

INVESTIGATION OF SOIL AMENDMENTS FOR USE IN GOLF COURSE
PUTTING GREEN CONSTRUCTION

By

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Turfgrass, like all living organisms, requires water for survival. Turfgrass professionals, such as golf course superintendents, sports, and athletic field managers often have a limited amount of water they can use due to consumptive use permits levied by regional regulatory agencies. Therefore, they are required to find alternate means of maintaining quality turf while using less water. Many turf professionals enlist the use of soil amendments because of their ability to increase moisture and nutrient availability. However, whether or not soil amendments actually influence the efficient use of water by turfgrass is not known. An objective of this research was to determine the influence of soil amendments and incorporation method of those amendments on water-use-efficiency (WUE) of Tifdwarf bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt Davy]. A further objective was to determine the influence of surfactant-modified soil amendments (SMSAs) on nitrogen (N) and phosphorus (P) leaching. To determine the influence of amendments on turfgrass WUE, Tifdwarf bermudagrass was established on

pots in a glasshouse at the University of Florida turfgrass Envirotron. Treatments consisted of sand, two zeolites, two calcined clays, two diatomaceous earths, Canadian sphagnum peat, iron humate, and a smectite. Treatments were arranged in a randomized complete block design with four replications. Pots were weighed, harvested, and rated weekly for turf quality for twelve weeks. To determine the influence of SMSAs on N and P leaching, soil columns were fabricated from 2.54 cm diam. polyvinyl chloride tubes. Each column was packed with a rootzone layer (30 cm) consisting of sand/peat (85:15) and a filter zone layer (5 cm) containing each treatment. Treatments were sand, zeolite, and two calcined clays. Treatments either remained unchanged or were surfactant-coated. Three replications were used for statistical analysis. In the glasshouse study, incorporation of iron humate increased turf yield, quality, and WUE above all other amendment regardless of incorporation method. This was attributed to an increase in N, Ca, and Fe availability as well as a 13% increase in plant available water which accompanied iron humate incorporation. Rootzone amended with calcined clays (CCs) produced 40% more dry matter yield and increased WUE 30% above sand/peat. However, calcined clays did not produce quality or WUE ratings above iron humate. Sand and zeolite produced quality and WUE ratings equal to that of sand/peat mixtures. Of the amendment investigated in this study, only iron humate and CCs consistently produced quality and WUE ratings above that of sand/peat rootzones. Incorporation of amendments following aeration reduced each amendment's influence on yield, quality, and WUE. Therefore, in order to maximize amendment influences on turf quality and WUE, amendment should be fully incorporated into the rootzone. Surfactant-modified amendments reduced NO_3 levels in leachate to 0.0%, reduced NH_4 to 4%, and

reduced P levels to 3% of that applied. Unmodified amendments had no influence on NO_3 leached, reduced NH_4 leaching, and retarded P leaching. Surfactant-modified amendments may be a plausible option to reduce N and P leaching in USGA putting greens.

CHAPTER 1 INTRODUCTION

Soil modification has been used for centuries to alter certain soil properties to improve soil-plant relationships. Generally, this is achieved via the use of soil amendments. Soil amendments may be organic or inorganic and are primarily used to increase plant available water, cation exchange capacity, or nutrient availability. However, ambiguity remains regarding their indirect influence on plant water use. Furthermore, nutrient additions may lead to leaching which can cause a variety of environmental problems. Compounding the situation, some amendments have the capacity to retain potential contaminants while others may enhance leaching. Therefore, this study investigates two primary influences of soil amendment incorporation: turfgrass water-use-efficiency and nutrient retention in USGA putting greens.

Water Use Efficiency

Every living organism on earth is dependent upon water for survival. In plants, water is the solvent in which vital nutrients are translocated to various plant parts. Water is also the initial proton donor during the first steps of photosynthesis. Thus, without water plants could not survive. Fortunately, the earth contains vast amounts of water in oceans, lakes, rivers, and in the atmosphere. However, only 0.6% of all water on earth is considered to be usable by plants and animals (Nace, 1967). With such a small portion of usable water and such a large number of organisms requiring water, demand for water is high.

Water used for recreational purposes is often scrutinized because it is not considered essential to sustain life. Turfgrass water use is receiving attention due to the overall quantity of water required to maintain acceptable quality turf. This attention has prompted regional regulatory agencies to impose consumptive use permits on many golf courses in many states including Florida. Superintendents are now faced with having to maintain an acceptable quality turf while using less water. To become more efficient at using water they are allotted, superintendents sometimes use soil amendments to alleviate the inherent low water retention capacity of United States Golf Association (USGA) putting greens.

Numerous soil amendments are commercially available in at least four distinctly different classes. This study compared different soil amendments (organic, zeolite, calcined clay, and diatomaceous earth) to identify materials capable of maximizing water-use-efficiency (WUE) of Tifdwarf bermudagrass. Published reports reveal many researchers have investigated the influence of soil amendments on turf establishment, soil compaction and aeration, soil hydraulic properties, and turfgrass response (Biran et al., 1981; Miller, 2000; McCoy 1992; Nus and Brauen 1991). Other studies have investigated WUE of grass species as well as how WUE is influenced by fertilization (Frank et al., 1987; Hatfield et al. 2001). However, studies to determine the influence of different rootzone media on WUE of turfgrass are limited. A series of glasshouse and field experiments were conducted in Gainesville, Florida, from 2001 to 2004 to investigate WUE of Tifdwarf bermudagrass as influenced by soil amendments.

The objectives of this study were (1) to determine the influence of various soil amendments (peat, Fe-humate, calcined clay, diatomaceous earth, zeolite, and smectite)

on WUE and quality Tifdwarf bermudagrass in a USGA putting green; (2) to determine the influence of soil amendment incorporation method on WUE and quality of Tifdwarf bermudagrass in a USGA putting green.

Nutrient Leaching

For many agronomically important crops, nitrogen (N) and phosphorous (P) are the two most limiting nutrients. As such, they are typically applied via fertilizers in greater quantities than many other nutrients. Most fertilizer applied N is in the form of nitrate (NO_3^-) or is rapidly converted to nitrate via nitrification. Most fertilizer applied P is in the form of phosphate (H_2PO_4^-). Being anions, both nitrate and phosphate are susceptible to leaching, the consequences of which are seen in the excessive algae growth in lakes and the elevated levels of P currently being detected in estuaries and in Everglades National Park (Malecki et al., 2004; White and Reddy, 2004). For this reason, N and P applied to agronomic crops and turfgrass has been closely monitored. Golf courses are often scrutinized due to their cultural practices and the unique fertilizer requirement of turfgrass, which often demand higher fertilizer application rates than many agronomic crops (Sartain, unpublished data, 1996).

This scrutiny has brought about best management practices (BMP), which allow a turfgrass manager to minimize environmental impact while still being able to maintain a quality playing surface. Generally, these practices include the use of controlled-released fertilizers as well as the proper timing and rate of application. A number of studies have shown the BMPs have been beneficial at reducing the potential impact golf courses have on the environment (Rodriquez and Miller, 2000; Sartain and Gooding, 2000; Snyder et al., 1984). However, leaching of N and P does still occur during unique periods such as turf establishment or excessive rain events. During periods of high rainfall, leached N

can be as much as ten times higher as during normal rainfall periods (Morton et al., 1988). This influence could be exacerbated on sand-based putting greens due to their inherently low nutrient retention capacity.

Hexadecyltrimethylammonium (HDTMA) is a cationic surfactant that can be electrostatically bound to the negatively charged surface of selected soil amendments and has been shown to remove anionic compounds, such as nitrate and chromate, from solution (Li, 1999). Due to its success, a surfactant modified soil amendment (SMSA) has been used to create permeable barriers for groundwater remediation (Bowman et al., 2001).

A series of lysimeters studies were conducted at the University of Florida between 2002 and 2003 to investigate the influence of SMSAs on anion leaching below the turfgrass rootzone. The objective of this study was to determine the influence of SMSAs on leached nitrate, phosphate, and ammonium in a simulated USGA putting green.

CHAPTER 2 LITERATURE REVIEW

Soil Amendments

The USGA has recommended putting greens be primarily sand-based (USGA, 1993). The high sand content of USGA putting greens allows greens to maintain adequate aeration and drainage while minimizing compaction. Due to the high traffic typically imposed on USGA greens, these characteristics are crucial to maintaining a quality-playing surface. However, sand-based greens do have limitations, the most important of which are low water and nutrient retention (Bigelow et al., 2000). Soil amendments counteract the tendency of sand-based root zones to be nutrient deficient and droughty (Crawley and Zabcik, 1985). The USGA recommends putting greens be amended with peat moss at a rate of 85% sand and 15% peat by volume (Beard, 1982). The addition of peat moss increases the cation exchange capacity (CEC) as well as the water holding capacity of the growing media. However, peats are organic and are subject to microbial degradation. Many years of peat decomposition may be detrimental to putting green performance.

In recent years, superintendents have shown a growing interest in inorganic soil amendments to use in place of peat. Inorganic amendments are not subject to biological degradation, and thus are considered to be more stable than organic amendments, which decompose with time. Many different types of inorganic soil amendments are currently marketed for golf green construction. These include calcined clays, zeolites,

diatomaceous earths, and water treatment residuals. Characteristics between organic and inorganic amendments differ greatly; thus each will be considered and discussed individually.

Peats

The oldest and most widely used organic amendment used on golf courses is peat (Beard, 2002). Peats are typically mined from deposits located in cool, flooded environments. Low temperatures decrease microbial activity and can increase peat accumulation. Flooded conditions further increase the likelihood of peat accumulation by limiting oxygen availability. Peats can vary dramatically in their characteristics in large part due to the environment and parent material from which they formed. Peats have been classified into three types: 1) moss peat, which is from sphagnum, hypnum, and other mosses; 2) reed-sedge peat, from reeds, sedges, and other swamp plants; and 3) peat humus, peat of any form that has degraded to the point where no plant parts are identifiable (Lucas et al., 1965). When investigating six different types of peat, Carlson et al. (1998) found the pH of these peats varied from 2.9 to 6.2, water retention varied from 33 to 60% by volume, and the organic matter content varied from 63 to 95%. Despite these differences in laboratory-analyzed characteristics, no differences were observed in turf quality when these peats were used to amend putting green root zones.

Benefits of adding peat to a turfgrass root zone include (a) release of soluble nutrients and gradual release of nutrients through microbial degradation, (b) increase CEC for nutrient retention and chemical buffering, and (c) increase moisture retention.

Peats provide a number of plant essential nutrients. Comer (1999) reported Mehlich-I extractable P, Mg, and Ca increased by 575, 525, and 340%, respectively, by adding peat to USGA sand. Correspondingly, plant uptake of P, Mg, and Ca were higher

in peat amended-sand than the control. These increased nutrients lead to an increase in total dry matter production of 7%. No differences in extractable K were observed by Comer, a trend that was also observed by Ok et al. (2003). Ok et al. investigated creeping bentgrass performance as influenced by three amended root zones and reported higher levels of P, Mg, and Ca in peat-amended root zones than the control.

Peats are composed of a variety of reactive, organic compounds. Polyphenols, polyquinones, and polysaccharides are a few compounds found in peat, each of which possesses hydroxyls, carboxyls, and phenolic groups that dissociate and give rise to a CEC by weight that is often higher than most inorganic soil amendments (Carrow et al., 2001). The charge associated with peat is pH dependent and, thus, changes in relation to the pH of the soil solution. As pH increases, some H^+ ions are neutralized by OH^- ions and the CEC of the peat increases. Conversely, as pH decreases, H^+ ions in solution become sufficient to saturate negative charges on organic matter and the CEC decreases. Incorporating peat into a sand-based root zone can increase the root zone CEC by as much as 425% (Bigelow et al., 2001a). This increase in CEC directly influences nutrient retention. At 20% (by volume) incorporation, peat can decrease NH_4 -N leaching from 96% to 37% of applied N (Bigelow et al., 2001a). Ammoniacal-N may then become available for plant uptake or be oxidized by nitrifying bacteria (Sylvia et al., 1997). Leaching of cationic nutrients such as K, Ca, and Mg have also been shown to decrease with peat incorporation (Snyder, 2003). However, additions of peat may increase leaching of anionic nutrients. Brown and Sartain (2000) observed a 30% increase in leached P by adding peat to uncoated sand, which may have been attributed to the soluble P content of peat which effectively increases total soil P.

Due to their fibrous, porous nature, peats can increase total soil porosity and thus increase soil moisture retention. Critical levels for optimum soil porosities have been suggested and range from 0.10 to 0.20 (Baver, 1956; Flocker et al., 1959, and Wesseling and van Wijk, 1957). Currently, the USGA specifies putting green root zones should have an aeration porosity of 0.15 to 0.30 (USGA, 1993). However, aeration porosity is typically not uniformly distributed throughout the 30 cm putting green root zone. Taylor et al. (1997) reported the bottom 9 cm of a sand/peat mixture had 3 to 7% air-filled porosity while the top 21 cm had 22 to 37%. Similar results were reported by Flury et al. (1999) in which the lower boundaries of experimental lysimeters were found to remain near saturation while the upper 80% of the soil columns exhibited a uniform moisture distribution.

The influence peat has on porosity also affects bulk density. Bigelow et al. (2001b) found incorporating peat (10% by volume) with sand decreased bulk density from 1.66 to 1.54 g cm⁻³, increased total porosity from 0.41 to 0.47, and increased air-filled porosity from 0.24 to 0.28. This increase in porosity allows sand amended with peat to retain more water than sand alone. Sphagnum peat moss has been found to hold 10-14 times its own weight in water (Hummel, 2000). When incorporating peat, soil moisture contents have been found to be higher than sand amended with zeolites and calcined clays (Bigelow et al., 2001b). After saturation followed by drainage for 48 hours, sand/peat mixtures were found to retain as much as 46% more water than sand alone (Taylor et al., 1997).

The organic matter associated with peat incorporation also influences plant available water (PAW). Hudson (1994) found the correlation between OM and PAW to

be significant ($r^2 = 0.79$), and that as OM content increased from 0.5 to 3%, PAW more than doubled. However, peat incorporation may not always be beneficial to PAW. McCoy (1992) found that Canadian sphagnum peat retained water within organic matter pores beyond that available to the plant. He further suggested that much of the water retained by organic amendments with fiber contents in excess of 45% is unavailable to plants. In the same study, Canadian sphagnum peat had a fiber content of 54%.

Addition of peat to sand-based root zones increases plant growth and soil productivity (Lucas et al., 1965). Incorporation of sphagnum peat to uncoated, coated, and artificially coated sand shortened turf establishment by 14 days and increased yield by 50% (Snyder, 2003). Following establishment, a 12-week maintenance study was conducted in which peat-amended pots produced 24% more dry matter than sand alone. These findings are in contrast to Smalley et al. (1962) who investigated the influence of peat and calcined clay (10% by volume) on Tifgreen bermudagrass and reported neither had any effect on dry matter yield. During this one-year study, 1022 and 484 kg of N and K ha⁻¹ were applied, respectively. At this fertilization rate, it is likely that turf on both the control and treated plots received adequate nutrients, and the influence of peat and calcined clay (CC) was minimized thus, no differences were observed. Other researchers have reported different results. Cooper et al. (1998) investigated the influence of four humic substances including peat on root mass and nutrient uptake of creeping bentgrass. They reported little or no difference in root mass or N, K, Ca, Mg, or Fe uptake between any humic compounds or the control.

Calcined Clays

Mined clays, typically smectites, are heated to 800–900 °C to harden the amendment and increase their stability (Bigelow et al., 1999). The clay is then sieved to

achieve a desired particle size and sold as calcined clays. Calcining the clay allows the amendment to maintain its beneficial characteristics such as CEC and moisture retention while eliminating shrinking and swelling, which can be detrimental to putting green performance. Calcined clay has the advantages of withstanding compaction, providing high infiltration, and allowing good aeration (Letey et al., 1966).

Cation exchange capacity of calcined clays arises from isomorphic substitution of Al^{+3} for Mg^{+2} in the octahedral sheet and, thus much of the charge is independent of pH. Reported CEC values of calcined clays vary from 24-34 $cmol(+)/kg$ (Richardson and Karcher, 2001; Carrow et al., 2001). Field plots modified with calcined clays have shown increases in CEC as well as increases in nutrient retention. Li et al. (2000) observed an 8% increase in CEC when comparing plots amended with calcined clays to a control. They also observed a 100% and 30% increase in exchangeable K and Mg, respectively. In the same study, exchangeable Ca decreased by 4%, a trend which was also observed by McCoy and Stehouwer (1998). The increase in CEC reported by Li is lower than results reported by Bigelow et al. (2001a). Exchange capacities in their study increased from 0.8 in the control to 2.4 $cmol(+)\ kg^{-1}$ in the calcined clay amended plot. Calcined clay was further shown to increase CEC above a zeolite treatment which was reported to be 1.6 $cmol(+)\ kg^{-1}$.

Calcined clays are incorporated with sand not only to increase the CEC, but also to aid in moisture retention. When sand is mixed with CCs (15% by volume), porosity has been reported to increase by as much as 15% over sand alone (Waltz et al., 2003). Correspondingly, total water retained after drainage also increased from 19.9 to 23.1 cm in sand and CC plots, respectively. Li et al. (2000) reported sand modified with calcined

clay retained 13% more water than sand alone. Li theorized that calcined clay probably provided for a more favorable ratio of macropores to micropores which equaled 3.77. Macropores play a vital role in hydraulic conductivity while micropores are more responsible for water retention (Rowell, 1994). Root zone modifications that alter pore space distribution and improve aeration and water conditions can favor turfgrass growth (Waddington, 1992).

Turf establishment and growth are generally increased by incorporating CCs into a sand-based rootzone. Waltz and McCarty (2000) conducted an experiment involving the incorporation of soil amendments and their influence on turf establishment. They found plots containing sand and CC achieved 75% and 100% establishment, respectively, at 9 months after seeding. Furthermore, calcined clay treatments produced a higher visual rating of density and color than plots with sand alone. However, these findings differ from those reported by Smalley et al. (1962). They investigated the influence of CC on turf yield and quality and reported that incorporating CC decreased yield and quality. They observed this effect was particularly evident during a droughty period, and concluded the decrease in yield and quality likely resulted from excessive aeration and consequent reduction in available moisture.

Zeolites

Zeolites are naturally occurring minerals that can form in a variety of environments. The most common zeolite used for agricultural purposes is clinoptilolite because it is the most common zeolite found in soil parent material (Boettinger and Ming, 2002). Like quartz, zeolites are tectosilicates, thus its structure prevents any shrinking or swelling that sometimes occurs with other soil minerals. However, unlike some tectosilicates, zeolites are porous, thus they tend to have low densities ($1.9\text{-}2.2\text{ g cm}^{-3}$)

(Breck, 1974). Their porous nature also increases their surface area and its cation exchange capacity. Clinoptilolite has been shown to have a void volume near 34% and a CEC as high as $220 \text{ cmol}(+) \text{ kg}^{-1}$ which arises from isomorphic substitution of Al^{3+} for Si^{4+} (Meier and Olson, 1988). The internal pores of clinoptilolite are small enough to limit the adsorption of some larger ions, thus clinoptilolite is highly selective for K^+ and NH_4^+ relative to Na^+ or divalent cations such as Ca^{2+} and Mg^{2+} (Ming and Mumpton, 1989). Goto and Ninaki (1980) determined the ion-exchange selectivity order of natural zeolites to be $\text{K}^+ > \text{NH}_4^+ > \text{H}^+ > \text{Na}^+ > \text{Sr}^{2+} > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{Li}^+$. The strong affinity zeolites have for K^+ and NH_4^+ has prompted municipalities to use zeolites for the removal of NH_4^+ from sewage (Mercer et al., 1970).

Their high CEC is the primary reason zeolites have been used to amend putting green root zones. Addition of zeolites to sand-based root zones has been shown to increase the CEC by as much as 200 fold (Huang and Petrovic, 1994). This increase in CEC helps to buffer the soil and increase retention of nutrients such as K, NH_4 , Ca, and Mg. Ferguson et al. (1986) observed that zeolite amended soils produced higher turf quality than non-amended soils. It was hypothesized that NH_4^+ produced from urea applications was adsorbed by the clinoptilolite and was slowly released, which resulted in a more healthy turf. In defense of this theory, an incubation study was conducted in which $\text{NH}_4\text{-N}$ was mixed with clinoptilolite amended USGA sand. After 25 days of incubation, NH_4^+ loss due to nitrification, denitrification, and/or volatilization was lower in clinoptilolite-amended sand than vials containing sand alone. This was attributed to the internally sorbed NH_4^+ being inaccessible to denitrifying bacteria (Ferguson and Pepper, 1987).

Decreased NH_4^+ leaching from zeolite-amended soils has also been attributed to the increased CEC that accompanies zeolite incorporation. When mixed at a rate of 50 g kg^{-1} , clinoptilolite has been shown to decrease $\text{NH}_4\text{-N}$ leached from 168 to 29 mg $\text{NH}_4\text{-N}$ (Mackown and Tucker, 1985). A number of studies have reported reductions in NO_3^- leaching with use of clinoptilolite. Huang and Petrovic (1994) not only reported that NO_3^- and NH_4^+ leaching was 86 and 99% lower, respectively, in zeolite-amended sand than sand alone, they also observed the fertilizer use efficiency of creeping bentgrass increased as much as 22%. Lewis et al. (1984) reported pots containing a loamy sand soil amended with clinoptilolite reduced NO_3^- leaching by 33% compared to the control when fertilized with ammonium sulfate. These reported reductions in NO_3^- leaching are likely attributed to NH_4^+ release from clinoptilolite being limited by diffusion and cation exchange reactions (Semmens, 1984; Allen et al., 1995).

The capacity zeolite has to retain cations may not always be beneficial. Some research suggests that the energy at which NH_4^+ is held by zeolite may be enough to render NH_4^+ inaccessible to plants. Ferguson et al. (1986) observed better bentgrass establishment on 5% than on 10% clinoptilolite amended plots. While this observation was attributed to high sodium content, more recent research suggests that high sodium levels may not be solely responsible for the decreased establishment, but rather N removal by NH_4^+ sorption which effectively reduces plant available N. Regardless, other studies have shown that the influence of zeolite on creeping bentgrass establishment compares favorably with peat (Nus and Brauen, 1991).

Zeolite incorporation typically increases turf establishment. Miller (2000) reported that bermudagrass was found to establish more rapidly and had greater growth on

Zeopro-amended plots than plots containing 100% sand and other rootzone mixtures. The higher nutrient levels accompanying incorporation of zeolite have been associated with more rapid establishment and high quality ratings of creeping bentgrass (Ok et al., 2003). It should be mentioned that studies conducted by Miller (2000) and Ok et al. (2003) involved the use of zeolite which contained as much as 0.1% N. Nitrogen loaded zeolite may act as an N source instead of an N sink which may increase turf growth and establishment. Natural zeolites do not contain N, thus turf grown on natural zeolite may react differently than turf established on N-loaded zeolite. This concept was also speculated by Ok et al. (2003). Nus and Braun (1991) investigated the incorporation of sawdust, peat, zeolite on establishment of creeping bentgrass and reported peat and zeolite were equally effective at increasing turf establishment.

Diatomaceous Earths

Algae, predominantly of marine origin, are responsible for the formation of diatomaceous earths (DE). Diatoms are microscopic, single-cell plants, which join to form sedimentary rock composed of fossilized skeletal remains of diatoms (Fresenberg, 1999). Chemically, DEs are like silica sand in that they are about 90 percent silica (SiO_2) with minor amounts of alumina (Al_2O_3) (Mannion, 1996). Some DEs are calcined during manufacturing. Calcined DEs are 50 percent harder and suffer one-quarter the wet attrition loss of uncalcined DEs (Mannion, 1996).

DEs are porous and, thus, have low bulk densities and can retain up to 150% its weight in water. Sands amended with DEs have been reported to have higher total porosity and overall water retention than sands amended with zeolite (Bigelow et al., 2004). However, Bigelow also reported that DE amended sand possessed the same porosity and water retention as peat and calcined clay amended sand. These findings

were similar to those reported by Waltz et al. (2003). Waltz investigated the hydraulic properties of several soil amendments including DE. Waltz reported that water retained at field capacity was greater in sand amended with peat than with DE. However, as plots were allowed to dry, DE and peat amended sand held more water than CC amended sand. Waltz further observed that DE and peat amended sand held more water in the top 15cm of a 30 cm profile than CC amended sand. While turf growth was not investigated, Waltz speculated that amendments that slow water movement and retain more water in the upper portion of the rootzone would result in turf with less water stress than turf grown on media that retained less water due to rapid drainage.

The influence of DEs on turf growth has been shown to be most pronounced during times of drought. Wehtje et al. (2003) evaluated bermudagrass growth as influenced by DE, zeolite, and calcined clays incorporated with sand at five rates. Their investigation consisted of measuring turf yield under luxury water and nutrient application and under drought conditions. When bermudagrass was supplied with adequate water and nutrients, sand amended with DE only produced more dry matter than un-amended soil at the highest incorporation rate (100% DE). However, under drought conditions DE increased dry matter production which, in general, increased with increasing incorporation rate. Experimental conditions during this study were variable. However, Wehtje et al. concluded that improvement in bermudagrass performance in amended sand relative to soil alone was most likely related to increased water-holding capacity. This theory was not only based upon their findings, but also upon previous research conducted by Ralston and Daniel (1973). During their research, Ralston and Daniel investigated the influence of calcined clay and DE on creeping bentgrass. After two 15 day dry down periods, they

found plots containing DE maintained normal growth without additional water applications while plots containing calcined clay required water after 5 days. More recent research has also shown turf grown on DE amended sand produced better coverage and more dry matter than CCs or peat during times of drought (Waltz and McCarty, 2000).

Water Treatment Residuals

Water treatment facilities use FeSO_4 to remove humic substances from water for human consumption. Water treatment residuals (WTRs) are products of this process. WTRs contains humic and fulvic acids as well as iron, which is a plant essential element (Salisbury and Ross, 1992).

In general, WTRs have a positive influence on soil moisture. Bugbee and Frink (1985) observed increases in soil moisture retention and aeration from WTR incorporation with soil. Increases in soil moisture retention were also observed by Rengasamy et al. (1980) and were attributed, in part, to the increase in soil aggregate stability which accompanied WTR incorporation. Increasing soil structure by adding WTRs has also been shown to increase soil drainage (Scambilis, 1977) which is crucial to putting green performance.

Applications of WTRs have been shown to increase plant growth. Basta et al. (2000) investigated the influence of WTRs on dry matter yield of bermudagrass. They reported bermudagrass grown on WTRs produced a yield of 26 g pot^{-1} while turf grown on native soil only produced 15 g pot^{-1} . WTRs used in the Basta study contained 140 and 130 ppm $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$, respectively. High N levels along with high levels of P, K, Ca, Mg, and Fe were likely the cause of the observed increase in turf growth. A similar explanation was given by Elliott and Singer (1988) when they studied the influence of

WTR on growth of tomato and observed an increase in yield following the incorporation of WTR. Ippolito et al. (1999) investigated the influence of co-application of biosolids with WTRs on biomass yield of two range grasses. They concluded that increasing the rate of WTR incorporation increased biomass production for both turf species. However, in general, turf grown on plots containing less than 150 g kg⁻¹ WTR did not show yield increases. Lower incorporation rates were used by Heil and Barbarick (1989) when investigating WTR incorporation and its effect on the growth of sorghum-sudangrass. By increasing WTR incorporation rate from 0 to 20 g kg⁻¹, Heil and Barbarick increased turf dry matter production from 6 to 20 g pot⁻¹. They attributed this increase in yield to an increase in plant available Fe which was not observed in the control pots, which exhibited Fe-deficiency symptoms. Other researchers have observed limited influence of WTRs on plant growth. Geertsema et al. (1994) applied WTR at three rates of 0, 36, and 52 dry Mg ha⁻¹ to loblolly pine (*Pinus rigida* Mill.) and reported no differences in plant growth between amended and unamended plots after 30 months of growth.

Water-Use-Efficiency

Water-use-efficiency (WUE) is defined as the quantity of dry matter produced per quantity evapotranspired water (g dry matter mL ET⁻¹). WUE may be influenced by plant species, nutrient availability, water availability, or cultural management practices.

Many studies have shown that water use is directly related to available soil moisture, and, to a point, WUE increases as soil moisture decreases. Youngner et al. (1981) investigated water use of two cool-season and two warm-season grasses. Soil moisture was maintained according to tensiometer readings of 0.015, 0.035, and 0.055 MPa. Regardless of turf species, water use was maximized under the highest soil moisture tension. Danielson et al. (1981) measured the water use of Kentucky bluegrass

under differing soil moisture levels including 100%, 80%, and 70% field capacity. They reported irrigation of 80% field capacity reduced water consumption by 20% with only minor reductions in turf quality. Similar results were reported by Meyer et al. (1985). They also used varying irrigation rates from 100 to 60% ET estimated values and reported that when irrigation rates were dropped to 80% ET, turf quality rates dropped only 3% for cool-season and 5% for warm-season grasses. Stout et al. (1988) investigated the influences of soil and N on WUE of tall fescue and concluded that based upon the regression of WUE and soil variables, the influence of soil on WUE increases during periods of limited water availability. This indicates that when water is limited, differences in WUE between different rootzone media may be more pronounced.

