COMPACTION ON SAND-BASED PUTTING GREENS IN THE LOWER FRASER VALLEY

by

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Abstract

Core aeration is a cultivation practice used to reduce soil compaction on sand-based putting greens. The objective of this study was to determine the effects of core aeration and play traffic on compaction of sand-based putting greens in the lower Fraser Valley of British Columbia. The experiment was carried out from March 2002 to May 2004 as a randomized complete block design with three replications. The treatments were (i) regular management practices, including core aeration, and high traffic (CA-HT), (ii) regular management practices, no core aeration, and high traffic (NCA-HT), and (iii) reduced management practices, no core aeration, and low traffic (NCA-LT).

Similar soil organic matter content and root weight density were found on treatments with and without core aeration with the exception of one date (March 27, 2002). Soil water content of the mat layer on CA-HT was lower relative to NCA-HT on three out of four sampling dates that occurred a month after core aeration. Two months following core aeration soil water contents were similar among all treatments. Water retention was not affected by core aeration or play traffic intensity.

Mat layer soil bulk density was lower on NCA-LT then NCA-HT and CA-HT at two out of six sampling dates. There was no difference in soil bulk density of the mat layer between CA-HT and NCA-HT, with an exception of one date (June 18, 2003). Soil penetration resistance on NCA-LT was lower relative to the other two treatments at depths below 3 cm. About one month after core aeration soil penetration resistance was lower for CA-HT than NCA-HT treatment. Greater water infiltration rates were observed on NCA-LT than on the other two treatments. Water infiltration rates showed that about a month after core aeration CA-HT had greater infiltration than NCA-HT. This difference disappeared when measurements were taken three and five months after core aeration.

Soil penetration resistance and water infiltration measurements indicated that core aeration reduced compaction on sand-based putting greens, but the effects were temporary and differences observed between treatments disappeared within several months following application.

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GLOSSARY

Aerification	A method of cultivation during which hollow or solid tines or spoons are inserted into and removed from the turf to control compaction and increase water and fertilizer penetration.
Brushing	Mechanical application of bristle brooms to promote horizontal turf growth and to improve quality of the cut.
Coring	Equivalent to core aeration.
Cultivation	The disturbance of soil and/or thatch layer without destroying the turf (e.g., aerifying, slicing, spiking, slitting, verti-cutting).
Mat	A tan to brown colored tightly intermingled layer of thatch intermixed with soil or sand.
Putting green	A highly maintained area of short cut turf (typically 3-4 mm) of about 400-600 m^2 where a cup is placed for players to putt into.
Rolling	Use of a mechanical roller to smooth the playing surface of putting greens.
Slicing	A turf cultivation practice where vertical blades (up to 15 cm long) are inserted into turfgrass to improve aeration and cut through stolons, rhizomes, and thatch.
Slitting	Occurs during the turf cultivation practice of verti-cutting where a narrow groove (1-2 mm wide) is cut down into turf, usually at a depth of 3to 25 mm depending on the desired impact on turf.
Sod	Vegetative planting material consisting of turfgrass strips with of without adhering soil.
Spiking	A turf cultivation practice where solid tines penetrate into turf and soil surfaces.
Thatch	A brown to black colored layer of dead grass leaves, stems, rhizomes, crowns, and stolons found between the living tissue and the soil or sand below.
Topdressing	Addition of a fine sand, soil, or fertilizer to surfaces of established turf. In the case of putting greens added sand is often brushed into turf surfaces.
Turf	An interconnected uniformly grown cover of mowed vegetation with roots and adhering soil and other below ground organisms.
Turfgrass	Plants that form a continuous ground cover that persist under regular mowing and traffic.
Verti-cutting	A turf cultivation practice where a narrow groove (1-2 mm wide) is cut down into turf, usually at a depth of 3 mm, to stimulate shoot growth or to remove organic matter.

Wetting Agent Substance that reduces surface tension and causes liquids to make better contact with root zone soil or sand.

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1. INTRODUCTION

British Columbia (BC) has the third largest number of golf courses (about 225) among all provinces and territories in Canada with about 11 million rounds of golf played per year (Royal Canadian Golf Association, 1999). A mild, humid maritime climate that allows almost year-round golf playing season and a wide variety of topography make the lower Fraser Valley of BC a highly suitable for golf course development. Hence, about 25% of BC's golf courses are located in this region.

Golf courses and particularly putting greens (areas where a cup is placed for players to putt into) are exposed to a large number of management practices (mowing, fertilizer application, cultivation, rolling, brushing, sand topdressing, irrigation). In addition, putting greens that occupy about 2% of the total area of a golf course receive more than 50% of foot or play traffic. These numerous disturbances may lead to soil compaction. Soil compaction is a process of increasing bulk density (and associated reduced porosity) by the application of external forces to the soil (Hillel, 1998). Plant growth can be limited on compacted soils due to loss of macropores and increase of micropores that in turn restrict aeration, root penetration, and drainage. The plant growth response may be more dependant on the extent to which soil-water relationships are affected by compaction than on absolute changes of soil physical properties (Unger and Kaspar, 1994).

