Sand-Based Rootzone Modification with Inorganic Soil Amendments and Sphagnum Peat Moss

Current player volume and maintenance practices call for research into changes in putting green construction materials.

by CALE A. BIGELOW, DAN BOWMAN, and KEITH CASSEL

"The pace of golf activity and traffic on golf courses is presently at a peak which has never been equaled. Many of our construction methods that were satisfactory before, will no longer produce greens which will withstand the wear now imposed upon them."

THESE WERE THE WORDS that prefaced the 1960 Green Section specifications for a method of putting green construction. Although we have had a widely accepted system for constructing putting greens for nearly 40 years, it seems that the same words also hold true today.

Four years ago, in an effort to further understand and improve putting greens, the USGA supported a series of scientific research projects at universities across the United States. One of the projects, entitled New Materials and Technologies for Putting Green Construction, was conducted at North Carolina State University. In this study we evaluated a variety of materials that could be used to amend sands used in putting green construction.

Basic Principles of Sand-Based Rootzones

Since 1960, the most widely accepted method of putting green construction has specified a high sand content rootzone. Sand is well suited for high-traffic areas like putting greens because it resists compaction, drains quickly, and maintains good aeration properties. Also, it is relatively inexpensive and generally is available most anywhere. Although sand is a good substrate for putting green rootzones, it does have limitations, most importantly poor water retention and nutrient retention.

To correct these deficiencies, sand has most often been amended with peat moss (Beard, 1982). Although peat moss may be the frequently used soil amendment for putting greens, other materials may also be suitable. As with any organic material, peat moss decomposes over time. This gradual decomposition may adversely affect the rootzone physical properties and this, in turn, may contribute to poor performance of turfgrasses grown on these declining rootzones. Turfgrass researchers have evaluated many inorganic soil amendments for sand rootzone construction with mixed success (Waddington et al., 1974; Schmidt, 1980; Ferguson et al., 1986; Nus and Brauen, 1991; Kussow, 1996; Carlson et al., 1998; McCoy and Stehouwer, 1998).

Renewed interest in inorganic soil amendments has resulted in many products being marketed for turfgrass areas. A few of the more commonly used inorganic soil amendments are the porous ceramics, diatomaceous earth, and zeolites. Some of the characteristics of these products that potentially make them desirable for improving the properties of sands are a large internal porosity that results in water retention, a uniform particle size distribution that allows them to be easily incorporated, and high cation exchange capacity that retains nutrients. Therefore, research exploring the suitability of newly marketed inorganic soil amendments that are not subject to biological degradation, but still provide water and nutrient retention, would be worthwhile.

A wide variety of soil amendments are available for amending putting green sands.

Table 1
Particle size distribution, geometric mean diameter, and particle density of three sand size classes and five rootzone amendments used for the simulated putting green rootzone mixtures

	Particle Size							Geometric	
	mm							Mean	Particle
Amendment	>2.0	1.0	0.5	0.25	0.10	0.05	<0.05	Diameter	Density
	g kg^{-1}							mm	Mg m^{-3}
Fine sand	0	0	0	0	1000	0	0	0.01	2.62
Medium sand	0	0	0	1000	0	0	0	0.25	2.62
Coarse sand	0	0	1000	0	0	0	0	0.50	2.62
Ecolite	0	<1	242	615	139	1	3	0.67	2.32
Greenschoice	0	3	871	108	11	7	<1	0.84	2.15
Isolite	0	5	446	534	10	5	<1	0.74	2.27
Profile	0	<1	0	714	272	14	<1	0.59	2.50
Sphagnum peat	–	–	–	–	–	–	–	NA	0.63

Considerations Before Selecting an Amendment

Before deciding on which amendment to use for improving the properties of a particular sand, you should consider a few questions. What effect will the amendment have on the overall particle size distribution of the rootzone mixture? Too many coarse or fine particles is undesirable. What impact will the amendment have on the chemical properties of the sand? Some amendments may dramatically change the soil pH or contribute unwanted nutrients. How stable is the amendment? Will it physically or biologically degrade and potentially clog up the drainage pores of the rootzone mixture? Lastly, it is important to consider availability and cost. An amendment could have the best physical and chemical properties in the world, but if it needs to be shipped across the country the benefits may not warrant the cost. Since all amendments do not have identical characteristics, an overview of some of the major properties of the more commonly marketed amendments follows.