Differences between WUE not only exist between different plant species, but also between different cultivars or varieties within a species. C-4 plants are more efficient users of water than C-3 plants during periods of high light and temperature (Black et al., 1969). This is due to more efficient carbon assimilation in C-4 plants. C-4 plants are able to take up more CO₂ through their stomata, thus less water is lost for every CO₂ molecule assimilated (Hull, 1992). WUE of C-4 grasses has been reported to be as much as 2x higher than C-3 grasses (Schantz and Piemeisel, 1927). These results were similar to Fu et al. (2003) who reported 'Meyer' zoysia to have a WUE more than 3x higher than 'Falcon II' tall fescue.

Cultural practices that influence WUE include: irrigation frequency, mowing height, and fertility program. Minner (1988) observed an increase in water use rate when irrigation frequency was increased. Minner also reported water use increased as mowing height increased which was attributed to an increase in leaf area index. Biran et al.

(1981) increased cutting height from 3 to 6 cm and found similar results with *Festuca arundinacea* and *Lolium perenne*. They reported a permanent increase in water consumption and growth, as well as an increase in chlorophyll per unit weight in clippings. However, Biran did not find any permanent increases in water consumption or plant growth in C-4 turfgrasses.

In general, the greatest single factor influencing WUE is soil fertility. Stout et al. (1988) studied the influence of 3 soils and 3 N rates on WUE of tall fescue. When N rates increased from 45 to 90 kg ha⁻¹ WUE increased by as much as 50%. Stout reported during fall harvests, N fertility was always the major component influencing WUE of tall fescue. Feldhake et al. (1983, 1984) used two N fertilization levels to determine the influence of N on water use of Kentucky bluegrass. They reported higher ET levels from turf supplied with 4 kg of N 1000 m⁻² mo⁻¹ than from turf supplied with 4 kg of N 1000 m⁻² yr⁻¹. A more recent study investigated the influence of 4 soils, 3 N rates, and 2 turf species and concluded N fertilization increased WUE at all application rates with the highest application rate having the greatest influence on WUE (Stout, 1992). The influence of N fertility on WUE has been shown to be most pronounced when water is limited. Stout and Schnabel (1997) investigated WUE of perennial ryegrass over a two-year period. During year one, when rainfall and irrigation supplied water were considered to be adequate for turf growth, N fertility increased WUE 154%. During year two, when rainfall and irrigation were low, N fertility increased WUE 455%.

Nitrogen in the Turfgrass Environment

In order to limit N leaching and the environmental impact of N fertilization, one must thoroughly understand the N cycle (Fig. 2-1) and the transformations that N

undergoes in a dynamic soil system. These processes include: plant uptake, soil retention and microbial immobilization, runoff and leaching, or atmospheric loss (Petrovic, 1990).

N Transformations in Soil

Soil N exists primarily in two forms: organic and inorganic. Organic N is present in a variety of compounds including proteins and amino acids. Forms of inorganic N include NH_4^+ and NO_3^- and are produced from the aerobic oxidation of organic N or from fertilizer input. From the standpoint of environmental impact and leaching, NH_4^+ and NO_3^- are the most important because it is these compounds that are mobile in the soil solution (Follett, 1989).

Organic N is converted to NH_4^+ by heterotrophic microorganisms during mineralization. N mineralization is strongly influenced by moisture and O_2 content. Maximum N mineralization occurs between 50 and 70% water-filled pore space (Havlin et al., 1999). Once in inorganic form, NH_4^+ may take a variety of paths including plant uptake, mineral fixation, volatilization, or nitrification. Nitrification is the conversion of NH_4^+ to NO_2^- and then to NO_3^- . Nitrification consists of two reactions. The first reaction is mediated primarily by microorganisms belonging to the group *Nitrosomonas*.



The second reaction oxidizes nitrite to nitrate and is mediated primarily by organisms in the *Nitrobacter* group.



Both reactions require O_2 , thus each reaction is highly dependent upon aeration and moisture content. In aerated soils, nitrification is normally a rapid process requiring only days to convert the NH_4^+ to NO_3^- . During a 53 week incubation study to investigate

mineralization rates in a variety of Florida soils, Reddy (1982) observed low levels of NH_4^+ in effluent of soil columns and found high concentrations of NO_3^- . These results were attributed to rapid nitrification of the mineralized NH_4^+ . Tate (1977) also reported rapid nitrification occurred in well-aerated soils which may result in little or no NH_4^+ accumulation.

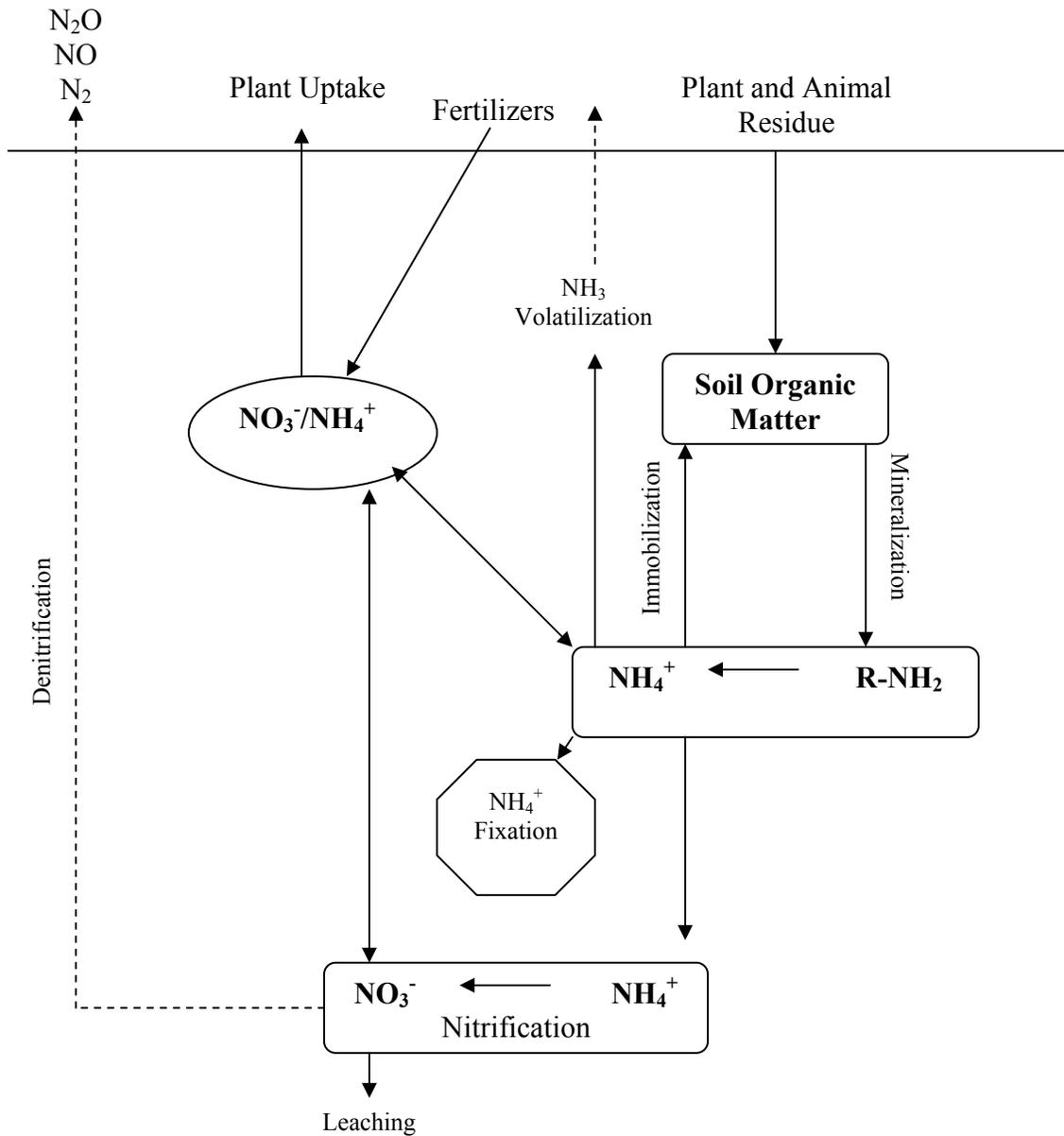


Figure 2-1. The Nitrogen Cycle (Havlin et al., 1999)

Leached N

The most common source of NO_3^- pollution of ground and surface water is agriculture (Halberg, 1987; Pratt, 1984). While turfgrass is not often thought of as an agricultural crop, golf courses and home lawns are maintained according to many of the same practices and, thus they are also sources of nitrate leaching (DeRoo, 1980; Morton et al., 1988).

Susceptibility of USGA putting greens to N leaching has been well documented. Snyder et al. (1984) investigated the influence of moisture-sensor irrigation on N leaching and reported 56% of applied N from ammonium nitrate was leached under a daily irrigation schedule. They also observed 85 to 98% of leached N occurred as $\text{NO}_3\text{-N}$ and that 75% of leached N occurred within 20 days of application. Bigelow et al. (2001a) used several laboratory studies to monitor leaching losses of N from a sand-based medium amended with 20% peat by volume and reported addition of peat decreased $\text{NO}_3\text{-N}$ leached from 98 to 95% of that applied, which was statistically significant. Peat had a greater influence on leached $\text{NH}_4\text{-N}$ dropping the percent $\text{NH}_4\text{-N}$ lost from 96 to 37% of that applied. Because of its positive charge, $\text{NH}_4\text{-N}$ can adsorb to soil particles and, thus may not leach readily. However, Sartain (1990) applied $(\text{NH}_4)_2\text{SO}_4$ to bare soil, encouraged leaching, and found after 112 days, 80% of applied N leached with 68% being $\text{NH}_4\text{-N}$. In most agricultural soils, N leaching is primarily as $\text{NO}_3\text{-N}$ simply due to the rapid oxidation of $\text{NH}_4\text{-N}$ to $\text{NO}_3\text{-N}$.

Because all N leaching occurs in soil solution, soil water content plays a major role in N movement through the soil profile. In general, N leaching potential increases as water application increases (Morton et al., 1988). Starrett et al. (1995) investigated two

irrigation regimes on N leaching and found 30 times more N leached when irrigation rates were increased by a factor of four.

Phosphorous in the Turfgrass Environment

Phosphorus is a macro nutrient used by plants to produce ATP, which in turn is used as an energy source which drives many metabolic processes. Phosphorus exists in soil solution primarily in anionic form (Fig. 2-2). Additions of P to soil solution arrive via desorption from soil exchange sites, dissolution of primary and secondary minerals, and mineralization of organic matter. In most agronomic situations, plant uptake and leaching are the only process whereby P is removed from the soil system.

P Reactions in Soil

Total P in most surface soils varies but is generally between 0.005 and 0.15% (Havlin et al., 1999). Of the total P, only a small portion actually exists as solution P which is that portion available for plant uptake. Solution P is maintained by dissolution of primary and secondary mineral, mineralization from organic matter, and by desorption from mineral and clay surfaces (Fig. 2-2). These processes are responsible for replenishing the soil solution P that is taken up by the plant. When these processes cannot adequately supply P, fertilizers must be used to artificially increase solution P concentrations. However, when solution P exceeds the amount needed by the plant, the potential for P leaching increases.

Leached P

Phosphorus is considered to be a critical nutrient responsible for eutrophication of surface water bodies. Eutrophication of surface water has been identified by the USEPA as a major cause for quality degradation of surface waters which may lead to problems

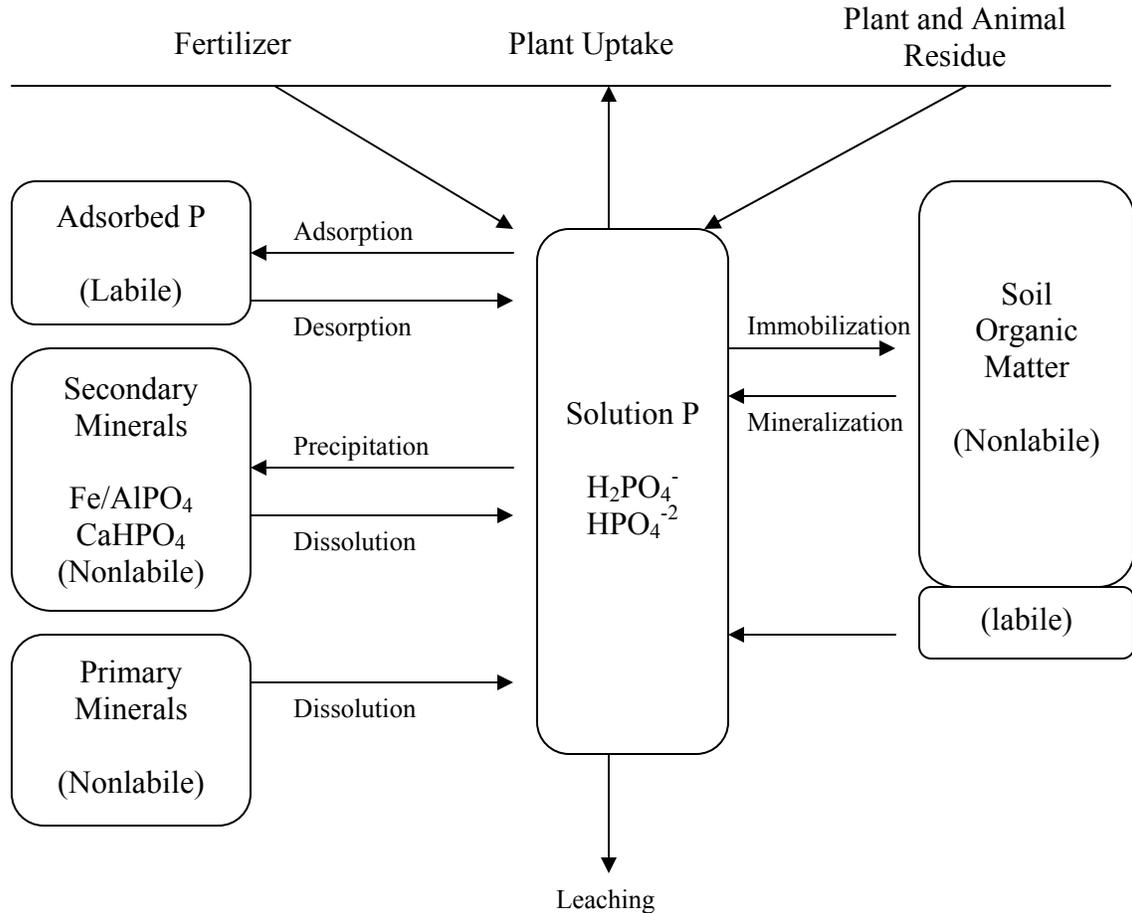


Figure 2-2. The P cycle (Havlin et al., 1999).

with their use for fisheries, recreation, industry, or drinking water (O'Connor and Sarkar, 1999). Periodic surface cyanobacteria blooms occur in drinking water and may pose a serious threat to livestock and humans (Lawtin and Codd, 1991; Martin and Cook, 1994).

In recent years, a number of studies have investigated P leaching. Brown and Sartain (2000) used several P fertilizers to investigate P retention in a variety of sand/amendment mixtures. They reported P leached from an uncoated sand/peat rootzone (85:15 by volume) was less than 7% of applied P. However, they also observed

twice as much P leached from peat amended sand than from sand alone. These findings are somewhat lower than that observed by Shuman (2001). Shuman investigated P leaching from a simulated USGA putting green in an environmentally controlled greenhouse and reported 27% of applied P was lost via leaching. Uncoated sands typically retain less P than coated sands. Harris et al. (1996) investigated the P sorption characteristics of coated and uncoated sands via a number of adsorption and desorption experiments. They reported the presence of sand grain coatings enhanced P adsorption and resistance to desorption.

Soil amendments have been used to reduce P concentrations in ground water. Porter and Sanchez (1992) reported that P sorption in a Histosol was correlated with soil ash and CaCO_3 content. Coale et al. (1994) applied gypsum and WTR and investigated their influence on P leaching. They reported decreased leachate P concentration from both amendments with gypsum causing the greatest decrease in leached P.

Hexadecyltrimethylammonium

Hexadecyltrimethylammonium (HDMTA) [$\text{CH}_3(\text{CH}_2)_{15}\text{N}(\text{CH}_3)_3$] is an amphoteric compound containing both hydrophobic and hydrophilic components. Each molecule possesses a positively charged head and a 16-carbon tail. The head groups of HDMTA are similar to NH_4^+ ; however, three protons in NH_4^+ are replaced by three methyl groups while the fourth is replaced by the tail (Fig. 2-3) (Li and Bowman, 1997). Its unique properties allow the surfactant to bind to solid particles that possess a CEC and effectively reverse their charge, thus the particle is now capable of adsorbing many anionic compounds.

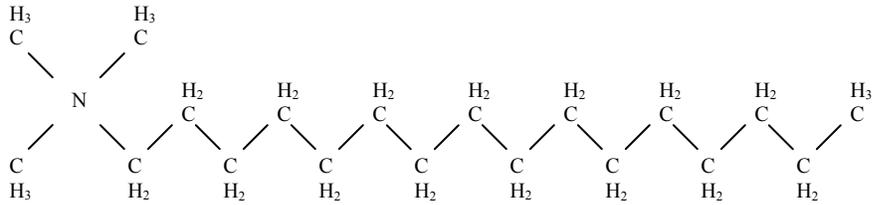


Figure 2-3. Hexadecyltrimethylammonium.

Bi-layer Formation

Bi-layer formation involves two steps. The first step involves direct attachment of HDTMA micelles to the amendment surface via electrostatic bonding. The second step involves HDTMA surface rearrangement, which is directly related to the initial surfactant input in relation to the ECEC of the amendment. If the initial surfactant input is less than the ECEC, each micelle will dissociate to form a monolayer. If surfactant input is greater than the ECEC but less than twice the ECEC, an incomplete or ‘patching’ bi-layer forms.

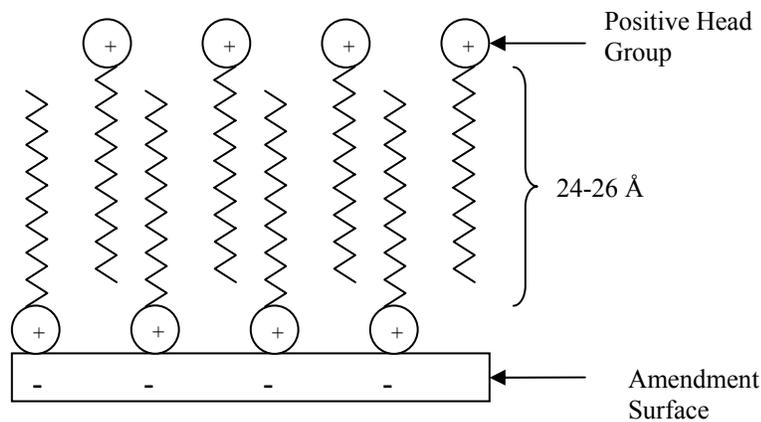


Figure 2-4. Schematic of HDTMA bi-layer formation.

If surfactant input is greater than twice the ECEC, a complete bi-layer will form (Fig. 2-4). The initial step is relatively fast generally requiring less than one hour. The second phase involves intraparticle diffusion, which can require as many as 48 h to achieve bi-layer formation depending upon the ECEC of the solid phase (Li, 1999). Cation exchange is responsible for retaining the lower layer while hydrophobic bonding causes formation of the upper surfactant layer (Li and Bowman, 1997).

Anion Sorption

Recent literature indicates HDTMA-modified solids are effective sorbents for multiple types of contaminants, such as chromate, naphthalene, perchloroethylene, and nitrate (Li and Bowman, 1997; Nzungu et al., 1996). While investigating the HDTMA counterion influence on chromate sorption, Li and Bowman (1997) observed sorption isotherms were well described by the Langmuir equation. Chromate sorption maximum was reported to be 16 mmol kg^{-1} . More importantly, Li and Bowman found the exchange ability of the counterion on HDTMA was more influential on chromate sorption than the initial HDTMA loading concentration. Other studies investigating NO_3^- sorption have found similar results. Li et al. (1998) investigated NO_3^- sorption isotherms, which like CrO_4^{2-} , were well described by the Langmuir equation. Sorption maximum for NO_3^- was 100 mmol kg^{-1} . The same study produced results that indicated NO_3^- is more suitably sorbed than CrO_4^{2-} , which seems unlikely since the divalent CrO_4^{2-} has a higher charge density than the monovalent NO_3^- and thus should be more selectively sorbed. Investigators theorized that because sorbed HDTMA onto an amendment surface does not form a rigid structure, the stability of the HDTMA- CrO_4 ion pair might be lower than the HDTMA- NO_3 ion pair, which may explain why NO_3^- is more suitably sorbed than CrO_4^{2-} .

Stability

The resistance of surfactant-modified soil amendments (SMSA) to biological degradation or physical weathering is crucial to their long-term effectiveness. Investigations into the influence of aqueous quaternary ammonium cations (QACs) on microbial growth have found aqueous QACs to be biocidal. Gilbert and Al-taae (1985) investigated a number of QACs with varying chain lengths with 4-22 carbons and reported bacteria strains were most sensitive to QACs containing 14 carbon tails while yeast and fungi were most sensitive to QACs containing 16 carbon tails. Microbial growth was least inhibited by QACs with shorter tails. In general, QACs with longer tails are more biocidal than those with shorter tails (Korai and Takeichi, 1970). Although QACs like HDTMA have been shown to be biocidal, they can be degraded microbially. Dean-Raymond and Alexander (1977) investigated the biodegradation of 10 QACs including HDTMA using sewage and soil as their sources for microorganisms. They reported decyltrimethylammonium and HDTMA were both metabolized by microorganisms from both sources. In the same study, Decyltrimethylammonium bromide was observed to be the sole carbon source for a mixed population of two bacteria from soil. Each of the preceding cases involved investigations on aqueous QACs. The influence of sorbed QACs on microbial growth is quite different. A study was conducted in New Mexico which involved microorganism growth on agar plates after being inoculated with a mixture of surfactant-modified zeolite (SMZ) and activated sewage sludge (Li et al., 1998). After 17 weeks of incubation, microorganism growth remained essentially the same between treated plates and the control. Toxicity from QACs is primarily from the alkyl chain (Korai and Takeichi, 1970). Surfactant-modified soil amendments which have been modified to ensure bi-layer formation have very few

tails exposed to soil solution, thus toxicity of SMSA is very low or non-existent (Li et al., 1998).

Investigations into the physical stability of SMSA are somewhat limited. However, Li et al. (1998) used SMZ in a series of leaching experiments to determine the extent of bi-layer removal. They used two types of water, Type I had an ionic strength of zero, and type II used K_2CrO_4 to increase the ionic strength to 8mM. They reported HDTMA desorption to be $0.34 \text{ mmol kg}^{-1} \text{ pore volume}^{-1}$ from type I water and $0.14 \text{ mmol kg}^{-1} \text{ pore volume}^{-1}$ from type II water. Based on these observations, they predicted that 65% of sorbed HDTMA would remain after 500 pore volumes of type II water. This hypothesis was later verified in a laboratory column test.

CHAPTER 3 MATERIALS AND METHODS

This research consisted of a variety of amendment characterization studies and two glasshouse studies.

Characterization Studies

Characterization studies were conducted in a number of soil laboratories at the University of Florida from fall 2001 to fall 2004.

Cation Exchange Capacity

Cation exchange capacity for each amendment and sand/amendment mixture was determined via the ammonium acetate pH 7.0 method (Soil Survey Laboratory Staff, 1996). Five grams of soil media were placed in leaching tubes and leached with 25 mL of 1 M NH₄OAc. Leaching tubes were then closed and an additional 25 mL 1 M NH₄OAc were applied and soil media remained in solution for 48 h. Leaching tubes were then opened followed by two applications of 100 mL ethanol. A total of 60 mL 1 M KCl were leached through each tube, collected, brought to 100 mL volume, and analyzed for NH₄⁺.

Moisture Retention

Moisture release curves were determined for each sand mixture according to the process described by Klute (1986). Field plots were originally established with the intention of mimicking the glasshouse studies. Each plot contained rootzones corresponding to the rootzone of glasshouse pots. However, due to experimental difficulties during the first 3 months of the study, establishment was delayed.

Furthermore, once data began to be collected from the plots, excessive rainfall from both hurricanes Frances and Jeane heavily skewed the data. Thus, no results from field plots were included in this study. However, since removing usable cores from glasshouse pots was not possible due to the rootzone depth required, cores were taken from the field plots using a brass ring (3 cm high \times 5.56 cm diameter). The ring was placed on a half-bar porous ceramic plate, which was then placed into a Model 1400 Tempe pressure cell (Soil Moisture Equipment, Santa Barbara, CA). Tempe cells were placed in a water bath until each cell achieved saturation. The cells were then placed on a rack and connected to a hanging-water column pressure system. Pressures applied corresponded to 0, 3.5, 10, 15, 20, 25, 30, 35, 50, 100, and 345 cm water (1 bar per 1035 cm water). After the final pressure of 15 bar (wilting point), the cell was opened, the brass ring was removed, and the soil was weighed. In order to conduct statistical analysis, two soil cores were used as replications.

Sorption Isotherms

All sorption isotherms followed procedures outlined by Li (1999). Nitrate-N, $\text{NH}_4\text{-N}$, and P sorption isotherms were conducted on HDTMA-coated and uncoated zeolite (Zeo Inc., McKinney, Tx) and two calcined clays [Soil Master Plus (Sport Turf Supply, Inc., Midland City, Al.), Profile (Profile LLC)], which will be referred to hereafter as calcined clay 1 and calcined clay 2, respectively. Nitrate isotherms were prepared by adding 0.5 grams of each amendment to 10 mL of solution containing 0, 10, 20, 100, 200, and 500 ppm $\text{NO}_3\text{-N}$ to achieve loading rates of 0.2, 0.4, 2.0, 4.0, and 10.0 g kg^{-1} . Ammonium isotherms were prepared by adding 0.25 grams of each amendment to 20 mL of solution containing 50, 100, 200, 500, and 1000 ppm $\text{NH}_4\text{-N}$ to achieve loading rates of 0, 4, 8, 16, 40, and 80 g kg^{-1} . Phosphorus isotherms were prepared by adding 1.0 g of each

amendment to 10 mL of solution containing 0, 10, 20, 100, 200, and 500 ppm P to achieve loading rates of 0.1, 0.2, 1.0, 2.0, and 5.0 g kg⁻¹. Samples for each isotherm were shaken on a mechanical shaker for 48 hours to achieve equilibrium. Samples were then centrifuged for 15 minutes at 4000 rpm to yield a clear supernatant. Nitrate and NH₄-N solutions were analyzed using an Alpkem RFA-300 auto analyzer (IRAMA Corporation, Milwaukie,OR), and P solutions were analyzed colorimetrically.

Surfactant Loading

Surfactant loading followed procedures outlined by Li and Bowman (1997). Previous analysis produced CEC values for each amendment, which were used to determine the ratio of solid to solution. Due to financial and equipment restraints, final solution concentration analysis of HDTMA was not possible, thus, the amount of amendment added to solution was divided by 2 to ensure bi-layer formation. The amounts of amendment used during surfactant loading were 71, 544, and 350g of zeolite, CC1, CC2, respectively. These amounts were determined to be the maximum amount of amendment, based upon each amendment's CEC, that could be added to HDTMA solution while assuring bi-layer formation. Amendments were placed in 2 L Erlenmeyer flasks, which were then filled to volume with 2 L of 0.066 M HDTMA solution. Each flask was stirred for 24 h by using a magnetic star bar and plate. Following equilibrium, the supernatant was removed, amendments were washed with 5 pore volumes of deionized water, and amendments were allowed to air-dry.

Thermal Analysis

Thermal gravimetry (TG) analysis cannot only be used to determine OM content, but it can also be use as an indicator of particle stability. Compounds that lose little weight when subjected to increasing heat are considered to be more thermally stable than

compounds that exhibit weight losses. It has been stated that the greatest strengths of inorganic amendments are their resistance to degradation and breakdown (Waltz and McCarty, 2000). Each amendment was subjected to TG on an Omnitherm Corporation instrument (Arlington Heights, IL) with a nitrogen gas purge. Temperatures ranged from 25-600 °C with a ramping rate of 20 °C min⁻¹ (Amonette, 2002).

