root zone mix, particularly near the interface of the root zone mix/coarse-textured sublayer.

Generally, USGA specification greens have performed well in terms of drainage rate and compaction resistance but, because of the high sand content of these greens, adequate moisture in the top few inches and nutrient retention are limiting factors for turfgrass growth. In an attempt to alleviate these problems, the USGA encourages the use of organic material in root zone mixtures to increase water retention, add cation exchange capacity (CEC), and increase porosity. The USGA no longer recommends a particular range in organic matter content. Rather, the quantity recommended is that arrived at through laboratory testing of sand and organic matter mixes for a combination that meets porosity and saturated flow rate standards (USGA, 1997). According to the USGA (1993), the organic material needs a minimum organic matter content of 85% by weight. Reasoning that as the organic matter decomposes, soil pores can otherwise become clogged with mineral matter and infiltration rates decline to unacceptable levels. Some researchers have cast serious doubt on the utility of this specification by demonstrating that a peat containing 65% organic matter can sustain very high quality turf (Kirkman, 1996; Carlson et al., 1998).

Traditionally, the organic amendment of choice for putting green construction has been peat (Waddington, 1992; Petrovic, 1993). Peat consists of partially decomposed plant residues from various species. The two characteristics having the greatest effect on the quality of the peat are (1) plant species and (2) decomposition stage (Mastalerz, 1977). Sphagnum is the type of peat moss used most often for putting green construction. By definition, sphagnum peat moss is composed of plants from the genus *Sphagnum*, contains at least 90% organic matter on a dry weight basis and a minimum of 75% fiber (Reed, 1996). Kussow (1992) thoroughly characterized the physical and chemical properties of five different types of peat with potential for use as root zone amendments. Included in the survey were Manitoba sphagnum, Michigan sphagnum, reed sedge peat, Wisconsin peat, and Iowa peat humus. The ranges in properties (Table 3) effectively demonstrate the degree of variability of materials classified as peat.

Although adding sphagnum peat to a root zone mix increases the CEC of the mix, researchers have shown that peat binds divalent cations such as Ca^{2+} and Mg^{2+} more tightly than monovalent cations such as K^{+} (Salmon, 1964; Kussow, 1987). A potential K management problem arises when irrigating a peat-amended root zone mix with Ca^{2+}- and Mg^{2+}-laden water. Potassium is easily leached out of the root zone and the turfgrass may become K-deficient unless frequent fertilizer K applications are made.

Another potential disadvantage to using peat moss is its limited stability. In high temperature and rainfall regions such as the southeastern United States, the organic matter incorporated into a sand-matrix green oxidizes rapidly and only a small percentage remains after the first year (Sartain, 1995). Additionally, high quality peat moss can be exceedingly costly to obtain in these southern regions due to the cost of transporting the material from the major production sites in Canada.

For the reasons cited above, interest has arisen in the use of inorganic amendments in sand-matrix greens. Inorganic amendments have physical characteristics similar to sand, thereby retaining rapid drainage and compaction resistance while adding CEC and water retention capacity. The two inorganic amendments that appear to have the greatest potential as root zone amendments are zeolites and calcined clays. Select physical and chemical properties of zeolites and calcined clays are listed in Table 4. In contrast to peat, these two amendments have a preference for bonding K^+ ions over Ca^{2+} ions (McCoy and Stehouwer, 1998; Li et al., 2000). This, plus the characteristics shown in Table 4, suggests that inorganic amendments are potential substitutes for organic amendments in sand-matrix putting greens. Yet, due to a lack of research (especially long term), the USGA does not recommend the use of inorganic amendments in putting green construction (USGA, 1993; Moore, 1999).

Calcined clays are derived from expanding clays such as illite and montmorillinite. The clay is heated to temperatures ranging from 260 – 980 ºC (Waltz and McCarty, 2000; Bigelow et al., 2000), which permanently transforms the clay into stable, porous particles. The heating temperature determines particle physical stability. The higher the temperature, the more stable the resulting particle. Clays that are heated to temperatures near the upper end of the range are referred to as porous ceramics. Calcined clays can be crushed and screened to the size range required for use as an amendment in sand root zones. Research on calcined clays in sand-matrix root zones dates back to the early 1960's. During that period, several researchers demonstrated that amending sands with calcined clays decreases bulk density, increases pore space, percolation rate, infiltration rate, and water retention (Beard, 1973). Waddington (1992) reported that although the addition of calcined clay to sand does increase water holding capacity, much of that water is bound so tightly that it is unavailable for turfgrass growth. Calcined clays are sometimes added to potting

Table 3. Select physical and chemical properties of 5 peats.†

Property	Range
pH‡	2.9 - 6.2
C: N ratio	16.7 - 54.9
Cation exchange capacity, cmol kg^{-1}§	74.6 - 141
Organic matter content, %¶	64.4 - 94.6
Water-holding capacity, %#	32.8 - 59.8
Bulk density, g cm^{-3}	0.13 - 0.29

† Adapted from Kussow (1992).
‡ 1: 1 soil: dilute $CaCl_2$.
§ CEC, cation exchange capacity, pH 7
¶ from total ash content
# volume basis

Table 4. Select physical and chemical properties of zeolites and calcined clays.†

Property	Zeolites	Calcined Clays
pH	6.5 - 8.9	5 - 7
Cation exchange capacity, cmol kg^{-1}	40 - 240	3 - 34
Water-holding capacity, % by volume	35	23 - 35

† Adapted from Bigelow et al. (2001), Ming and Bish (2001), and Richardson and Karcher (2001).

media in the greenhouse industry primarily to increase porosity, aeration, and drainage. The resulting increase in CEC is of secondary importance, and the water holding capacity is not considered a benefit in the greenhouse industry (Reed, 1996). Perhaps the most important property of any particular calcined clay used for putting green construction is its physical stability. Particle stability can be predicted in the laboratory by resistance to physical and chemical breakdown. Field degradation of calcined clays has been reported (Hummel, 1993a); resulting in pore space reductions, retarded infiltration rates, and eventual putting green failure. Yet, other calcined clay products have been found intact in root zones after 30 years (manufacturer claim). Many early studies on calcined clays were focused on the effects the amendment had on aeration, compaction, and moisture retention in root zone mixes. Nutrient retention effects are more recent considerations.

The clays from which the calcined clays are derived have CEC's ranging from 30 - 100 $\text{cmol}_+ \text{ kg}^{-1}$ while the CEC's of calcined clays reportedly range from 3 - 34 $\text{cmol}_+ \text{ kg}^{-1}$ (Reed, 1996; Li et al., 2000). The CEC values reported for Profile®, a porous ceramic material used frequently as an inorganic amendment, vary by as much as 73% (Table 5).

Two recent studies have demonstrated the effects of calcined clays on nutrient leaching. McCoy and Stehouwer (1998) found that calcined clay exhibits selectivity for K^+ over Ca^{2+} on exchange sites. During calcination, the authors claim, the non-selective interlayer exchange sites are eliminated and the remaining CEC is likely associated with highly-K^+ selective edge or wedge exchange sites. Similarly, Li and others (2000) found that amending sand with porous ceramic clay (calcined clay) resulted in a 100% increase in exchangeable K and a 4% decrease in exchangeable Ca compared to unamended sand. A

Table 5. Cation exchange capacity of Profile®.

Citation	CEC	Saturating solution	Displacing solution	pH
	cmol kg^{-1}			
Li et al., 2000	33.6	1 M NH_4OAc	sum of cations	7.0
McCoy and Strehouwer, 1998	9.1	0.5 M HCl	0.5 M $Ba(OAc)_2$	NR
Richardson and Karcher, 2001	24.0	1 M NH_4OAc	sum of cations	7.0

second leaching study (Bigelow et al., 2000) reported that as the percentage of calcined clay increased in a root zone mixture, NH_4-N leaching decreased. The authors concluded that the decrease in NH_4-N leaching was a direct result of the increase in the CEC of the root zone mix. In the same study, amending sand with 20% calcined clay (v/v) reduced NH_4-N leaching by 75% compared to unamended sand. The authors found no treatment effects on NO_3-N leaching.

Other reported benefits of using calcined clays have been the reduction of localized dry spot (Minner et al., 1997) and improved turf quality during times of severe moisture stress (Miller, 2000). McCoy and Stehouwer (1998) suggest a bimodal water retention curve for internally porous inorganic amendments such as calcined clay resulting from a rapid release of water at low tensions followed by another smaller release of moisture at a higher tension (near -1000 cm H_2O). The latter is attributed to release of internal porosity water.

Another inorganic amendment which has been of interest to the golf course industry since the 1980's is the group of minerals known as zeolites. Zeolites are a large class of naturally occurring secondary minerals consisting of aluminosilicate frameworks with loosely bonded alkali and/or alkali-earth cations and water molecules that occupy extraframework positions (Hey, 1930). They are commonly formed at low temperature and pressure in the presence of water (Armbruster and Gunter, 2001). Over 80 natural zeolite species have been identified (Coombs et al., 1998). Of these, chazabite, clinoptilolite, erionite, mordenite, and phillipsite are the most commonly used zeolites for agronomic, horticultural, and soil remediation applications (Ming and Allen, 2001). Zeolites have two properties that make them desirable for agronomic and horticultural use: (1) a theoretical CEC of 200 to 300 $\text{cmol}_+\ \text{kg}^{-1}$ due to the substitution of Al^{+3} for Si^{+4} during formation (Ming and Allen, 2001) and (2) large internal channels created by the three dimensional (3-D) framework of silica and aluminum tetrahedron that give zeolites low bulk densities and allow for the retention of water and exchange of cations (Ming and Allen, 2001). The size of the internal channels determines the cation selectivity sequence of individual zeolites, which varies among zeolite species. The selectivity sequence of chabazite reported by Barrer et al. (1969) is:

$$\text{K}^+ > \text{Ag}^+ > \text{Rb}^+ > \text{NH}_4^+ > \text{Pb}^{2+} > \text{Na}^+ = \text{Ba}^{2+} > \text{Sr}^{2+} > \text{Ca}^{2+} > \text{Li}^+.$$

The selectivity sequence of clinoptilolite (Ames, 1960) is:

$$\text{Cs}^+ > \text{Rb}^+ > \text{K}^+ > \text{NH}_4^+ > \text{Ba}^{2+} > \text{Sr}^{2+} > \text{Na}^+ > \text{Ca}^{2+} > \text{Al}^{3+} > \text{Mg}^{2+} > \text{Li}^+$$

Large zeolite deposits exist around the globe and vary considerably in hardness and durability (Handreck and Black, 2001). High cost and lack of research currently limit their use as soil amendments. Studies on the effects of zeolite amendments in coarse textured soils and putting green root zone mixes began in the 1980's. By this time, the beneficial properties of zeolites were already being put to use by municipal water treatment facilities to remove NH_4^+ and heavy metals from wastewater (Kallo, 2001).

Researchers have found many advantages to amending sand root zones with zeolite. The major advantages reported are:

1. Decreased NH_4-N leaching in soil columns or field plots amended with zeolites (Mackown and Tucker, 1985; Fergeson and Pepper 1987, Huang and Petrovic, 1994; Perrin et al., 1998; Bigelow et al., 2001; Handreck and Black, 2001).
2. Reductions in NO_3-N leaching (Huang and Petrovic, 1994).
3. Increased shoot growth rate of creeping bentgrass without affecting evapotranspiration rate during drought stress (Huang and Petrovic, 1996).
4. A 16 – 32% improvement in nitrogen use efficiency by creeping bentgrass (Fergeson et al., 1986; Huang, 1994).
5. Improved turfgrass germination and establishment rates (Fergeson et al., 1986; Nus and Brauen, 1991; Andrews et al, 1999).
6. Improved turf quality (Fergeson et al., 1986; Ok, 2001).

Disadvantages often associated with amending root zones with zeolite are high cost (Moore, 1999; Handreck and Black, 2001; Nelson, 2003) and potential salinity problems (Fergeson et al., 1986; Qian et al., 2001). Moore (1999) estimates that for a typical 19-green construction project, the cost of an inorganic amendment will be over 6 times that of peat. Nelson (2003) considered the scenario for a hypothetical 18-hole putting green construction project and calculated that amending the greens with an average-priced inorganic amendment at a 9: 1 ratio by volume can increase the cost of construction by

\$86,594 compared to amending the greens with sphagnum peat at the same incorporation ratio. He concluded that, based on current independent research, this cost is difficult to justify from an agronomic perspective.

Additionally, some zeolites contain high amounts of soluble salts. This is the case for zeolite deposits in semi-arid to arid regions where salts accumulate. Qian and others (2001) reported that sand amended with zeolite and irrigated with irrigation waters of 3 different salinity levels [0.25 (control), 3.5, or 6.5 dS m^{-1}] improved turf quality during the second and third months at the two highest salinity levels. Between months 5 and 6, the beneficial effects of the zeolite amendment diminished. The authors concluded that although amending sand with zeolite may buffer the soil solution Na^+ concentration in the short-term, a substantial amount of Na^+ may be retained concurrent with Ca^{2+} and Mg^{2+} exchange, potentially increasing sodicity and salinity problems in the long-term.

Ferguson et al. (1986) observed greater improvements in turf establishment on plots amended with 5% clinoptilolite zeolite than with 10% of the mineral. They attributed the difference to excessive exchangeable Na^+ in the zeolite. After 1 year, there were no statistical differences in Na^+ concentrations of the leachates from the unamended control and the 5% zeolite treatment. By that time, the Na^+ concentrations in the leachate at the 10% zeolite incorporation rate had declined by 72%, and the 10% zeolite treatment began to sustain better turf quality than the 5% zeolite treatment. The authors attributed the difference in turf quality to leaching of excess Na^+ in the root zone and greater potential for NH_4^+ retention in the 10% zeolite treatment. Unfortunately, the authors failed to report the composition and electrical conductivity of the irrigation water used. When poor quality water such as tertiary effluent is used as irrigation water, exchangeable Na^+ may not be leached out of the root zone as readily.

To date, nearly all of the investigations of zeolites as turfgrass root zone amendments involve those dominated by the mineral clinoptilolite, the type of zeolite most readily available in the United States. Because zeolites vary in physical and chemical properties; each zeolite should be thoroughly researched before it is employed as a putting green construction material.

If and when inorganic materials are to replace organic materials as root zone amendments, one or more compelling advantages of doing so needs to be demonstrated. For golf courses seeking permits for construction on environmentally sensitive sites, reductions in leaching of N and P could be crucial. However, in most cases the overriding issue is more likely cost. The cost of the inorganic materials will have to be offset, at least in part, by reductions in water and fertilizer use. This must be accomplished without compromising turfgrass quality. Many factors influence water and fertilizer use and turf quality. They include: root zone moisture retention, infiltration rate, saturated hydraulic conductivity, root development, CEC, and root zone affinity for P and K. The objective of this study was to investigate these factors and others to establish the agronomic, economic, and environmental merits of using two zeolites and a porous ceramic material as root zone amendments for golf course putting green construction.

METHODS

Field Methods

The site for the field study is a putting green constructed during the fall of 2001 at the O.J. Noer Turfgrass Research and Education Facility in Verona, WI. The green is comprised of twenty 1.8- by 2.4-m cells consisting of 30 cm of root zone mix overlaying a 10-cm pea gravel blanket with imbedded drain pipe. A plywood grid lined with 6-mil plastic sheeting extends the full depth of the root zone, physically isolating each cell. Each cell is outfitted with a 30-cm diameter well for insertion of time domain reflectometry (TDR) probes at root zone depths of 5, 10, 15, 20 and 25 cm for volumetric soil moisture measurement. In the center of each cell is a low tension lysimeter based on the design described by Holder et al. (1991) for leachate collection. The top of the lysimeter is positioned at the interface between the root zone mix and pea gravel blanket. The tension being applied to the drainage water is determined by the length of the fiberglass wick. For this study the tension was set to 10 cm. The diameter of the circular collection plate is 20 cm and the plastic storage bottle holds 4.6 L of leachate.

The cells are arrayed in 4 rows of 5 cells each. Each row of cells constitutes a replicate of randomly located treatments. The treatments are root zone mixes with different amendments. The treatments include: (1) sand + AgriBoost® (phillipsitic zeolite, ASI Industries, Washington D.C.); (2) sand + Profile® (porous ceramic, Profile Products LLC, Buffalo Grove, IL); (3) sand + GSA ZK406H (clinoptilolitic zeolite; GSA Resources, Inc., Tucson, AZ); (4) sand + Canadian sphagnum peat moss (Fafard, Inc, Agawam, MA, Canada); and (5) pure sand (Waupaca Sand and Solutions, Waupaca, WI). The ratio of sand: amendment in all mixes is 9: 1 (v/v).

The root zone mixes were prepared by measuring out the volume of sand required for each treatment, placing it in a windrow on a paved surface, and spreading the proper volume of amendment over the windrows. The sand and amendments were blended thoroughly by making several passes through the windrow with a tractor-mounted compost pile mixer. The root zone mixes were loaded into the cells by hand. Once the individual cells were filled, a water-permeable cover was placed over the green to minimize wind erosion and contamination of the mixes during the winter months. In the spring of 2002, root zone mix was added or removed from the cells as needed to level the putting green surface. On 15 May 2002 the plots were seeded with ‘L-93' creeping bentgrass (*Agrostis palustris* **Huds.**). GroWin® (Emerald Isle, Ltd., Ann Arbor, MI) was incorporated into the top 10 cm of the pure sand treatment only at a rate of 1221 kg ha^{-1} (25 lbs M^{-1})[1] to aid in establishment. GroWin® is a temporary granular root zone amendment with higher water holding capacity and a guaranteed analysis of 5-1-2; the incorporation of GroWin® resulted in the addition of 61 kg N ha^{-1} (1.25 lbs. N M^{-1}).

Fertilizer application dates and rates for 2002 are given in Table 6. For 2002, the grow-in season, the total quantities of N, P_2O_5, and K_2O applied were 308, 173, and 218 kg ha^{-1}, respectively. Although deemed adequate based on turfgrass color, this amount of N was modest compared to rates often employed by persons that specialize in rapid grow-in of putting greens, who may apply 600 kg N ha^{-1} or more (Beard, 1973; Kussow,

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[1] M = 1000 ft^2

Table 6. 2002 field fertilization schedule.

Application Date	Fertilizer Grade	Fertilization Rate	N Source	Treatments Fertilized
	% N - P_2O_5 - K_2O	kg N - P_2O_5 - K_2O / ha		
05/15/02	14-28-12	48.8 - 97.6 - 39.1	42% Ammoniacal N 14% Urea N 26% WSN† 18% WIN‡	All
05/15/02	5-1-2	61.0 - 12.2 - 24.4	10% Ammoniacal N 90% WIN	Sand
05/30/02	46-0-0	12.2 - 0.0 - 0.0	100% Urea N	Profile, Peat, Sand
06/10/02	46-0-0	14.6 - 0.0 - 0.0	100% Urea N	All
06/14/02	18-3-4	4.9 - 1.0 - 1.0	19% Ammoniacal N 81% Urea N	All
06/21/02	18-3-4	4.9 - 1.0 - 1.0	19% Ammoniacal N 81% Urea N	All
06/26/02	14-28-12	24.4 - 48.8 - 19.6	42% Ammoniacal N 14% Urea N 26% WSN† 18% WIN‡	All
07/08/02	46-0-0	24.4 - 0.0 - 0.0	100% Urea N	All
07/12/02	18-3-4	4.9 - 1.0 - 1.0	19% Ammoniacal N 81% Urea N	All
07/25/02	46-0-0	39.1 - 0.0 - 0.0	100% Urea N	All
08/02/02	18-3-18	24.4 - 4.9 - 24.4	13% Ammoniacal N 22% Urea N 40% WSN† 25% WIN‡	All
09/03/02	14-28-12	24.4 - 48.8 - 19.6	42% Ammoniacal N 14% Urea N 26% WSN† 18% WIN‡	All

- continued -

† WSN, water soluble nitrogen
‡ WIN, water insoluble nitrogen

Table 6. (continued)

Application Date	Fertilizer Grade	Fertilization Rate	N Source	Treatments Fertilized
10/26/02	0-0-50	0.0 - 0.0 - 78.1		All
10/27/02	24-2-12	19.5 - 1.5 - 9.8	3% Ammoniacal N 38% Urea N 22% WSN† 37% WIN‡	All

† WSN, water soluble nitrogen

‡ WIN, water insoluble nitrogen

1999). Fertilizer rates typical of those of an established putting green were used in 2003 (Appendix Table A-1).