Types of Amendments

There are essentially two major classes of amendments: 1) organic materials, which are derived from decomposed plant materials, and 2) inorganic materials, which are mineral based.

Organic materials are typically inexpensive and, depending on the origin, may be somewhat short-lived in the rootzone. The benefits of adding organic matter to most any soil are numerous. It does an excellent job of enhancing soil structure by improving aggregation and can be an excellent substrate for microbial growth. Increasing aggregation also enhances soil aeration, which may ultimately improve turfgrass health.

In addition to the structural benefits, most organic matter can hold several times its weight in water. When taken advantage of in coarse-textured soils, this property can greatly improve moisture retention. A certain amount of organic matter improves the resiliency or the ability of soils to withstand traffic.

In addition to improving soil physical properties, organic matter may have moderate nutrient-holding capacities, depending on soil pH. If an organic material is used for soil modification, it is important to use well-decomposed materials because they are more stable and less likely to negatively impact the physical properties that you have worked so hard to achieve.

Inorganic materials are derived from large, naturally occurring mineral deposits, and these products are generally mined from the ground. These products range from low to high in cost, depending on the particular material and its availability. Several inorganic materials have been marketed over the years for soil modification. Some of the more commonly used products include: calcined clays, porous ceramics, expanded shale, diatomacous earth, and the zeolites.

Calcined clays, also marketed as porous ceramics, are products that have been heat treated at a very high temperature (1000-1800°F). This heating increases the structural integrity of the particles while retaining their chemical properties. Once calcined, most products are often screened to a uniform particle size that makes them well sized for use in putting green rootzones. Since these products are clays by nature, they also have a very high inherent moisture-holding capacity. This high moisture retention is the result of many small internal pores. Earlier research has suggested that particles comprised of many small pores may hold moisture so tightly that it may not be available to plants (Davis et al., 1970). Another benefit of these clay-based minerals is that, because they are clays, they have some nutrient-holding capacity, particularly for cations like the ammonium (NH_4^+) ion.

Diatomaceous earth is a material that has been mined from deposits of diatom shells. Diatoms are one-celled ocean organisms whose cell walls consist of interlocking parts and valves containing silica. The skeletons of these diatoms have a high degree of internal pore structure, and thus, like the clays, retain significant quantities of water. These products have been marketed with and without clay binders. The clay addition certainly affects the water-holding capacity of the product. Like the clay-based amendments, the availability of water to plants and the long-term stability of these materials is not fully understood.

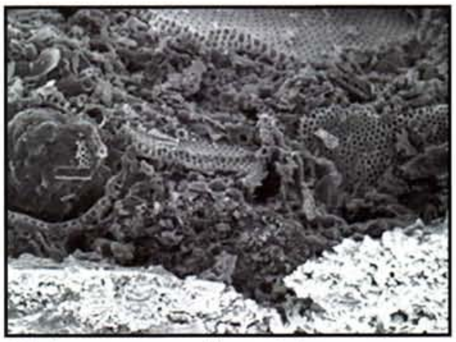
Zeolites are a relatively new class of amendments being widely used for turfgrass rootzones. The main attraction of zeolites is that they are tremendous absorbers. They have long been used in removing environmental pollutants and in many industrial processes. Some zeolites have even been fed directly to livestock to improve gastrointestinal performance. The use of these minerals in turf has become popular because they have a strong affinity for cations. In fact, the cation exchange capacity (CEC) of some zeolites has been measured at 200 cmol$_c$/kg or more (Ming and Mumpton, 1989). For comparison, the CEC of quartz sand is < 1 cmol$_c$/kg. Zeolites do have internal porosity and hold significant amounts of moisture, but generally do not retain as much as the clay-based products.