HDTMA was subjected to thermal analysis to determine the temperature at which oxidation occurred (Fig. A-1). This temperature was then used when analyzing SMSA to determine the extent of surfactant coating. Surfactant coating was determined according to eq. 3.3.

$$S = (A / 0.85) \times 10,000 \text{ mg kg}^{-1} \quad \text{eq. 3.3.}$$

Where: S = amount HDTMA sorbed (mg kg⁻¹)
 A = weight loss due to oxidized HDTMA (%)
 B = amount of HDTMA that oxidizes (%)

From thermal analysis, effective anion exchange capacity (EAEC) was determined according to eq. 3.4.

$$\{ [(C \times S_{\text{HDTMA}}) / 2] / MW_{\text{N}} \} \times 100 = \text{cmol kg}^{-1} \quad \text{eq. 3.4.}$$

Where: C = MW_N / FW_{HDTMA - (MW_{Br})/2} (%)
 S_{HDTMA} = HDMTA sorbed (g kg⁻¹)
 FW_{HDTMA} = formula weight of HDTMA (g mole⁻¹)
 MW_N = molecular weight of nitrogen (g mole⁻¹)
 MW_{Br} = molecular weight of bromide (g mole⁻¹)

Assumptions made during determination of EAEC included: 1.) percent HDTMA oxidation from SMSA was equal to the percent oxidation of pure HDMTA, 2.) all

surfactant sorbed by amendments was in a bi-layer formation, and 3.) after bi-layer formation, all anion exchange sites in solution equaled $\frac{1}{2}$ the total exchange sites and were occupied by Br^{-1} .

X-Ray Diffraction

In order to determine mineral composition, each amendment was subjected to x-ray diffraction using a computer-controlled x-ray diffractometer equipped with a stepping motor and graphite crystal monochromator (Nicolet I2/L11 Polycrystalline X-Ray Diffraction System, Madison, WI). Amendments were crushed using a mortar and pestle then placed in a side-packed powder mount with an Al-glass holder. Samples were scanned from 2 to 40° 2 θ at 2° 2 θ per minute using $\text{CuK}\alpha$ radiation (Amonette, 2002).

Nutrient Analysis

All amendments and sand mixes were analyzed for P, K, Ca, Mg, Fe, Mn, Zn, and Cu. Analysis followed procedures outlined by Olsen and Sommers (1982). Five grams of each amendment (3 g of peat) were extracted using 20 mL of Mehlich-I solution (0.025 M HCl and 0.0125 M H_2SO_4), then shaken for five minutes on a mechanical shaker. Samples were then filtered with a Whatman no. 42 filter paper and collected in 25 mL scintillation vials. Samples were analyzed at the University of Florida analytical research laboratory using a model 61E Thermo Jarrell-Ash ICAP 9000 spectrophotometer (Franklin, MA).

Sand Mixes

Rooting media for each glasshouse study, the field study, and the leaching study were mixed by hand using 85% USGA sand and 15% amendment by volume with the exception of smectite, which was incorporated at 97.5% USGA sand and 2.5%

Table 3-1. Sand size analysis of amendments and sand mixes.

	Sand					
	Very coarse	Coarse	Medium	Fine	Very fine†	Silt + Clay
	1.0 - 2.0 mm	0.5 - 1.0 mm	0.25 - 0.50 mm	0.10 - 0.25 mm	0.05 - 0.10 mm	<0.05 mm
<u>Amendment</u>	-----% by weight-----					
Clinoptilolite 1	45.4	48.0	6.8	0.0	0.0	0.0
Clinoptilolite 2	31.3	67.9	0.9	0.0	0.0	0.2
Calcined Clay 1	0.3	46.6	52.9	0.7	0.0	0.0
Calcined Clay 2	0.0	50.9	49.0	0.2	0.1	0.1
Diatomaceous Earth 1	27.7	56.5	15.3	0.4	0.1	0.2
Diatomaceous Earth 2	27.0	64.6	5.1	1.2	1.0	1.2
Peat	44.7	15.3	16.4	14.3	7.8	1.7
Montmorillonite	10.2	16.5	16.8	18.2	32.5	4.8
Iron Humate	11.8	17.2	31.5	32.9	5.4	1.1
<u>Sand Mixture‡</u>						
Sand	7.2	41.2	35.7	15.9	0.9	0.0
Clinoptilolite 1	11.9	39.9	31.2	16.7	0.3	0.2
Clinoptilolite 2	10.1	42.6	30.3	16.2	0.5	0.1
Calcined Clay 1	7.1	40.1	35.3	16.7	0.3	0.0
Calcined Clay 2	6.0	37.8	35.0	20.2	0.8	0.1
Diatomaceous Earth 1	7.1	36.7	33.9	21.4	0.7	0.0
Diatomaceous Earth 2	7.6	38.3	33.1	19.8	0.6	0.4
Peat	4.0	22.9	54.5	17.6	0.4	0.2
Montmorillonite §	7.4	39.3	35.0	17.5	0.4	0.1
Iron Humate	8.8	37.0	33.1	19.3	1.1	0.3
USGA ¶						
Specifications	≤ 10%	≥ 60%		≤ 20%	≤ 5%	≤ 8%

† Based on USGA range of 0.25 - .015 mm.

‡ 85% USGA uncoated sand plus 15% amendment by volume

§ 2.5% by volume

¶ United States Golf Association

smectite. Particle size analysis was determined for each amendment and sand/amendment mixture according to procedures described by Day (1965) (Table 3-1). Sand used in each study was found to be slightly coated. According to the United States Department of Agriculture, sands are considered to be slightly coated if they contain < 5% sand plus silt, but contain clay coatings. Harris et al. (1996) concluded the presence or absence of clay coatings can be discrete and readily observable. Upon visual

inspection, coatings can be seen via their color, opacity, and rough surface texture. Sand grain coating can include Fe & Al hydroxides, kaolinite, gibbsite, or goethite.

Water Use Efficiency Calculations

Water-use-efficiency was determined for each glasshouse study and the field study according to eq. 3.5 as stated by Gregory et al. (2000). Dry matter yield for each week was compared to the amount of water lost during that week as determined by weighing each pot before and after each harvest.

$$\text{WUE} = \text{dry matter yield (mg)} / \text{evapotranspired water (g)} \quad \text{Eq. 3.5.}$$

Estimations of water use assumed the density of water was 1 g cm^{-3} for each treatment, and all water not evaporated was used by the turf.

Glasshouse Studies

Glasshouse studies were conducted from August to December 2002 and 2003 at the University of Florida Turfgrass Envirotron in Gainesville, FL. The objectives of each study were:

1. To determine the influence of soil amendments on WUE and quality of Tifdwarf bermudagrass
2. To determine the influence of incorporation method on WUE and quality of Tifdwarf bermudagrass

Year 1

The objective of this study was to determine the influence of soil amendments on WUE, turf quality, and dry matter yield of Tifdwarf bermudagrass. Tifdwarf bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt Davy] was established during spring 2002 in a glasshouse on pots (203 mm wide at top, tapering to 175 mm at bottom, and 203 mm deep) using USGA-specified greens sand. Treatments

consisted of an amendment/sand mixture and incorporation method and were arranged in a split plot design with 4 replications. Amendments included two zeolites [Ecosand (Zeo Inc., McKinney, Tx.) (clinoptilolite 1); Ecolite (Ecolite Mfg Co., Spokane, WA) (clinoptilolite 2)] which were determined to be clinoptilolite via X-ray diffraction, two calcined clays [Soil Master Plus (Sport Turf Supply, Inc., Midland City, AL) (calcined clay 1); Profile (Profile LLC) (calcined clay 2)], one calcined diatomaceous earth [Axis (Agro Tech 2000, Norristown, PA) (diatomaceous earth 1)], one diatomaceous earth [PSA (Golf Ventures, Lakeland, FL) (diatomaceous earth 2)], Canadian sphagnum peat, Fe-humate (Vigiron, Winter Haven, FL), clay (montmorillonite), and sand.

Prior to establishment, each pot was saturated and allowed to drain for 24 h. Pot weight after drainage was recorded and labeled as 'pot capacity'. An overhead mist-irrigation system was used during establishment. Percent cover ratings were taken after week one and were subsequently taken at one week intervals until full coverage was achieved. Percent coverage was considered to be that portion of the pot surface that was covered by turf. Following establishment, irrigation ceased and all further applications of water were done by hand. The primary study lasted 18 weeks and began once all pots achieved 100 percent coverage and were uniform. However, data was only collected from week 3 to week 15 due to inaccuracies during the first three weeks and decreased growth during the last 3 weeks when decreasing daylight reduced turf growth.

Following establishment, all pots were uniformly fertilized with NH_4NO_3 , concentrated super phosphate (CSP), and muriate of potash (KCl) at 5 g N m^{-2} , 2.5 g P m^{-2} , and 2.5 g K m^{-2} at week one and six. Micronutrients and sulfur (as sulfate) were

applied together using a commercially available micronutrient solution at a rate of 11.2 kg Fe ha⁻¹.

One primary function of soil amendments is nutrient retention which, in turn, may increase turf quality. A turf quality rating is a subjective measurement of overall turf health and appearance, which is crucial when assessing turf aesthetic value and playability. During the 12 week study, visual quality ratings were recorded on a weekly basis on a scale of 1 to 9, where 9 = ideal, 5.5 acceptable, and 1 = completely dead or dormant.

Twice weekly, pots were weighed and water was applied to bring each pot back to 90% pot capacity. The amount of water was recorded and labeled 'applied water'. Weekly, clippings were harvested by hand at 3 cm height, dried at 100 °C for 24 h, and weekly harvested weight was recorded and labeled as 'dry matter yield'.

Upon completion of the 12 week study, overhead irrigation was used to bring all pots back to uniformity. Water applied was then stopped and pots were allowed to dry to determine number of days to wilt.

The null hypothesis for the 2002 glasshouse study was soil amendments do not influence turf quality, dry matter yield, or WUE.

Year 2

All materials and methods for the 2003 glasshouse study were identical to the 2002 glasshouse study with two exceptions. First, a bacteriacide used to clean glasshouse cooling pads was unintentionally applied to one replication of the full incorporation method, thus this replication was removed, reducing the total number of pots from 120 to 110. Secondly, three incorporation methods were used (Fig. 3-1). Incorporation method one involved mixing each amendment with sand (85:15 v:v) prior to turf establishment.

Incorporation method two involved incorporating each treatment into an 85:15 sand/peat rootzone after turf establishment. This was accomplished by removing 9 or 4 aerification cores (20 mm wide \times 100 mm deep on 50 mm centers) and back-filling each core with a 50:50 sand/amendment mixture. All procedures and sample analysis followed procedures and sample analysis from the 2002 study.

The null hypotheses used during the 2003 glasshouse study were: 1. Soil amendments do not influence turf quality, dry matter yield, or WUE, and 2. Incorporation method does not influence turf quality, dry matter yield, or WUE.

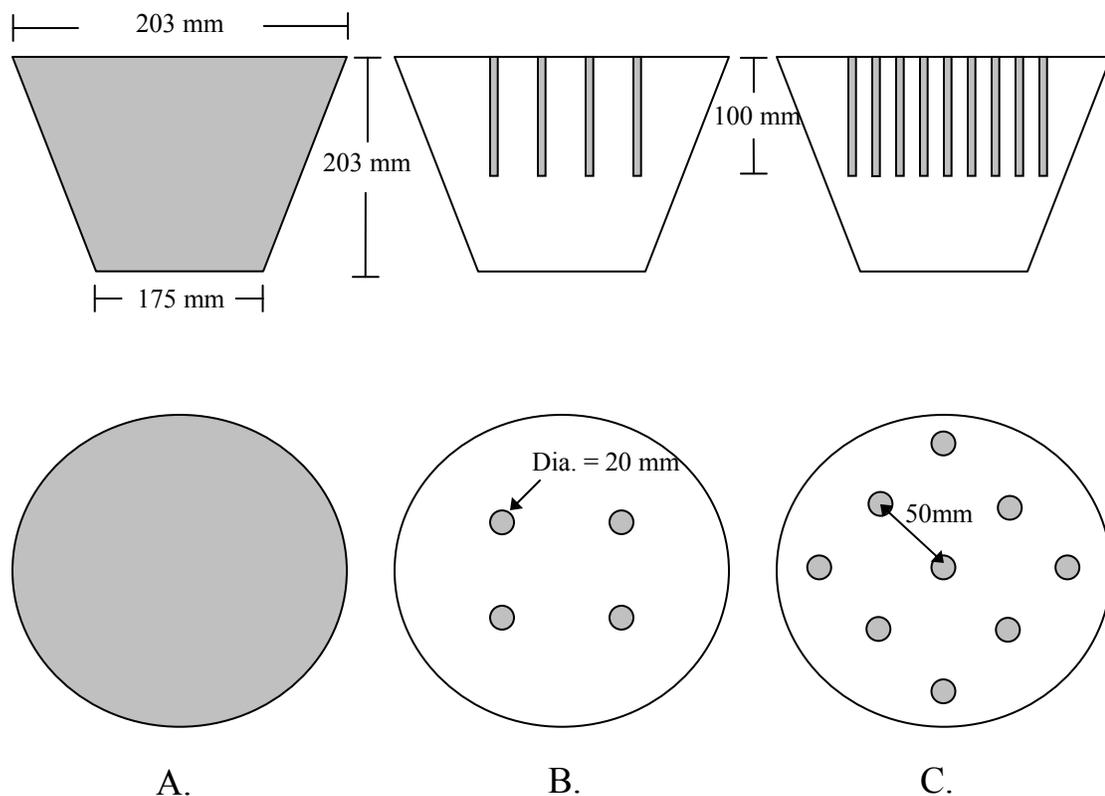


Figure 3-1. Schematic diagram of pot set-up used in glasshouse studies showing side and top view of amendment incorporation methods where A = 85:15 sand/amendment, B = 4 tine aerification with 50:50 sand/amendment, and C = 9 tine aerification with 50:50 sand amendment.

Nutrient Leaching Study

The objective of this study was to determine the influence of soil amendments and SMSA on NO_3^- -N, NH_4^+ -N, PO_4^{2-} leaching in a golf course putting green. Twenty-four lysimeters (2.54 cm diam. by 35 cm length) were constructed using polyvinyl chloride (PVC). The top 30 cm of each lysimeter contained a USGA sand:peat mixture (85:15 by volume) packed to a density of 1.33 g cm^{-3} . During a preliminary study, turf grown in a mixture of SMSAs and sand did not establish which may be a result of the biocidal influences of cationic surfactants (Gilbert and Al-taae, 1985). Therefore, treatments were placed below the rootzone in the bottom 5 cm (Fig. 3-2) and included one zeolite [Ecosand (Zeo Inc., McKinney, TX) which was determined to be clinoptilolite via X-ray diffraction, two calcined clays [Profile (Profile LLC), Soil Master Plus (Sport Turf Supply, Inc., Midland City, AL)] and two controls (control 1 = top 30 cm sand/peat, bottom 5 cm sand; control 2 = top 30 cm sand, bottom 5 cm sand). Each amendment was either coated with HDTMA or remained uncoated. Surfactant coating consisted of mixing a given amount of solid phase (according to each amendments CEC) with a solution of 67 mmol HDTMA. Previous research has determined bi-layer formation occurs when HDTMA equilibrium concentration after addition of a solid phase is at least twice the CEC of the solid phase (Li and Bowman, 1997). Sorbed HDTMA was determined via thermal gravimetry (Table 4-1). Lysimeters were then capped at each end with TyparTM landscape fabric (Reemay, Inc. Old Hickory, TN) and sealed with a domed, PVC cap. A 1-cm threaded hole was installed in the middle of each cap to allow a nutrient solution tube to be added to the top and a leachate collection tube to be added to the bottom of each lysimeter. Each lysimeter was vertically secured to a stand. The

nutrient solution tube attached to the top of each lysimeter was connected to a Gilson Model 302 steady-flow pump (Gilson Medical Electronics, Inc., Middleton, WI). The pump was set to deliver 10.0 ml of deionized water per minute. A valve was installed between the pump and lysimeter to which a 10 cm³ syringe was attached to inject nutrient solution. Nutrient solution contained 2300 ppm NO₃⁻-N, 2480 ppm NH₄⁺-N, and 4400 ppm PO₄²⁻. Leaching procedure consisted of first saturating the soil column with deionized water, injecting 10 mL of nutrient solution, and collecting leachate using a model 273 fraction collector (Instrumentation Specialties

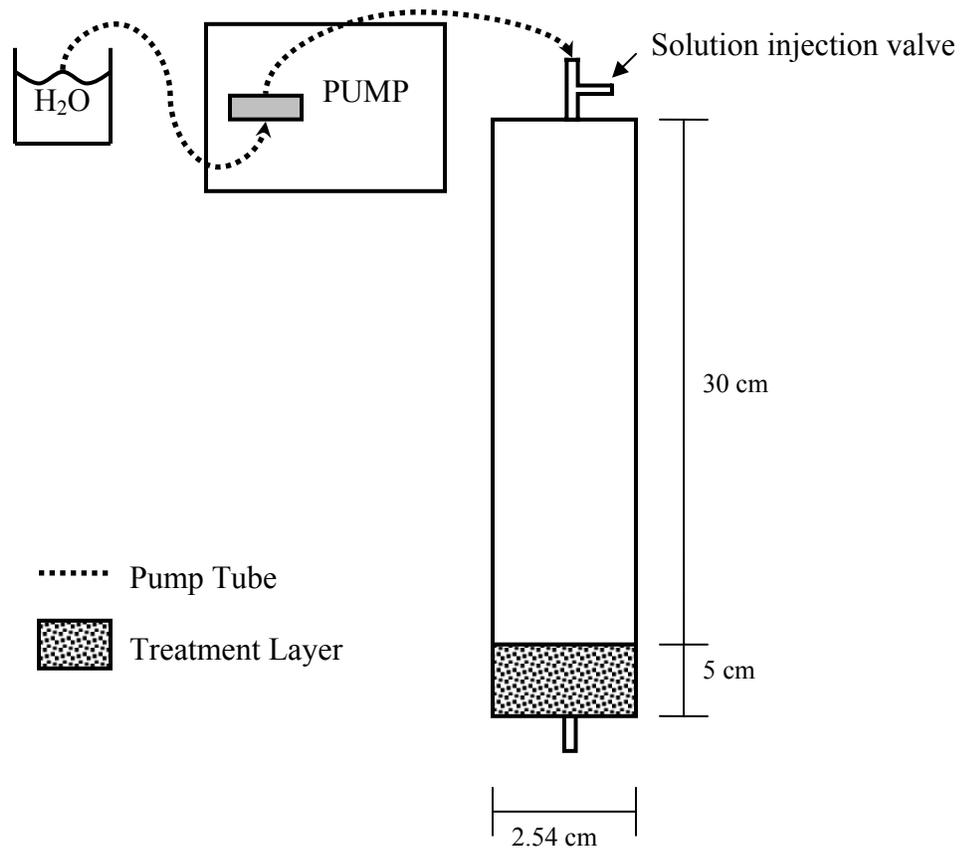


Figure 3-2. Schematic diagram of lysimeter set-up used in leaching studies.

Co.) set to take a sample every 60 seconds until four pore volumes had been collected. Each column was leached individually within each block. All samples were analyzed for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ using an Alpkem RFA-300 auto analyzer. Phosphorous was determined colorimetrically using a model 680 microplate reader (Bio-Rad Laboratories, Hercules, CA). Treatments were arranged in randomized complete block design with three replications, and statistical analyses were performed using SAS for analysis of variance (SAS Institute, 1987).

The following transport models were used to simulate movement of $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$ and P through soil amendments. The convective-dispersive model (CD model) can be written in dimensionless form (Brenner, 1958).

A. The Convective -Dispersive (CD) Model:

$$R \left(\frac{\partial C^*}{\partial t} \right) = (1/P) \left(\frac{\partial^2 C^*}{\partial X^2} \right) - \left(\frac{\partial C^*}{\partial X} \right) \quad 3.6a$$

$$P = vL/D \quad R = (1 + \rho K_D / \theta) \quad 3.6b$$

$$X = x/L \quad p = vt/L \quad C^* = C/C_0 \quad 3.6c$$

$$T = \text{Pulse applied in pore volumes} \quad 3.6d$$

where C^* is the solute concentration in the effluent (C , $\mu\text{g/ml}$) normalized to the initial solute concentration (C_0 , $\mu\text{g/ml}$), x is the distance along the column (cm), t is the time of flow (h), v (cm/h) is the pore water velocity, L (cm) is column length, D (cm^2/h) is the hydrodynamic dispersion coefficient, P is the Peclet number, R is the retardation factor, and p is the pore volume, K_D (ml/g) is the sorption coefficient, ρ is the soil bulk density, and θ is the volumetric water content.

B. The Two Site Nonequilibrium (TSN) Model:

The TSN model can also be described according to (Nkedi-Kizza et al., 1989). With first order kinetics, the sorption occurs in two domains, such that:

$$C : S_1WS_2$$

$$S_1 = FK_D C \quad 3.7a$$

$$dS_2/dt = k_1S_1 - k_2S_2 \quad 3.7b$$

where $S_1(\mu\text{g/g})$ is the adsorbed concentration in the instantaneous domain, $S_2(\mu\text{g/g})$ is the adsorbed concentration in the time dependent sorption domain, F is fraction of sorbent that is at equilibrium, k_1 and k_2 are the forward and backward first order sorption rate coefficients (1/h), respectively, other parameters have been defined for the CD-model.

For an adsorbing solute the one dimensional equation at steady state water flow can be written in dimensionless form:

$$MC^*/M\phi + (\beta R - 1) MC^*/M\phi + (1 - \beta)R MS^*/M\phi = (1/P) (MC^*/MX^2) - (MC^*/MX) \quad 3.8a$$

$$(1 - \beta)R MS^*/M\phi = \omega (C^* - S^*) \quad 3.8b$$

where:

$$S^* = S_2 / (1 - F) K_D C_0 \quad 3.8c$$

$$\beta = [1 + F (\rho K_D / \theta)] / R \quad 3.8d$$

$$\omega = k_2 (1 - \beta) R L / v \quad 3.8e$$

Other parameters (p , P , R , C^* and X) in eq. 3.8a have been defined for the CD-model.

The Peclet number (P) reflects the ratio of the residence time due to dispersion and the residence time due to convection emphasizing the effect of dispersion on solute transport, the retardation factor (R) is the ratio of pore water velocity and solute velocity which represents the effect of sorption on solute transport, β is the fraction of total retardation due to sorption in the instantaneous domain, ω is a number that gives the degree of

sorption nonequilibrium for the solute, it reflects the ratio of the time for solute sorption to the residence time for the solute due to convection.

Parameters for the CD-model (R and P) and for the TSN-model (R, β , and ω) were calculated from the measured breakthrough curves (BTCs) using the non-linear least-squares optimization technique in the curve fitting program CFITIM (Van Genuchten, 1981). The parameter (T) was measured and as such was not optimized for either model. The parameter P was calculated by fitting the CD-model to the BTCs of $\text{NO}_3\text{-N}$ for a given amendment. The obtained value of P from the CD-model was then used in the TSN-model as a fixed parameter.

The null hypotheses used during the nutrient leaching study were: 1) Soil amendments do not decrease NO_3^- , NH_4^+ , or PO_4^{2-} leaching, and 2) SMSA do not decrease NO_3^- , NH_4^+ , or PO_4^{2-} leaching.

CHAPTER 4 RESULTS AND DISCUSSION

Amendment Characterizations

Surfactant Sorption

Via thermal analysis, greater weight loss was observed from HDTMA calcined clay 1 than from HDTMA calcined clay 2 (Fig. A-2, A-3). HDTMA clinoptilolite showed the least weight loss and thus sorbed the least HDTMA (Fig A-4). For each amendment, increased weight loss due to oxidation of HDTMA began at approximately 230 °C, which corresponded well with oxidation of pure HDTMA which began at 250 °C. Oxidation of HDTMA from coated amendments was nearly complete at 300 °C, which also compares favorably with oxidation of pure HDTMA. Impurities inherent within SMSA likely caused the minor differences between oxidation of pure and sorbed HDTMA. These findings indicate the extent of HDTMA coating can be well described by thermal gravimetry analysis.

Surfactant sorption capacity of each amendment can be seen in table 4-1. Although clinoptilolite had a CEC 4 times higher than either of the calcined clays, it retained the least amount of HDTMA. Several studies have shown the majority of CEC on clinoptilolite is internal and inaccessible to HDTMA (Li et al., 1999; Li, 1999; Li and Bowman, 1997). Following surfactant sorption, calcined clays retained approximately one-half of their original CEC. Of the SMSA, calcined clay 1 retained the greatest amount of HDTMA followed by Calcined clay 2 and Clinoptilolite 1 (Table 4-1).

Table 4-1. Ion exchange capacity and surfactant sorption as influenced by soil amendment.

Solid Phase	HDTMA Sorbed -- (g kg ⁻¹) --	CEC† ---- cmol (+) kg ⁻¹ ---	ECEC‡ ---	EAEC§ cmol (-) kg ⁻¹
Clinoptilolite	27.1	97.4	93.3	4.1
Calcined Clay 1	73.4	20.9	9.6	11.3
Calcined Clay 2	62.9	21.8	12.1	9.7

† Cation exchange capacity

‡ Effective cation exchange capacity

§ Effective anion exchange capacity

Mineral Composition

Neither DE contained any discernable minerals (Fig. A-5). While definitive analysis of DE mineral composition via XRD is ambiguous, the broad peaks observed from both DEs around a d-spacing of 4.0691 are indicative of amorphous silica. Silica contents of DE have been reported to about 86 to 88% (Sylvia et al., 1997).

X-ray diffraction analysis of calcined clays can be seen in fig. A-6. Both clays contain quartz, goethite, and small amounts of mica. The only significant difference between calcined clays is the quartz peak (d= 3.35), which is likely evidence that calcined clay 1 contains more quartz than calcined clay 2.

Zeolites used in this study were concluded to be clinoptilolite based upon XRD analysis (Fig. A-7). No other minerals were apparent in either zeolite sample.

Nutrient Composition

Because soil nutrient status has been shown to positively influence WUE (Viets, 1962; Hatfield et al., 2001), the initial elemental content of each amendment and sand/amendment mixture was determined via Mehlich I and KCl extraction.

Sand/amendment mixture samples were taken from before turf sprigs were applied.

Nitrogen

Only peat and iron humate contained detectable levels of N (Table 4-2). Nitrogen content of iron humate was lower than that observed by previous researchers. Varshovi and Sartain (1993) determined the N content of a commercially available humate to be 0.85%. Lower N content determined in this study could be due to different humate sources.

While peat contained more TKN prior to incorporation with sand, both peat and iron humate produced equal amounts after incorporation (Table 4-3). Incorporation of sand likely diluted any treatment influence, thus, no differences were observed.

Phosphorus

Extractable P did not follow any clear trends across soil amendment class. However, in general, highest P levels were found in smectite while the lowest levels were observed in iron humate (Table 4-2). Iron-based water treatment residuals have been shown to be effective long-term P immobilizers. Furthermore, much of the P sorbed by water treatment residuals is internal and considered to be irreversibly bound (Makris et al., 2004). As expected, the control (USGA sand) was found to contain low levels of P. While quartz sand is largely considered to be inert, sand grain coatings have been shown to increase P retention (Harris et al., 1996) and may be responsible for the observed P levels. After incorporation with sand, P levels were diluted for all amendments except iron humate (Table 4-3). Because samples were taken from field plots which were encouraged to settle by using daily irrigation for 10 days, P from irrigation water (Table A-1) may have been responsible for the increased P in the iron humate treatment. Smectite contained the highest level of extractable P before and after sand incorporation. Diatomaceous earths were the only amendments that did not increase extractable P levels above the sand/peat mixture.

Table 4-2. Chemical properties of amendments used in glasshouse and field studies.