Prior to 1950s the majority of putting greens were constructed on naturally developed soils but raised intensity of management practices and play traffic often led to soil compaction and poor turf quality (Mayer, 1998). The initial solution to overcome these problems was to construct putting greens on mixes of sand, soil, and organic matter (at volume ratio of 1:1:1). In spite of sand additions those putting greens still needed intensive application of various management practices. The first specifications for construction of sand-based putting greens were published by the United States Golf Association in 1960 (USGA Green Section Staff, 1960). Subsequent revisions, published in 1973, 1989, and 1993, recommended that pure sand (less than 8% silt and clay) be used to improve drainage and resistance to compaction (USGA Green Section Staff, 1993). Sand as a non-cohesive material resists compaction better than either medium- or fine-textured soils. This is particularly true for sand in dry and saturated states. Loose, dry sand (with very little or no organic matter) is characterized by low bulk density and high porosity, due to open packing of individual sand grains. As dry sand is exposed to a pressure or application of vibratory action, packing density increases (i.e., becomes closely packed), thus increasing bulk density and reducing porosity. The same is true for sand under saturated conditions.

Even though sand-based putting greens are generally less susceptible to compaction than the soil-based putting greens, cultivation practices (such as core aeration) are still frequently used. Core aeration has been commonly used since the development of the first core aeration machine in 1946 by the West Point Products Corporation (Hanson et al., 1969). This practice was originally developed to reduce compaction and improve drainage and aeration on putting greens developed on fine to medium-textured soil. During core aeration small cores of soil and turfgrass are removed from the surface leaving holes usually of 1-1.9 cm in diameter and 5-10 cm deep (depending on tine size). The holes are filled with sand to prevent collapse or deformation of the turf surface and to improve water infiltration and drying of the putting green surface. The overall outcome of core aeration is creation of a deeper and more extensive root system and enhanced shoot density (Beard, 1973). The positive effects of core aeration are temporary and this practice is usually repeated several times per year as well as from year to year to ensure consistent turf health. For example, greater water infiltration rates on core aerated greens lasted for five to eight weeks before dropping to initial values on sand-based putting greens with creeping bentgrass (*Agrostis stolonifera* L.) and annual bluegrass (*Poa annua L.*) in Georgia (Carrow, 2004).

On most golf courses in North America as well as in the lower Fraser Valley of BC two applications of core aeration (spring and fall) are done annually on sand-based putting greens regardless of root zone conditions. Core aeration is highly disruptive to the turf surface of putting greens and expensive to implement. Consequently, identification of the most appropriate soil and vegetation indicators is essential for evaluating usefulness of core aeration on sand-based putting greens.

The objective of this study was to determine impacts of core aeration and foot traffic on compaction of sand-based putting greens in lower Fraser Valley. This study tested the hypotheses that (i) core aeration creates less compacted sand-based greens relative to the greens without this practice and (ii) high foot traffic leads to more compacted sand-based greens relative to greens with low foot traffic.

2. LITERATURE REVIEW

2.1 Core Aeration

Core aeration is a cultivation practice that involves the vertical penetration (up to 5 – 10 cm depth) of hollow tines (1.0 – 2.5 cm inside diameter) to remove soil cores from turfgrass. The first effective core aeration machine was developed in 1946 by West Point Products Corporation (Hanson et al., 1969) allowing for improved management of soil compaction. The primary goal of core aeration is to reduce soil compaction (McCarty, 2001). Carrow et al. (2004) indicated that core aeration will continue to be used, even on sand-based putting greens to ensure appropriate infiltration and drainage in the zone of highest organic matter accumulation.

Typically in most regions in North America, core aeration consists of spring and fall aeration events that are carried out to reduce soil compaction and accumulation of organic matter, integrate sand into the root zone, and increase soil aeration and water infiltration. Even though core aeration has many benefits its greatest disadvantages are disruptiveness of the turf surfaces and high cost.

A study by Wu et al. (2001) conducted in California on USGA designed greens with 89% sand, 7% silt, and 4% clay showed that water injection cultivation was equivalent to or better than core aeration at reducing soil bulk density and increasing porosity and saturated hydraulic conductivity at the top 7 cm of the turf surface. Infiltration rates were found to be 1.6 to 6.8 times greater for water injection cultivation than control plots with highest measurements recorded at 210 mm h^{-1}. Even though studies (Vanini, personal communication 2001; Wu et al., 2001) have tried to show that core aeration is not the only cultivation practice that can result in an increase of soil aeration and porosity, methods such as water injection, solid tine aeration, slicing, and spiking do not remove organic matter. According to Carrow (1997) summer cultivation practices that do not remove organic matter will not substitute for spring and fall core aeration followed with sand topdressing, since core aeration consistently maintains water infiltration rates by removing organic matter from the root zone. A study by Carrow (2004) recorded core aeration plots having saturated hydraulic conductivity rates that were 1.6 to 4 times greater than control without core aeration.