The primary interest in using these materials is for improved nutrient retention. Several university studies have documented dramatic reductions in fertilizer needs in zeolite-amended sands (Nus and Brauen, 1991; Huang and Petrovic, 1994). Currently, some of the zeolite products are being sold "precharged" with fertilizers. Applications of these zeolites may be like applying fertilizer and improving CEC all at once. Theoretically, the plant is able to use the fertilizer contained in the zeolite, and it can be "re-charged" by subsequent fertilizer applications.

One precaution when selecting a zeolite is that some of the zeolites may have rather high residual sodium contents, which is harmful to turfgrasses in large quantities. Therefore, before purchasing a zeolite, it is advisable to determine how much, if any, sodium may be present. As with the other amendments, the long-term particle stability under turfgrass cultivation and freeze-thaw cycles is still undefined.

Materials and Methods

Experiments were conducted to examine the suitability of several commercially available inorganic amendments for use in sand-based rootzones. Specifically, amendments were tested to determine their effect on the physical properties of three contrasting sand size classes and their ability to limit nitrogen leaching. A locally available quartz sand was mechanically screened into three uniform size classes (fine: 0.1-0.25 mm, medium: 0.25-0.50 mm, and coarse: 0.5-1.0 mm). Five amendments (two porous ceramics: Profile and Greenschoice; a diatomaceous earth containing a clay binder: Isolite; a clinoptilolite zeolite: Ecolite; and sphagnum peat moss) were studied. Amendments were tested at two rates (10% or 20% by volume).



Diatomaceous earth contains many small diatoms that possess a large network of internal pores.

The following physical properties of the amendments, sands, and the respective rootzone mixtures were measured: particle size distribution and density, water retention, bulk density, and saturated hydraulic conductivity (percolation rate). Nitrogen leaching was determined using amendments mixed with a predominately medium-sized sand. Rootzone mixtures (12" deep) were installed in acrylic cylinders placed above a 4" layer of gravel, saturated and drained for 24 hours. A liquid solution of ammonium nitrate, equivalent to 1 lb. of N per 1,000 sq. ft., was applied to the surface of the rootzone mixtures and leached with distilled deionized water. The effluent was collected and analyzed for the presence of ammonium and nitrate.

In addition to the laboratory analysis, a field study was conducted to determine the effect of some of the amendments on creeping bentgrass establishment when mixed at 10% by volume in a medium-sized sand. The sand/amendment mixtures were installed into field plots constructed according to USGA guidelines (USGA, 1993). The experimental greens were then seeded to creeping bentgrass in October of 1997 at the Turfgrass Field Laboratory in Raleigh, N.C. Creeping bentgrass establishment was rated visually by percentage ground cover until full coverage was achieved. Due to space limitations, only a portion of the data collected in the entire study will be presented in this article.

Results and Discussion

Physical Properties

Porosity and Water Retention: Sand size significantly affected porosity and water retention. Fine sand had the greatest total porosity of the three size classes but was not significantly differend from medium sand, which was similar to coarse sand. Although fine sand was similar to medium sand for total porosity, the pore size distributions and inherent water retention were very different. Fine sand contained almost 20% less macropores, or air-filled pores, than either medium or coarse sand. Although fine sand had less air-filled pores, it had much higher > 20% capillary water retention, measured at a -40cm tension.