Amendment	CEC cmol (+) kg ⁻¹	pH†	EC† µS cm ⁻¹	TKN %	P‡	K‡	Ca‡	Mg‡	Zn‡	Mn‡	Cu‡	Fe‡
					----- mg kg ⁻¹ -----							
Sand (1)	0.7	5.9	8.3	0.00	3.2	2.6	23.9	2.5	2.5	0.2	0.1	3.4
Peat (2)	114.5	7.3	76.9	0.55	3.9	53.4	2769.3	840.3	3.5	13.9	0.1	21.1
Calcined clay 1 (3)	21.7	5.4	201.3	0.00	33.2	993.7	766.5	528.3	4.9	14.7	0.2	124.0
Calcined clay 2 (3)	21.5	5.6	48.0	0.00	58.2	1129.9	747.5	339.2	3.9	3.4	0.1	102.6
Clinoptilolite 1 (4)	97.8	5.5	8145.0	0.00	15.1	764.8	2386.7	117.7	2.2	6.2	0.1	9.1
Clinoptilolite 2 (4)	35.1	6.3	72.2	0.00	107.1	591.5	1844.5	287.1	3.0	5.0	0.2	6.7
Diatomaceous earth 1 (5)	7.8	7.9	979.3	0.00	24.2	112.1	166.0	78.1	2.3	2.3	1.3	233.9
Diatomaceous earth 2 (5)	34.1	4.6	181.1	0.00	48.6	671.5	1257.7	279.6	3.1	7.7	0.8	32.5
Smectite (6)	20.4	6.0	2154.0	0.00	652.7	95.9	5165.3	1129.2	1.0	1.3	0.0	0.1
Iron Humate (7)	41.2	4.8	300.3	0.42	1.5	2686.7	6873.3	345.1	5.8	65.4	2.3	30.0
Contrast: 1 vs. 2	***	***	NS	***	NS	NS	***	***	NS	***	NS	***
Contrast: 2 vs. others	***	***	***	***	***	***	***	***	NS	**	***	***
Contrast: 2 vs. 3	***	***	NS	***	NS	***	***	***	NS	***	**	***
Contrast: 2 vs. 4	***	***	***	***	NS	***	***	***	NS	***	*	***
Contrast: 2 vs. 5	***	***	***	***	NS	***	***	***	NS	***	***	***
Contrast: 2 vs. 6	***	***	***	***	***	NS	***	***	NS	***	NS	***
Contrast: 2 vs. 7	***	***	***	***	NS	***	***	***	*	***	***	***
Contrast: 3 vs. 5	NS	***	***	NS	NS	***	NS	***	*	***	***	***
Contrast: 3 vs. 7	***	***	***	***	NS	***	***	**	NS	***	***	***
CV (%)	15.5	1.9	3.4	5.6	43.1	4.4	9.1	14.9	31.3	13.1	9.2	3.0

NS, *, **, *** Not significant, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† 2:1 deionized water:soil

‡ Mehlich-1 extractable

Table 4-3. Chemical properties of 85:15 sand/amendment mixtures used in glasshouse and field studies.

Amendment	CEC cmol (+) kg ⁻¹	pH†	EC† µS cm ⁻¹	TKN %	P‡	K‡	Ca‡	Mg‡	Zn‡	Mn‡	Cu‡	Fe‡
					----- mg kg ⁻¹ -----							
Sand (1)	0.7	5.9	8.3	0.00	3.2	2.6	23.9	2.5	2.5	0.2	0.1	3.4
Peat (2)	1.8	7.1	23.7	0.03	3.5	2.3	276.9	107.6	1.3	0.5	0.0	7.4
Calcined clay 1 (3)	2.7	6.7	22.1	0.00	10.1	85.2	191.5	54.2	1.3	0.4	0.1	33.9
Calcined clay 2 (3)	2.8	6.7	26.6	0.00	6.6	66.8	149.7	47.9	1.5	1.4	0.1	30.5
Clinoptilolite 1 (4)	25.7	6.4	84.7	0.00	5.7	338.1	358.0	19.7	1.6	1.0	0.1	6.3
Clinoptilolite 2 (4)	16.0	6.9	13.5	0.00	15.7	115.9	228.8	36.2	5.7	1.4	0.1	4.5
Diatomaceous earth 1 (5)	5.3	8.6	36.2	0.00	8.3	45.8	198.8	36.6	1.5	0.9	0.2	10.4
Diatomaceous earth 2 (5)	1.2	7.1	27.1	0.00	3.9	5.9	46.1	7.9	3.0	0.3	0.1	22.5
Smectite (6)	1.3	6.3	14.2	0.00	126.8	8.8	677.3	155.1	1.6	0.5	0.1	12.4
Iron Humate (7)	6.4	6.2	8.9	0.03	28.3	63.6	920.4	19.5	2.5	11.3	3.0	799.5
Contrast: 1 vs. 2	NS	***	***	***	NS	NS	***	***	NS	NS	NS	NS
Contrast: 2 vs. others	***	***	***	***	***	***	NS	***	NS	***	***	***
Contrast: 2 vs. 3	NS	***	NS	***	*	***	**	***	NS	NS	NS	***
Contrast: 2 vs. 4	***	***	***	***	**	***	NS	***	NS	**	NS	NS
Contrast: 2 vs. 5	NS	***	***	***	NS	***	***	***	NS	NS	*	*
Contrast: 2 vs. 6	NS	***	***	***	***	NS	***	***	NS	NS	NS	NS
Contrast: 2 vs. 7	*	***	***	NS	***	***	***	***	NS	***	***	***
Contrast: 3 vs. 5	NS	***	***	NS	NS	***	NS	***	NS	NS	*	***
Contrast: 3 vs. 7	*	***	***	***	***	**	***	***	NS	***	***	***
CV (%)	31.7	1.9	4.7	38.4	15.2	7.1	13.5	12.8	110.2	15.6	14.9	6.2

NS, *, **, *** Not significant, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† 2:1 deionized water:soil

‡ Mehlich-1 extractable

Potassium

Unlike P, clear trends were observed between amendment classes for Mehlich-1 extractable K of the pure amendment samples (Table 4-2). Calcined clays contained higher levels of extractable K than zeolites which were followed by DEs. Sand contained the lowest K levels while iron humate contained the highest. All amendments except sand and smectite contained higher K levels than peat.

All K levels dropped after incorporation with sand (Table 4-3). Zeolites contained the highest levels of K followed by CCs and DEs. Sand and sand/peat treatments contained the lowest amount of extractable K. All amendments except smectite increased extractable K above the sand/peat treatment.

Calcium

Of the pure amendment samples, highest Ca levels were found in iron humate followed by smectite (Table 4-2). Of the remaining amendments, sand/peat contained higher Ca levels than zeolites followed by CCs, DEs, and sand. Following sand incorporation, Ca levels dropped for all amendments. Both iron humate and smectite continued to exhibit the highest Ca levels after sand incorporation (Table 4-3). The primary difference between Ca levels of amendments alone and amendment/sand mixtures is that zeolites possessed lower Ca levels than peat before sand incorporation while they contained similar Ca levels after incorporation. These results compare favorably with those reported by Ok et al. (2003) where zeolite amended sand was found to have the same Ca levels as sand/peat mixtures both before and after turf establishment. With regards to initial retention of P, K, and Ca, these results show that amendment classes may be used when considering the potential influence of plant available K and Ca. However, incorporation of CCs or zeolites may decrease plant available Ca.

Phosphorus availability may increase with incorporation of CCs or zeolites, but it appears that individual amendments should be recommended instead of amendment classes.

pH and EC

Salinity levels dropped after incorporation with sand (Table 4-3). Because sand/amendment samples were taken from plots that were allowed to settle by irrigation, the excess salts which were initially observed in the pure amendment samples were likely leached out of the soil media.

Soil acidity also became more basic after sand incorporation. Acidity levels of 5.5 of pure amendments rose to near 6.5 after sand incorporation. This may also be due to excess leaching with water high in Ca (Table A-1).

Moisture Retention

Analysis of moisture retention data revealed incorporation of amendments provided a variety of beneficial physical characteristics to a sand-based rootzone. Moisture content at field capacity, moisture content at wilting point, and plant available water increased with the addition of soil amendments (Table 4-4). These parameters were influenced primarily by the increase in total and micro porosity which accompanied amendment incorporation.

Saturated hydraulic conductivity was found to be within acceptable ranges as recommended by the USGA (Table 4-4). Diatomaceous earth 1 and 2 and clinoptilolite 2 reduced K_{sat} while all other amendments were similar to pure sand. Water flow in a saturated soil is primarily through macropores (Hillel, 1998). However, this researcher observed soils that produced the highest K_{sat} values also possessed the lowest macroporosities. While this seems counterintuitive, McIntyre 1974 states that soils prepared for K_{sat} analysis must be taken from undisturbed core samples. Core samples in

this analysis were taken from recently renovated soils and, thus, physical analysis may not entirely agree with analysis of undisturbed soils.

Soil porosities varied from 32.2 to 38.9% (Table 4-4). Only clinoptilolite 1 failed to increase total porosity above that of sand. This is likely due to clinoptilolite 1 having the highest percentage of very coarse sand-sized particles (Table 3-1), and may explain why clinoptilolite 1 was the only amendment that had a lower volumetric water content at saturation than sand alone (Fig. 4-1). Both CCs increased macroporosity above sand while all other amendments decreased macroporosity. The greatest influence of soil amendments on porosity was observed in microporosity. All amendments increased microporosity above sand alone. Diatomaceous earth 1 and iron humate were shown to have the greatest influence, increasing microporosity from 7.7 to 15.6%. This is likely due to iron humate having the largest percentage by weight of medium and fine sand size particles than any other amendment (Table 3-1). Diatomaceous earths contain a large number of internal channels which may contribute to the influence of diatomaceous earth 1 on microporosity.

Of the water held in macro and micropores, only water held in micropores is considered to be available for plant uptake. Thus, correlation between microporosity and plant available water should be high. The relation between microporosity and PAW was found to be well correlated ($R^2 = 0.83$; Fig. A-8).

As expected, amendment incorporation increased moisture held at field capacity and wilting point. Correspondingly, plant available water also increased with amendment incorporation. The greatest increase in moisture held at wilting point was observed from diatomaceous earth 1 where percent moisture increased by more than 8 times that of

Table 4-4. Physical analysis of amendment/sand mixture at 85:15 by volume.

Amendment	K _{sat} †† cm hr ⁻¹	----- Pore Space -----			PD #	BD †† g cm ⁻³	FC ‡‡ %	PWP §§ %	PAW ¶¶
		Total	Micro § %	Macro ¶					
Sand	61.0 ab	33.3 b	7.7 e	25.6 abc	2.34 a	1.56 a	7.7 e	0.4 f	7.3 f
Peat	66.2 ab	35.3 ab	13.5 b	21.8 cd	2.13 bc	1.37 f	13.5 b	1.2 e	12.3 b
Calcined clay 1	52.4 ab	38.9 a	12.5 bc	26.4 ab	2.29 ab	1.39 ef	12.5 bc	2.4 b	10.0 de
Calcined clay 2	55.6 ab	38.2 a	11.2 cd	26.9 a	2.36 a	1.46 bcd	11.2 cd	3.4 a	7.8 f
Diatomaceous earth 1	25.5 c	38.3 a	15.6 a	22.6 bcd	2.27 abc	1.40 def	15.6 a	3.5 a	12.1 b
Diatomaceous earth 2	44.5 bc	35.9 ab	13.7 b	22.1 cd	2.11 c	1.35 f	13.7 b	2.1 bc	11.6 bc
Clinoptilolite 1	63.1 ab	32.2 b	11.4 cd	20.7 d	2.14 bc	1.45 cde	11.4 cd	1.9 bcd	9.4 e
Clinoptilolite 2	43.4 bc	35.0 ab	10.9 d	24.1 abcd	2.24 abc	1.45 cde	10.9 d	1.5 cde	9.3 e
Smectite	71.3 a	36.2 ab	13.1 b	23.1 abcd	2.39 a	1.52 ab	13.1 b	2.4 b	10.6 cd
Fe-Humate	51.7 ab	36.7 ab	15.5 a	21.1 d	2.32 a	1.47 bc	15.5 a	1.4 de	14.1 a
CV (%)	17.2	5.1	4.3	7.1	3.0	1.8	4.3	12.8	4.4

Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

† saturated hydraulic conductivity

‡ USGA recommendations are 15-30 (normal) and 30-60 (accelerated) cm hr⁻¹

§ micropores (pores that contain water at 35 cm tension)

¶ macropores (pores that contain air at 35 cm tension)

particle density

†† bulk density

‡‡ field capacity, by volume

§§ plant wilting point, by volume

¶¶ plant available water, by volume

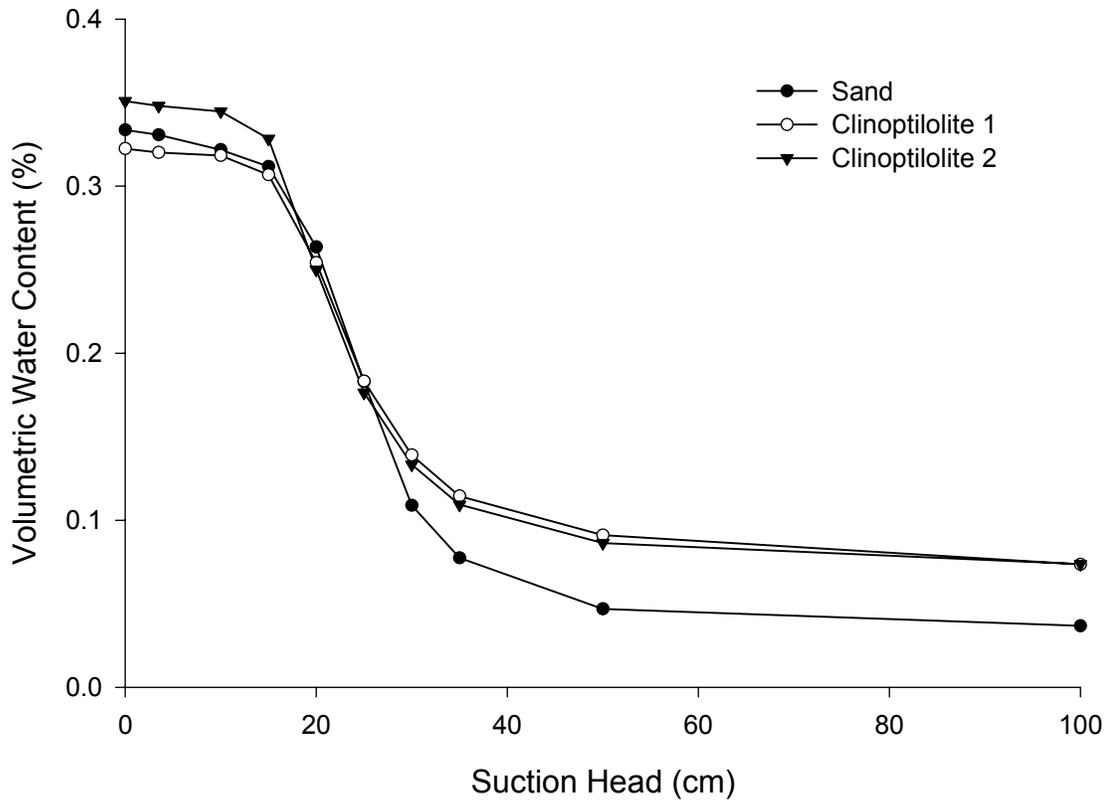


Figure 4-1. Moisture release curve for USGA sand amended with zeolites at 85:15 by volume.

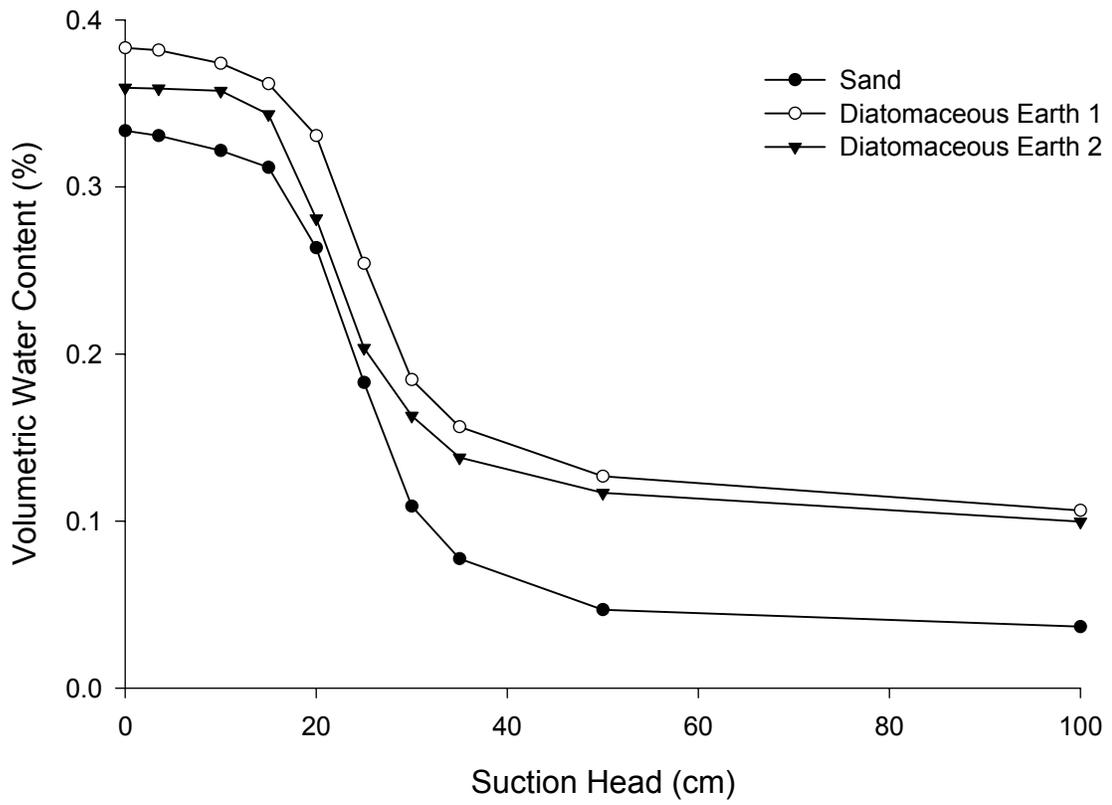


Figure 4-2. Moisture release curve for USGA sand amended with diatomaceous earths at 85:15 by volume.

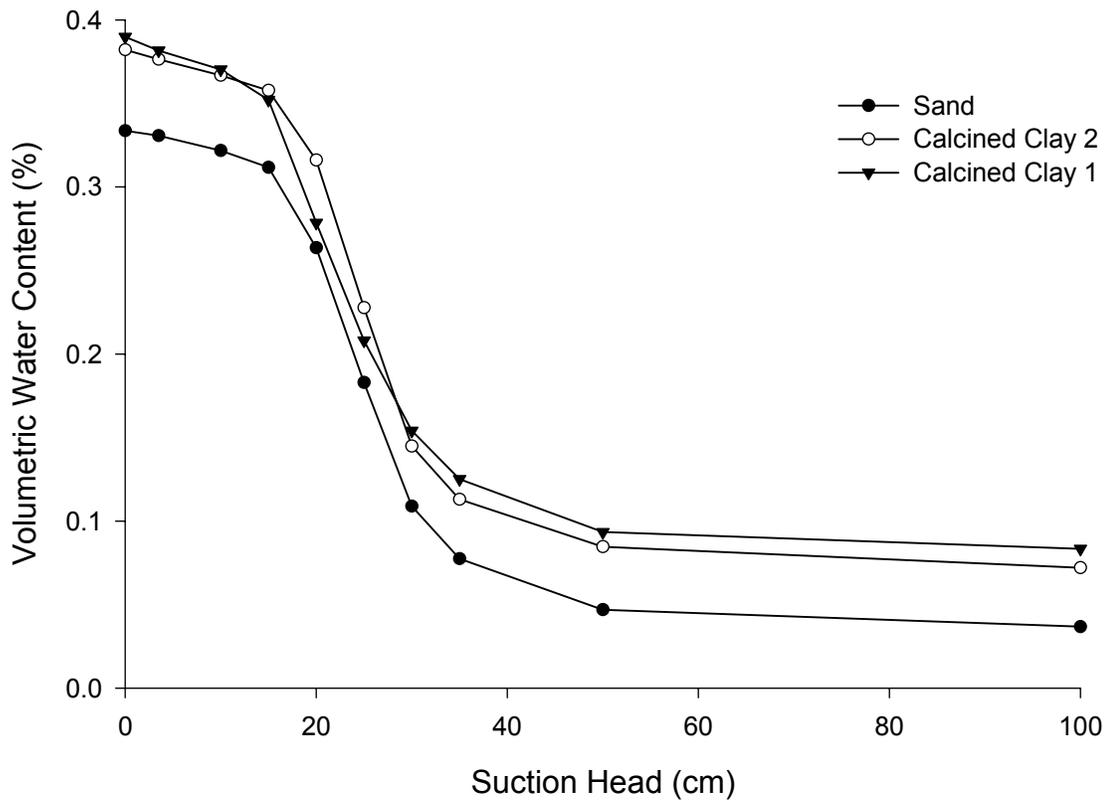


Figure 4-3. Moisture release curve for USGA sand amended with calcined clays at 85:15 by volume.

sand. Interestingly, peat and iron humate contained two of the lowest moisture contents at wilting point but had the two highest PAW contents. This indicates that in order to have the greatest influence on PAW, amendment must not only increase water held at FC, but must also decrease water held at WP.

Moisture release curves indicated incorporation of soil amendments with sand increased moisture content and moisture retention. Diatomaceous earths (Fig. 4-2), as a class, produced greater moisture retention than calcined clays (Fig. 4-3) or zeolites. Zeolites were observed to have the least influence on moisture held at saturation and moisture held against 50 cm of head (Fig. 4-1), which is likely due to zeolites also having the least influence on total pore space (Table 4-4). This relation between available water and porosity was also noted by Brown and Doble (1975). Waltz et al. (2003) observed amendments with the lowest soil porosity were also observed to retain the least amount of water against gravity. Waltz et al. further noted sand amended with peat produced more suitable physical and hydraulic properties for turfgrass growth than either calcined clay or diatomaceous earth. However, of the two inorganic amendments Waltz investigated, diatomaceous earths were found to be the most suitable replacement for peat. These observations by Waltz both agree and contradict those found during this research. When only physical and hydraulic properties are considered, diatomaceous earths increased moisture held against gravity above that of peat while providing similar or adequate PAW and conductivity. Thus, diatomaceous earths are not only the most suitable inorganics replacement for peat, but they are actually more suitable than peat.

Of the amendments used, Fe-humate produced the greatest beneficial influence on the putting green rootzone physical properties. The observed increase in moisture held

against gravity (Fig. 4-4) was matched only by diatomaceous earth 1. Correspondingly, Fe-humate amended sand produced the highest amount of plant available water while maintaining adequate hydraulic conductivity and bulk density (Table 4-4).

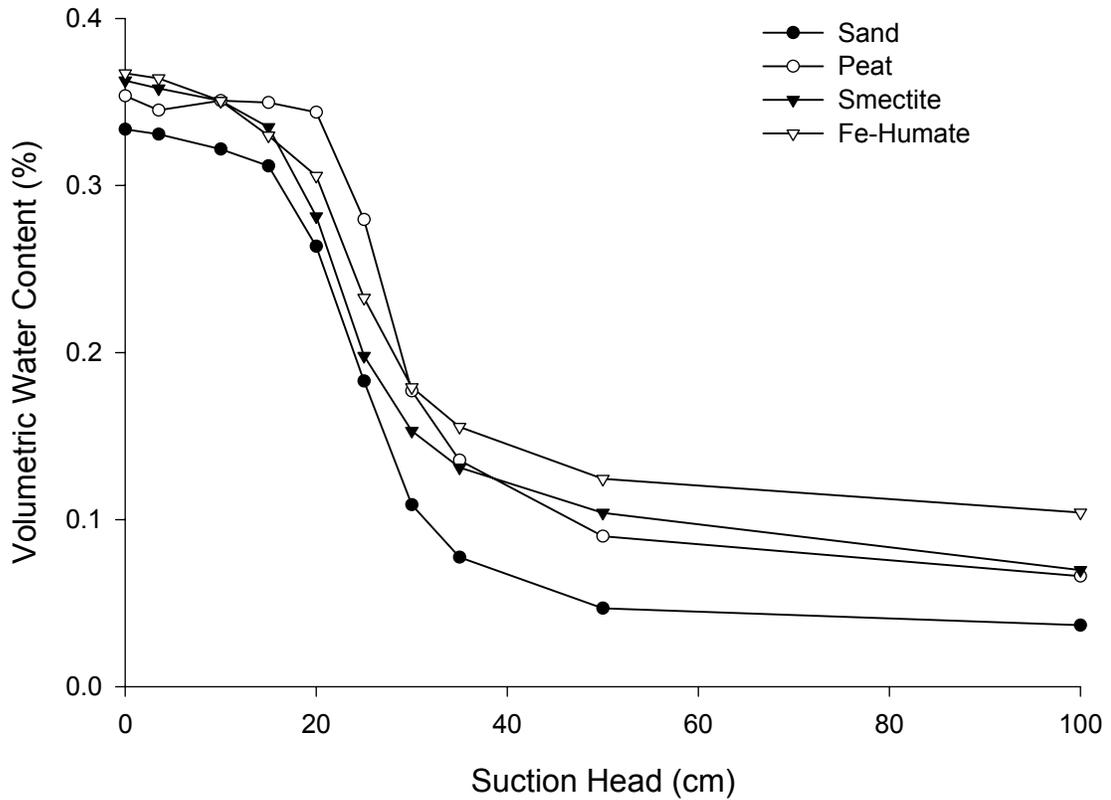


Figure 4-4. Moisture release curve for USGA sand amended with peat or Fe-Humate at 85:15 by volume or with smectite at 97.5:2.5 by volume.

Glasshouse 2002

Establishment

Analysis of turfgrass establishment revealed amendment influence was dependent upon amendment source (Fig. 4-5). Pots containing clinoptilolite 1, diatomaceous earth 2, calcined clay 1, or calcined clay 2 did not change the establishment rating compared to pots containing sand alone. Clinoptilolite 2, diatomaceous earth 1, and Fe-humate decreased the rate of turf establishment while only peat and smectite increased turf establishment above pots containing only sand. No amendment increased the rate of turf establishment above pots containing the sand/peat mixture.

The influence of the zeolite treatment on turf establishment is in contrast to finding reported by Nus and Brauen (1991). They reported plots containing zeolite were over 90% established 28 DAP while plots containing equal volumes of peat were 87% established. Furthermore, they reportedly failed to establish turf on 100% sand plots. However, Ferguson et al. (1986) reported decreased growth with the incorporation of zeolite to pure sand. Findings by Ferguson are similar to those found by this researcher. Because NH_4NO_3 was used as the sole source of N during establishment, and due to the affinity zeolites have for NH_4 (Ferguson and Pepper, 1987), it is likely turf establishment did not increase with zeolite incorporation because much of the N was sorbed out of soil solution which effectively decreased the amount of plant available N.

Diatomaceous earths reacted similarly to zeolites with diatomaceous earth 2 producing nearly identical establishment ratings as sand alone and diatomaceous earth 1 lowering the turf establishment rate. While DEs tend to increase soil moisture, they have low CECs which may be crucial during turf establishment. Nutrients applied during establishment may be continually leached due to excessive water applications

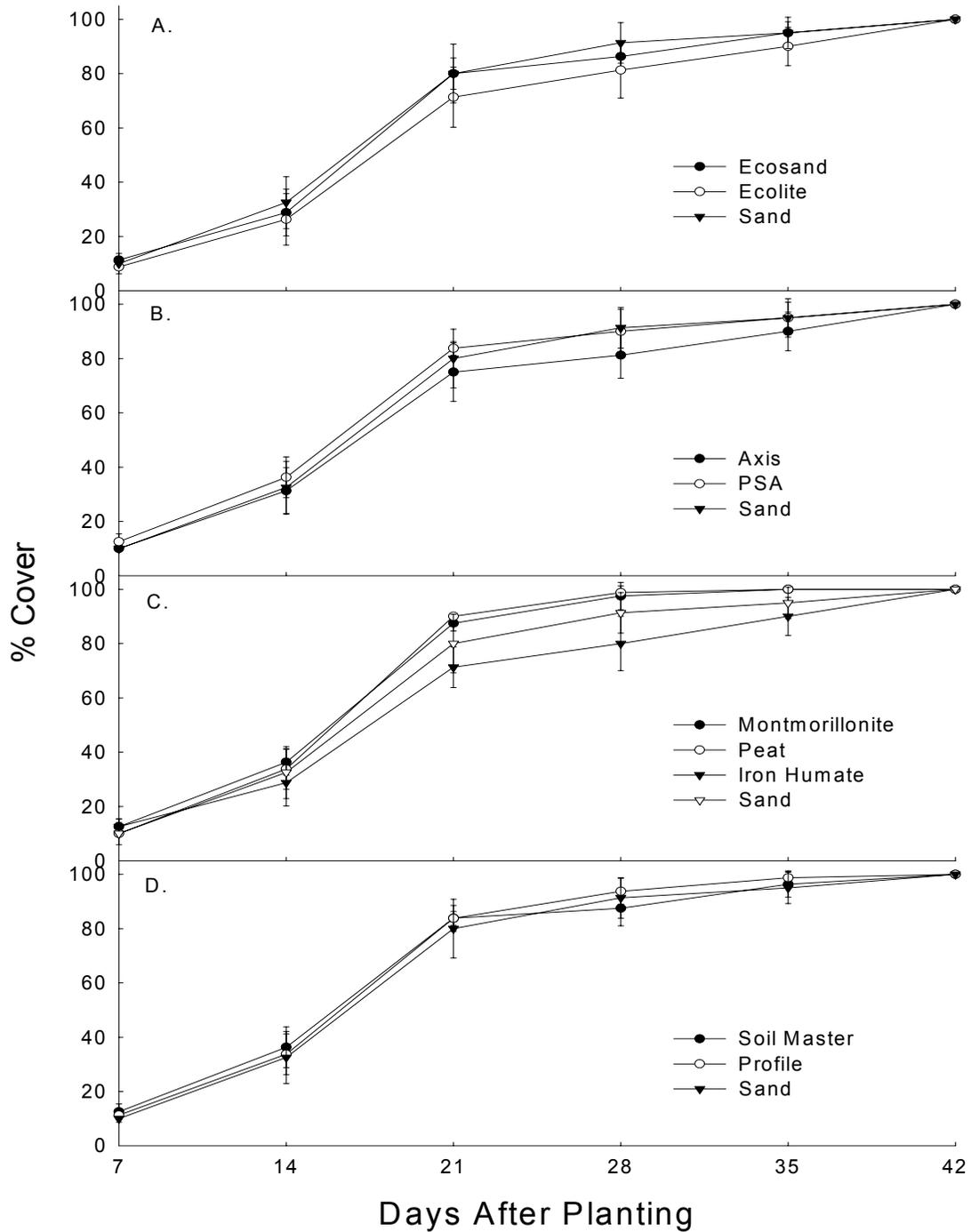


Figure 4-5. Establishment of Tifdwarf bermudagrass during summer 2002 as influenced by (A.) zeolites, (B.) diatomaceous earths, (C.) clay and organics, and (D.) calcined clays. Vertical bars denote standard error.

which are typically applied during the first weeks of establishment (Shaddox, 2001). Thus, low CEC rootzones may be more susceptible to nutrient depletions which may lead to plant deficiencies and decreased growth.