Numerous benefits of core aeration have been summarized by McCarty (2001) as:

- Releases toxic gases from the soil (reduction in formation of "black layering")
- Improves water infiltration on hydrophobic soils

- Accelerates drying of persistently wet soils
- Increases water infiltration rate, especially when compaction, thatch or organic matter accumulation limit infiltration
- Encourages thatch control by stimulation of microorganism activity
- Improves turf resiliency and soil cushioning
- Disrupts soil layering when followed by sand topdressing
- Controls thatch better, especially when sand topdressing follows core aeration
- Improves turfgrass response to fertilizers

In spite of many benefits of core aeration, Turgeon (2002) also outlined some disadvantages:

- Disrupts the turf surface temporarily while core aeration holes are healing
- Increases potential for turfgrass desiccation as roots are exposed
- Increases weed infestation
- Increases damage from cutworms and other insects that reside in core aeration holes

Probably one of the greatest disadvantages of core aeration is the loss of revenue from a lack of play due to poor turf quality and smoothness following the core aeration. Golf courses are usually closed for three days while core aeration is being done on putting greens. Due to its very abrasive nature core aeration leaves putting greens extremely rough and unplayable for another three to four days. During this first week of turf disruption revenue losses are as high as 100%. Depending on environmental conditions it will often take up to an additional seven days for optimal playing conditions to return on putting greens. During this time of turf healing revenue losses can exceed 50% as players search out other courses to play golf. Golf course revenue loss can exceed $125,000 per year during core aeration events (Anonymous, personal communication 2004). Consequently, turf managers are continually searching for less disruptive methods to alleviate compaction, control organic matter accumulation, and aerate soil.

Frequency of core aeration application depends on several factors including traffic dynamics, soil water content, soil texture, soil structure, and turfgrass species. McCarty (2001) reported that areas receiving intense daily traffic (such as putting greens) require three to four core aerations annually and additional core aeration may be needed on relatively small putting greens with more concentrated traffic. Generally, soils having high silt or clay contents need aerifying with small diameter tines (10 mm internal diameter) every four to six weeks during the growing season since soil compaction improvements are effective only for a short duration. A study by Carrow (2004) reported that increased infiltration rate on putting greens lasted five to eight weeks before dropping to initial values after core aeration (using 16 mm inside diameter tines). In a study by Geurtal et al. (2003) on a loamy sand soil (>80% sand) the effects of deep-tine aeration usually lasted about three to seven weeks. Guertal et al. measured soil strength on treatments that were core aerated either once (July), twice (July and October) or four times (July, October, January, April) per year. At the heavily trafficked site, every additional core aeration in a given year decreased soil resistance. This was not the case at the lightly compacted site, where one core aeration event was enough in a given year to produce a reduction in soil resistance.

When cultivation practices are carried out at the same depth over long period of time a compaction pan commonly forms (Guertal and Han, 2002). To prevent formation of this pan, depth of core aeration (surficial vs. deep) and core types (hollow vs. solid) should be rotated (Bunnell and McCarty, 1999). Deep-tine aeration up to 30 cm depth can alleviate pan development on putting greens (Guertal and Han, 2002). On sand-based putting greens core aeration should not be used as a routine management practice but only as needed to reduce occurrence of localized dry spots and excessive buildup of thatch and organic matter and soil compaction. Research carried out by Guertal et al. (2003) at the Auburn University in Alabama found that core aeration was less likely to have an effect on reducing bulk density when soils were not compacted.

The south eastern region of the USGA agronomists has recommended impacting between 20 and 25% of the surface area annually to keep organic matter under control in sand-based putting greens (O'Brien and Hartwiger, 2003). Core aerating by using 24 mm tines (inside diameter) with a square spacing of 5 $\times$ 5 cm would impact 20% of a putting greens' total surface area. Using the above core aeration specifications removes enough organic matter in a single core aeration event per year; however, as reported by Carrow (2004) non-disruptive summer cultivation may be needed to keep infiltration rates at acceptable levels through the growing season.

Sand topdressing is the most common method of refilling core aeration holes to ensure putting greens surface integrity. Sand topdressing following core aeration must be carried out with sand of a similar size as found in the root zone or soil layering may occur. Study by Lunt (1956) indicated that unaggregated silt and clay particles are subject to migration, but may stop at a barrier in the root zone profile. Common barriers in putting greens include zones of compaction, dense organic matter accumulation, or deeply buried thatch. Turgeon (2002) also reported that small differences in soil properties between adjacent layers may have adverse effects on water movement. For example, the presence of a 4-mm thick layer of fine sand is enough to cause drainage problems in a medium to coarse sand that is otherwise a perfectly draining soil (McCarty, 2001).