Capillary water retention is a very important property of a rootzone mixture because it represents free water

Table 2
Porosity and water retention of three sand size classes and five rootzone amendments

Rootzone Component	Porosity Total	Porosity Macro	Porosity Capillary*	Water Retention -20cm	Water Retention -500cm	Water Retention AWHC**	Bulk Density
	Percent (%)						g cm^{-3}
Fine sand	45.0 c	18.2 b	26.8 bc	44.6 b	2.5 c	24.4 a	1.42
Medium sand	42.9 c	37.8 a	5.1 d	14.8 d	2.9 c	2.2 c	1.47
Coarse sand	38.4 c	34.7 a	3.7 d	4.7 e	0.6 c	3.1 c	1.59
Ecolite	60.6 b	37.2 a	23.4 c	24.7 c	20.6 b	2.8 c	0.87
Greenschoice	56.7 b	32.1 a	24.6 c	25.0 c	20.8 b	3.8 c	0.84
Isolite	72.2 a	36.4 a	35.8 b	36.1 b	34.2 a	1.6 c	0.59
Profile	73.4 a	38.0 a	35.4 b	39.6 b	33.2 a	2.2 c	0.64
Peat moss	74.4 a	22.4 b	52.0 a	61.5 a	34.3 a	17.7 b	0.15

*Capillary porosity refers to water retained at -40cm

**Available water holding capacity (AWHC) equals capillary water retention minus -500cm

Means followed by the same letter in the same column are not significantly different under Fisher's protected LSD (p = 0.05) that remains after gravitational drainage stops. Thus, most of this water functions as water that may be used for plant growth. As a benchmark, most successful sand-based rootzones contain ≥ 15% water by volume (Bingaman and Kohnke, 1970). In addition to capillary water, another important property of a rootzone mixture is the available water-holding capacity.

For these experimental rootzone mixtures, available water was defined as the difference between water retained at a -40cm and a -500cm tension. The -500cm tension was selected as the theoretical "permanent wilting point' because under most normal putting green irrigation cycles a rootzone would rarely be allowed to exceed this value before resupplying water. For comparison, many soil scientists commonly calculate available water for field crop soils as water retained between a -333cm and a -15,000cm tension. The difference between putting green soils and field crop soils is that under natural field systems the soils often possess more silt and clay, are much deeper, and often contain a much deeper rooted unmowed crop. Thus, the -500cm value seems more appropriate for our shallow, coarse-textured putting green rootzone system.

With that in mind, fine sand retained significantly more water at all soil water tensions than any sand, and most importantly, had 10 times the available water than either medium or coarse sand alone. Further, the medium and coarse sand had capillary water retention less than 6% and a correspondingly very low available water status. If these sands were to be considered for constructing a sand-based putting green rootzone, they would certainly need to be amended.

Comparing the amendments by themselves to the sands showed that the amendments had significantly greater total porosity than any of the sands. Total porosity for each rootzone component ranked in the order: peat moss = Profile = Isolite > Ecolite = Greenschoice > fine = medium = coarse sand. Peat moss, Profile, and Isolite had greater than 70% total porosity, compared to the sands, which had 40-45%. Both peat moss and the inorganic amendments had 10% to 28% greater total porosity than the most porous sand, fine sand.

These data illustrate that in order to have such high total porosities, the inorganic amendments must possess a relatively large internal pore space. These internal pores probably account for much of their water-holding capacity. The percent air-filled pores were generally similar, > 30%, for all amendments and the medium and coarse sand. The corresponding percent capillary pores were highest for the inorganic amendments Profile and Isolite, > 35%, and lowest in Greenschoice and Ecolite, with < 25%, but still greater than any sand.

Although porosity is an important property for relatively shallow rootzones like putting greens (≤ 12"), another important property is the amount of water released at a relatively low tension (-20cm tension) and how much water remains at the defined wilting point (-500cm tension). These data provide information regarding overall amendment particle size, pore size architecture, and possible field performance. For example, if an amendment releases most of its water at a relatively low tension and retains little at a moderate tension, it is probably composed of relatively coarse-textured particles and may be of little use in an already coarse-textured medium like sand. Conversely, if an amendment releases little water at low tensions and retains significant amounts at high tensions, this amendment is probably composed of many very small pores, a situation that also may be undesirable because the water might not be available to the plant during stress periods.