Peat and smectite were the only amendments that increased the rate of turf establishment above sand alone. The influence of peat on turf establishment has been well documented and has been primarily attributed to the increase in moisture retention, CEC, and additional nutrients which are mineralized from peat during the establishment period (Bigelow et al., 2001b; Carlson et al., 1998). Smectite was found to produce high moisture retention and possessed a CEC of 20 cmol(+) kg⁻¹. These parameters may have been sufficient to produce establishment equal to peat.

Turf Quality

Turf quality ratings were taken each week to assess overall turf health during the 12 week study (Table 4-5). Pots containing only sand produced the lowest quality turf while pots containing calcined clay 2 and iron humate produced the highest quality. These results correspond well with each amendment's physical and chemical characteristics. Sand exhibited low moisture retention (Fig 4-4) and low nutrient content (Table 4-3) and, thus, pots containing only sand exhibit poor turf quality. Pots containing calcined clay 2 or iron humate were observed to increase soil moisture and nutrient content and, thus, pots containing these amendments produced superior turf quality. Turf quality for the inorganic amendments fit well within amendment classes. Calcined clays produced the highest quality turf followed by DEs and zeolites. The low quality rating from pots containing zeolites are likely due to the low moisture retention which accompanies zeolite incorporation. The influence of soil amendments on turf growth was investigated

Table 4-5. Visual quality rating of bermudagrass as influenced by 85:15 sand/amendment rootzone during 2002 glasshouse study.

Treatment	Week												Mean
	1	2	3	4	5	6	7	8	9	10	11	12	
Sand	4.7 e	5.1 ef	4.7 e	5.7 de	5.0 b	4.7 b	4.7 f	4.7 c	5.0 d	5.1 d	5.0 c	5.2 d	5.0 e
Peat	5.8 bcd	6.5 abcd	6.1 cd	6.2 bcd	6.6 a	6.2 bc	6.2 cde	6.2 b	6.7 abc	6.5 bc	6.3 b	6.5 bc	6.3 c
Calcined clay 1	6.8 a	6.8 ab	6.8 abc	6.3 bcd	6.7 a	7.0 ab	7.1 ab	7.1 a	6.6 abc	7.1 ab	7.6 a	7.1 ab	6.9 b
Calcined clay 2	7.1 a	7.1 a	7.3 a	6.7 abc	7.0 a	7.6 a	7.2 ab	7.3 a	7.1 ab	7.2 ab	7.5 a	7.3 a	7.2 ab
Diatomaceous earth 1	6.3 abc	5.7 cdef	6.3 bcd	6.2 bcd	6.6 a	6.3 bc	6.5 bcd	6.6 ab	6.5 bc	6.3 bc	6.3 b	6.1 c	6.3 c
Diatomaceous earth 2	5.7 cd	6.0 bcde	6.6 abc	6.0 cde	6.5 a	6.3 bc	7.0 abc	6.0 b	6.5 bc	6.6 bc	6.1 b	6.8 abc	6.3 c
Clinoptilolite 1	4.8 e	5.0 f	5.1 e	5.2 e	5.6 b	5.6 c	5.7 de	5.8 b	6.1 c	5.8 cd	6.2 b	6.2 c	5.6 d
Clinoptilolite 2	5.3 de	5.6 def	5.5 de	5.8 de	5.6 b	5.8 c	5.6 e	5.8 b	6.3 bc	6.1 c	6.3 b	6.1 c	5.8 d
Smectite	6.6 ab	6.6 abc	6.3 bcd	7.0 ab	6.8 a	6.0 c	6.1 de	6.7 ab	7.1 ab	6.3 bc	6.5 b	6.3 bc	6.5 c
Iron Humate	7.0 a	7.1 a	7.1 ab	7.2 a	6.8 a	7.3 a	7.3 a	7.5 a	7.5 a	7.8 a	7.8 a	7.6 a	7.3 a
CV (%)	9.0	9.5	9.0	8.3	7.0	9.1	8.1	8.5	8.6	8.7	9.5	7.7	3.2

Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

by Wehtje et al. (2003). They investigated the influence of zeolite, DE, and CC incorporation with native soil and concluded that improvement in bermudagrass performance is most likely related to increases in soil moisture. Overall, these findings agree with findings reported by Miller (2000). Miller (2000) investigated several inorganic amendments along with peat and reported turf may perform differently when grown in various rootzone media. However, Miller (2000) not only reported little differences between amendments, but also observed some amendments performed similarly to pots amended with pure sand. In this researcher's study, all amendments increased turf quality above that of sand. The reported differences between the two studies are likely due to the method in which amendments were incorporated into the rooting zone. Amendments in Miller's study were introduced by first aerifying and then back-filling those holes with each amendment. This may have decreased the homogeneity of the amendment/sand rootzone and may have decreased each amendments influence on turf growth.

Water Use Efficiency

No differences in clipping yield, applied water, or WUE were observed between sand and sand/peat rootzones (Table 4-6). Only zeolite amended pots failed to increase WUE above that of sand/peat. Due to the source of N used (NH_4NO_3) and to the affinity zeolites have for NH_4 , it is likely that as much as $\frac{1}{2}$ of the applied N may have been rendered inaccessible to plant uptake, thus, plant growth was hindered. Absorption of NH_4 by zeolite amended soils has been observed by Bigelow et al. (2000). They also noted that rootzones amended with zeolite were less effective during turf establishment than those amended with peat. Other researchers have also noted this apparent negative

Table 4-6. Tissue yield, applied water, and water-use-efficiency of Tifdwarf bermudagrass as influenced by soil amendments during glasshouse 2002 study.

Rootzone Mixture†	Clipping Yield (g)	Applied Water (ml)	WUE‡ (mg g ⁻¹)
Sand (1)	3.4	3363.3	1.0
Peat (2)	3.8	3628.3	1.1
Calcined clay 1 (3)	6.5	4453.3	1.5
Calcined clay 2 (3)	5.9	4210.8	1.4
Diatomaceous earth 1 (4)	5.5	4376.8	1.3
Diatomaceous earth 2 (4)	5.9	4298.3	1.4
Clinoptilolite 1 (5)	4.1	3544.8	1.2
Clinoptilolite 2 (5)	4.4	3858.5	1.1
Smectite (6)§	4.6	3677.3	1.3
Iron Humate (7)	4.7	3215.5	1.5
<hr/>			
Contrast: 1 vs. 2	NS	NS	NS
Contrast: 2 vs. others	***	**	***
Contrast: 2 vs. 3	***	***	***
Contrast: 2 vs. 4	***	***	***
Contrast: 2 vs. 5	NS	NS	NS
Contrast: 2 vs. 6	**	NS	*
Contrast: 2 vs. 7	***	***	***
Contrast: 3 vs. 4	*	NS	*
Contrast: 3 vs. 7	***	***	NS
<hr/>			
CV	8.0	3.9	7.4

NS, *, **, ***, Not significant, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† 85% USGA uncoated sand plus 15% amendment by volume

‡ Water Use Efficiency = clipping yield / applied water

§ 2.5% by volume

characteristic inherent in natural zeolites and attempted to overcome them by using zeolites which have been pre-loaded with NH₄. Incorporation of these products has been shown to lead to rapid establishment and high quality turf (Andrews et al., 1999; Miller, 2000). Therefore, it is reasonable to assume the low clipping yield and WUE produced by the zeolite treatment was due to the removal of plant available N. However, if this is the case, it is also likely that over time, the zeolite will come to equilibrium with NH₄ in

soil solution and, thus, provide a buffer for plant consumption when NH_4 in soil solution is low.

Calcined clays and iron humate were equally effective and produced the greatest increase in turf WUE (Table 4-6). This is likely due to CCs and iron humate providing both an increase in plant available P and K (Table 4-3) and moisture retention (Fig. 4-4). Rootzone mixtures ranked in order of decreasing effectiveness were: iron humate = CCs > DEs = smectite > zeolites = peat = sand.

Amendments that produced the greatest increase in WUE were those amendments that provided adequate moisture retention and adequate CEC and initial nutrient content. While peat did increase PAW comparable to that of inorganic amendments (Table 4-4), peat did not increase CEC, available P, or K above that provided by sand alone (Table 4-3). A similar trend is also clear regarding zeolites. Zeolites not only increased the rootzone CEC above all other amendments, but they also provide adequate P and the highest amount of K. However, zeolites had the lowest influence on moisture held at field capacity. According to these findings, in order to maximize turf WUE by incorporating soil amendments, the amendment must be able to increase moisture retention, provide adequate available nutrients, and retain those nutrients via cation exchange.

Glasshouse 2003

Establishment

During the 2003 establishment phase, all amendments increased turf establishment rate above that of pots containing only sand (Fig. 4-6). Peat and iron humate produced the greatest increase in establishment while pots containing smectite produced the lowest increase. Iron humate was the only amendment that produced higher establishment

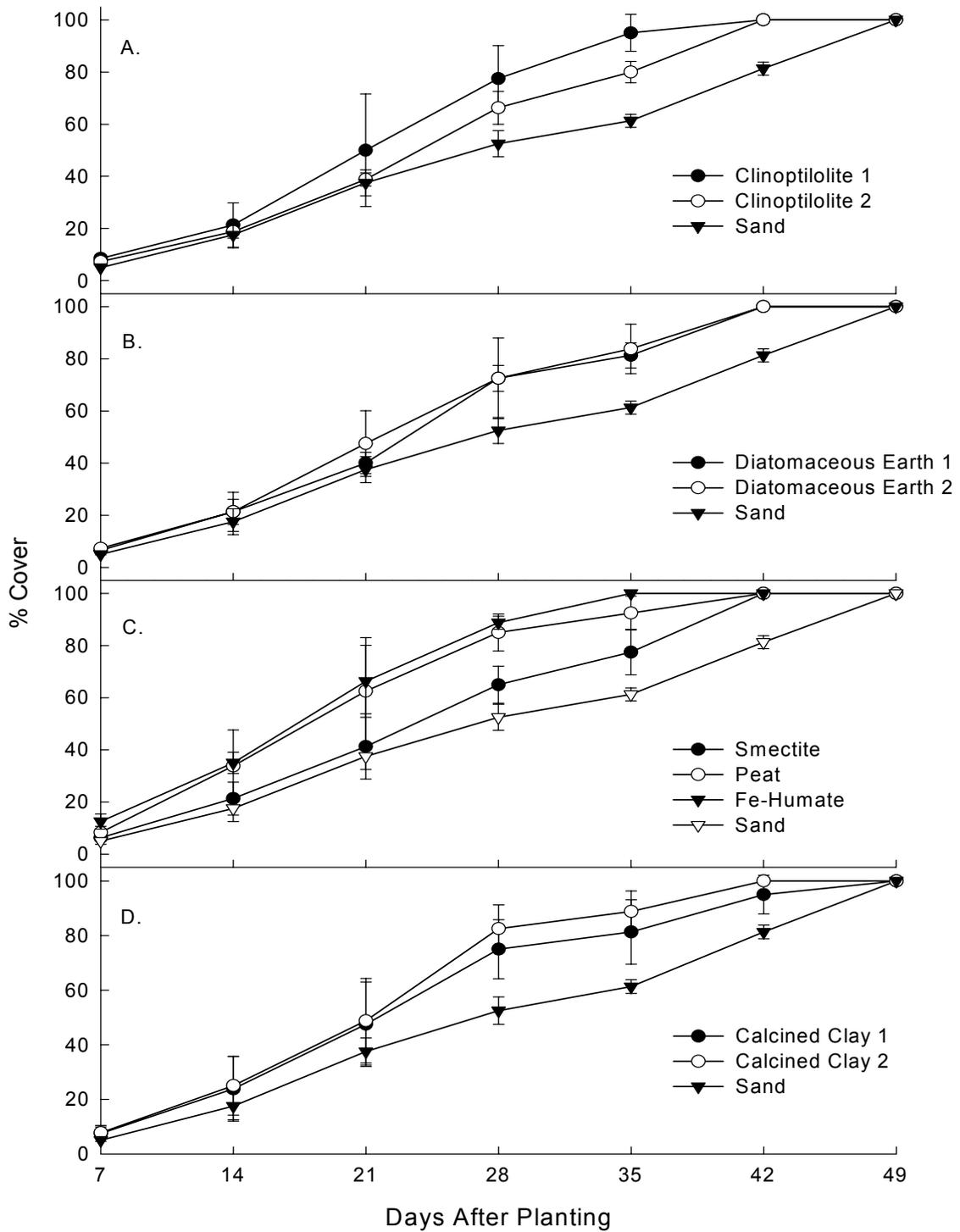


Figure 4-6. Establishment of Tifdwarf bermudagrass during summer 2003 as influenced by (A.) zeolite, (B.) diatomaceous earths, (C.) clay and organics, and (D.) calcined clays. Vertical bars denote standard error.

ratings than pots containing sand/peat. These findings are different than those found during the 2002 study in which only peat and smectite produced higher rating than pots containing only sand. While the reason for this difference is unknown, difference between irrigation manifolds between the two studies may have allowed more water to be applied during the 2002 study, thus decreasing the influence of each amendments moisture retention capabilities.

No inorganic amendment produced higher establishment ratings than did pots containing sand/peat. These findings agree with those reported by Bigelow et al. (1999). They investigated the influence of CCs, DEs, and zeolites on turf establishment and also reported that no inorganic amendment produced faster establishment than peat.

As in the 2002 study, differences between establishment rates of inorganic amendments were minimal. All pots containing organic or inorganic amendments were fully established at 42 days after planting (DAP). This is over 7 days longer than the 2002 study. This may also be due to the different irrigation manifolds used between the two studies.

Turf Quality

Upon analysis of turf quality, turf grass response was dependent upon the method × treatment interaction (Table 4-7). Therefore, amendment influences were determined within each method.

Analysis of turf quality as influenced by sand/amendment mixtures revealed quality was dependent upon amendment type (Table 4-8). All amendments increased turf quality above that of sand alone. However, only CCs and iron humate increased quality above pots containing sand/peat. Amendments influence on turf quality in order of decreasing

Table 4-7. Analysis of variance of mean squares on turf quality during 2003 study as influenced by incorporation method and amendment type.

Source of Variation	df	Mean Squares	F value
Block	3	0.10	2.79 *
Method (M)	2	0.54	14.35 ***
Error (a)	5	0.03	
Amendment (A)	9	2.11	66.28 ***
A × M	18	0.40	12.60 ***
Error (b)	72	0.03	
Total	109		

*, ***, Significant at 0.05, 0.001 probability levels, respectively.

effectiveness followed: iron humate > CCs > smectite = peat = DEs > zeolites > sand. As observed during 2002, iron humate produced superior turf quality above all other amendments. This is likely due to the iron humate providing background levels of P and K, but more importantly providing the greatest amount of PAW (Table 4-4). Moisture has been noted as being the primary limiting factor when assessing turf establishment and quality. Bigelow et al. (1999) stated moisture appeared to be the main limiting factor when assessing amendments influence on turf establishment. Waltz and McCarty (2000) hypothesized that more moisture held near the soil surface by peat-amended soils provided a faster establishment for seeded bentgrass than soil amended with inorganic amendments. Bigelow et al. (2001b) also determined that improved turf quality of amended sand rootzone was due to higher water holding capacities. However, according to findings by this researcher, moisture content may not be the primary variable influencing turf quality. This is clearly observable in the case of DEs. Diatomaceous earths produced 30% more PAW than CCs (Table 4-4), but DEs produce quality ratings nearly 1 unit lower than CCs. Clearly available water is not the only variable dictating the influence of amendments on turf quality. It seems more likely that the combination of available water and nutrient content of amended rootzones was the primary influencing factor during this study.

Table 4-8. Visual quality rating of bermudagrass as influenced by 85:15 sand/amendment rootzone during 2003 glasshouse study.

Treatment	----- Week -----												Mean
	1	2	3	4	5	6	7	8	9	10	11	12	
Sand	4.6 e	4.8 d	4.6 d	5.1 e	5.0 e	4.8 e	4.8 f	4.8 e	4.8 e	4.8 d	5.0 e	5.0 d	4.8 e
Peat	6.3 bc	6.5 b	6.3 b	6.1 bcd	6.6 bcd	6.6 abc	6.3 cde	6.3 cd	6.5 bcd	6.6 bc	6.5 cd	6.6 bc	6.4 c
Calcined clay 1	7.1 ab	6.8 ab	6.6 ab	7.0 b	7.1 ab	7.0 ab	7.1 b	7.3 ab	7.1 ab	7.3 b	7.6 ab	7.3 ab	7.1 b
Calcined clay 2	7.0 ab	7.5 a	7.3 a	7.0 b	7.0 abc	7.3 ab	7.0 bc	7.1 abc	7.1 ab	7.3 b	7.3 abc	7.1 ab	7.1 b
Diatomaceous earth 1	6.5 abc	6.3 bc	6.3 b	6.1 bcd	6.5 cd	6.6 abc	6.8 bcd	6.6 bcd	6.3 bcd	6.3 c	6.3 cd	6.0 c	6.4 c
Diatomaceous earth 2	6.0 cd	6.0 bc	5.8 bc	6.0 cde	6.1 d	6.5 bcd	6.6 bcd	6.3 cd	6.3 bcd	6.6 bc	6.5 cd	6.6 bc	6.3 c
Clinoptilolite 1	4.6 e	4.6 d	5.0 cd	5.3 de	5.5 e	5.8 cd	5.8 e	6.0 d	6.0 d	6.1 c	6.0 d	6.1 c	5.5 d
Clinoptilolite 2	5.3 de	5.5 cd	5.3 cd	5.6 de	5.5 e	5.6 de	5.8 e	6.0 d	6.1 cd	6.1 c	6.3 cd	6.1 c	5.8 d
Smectite	6.6 abc	6.3 bc	6.3 b	6.8 bc	6.6 bcd	6.0 cd	6.1 de	6.8 bcd	7.0 abc	6.1 c	6.8 bcd	6.8 abc	6.5 c
Iron Humate	7.3 a	7.5 a	7.5 a	7.8 a	7.3 a	7.5 a	8.0 a	7.8 a	7.6 a	8.1 a	8.1 a	7.6 a	7.7 a
CV (%)	7.4	8.0	8.6	7.1	4.8	7.6	6.4	7.8	6.8	6.7	8.4	7.1	4.3

Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

Minimal differences in turf quality were observed between amendments when amendments were incorporated after 4 tine aerification (Table 4-9). All amendments produced turf above the minimal acceptable quality ratings. During the aerification study, the rootzone consisted primarily of sand/peat mixture. This likely decreased the influence of amendments on turf quality, thus pots modified with sand, DEs, and zeolites produced quality ratings equal to that of pots containing only sand/peat. Only CCs, smectite, and iron humate produced ratings higher than pots modified with pure sand. Highest quality ratings were observed from iron humate amended pots followed by CCs. This trend was also observed when amendments were fully incorporated into the rootzone.

Greater difference between treatment means were observed when amendments were incorporated after 9 tine aerification than after 4 tine (Table 4-10). This result was anticipated and is most likely due to a large portion of the rootzone being replaced by each treatment in the 9 tine aerification versus the 4 tine. Only diatomaceous earth 1 failed to increase turf quality above that of pots modified with only sand. As in the full mixture and 4 tine aerification methods, iron humate produced the highest quality turf followed by CCs. Sartain (1999) reported iron humate can positively influence bermudagrass growth and quality when adequate N is available. Sartain attributed bermudagrass response to the addition of iron which accompanies iron humate incorporation. The increase in Fe, along with N, in iron humate is likely the cause of the observed increase in turf quality.

Table 4-9. Visual quality rating of Tifdwarf bermudagrass as influenced by 4 tine aerification during 2003 glasshouse study.

Treatment	Week												mean
	1	2	3	4	5	6	7	8	9	10	11	12	
Sand	6.2 bc	6.3 a	6.5 b	6.0 b	6.0 b	6.3 a	6.2 b	6.6 b	6.5 bc	6.3 b	6.6 abc	6.7 bc	6.3 d
Peat	6.3 bc	6.5 a	6.6 b	6.3 b	6.5 ab	6.7 a	6.3 b	6.7 ab	6.7 bc	6.2 b	7.0 ab	6.5 bc	6.5 bcd
Calcined clay 1	6.7 ab	6.6 a	6.5 b	6.8 ab	6.8 ab	6.3 a	6.3 b	7.0 ab	6.2 c	7.0 ab	6.3 bc	7.0 ab	6.6 bc
Calcined clay 2	6.3 bc	6.7 a	6.8 ab	6.8 ab	6.5 ab	7.0 a	6.8 ab	6.5 b	7.0 ab	6.7 ab	6.3 bc	7.0 ab	6.7 b
Diatomaceous earth 1	6.2 bc	6.2 a	6.5 b	6.2 b	6.2 ab	6.8 a	6.2 b	6.5 b	6.5 bc	6.6 ab	6.1 c	6.5 bc	6.4 d
Diatomaceous earth 2	5.7 c	6.2 a	6.2 b	6.3 b	6.0 b	6.6 a	6.6 b	6.3 b	6.5 bc	6.7 ab	6.7 abc	7.0 ab	6.4 d
Clinoptilolite 1	6.1 bc	6.5 a	6.1 b	6.1 b	6.6 ab	6.6 a	6.3 b	6.6 b	6.3 bc	6.6 ab	6.5 bc	6.3 bc	6.4 d
Clinoptilolite 2	6.0 c	6.7 a	6.7 ab	6.5 b	6.6 ab	7.1 a	6.1 b	6.6 b	6.7 bc	6.5 ab	6.6 abc	6.1 c	6.5 cd
Smectite	6.3 bc	7.0 a	6.7 ab	6.2 ab	6.2 ab	6.3 a	6.5 b	7.1 ab	6.7 bc	6.7 ab	6.6 abc	6.7 bc	6.6 bc
Fe-Humate	7.1 a	7.0 a	7.5 a	7.6 a	7.1 a	7.1 a	7.5 b	7.5 a	7.5 a	7.3 a	7.3 a	7.6 a	7.3 a
CV (%)	6.5	6.7	7.5	8.1	8.6	7.5	7.2	7.4	6.5	7.8	7.6	6.6	1.8

Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

Table 4-10. Visual quality rating of Tifdwarf bermudagrass as influenced by 9 tine aerification during 2003 glasshouse study.

Treatment	----- Week -----												mean
	1	2	3	4	5	6	7	8	9	10	11	12	
Sand	6.0 c	6.2 d	5.8 d	6.1 c	6.1 b	6.1 c	6.0 d	6.0 b	6.6 b	6.3 bc	6.5 b	6.7 b	6.2 f
Peat	6.5 abc	6.3 d	6.5 cd	6.8 bc	6.6 ab	6.8 abc	6.6 bc	6.5 b	7.0 ab	6.3 bc	6.6 b	6.3 b	6.5 cd
Calcined clay 1	6.8 ab	6.5 bcd	6.8 bc	7.0 ab	6.8 ab	6.6 bc	6.7 bc	6.8 ab	6.3 b	6.8 b	6.6 b	7.1 ab	6.7 bc
Calcined clay 2	6.6 abc	7.3 a	7.2 ab	6.6 bc	6.5 ab	7.1 ab	6.7 bc	6.6 ab	6.7 ab	6.8 b	6.5 b	6.7 b	6.8 b
Diatomaceous earth 1	6.5 abc	6.1 d	6.0 d	6.3 bc	6.2 b	6.8 ab	6.8 b	6.6 ab	6.3 b	5.8 c	6.2 b	6.3 b	6.3 ef
Diatomaceous earth 2	6.3 abc	6.3 cd	6.5 cd	6.6 bc	6.2 b	6.5 bc	6.6 bcd	6.3 b	6.6 b	6.7 b	6.6 b	6.7 b	6.5 de
Clinoptilolite 2	6.1 bc	6.2 d	6.3 cd	6.3 bc	6.3 ab	7.0 ab	6.1 cd	6.5 b	6.8 ab	6.1 bc	6.8 ab	6.8 ab	6.4 de
Clinoptilolite 1	5.8 c	6.5 bcd	5.8 d	6.2 bc	6.7 ab	7.0 ab	6.3 bcd	6.5 b	6.5 b	6.6 bc	6.5 b	6.6 b	6.4 de
Smectite	6.6 abc	7.0 abc	7.0 abc	6.7 bc	7.0 ab	6.5 bc	6.5 bcd	6.8 ab	6.8 ab	6.8 b	6.6 b	6.8 ab	6.7 bc
Fe-Humate	7.1 a	7.1 ab	7.5 a	7.6 a	7.2 a	7.3 a	7.7 a	7.5 a	7.3 a	7.7 a	7.5 a	7.6 a	7.4 a
CV (%)	7.7	6.0	5.9	7.0	8.1	6.4	5.9	8.7	6.5	6.9	7.8	7.1	1.9

Within columns, means followed by the same letter are not significantly different according to Duncan's multiple range test (0.05).

Days to Wilt

In order to further determine the influence of soil amendments on turf growth, water application was stopped at the end of the study and days-to-wilt (DTW) was observed. Upon analysis of DTW, the method \times treatment interaction was not significant. Therefore, treatments effects were averaged across methods (Table 4-11).

Table 4-11. Analysis of variance of mean squares on Tifdwarf days to wilt during 2003 study as influenced by incorporation method and amendment type.

Source of Variation	df	Mean Squares	F value
Block	3	5.07	1.78
Method (M)	2	4.90	1.72
Error (a)	5	2.84	
Amendment (A)	9	3.10	0.78
A \times M	18	5.05	1.26
Error (b)	72	4.00	
Total	109		

Turf grown in pots containing sand/peat was observed to wilt at 8.9 days. No amendment increased DTW above sand/peat (Table 4-12). While turf grown with iron humate and diatomaceous earth 1 was observed to extend DTW to 9.8, it was not considered statistically significant. These findings agree with those reported by Miller (2000). Miller observed turf grown in pots containing calcined clays, diatomaceous earths, and zeolites required the same time to reach DTW as pots containing sand/peat. Miller observed only sand and one zeolite treatment reduced DTW below sand/peat. The lack of differences between amendments is likely due to the method in which amendments were incorporated. When amendments were incorporated after aeration versus full incorporation, the influence of each amendment on dry matter yield and WUE

was reduced (Table 4-14, Table 4-15). If full incorporation were the only method analyzed, amendments may influence DTW.

Table 4-12. Days to wilt of Tifdwarf bermudagrass as influenced by 85:15 sand/amendment rootzone during 2003 glasshouse study.

Treatment	Days to Wilt
	--- d ---
Sand (1)	9.1
Peat (2)	8.9
Calcined clay 1 (3)	8.8
Calcined clay 2 (3)	9.3
Diatomaceous earth 1 (4)	9.8
Diatomaceous earth 2 (4)	9.4
Clinoptilolite 1 (5)	9.0
Clinoptilolite 2 (5)	8.0
Smectite (6)	9.0
Iron Humate (7)	9.8
Contrast: 1 vs. 2	NS
Contrast: 2 vs. others	NS
Contrast: 2 vs. 3	NS
Contrast: 2 vs. 4	NS
Contrast: 2 vs. 5	NS
Contrast: 2 vs. 6	NS
Contrast: 2 vs. 7	NS
Contrast: 3 vs. 4	NS
Contrast: 3 vs. 7	NS
CV (%)	21.6

Water Use Efficiency

Upon analysis of WUE for the 2003 study, Tifdwarf WUE was dependent upon the method × treatment interaction (Table 4-13). Therefore, amendment influences were determined within each method.