2.2. Sand-Based Putting Greens

The primary reason for introduction of sand-based putting greens was to improve turf quality. Two of the principal requirements in growing quality turf in high-traffic areas such as putting greens are compaction resistance and good drainage. Beard (1982) indicated that rapid removal of excess water from the soil surface minimizes compaction and contributes to favorable playing conditions on putting greens. Few natural soils would be able to provide these requirements under intensive traffic; therefore, it is necessary to use sand mixed with a natural soil, or organic matter. Study by Lunt (1956) carried out using soil columns showed that soil mixtures with 80% sand were still compactable enough that percolation rates were reduced, while an increase in sand content to 90% corresponded with minimal compaction and no reduction in percolation rates. In the study mentioned above, 85% sand root zone mix resisted compaction and retained water and nutrients through its remaining 15% of silt, clay, and organic matter components.

During 1960 to 1968 more than 2000 putting greens were constructed in North America using USGA specifications (Bengeyfield, 1968). Based on the performance of these putting greens and additional research, revised recommendations were published by the USGA Green Section in 1973, 1989, and 1993. In these revised specifications, drainage and resistance to compaction were still emphasized as the primary factors for good turf growth. The major change in the revised recommendations is the use of a pure sand root zone instead of mixing soil into the root zone.

In general, coarse textured soils (such as sand) are the least compressible, especially when large pores have been removed by close packing of sand particles (Hillel, 1998). Specifications by the USGA for the particular sand size used in the root zone are highly stringent, ensuring the best possible combination of soil components that create the best turf growing conditions under high traffic intensity (Table 2.1). Additional recommendations for the root zone include water retention capacity at 40 cm tension for oven dry soils of 12-25% (by weight), and available water content of > 5% (by volume) (McCarty, 2001).

Table 2.1. Particle size distribution of the USGA root zone mix.

Particle Name	Particle Diameter (mm)	Recommendation by Weight
Fine gravel	2.0 – 3.4	< 3%
Very coarse sand	1.0 – 2.0	< 7%
Coarse sand	0.5 – 1.0	< 45%
Medium sand	0.25 – 0.5	> 35% (ideal 75%)
Fine sand	0.15 – 0.25	< 20%
Very fine sand	0 05 – 0.15	< 5%
Silt	0.002 – 0.05	< 5%
Clay	< 0.002	< 3%

Total Fines: very fine sand, silt, and clay must be less than 10% in combination.
Coarse and Medium sand: should total greater than 60% in combination

Specifications from the USGA (USGA, 1993) for putting green construction indicate that following layers need to be present: (1) a root zone layer that is 30-35 cm thick, and which needs to meet certain physical requirements of porosity, bulk density, moisture retention, and water infiltration as outlined in Table 2.2, (2) a coarse sand layer that is 5-10 cm thick, and (3) a gravel layer 10 cm thick with imbedded drain pipe for rapid removal of water (Figure 2.1).

Table 2.2. Physical properties of the USGA root zone mix.

Property	Recommended Range
Total porosity	33 – 55%
Air-filled porosity	15 – 30%
Capillary porosity	15 – 25%
Saturated hydraulic conductivity	150 - 300 mm h^{-1}
Accelerated saturated hydraulic conductivity	300 - 600 mm h^{-1}
Bulk density	1.2 – 1.6 g cm^{-3}