In these experiments, all sands and amendments except fine sand released 28% to 36% of their water between saturation and -20cm. Water released at this low tension is associated with gravitational drainage and generally would not be retained in rootzones exceeding 8" depth. In contrast to these rapidly draining sands and amendments, fine sand released only 0.4% of its water at this low tension. Thus, the fine sand retains a rather substantial amount of water, which may be useful as rootzone depth increases.

To further characterize the moisture release properties of the amendments and three sands, water retention data were collected for a range of increasing soil water tensions. Each rootzone component seemed to have a characteristic tension where most of the water was released. This critical tension appeared to be directly related to particle size, with finer textures requiring higher tensions to release water. For example, coarse sand abruptly released most of its water between -10cm and -20cm, medium sand between -10cm and -40cm, and fine sand between -20cm and -100cm.

Compared to the sands, the inorganic amendments and peat contained significantly more water at saturation, > 55%, and released their water more gradually with increasing tensions up to -60cm. Once the bulk of water was released, the water content of the amendments leveled off and remained relatively constant for all four inorganic amendments out to the -15,000cm tension. Peat moss, on the other hand, had the most gradual release of any of the rootzone components at all tensions. This property was attributed to the wide distribution of pore sizes created by the fibrous particles of peat moss. For the sand/amendment mixtures, the water release curves were generally similar to the curves for each sand. The only difference was that amended sands retained slightly more

Table 3
Percentage loss of NH$_4$-N and NO$_3$-N in the effluent of sand amended at 20% by volume with four inorganic soil amendments and sphagnum peat moss

	Form of Nitrogen in the Effluent	
Soil Amendment	NH$_4$-N Loss	NO$_3$-N Loss
	---------- Percent N Lost (%) ----------	
Unamended Sand	96.2 a	98.1 a
Ecolite	7.8 e	99.2 a
Greenschoice	69.4 b	95.4 b
Isolite	63.9 b	97.8 ab
Profile	21.3 d	96.1 ab
Sphagnum Peat Moss	37.7 c	95.1 b

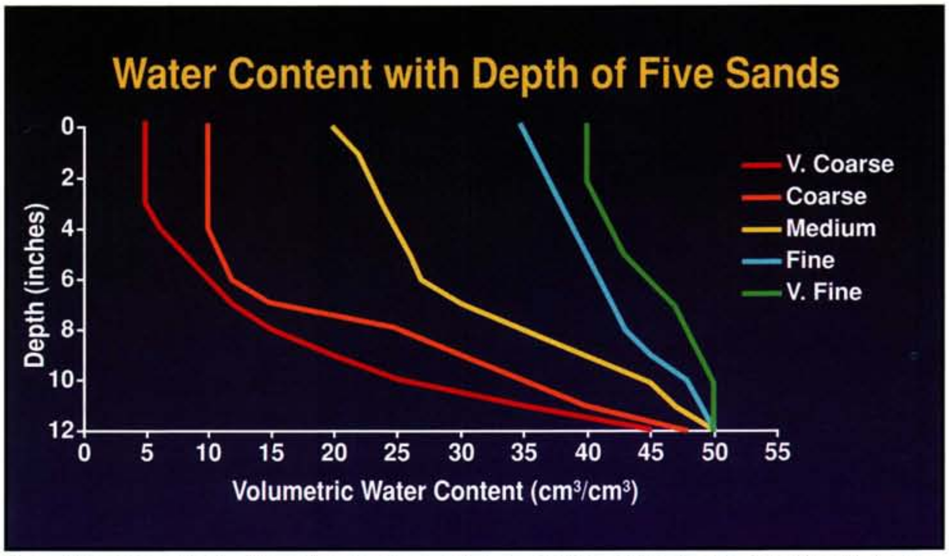
Means in the same column followed by the same letter are not significantly different under Fisher's protected LSD (p = 0.05) water than unamended sands at each tension (data not shown).