As observed in the 2002 study, no differences in mean clipping yield, applied water, or WUE were observed between sand and sand/peat rootzones (Table 4-14). This was unexpected due to the greater amount of PAW retained in the peat amended rootzone versus sand alone (Table 4-4), as well as larger quantities of TKN, Ca, and Mg found in

Table 4-13. Analysis of variance of mean squares on Tifdwarf water use efficiency during 2003 study as influenced by incorporation method and amendment type.

Source of Variation	df	Mean Squares	F value
Block	3	0.001	0.72
Method (M)	2	0.853	385.88 ***
Error (a)	5	0.002	
Amendment (A)	9	0.287	139.13 ***
A × M	18	0.084	41.00 ***
Error (b)	72	0.002	
Total	109		

*, ***, Significant at 0.05, 0.001 probability levels, respectively.

peat amended pots (Table 4-3). These findings contradict those found by Snyder (2003) who reported a 32% increase in clipping yield of bermudagrass when peat was incorporated into an uncoated sand-based rootzone. However, similar findings were reported by Comer (1999) who investigated the incorporation of a variety of soil amendments with and without peat into a sand-based putting green. Comer reported that pots containing amendments produced less dry matter when peat was incorporated than when peat was withheld. Similar trends were observed between the control containing only sand and the control containing sand/peat. Differences were attributed to N immobilization by microbes in the sand/peat pots which would effectively reduce plant available N. If a large supply of C relative to inorganic N is provided by peat, N consumption by microbes will be stimulated (Pierzynski et al., 1994).

Only pots amended with zeolites failed to produce clipping yields and WUE ratings above pots containing sand/peat (Table 4-14). Explanations for this response regarding NH_4 immobilization by zeolites have been addressed in the preceding section. Zeolite- amended pots required 17% more water to produce essentially the same biomass as sand/peat pots. During both the 2002 and 2003 studies, zeolite amended pots did not produce quality ratings, clipping yields, or WUE ratings superior to that of peat. These

Table 4-14. Tissue yield, applied water, and water-use-efficiency of Tifdwarf bermudagrass as influenced by fully incorporated soil amendments during glasshouse 2003 study.

Rootzone Mixture†	Clipping Yield (g)	Applied Water (mL)	WUE‡ (mg g ⁻¹)
Sand (1)	3.5	3181.8	1.1
Peat (2)	3.6	2986.1	1.2
Calcined clay 1 (3)	4.7	2745.1	1.7
Calcined clay 2 (3)	5.0	3325.6	1.5
Diatomaceous earth 1 (4)	4.9	3037.5	1.6
Diatomaceous earth 2 (4)	4.4	3176.2	1.4
Clinoptilolite 1 (5)	3.8	3478.8	1.1
Clinoptilolite 2 (5)	4.2	3516.7	1.2
Smectite (6)§	4.5	2522.2	1.8
Iron Humate (7)	7.1	3925.0	1.8
<hr/>			
Contrast: 1 vs. 2	NS	NS	NS
Contrast: 2 vs. others	***	***	***
Contrast: 2 vs. 3	***	NS	***
Contrast: 2 vs. 4	**	NS	**
Contrast: 2 vs. 5	NS	**	NS
Contrast: 2 vs. 6	*	**	***
Contrast: 2 vs. 7	***	***	***
Contrast: 3 vs. 4	NS	NS	NS
Contrast: 3 vs. 7	***	***	*
CV (%)	11.2	5.9	6.8

NS, *, **, ***, Not significant, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† 85% USGA uncoated sand plus 15% amendment by volume

‡ Water Use Efficiency = clipping yield / applied water

§ 2.5% by volume

results suggest zeolite is not a suitable replacement for peat in sand-based putting greens if increasing turf quality or WUE is desired. However, zeolites may be considered as an amendment to increase putting green CEC (Table 4-3).

No differences in applied water were observed between peat and CCs and peat and DEs, yet differences were observed between clipping yield and WUE (Table 4-14).

Because the same amount of water and nutrients were applied to CCs, DEs, and peat

Table 4-15. Tissue yield, applied water, and water-use-efficiency of Tifdwarf bermudagrass as influenced by soil amendments after 9 tine aerification during glasshouse 2003 study.

Rootzone Mixture†	Clipping Yield (g)	Applied Water (ml)	WUE‡ (mg g ⁻¹)
Sand (1)	4.1	3388.9	1.2
Peat (2)	3.5	3531.7	1.0
Calcined clay 1 (3)	4.0	3056.4	1.3
Calcined clay 2 (3)	3.8	3156.9	1.2
Diatomaceous earth 1 (4)	3.9	3568.2	1.1
Diatomaceous earth 2 (4)	4.0	3352.8	1.2
Clinoptilolite 1 (5)	3.7	3353.0	1.1
Clinoptilolite 2 (5)	3.7	3680.0	1.0
Smectite (6)§	3.9	3542.4	1.1
Iron Humate (7)	6.7	4164.6	1.6
Contrast: 1 vs. 2	NS	NS	*
Contrast: 2 vs. others	*	NS	**
Contrast: 2 vs. 3	NS	***	**
Contrast: 2 vs. 4	NS	NS	NS
Contrast: 2 vs. 5	NS	NS	NS
Contrast: 2 vs. 6	NS	NS	NS
Contrast: 2 vs. 7	***	***	***
Contrast: 3 vs. 4	NS	**	NS
Contrast: 3 vs. 7	***	***	***
CV (%)	15.4	7.5	8.3

NS, *, **, ***, Not significant, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† 85% USGA uncoated sand plus 15% amendment by volume

‡ Water Use Efficiency = clipping yield / applied water

§ 2.5% by volume

amended pots, and CCs and DEs were found to have similar amounts of PAW as peat, it is likely nutrients applied to pots containing CCs and DEs were more plant available than that applied to pots containing peat. Mehlich I extractable levels of P, K, and Fe from CCs and DEs were found to be higher than those from peat amended pots (Table 4-3). Thus, higher WUE ratings were observed from CCs and DEs than from peat.

Water-use-efficiency ratings from iron-humate and smectite were identical and higher than all other amended pots (Table 4-14). These results regarding iron humate

contradict those reported by Sartain and Comer (2004). They investigated WUE of bermudagrass one year after establishment and observed pots containing peat had greater WUE ratings than pots containing sand/iron humate or sand alone. Iron humate is a residual product of water treatment facilities. As such, its consistency over time may vary along with its organic matter and nutrient content. Iron humate used in this study contained higher levels of N, K, Ca, and Fe than iron humate used in the study by Comer (1999). This could account for the different responses observed during this study.

When amendments were incorporated following 9-tine aerification, differences between treatment means became less apparent (Table 4-15). Only iron humate, CCs, and sand increased WUE above that of the sand/peat mixture. The increase in WUE from CCs was largely due to a 13% decrease in water required to maintain 90% field capacity. Iron humate required 17% more water than peat, but produced 90% more dry matter. This may be indicative of an increase in nutrient uptake by turf grown in iron humate amended sand. Iron humate produce 23% greater WUE than CCs which produced the second highest WUE response. Lowest WUE responses were observed from peat and zeolite amended pots. During 2003, incorporation of soil amendments via 9-tine aerification produced 22% lower WUE than when amendments were fully mixed into the rootzone. Fully mixing amendments with sand allows for greater consistency and homogeneity. Thus, fully-mixed amendments had a greater influence on turf growth than when amendments were incorporated in localized regions throughout the rootzone as was the case in each aerification method.

Incorporation of soil amendments via 4-tine aerification had a similar influence on turf WUE as 9-tine aerification (Table 4-16). The only amendment that increased WUE

Table 4-16. Tissue yield, applied water, and water-use-efficiency of Tifdwarf bermudagrass as influenced by soil amendments after 4 tine aerification during glasshouse 2003 study.

Rootzone Mixture†	Clipping Yield (g)	Applied Water (ml)	WUE‡ (mg g ⁻¹)
Sand (1)	3.8	3456.1	1.1
Peat (2)	3.8	3193.2	1.2
Calcined clay 1 (3)	3.9	3033.3	1.3
Calcined clay 2 (3)	3.8	3141.7	1.2
Diatomaceous earth 1 (4)	3.9	3533.3	1.1
Diatomaceous earth 2 (4)	4.3	3559.7	1.2
Clinoptilolite 1 (5)	4.2	3472.2	1.2
Clinoptilolite 2 (5)	3.8	3460.6	1.1
Smectite (6)§	3.9	3515.2	1.1
Iron Humate (7)	5.7	4085.7	1.4
<hr/>			
Contrast: 1 vs. 2	NS	NS	NS
Contrast: 2 vs. others	*	*	NS
Contrast: 2 vs. 3	NS	NS	NS
Contrast: 2 vs. 4	NS	*	NS
Contrast: 2 vs. 5	NS	NS	NS
Contrast: 2 vs. 6	NS	*	NS
Contrast: 2 vs. 7	***	***	**
Contrast: 3 vs. 4	NS	*	NS
Contrast: 3 vs. 7	***	***	*
<hr/>			
CV (%)	13.1	6.9	9.2

NS, *, **, ***, Not significant, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† 85% USGA uncoated sand plus 15% amendment by volume

‡ Water Use Efficiency = clipping yield / applied water

§ 2.5% by volume

above peat was iron humate. This trend remained consistent across all incorporation methods. However, the influence of iron humate on WUE decreased in the order of: full incorporation > 9-tine aerification > 4-tine aerification. However, no differences were observed between the overall mean of treatments from 9-tine and 4-tine aerification (Table 4-17). According to these results, soil amendments may not increase WUE when incorporated after aerification compared to full incorporation. Moreover, it seems the likelihood of producing an increase in WUE will increase as more of the rootzone is

removed during aerification. However, incorporation of amendments into a sand-based rootzone will produce the greatest increase in turf quality, clipping yield, and WUE when the amendment is fully incorporated into the rootzone (Table 4-17). This allows for a more even distribution of nutrients and moisture for turf uptake.

Table 4-17. Water use efficiency of Tifdwarf bermudagrass as influenced by incorporation method.

Method	Water Use Efficiency
Full (1)	1.4
4 Tine (2)	1.1
9 Tine (3)	1.1
Contrast: 1 vs. 2	***
Contrast: 2 vs. 3	NS
CV (%)	3.5

Nutrient Leaching Study

As previously mentioned, a primary concern in the golf industry is to minimize any environmental impact that may arise from fertilizer applications. This phase of the study compares 3 soil amendments and their capacity to retain NO_3^- , NH_4^+ , and P during periods of normal nutrient but high water applications.

Nitrate

No differences were observed between the $\text{NO}_3\text{-N}$ breakthrough curves of sand and sand/peat rootzones (Fig. 4-7). As desired, nitrate-N leached as a pulse. Maximum $\text{NO}_3\text{-N}$ concentration reached $0.2 C/C_0$ at one pore volume and quickly dropped, tapering off to no detectable $\text{NO}_3\text{-N}$ at near 2.5 pore volumes. Both sand and sand/peat leaching patterns were well described by the CD model. Thus, nitrate can be assumed to have moved through the column with the wetting front, and the primary mode of leaching was convection.

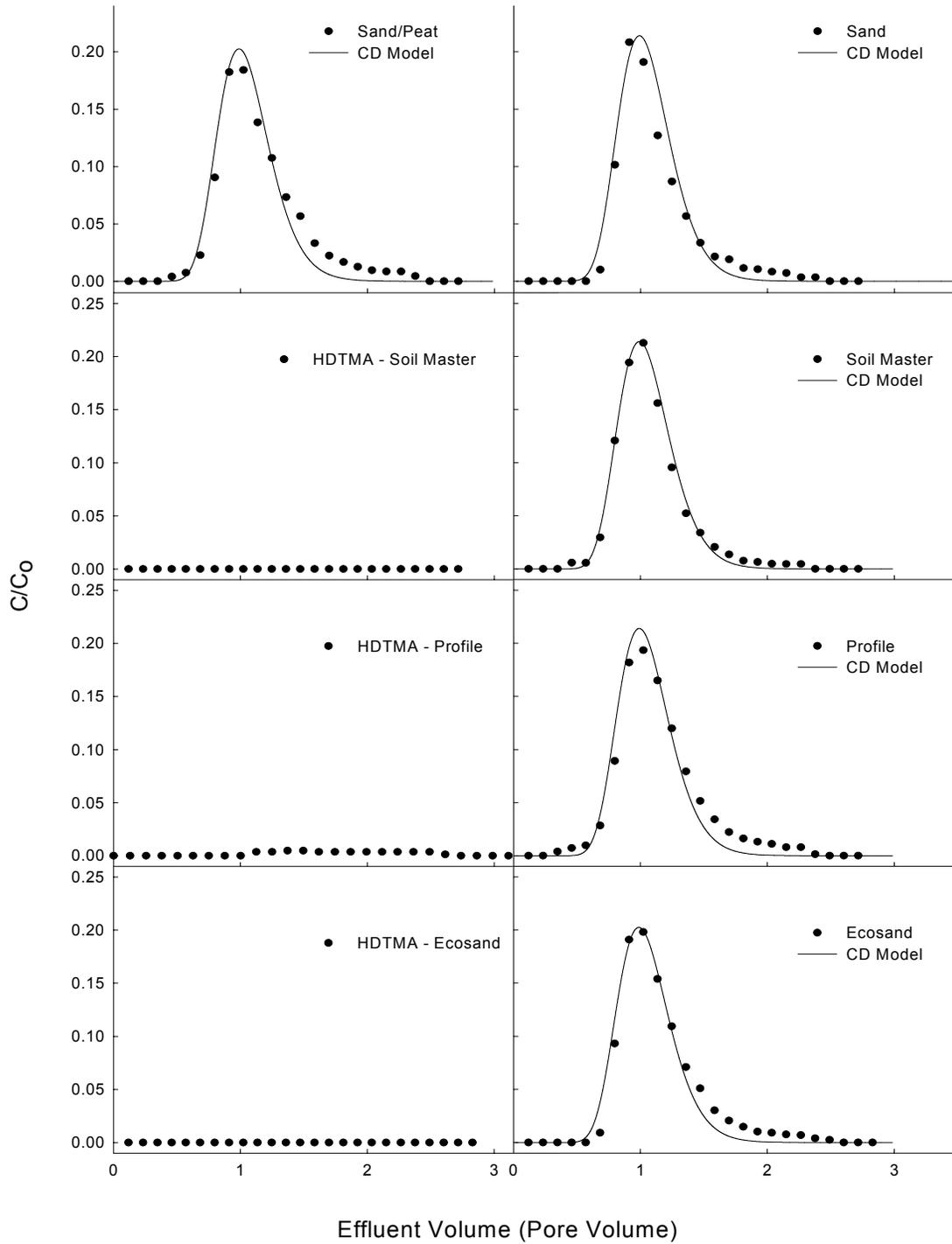


Figure 4-7. Nitrate breakthrough curves as influenced by filter zone media.

Both CCs were found to have similar NO_3 breakthrough curves to that of sand and sand/peat (Fig. 4-7). Calcined clays, sand, and peat have effectively no anion exchange capacity, thus similar leaching patterns were expected. These findings agree with those reported by Bigelow et al., (2004) who also investigated NO_3 leaching through sand amended with CCs. They reported that more than 90% of applied $\text{NO}_3\text{-N}$ leached through all rootzone mixtures, and, in general, non-amended sand and sand/amendment mixtures were similar regarding $\text{NO}_3\text{-N}$ leaching.

Leaching patterns from columns containing zeolite differed from columns containing CCs or peat. Minimal retention of $\text{NO}_3\text{-N}$ was observed in columns containing zeolite (Fig. 4-7). Maximum $\text{NO}_3\text{-N}$ concentration in leachate from zeolite columns were approximately 5% lower than columns containing sand as the filter zone media. Due to the high CEC of zeolite, this result was not expected and it is unlikely that any $\text{NO}_3\text{-N}$ was retained directly. However, it is possible that as NH_4 ions were absorbed into the zeolite structure, movement of the NO_3 ion, previously associated with the NH_4 ion, through the column was delayed via its ion pair. This 'ion pair' hypothesis has been previously proposed by Brown (2003) when studying the movement of $\text{Ca}(\text{NO}_3)_2$ through turfgrass covered soil columns. Unfortunately, evidence of this phenomenon was not substantiated. However, these results indicate decreased leaching of one ion due to retention of its counterion may occur.

When each amendment was coated with HDTMA, nitrate-N was removed from solution to the extent that the CD model did not fit the data (Fig 4-7). All $\text{NO}_3\text{-N}$ was retained by SMSA following 4 pore volumes, except calcined clay 2 in which 5% of applied $\text{NO}_3\text{-N}$ eventually leached (Table 4-18). Columns that contained unmodified soil

amendments leached between 94 and 102% of applied NO₃-N. These results are substantially higher than those reported by previous researchers when using the same fertilizer source (Brown et al., 1982; Snyder et al., 1984). However, both Brown and Snyder conducted leaching studies over longer periods of time compared to this study in which NO₃-N remained in columns for less than 20 minutes. The longer time period would subject NO₃-N to a variety of conversion processes and potentially decrease NO₃ leaching.

Nitrate-N sorption isotherms may help to explain the leaching patterns and retention by SMSAs (Fig. A-9). Uncoated amendments did not sorb any NO₃-N (data not included on graph). Surfactant-coated calcined clay 1 sorbed more NO₃-N than calcined

Table 4-18. Total NO₃-N leached as influenced by filter zone media.

Root zone media	Filter zone media	NO ₃ -N Leached	
		(mg)	% of Applied
Sand	Sand (1)	21.6	96.0
Sand/Peat	Sand (2)	22.1	98.2
Sand/Peat	Clinoptilolite 1 (3)	21.5	95.5
Sand/Peat	Calcined clay 2 (4)	23.1	102.6
Sand/Peat	Calcined clay 1 (5)	21.3	94.6
Sand/Peat	HDTMA-Clinoptilolite 1 (6)	0.0	0.0
Sand/Peat	HDTMA-Calcined clay 2 (7)	1.0	4.4
Sand/Peat	HDTMA-Calcined clay 1 (8)	0.0	0.0
Contrast: 1 vs. 2		NS	
Contrast: 2 vs. 6		***	
Contrast: 2 vs. 7		***	
Contrast: 2 vs. 8		***	
Contrast: 3 vs. 6		***	
Contrast: 4 vs. 7		***	
Contrast: 5 vs. 8		***	
CV (%)		9.8	

NS, ***, Not significant, significant at 0.001 probability level respectively.

clay 2 or clinoptilolite 1. Calcined clay 2 and clinoptilolite 1 produced similar isotherms with calcined clay 2 retaining slightly more $\text{NO}_3\text{-N}$ than clinoptilolite 1. These isotherms relate well with each amendment's effective anion exchange capacity (EAEC) (Table 4-1). Calcined clay 1 and clinoptilolite 1 had the highest and lowest EAEC, respectively. Thus, calcined clay 1 and clinoptilolite 1 produced the highest and lowest S_{max} , respectively.

Ammonium

When HDTMA is coated onto a solid phase that possesses a CEC, the effective CEC of that solid may decrease (Table 4-1). This is due to a portion of the original cation exchange sites being occupied by HDTMA head groups. Due to this decrease in CEC, sorption or retention of cations from soil solution may also decrease. This phenomenon was observed during analysis of $\text{NH}_4\text{-N}$ leaching.

Leaching patterns of $\text{NH}_4\text{-N}$ through columns containing only sand were similar to leaching patterns of $\text{NO}_3\text{-N}$ through the same columns (Fig. 4-8) and were well described by the 2-site model. The 2-site model parameters can be seen in table A-2. Maximum $\text{NH}_4\text{-N}$ concentrations reached 0.21 C/C_0 and were observed at 1.09 pore volumes. This indicates that, under these experimental conditions, the movement and retention of $\text{NH}_4\text{-N}$ is not influenced by USGA sand. These findings support previous work conducted under similar experimental conditions (Bigelow et al., 2003).

Addition of peat into the rootzone mixture decreased maximum $\text{NH}_4\text{-N}$ concentration in leachate by 25% (Fig. 4-8). Furthermore, peak concentrations were observed at 1.1 pore volumes which lead to a higher retardation factor (R). However, no

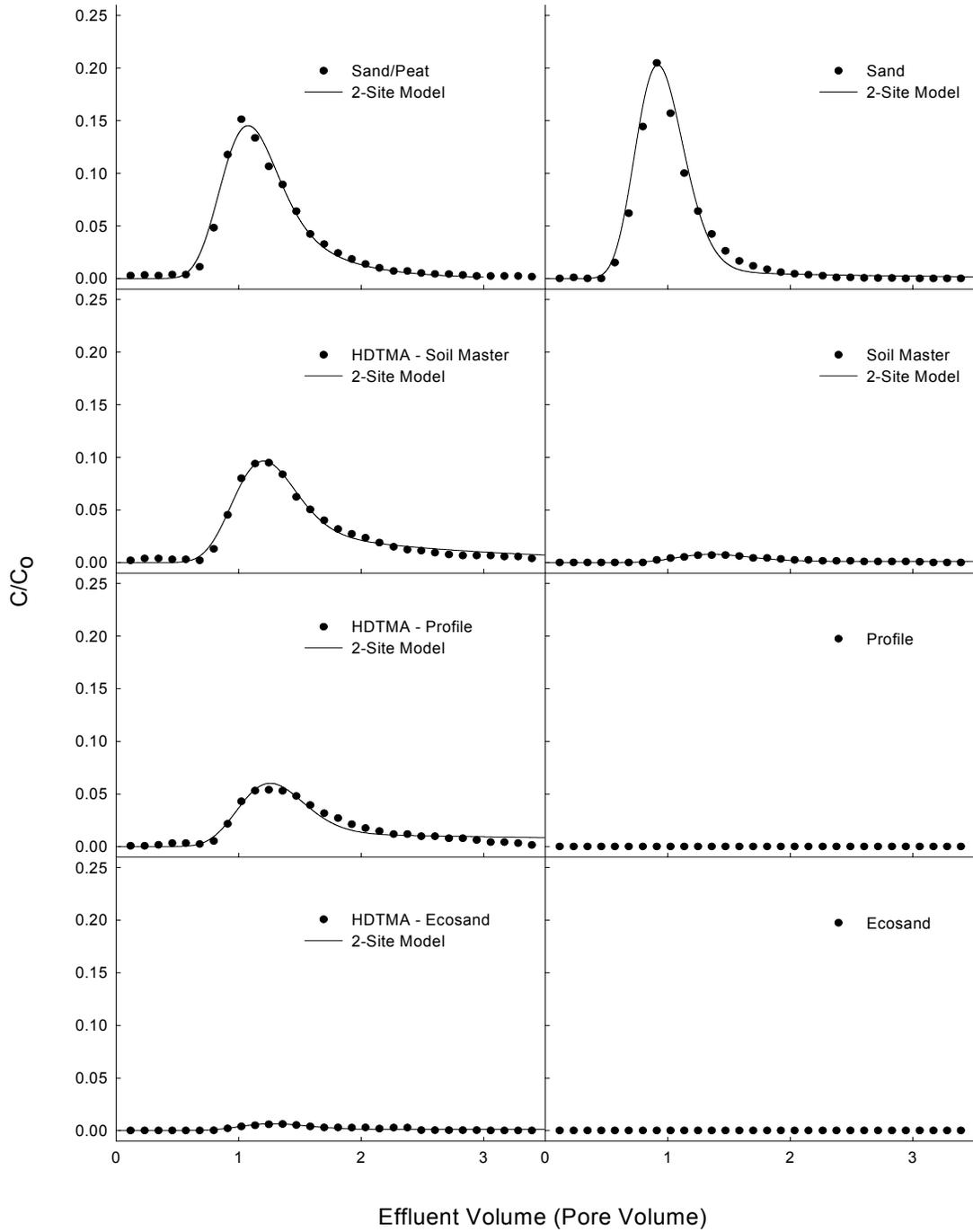


Figure 4-8. Ammonium breakthrough curves as influenced by filter zone media.

differences in total $\text{NH}_4\text{-N}$ leached were observed between columns containing sand and sand/peat. This indicates the CEC increase associated with peat addition (Table 4-3) is enough to delay $\text{NH}_4\text{-N}$ leaching, but will not prevent $\text{NH}_4\text{-N}$ from leaching under these conditions. These findings are in contrast to previous research. In general, past research has shown that under normal growing conditions, leaching of $\text{NH}_4\text{-N}$ is minimal due primarily to the rapid conversion of $\text{NH}_4\text{-N}$ to $\text{NO}_3\text{-N}$ in well-aerated soils that contain an adequate microbe population (Petrovic 1990; Reddy, 1982; Tate, 1977). Thus, inclusion of peat into a sand-based media has been shown to reduce $\text{NH}_4\text{-N}$ leaching by as much as 70% (Bigelow et al., 2003). However, this study was conducted under a worse-case scenario in which oxygen was limited and percolation rates were high. Therefore, nitrification was likely limited and, thus, peat did not have as great an influence on total $\text{NH}_4\text{-N}$ leached as previous research might indicate.

Addition of a filter layer containing unmodified amendments reduced $\text{NH}_4\text{-N}$ leaching by 98%. (Table 4-18). No $\text{NH}_4\text{-N}$ was detected in leachate from columns containing zeolite while 6% of applied $\text{NH}_4\text{-N}$ leached through calcined clay 1. Decreased $\text{NH}_4\text{-N}$ leaching from zeolite amended sand than from CC amended sand was also observed by Bigelow et al. (2003). The removal of $\text{NH}_4\text{-N}$ from leachate in this study was likely due to two factors. First, because CCs and zeolites possess relatively high CECs (Table 4-2), they each have the capacity to remove large amounts of cations from solution. Sorption isotherms showed that CCs are capable of adsorbing between 55 and 65 mg kg^{-1} $\text{NH}_4\text{-N}$, while zeolites which possess a higher CEC are capable of adsorbing 260 mg kg^{-1} $\text{NH}_4\text{-N}$ (Fig A-10, Fig A-11, Fig A-12). Secondly, amendments were placed in each column in a 2 cm thick layer below the rootzone which forced all

Table 4-18. Total NH₄-N leached as influenced by filter zone media.

Root zone media	Filter zone media	NH ₄ -N Leached	
		--- (mg) ---	% of Applied
Sand/Peat	Clinoptilolite 1 (1)	0.0	0.0
Sand/Peat	Calcined clay 2 (2)	0.0	0.0
Sand/Peat	Calcined clay 1 (3)	1.5	6.0
Sand/Peat	HDTMA-Clinoptilolite 1 (4)	1.0	4.0
Sand/Peat	HDTMA-Calcined clay 2 (5)	12.5	50.4
Sand/Peat	HDTMA-Calcined clay 1 (6)	18.2	73.3
Sand/Peat	Sand (7)	22.7	91.5
Sand	Sand (8)	23.1	93.1
Contrast: 1 vs. 4		NS	
Contrast: 2 vs. 5		***	
Contrast: 3 vs. 6		***	
Contrast: 7 vs. 8		NS	
Contrast: 7 vs. 4		***	
Contrast: 7 vs. 5		***	
Contrast: 7 vs. 6		***	
CV (%)		12.9	

NS, ***, Not significant, significant at 0.001 probability level respectively.

leachate to pass through each amendment. It is probable that the thickness of this layer directly influences the retention of potential contaminants. The influence of filter layer thickness is of concern and future research in this area would be valuable.

When CCs were coated with HDTMA, each amendments capacity to retain NH₄-N decreased (Fig A-10, Fig A-11). Thus, more NH₄-N leached through columns containing HDTMA-coated calcined clay 1 and calcined clay 2 than columns containing their unmodified counterparts (Table 4-18). Only a minor decrease in NH₄-N retention was observed from HDTMA-clinoptilolite 1 (Fig A-12). Thus, columns containing clinoptilolite 1 and HDTMA-clinoptilolite 1 leached similar amounts of NH₄-N (Table 4-18). The influence of SMSA on decreasing NH₄-N leaching in order of decreasing effectiveness was: clinoptilolite 1 > calcined clay 2 > calcined clay 1. These results

correspond well with each amendment's CEC and S_{\max} . Clinoptilolite 1 had the highest CEC and S_{\max} and, thus, leached the least amount of $\text{NH}_4\text{-N}$. Coated calcined clay 2 had a higher ECEC than coated calcined clay 1 and, thus, less $\text{NH}_4\text{-N}$ leached through columns containing HDTMA-calcined clay 2 than HDTMA-calcined clay 1 (Table 4-18).