Over the duration of the study, several plant parameters were measured and related to physical and chemical root zone mix properties. Some of the parameters, such as clipping weights and turfgrass clipping nutrient status are quantitative values. Others are subjective visual ratings which rely on the interpretive skills and experience of the evaluator.

Turfgrass is unique in that it is not grown for yield or nutritive value as are many other agricultural crops. Therefore, a single objective measurement cannot be used to successfully judge the quality of turfgrass. Instead, researchers use a subjective visual turf quality rating method taking into account color, density, uniformity, and overall appeal of the stand of turfgrass to judge turfgrass performance (Skogley and Sawyer, 1991). The visual turf quality ratings are on a scale of 1 – 9, with 1 being dead or dormant turf and 9 being the highest quality turf possible as judged by the evaluator. A rating of 6 indicates minimally acceptable turf quality. A study conducted on the utility of visual evaluation techniques (Horst et al., 1984) suggests that subjective ratings can vary significantly between evaluators and "results from national or regional turfgrass cultivar evaluation trials should be considered with caution." However, the authors concede that evaluations made by individuals are still valuable for comparison because subjective ratings are usually consistent within individual evaluators. While the authors used only visual quality and density ratings to draw their conclusions, it is reasonable to assume that turfgrass color ratings are subject to the same variation as other subjective ratings. For the present study, visual turf quality ratings were taken on a monthly basis after the grow-in period had commenced in 2002 and on a bimonthly basis in 2003.

Of the parameters included in a quality rating, color is one of the most influential. Color is a measure of the light reflected from the turf (Turgeon, 2002). For years color ratings have been reliably used as indicators of turfgrass health. In general, turfgrass will begin to yellow at the onset of certain nutrient deficiencies, moisture stress, disease pressure, and other plant-health related factors. Color ratings were taken on a weekly basis during the 2002 growing season after the grow-in period and on a bimonthly basis during the 2003 growing season. The color ratings were used to determine the need for fertilization throughout the course of the study.

Another important subjective parameter included in the turf quality rating is stand density and uniformity. Stand density is a function of turfgrass cover measured on a 1 – 9 scale, with 1 being 0% cover and 9 being 100% cover. Stand density was used to define the grow-in period for this study. When the last plot had reached 100% cover (density rating = 9), the grow-in period was deemed complete, although the green was probably not yet ready for heavy traffic. Uniformity is a measure of the consistency of the stand and is also measured on a 1 – 9 scale, with 1 being no uniformity and 9 being perfect uniformity. Intuitively, uniformity is difficult to measure independently of stand density, and for the purposes of this study density and uniformity ratings were combined into a single measurement and recorded on a bimonthly basis during the 2002 growing season.

Yield is an objective measure of turfgrass growth. In this study, measurement of yield was achieved by making one pass with a Toro 1000 Greensmaster® [53.3 cm mowing width (21 in.), 11 blade reel] down the center of each plot and collecting the grass clippings. One pass removed clippings from an area of 1.02 m^2 (10.94 ft^2). The clippings were dried at 60° C and weighed. Clipping yield is primarily a response to nutrient supply and irrigation practices except when turfgrass growth is limited by extreme air or soil temperatures. Throughout this study, fertilization and irrigation were held as constant as feasible; subsequently, yield was interpreted as a measure of the plant response to root zone mix characteristics such as available water and nutrients and, at times, heat stress. Yield measurements were taken bimonthly over the course of the study.

Root growth was measured as root mass density to characterize any treatment effects. Three soil cores were taken to a depth of 30 cm in each plot with a 1.91-cm diameter soil probe. The cores were placed on a 2-mm sieve and the roots washed free of soil by a stream of water. The roots were dried and root weight was determined by loss on ignition at 600 ºC after 2 hours to compensate for any mineral matter still present. Root growth measurements were taken in the spring, summer, and fall of each season.

A primary reason for amending sand with organic or inorganic materials is to increase the water holding capacity of the root zone mix. Volumetric water content of the root zone mixes was measured 3 times in 2002 and 3 times in 2003 by time domain reflectometrey (TDR) to discern treatment effects. The measurement device consisted of two 15-cm probes connected to a Tektronix 1502B TDR cable tester (Tektronix, Inc., Beaverton, OR). The cable tester measures the dielectric constant which is related to volumetric water content of the root zone through the use of an equation described by Topp and others (1980). The equation is:

$$\Theta = -5.3E\text{-}02 + 2.92E\text{-}02K_a - 5.5E\text{-}04K_a^2 + 4.3E\text{-}06K_a^3$$

where Θ is the volumetric water content and K_a is the dielectric constant. The K_a is calculated by the following equation:

$$K_a = [(x_2 - x_1) / (L * V_p)]^2$$

where x_2 is the location of the inflection point of the right-most peak, x_1 is the location of the inflection point of the left-most peak, L is the probe length (0.15 m in this case), and V_p is the relative velocity of propagation (set to 0.99 in this case). Measurements were taken 24 – 48 hours after a saturating rainfall occurred. Irrigation was withheld during this period to ensure even moisture distribution among the root zone mixes.

Infiltration rate is another important characteristic of any putting green. The infiltration rate is a function of the K_{sat} of the soil, gravitational force, and soil suction (Beard, 1973). A green with an insufficient infiltration rate will eventually fail due to decreased aeration and increased compaction, both of which lead to poor rooting. A green with an excessive infiltration rate will be very susceptible to moisture stress, as maintaining adequate soil moisture is a challenge. Root zones with high infiltration rates also have greater potential for leaching losses due to the need for more frequent irrigation. Infiltration rates are initially high when the soil is unsaturated. As the soil becomes saturated the infiltration rate declines and approaches a limit controlled by the rate of soil water movement (Beard, 1973). For this study, the infiltration rate was measured using a double-ring infiltrometer with inner and outer ring diameters of 6.5 and 10.7 cm respectively (Turf-Tec International, Oakland Park, FL). Infiltration rate was measured in the fall of 2002 and again in the summer of 2003.

Because of the relatively high cost associated with building greens with inorganic materials, the management practices of the experimental putting green were those of a typical upscale Wisconsin golf course. After the grow-in period was complete, the green was mowed 6 times weekly at a height of 3 mm (0.120 in.). For the 2002 season, irrigation was applied nightly to replace 100% of estimated evapotranspiration (ET). For the 2003 season, irrigation was applied every other night to replace 100% of the estimated ET loss from the previous day only. This change was made to account for overestimation of ET losses that were manifested in excessive amounts of drainage. Supplemental irrigation was applied by handwatering when necessary. The putting green was topdressed with pure sand frequently during the first growing season to smooth the surface and facilitate low mowing height. Topdressing was less frequent during the second growing season, with light applications typically occurring bimonthly. The particle size distribution of the topdressing sand is listed in Table 7. Application dates and rates of fungicides are listed in Table A-2.

Laboratory Methods

Relevant physical and chemical properties of all root zone mixes and materials were characterized in the laboratory. These characteristics are necessary to explain the differences found in putting green performance over the course of the study. Properties

Table 7. Particle size distribution of the root zone mixes and topdressing sand used.

Sieve #	Particle diameter	AgriBoost	Profile	GSA ZK406H	Peat	Pure sand	Topdressing sand
	mm	----------------------------------		%	--------------------------------		
10	>2.0	1.6	1.2	1.6	1.0	0.7	0.0
18	1.0 - 2.0	7.5	4.5	7.65	5.9	4.9	0.0
35	0.5 - 1.0	22.0	26.9	26.9	21.1	21.3	6.6
60	0.25 - 0.5	41.3	42.8	40.2	43.6	46.2	46.1
100	0.150 - 0.25	21.1	18.6	18.3	21.8	21.4	38.8
270	0.053 - 0.150	6.2	5.8	5.2	6.4	5.3	8.5
pan	<0.053	0.3	0.2	0.2	0.2	0.2	<0.1

characterized included: particle size distribution, calcium carbonate equivalence (CCE), P sorption and desorption, K sorption, moisture release curves, saturated hydraulic conductivity (K_{sat}), and cation exchange capacity (CEC).

In Wisconsin and much of the Midwest, the sand available for putting green construction typically contains significant amounts of carbonates. When carbonates are present in a root zone mix, they control pH and adsorb considerable amounts of P (Brady and Weil, 2002). Calcium carbonate equivalence of root zone mixes and materials were measured with a method based on the neutralization of acetic acid (Loeppert and Suarez, 1996).

As mentioned above, P sorption capacity is often related to the presence of carbonates in calcareous soils like the sand used in this study. The adsorbed P may be unavailable for plant uptake, creating tissue P deficiency that results in a growth reduction, especially evident during the early stages of turfgrass growth. However, in a sand-matrix root zone without sufficient P sorption, the fertilizer P may be excessively mobile and may be leached out of the root zone. For these reasons the P sorption capacities of the root zone mixes were examined. Twenty-five milliliters of a 40 mg L^{-1} P solution (as MAP) was mixed with 10 g of root zone mix taken from the experimental green on 09 Sept. 2002. The soil and solution were shaken for 24 hours and filtered through Whatman 42 filter paper. The amount of inorganic P in solution was determined using a colorimetric technique (Murphy and Riley, 1962; Watanabe and Olsen, 1965).

To compliment the P sorption study, a P desorption study was conducted to estimate the amount of plant available P in each root zone mix. The method described by

Kuo (1996), involving iron oxide-impregnated filter paper, was used to assess P availability in the root zone mixes. The iron oxide sorbs P from the solution, thereby simulating removal by roots and facilitating continuous P desorption from the mixes.

Potassium retention is also an important characteristic of a putting green root zone mix. Traditional mixes using only sand or sand + peat do not retain significant amounts of K, often creating deficiencies or the need for specialized K management strategies (Kussow, 1987). The K sorption capacity of the root zone mixes was measured by shaking 1.5 g of each amendment (.15 g of peat) in 15-ml solutions containing either 0, 1, 5, 10, 50, or 100 mg L^{-1} K^{+} for 2 hours. After 2 hours of equilibration, the solutions were analyzed for exchangeable cations by inductively coupled plasma-atomic emission spectroscopy (ICP-AES).

Another important chemical property of a root zone mix is its CEC. Due to the nature of the materials used in this project, special methodology is required for reliable CEC estimation. Separate methods were used to measure the CEC of the inorganic amendments, the peat, and the field samples. The CEC of field samples and amendments were determined using NaOAc saturation and displacement by NH_4OAc as described by Bower et al. (1952) and modified by Avila (1999). The CEC of the peat was determined using a compulsive exchange method (Gilman, 1979; Avila, 1999).

Field soil samples of ~400 mg were weighed into 1.5-mL microcentrifuge tubes, recording the weight of the soil and the weight of the tube to ± 0.1 mg. One and two-tenths milliliters of 1 M NaOAc (pH 8.2) was added to the tubes and the samples were shaken for 10 minutes using a vortex action shaker. The high pH of the saturating solution was meant to prevent appreciable $CaCO_3$ dissolution. Samples were then placed in a microcentrifuge and spun at ~10,000 rpm for 3 min. The supernatant was decanted and discarded. The samples were treated in this manner a total of 3 times. After Na^+ saturation, 1.2 mL of deionized water was added to the samples, which were then shaken for 10 minutes using a vortex shaker, and centrifuged at ~10,000 rpm for 3 min. The samples were rinsed with deionized water in this manner a total of three times. After rinsing, exchangeable Na^+ was extracted three times with 1.2-mL aliquots of 1 M NH_4OAc (pH 7) with mixing, shaking, and centrifuging as described for the saturation procedure. The NH_4OAc extracts of each sample were decanted directly into a 10-mL tube, heated at 90°C to force NH_4OAc volatilization and dried. Five milliliters of deionized water was added to the tubes, and Na was determined by flame photometery, making further dilutions when necessary.

For CEC determination of the inorganic amendments, 10 g of the material was placed in 50-ml centrifuge tubes and 25 ml of 1 M NaOAc (pH 5.0) added. The low pH of the saturating solution was meant to dissolve any $CaCO_3$ present in the samples. The amendments were suspended using a vortex mixer, shaken horizontally for 10 minutes, and centrifuged for 10 at 3,000 rpm. The supernatant was decanted and discarded. The samples were treated in this manner a total of 3 times. The samples were rinsed with deionized water using the same procedure 4 times and freeze-dried. Subsamples were weighed and added to the microcentrifuge tubes for NH_4OAc extraction described above.

A compulsive exchange method (Gilman, 1979; Avila, 1999) was used to determine the CEC of the peat amendment at pH 5, 6, 7, and 8. Approximately 50 mg samples of the peat were placed into weighed 1.5-mL microcentrifuge tubes, 1.2 mL of

100 m*M* $BaCl_2$ buffered to the proper pH was added to the tubes and shaken for 10 minutes using a vortex shaker. After shaking, the samples were centrifuged at ~10,000 rpm for 3 minutes and the supernatant discarded. The samples were treated in this manner a total of 3 times. The samples were then washed 3 times by adding 1.2 mL of deionized water, shaking for 10 minutes, centrifuging at ~10,000 rpm, and decanting and discarding the supernatant. The peat samples were transferred to 30-mL centrifuge tubes and 10 mL of 5 m*M* $MgSO_4$ was added to the pH 4 peat samples, and 10 mL of 10 m*M* $MgSO_4$ was added to the pH 6, 7, and 8 peat samples to compulsively exchange Ba^{2+} with Mg^{2+}. The samples were shaken for 1 hour and then filtered using Whatman 42 filter paper. The filtered samples were sent to the University of Wisconsin Soil and Plant Testing Laboratory for Mg analysis by ICP-AES. Cation exchange capacity was calculated as the difference between the total amount of Mg added to each sample by the original $MgSO_4$ solution and the Mg remaining in solution after compulsive exchange of Ba upon $BaSO_4$ precipitation.

Physical properties are at least as important as chemical properties in determining the suitability of a root zone mix as a medium for turfgrass growth. Saturated hydraulic conductivity is one of the most important physical properties of a root zone mix. The USGA recommends that the K_{sat} be between 15 and 30 cm hr^{-1} (6 to 12 in. hr^{-1}) for ‘normal’ regions, including southern Wisconsin, and 30 to 45 cm hr^{-1} (12 – 24 in. hr^{-1}) for ‘accelerated’ regions which experience greater amounts of rainfall. The K_{sat} is directly proportional to the volume of water moving through a packed soil column per unit time and is a function of the pore diameters in the soil column (Jury et al., 1991). For this study, root zone mixes (-40 cm H_2O) were placed into 7.62-cm diameter cylinders and compacted by dropping a 3.18-kg (7 lb.) hammer 7 times from a height of 631 mm (2.07 ft.). This compaction level is the USGA standard for evaluating root zone mixes (Hummel, 1993b) and is assumed to mimic a heavily trafficked putting green. The K_{sat} of the root zone mixes was measured using a falling head permeameter with a diameter of 3.18 cm (1.25 in.). The water level was measured every 10 seconds and carried out for at least 120 seconds. Saturated conductivities of the mixes were calculated for each time interval using the following equation and then averaged over all readings.

$$K_{sat} = [(a \cdot L) / (A \cdot \Delta t)] \cdot \ln (H_0 / H_1),$$

where a is the cross sectional area of the water column, L is the length of the soil core, A is the cross sectional area of the soil core, Δt is the time interval between readings, H_0 is the height of the water column at the beginning of the time interval, and H_1 is the height of the water column at the end of the time interval.

The USGA also provides recommendations for total porosity, capillary porosity, and air-filled porosity (Table 2). These were determined following the procedures described by Hummel (1993b).

Moisture release is another important physical property of a root zone mix. Moisture release curves were developed using a hanging column tension table to examine the tensions at which water held in the root zone mixes may become available to turfgrass. Root zone mixes were placed in 7.6-cm diameter cores and compacted according to USGA standards (Hummel, 1993b). The cores were saturated before being placed on the hanging column tension table (McGuire and Lowery, 1992). The volume of water extracted was measured for each mix at tensions of -5, -10, -15, -25, -35, -60, -100, -150, and -200 cm H_2O.

Field soil samples were taken to a depth of 10 cm (4 in.) and available P and K measured on 6 sampling dates using the Bray-1 extractant. Analysis of P and K was by way of colorimetry and flame photometry respectively (Liegel et al., 1980). pH of soil samples and amendments were measured using a 1: 1 soil: water ratio (Thomas, 1996). Water soluble P was measured on 1 sampling date by way of extraction with 0.01 M $CaCl_2$ (Kuo, 1996).

Each set of dried and weighed bentgrass clippings was analyzed for N, P, and K concentration. Nitrogen content was determined using a micro-Kjeldahl method following digestion of tissue in H_2SO_4 containing a mixture of Na_2SO_4, $CuSO_4$ and Se (duPreez and Bale, 1989). Tissue P was determined colorimetrically following the procedure of Kitson and Mellon (1944) and tissue K was determined by flame photometry after igniting the tissue samples in a muffle furnace for 2 hours at 500ºC and dissolving the ash in 2 N HCl and diluting the sample to 25 ml.

Leachate samples were analyzed for mineral N, P, and K content. Ammonium and nitrate N concentrations were determined by steam distillation (Mulvaney, 1996). Phosphorous concentrations in the leachate were determined colorimetrically (Murphy and Riley, 1962; Watanabe and Olsen, 1965), and K concentration was determined by flame photometry.

Greenhouse Methods

A greenhouse study was initiated in January 2003; the primary purpose being to determine root zone mix effects on moisture retention and drainage rates. Both factors have implications regarding irrigation practices – the rates and frequencies of irrigation, and ultimately, total water use.

Simulated putting greens were constructed using 20-cm diameter by 40-cm long PVC pipe fitted with an end cap. PVC cement was used to adhere a thin layer of the appropriate root zone mix on the inside wall of each cylinder in an attempt to lessen the effects of preferential water flow along the cylinder wall. Thirty centimeters of each root zone mix were placed over 10 cm of pea gravel in the cylinders. The mixes were added in 7.6-cm increments, which were compacted before adding the next increment. This process resulted in root zone soil bulk densities ranging from 1.40 (Profile®) to 1.47 g cm^{-3} (pure sand), which are typical for newly constructed putting greens. An intermediate coarse sand layer between the root zone mix and pea gravel blanket was not used. Holes were drilled near the bottom of each end cap to allow for the collection of leachate during the experiment. The cylinders were seeded with 'L-93' creeping bentgrass at a rate of 88 kg ha^{-1}. Starter fertilizer was incorporated into the top 7.6 cm of the root zone mix. GroWin® was incorporated into the top 10 cm of the pure sand treatment at a rate of 1221 kg ha^{-1} (25 lbs M^{-1}) to reproduce field conditions as closely as possible.

Tap water was applied to the cylinders in equal amounts during the establishment phase. Drainage rate was not monitored until the cylinders reached 100% turfgrass cover.

Until this time, treatment effects on bentgrass establishment, color, growth, leachate volume and composition were recorded.

Leachate was collected intermittently during bentgrass establishment from 4 Feb. to 12 Apr. 2003. Leachate volumes were recorded and composition determined. Nitrate N and NH_4-N were determined using the micro-Kjeldahl method (duPreez and Bale, 1989), and P, K, Ca, Mg, and Na were determined by the University of Wisconsin Soil and Plant Testing Laboratory using ICP-AES.

Six Decagon ECH_2O EC-10 (Decagon Devices, Inc., Pullman, WA) probes were employed to measure volumetric water content at 6 different depths in the root zone profiles. Narrow slits were cut into each PVC cylinder to accommodate the 3.17 cm wide and 0.15 cm thick probes. The 6 depths as measured from the center of the probe to the soil surface were 2.5, 7.6, 12.7, 17.8, 22.9, and 28.0 cm. The probes were staggered in two columns 7.9 cm apart in an attempt to minimize any interference between neighboring probes.