Water retained at theoretical wilt (-500cm) was greatest for the amendments, ranging 20% to 34% by volume, and least in unamended sands, 0.6% to 3%. Of all the rootzone components, available water was highest for the fine sand, 24%, whereas the other sands had less than 3% available water. This suggests that particle size and the architecture of adjacent particles when in contact, not a high degree of internal pore space, may be a more important determinant for available water.

Substantial data were generated on how the amendments responded in each different sized sand. However, for the sake of brevity, a general summary of the sand/amendment responses follows. Overall, amendments when mixed with the three sands had the most predictable response on porosity and water retention in the coarse sand and the least in fine sand. Fine sand and amended fine sand mixtures were the only rootzone mixtures that consistently met USGA guidelines for pore size distributions, 15% to 30% and 15% to 25% for air-filled porosity and capillary water retention, respectively (USGA, 1993).

The medium and coarse sand classes failed to meet specifications because they contained an excessive volume of air-filled pores, which would promote droughty conditions. The only exception was medium sand mixed with 20% peat, which also met guidelines. Although fine sand mixtures generally met specifications, not all fine sand mixtures met guidelines. Mixtures that failed were 10% and 20% peat or 20% Isolite and Profile amended sands. These mixtures were unsuitable because they retained too much water. Rootzones constructed with these mixtures may be undesirable because of excess soil wetness. This condition would probably contribute to poor turfgrass rooting, inadequate soil gas exchange, and problems with ball marking, footprinting, etc.

Bulk Density: As expected, amendment additions decreased bulk density for all three sand sizes, with peat-amended sands resulting in the lowest bulk density of all amendment mixtures. This result was anticipated because peat has the lowest particle density of the rootzone components. It is important to remember, though, that bulk density values alone generally are not an indicator of a successful rootzone mixture.



Selecting properly sized sand for constructing a putting green rootzone is the first step in providing the proper balance between rootzone moisture and aeration. Very fine sands are too wet throughout the entire rootzone depth. Very coarse sands are too dry and will require significant and potentially costly quantities of soil amendments to ensure they meet guidelines for putting green physical properties.

Percolation Rate: Saturated hydraulic conductivity, or percolation rates, were very high for all three sand sizes, > 35" per hour, and ranked in the following order: coarse > medium > fine sand. All sand mixtures had percolation rates that were much higher than the recommended 6" to 12" per hour, probably due to the highly uniform sands used. This observation is not unusual when working with very uniform sands (Bingaman and Kohnke, 1970).