Phosphorus

Similar peak P concentrations were observed in leachate from columns containing sand and sand/peat (Fig. 4-9). However, a broader peak produced from sand/peat columns than from sand alone. Background levels of P in leachate between 0.0-0.5 pore volumes indicate columns containing sand/peat leached P not associated with the nutrient solution. When determining P leached as a percent of applied, this would artificially inflate the amount of P applied. However, columns containing sand/peat underlined with unmodified amendments leached 101% of applied P (Table 4-19). This amount seemed reasonable until leachate from columns containing only sand were analyzed. Only 88% of applied P leached from the column that contained only sand. These results indicate that a portion of P applied to sand/peat rootzones may be retained by sand, while peat may exacerbate P leaching. These findings agree with previous researcher by Brown and Sartain (2000). Brown and Sartain investigated P leaching from USGA greens from three P-source fertilizers. They reported as much as 70% more P leached from columns containing peat than from those containing only sand. Despite fertilizer source, columns in Brown and Sartain's study containing sand/peat leached more P than those without peat, in all cases.

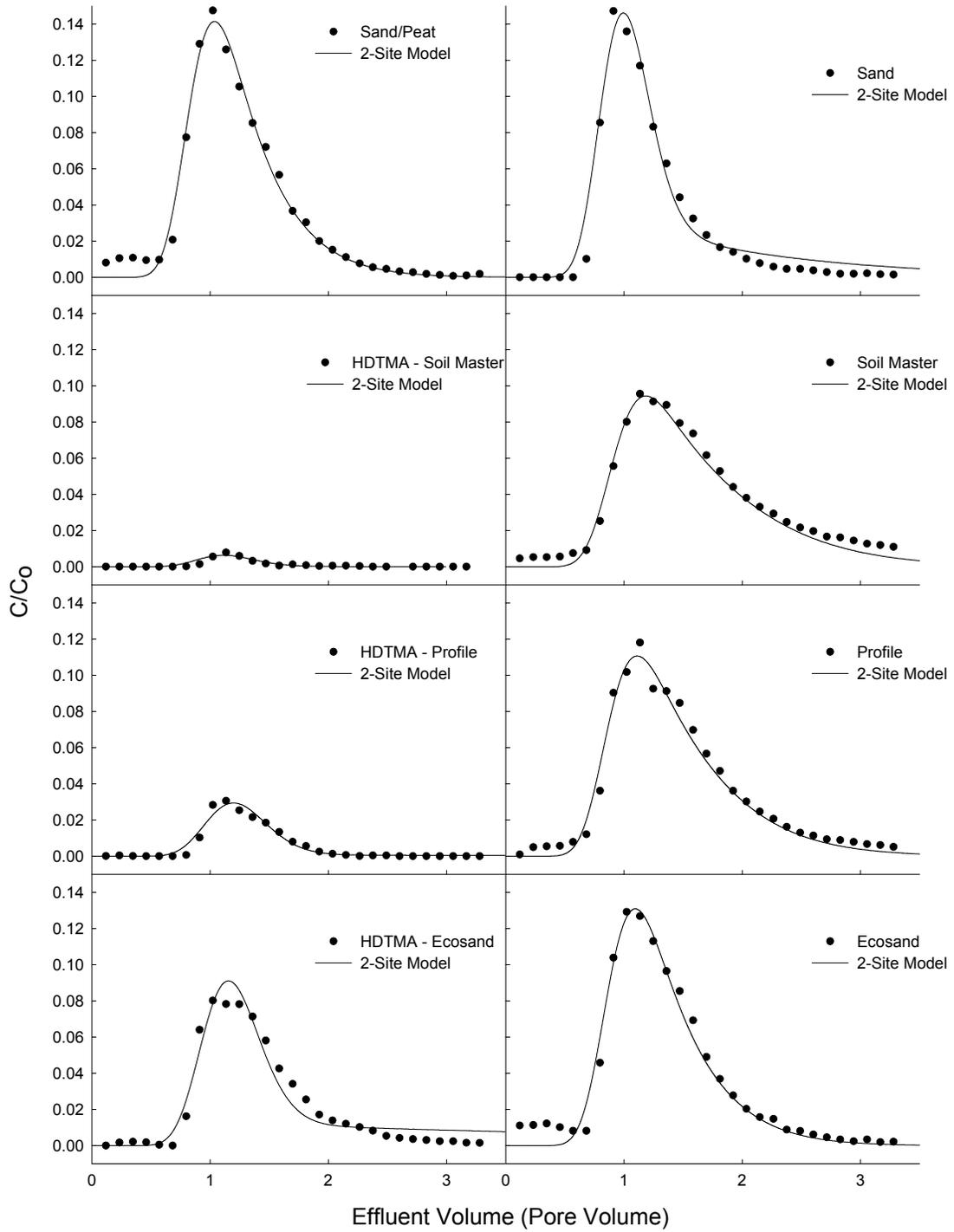


Figure 4-9. Phosphorus breakthrough curves as influenced filter zone media.

Breakthrough curves produced from columns containing CCs indicate P movement was retarded (Fig 4-9). Calcined clays reduced maximum effluent concentration by as much as 30%. However, they were unable to retain P against percolate flow as indicated by the broaden peaks. This is further reinforced by the percent of applied P that was leached (Table 4-19). Since neither CCs possesses any appreciable AEC, retardation of P through CC amended columns is likely due to the Fe levels determined via Mehlich I extraction (Table 4-2). Phosphorus has been shown to be strongly sorbed by Fe-containing compounds (Makris et al., 2004; Brown and Sartain, 2000). Furthermore, sorption isotherms indicate calcined clay 1 and calcined clay 2 are capable of sorbing approximately 1600 and 700 mg P kg⁻¹ (Fig A-13, A-14).

When CCs were coated with HDTMA, maximum effluent P concentrations were

Table 4-19. Total Phosphorous leached as influenced by filter zone media.

Root zone media	Filter zone media	P Leached	
		--- (mg) ---	% of Applied
Sand/Peat	Clinoptilolite 1 (1)	44.2	100.4
Sand/Peat	Calcined clay 2 (2)	44.3	100.6
Sand/Peat	Calcined clay 1 (3)	44.8	101.8
Sand/Peat	HDTMA-Clinoptilolite 1 (4)	23.7	53.8
Sand/Peat	HDTMA-Calcined clay 2 (5)	7.2	16.3
Sand/Peat	HDTMA-Calcined clay 1 (6)	1.3	2.9
Sand/Peat	Sand (7)	44.5	101.1
Sand	Sand (8)	38.6	87.7
Contrast: 1 vs. 4		***	
Contrast: 2 vs. 5		***	
Contrast: 3 vs. 6		***	
Contrast: 7 vs. 8		**	
Contrast: 7 vs. 4		***	
Contrast: 7 vs. 5		***	
Contrast: 7 vs. 6		***	
CV (%)		6.9	

** , *** , Significant at 0.01, 0.001 probability level respectively.

reduced by approximately 90%. Breakthrough curves for coated CCs indicated P movement was not only retarded, but P was also retained against water flow. Columns containing coated calcined clay 1 leached 3% of applied P while coated calcined clay 2 leached 16% (Table 4-19). The amount of P leached from CCs directly correlated with each amendments EAEC (Table 4-1). Furthermore, analysis of sorption isotherms indicates that HDTMA coating can increase its capacity to sorb P by as much as 100% (Fig A-14).

No differences were observed between the breakthrough curves for columns containing clinoptilolite 1 versus sand as the filter zone media (Fig. 4-9). Clinoptilolite 1 has extractable iron levels similar to that of USGA sand, thus, little or no differences were observed. However, coated clinoptilolite 1 both retained and retarded P movement. Addition of coated clinoptilolite 1 reduced P leaching by 46% (Table 4-19). Sorption isotherms indicate S_{\max} of HDTMA-clinoptilolite 1 is 5 times lower than that of calcined clay 1 (Fig. A-15). Thus, greater P leaching was observed from zeolite than from CCs.

CHAPTER 5 CONCLUSIONS

Soil Amendments

I reject H_0 : soil amendments do not influence turf quality, dry matter yield, or WUE and conclude soil amendments do influence turf quality, dry matter yield, and WUE of Tifdwarf bermudagrass. Iron humate, and to a lesser degree CCs, provided superior turf quality, dry matter yield, and WUE than all other amendments investigated. Turf grown in pure sand produced unacceptable turf quality, decreased turf yield, and low WUE. Therefore, it is recommended that iron humate or CCs be used when attempting to increase turf quality or WUE of Tifdwarf bermudagrass. However, if an N-source fertilizer containing primarily NO_3 instead of NH_4 was used, or if zeolites were NH_4 -loaded prior to incorporation, zeolites may be an effective amendment for use in putting green construction. Additional research in this area would be valuable.

Incorporation Method

I reject H_0 : incorporation method does not influence turf quality, dry matter yield, or WUE and conclude incorporation method does influence turf quality, dry matter yield, and WUE of Tifdwarf bermudagrass. Only iron humate produced superior quality, yield, and WUE than other amendments regardless of incorporation method. The influence of all other amendments was reduced upon incorporation following aerification. Therefore, it is recommended that amendments be fully incorporated into putting green rootzones in order to maximize their effectiveness. The practical implications of this research are that during periods of low moisture availability, Tifdwarf WUE can be increased while

maintaining acceptable turf quality via the use of certain soil amendments. However, the influence of soil amendments on turf WUE and quality during periods of adequate moisture and nutrients availability remains ambiguous. It is likely that during these periods, soil amendments may not influence turf growth and development. Thus, further research regarding this concern would be valuable.

Nutrient Leaching

I fail to reject H_0 : soil amendments do not reduce NO_3^- or PO_4^{-2} leaching. Nitrate breakthrough curves and applied NO_3 leached show soil amendments have little or no influence on NO_3 leaching. Calcined clays did slow P movement but were incapable of reducing total P leached. These results show that P movement can be slowed by incorporating CCs into a filter-zone below the rootzone of USGA putting greens. However, if water movement persists, P may not be retained and could leach to ground water. I reject H_0 : soil amendments do not reduce NH_4 leaching, and conclude soil amendments do reduce NH_4 leaching. Ammonium leaching was nearly eliminated via soil amendment incorporation. Higher CEC amendments, such as zeolites, may have a greater affinity and capacity to retain NH_4 against leaching than CCs. Future research in this area would be warranted.

I reject H_0 : SMSA do not reduce NO_3^- , NH_4^+ , or PO_4^{-2} leaching, and conclude soil amendments do reduce NO_3^- , NH_4^+ , or PO_4^{-2} leaching. The influence of SMSA on reducing nutrient leaching was directly or, in the case of NH_4^+ indirectly, related to each amendment's EAEC. With the incorporation of SMSA into the filter layer, NO_3^- and PO_4^{-2} movement may not only be slowed but may be retained, effectively reducing the potential for groundwater contamination. The practical implications of this study are that during periods of normal fertilizer applications but excessive leaching, N and P

movement through golf course putting greens can be reduced or eliminated via the use of surfactant-modified soil amendments. However, further research is needed prior to use recommendations. Bi-layer stability and longevity in a dynamic soil system have not been investigated nor have any potential environmental influences. Furthermore, the influence of SMSA on turf growth and development is unknown and may be detrimental. Research in this area must be conducted prior to incorporating these products in a putting green.

APPENDIX
MISCALLENEOUS GRAPHS AND TABLES

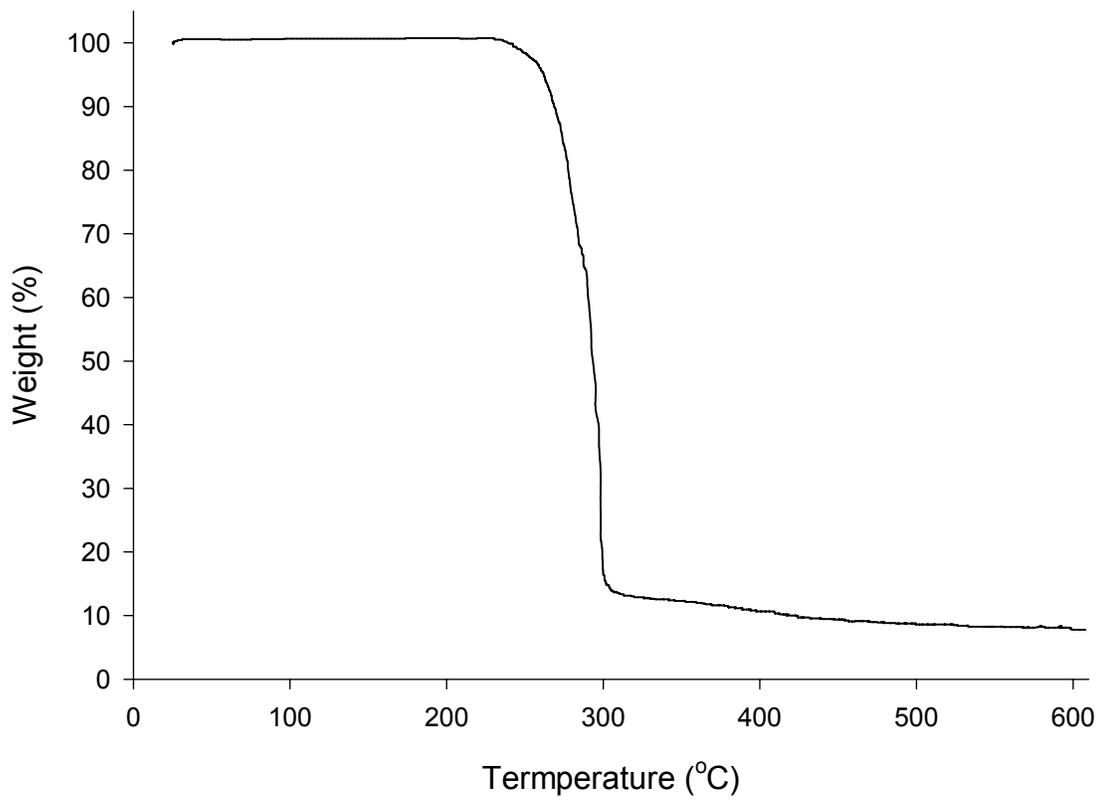


Figure A-1. Thermal gravimetry analysis of HDTMA.

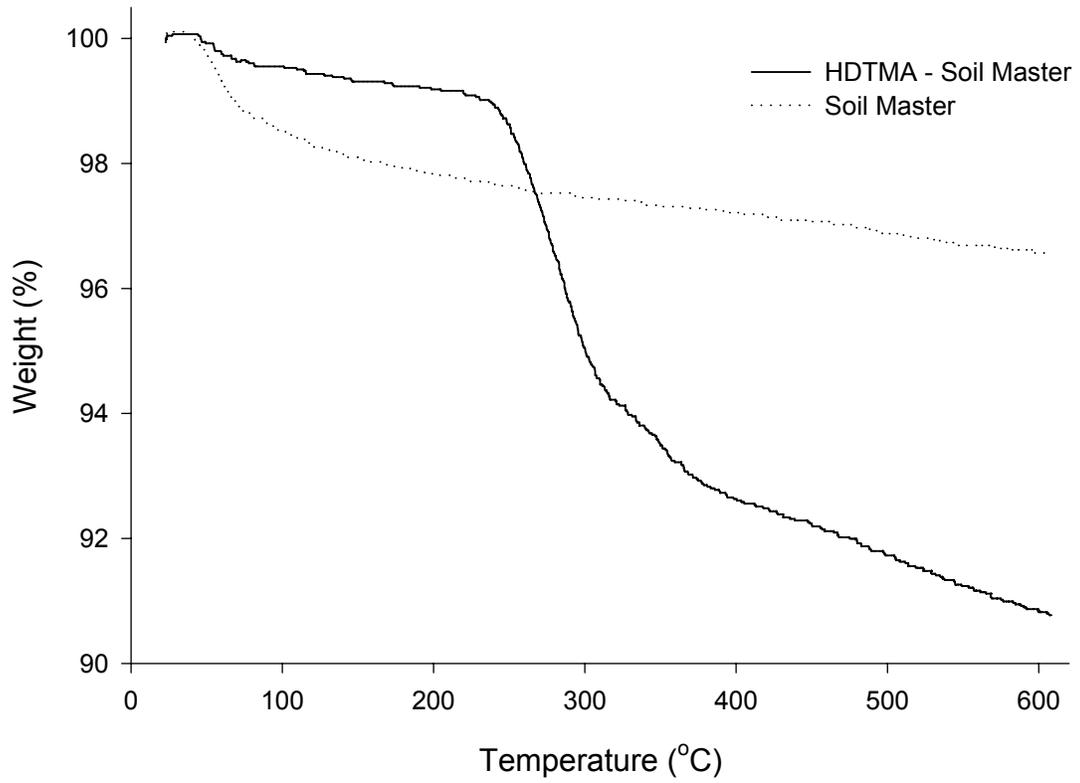


Figure A-2. Thermal gravimetry analysis of HDTMA coated calcined clay 1.

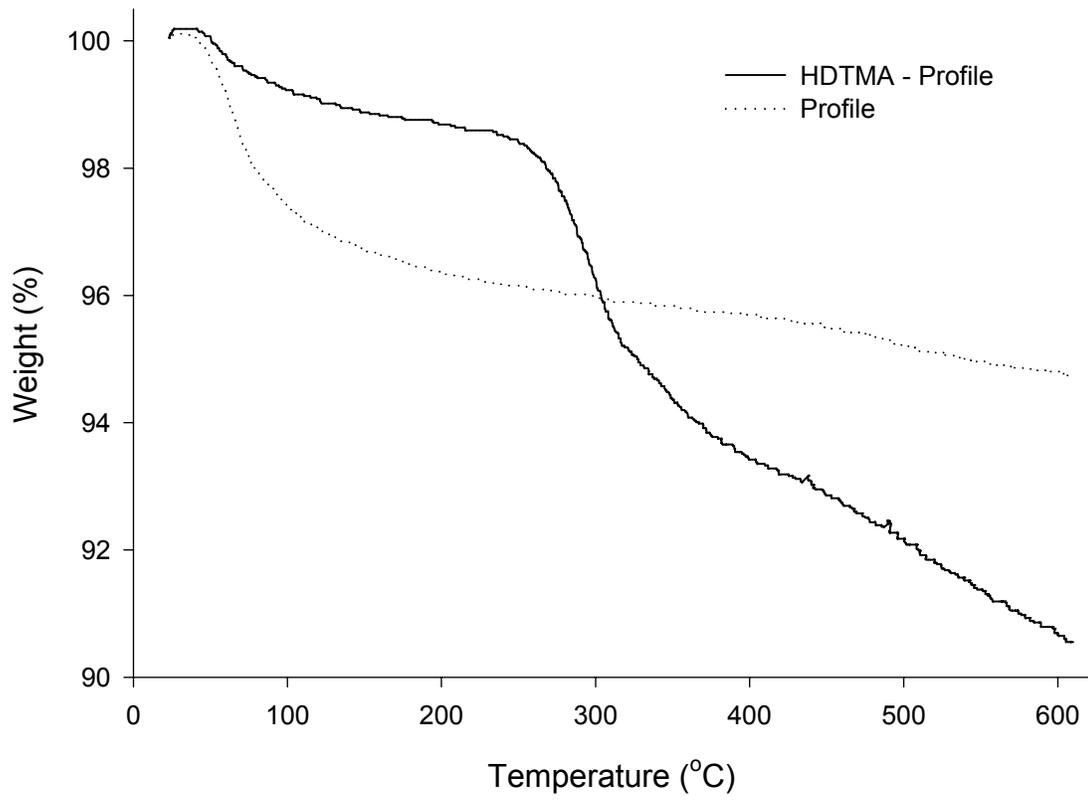


Figure A-3. Thermal gravimetry analysis of HDTMA coated calcined clay 2.

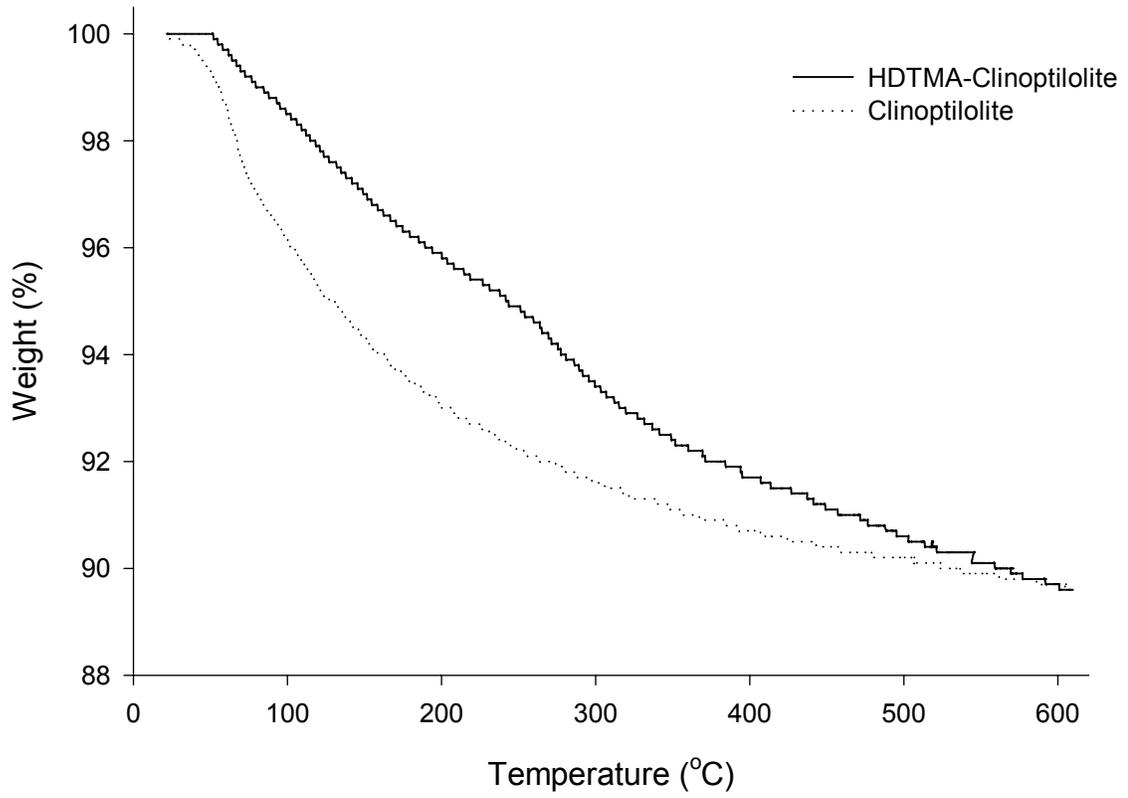


Figure A-4. Thermal gravimetry analysis of HDTMA coated clinoptilolite.

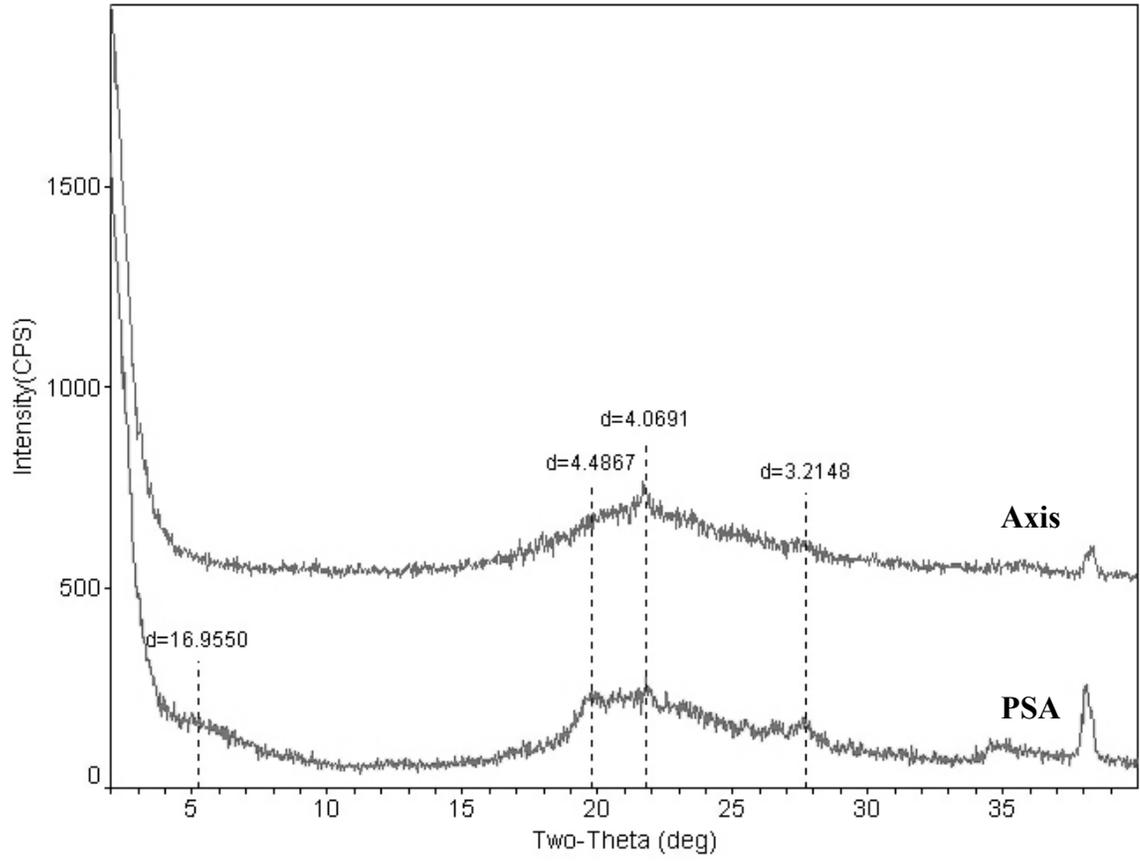


Figure A-5. X-ray diffractogram of diatomaceous earths in a side-packed powder mount.

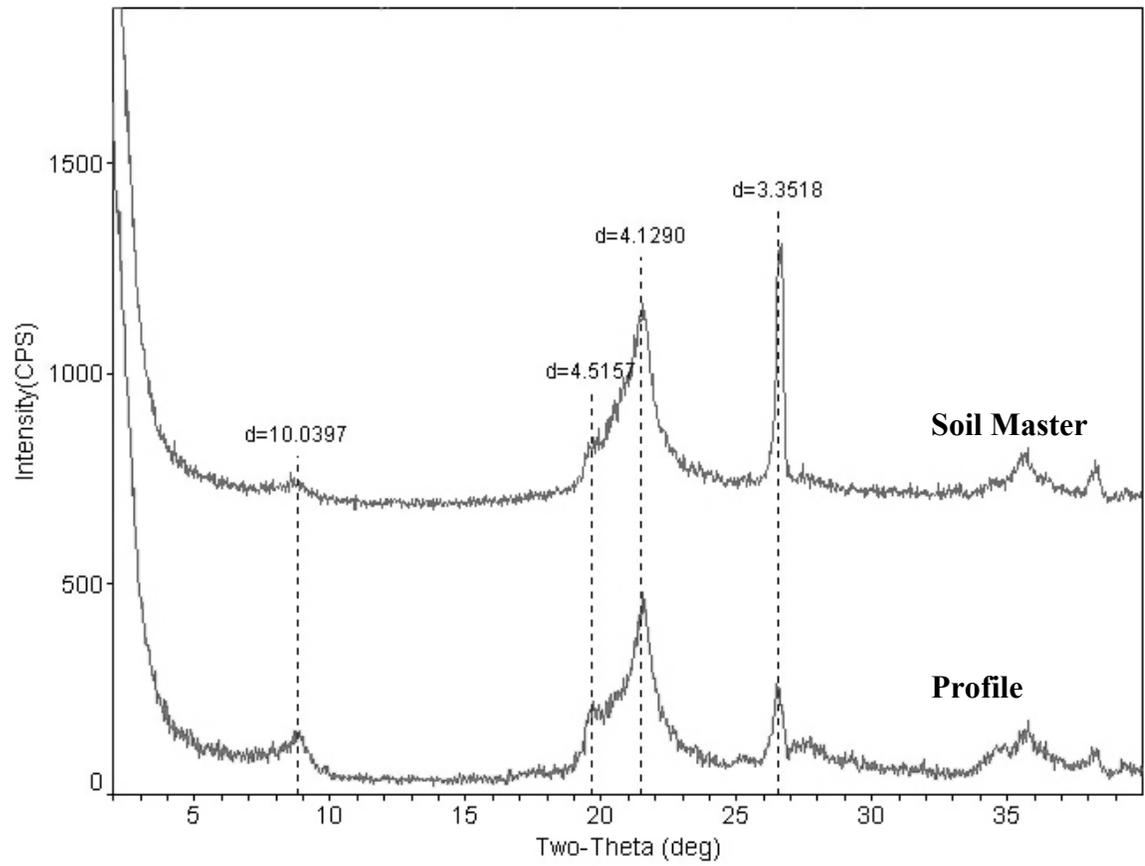


Figure A-6. X-Ray diffractogram of calcined clays in a side-packed powder mount.