Cylinders were saturated and allowed to drain for 24 hours. At the end of the 24 hour period, 1.3 cm of water was applied evenly by adding the volume of water to a PVC end cap with several 1-mm diameter holes placed on top of the turf. Drainage measurements were recorded by a datalogger every minute during the first hour following irrigation, and hourly thereafter for 48 hours, at which time another 1.3 cm of water was applied. This procedure was followed a total of four times. At the end of the fourth 48 hour period, irrigation was withheld and soil moisture monitored until bentgrass wilt occurred.

At this time the probes were inserted into the next cylinder to be studied and the above process repeated.

RESULTS

Root Zone Mix Properties

The properties of the root zone mixes listed in Table 8 are used by turfgrass professionals and researchers to quickly evaluate the suitability of the root zone mix for putting green construction. Furthermore, values of K_{sat} and porosity are specifically included in the USGA recommendations for physical properties of root zone mixes (Table 2).

The USGA considers southern Wisconsin to be in the 'normal' range for its K_{sat} recommendations (K_{sat} between 15 to 30 cm hr^{-1}). Of the mixes used in this study, only the AgriBoost® amended mix met the USGA's recommendation. All remaining treatments exceeded the recommendation of 30 cm hr^{-1}, with the GSA ZK406H and Profile® treatments exceeding it by 67 and 75% respectively. One of the issues surrounding laboratory measurement of K_{sat} is that it does not accurately reflect field values. Saturated hydraulic conductivity is a function of soil pore radius, and thus soil particle size. Topdressing is a common cultural practice that has a pronounced effect on K_{sat}. Topdressing involves applying primarily fine and very fine sand to the surface of a putting green and brushing it down into turfgrass canopy to smooth out the surface and dilute the plant material accumulating below the surface (thatch). Because mower pick-up of sand sized particles substantially decreases the life of the mowing reel and bedknife; golf course superintendents deliberately choose sands that can be easily brushed down into the thatch layer, thus preventing excessive contact with mowers. Years of brushing fine and very fine sands into the greens creates a layer of finer textured materials over coarser materials, reducing the K_{sat} and infiltration rate of the root zone mix. After as little as 1 year, the effect of topdressing can become apparent. If the topdressing material is chosen to match the particle size of the original root zone mix, it is possible the laboratory K_{sat} value can be maintained in the field for a number of years; however, the additional wear on the mowers from using coarser topdressing sand is a price most golf course superintendents are unwilling to pay.

The widespread practice of topdressing compromises the utility of the USGA's K_{sat} recommendation. A root zone mix that initially exceeds the upper limit set by the USGA may eventually meet the K_{sat} recommendation after a few years of topdressing; while a root zone mix initially meeting the USGA's target may fall below the recommended range over a short period of time. Additional research on the effects of topdressing materials on K_{sat} is warranted.

Infiltration rates were measured on one replicate in the fall of 2002 and on all replications during the summer of 2003. No significant differences in infiltration rates existed between the treatments in 2003 (Table 9). Variation within treatments was relatively large. Results are shown along side the K_{sat} values determined in the laboratory. The infiltration rates of 2003 tend to be about ½ of the 2002 values. There does not appear to be any correlation between field infiltration rates and K_{sat}. It is likely that the severe amount of compaction applied to the laboratory samples prior to K_{sat} determination accounts for the inconsistencies between the laboratory K_{sat} and field infiltration values.

A primary reason root zone mixes are amended with organic or inorganic materials is to increase nutrient holding capacity. The sands used for constructing sand-matrix

Table 8. Physical and chemical properties of the root zone mixes used.

Root zone mix	D_b†	pH‡	CEC§	K_{sat}#	Porosity Total	 Capillary	 Air-filled	Θ_w††
	g cm^{-1}		$cmol_+ kg^{-1}$	in hr^{-1}	----------------	%	----------------	%
AgriBoost	1.52	7.98	5.6	10.89	42.7	23.8	18.9	15.7
Profile	1.47	7.65	0.5	20.67	44.4	24.3	20.1	16.6
GSA ZK406H	1.43	7.60	1.5	19.87	46.1	25.6	20.5	17.2
Peat	1.45	7.09	0.6	13.49	45.2	24.5	20.7	16.9
Pure sand	1.54	7.85	0.2	14.53	41.8	22.7	19.1	14.7
$LSD_{0.05}$	0.11	0.08	0.32	3.31	4.15	NS	NS	NS

† D_b, dry bulk density.
‡ pH 1: 1, water: material.
§ CEC, cation exchange capacity pH 8.2.
# K_{sat}, saturated hydraulic conductivity.
†† Θ_w, water retention at -40 cm H_2O.

Table 9. Root zone mix effects on laboratory determined K_{sat} and field infiltration rates.

Root zone mix	Infiltration Rate 2002	 2003	K_{sat}
	-----------------------------	cm hr^{-1}	----------------------------
AgriBoost	33.6	18.0	10.9
Profile	38.6	18.3	20.7
GSA ZK406H	34.5	16.3	19.9
Peat	22.2	18.0	13.5
Pure sand	32.4	13.5	14.5
$LSD_{0.05}$	NA	NS	3.31

putting greens typically have negligible CECs. The CEC of the sand used in this study was 0.02 $\text{cmol}_+ \text{ kg}^{-1}$ (Table 10). The CEC of the AgriBoost® amendment was approximately twice as great as that of the GSA ZK406H zeolite (Table 10). The CEC of the AgriBoost® root zone mix is comparable to the CEC of a native soil “push-up” putting green. The CECs of the other root zone mixes were below 1.5 $\text{cmol}_+ \text{ kg}^{-1}$, low by any standard. The CECs of the Profile® amendment and root zone mix were 4.6 and 0.5 $\text{cmol}_+ \text{ kg}^{-1}$ respectively. These values are lower than those that have been previously reported in the literature (Table 5; Li et al., 2000). The CEC of the peat was very pH dependant, as expected (Figure 1). Peat also had the greatest CEC of all amendments, but because it is a low bulk density material and is incorporated into the root zone mix on a volume basis, the CEC of the peat-sand mix is negligible (Table 8).

The sand used for this study contains 21.4% fine sand (0.15 – 0.25-mm particle diameter) and 5.3% very fine sand (0.05 – 0.15-mm particle diameter) (Table 7), both greater than allowable by USGA standards (Table 1) by 1.4% and 0.3% respectively. The particle size distribution of AgriBoost® fails to meet USGA specifications in nearly every size fraction. Incorporating AgriBoost® into the sand resulted in a 14.5% increase in very fine sand content which already exceeded USGA standards. However, the superior performance of this particular root zone mix during the course of the study suggests that, at least for southern Wisconsin, a root zone mix having a very fine sand content up to 6.5% or more is acceptable. Further, the particle size recommendations of the USGA might be relaxed with more emphasis placed on maintaining a K_{sat} between 15 and 30 cm hr^{-1}.

Table 10. Physical and chemical properties of the root zone amendments and construction sand used.

Amendment	pH†	Bulk Density	CCE‡	CEC§
		g cm^{-3}	%	$cmol_+ \, kg^{-1}$
AgriBoost	8.03	1.36	3.95	66.8
Profile	6.05	0.56	0.66	4.6
GSA ZK406H	7.58	0.91	0.52	34.5
Peat	2.83	0.18	ND#	152
Pure sand	7.88	1.54	4.34	0.02
$LSD_{0.05}$	0.11	NA	0.23	NA

† 1: 1 water: amendment

‡ CCE, calcium carbonate equivalence

§ CEC, cation exchange capacity pH 5.0 for sand and amendments, 7.0 for peat

ND, no data

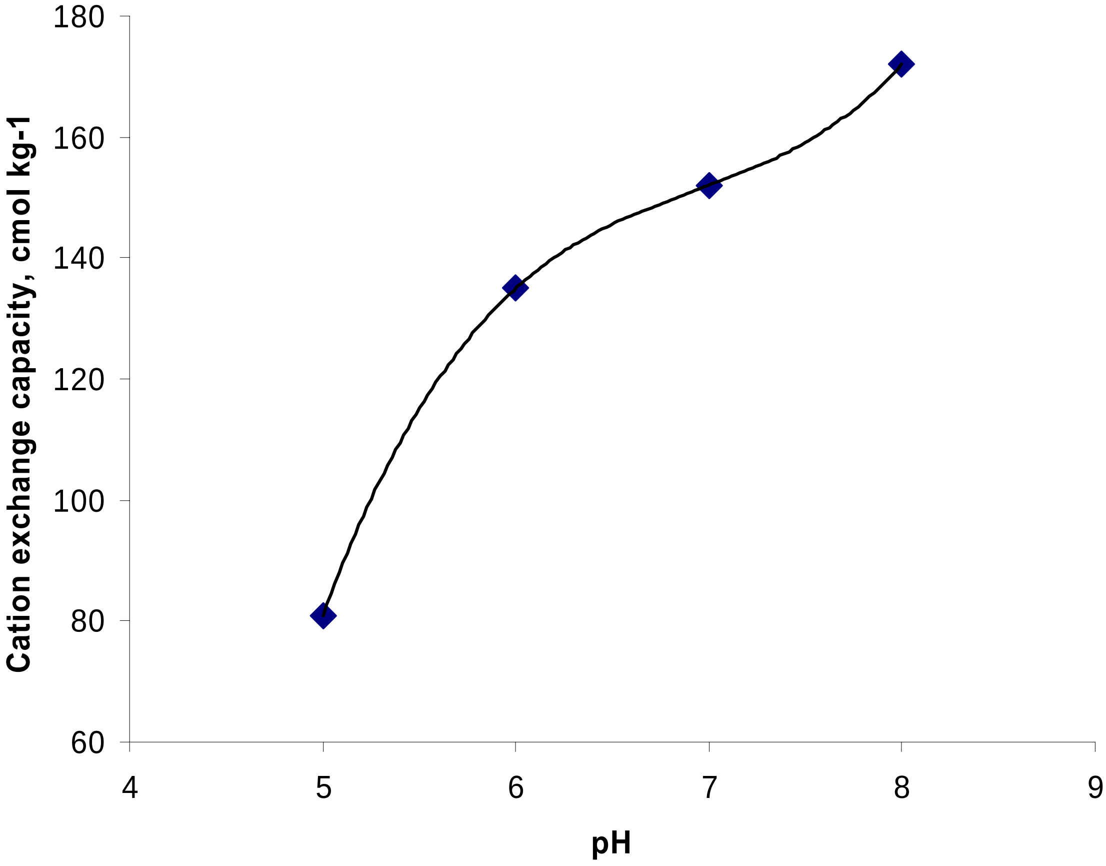

Figure 1. Cation exchange capacity of peat as a function of pH.

From an economic perspective, the relatively finer particle size distribution of the AgriBoost® treatment could prove advantageous. The greater amounts of water retained and the slower drainage rates expected from a finer textured root zone mix could translate into savings from lower irrigation requirements.

The USGA recommends that at least 60% of the particles in root zone mix be in the 0.25 to 1.0 mm size range (Table 1) to impart compaction resistance. Profile® had the most uniform particles size of all the amendments used in this study. Nearly 98% of the product was classified as either coarse or medium sand (0.25 – 1.0 mm particle diameter) (Table 11). The GSA zeolite was slightly coarser with 92% of the particles classified as very coarse or coarse sand (0.5 – 2.0 mm particle diameter) (Table 11). The peat used in this study was not pulverized before incorporation as is common in commercial sand-peat blends. Thirty-seven percent of the peat was > 2.0 mm and 45.1% fell between 0.5 and 2.0 mm (Table 11). Profile® was the only amendment that met the particle size distribution recommendations of the USGA and therefore, should have the highest compaction resistance among the 5 root zone mixes.

Moisture release curves were established for each of the root zone mixes (Figure 2). The peat treatment held significantly more water than the sand treatment at tensions of -5, -10, -15, -25, -35, -45, -100, and -150 cm H_2O. Peat and Profile® released significantly greater amounts of water than pure sand and AgriBoost® at -35 cm H_2O, and pure sand, GSA zeolite, and AgriBoost® at -45 cm H_2O.

Indeed, other researchers have found Profile® to release significantly more water than pure sand (Li, 2000; McCoy and Stehouwer, 1998; Bigelow et al., 2000). These

Table 11. Particle size distribution of the root zone amendments.

		Root zone amendment			
Sieve #	Particle Diameter Range	AgriBoost	Profile	GSA ZK406H	peat
	mm	----------------------------	%	----------------------------	
10	>2.0	1.6	0.0	0.0	37.4
18	1.0 - 2.0	18.0	0.0	26.0	23.3
35	0.5 - 1.0	24.4	60.1	66.3	21.8
60	0.25 - 0.5	19.5	37.7	7.4	11.3
140	0.106 - 0.25	20.9	2.1	0.3	4.0
270	0.053 - 0.106	9.8	< 0.1	< 0.1	2.1
pan	< 0.053	5.9	< 0.1	< 0.1	< 0.1

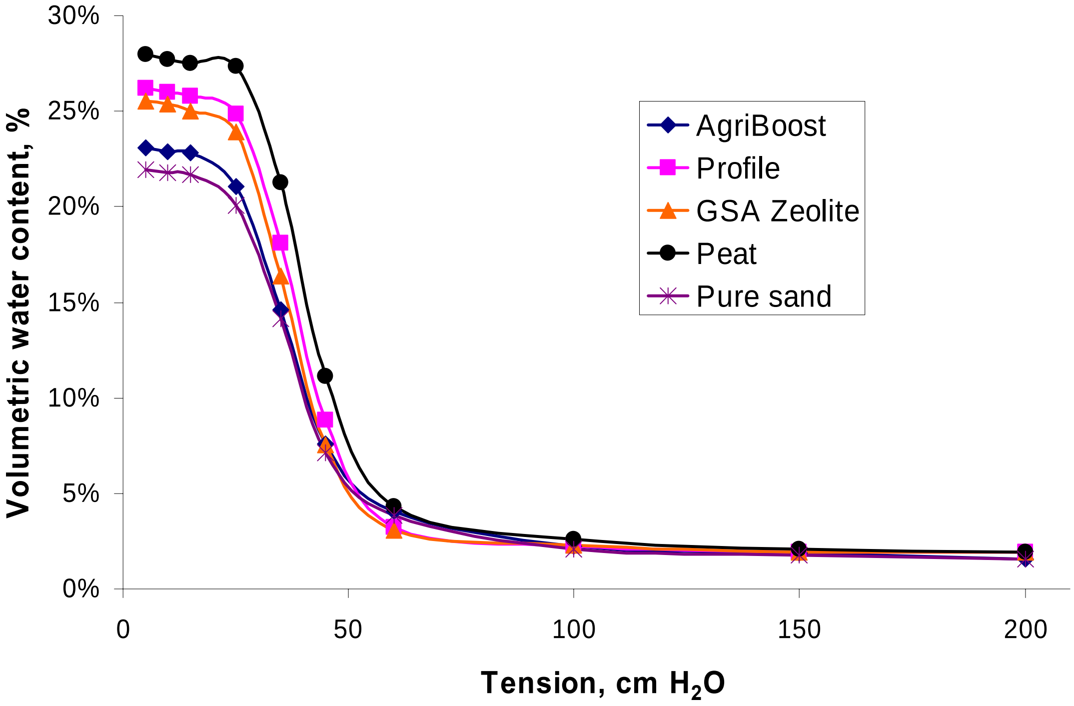

Figure 2. Moisture release properties of root zone mixes.

results provide an explanation for the claims that Profile® improves turfgrass quality under drought stress (Miller, 2000). Although some significant differences were found in this study, the differences in water retention between the root zone mixes tended to be small and can be attributed to the relatively fine texture of the sand used (relatively high water holding capacity). It is important to note that the peat-amended root zone mix released more water at every tension than all other mixes analyzed (including Profile®), suggesting that if increased moisture holding capacity is the main goal of a putting green construction project, peat moss should have preference over inorganic amendments.

Potassium is a cation which binds electrostatically to exchange sites in the root zone and is required in relatively large quantities by turfgrass, typically accounting for 2 – 3 % of dry tissue weight. Root zones mixes with inadequate CECs are unable to retain sufficient amounts of K for an entire growing season. Much of the applied K leaches out of the root zone after a K fertilizer application. In order to maintain adequate soil test K and prevent K deficiencies in turfgrass grown on a sand-matrix root zone, several small applications of K are required throughout the growing season. Besides the fertilizer cost, these additional applications increase labor costs. The CECs of the zeolite treatments suggest that those treatments might be able to retain sufficient quantities of K for turfgrass growth for an entire season. Potassium sorption curves (Figure 3) showed that there are large differences in K retention among the amendments and construction sand. The peat and construction sand appear to have very little K buffering capacity. Also evident were differences in K buffering capacity between the zeolite amendments and the calcined clay. The slopes of the individual sorption curves indicate that the zeolites have a greater K

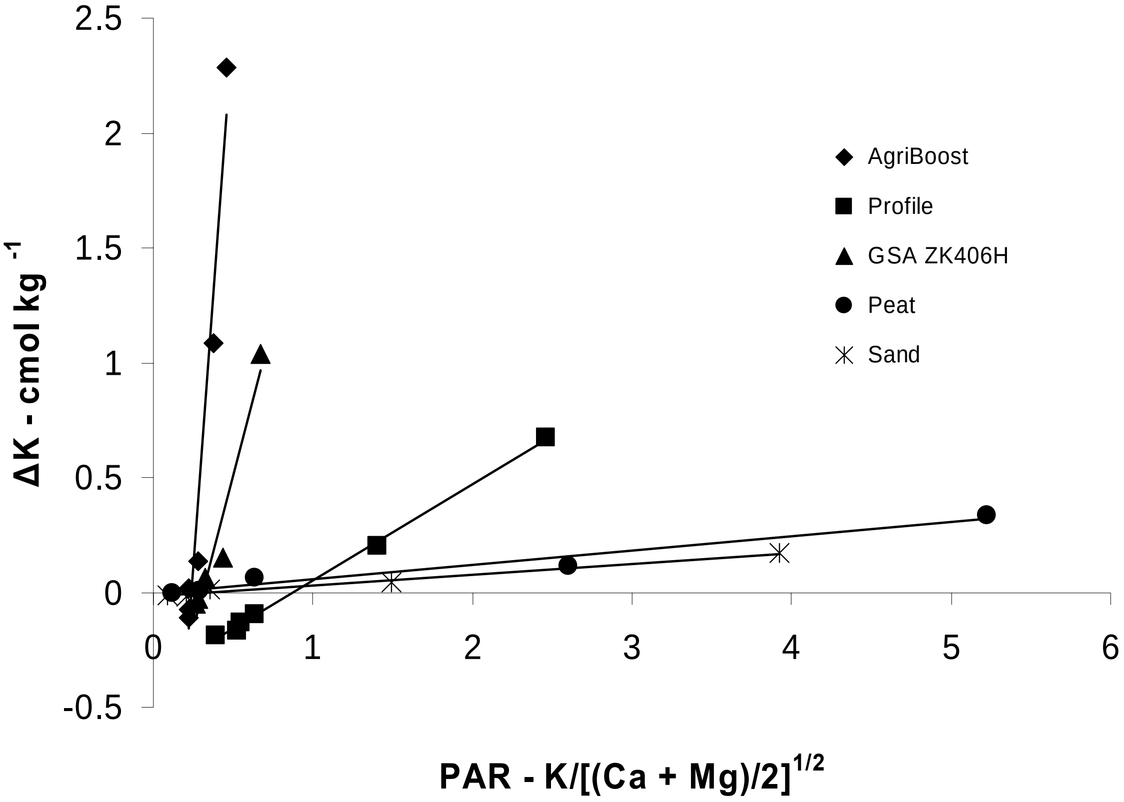

Figure 3. Affinity of amendments and pure sand for K.

buffering capacity than Profile. These results suggest differences in K fertilizer requirement and use efficiency will exist among the treatments.