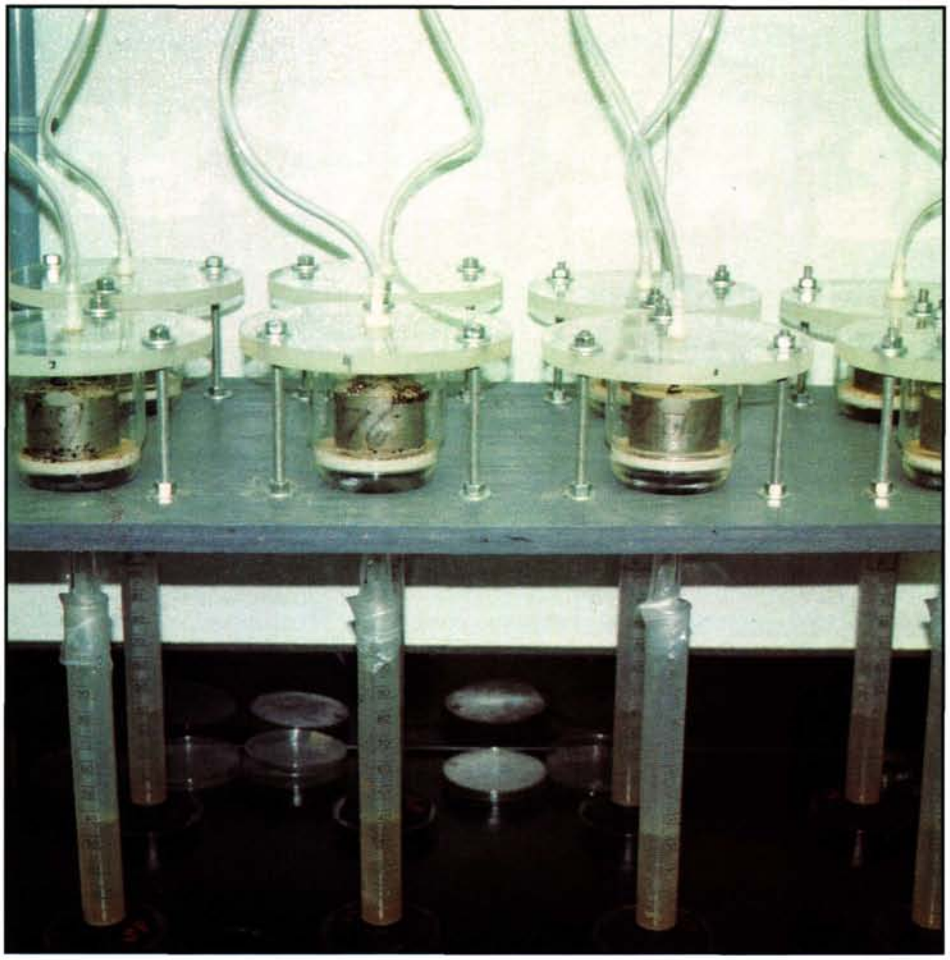
Amendments generally decreased the percolation rate of the sands, but considerable variation occurred. The average percolation rates for each amendment across all three sand classes ranked in the following order: Greenschoice = Ecolite ≥ unamended sand ≥ Isolite ≥ Profile > peat moss. As expected, the 20% amendment rate significantly decreased percolation rates more than the 10% rate. It is important to note that no amendment or incorporation rate resulted in percolation rates falling below USGA guidelines.

Nitrogen Leaching

Ammonium: Amendment additions significantly affected nitrogen leaching, most noticeably due to a wide range in ammonium (NH_4^+-N) leaching. Nitrogen appeared rapidly in the effluent of all rootzone mixtures, with peak concentrations around 70 ppm occurring near 0.5 pore volumes of leaching water. As expected, significantly higher peak NH_4^+-N concentrations and more cumulative NH_4^+-N leached from unamended sand than from 20% (v:v) amended mixtures. Leaching decreased in the order of unamended sand > Greenschoice = Isolite > peat > Profile > Ecolite. The most effective amendments, Profile and Ecolite, decreased NH_4^+-N leaching by 75% and 88%, respectively, compared to unamended sand. The effectiveness of these amendments for decreasing NH_4^+-N leaching is directly related to their relatively high CEC compared to the other products.

A second study evaluating incorporation rates for Profile and Ecolite ranging from 1% to 20% by volume demonstrated that the loss of NH_4^+-N and the peak concentrations decreased in a stepwise manner, as incorporation rate increased. The highest rate, 20% by volume, resulted in the least NH_4^+-N lost for each of these amendments. This response is consistent with the results of MacKown and Tucker (1985), who reported decreasing NH_4^+-N losses with increasing zeolite percentage in sand mixtures. In the present study, no difference in leaching between Ecolite and Profile were detected except at the 20% rate. At this rate, significantly less NH_4^+-N leached for the Ecolite-amended sand. Although the 20% amendment rate was most effective, this quantity of product may not be economically practical when blending rootzone materials for green construction.