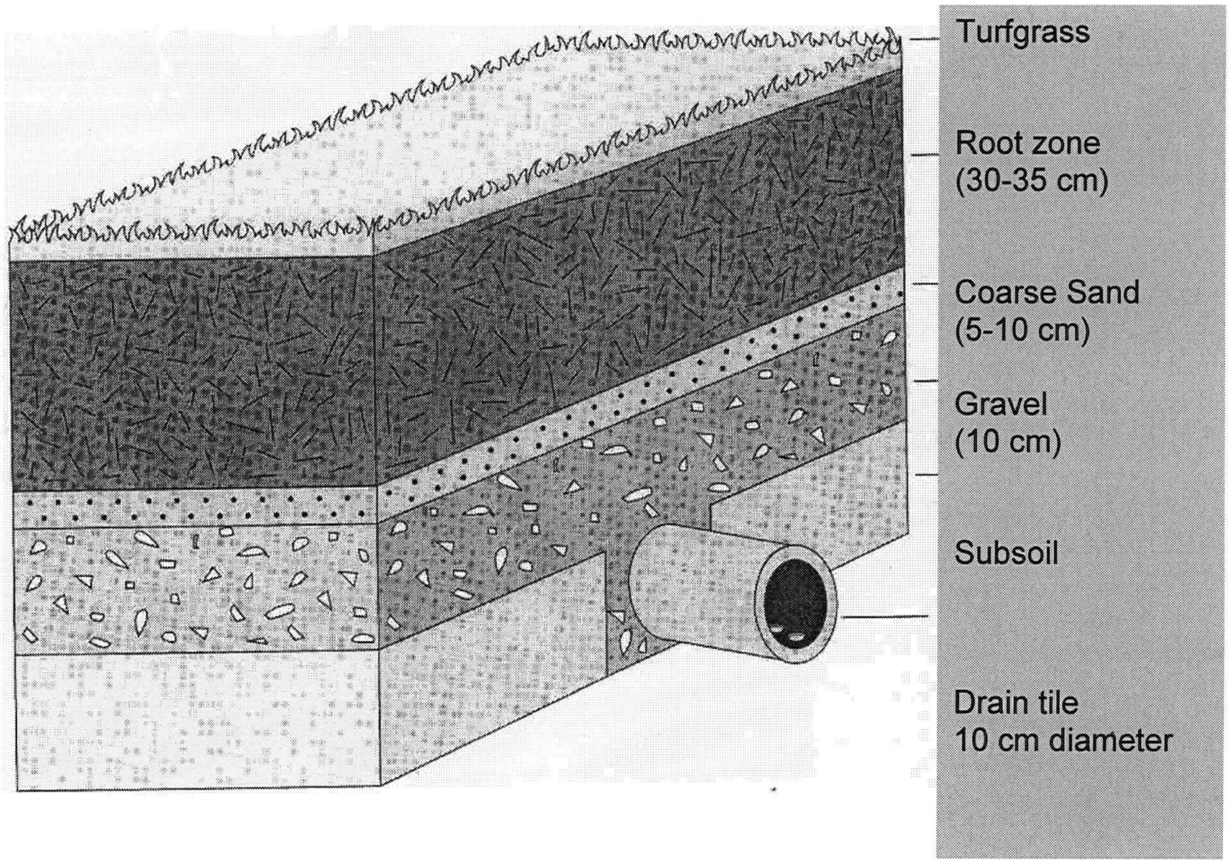

Figure 2.1. Cross section of a USGA putting green profile from McCarty (2001).

The USGA construction specifications include a coarse sand ("choker") layer at 5-10 cm below the root zone. This layer should be present to (1) create a perched water table and (2) prevent migration of fine sand into the gravel layer. When soils of different textures interface water movement is impeded. The root zone must reach near saturation before it will drain. The reason for this failure to drain is a matter of poor hydraulic conductivity of coarse sand at field capacity tensions as well as surface tension over powering gravitation force. The textural difference, between root zone and choker layer, can then be used to increase the water holding capacity of the above sand. When the root zone reaches saturation it will drain into the underlying layer, hence the plant is not depleted of oxygen for prolonged periods of time (Hanson, 1969).

Although sand is an excellent medium for growing turfgrass, there are a few initial disadvantages to using sand in the root zone. The most common problems include (1) the unstable nature of sand prior to turfgrass rooting, (2) poor water and nutrient holding capacity, and (3) loose sand will often settle under the turf canopy of newly established greens. These disadvantages are usually temporary. Organic matter deposition from turfgrass root growth stabilizes the root zone and improves water and nutrient holding capacity of sand. In addition, nutrient availability can be maintained and controlled with the use of slow-release fertilizers or through low and frequent applications of a liquid fertilizer (referred to as "spoon feeding" the greens). Also, management practices such as sand topdressing and rolling enhance sand settlement resulting in smooth turf surfaces.

An important advantage of sand-based putting greens over putting greens constructed on natural soils is the development of a putting surface that holds a proper golf shot without being too wet. Additional advantages of sand root zones include (1) increased depth of turfgrass rooting, (2) reduced impact of salinity from irrigation on turf due to adequate drainage, (3) reduced incidence of disease because of drier turf. These advantages are related to improved soil aeration (i.e., larger percentage of macropores) of sand-based putting greens.

Bulk density values of natural sandy soils can range from 1.2 to 1.8 g cm^{-3} (McCarty, 2001) and bulk densities greater than 1.7 g cm^{-3} are generally considered restrictive to root growth (Brady and Weil, 1999). In comparison, the USGA recommendation for the ideal bulk density range for sand-based putting greens is between 1.2 and 1.6 g cm^{-3}, with an optimal level of 1.4 g cm^{-3} (McCarty, 2001).

Shape of individual sand particles affects percolation rates and soil surface stability (McCarty, 2001). Sub-angular sands are preferred because they form stable footing, are resistant to compaction, and provide good drainage capabilities. While angular sand particles pack well leading to excessive compaction, round sand particles lead to instability due to marble like rolling of particles on one another. In addition, round sand particles have high percolation rates. Crushed sand is more compactable and can damage roots with its sharp edges. The percent of coarse/medium/fine sand also is important when selecting a root zone medium. A study by Hannaford and Baker (2000) in West Yorkshire, UK on *Festuca/Agrostis/Poa annua* on sand-based putting greens showed significant differences in soil penetration resistance for medium sand compared to medium-coarse sand. The medium-coarse sand had greater soil penetration measurements.