Phosphorus is another nutrient required in relatively large quantities by turfgrass, typically accounting for over 0.5 % of the dry tissue weight. Adequate buffering of the solution P is of special importance during the establishment phase. In sand-matrix putting greens, adsorbed P controls solution P and, in calcareous root zone mixes, carbonates control P sorption. Phosphorus sorption properties of the root zone mixes (Figure 4) show that the root zone mix containing AgriBoost® adsorbed nearly 50% of the P added, which is 1.8 to 2.7 times as much P as that absorbed by remaining treatments. Surprisingly, the root zone mix containing peat adsorbed significantly less P than all other treatments. Iron and Al associated with this pH 2.83 sphagnum peat moss (Table 10) were expected to significantly increase P sorption as compared to the pure sand control. The implication here is that the organic constituents in the peat reduced P adsorption by reacting with the carbonates in the root zone mix.

To complement the P sorption results, another study was conducted to discern treatment effects on P desorption. Results shown in Figure 5 show that P is desorbed most easily from the root zone mix containing Profile®, which released 1.9 to 2.7 times as much P as the remaining treatments. Also shown in Figure 5 are the amounts of P leached during 2002 from each treatment. Understandably, there was a clear relationship between P desorption and P leaching rates.

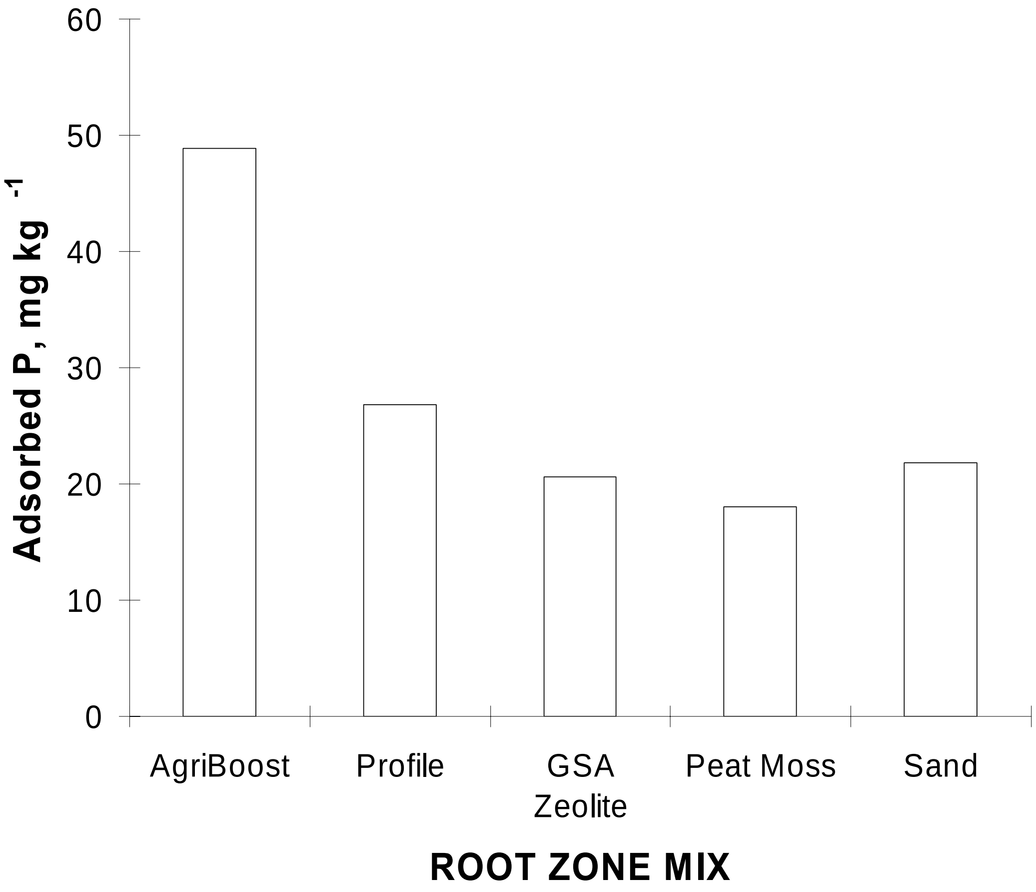

Figure 4. P sorption capacities of root zone mixes.

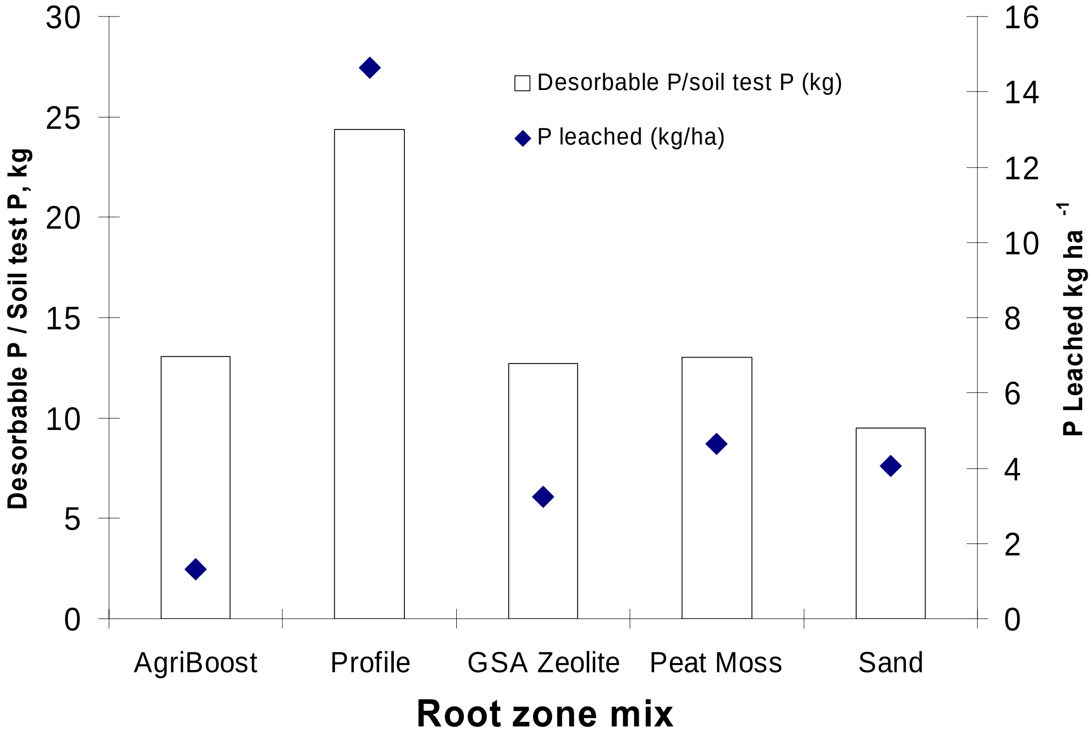

Figure 5. Relationship between desorbable P and total P leached in 2002.

Greenhouse Observations

Establishment

All amendments improved establishment compared to pure sand. AgriBoost® and peat improved establishment compared to GSA and Profile® (Figure 6). All amendments improved turfgrass color (Figure 7) and clipping yield (Figure 8) compared to unamended sand. Color rating and clipping yield differences among the amended treatments were inconsistent.

The greatest amount of leachate was collected from the pure sand treatment, the least amount from the peat treatment (Table 12). The GSA ZK406H zeolite treatment reduced NO_3-N leaching compared to all other treatments. Adding Profile® to the sand increased P leaching compared to the other amended-sand treatments. The pure sand treatment exhibited a large amount of P leaching compared to the other treatments. However, 68% of the total amount occurred from one collection date, suggesting a large isolated P leaching event due to macropore or preferential flow rather than elevated concentrations in the leachate over time, as was demonstrated by the Profile® treatment. The AgriBoost® treatment initially leached Na in concentrations of ~700 mg L^{-1}. After 3 months of irrigation, a total of 3.1 L of leachate was collected, and the Na concentrations had dropped to ~140 mg L^{-1}. Leachate Na concentrations for the remaining treatments ranged from 2 - 16 mg L^{-1}.

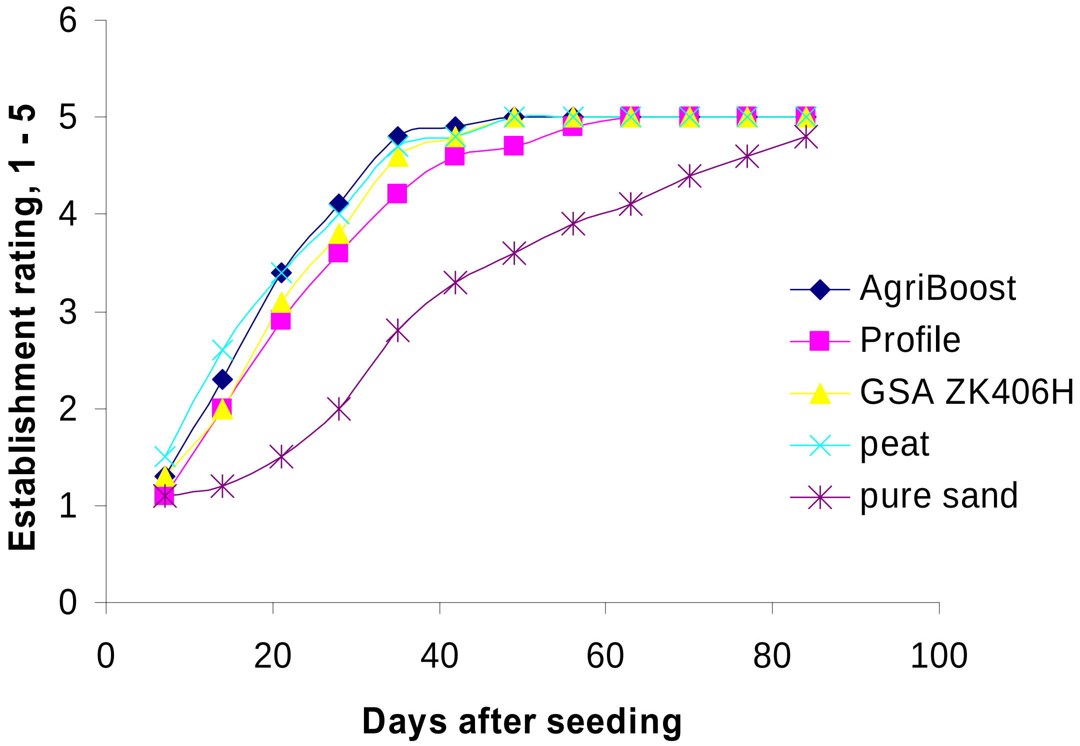

Figure 6. Root zone mix effects on establishment rating (greenhouse study).

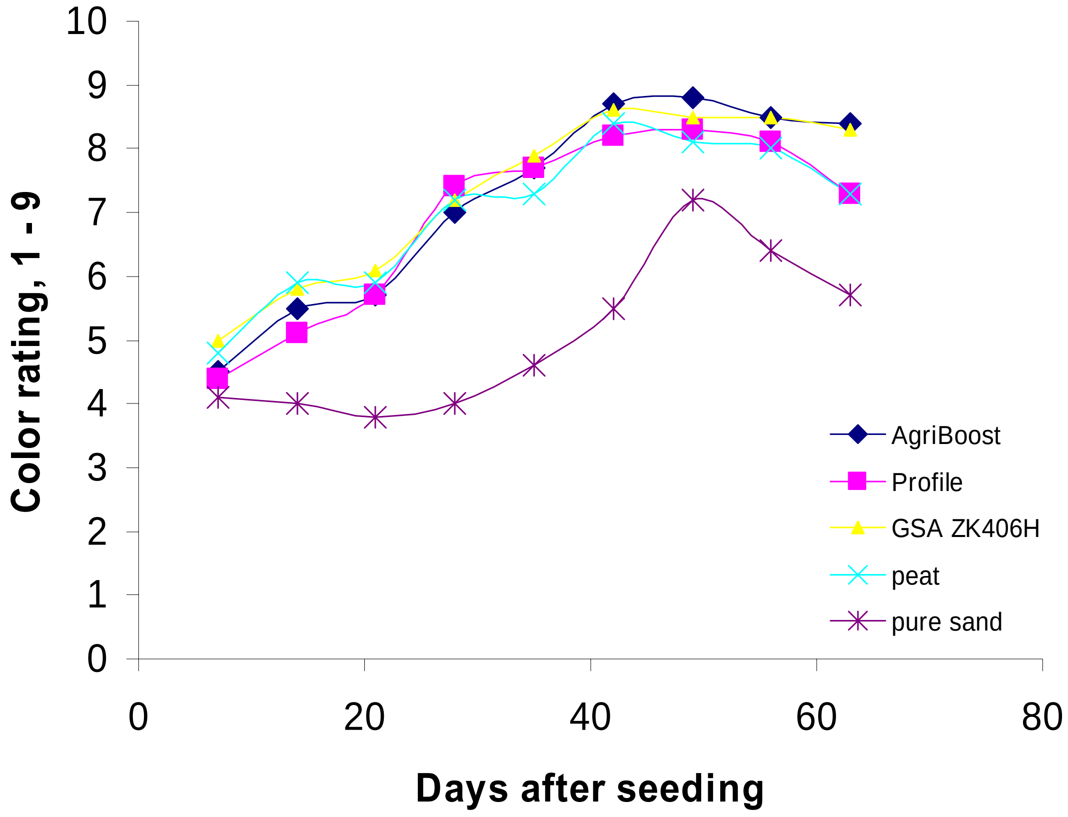

Figure 7. Root zone mix effects on color rating (greenhouse study).

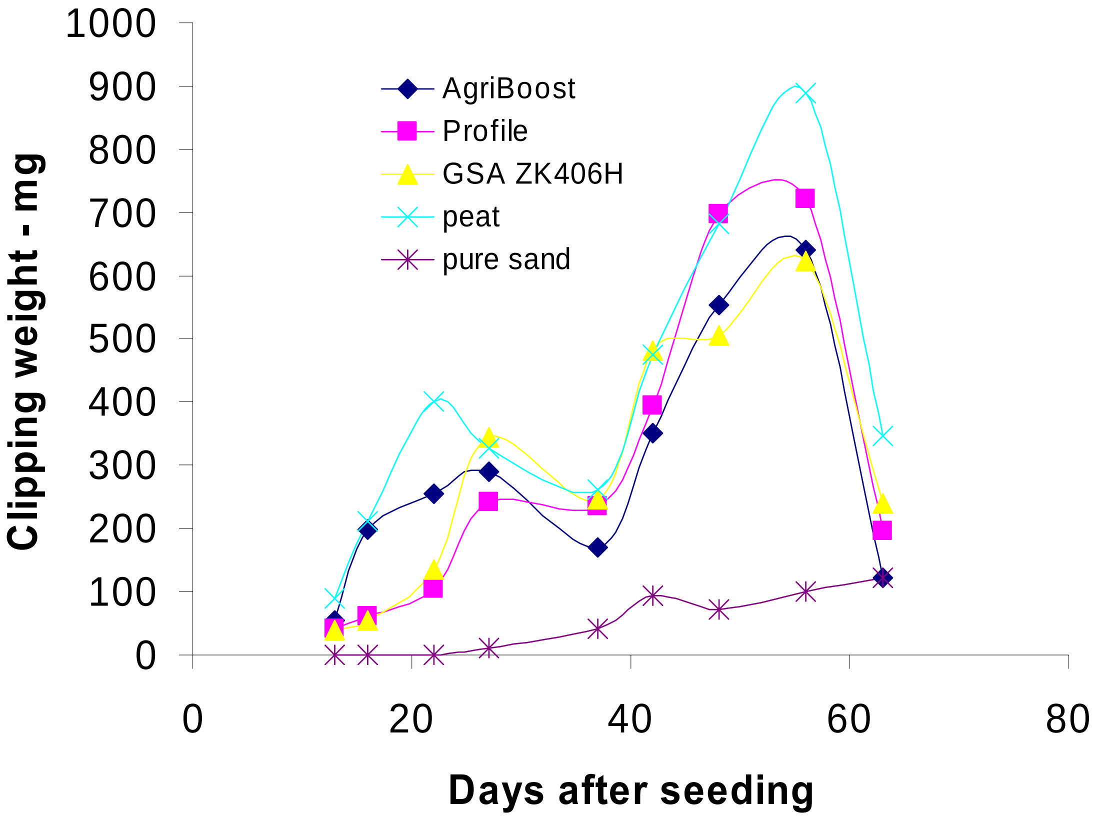

Figure 8. Root zone mix effects on clipping yield (greenhouse study).

Drainage Rates

Figures 9 - 14 display the mean volumetric water contents of each root zone mix at various depths as a function of time over a 48-hour period. These curves show the mean root zone mix moisture content every minute during the first hour following irrigation, and hourly thereafter. Root zone mix differences in the appearance of peaks coinciding with drainage existed. The height of the peaks decreased with each depth. At the first depth (2.5 cm) peaks occurred ~1 minute earlier in the two zeolite-amended root zone mixes than in the other mixes (Figure 9). At all other depths the peak of the peat-amended mix occurred later than in all other mixes. As expected, the difference between the peat treatment's peak and the other treatments' peaks increased with depth. At the 28.0-cm depth, the differences among the peaks of the peat treatment and remaining treatments ranged from ~ 5 to 6.5 hours (Figure 14). These data indicate that drainage rate differences exist between the peat-amended mix and the remaining treatments. These differences could be translated into differences in irrigation requirements.

Table 13 summarizes the treatment effects of the root zone mixes on volumetric water content at various depths at the end of the 48 hour period. The AgriBoost®, GSA ZK406H, and pure sand treatments had 3.5 – 5.2% greater root zone moisture contents than the peat and Profile® treatments.

Table 12. Root zone mix effects on nutrient leaching (greenhouse study).

Root zone mix	Leachate volume	NO_3	NH_4	P	K	Ca	Mg	Na
	L	----------------------------			kg ha^{-1}	---------------------------		
AgriBoost	3.14	3.92	0.44	0.19	10.1	83.6	35.3	282.7
Profile	3.44	1.03	0.29	0.41	9.4	99.1	27.6	17.2
GSA ZK406H	3.44	0.32	0.42	0.09	4.8	90.34	20.76	22.3
Peat	2.73	3.22	0.45	0.13	5.9	80.8	28.8	11.0
Pure sand	4.65	2.92	0.41	4.74†	16.6	119.2	37.2	22.4

†68% of this value occurred on 13 Mar. 2003.

Table 13. Mean volumetric water content of root zone mixes as a function of depth 48 hours after application of 13mm of water (greenhouse study).

	Depth - cm						
Root zone mix	2.5	7.6	12.7	17.8	22.9	28.0	Mean
	-------------		% water content by volume			-------------	
AgriBoost	4.7	10.5	10.4	14.8	22.1	31.4	15.6
Profile	2.2	5.3	6.2	6.9	15.8	27.0	10.5
GSA ZK406H	6.8	8.6	9.8	11.2	19.4	34.7	15.1
Peat	0.0	8.5	9.0	10.7	15.2	26.0	11.6
Pure sand	8.5	9.2	9.8	12.7	19.9	34.3	15.7

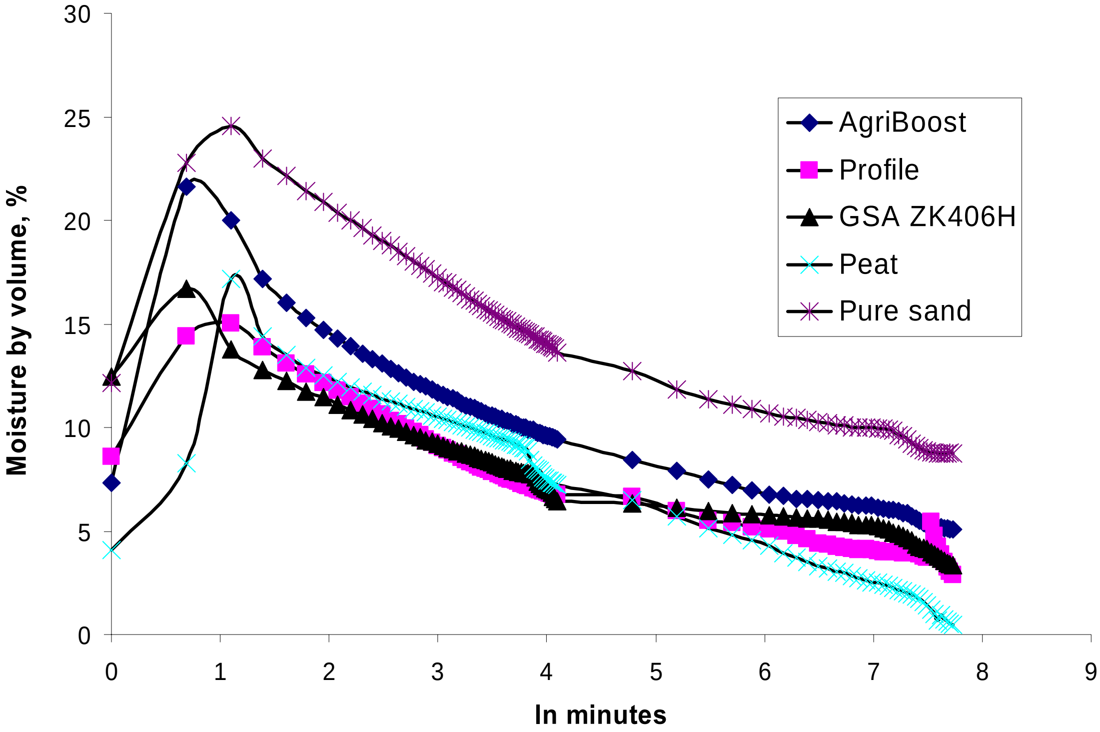

Figure 9. Mean root zone mix volumetric water content at 2.5 cm (1 in.) over 48-hour period (greenhouse study).