A third study determined the influence of amendment incorporation depth of 10% Ecolite and Profile, and



Rootzone components and sand amendment mixtures were analyzed for their ability to retain water using a water desorption technique in a constant temperature room.

demonstrated that incorporation depth significantly affected leaching. Even at a relatively shallow incorporation depth of 1", these amendments decreased cumulative NH_4^+-N losses by almost 25%. Further, like the rate study, increasing the depth of the amendment resulted in a step-wise reduction of NH_4^+-N leaching: Incorporation throughout the entire 12" deep rootzone resulted in the least NH_4^+-N leaching.

Nitrate: Although Ecolite and Profile were effective at decreasing NH_4^+-N leaching, they were without effect on nitrate (NO_3^--N) leaching. For all rootzone mixtures, more than 90% of the applied nitrate was recovered in the leachate. In general, unamended sand and amended sand mixtures in all experiments were similar regarding high NO_3^--N leaching losses.

Turfgrass Establishment

Creeping bentgrass establishment on these sand rootzone mixtures was relatively slow, requiring > 250 days to reach 100% coverage. This response may have been due to the somewhat droughty nature of this predominately medium-sized sand. This sand size was selected to best evalute the water-holding benefits of the amendments tested. Although establishment was relatively slow, the significant effects and benefits of a rootzone amendment in this sand were obvious. Compared to unamended sand, bentgrass established faster on any of the amended sands. Rootzone mixtures ranked in order of increasing effectiveness were: unamended sand = Greenschoice < Profile = Ecolite < peat moss, with Greenschoice being similar to unamended sand on two rating dates.

The faster establishment of the amended sands is attributed directly to the greater water retention and, to a somewhat lesser degree, the increased nutrient retention compared to unamended sand. Although there was little difference in final establishment between sphagnum peat moss and the inorganic amendments Ecolite and Profile, there is a difference in cost between these materials. In most cases, inorganic amendments cost considerably more than sphagnum peat moss when used at the same incorporate rate (Moore, 1999). This may explain the continued popularity of peat moss for amending sand-based rootzones.

Conclusion

Amending sand with inorganic amendments or peat moss had significant beneficial effects on rootzone mixture physical properties, nitrogen leaching, and creeping bentgrass establishment. **Although many of the inorganic amendments hold considerable water, it appears that if water retention and availability are important characteristics for a desirable rootzone mixture, then the most suitable amendment from both a quantitative physical analysis and an economic standpoint is peat moss.** This fact is particularly pertinent in coarse-textured sands, where a rather substantial quantity of the amendment would be required to effectively improve the water retention of these sands.

Furthermore, inorganic amendments vary in their ability to limit nitrogen losses. No amendment had a dramatic effect on NO_3^--N leaching. However, NH_4^+-N leaching losses can be substantially decreased to 8% or less by various incorporation rates and depths of the clinoptilolite zeolite, Ecolite, and the porous ceramic, Profile, and to a lesser extent, sphagnum peat moss. Again, NO_3^--N leaching continues to be a concern in sand-based putting green media, particularly during turfgrass establishment when turfgrass root systems are small and when soluble fertilizers are used. However, it may be possible to minimize NO_3^--N leaching by constructing putting greens from sands amended with peat moss combined with either a zeolite or porous ceramic and using an NH_4^+-N-based fertilizer program. The peat moss would be beneficial for the water-holding properties and the inorganic amendment would provide nutrient retention. The use of slow-release fertilizer products and the practice of spoon feeding greens during establishment are other proven methods to reduce nutrient leaching.

Lastly, it is important to remember that not all amendments are suitable for every rootzone amendment situation. Each amendment may react differently depending on the particle size range of the base sand used and the quantity of the amendment incorporated. Some sands may hold too much water and others not enough. Therefore, it is extremely important to submit a potential sand and sand/amendment rootzone mixture to an accredited laboratory for physical analysis to determine if it meets specifications. Finally, although most of the amendments seem physically stable enough for modern putting greens, more research needs to be conducted to determine the long-term field performance before they can be widely prescribed.

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Figure 1

Water release of three sand size classes and five amendments