Although the introduction of sand based putting greens reduced the impacts of compaction, sand can be compacted when the appropriate conditions are present. Sand that is predominantly of less than 0.2 mm in size has compaction tendencies (Beard, 1973). Sand particles can shift and settle and become tightly packed after years of foot traffic (Taylor et al., 1981). Curtis and Pulis (2001) reported that pure sand is very difficult to compact to any degree; however, when organic matter content is greater than 3%, it and the sand particles become very readily compactable and can seal off root zones. Carrow et al. (2001) also indicated that once the individual sand particles are separated by organic matter the surface no longer resists compacting forces and is prone to formation of a layer at the thatch-soil interface. This interface is composed of compacted organic matter with a slick, moist appearance.

In a study by Hanson (1969), root zones had a minimum infiltration rate of 125 mm h^{-1} of water and a maximum of 375 mm h^{-1} when subjected to 6 mm of hydraulic head after compaction and settling of the soil columns. Sand-based putting greens must balance out the need for water holding capacity for plant needs and high infiltration rates for dry turf surfaces. Pure sand has very poor water holding capacity; hence specifications for sand-based putting greens mixes often require that an organic matter amendment is incorporated. The most commonly added organic amendment to sand-based putting greens is peat. Usually 2% by weight (5-20% by volume) of organic matter is added to sand-based putting greens for the initial construction of the root zone mix (Carrow, 1997). A study by Hannaford and Baker (2000) in West Yorkshire, UK on *Festuca/Agrostis/Poa annua* on sand-based putting greens showed significant differences on soil penetration resistance for peat amended compared to soil amended root zones. The above study mixed peat or soil into a pure sand root zone at volume ratios of 70:30, 80:20, and 90:10 (sand to amendment) and found that soil penetration resistance was always greater in the soil amended root zone. By the end of this three year study soil penetration resistance for the soil amended sand was up to 29% greater than the peat amended sand root zone (2100 kPa versus 1500 kPa).

2.3. Accumulation of Organic Matter

The most consistent and dramatic change that occurs on sand-based putting greens after turf has established is the accumulation of organic matter from continuous root dying off and regeneration (Carrow, 2004). Creeping bentgrass (*Agrostis palustris L.*) has an abundant root biomass, especially within the surface 5 cm. The organic matter deposited from dead root and shoot tissue of putting greens grass species often plugs most of the pore space in the top 5 cm, but, may also plug pores deeper if a large root mass has grown deeper. Organic matter content at the surface (0-5 cm) of mature putting greens can frequently exceed about 10% (by weight) where no cultivation practices have occurred (Carrow, 1997). Carrow et al. (2001) reported that organic matter increased from initial 2% to above 4% (by weight in the surface 3.2 cm) in just two years when no core aeration occurred on sand-based putting greens.

As organic matter accumulates in the layer of actively growing turf soil physical properties are changed significantly from the original root zone mix. Habeck (2000) reported that relative to the initial measurements of the root zone mix prior to turf establishment, a one-year-old putting green had an increase of 19% in total porosity, accompanied by a 53% increase in the water retention and a 53% decrease in saturated hydraulic conductivity. Curtis and Pulis (2001) indicated that a decrease in infiltration rate of maturing putting greens was due to the accumulation of dense plant matter in the top 5 cm rather than the compaction of organic matter. All USGA golf green root zone components are selected to have very high infiltration rates to maintain acceptable hydraulic conductivity rates as more organic matter is accumulated through turf growth.

Once turf has established and is growing vigorously, infiltration rates decline to 25-40% of initial laboratory rates due to plugging of the surface pores by living roots and soil organic matter (Carrow, 1997). Carrow (1997) also stated that approximately 5% organic matter (by weight) is sufficient to significantly plug most sand root zones when the organic matter is added as an amendment. Carrow et al. (2001) has reported the value of organic matter may be as high as 10-14% if it is mainly present as live roots. Structurally roots are long cylinders that allow adequate water infiltration and gas exchange within the root. Continued accumulation of total organic matter without corrective or preventative management practices will eventually seal surface pores. The cool, temperate climate characteristic of northern United States, eastern Canada, BC, New Zealand, and northern Europe contribute to a steady build up of organic matter at the surface and deeper in the profile of sand-based putting greens. These regions have prolonged periods of adequate soil temperatures for continuous turf growth (above 0°C), but not for decomposition of organic matter by microorganisms (below approximately 12°C) (Carrow et al., 2001; O'Brien and Hartwiger, 2003). Manipulation of this layer with high organic matter content by core aeration followed by sand topdressing is the greatest safeguard in ensuring the long-term integrity of the root zone (Curtis and Pulis, 2001).