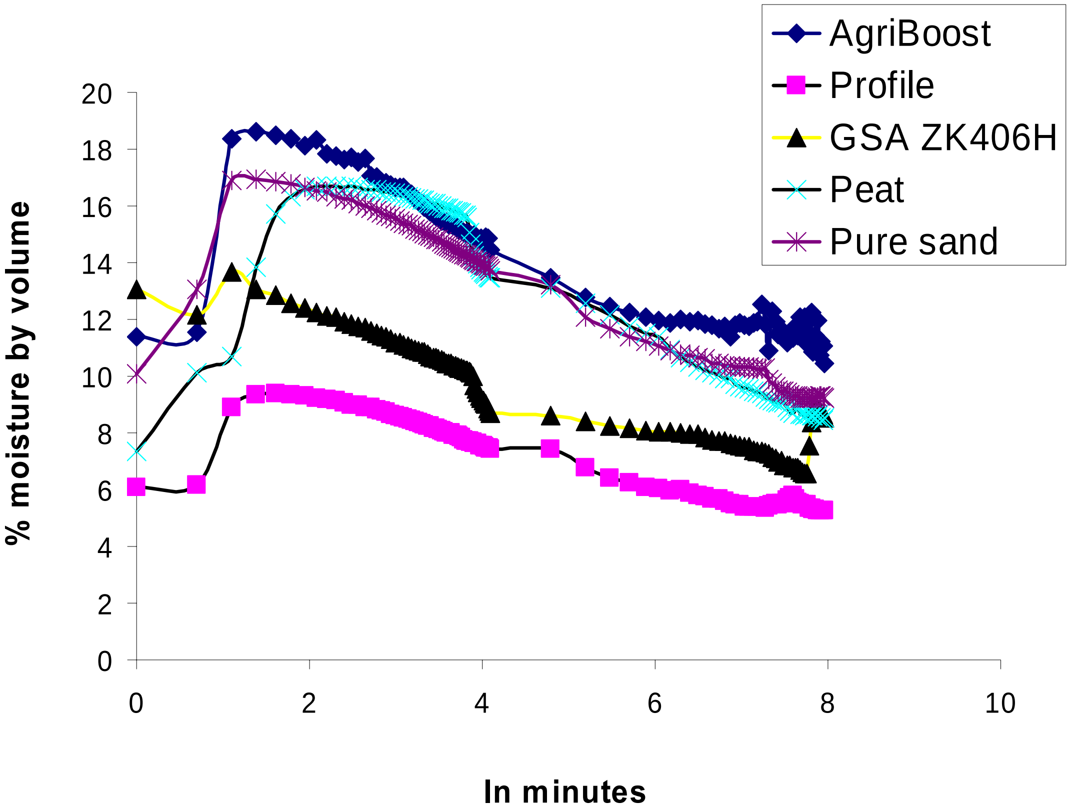

Figure 10. Mean root zone mix volumetric water content at 7.6 (3 in.) cm over 48-hour period (greenhouse study).

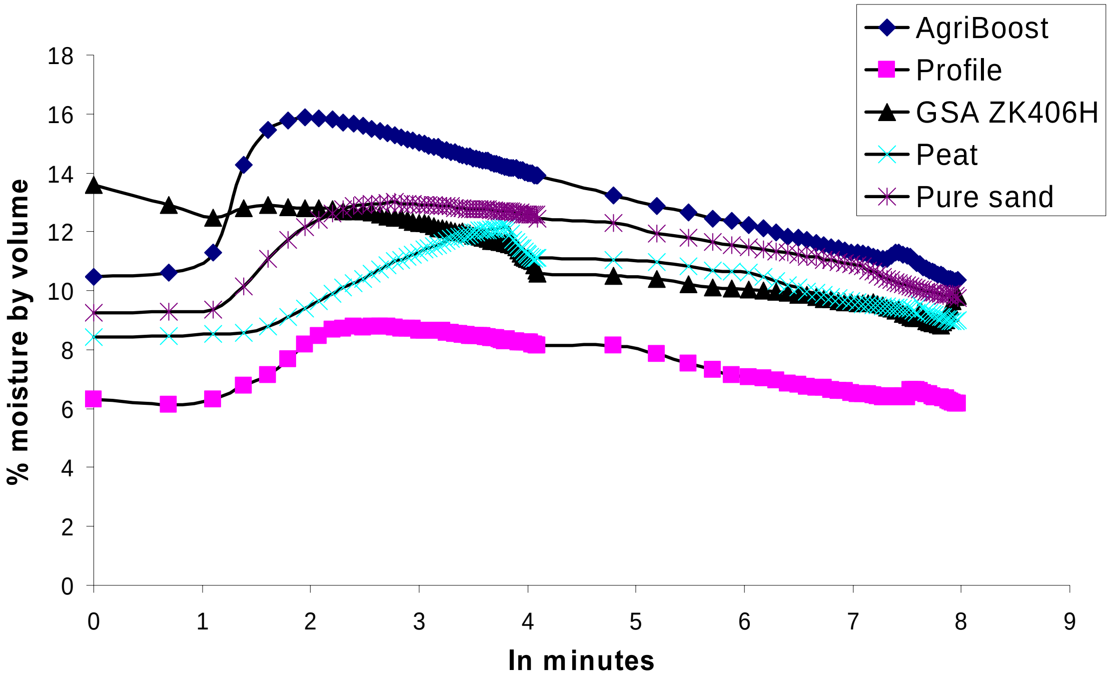

Figure 11. Mean root zone mix volumetric water content at 12.7 cm (5 in.) over 48-hour period (greenhouse study).

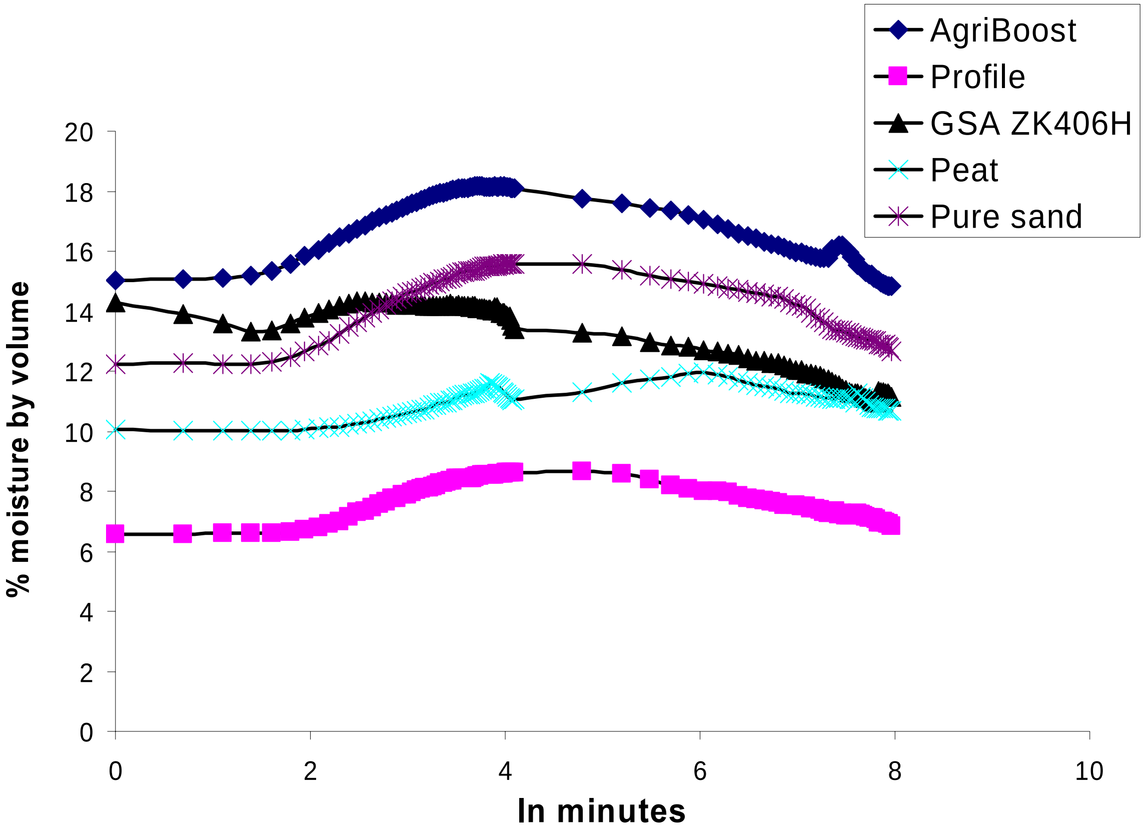

Figure 12. Mean root zone mix volumetric water content at 17.8 cm (7 in.) over 48-hour period (greenhouse study).

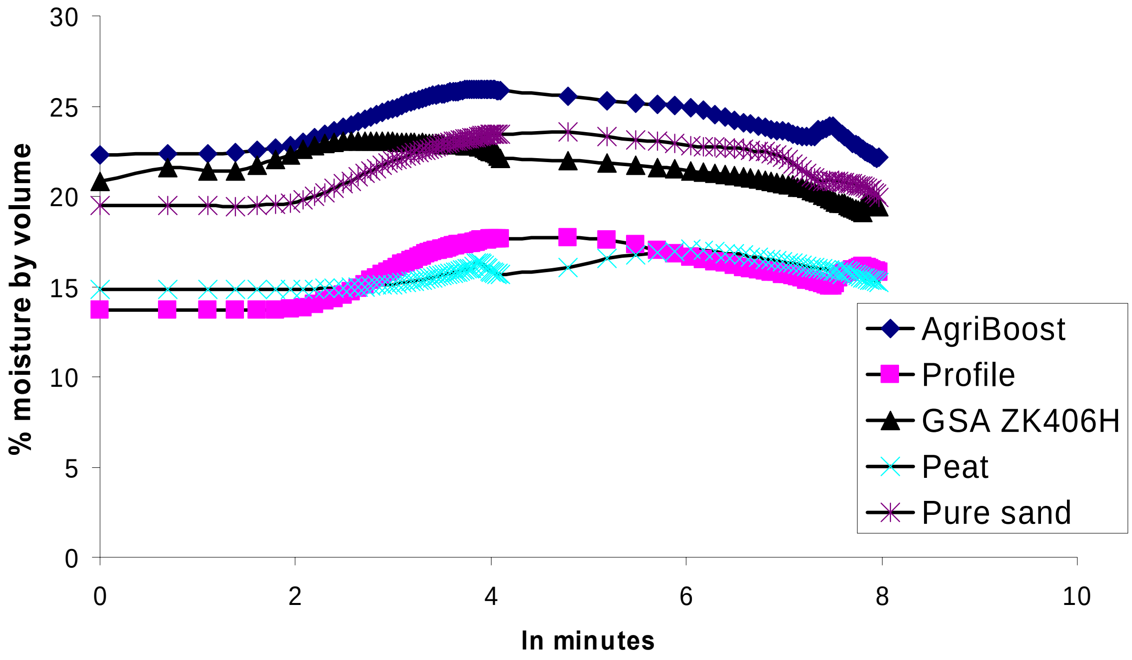

Figure 13. Mean root zone mix volumetric water content at 22.9 cm (9 in.) over 48-hour period (greenhouse study).

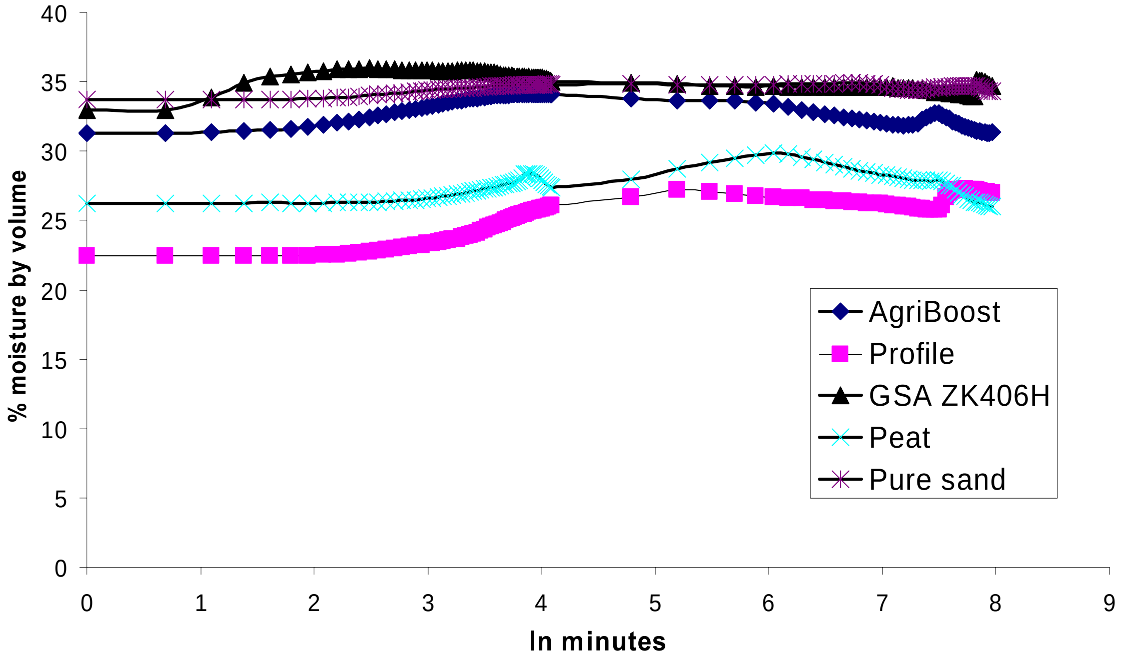

Figure 14. Mean root zone mix volumetric water at content at 28.0 cm (11 in.) over 48-hour period (greenhouse study)

Field Results

Bentgrass Establishment

An improved turfgrass establishment rate can be a valuable asset of a root zone mix. Rapid establishment allows a golf course to open earlier, thereby creating an earlier revenue stream on an investment of several million dollars. However, some turfgrass managers (often under pressure from management) use excessive amounts of N fertilizer to speed the turfgrass growth rate (Kussow, 1999). While a large amount of applied N increases top-growth, it does so at the expense of root growth and leaching of excessive amounts of N. The result is a healthy appearing putting green with a weak root system and likely contamination of ground and surface waters. The green is opened for play prematurely and the turf cannot recuperate from the damage done by ball marks and golf shoes, and becomes particularly susceptible to annual bluegrass invasion.

Therefore, a root zone mix that can facilitate rapid establishment rates without excessive N applications is of value to the golf course industry. This root zone mix must also demonstrate the ability to rapidly develop and sustain a deep rooting system. A relatively modest amount of N fertilizer was used during the grow-in period (190 - 264 kg N ha^{-1}) with the purpose of finding such a benefit. Fertilizer applications were based on turfgrass color. Due to color differences evident during the grow-in period, an extra N fertilizer application (12 kg N ha^{-1} as urea) was required for the pure sand, peat, and Profile® treatments. This suggests that both zeolite treatments retained greater amounts of N, as each was able to sustain a darker green color for an extended period of time. Table 14 summarizes treatment effects on density/uniformity, color, and root mass density during

Table 14. Root zone mix effects on turf color, density, and root mass density during establishment period (15 May 2002 – 5 Aug. 2002).

Root zone mix	Mean color rating	Mean density rating	Root mass density†
	1 - 9	1 - 9	kg m^{-3}
AgriBoost	6.68	6.64	0.91
Profile	6.59	6.13	1.04
GSA ZK406H	6.57	6.26	1.30
Peat	6.55	6.61	1.47
Pure Sand	6.60	5.55	1.28
$LSD_{0.05}$	NS	0.31	0.35

† Root mass density on 12 July 2002.

grow-in. The AgriBoost® and peat treatments had significantly greater bentgrass density/uniformity ratings than all other treatments. The Profile® and GSA treatments showed improved density/uniformity ratings compared to pure sand. The GSA treatment exhibited the greatest root mass density, statistically greater than AgriBoost® and peat.

Leachate Analysis

Groundwater is the main source for drinking water in many urban areas. Therefore, it is important to preserve the quality of the groundwater which we rely heavily upon. Organic and ammoniacal forms of N are transformed into NO_3^- in aerobic soils. Nitrate is a major groundwater pollutant because of the quantity of N inputs to soils and its high solubility. The EPA considers drinking water with a NO_3-N concentration in excess of 10 mg L^{-1} as unsafe for human consumption.

Nitrate leaching is a concern during the grow-in period of sand-matrix greens because of the high water infiltration rates, lack of substantial root systems, and frequent applications of irrigation water and soluble N fertilizers often associated with them. Soil texture, N source and rate applied, timing of the application, and precipitation/irrigation amounts all significantly influence NO_3-N leaching (Petrovic, 1990). However, it has been shown that N leaching losses from sand-matrix putting greens are minimal during the short grow-in period and minimal to non-existent after this period when best management practices are followed (Petrovic, 1990; Brauen and Stahnke, 1995).

Several researchers have examined the effects of zeolite incorporation on N leaching in sand-matrix root zones (MacKown and Tucker, 1985; Ferguson and Pepper, 1987; Huang and Petrovic, 1994; Perrin et al., 1998; Bigelow et al., 2001). These researchers have demonstrated that NH_4-N leaching decreases with increasing root zone CEC. Results regarding NO_3-N leaching losses are mixed. Bigelow and others (2001) reported 99% of applied NO_3-N was lost through leaching when 50 kg ha^{-1} of N as NH_4NO_3 was applied to a soil column and immediately followed by 2.5 pore volumes of distilled water. From this they concluded that zeolite incorporation (8: 1, v/v) does not decrease NO_3-N leaching compared to an unamended control. Huang and Petrovic (1994) examined N leaching in root zones mixes supporting bentgrass. The authors reported an 86 and 99% reduction in NO_3-N and NH_4-N leaching respectively over an 18-week period when a clinoptilolitic zeolite was incorporated into sand (9: 1, v/v) and $(NH_4)_2SO_4$ was used as the N source.

Fergeson and Pepper (1987) recognized that clinoptilolite has the potential to protect NH_4^+ from nitrification, thereby reducing volatilization losses. Many of the exchange sites associated with zeolites are found within 3- to 8-Å ($< 10^{-9}$ m) diameter channels. Because of the small size of the channels, the authors speculated that the NH_4^+ bonded to these exchange sites is not accessible to nitrifying bacteria ($\sim 10^{-6}$ m) and, therefore, NH_3 volatilization and NO_3-N leaching are retarded. Thus, it is not surprising that Huang and Petrovic (1996) were able to quantify a reduction in NO_3-N leaching and Bigelow and others (2001) were not. Reductions in NO_3-N leaching are achieved by the retention of significant quantities of NH_4^+ by the root zone mix resulting in increased N use efficiency, not by the physical retention of the NO_3^- ion.