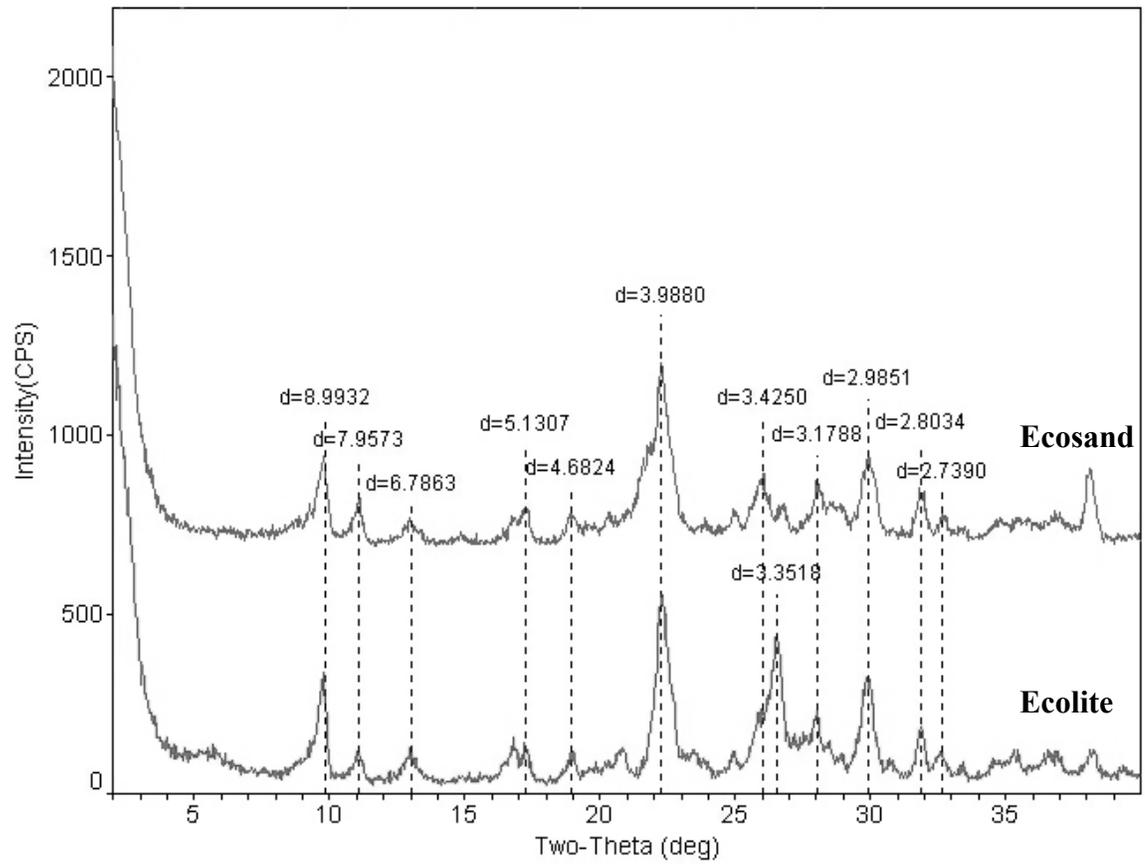


Figure A-7. X-Ray diffractogram of zeolites in a side-packed powder mount.

Table A-1. Chemical properties of irrigation water used in glasshouse and field studies.

	Field	Glasshouse
pH	7.1	6.8
EC ($\mu\text{S cm}^{-1}$)	0.2	0.1
P (mg L^{-1})	0.2	0.1
K (mg L^{-1})	0.9	0.2
Ca (mg L^{-1})	81.9	45.2
Mg (mg L^{-1})	9.6	2.2
Zn (mg L^{-1})	0.0	0.0
Mn (mg L^{-1})	0.0	0.0
Cu (mg L^{-1})	0.0	0.0
Fe (mg L^{-1})	0.0	0.0

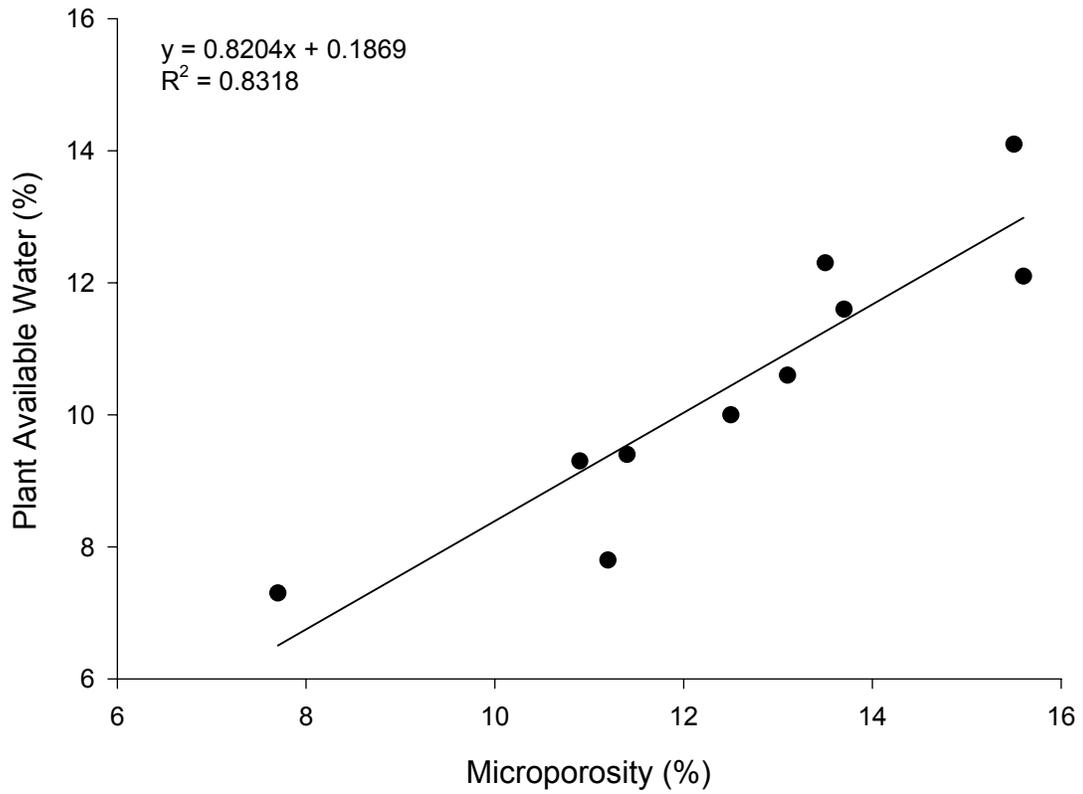


Figure A-8. Correlation between microporosity and plant available water of amendment/sand mixture at 85:15 by volume.

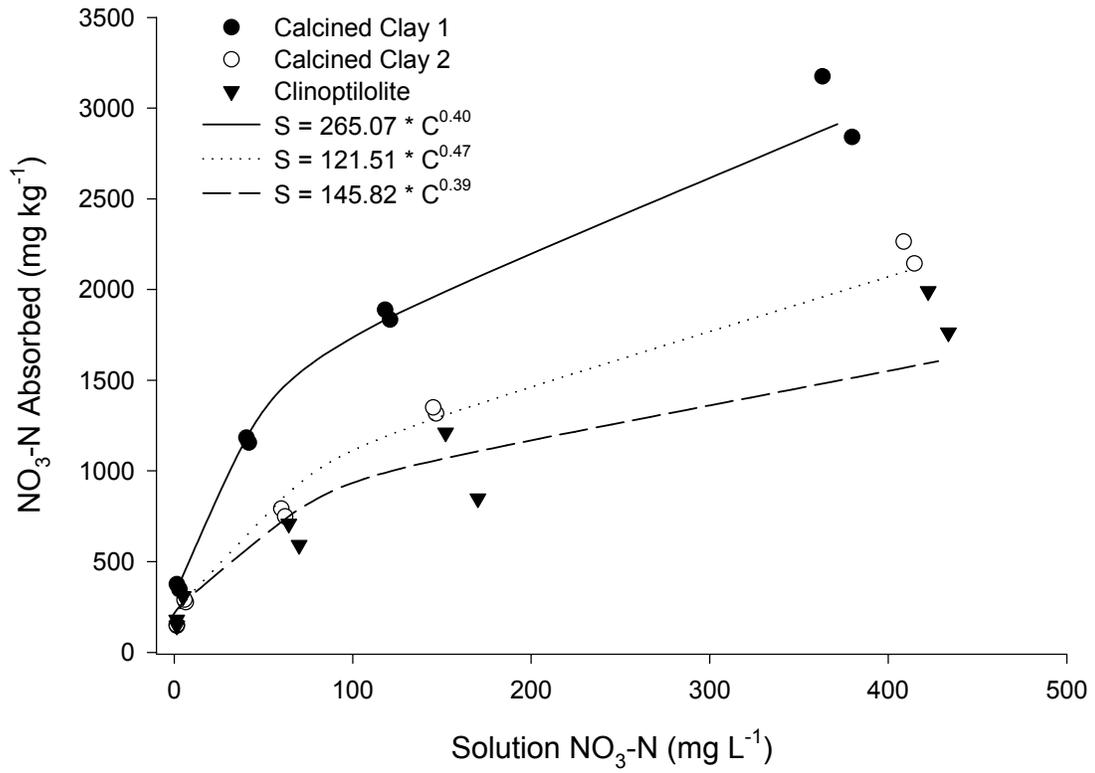


Figure A-9. Nitrate sorption isotherm for surfactant-modified soil amendments.

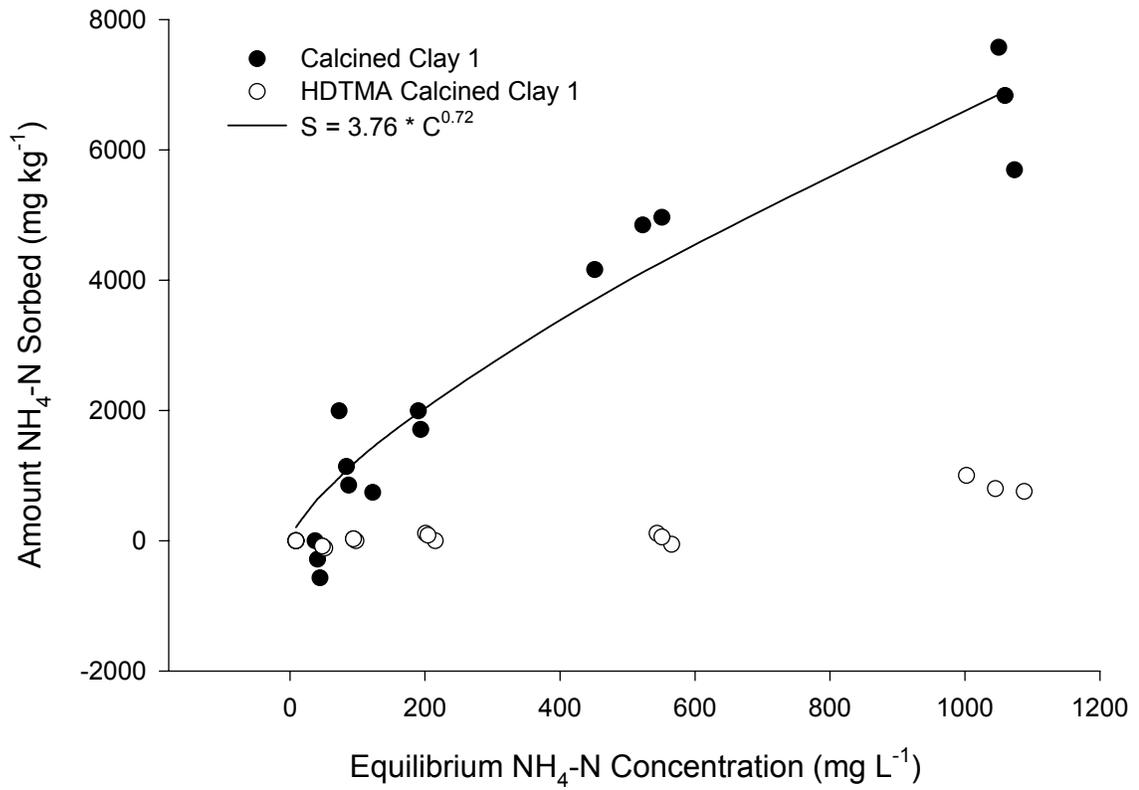


Figure A-10. Ammonium sorption isotherm for uncoated and HDTMA coated calcined clay 1.

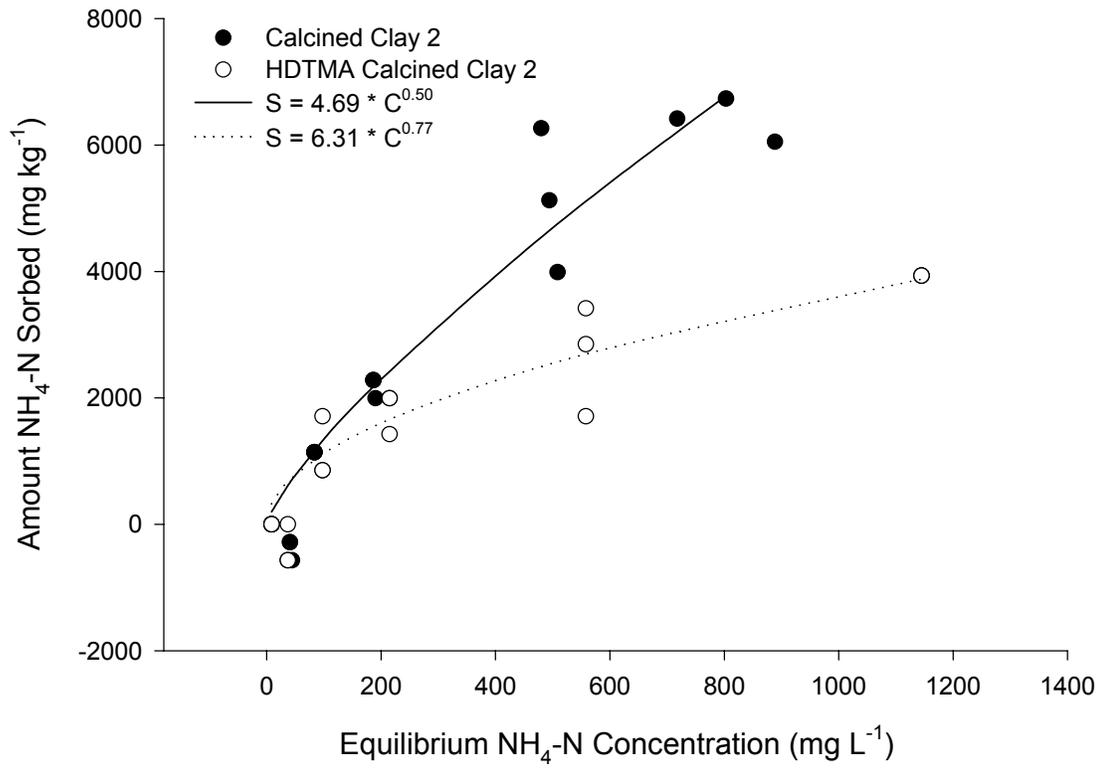


Figure A-11. Ammonium sorption isotherm for uncoated and HDTMA coated calcined clay 2.

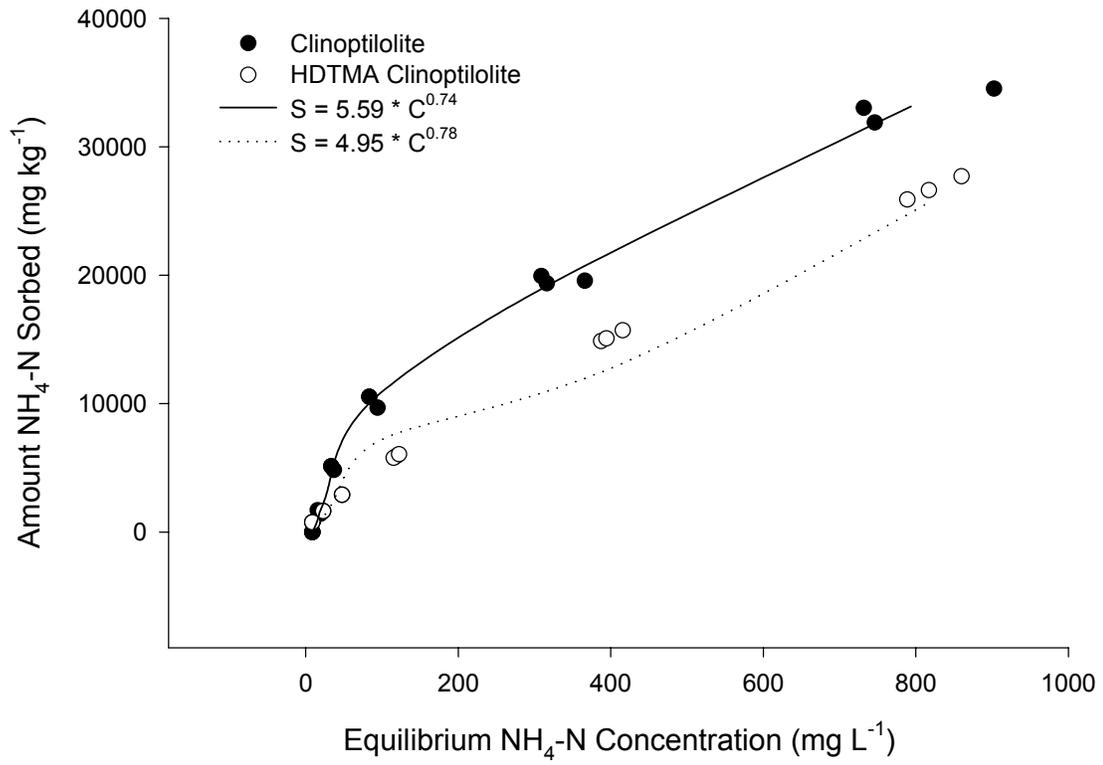


Figure A-12. Ammonium sorption isotherm for uncoated and HDTMA coated clinoptilolite.

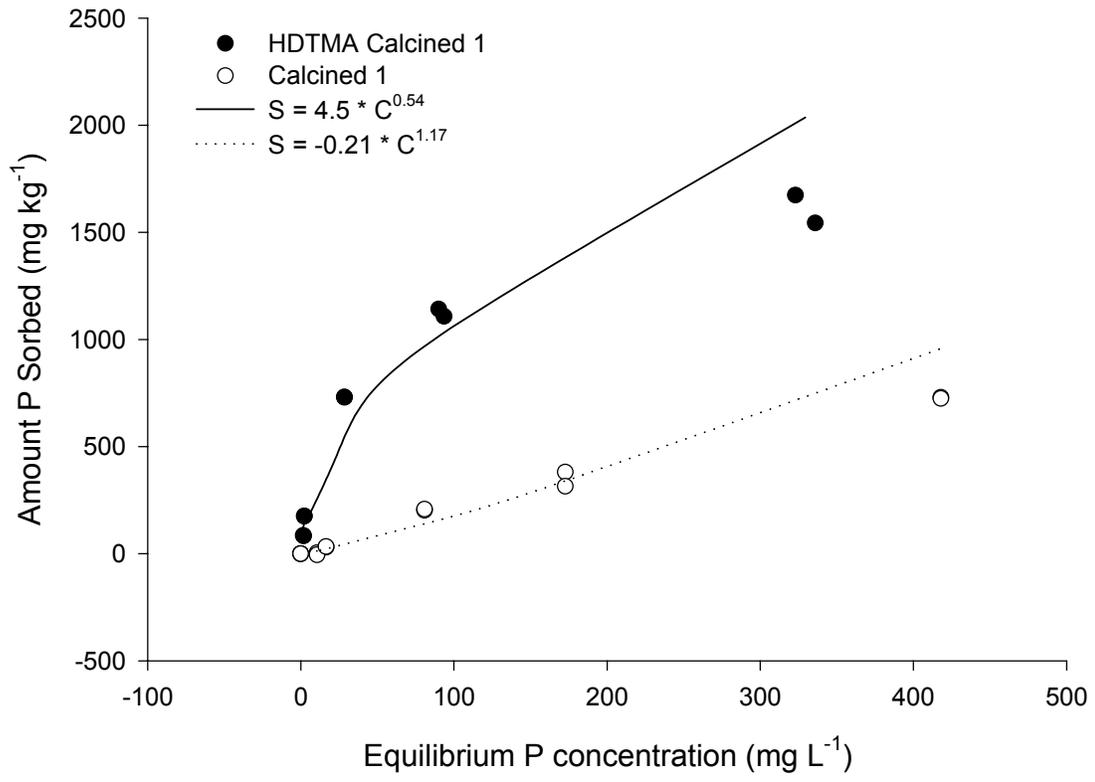


Figure A-13. Phosphorus sorption isotherm for uncoated and HDTMA coated calcined clay 1.

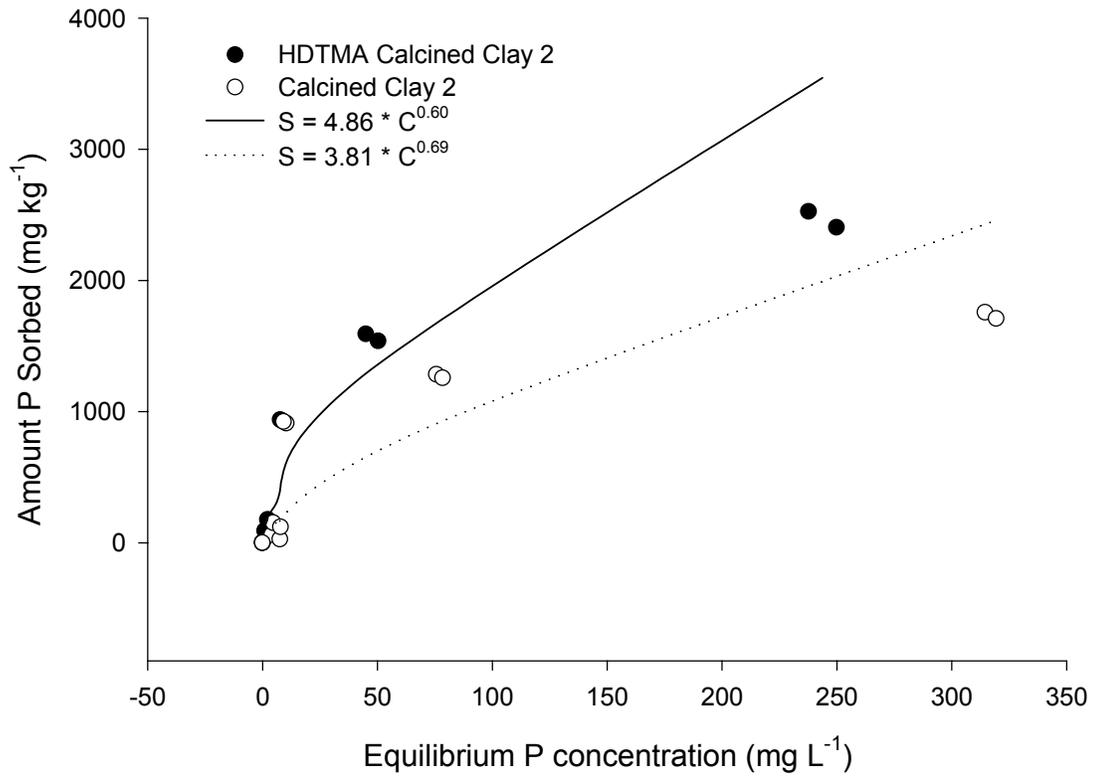


Figure A-14. Phosphorus sorption isotherm for uncoated and HDTMA coated calcined clay 2.

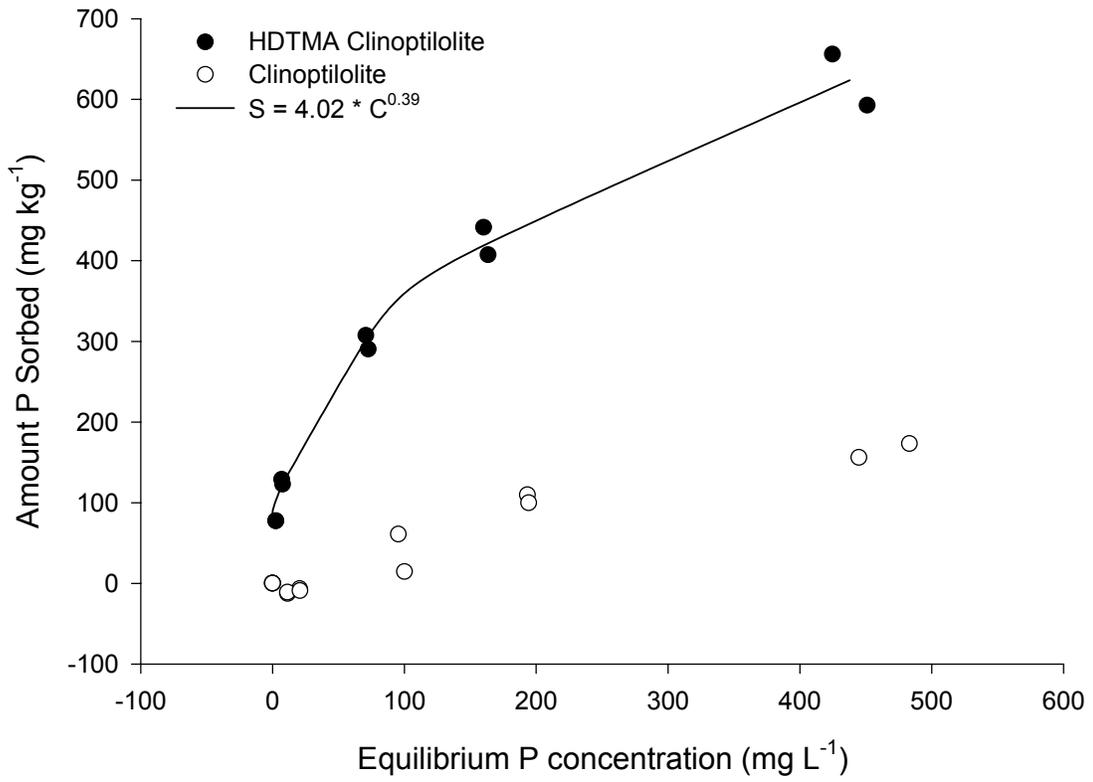


Figure A-15. Phosphorus sorption isotherm for uncoated and HDTMA coated clinoptilolite.

Table A-2. Phosphorous and ammonium leaching parameters for the 2-site model.

Root zone media	Filter zone media	----- P -----				----- NH ₄ -----			
		P†	β‡	ω§	R¶	P	β	ω	R
Sand/Peat	Zeolite 1	43	0.810	1.05	1.26	UD#	UD	UD	UD
Sand/Peat	CC 2	43	0.740	1.32	1.38	UD	UD	UD	UD
Sand/Peat	CC 1	43	0.700	1.41	1.56	43	0.030	3.22	51.8
Sand/Peat	HDTMA-Zeolite 1	43	0.340	0.74	3.46	43	0.029	3.52	50.83
Sand/Peat	HDTMA- CC 2	43	0.012	1.84	108.04	43	0.308	1.02	4.26
Sand/Peat	HDTMA- CC 1	43	0.003	3.65	405.27	43	0.650	0.62	1.86
Sand/Peat	Sand	43	0.820	0.99	1.18	43	0.880	0.12	1.29
Sand	Sand	43	0.680	0.44	1.45	43	0.830	0.12	1.09

† Peclet number

‡ fraction of instantaneous retardation

§ Damkohler number

¶ Retardation Factor

undetermined

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BIOGRAPHICAL SKETCH

Travis Shaddox was born in Shawnee, Oklahoma, on February 10, 1976. After receiving his bachelor's degree in horticulture from Oklahoma State University in 1999, he moved to Gainesville with the hopes of attending the University of Florida. He was accepted to the university as a graduate student with Dr. Jerry Sartain. Throughout the next two years he investigated nitrogen leaching during turfgrass establishment, and in 2001, he fulfilled his requirements and was awarded a Master of Science degree.

Having enjoyed his experience in Gainesville, he wished to remain there to continue working on his doctorate degree. As luck would have it, Dr. Sartain again received Travis as his graduate student to continue his work towards a Ph.D. degree in the Soil and Water Science Department at the University of Florida. After earning his degree, Travis would like to continue using his knowledge and skills in fertilizers and soil fertility at either a university or industry position.