2.4. Summary of Literature Review

Growing good quality turf on high-traffic areas, such as golf putting greens, is challenging. Compaction and accumulation of organic matter in the root zone are two primary problems that turf managers need to address on sand-based putting greens. If left unattended these primary problems will lead to degradation of turf surfaces beyond the level of acceptability by players and managers alike.

Destruction of macropores by excessive accumulation of organic matter or soil compaction leads to: (1) reduction of air exchange within the root zone, (2) decrease of water infiltration rate, and (3) increase of water content. These alterations in soil physical properties may contribute to numerous additional problems such as greater incidence of disease, creation of soft putting surfaces, poor root growth, greater degree of black layering, and more frequent direct/indirect high temperature injury. Core aeration is the most common management practice used to reduce compaction, improve soil aeration, remove organic matter, and increases water infiltration and drainage. When core aeration is accompanied with sand topdressing, sand is incorporated into the root zone. It is unclear how many aeration practices should be applied per year to allow optimum growing conditions in the root zone. In southeastern United States it is recommended that core aeration should impact 20-25% of the surface area annually. Core aeration with square spacing of 25 × 25 mm and 12.7 mm inside diameter hollow tines impacts 23% of the putting greens surface area. Carrying out core aeration in both spring and fall may not be necessary, especially if one well-timed aeration event could impact enough putting greens surface area to improve soil aeration.

Presently, most putting greens are built with sand as the dominant component of the root zone. Development of sand-based putting greens led to better turf quality by improving drainage and water infiltration. Introduction of the sand-based putting greens parallels to some extent the improvements brought about by core aeration; however, sand-based putting greens have their own unique set of problems that may still require core aeration to grow the best quality turfgrass.

3. MATERIALS AND METHODS

3.1. Study Site

The study was carried out from March 2002 to May 2004 on three putting greens at the Northview Golf and Country Club Ltd. in Surrey, BC located about 45 km south-east of Vancouver (49° 05' N, 123° 10' W). Climate of the region is humid maritime with cool wet winters and relatively warm summers (Environment Canada, 2005). The mean annual air temperature is 10.2°C (Figure 3.1), while annual precipitation is 1320 mm (Figure 3.2). The original soil on the study site was Gleysol developed on marine parent material, but the soil was either completely removed or used for landscape re-shaping during construction of the golf course (was not used for construction of the putting greens).

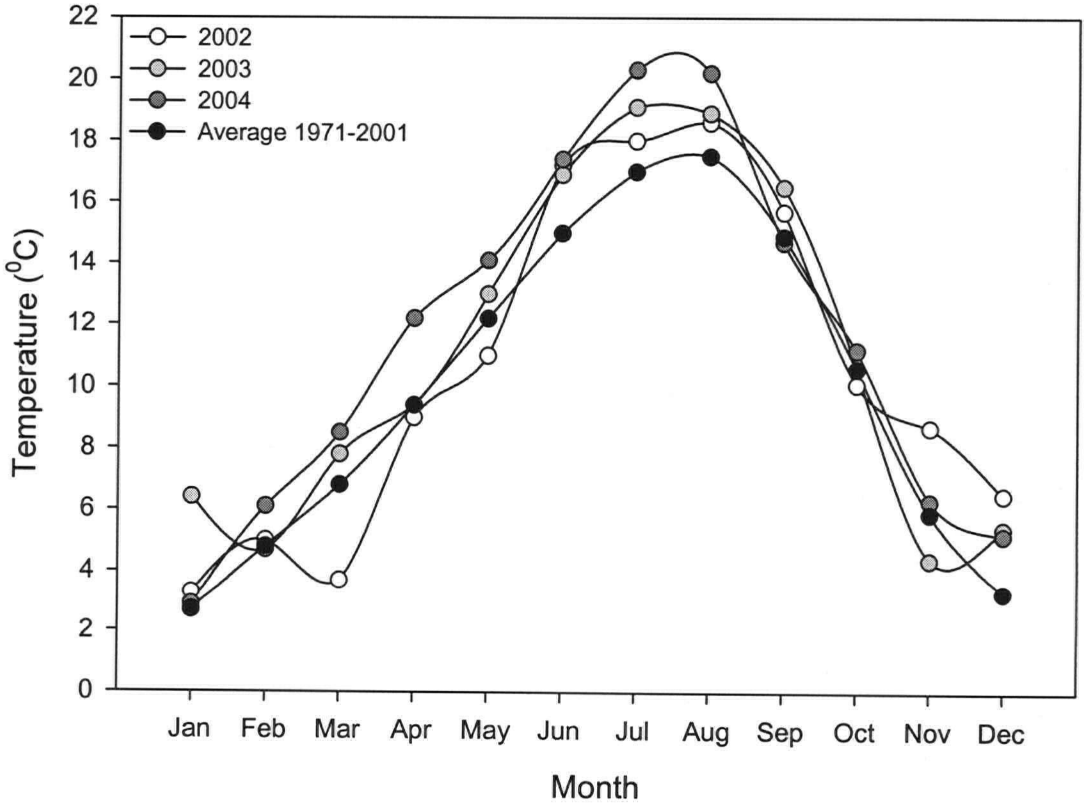

Figure 3.1. Monthly average air temperatures for Surrey, BC as recorded at the Surrey Municipal Hall, BC weather station. (Source: Environment Canada, 2005).