Quantification of the effects of zeolite on NO_3-N leaching under field conditions is important and was an objective of the present study. If zeolites prove to be effective in significantly reducing NO_3-N leaching during grow-in periods (when NO_3^- is most susceptible to leaching), golf course superintendents may incorporate zeolite into their root zone mixes as a means of satisfying regulatory agent requirements for construction in environmentally sensitive areas.

Leachate was collected from each plot on a monthly and bimonthly basis during 2002 and 2003 respectively. Total leachate volumes were recorded and a sample saved for nutrient analysis. Samples were refrigerated and concentrations of NO_3-N and NH_4-N were measured promptly. The concentrations of N were converted to mass of N by taking into consideration the volumes of leachate collected. Relatively large treatment effects on N leaching were observed during the first 3 months of the data collection coinciding with the grow-in period (Table 15). After the grow-in period, significant differences in NO_3-N leaching between treatments were found in only 1 of 12 sampling dates (Tables 16a and 16b). Therefore, the NO_3-N leaching discussion will focus on the results from the grow-in period.

The GSA ZK406H treatment reduced NO_3-N leaching by 70% compared to the AgriBoost® treatment 79% compared to the peat treatment (Table 15). Over twice as much NO_3-N was recovered in the leachate of the pure sand and Profile® treatments compared to the GSA ZK406H treatment; however, due to large variation within treatments these differences were not statistically significant at the $p = 0.05$ level. The difference between the GSA ZK406H and the peat treatment was the lone statistically significant difference.

Table 15. Root zone mix effects on N leaching during establishment period (15 May 2002 – 5 Aug. 2002).

Root zone mix	N applied	NO_3-N leached	NH_4-N leached	Turfgrass N uptake†	Leachate collected	Applied N recovered in leachate
	----------------------kg ha^{-1}			-------------------	m^3 ha^{-1}	%
AgriBoost	224.8	30.01	2.18	7.17	126	14.3
Profile	237.0	18.92	2.36	6.36	129	9.0
GSA ZK406H	224.8	9.05	2.83	7.00	129	5.3
Peat	237.0	43.02	6.10	7.43	129	20.7
Pure Sand	307.9	26.21	4.06	9.23	120	9.8

† Total N recovered in turfgrass clippings on 6/18/02, 7/8/02, 7/22/02, and 8/5/02.

Table 16a. Nitrogen leached as NO_3^- in 2002.

Root zone mix	6/06	7/08	8/11	9/09	9/27	10/14	11/29	Total
	--------------------------------			kg N ha^{-1}			--------------------------------	
AgriBoost	21.04	5.37	1.42	1.08	0.79	1.04	1.46	32.20
Profile	9.23	5.87	1.46	1.15	1.17	1.08	1.07	21.03
GSA ZK406H	4.09	0.86	1.27	1.05	1.13	1.07	1.29	10.76
Peat	27.49	8.45	0.98	0.96	1.09	0.94	1.14	41.05
Pure Sand	14.20	6.74	1.21	1.19	0.88	1.02	1.11	26.35
$LSD_{0.05}$	12.63	NS	0.21	NS	NS	0.11	NS	22.80

Table 16b. Nitrogen leached as NO_3^- in 2003.

Root zone mix	4/23	5/01	5/06	5/13	5/27	6/10	6/24	7/08	Total
	------------------------------------				kg N ha^{-1}			----------------------------------	
AgriBoost	2.23	2.03	1.02	2.09	1.00	2.05	1.13	0.66	12.21
Profile	1.71	0.93	0.26	1.99	0.46	1.72	1.29	0.11	8.46
GSA ZK406H	0.26	0.98	0.19	0.91	0.53	4.47	1.17	0.33	8.83
Peat	0.50	1.29	0.33	1.20	1.65	4.09	0.96	0.27	10.30
Pure Sand	0.61	1.22	0.45	1.32	1.47	2.67	0.79	0.39	8.93
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	NS	NS	NS

When large differences in N leaching occur, they are typically associated with large differences in leachate volumes. In this study, leachate volumes failed to account for differences in N leached during the grow-in period (Tables 17a and 17b). Although significant differences in leachate volume existed on several dates, the trends found in volume differences did not coincide with trends found in total N leaching. Total N differences were a function of NO_3-N and NH_4-N concentrations in the leachate.

Surprisingly, AgriBoost® failed to reduce NO_3-N leaching compared to the other treatments except for peat. Amendment particle size appears to affect N leaching. Perrin and others (1998) found clinoptilolite having a particle size < 0.25 mm increased NO_3-N leaching by 48% compared to the same amendment having a particle size of 2 to 4 mm. Although not the same minerals, the NO_3-N leaching difference in the two zeolites used in this study could be attributed to the particle size differences between them.

Nus and Brauen (1991) reported that the CEC and exchangeable K content of clinoptilolitic zeolite increased with decreasing particle size. Consistent with these results, AgriBoost® exhibited a greater CEC than GSA ZK406H (Table 10). These two separate studies report seemingly conflicting results. As the particle size of zeolite increases, NO_3-N leaching decreases (Perrin et al, 1998) but CEC decreases (Nus and Brauen, 1991), suggesting a more complicated mechanism for NO_3-N leaching reductions than just the quantitative retention of NH_4^+. The particle size of zeolites may be just as important to the chemical properties of the root zone mix as they are to the physical properties.

If differences in root mass between the 2 zeolite treatments are to offer an explanation to the differences in NO_3-N leaching, then treatment differences in N uptake

Table 17a. Leachate volumes collected in 2002.

Root zone mix	6/06	7/08	8/11	9/09	9/27	10/14	11/29	Total
	------	------	------	------ m^3 ha^{-1} ------	------	------	------	
AgriBoost	40.5	42.5	42.8	43.0	42.8	42.1	32.4	286
Profile	42.0	43.9	43.2	43.3	42.8	42.4	37.9	296
GSA ZK406H	41.3	43.5	44.0	44.2	42.7	42.3	32.8	291
Peat	42.4	43.3	42.9	42.8	42.4	41.2	25.2	280
Pure Sand	38.4	41.0	41.0	41.2	40.6	39.8	32.4	274
$LSD_{0.05}$	NS	2.60	2.80	2.80	NS	NS	8.30	18.4

Table 17b. Leachate volumes collected in 2003.

Root zone mix	4/23	5/01	5/06	5/13	5/27	6/10	6/24	7/08	Total
	------	------	------	------	m^3 ha^{-1} ------	------	------	------	
AgriBoost	41.2	42.3	42.0	41.7	39.7	41.6	40.6	40.8	330
Profile	38.5	42.2	41.7	41.1	32.9	40.6	41.6	42.0	320
GSA ZK406H	40.0	41.0	42.1	39.7	37.1	41.6	40.6	41.6	324
Peat	38.9	41.4	42.1	41.1	33.9	41.6	41.8	42.2	323
Pure Sand	37.3	40.6	40.2	39.6	37.9	39.9	39.7	39.8	315
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	NS	NS	NS

should be apparent. The GSA ZK406H treatment had 43% greater root mass density than the AgriBoost® treatment on 12 July 2002; however, N uptake was greater in the AgriBoost® treatment than in the GSA treatment during the establishment period (Table 15).

By monitoring leachate from the base of the 30-cm root zone for the purposes of examining putting green effects on groundwater quality, one is making the shaky assumption that all or the majority of the leachate ends up moving to groundwater. USGA putting greens are outfitted with drain tile that carries the percolate elsewhere, often to surface waters. This should be kept in mind when discussing the effects of NO_3-N leaching from putting greens on groundwater quality.

From an environmentalist's perspective, monitoring NO_3-N concentrations in the leachate is as important as quantifying total N loads over a prolonged period of time. During the initial grow-in period (3 months) 12 of 60 leachate samples exceeded the drinking water standard of 10 mg L^{-1} (Table 18a). Sixteen of the 60 samples exceeded 7 mg L^{-1} [the amount found in the irrigation water (Table A-3)], and the average NO_3-N concentration during the grow-in period was 5.7 mg L^{-1}. After the grow-in, NO_3-N concentrations declined markedly. None of the 80 samples collected exceeded 7 mg L^{-1} NO_3-N and the mean concentration in the 80 samples was 0.9 mg L^{-1} (Table 18b). In 2003, no significant differences were found between treatments on any of the 8 sampling dates (Table 16b). The average NO_3-N concentration over those sampling dates was 1.0 mg L^{-1} (Table 18c), less than 1/5 the concentration of the NO_3-N found in the irrigation water. No sample exceeded 10 mg L^{-1} NO_3-N and only 2 of the 160 samples analyzed

Table 18a. Summary of NO_3-N leaching concentrations during establishment period in 2002.

	AgriBoost	Profile	GSA ZK406H	Peat	Pure sand	All mixes
	------------------------ mg NO_3-N L^{-1} ---------------------------					
Maximum conc.	24.5	8.3	8.1	31.7	22.0	31.7
Minimum conc.	0.3	0.6	0.2	0.0	0.1	0.0
Mean conc.	7.3	4.1	1.6	9.4	6.2	5.7
	-----------------------Number of samples collected---------------------					
< 7 mg NO_3-N L^{-1}	7	10	11	7	9	44
> 7 mg NO_3-N L^{-1}	5	2	1	5	3	16
> 10 mg NO_3-N L^{-1}	4	0	0	5	3	12

Table 18b. Summary of NO_3-N leaching concentrations following establishment period in 2002.

	AgriBoost	Profile	GSA ZK406H	Peat	Pure sand	All mixes
	------------------------ mg NO_3-N L^{-1} ---------------------------					
Maximum conc.	2.7	1.0	1.9	2.5	1.3	2.7
Minimum conc.	0.1	0.7	0.6	0.6	0.3	0.1
Mean conc.	1.0	0.9	0.9	0.9	0.9	0.9
	-----------------------Number of samples collected---------------------					
< 7 mg NO_3-N L^{-1}	16	16	16	16	16	16
> 7 mg NO_3-N L^{-1}	0	0	0	0	0	0
> 10 mg NO_3-N L^{-1}	0	0	0	0	0	0

Table 18c. Summary of NO_3-N leaching concentrations in 2003.

	AgriBoost	Profile	GSA ZK406H	Peat	Pure sand	All mixes
	------------------------- mg NO_3-N L^{-1} ----------------------------					
Maximum conc.	7.6	5.2	6.3	7.4	3.6	7.6
Minimum conc.	0.0	0.0	0.0	0.0	0.0	0.0
Mean conc.	1.3	0.9	1.0	1.0	0.9	1.0
	-------------------------Number of samples collected----------------------					
< 7 mg NO_3-N L^{-1}	31	32	32	31	32	158
> 7 mg NO_3-N L^{-1}	1	0	0	1	0	2
> 10 mg NO_3-N L^{-1}	0	0	0	0	0	0

exceeded 7 mg L^{-1}. These results are consistent with several sand-matrix putting green NO_3-N leaching studies that have been conducted over the years (Snyder et al., 1981; Sheard et al., 1985; Brauen and Stahnke, 1995; Gonzalez-Carroscosa et al., 1995).

During the establishment period, NH_4-N accounted for 7 – 31% of the total N leached for all treatments. The peat treatment leached the greatest amount of NH_4-N followed by the pure sand treatment. The inorganic amended treatments leached statistically similar amounts of NH_4-N, 36 – 46% less than the peat treatment.
After the establishment period, significant differences in NH_4-N leaching existed on 4 of 12 sampling dates (Tables 19a and 19b). The AgriBoost® and Profile® treatments significantly reduced the total amount of NH_4-N leached in 2002 compared to the peat treatment. In 2003, NH_4-N leaching accounted for 12 – 27 % of the total N leached. Treatment differences did not exist in regard to total NH_4-N leaching in 2003.

From the laboratory K sorption curves (Figure 3), treatment differences in K leaching were expected. However, the curves failed to characterize the K leaching observed in the field plots. In 2002, the Profile® and AgriBoost® treatments leached significantly more K than the GSA ZK406H, peat, and pure sand treatments, which were statistically similar to each other (Table 20a). The grow-in period appeared to have little effect on K leaching. All amendments increased K leaching compared to the pure sand treatment during 2002. In 2003, the pure sand and GSA treatments significantly reduced K leaching compared to the peat treatment which exhibited significantly less K leaching than the Profile® and AgriBoost® treatments (Table 20b). During the 2003 season the Profile® treatment leached 71% more K than the GSA ZK406H treatment.

Table 19a. Nitrogen leached as NH_4^+ in 2002.

Root zone mix	06/06	07/08	08/11	09/09	09/27	10/14	11/29	Total
	------------------------------			kg N ha^{-1}		------------------------------		
AgriBoost	1.15	0.12	0.91	0.67	0.35	0.86	1.23	5.29
Profile	1.19	0.15	1.02	0.74	0.71	0.89	0.98	5.68
GSA ZK406H	1.57	0.19	1.07	0.84	0.81	0.84	1.03	6.35
Peat	5.07	0.11	0.92	0.57	0.64	0.69	0.80	8.80
Pure Sand	2.00	1.14	0.92	0.98	0.82	0.68	1.06	7.60
$LSD_{0.05}$	2.42	0.99	NS	NS	0.38	0.13	NS	3.08

Table 19b. Nitrogen leached as NH_4^+ in 2003.

Root zone mix	04/23	05/01	05/06	05/13	05/27	06/10	06/24	07/08	Total
	------------------------------------				kg N ha^{-1}		----------------------------------		
AgriBoost	1.10	0.46	1.00	0.71	0.26	0.45	0.19	0.31	4.48
Profile	0.95	0.27	0.26	0.65	0.30	0.26	0.79	0.04	3.53
GSA ZK406H	0.57	0.13	0.19	0.18	0.09	0.33	0.20	0.01	1.71
Peat	0.24	0.19	0.33	0.32	0.00	0.34	0.00	0.00	1.42
Pure Sand	0.36	0.25	0.45	0.38	0.06	0.16	0.00	0.00	1.46
$LSD_{0.05}$	NS	NS	NS	NS	NS	NS	0.65	0.27	NS

Table 20a. Potassium leached in 2002.

Root zone mix	06/06	07/08	08/11	09/09	09/27	10/14	11/29	Total
	----------------------------------			kg K ha^{-1}			---------------------------------	
AgriBoost	4.26	5.61	6.90	6.86	6.70	5.66	3.39	39.40
Profile	4.89	5.99	7.21	6.00	7.43	6.78	4.72	43.0
GSA ZK406H	2.96	4.32	5.88	6.20	5.50	4.77	2.89	32.5
Peat	3.50	4.03	5.66	5.43	5.40	4.78	2.33	31.1
Pure Sand	3.94	3.87	5.01	5.23	4.81	4.41	2.69	30.0
LSD$_{0.05}$	NS	1.49	0.67	1.58	0.77	0.55	1.00	5.05

Table 20b. Potassium leached in 2003.

Root zone mix	04/23	05/01	05/06	05/13	05/27	06/10	06/24	07/08	Total
	----------------------------------				kg K ha^{-1}			---------------------------------	
AgriBoost	7.94	5.77	4.61	4.94	5.37	6.79	5.31	5.01	44.9
Profile	8.92	6.83	6.30	7.05	6.08	7.13	4.49	8.60	56.2
GSA ZK406H	5.23	2.81	2.42	2.64	2.72	3.56	2.76	3.89	26.1
Peat	6.06	3.90	2.92	3.66	3.02	5.78	2.83	4.54	32.7
Pure Sand	4.82	3.48	3.02	3.70	3.26	3.58	2.42	4.61	28.9
LSD$_{0.05}$	3.84	0.75	0.64	1.00	0.81	1.79	0.77	2.81	6.52

Phosphorus leaching has not been quantified in many putting green root zone mix studies conducted under field conditions. Soluble P fertilizers are perennially applied to putting greens having relatively high infiltration rates. Although P leaching is typically low in mineral soils, there is reason to believe that P is quite susceptible to leaching in sand-matrix root zones. A large portion of the water that leaches through the sand-matrix root zone is carried off by drain pipe embedded in the pea gravel layer below the root zone mix. The final destination of the leachate is commonly a body of water of one type or another rather than groundwater, as is often mistakenly assumed. Therefore, monitoring P in leachate from well drained putting greens becomes important in protecting surface water quality.

Profile® leached 3 – 11 times more P than the remaining treatments during 2002, with concentrations of ortho-phosphate typically exceeding 1 mg L^{-1} in the leachate – a level 3-4 times greater than that of a hypereutrophic body of water. Differences between the remaining treatments were not significant (Table 21a). In 2003, P leaching was unexpectedly high in all treatments except AgriBoost® (Table 21b). Figure 15 shows the mean concentration of inorganic P in the leachate of each treatment on 13 sampling dates. Three apparent trends are observed: (1) P concentrations were high for the Profile® treatment over the entire sampling period, (2) P concentrations increased with time for the GSA, peat, and pure sand treatments, and (3) P concentrations were consistently low for the AgriBoost® treatment over the 2 year period. Soil testing has yet to adequately explain these results. Water soluble P and Bray-1 P did not reveal any significant correlation with P leaching. Brye and others (2002) studied P leaching under a restored tallgrass prairie and

Table 21a. Phosphorus leached in 2002.

Root zone mix	06/06	07/08	08/11	09/09	09/27	10/14	11/29	Total
	---------------------------------			kg P ha^{-1}			--------------------------------	
AgriBoost	0.13	0.32	0.15	0.12	0.09	0.10	0.12	1.03
Profile	2.17	3.48	1.16	1.11	0.88	1.06	1.27	11.13
GSA ZK406H	0.13	0.45	0.58	0.38	0.26	0.31	0.38	2.49
Peat	0.79	1.03	0.68	0.27	0.25	0.30	0.36	3.67
Pure Sand	0.53	0.67	0.54	0.45	0.32	0.38	0.45	3.34
LSD$_{0.05}$	1.37	2.42	0.73	0.43	0.27	0.32	0.31	4.46

Table 21b. Phosphorus leached in 2003.

Root zone mix	04/23	05/01	05/06	05/13	05/27	06/10	06/24	07/08	Total
	--------------------------------				kg P ha^{-1}			----------------------------------	
AgriBoost	0.17	0.14	0.23	0.24	0.21	0.21	0.23	0.29	1.8
Profile	1.27	2.10	2.68	3.06	2.42	3.34	3.24	2.80	21.2
GSA ZK406H	0.65	1.79	2.76	2.61	2.47	5.34	2.85	2.53	21.0
Peat	1.20	1.76	2.56	2.64	2.47	4.99	2.51	2.09	20.3
Pure Sand	1.00	1.68	2.61	2.69	2.42	5.03	2.57	2.26	20.5
LSD$_{0.05}$	0.63	0.62	0.50	0.70	0.65	0.88	0.82	0.48	4.13

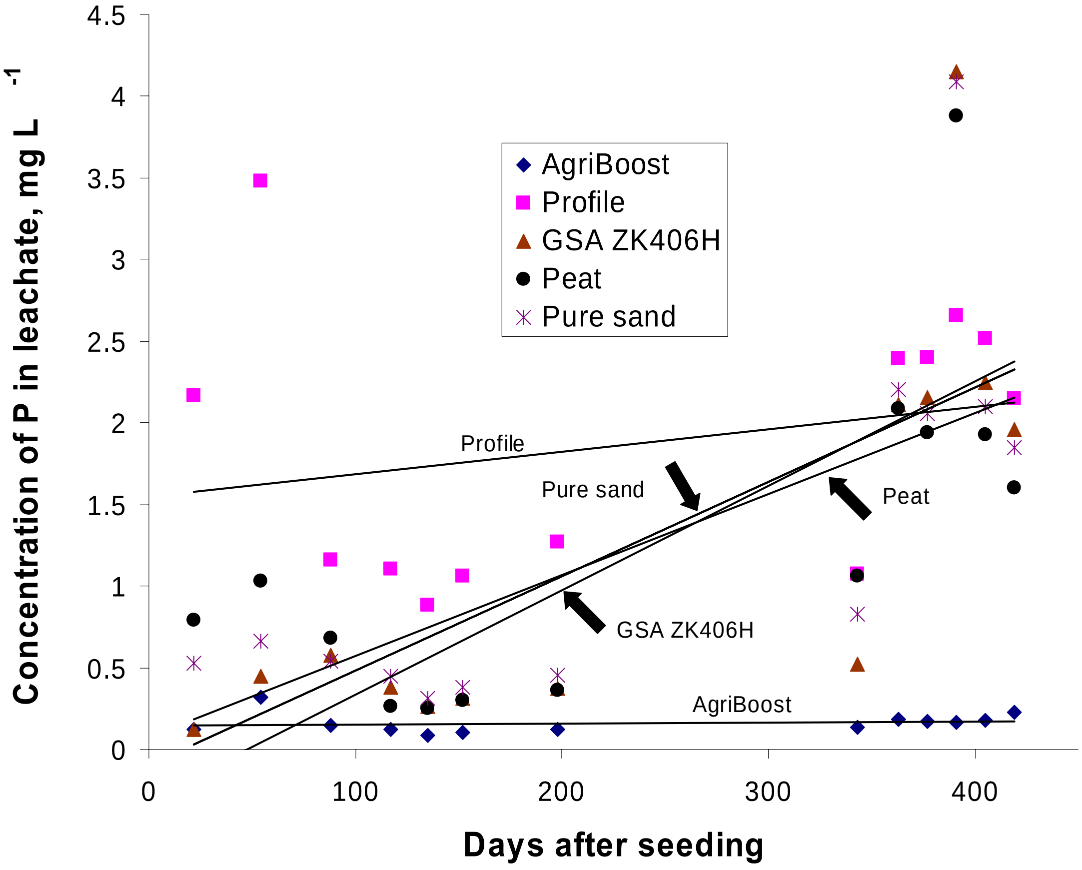

Figure 15. Root zone mix effects on concentrations of P in leachate over time.

corn agroecosystems in southern WI. The authors also failed to find any correlation between P leaching and water soluble or Bray-1 P. The presence of carbonates in the root zone mix can affect P leaching, although AgriBoost® has a relatively large amount of carbonates, no significant differences in % CCE were found in soil samples taken on 17 June 2003. The mean CCE value for all treatments was 2.1% with a standard deviation of 0.43.

Soil Tests

On 21 Sept. 2002 soil samples were taken at various depths and analyzed for Bray-1 P and K. Relatively high soil test K values were observed in the AgriBoost® treatment compared to the remaining treatments on this sampling date (Table A-4); therefore, K applications were based on soil test results during the 2003 season. This resulted in 195 kg ha^{-1} less K applied on the AgriBoost® treatment. Bray-1 K continued to remain significantly higher in the AgriBoost® treatment than any other treatment on all soil testing dates (Table 22) despite not receiving any noteworthy K applications (Table A-1). These observations imply that a root zone amended with AgriBoost® will significantly improve fertilizer K use efficiency, resulting in economic savings.

Another approach to managing K nutrition on sand-matrix root zones is to apply K based upon tissue testing. For creeping bentgrass, sufficient tissue K is between 2.20 – 2.60 mg K g^{-1} (McCarty, 2001). In this study, tissue K seemed fairly independent of Bray-1 K. The AgriBoost® treatment had tissue K levels below optimum on 4 of 13 dates (Table A-11), but Bray-1 K never dipped below the University of Wisconsin's sufficient interpretation for golf course soils (Table 23). Conversely, every treatment except AgriBoost® exhibited low to very low Bray-1 K on all sampling dates (Table 22), yet tissue K was at least sufficient on 8 of 13 dates (Table A-11). Soil samples and tissue samples were taken concurrently on 3 dates in 2003. A plot of tissue K vs. Bray-1 K for these 3 dates suggests that 6 mg kg^{-1} Bray-1 K was sufficient for sand-matrix putting greens and that UW soil test interpretations (Table 23) for golf turf require separate soil test K interpretations for sand-matrix putting greens (Figure 16).

The AgriBoost® treatment consistently had the highest soil test P for all sampling dates, and maintained significantly more Bray-1 P than the Profile®, peat, and GSA ZK406H treatments throughout the 2003 season (Table 24). The soil test P of any treatment never dipped below the University of Wisconsin's 'Medium' soil test interpretation for golf turf (Table 23). Additionally, most values were in the sufficient range for all sampling dates.

Changes in root zone mix pH were observed over time (Table 25). The general trend observed is that of decreasing pH with time until July 2003 when the pH values of all treatments appear to be increasing. Additional measurements in coming years are needed to draw more extensive conclusions.

Plant Parameters

Turfgrass clipping yield, color, and quality are the ultimate indicators the agronomic performance of a root zone mix. In an effort to explain treatment differences

Table 22. Soil Bray 1- K for sampling dates in 2003.

Root zone mix	4/15	5/12	6/03	6/13	7/03	Mean
	--------------------------------	----------	mg L^{-1}	----------	----------	--------------------------------
AgriBoost	78.3	98.5	30.8	78.6	72.3	78.3
Profile	21.9	26.8	26.2	16.1	29.9	21.9
GSA ZK406H	29.4	36.4	22.0	19.4	36.2	29.4
Peat	11.6	15.0	6.2	7.9	21.0	11.6
Pure Sand	13.1	12.7	6.8	10.5	17.3	13.1
$LSD_{0.05}$	8.53	22.41	17.43	10.13	13.80	8.53

Table 23. University of Wisconsin soil test interpretations for golf turf.

Interpretation	pH	Phosphorus	Potassium
		------------------mg L^{-1}	------------------
Very low	< 5.0	0 - 5	0 - 25
Low	5.0 - 5.5	6 - 10	26 - 50
Medium	5.5 - 6.0	11 - 15	51 - 75
Sufficient	6.0 - 7.0	16 - 25	76 - 90
High	7.0 - 7.5	26 - 35	90 - 120
Excessive	> 7.5	> 35	> 120

Table 24. Soil Bray 1- P for sampling dates in 2003.

Root zone mix	4/15	05/12	06/03	06/17	07/01	Mean
	---------------------------------mg L^{-1}-----------------------------					
AgriBoost	24.5	26.0	17.5	18.7	18.1	24.5
Profile	16.4	21.4	16.5	14.6	12.1	16.4
GSA ZK406H	18.5	20.5	15.1	14.7	14.0	18.5
Peat	14.3	15.2	11.9	9.27	10.0	14.3
Pure Sand	21.2	21.4	16.8	16.6	14.7	21.2
$LSD_{0.05}$	4.59	4.96	NS	3.88	6.50	4.57

Table 25. Changes in root zone mix pH over time.

Root zone mix	Initial pH†	09/21/02	04/15/03	07/01/03
AgriBoost	9.03	8.48	7.81	7.86
Profile	8.68	8.04	7.43	7.53
GSA ZK406H	9.01	8.20	7.50	7.53
Peat	8.16	7.20	7.21	7.41
Pure Sand	8.94	8.04	7.35	7.58
$LSD_{0.05}$	0.16	0.28	0.16	0.13

† pH of root zone mixes prior to putting green construction.

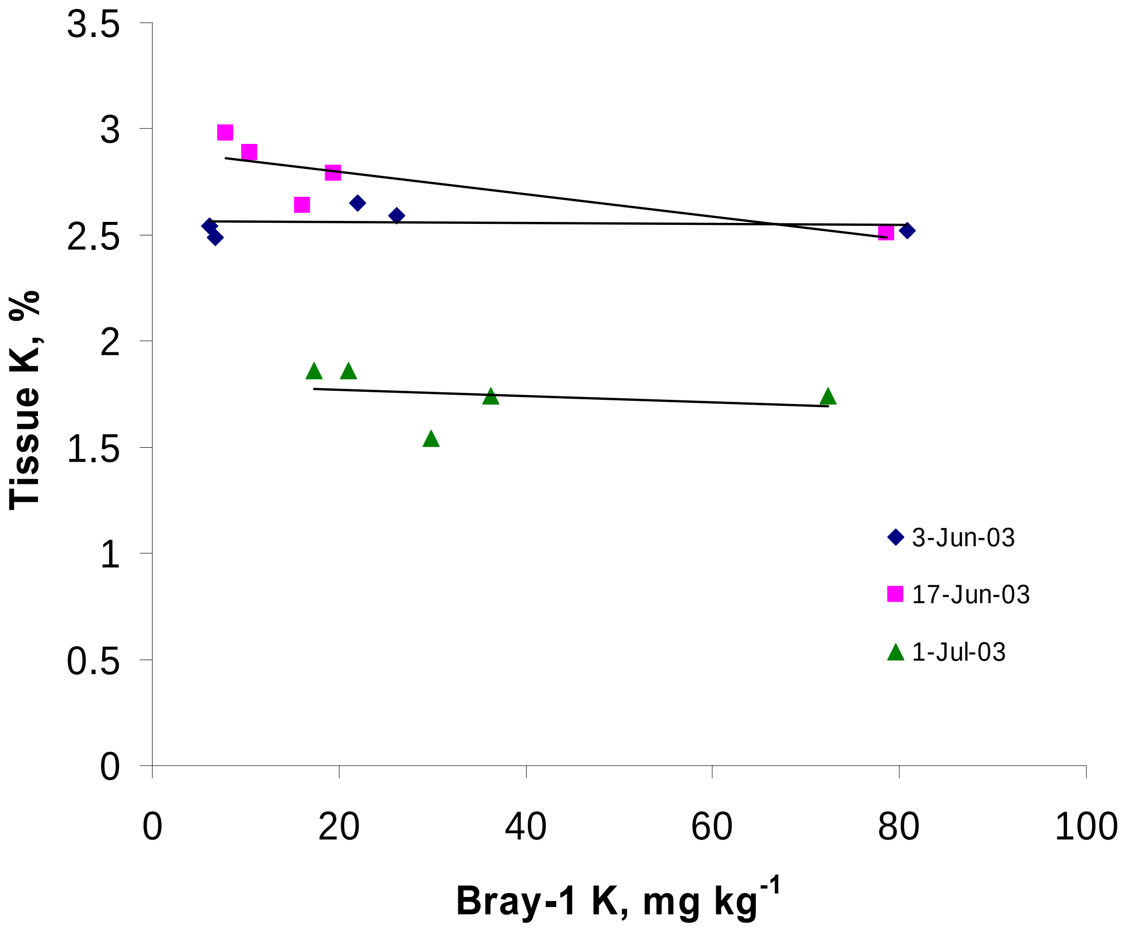

Figure 16. Relationship between soil Bray-1 K and %K in turfgrass tissue on 3 sampling dates.

among these parameters, other parameters such as clipping nutrient content, root mass density, and root zone moisture content were measured.

Significant differences among treatments in bentgrass clipping yields were observed only for the first 3 clipping collection dates in 2002 (Table 26). These differences appeared to reflect grow-in differences between the treatments in that they followed the trend of density ratings (Table 14). An exception to this relationship was that the sand treatment consistently had the greatest clipping yields but the lowest density ratings.

Turf quality ratings were taken routinely following the establishment period. The AgriBoost® treatment had the highest quality rating when averaged over data from 2002 and 2003, and had a statistically better turf quality rating than the Profile® treatment (Table 27). Differences among all other treatments over the same period were not significant at the $p = 0.05$ level.

Turf color ratings were taken periodically throughout the 2002 and 2003 season, including during the establishment period. In 2002, color rating differences among the treatments were non-significant (Table 28a); while in 2003, the peat treatment produced a statistically higher mean turf color rating than the Profile® treatment (Table 28b). Differences among all other treatments were non-significant at the $p = 0.05$ level.

In this study, based on the 3 indicators of agronomic performance mentioned above, the root zone amendments did not significantly affect the agronomic performance of the putting greens after the establishment period, except in the comparison of the peat and AgriBoost® treatments, which demonstrated certain agronomic advantages (turf color and quality) compared to the Profile® treatment.

Table 26. Root zone mix effects on bentgrass clipping yields for 2002.

Root zone mix	06/18	07/08	07/22	08/05	08/19	09/17	10/01	10/15	Mean
	------------------------------------				kg ha^{-1}	----------------------------------			
AgriBoost	24.3	93.2	49.1	29.6	22.3	45.5	23.2	12.8	37.5
Profile	19.0	80.6	45.7	34.2	25.7	51.7	25.3	16.6	37.4
GSA ZK406H	22.5	86.7	48.5	34.6	22.1	49.1	22.5	13.6	37.4
Peat	32.0	89.7	53.2	32.1	22.5	49.0	20.5	13.3	39.0
Pure Sand	39.1	106.2	58.2	33.0	24.0	55.1	25.2	17.2	44.7
$LSD_{0.05}$	15.23	20.89	10.90	NS	NS	NS	NS	NS	NS

Table 27. Bentgrass quality ratings in 2002 and 2003†.

	2002		2003						
Root zone mix	8/05	9/09	5/01	5/13	5/27	6/09	6/24	7/08	Mean
AgriBoost	7.75	8.25	5.50	6.38	6.25	7.25	8.50	7.38	7.16
Profile	7.75	8.25	4.38	5.75	6.00	7.25	7.00	7.13	6.69
GSA ZK406H	7.63	8.13	5.13	6.13	6.50	7.25	7.50	7.13	6.92
Peat	7.63	8.13	5.75	6.63	6.25	7.38	7.63	7.50	7.11
Pure sand	7.25	8.25	5.50	6.25	6.00	7.25	7.75	7.25	6.94
$LSD_{0.05}$	0.25	NS	0.74	0.69	NS	NS	1.21	NS	0.43

†1 - 9 scale where 1 = dead or dormant turf, 6 = minimally acceptable, 9 = highest quality possible

Table 28a. Bentgrass color ratings in 2002†.

Root zone mix	5/30	6/06	6/14	6/27	7/12	8/02	8/20	9/09	10/01	Mean
AgriBoost	6.58	3.65	5.68	6.53	6.90	7.48	7.83	7.85	7.90	7.03
Profile	4.95	6.73	6.05	6.35	7.08	8.00	7.83	7.85	7.85	6.96
GSA ZK406H	5.90	6.35	5.85	6.33	6.90	7.75	7.85	7.88	7.98	6.98
Peat	4.08	6.95	6.35	6.30	7.05	8.15	7.85	7.90	8.10	6.97
Pure sand	3.88	6.63	6.63	6.75	6.93	8.00	7.95	7.98	8.05	6.98
$LSD_{0.05}$	0.37	0.46	0.51	0.23	NS	0.52	NS	0.12	0.23	NS

†1 - 9 scale where 1 = brown, 6 = minimally acceptable color, 9 = darkest green possible

Table 28b. Bentgrass color ratings in 2003†.

Root zone mix	5/13	5/27	6/09	6/24	7/08	Mean
AgriBoost	6.55	6.00	7.73	7.98	7.75	7.20
Profile	6.20	5.75	7.75	7.63	7.25	6.92
GSA ZK406H	6.50	6.10	7.70	7.95	7.55	7.16
Peat	6.68	6.13	7.85	7.90	7.80	7.27
Pure sand	6.40	5.93	7.73	7.88	7.40	7.07
$LSD_{0.05}$	NS	0.35	NS	0.26	0.53	0.31

†1 - 9 scale where 1 = brown, 6 = minimally acceptable color, 9 = darkest green possible

The clipping N, P, and K concentrations (Tables A-6 – A-11) and root growth results (Table A-12) failed to account for the differences in color and quality among the AgriBoost®, peat and Profile® treatments. The greater clipping yield produced by the sand treatment was supported by that treatment's relatively high N, P, and K tissue concentrations.

Soil moisture readings were taken on 3 dates each in 2002 and 2003. Measurements were taken at 5 depths within each root zone. AgriBoost® had the greatest volumetric moisture content of all the root zone mixes in 2002 and 2003 (Table 29). The moisture content of the Profile® treatment was statistically similar to that of the peat treatment in 2002 and 2003. These results do not reflect the differences in turf color and quality found among the AgriBoost®, peat, and Profile® treatments. This may be expected, given that root zone moisture content measurement by way of TDR does not estimate plant available water. Waddington (1992) has shown that calcined clays hold water at tensions unavailable for turfgrass use. The benefit of the calcined clay amendment is seen only during times of extreme moisture stress (Miller, 2000), which never occurred during this study. Under typical climatic conditions, the available water content of the Profile® is thought to be lower than in other treatments, thus providing an explanation for the root zone mix performance differences among the AgriBoost®, peat, and Profile® treatments.

Similar to findings reported by Kirkman (1996), a decrease in volumetric water content of all root zone mixes was observed from the 1st year to the 2nd year (Table 29). Kirkman (1996) attributed this decrease to the loss of organic matter through oxidation. The same trend was observed in the present study for inorganic-amended root zone mixes

Table 29. Root zone volumetric moisture content means for sampling dates in 2002 and 2003.

	2002				2003			
Root zone mix	7/23	8/15	10/03	Mean	6/12	6/25	7/16	Mean
	---------------------	% water by volume	----------------------					
AgriBoost	14.9	15.3	13.7	14.6	7.1	10.5	10.5	9.4
Profile	15.0	12.8	13.0	13.6	3.6	7.5	8.9	6.7
GSA ZK406H	14.1	11.2	11.3	12.2	4.2	6.7	5.5	5.5
Peat	13.8	11.7	10.6	12.0	4.6	7.3	7.1	6.3
Pure sand	14.0	12.4	11.1	12.5	5.0	7.3	5.9	6.0
$LSD_{0.05}$	1.31	2.75	1.04	1.55	0.83	1.36	1.58	1.04

devoid of organic matter. This suggests an explanation for the decrease lies elsewhere. Tucker et al. (1990) documented the presence of hydrophobic organic coatings on sand particles coinciding with the presence of localized dry spot. It is possible that an accumulation of these hydrophobic coatings led to the decrease in soil moisture content in this study from one year to the next.

SUMMARY AND CONCLUSIONS

The purpose of this research project was to assess the agronomic, environmental, and economic advantages and disadvantages of using inorganic amendments in place of sphagnum peat or no amendment in sand-matrix golf putting green root zone mixes. Data collected from a 15-month field trial, a greenhouse investigation of water retention and drainage rates, and numerous laboratory measurements support the following conclusions.

Agronomic Merits of the Root Zone Amendments

Over the course of this study, several agronomic responses to the various root zone mixer were recorded. They included turfgrass quality, color, and establishment rate. Rapid bentgrass establishment is a desirable characteristic with economic implications. During the establishment period, The AgriBoost® and peat treatments improved bentgrass establishment compared to all other treatments while the GSA ZK406H and Profile® treatments significantly improved turfgrass establishment compared to the pure sand treatment (Table 14). Once the putting greens are in play, the ability to sustain a high quality playing surface is of paramount importance. The AgriBoost® treatment out-performed the Profile® treatment in terms of turfgrass quality over the duration of the study. The peat treatment had a significantly better mean color rating than the Profile® treatment in 2003 (Table 28b). No single root zone mix characteristic could account for these differences.

Although relatively large differences in root mass density were found among treatments, those differences were not manifested in visual ratings. The GSA ZK406H, Profile®, and pure sand treatments had significantly greater root mass density than the AgriBoost® and peat treatments during the 2002 and 2003 seasons (Table A-12).

In summary, greens amended with AgriBoost® or Canadian sphagnum peat provided agronomic advantages over unamended greens and those amended with GSA ZK406H and Profile®.

Environmental Merits of the Root Zone Amendments

Environmental merits are more difficult to quantify in comparison to agronomic and economic merits. The primary environmental parameter measured in this study was nutrient leaching. The AgriBoost® treatment greatly reduced the amount of P leached compared to all other treatments during the first 2 growing seasons (Tables 21a and 21b). The GSA ZK406H treatment decreased NO_3-N leaching significantly compared to the peat treatment during establishment (Table 15). The value of each of these reductions in nutrient leaching is specific to the needs of the individual construction site. The reduction of NO_3-N leaching attained by amending a root zone mix with GSA ZK406H pertained only to the three month establishment period, after which the leaching of NO_3-N from all treatments declined to a level 7 times lower than the NO_3-N concentration found in the irrigation water when common management practices were followed. However, P leaching increased with respect to time for most treatments and K leaching appeared to be relatively constant over time throughout the course of the study.

Many golf courses use a small on-site pond (often replenished by well water) as the irrigation water supply. The pond is also a reservoir for the drainage water from nearby putting greens. Long-term P loading from the drainage water will degrade the quality of the surface water, leading to a hypereutrophic system which invites costly renovations. Therefore, a putting green amendment with the potential to reduce P loads in the drainage water can be of enormous economic benefit to a golf course in this situation. Furthermore, golf courses discharging drainage water into streams running through the course may be subject to scrutiny by local, state, or national regulatory agencies. Amelioration costs could be substantial.

Economic Merits of the Root Zone Amendments

Historically, prices of inorganic amendments have been relatively high compared to organic amendments like peat. A typical 19-green construction project requires 5,352 m^3 of root zone mix (Moore, 1999). Using this figure to create a 90% sand 10% amendment mix (v/v), 535 m^3 of each amendment would be required. Figure 17 shows the cost of the amendments and mixes used in this study using Moore’s (1999) calculations for amount of root zone mix needed. The costs do not include shipping or blending. There is little doubt that in this study the use of inorganic amendments greatly increased the total cost of the corresponding root zone mix. Interestingly, amending the mix with peat actually decreased the cost of the mix as the cost of peat was less than that of sand on a volume basis (blending costs aside). AgriBoost® was the least expensive of the inorganic materials used

- 40% and 60% less expensive than GSA ZK406H on a volume and weight basis respectively (Figure 17).

Nelson (2003) correctly reports that several researchers failed to show agronomic benefits from using inorganic amendments in place of peat and uses this as the basis for concluding that the use of inorganic amendments is not economically justifiable. However, the author failed to mention studies that have shown environmental benefits of using inorganic amendments. Although a price cannot be put on the 79% reduction in NO_3-N leaching during grow-in when GSA ZK406H was substituted as an amendment for peat in this study (Table 15), it is unfair to conclude that this benefit does not have any value to the turf industry. Similarly, the incorporation of AgriBoost® significantly reduced P leaching compared to all other treatments including peat over the first two seasons of this study (Figure 15). The value of such characteristics was alluded to in the previous section.

The root zone mixes did not differ significantly in pesticide or N and P fertilizer requirements. However, the AgriBoost® treatment required only a fraction of the K fertilizer needed by the other treatments to maintain adequate soil test K. During the 2003 season, soil test results indicated no need for K applications to the AgriBoost® green, whereas other greens received 195 kg K_2O ha^{-1} and soil tests still indicated the need for additional K. This translates into a significant economic savings not only in reductions in K fertilizer use, but also the labor required to make extra K applications.

In this study, the only economic variables that differed among treatments were the cost of root zone mix materials, and the K fertilizer requirement. The AgriBoost® green required 90% less fertilizer K in 2003 than all other treatments. Assuming a conservative

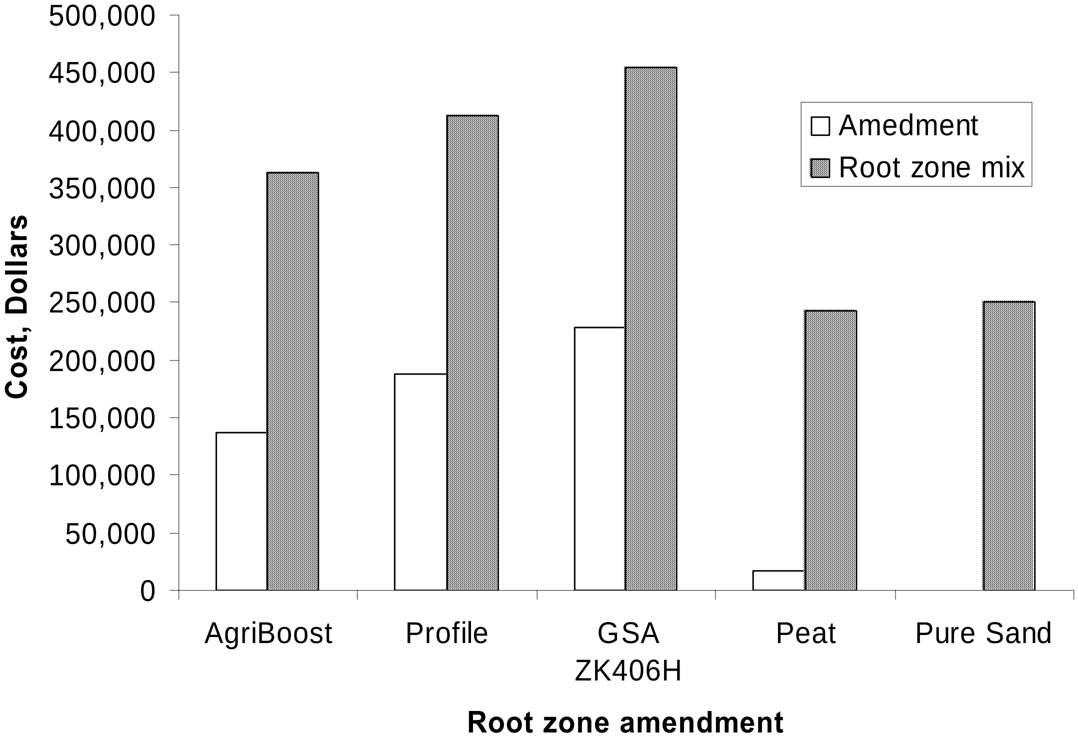

Figure 17. Cost of root zone mixes and amendments for a typical 19-green construction project.

75% reduction in K fertilizer requirement each year for the life of the green (1 vs. 4 lb K_2O M^{-1}), and a price of \$1.10 kg^{-1} K_2O, the fertilizer savings for 13,006 m^2 [from Nelson (2003)] of AgriBoost®-amended putting green surfaces compared to the other greens examined in this study would be \$1050, \$2100, and \$4200 after 5, 10, and 20 years respectively.

During bentgrass grow-in, a 12 kg N ha^{-1} application was skipped on both zeolite treatments due to color differences among treatments. Although the economic savings was insignificant, reductions in fertilizer N use are known to increase root mass density. The enhancement of the root system is more valuable than the fertilizer savings.

Reductions in water use could contribute to economic savings in situations where the golf course uses municipal water for irrigation (urban areas). The results from the field volumetric moisture content measurement of the root zone mixes suggests that AgriBoost® has the potential to reduce water use compared to all other amendments. Laboratory moisture release curves indicate that peat is an effective amendment for increasing plant available water. Due to the limitations of the field irrigation system, treatment differences regarding water use were not quantified.

Based on the results from this research project, the substitution of inorganic materials in place of sphagnum peat is not warranted based on agronomic merits alone. However, in situations where a reduction in N or P leaching is necessary, the high initial cost of the inorganic-amended root zone mix is justified.

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APPENDIX

Table A-1. 2003 field fertilization schedule

Application Date	Fertilizer Grade	Fertilization Rate	N source	Treatments Fertilized
	% N - P_2O_5 - K_2O	kg N - P_2O_5 - K_2O / ha		
04/15/03	46-0-0	19.5 - 0.0 - 0.0	100% Urea N	All
05/03/03	18-3-4	2.9 - 0.5 - 0.5	19% Ammoniacal N 81% Urea N	All
05/08/03	24-4-12	26.4 - 4.4 - 13.2	3% Ammoniacal N 38% Urea N 22% WSN† 37% WIN‡	All
05/21/03	18-0-3	4.9 - 0.0 - 1.0	74% Ammoniacal N 26% WIN‡	All
05/27/03	46-0-0	29.2 - 0.0 - 0.0	100% Urea N	All
06/09/03	0-0-50	0.0 - 0.0 - 97.6		Profile, GSA, Peat, Pure sand
06/25/03	0-0-50	0.0 - 0.0 - 97.6		Profile, GSA, Peat, Pure sand
07/08/03	46-0-0	12.2 - 2.0 - 6.1	100% Urea N	All
07/10/03	18-0-3	4.9 - 0.0 - 1.0	74% Ammoniacal N 26% WIN‡	All

† WSN, water soluble nitrogen

‡ WIN, water insoluble nitrogen

Table A-2. 2002 - 03 fungicide applications.

Application Date	Pesticide Name	Rate
06/14/02	fosetyl-aluminum	8 oz/M
07/05/02	fosetyl-aluminum	8 oz/M
08/28/02	chlorothalonil	6 oz/M
09/23/02	iprodione	4 oz/M
11/02/02	chlorothalonil	2.75 oz/M
11/02/02	iprodione	2 oz/M
11/11/02	chlorothalonil	2.75 oz/M
11/11/02	iprodione	2 oz/M
06/13/03	chlorothalonil	6 oz/M

Table A-3. Chemical properties of irrigation water.

Chemical property	Value
pH	8.2
Bicarbonate, ppm	359.3
Electrical conductivity, mmhos cm^{-1}	0.70
Total soluble salts, ppm	448
Sodium Absorption Ratio, meq L^{-1}	0.50
Na, ppm	9.0
Cl, ppm	43
B, ppm	0.01
NO_3, ppm	7.10
PO_4, ppm	0.01
K, ppm	1.30
Mg, ppm	46.0
Ca, ppm	68.9
SO_4, ppm	21.0
Mn, ppm	0.01
Fe, ppm	0.02

Table A-4. Bray-1 P and K by depth for root zone mixes sampled on 21 Sept. 2002.

Root zone mix	Depth	Bray-1 P	Bray-1 K
	cm	-------------- mg kg-1	-------------
AgriBoost	0 to 1	61.7	69.6
	1 to 2	25.4	83.3
	2 to 3	18.6	91.7
	3 to 4	13.2	109.9
	4 to 5	11.4	121.0
	5 to 7	8.7	74.5
	7 to 9	7.6	110.1
	9 to 11	7.2	112.4
	11 to 13	6.5	125.8
	13 to 15	6.0	110.2
	15 to 19	5.9	99.7
	below 19	5.2	122.5
Profile	0 to 1	58.4	18.5
	1 to 2	24.8	15.2
	2 to 3	16.3	14.8
	3 to 4	10.6	15.3
	4 to 5	8.8	15.4
	5 to 7	7.7	15.7
	7 to 9	7.2	16.0
	9 to 11	6.1	17.2
	11 to 13	5.4	16.2
	13 to 15	5.2	16.8

- continued -

Table A-4. (continued)

Root zone mix	Depth	Bray-1 P	Bray-1 K
	cm	------------- mg kg-1	------------
Profile	15 to 19	5.1	16.8
	below 19	4.9	17.2
GSA ZK406H	0 to 1	70.6	26.1
	1 to 2	28.6	21.4
	2 to 3	17.2	21.4
	3 to 4	12.8	20.9
	4 to 5	10.9	21.0
	5 to 7	11.1	20.5
	7 to 9	8.6	22.6
	9 to 11	6.5	22.5
	11 to 13	6.1	22.2
	13 to 15	5.9	21.1
	15 to 19	5.8	22.1
	below 19	4.1	22.6
Peat	0 to 1	44.4	13.8
	1 to 2	21.7	12.9
	2 to 3	13.7	12.7
	3 to 4	11.7	12.8
	4 to 5	10.1	12.7
	5 to 7	9.7	12.7
	7 to 9	8.3	12.7

- continued -

Table A-4. (continued)

Root zone mix	Depth	Bray-1 P	Bray-1 K
	cm	-------------- mg kg-1	-------------
Peat	9 to 11	7.1	12.6
	11 to 13	6.6	12.7
	13 to 15	5.7	12.7
	15 to 19	4.6	12.7
	below 19	3.3	12.7
Pure sand	0 to 1	60.4	14.1
	1 to 2	36.6	12.9
	2 to 3	22.2	12.7
	3 to 4	13.5	12.8
	4 to 5	8.7	12.7
	5 to 7	7.7	12.8
	7 to 9	6.4	12.7
	9 to 11	6.2	12.8
	11 to 13	5.0	12.7
	13 to 15	4.7	12.7
	15 to 19	4.8	12.7
	below 19	3.5	12.7

Table A-5. Root zone mix effects on bentgrass clipping yields in 2003.

Root zone mix	05/21	06/03	06/17	07/01	Mean
	-----------------------------		kg ha^{-1}	----------------------------	
AgriBoost	14.53	26.08	30.98	27.08	24.67
Profile	13.11	24.02	29.71	34.80	25.41
GSA ZK406H	16.77	26.96	30.15	30.61	26.12
Peat	18.65	27.99	31.79	34.76	28.30
Pure Sand	18.46	25.37	34.78	31.59	27.55
$LSD_{0.05}$	NS	NS	NS	NS	NS

Table A-6. Nitrogen concentrations in bentgrass clippings in 2002..

Root zone mix	06/18	07/08	07/22	08/05	08/19	09/17	10/01	10/15	Mean
	---------------------------------				mg N g^{-1}	--------------------------------			
AgriBoost	2.72	3.47	4.02	4.34	3.29	4.20	3.20	3.49	3.56
Profile	2.65	3.36	3.93	4.24	3.26	3.75	3.23	3.44	3.49
GSA ZK406H	3.12	3.47	3.75	4.23	3.35	4.10	3.35	3.51	3.60
Peat	2.96	3.43	3.92	4.05	3.26	3.95	3.35	3.68	3.59
Pure Sand	3.43	3.87	3.99	4.30	3.54	4.00	3.20	3.44	3.73
$LSD_{0.05}$	0.52	0.32	NS	NS	NS	0.17	NS	0.27	0.15

Table A-7. Nitrogen concentrations in bentgrass clippings in 2003.

Root zone mix	05/21	06/03	06/17	07/01	Mean
	----------------------------		mg N g^{-1}		---------------------------
AgriBoost	3.45	3.94	3.59	2.96	3.48
Profile	3.38	3.94	3.40	2.90	3.42
GSA ZK406H	3.51	4.04	3.61	2.90	3.51
Peat	3.46	4.08	3.63	2.72	3.47
Pure Sand	3.45	4.15	3.55	2.82	3.49
$LSD_{0.05}$	NS	NS	NS	NS	NS

Table A-8. Phosphorus concentrations in bentgrass clippings in 2002.

Root zone mix	06/18	07/08	07/22	08/05	08/19	09/17	10/01	10/15	Mean
	----------------------------------				mg P g^{-1}			--------------------------------	
AgriBoost	0.40	0.44	0.48	0.41	0.39	0.47	0.39	0.34	0.41
Profile	0.33	0.40	0.43	0.43	0.38	0.42	0.39	0.33	0.39
GSA ZK406H	0.42	0.46	0.51	0.47	0.42	0.50	0.40	0.34	0.44
Peat	0.40	0.48	0.50	0.45	0.41	0.49	0.39	0.34	0.43
Pure Sand	0.40	0.48	0.52	0.46	0.40	0.51	0.39	0.35	0.44
$LSD_{0.05}$	NS	0.03	0.04	0.04	0.02	0.07	NS	0.01	0.01

Table A-9. Phosphorus concentrations in bentgrass clippings in 2003.

Root zone mix	05/21	06/03	06/17	07/01	Mean
	---------------------------		mg K g^{-1}	--------------------------	
AgriBoost	0.76	0.80	0.79	0.61	0.74
Profile	0.70	0.78	0.74	0.56	0.69
GSA ZK406H	0.78	0.87	0.81	0.75	0.80
Peat	0.73	0.85	0.86	0.62	0.76
Pure Sand	0.75	0.89	0.80	0.71	0.79
$LSD_{0.05}$	0.06	0.05	0.08	0.10	0.05

Table A-10. Potassium concentrations in bentgrass clippings in 2002.

Root zone mix	06/18	07/08	07/22	08/05	08/19	09/17	10/01	10/15	Mean
	----------------------------------				mg K g^{-1}			--------------------------------	
AgriBoost	1.72	2.16	3.17	2.58	2.48	2.63	2.16	2.44	2.42
Profile	1.29	2.06	2.87	2.75	2.68	2.40	2.02	2.36	2.30
GSA ZK406H	1.68	1.82	3.43	2.90	2.53	2.83	2.38	2.47	2.51
Peat	1.49	1.68	2.71	2.53	2.51	2.87	2.25	2.42	2.31
Pure Sand	1.81	2.03	3.08	2.83	2.55	3.09	2.25	2.52	2.52
$LSD_{0.05}$	0.26	0.46	0.58	0.24	NS	0.49	0.22	NS	0.16

Table A-11. Potassium concentrations in bentgrass clippings in 2003.

Root zone mix	05/21	05/27	06/03	06/17	07/01	Mean
	---------------------------		mg K g^{-1}		--------------------------	
AgriBoost	2.21	2.64	2.52	2.51	1.74	2.32
Profile	2.07	2.48	2.59	2.64	1.54	2.27
GSA ZK406H	2.08	2.59	2.65	2.79	1.74	2.37
Peat	2.05	2.45	2.54	2.98	1.86	2.38
Pure Sand	2.14	2.54	2.49	2.89	1.86	2.39
$LSD_{0.05}$	NS	0.09	NS	0.36	NS	NS

Table A-12. Root zone mix effects on root mass density on 5 sampling dates.

Root zone mix	7/12/02	9/21/02	10/30/02	5/13/03	7/8/03	Mean
	----------------------------------	kg m^{-3}	----------------------------------			
AgriBoost	0.91	2.06	2.15	2.63	1.35	1.82
Profile	1.04	3.10	3.09	1.89	1.99	2.22
GSA ZK406H	1.30	3.75	2.73	1.99	1.71	2.30
Peat	1.47	2.21	1.58	2.31	1.76	1.86
Pure sand	1.28	2.79	2.98	1.91	1.82	2.16
$LSD_{0.05}$	0.35	0.51	0.84	0.34	0.22	0.24

Table A-13. Volumetric water contents of all treatments averaged by depth.

	2002				2003			
Depth	7/23	8/15	10/03	Mean	6/12	6/25	7/16	Mean
cm	-------------------------			% water by volume		-------------------------		
5	8.5	4.8	6.6	6.6	5.1	4.5	5.5	5.0
10	10.3	7.3	ND	8.8	3.6	4.2	3.2	3.7
15	12.8	10.8	7.8	10.5	3.7	5.7	4.7	4.7
20	16.6	14.8	ND	15.7	4.9	9.4	8.5	7.6
25	23.4	25.8	11.3	20.1	7.2	15.1	16.1	12.8
$LSD_{0.05}$	1.31	2.75	0.40	NA	0.83	1.36	1.58	1.04

Table A-14. Volumetric water contents of treatments by depth.

Root zone mix	Depth	7/23	8/15	10/03	6/12	6/25	7/16
	cm	--------------% volumetric water content--------------					
AgriBoost	5	8.0	4.9	7.6	6.6	7.0	7.6
	10	10.4	8.7	ND	4.9	6.3	5.0
	15	13.3	13.5	8.3	5.2	8.2	7.3
	20	18.3	17.0	ND	7.5	12.6	13.1
	25	24.2	32.6	12.7	11.4	18.5	19.5
Profile	5	9.0	4.0	7.1	3.8	2.3	4.1
	10	10.0	6.6	ND	2.8	3.8	3.4
	15	13.3	10.9	8.6	3.3	5.7	5.5
	20	17.3	15.9	ND	3.3	9.7	10.8
	25	25.3	26.9	13.6	4.9	15.8	20.5
GSA ZK406H	5	9.0	4.6	6.5	3.8	2.3	3.6
	10	10.6	7.3	ND	2.7	3.3	1.6
	15	12.9	9.8	7.7	3.8	4.9	2.9
	20	17.0	14.7	ND	4.4	8.9	6.8
	25	20.6	19.5	10.6	6.1	14.0	12.5
Peat	5	10.2	7.0	6.6	6.0	7.4	7.6
	10	11.1	8.7	ND	4.4	5.4	5.0
	15	12.9	10.9	7.3	3.3	5.9	4.8
	20	15.1	13.5	ND	3.9	7.7	6.8
	25	19.7	18.7	8.7	5.2	10.1	11.4
Pure sand	5	6.3	3.3	5.3	5.3	3.5	4.6
	10	9.2	5.3	ND	3.2	2.3	0.7
	15	11.7	9.1	6.9	2.9	3.9	2.7
	20	15.3	12.7	ND	5.4	7.9	5.1
	25	27.2	31.5	10.9	8.4	17.0	16.5