The Northview Golf and Country Club covers an area of 162 ha of which 2.3 ha consists of putting greens. Average size of these greens is 500 m^2. All putting greens at this golf club were constructed in 1993 according to the USGA specifications (USGA, 1993) using a mix that consisted of 0.4% very coarse sand, 5.1% coarse sand, 77.3% medium sand, 10.8% fine sand,6.4% very fine sand/silt/clay, and 0.24% organic matter. The greens were seeded to Providence creeping bentgrass (*Agrostis palustris* L.) at the seeding rate of about 74 kg ha^{-1} (1.5 lbs 1000 ft^{-2}). However, Annual bluegrass (*Poa annuae* L.) has invaded all the greens and is currently the dominant turfgrass species covering 50-60% of their surface.

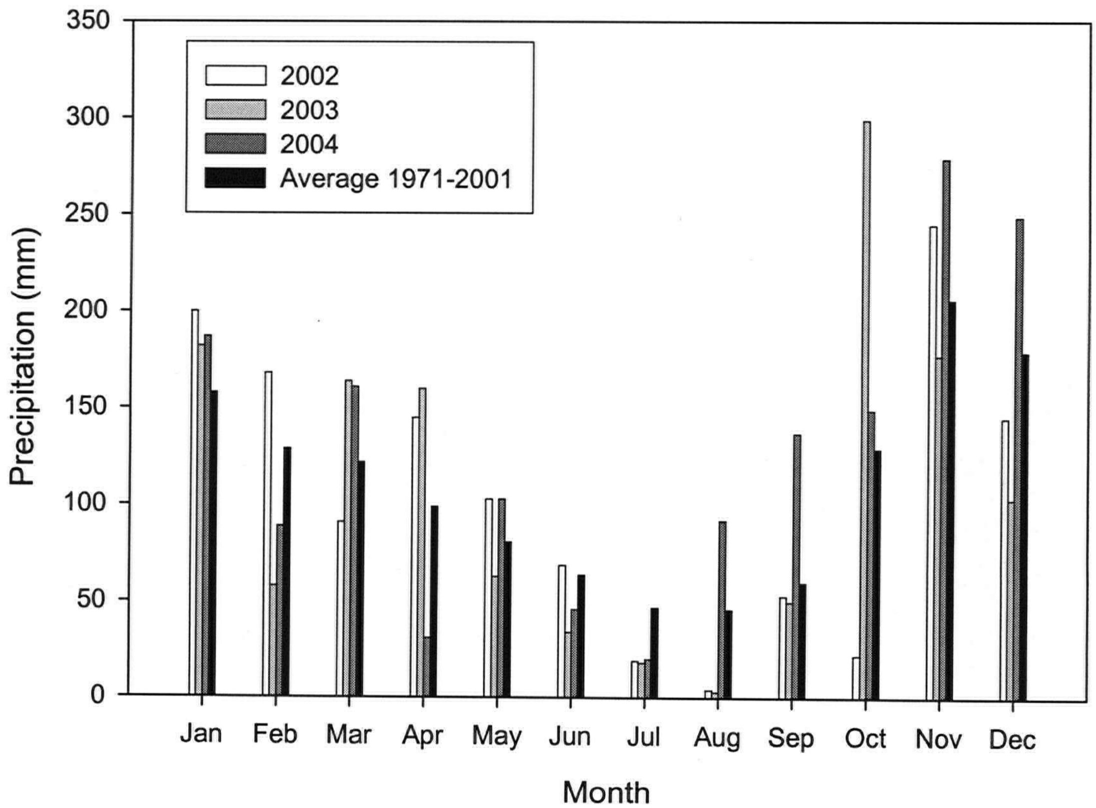

Figure 3.2. Monthly average precipitation for Surrey, BC as recorded at the Surrey Kwantlen Park, BC weather station. (Source: Environment Canada, 2005).

Root zones of sand-based putting greens are characterized by a very distinct break between mat layer (upper layer in which organic matter tends to accumulate) and sand layer (lower layer with no organic matter accumulation). During this study the depth of the mat layer ranged from 3.8 to 11.6 cm (with an average depth of 7.5 cm) and the depth of the sand layer was from 5.9 to 13.7 cm (with an average depth of 10 cm). The mat layer of greens in this study had 95.2% sand, 2.3% silt, 2.5% clay, cation exchange capacity 5.54 $cmol_c$ kg^{-1}, and electrical conductivity 1.09 dS m^{-1}.

The experiment was carried out as a randomized complete block design with three treatments and three replications (Figure 3.3). Study treatments were:

1) regular management practices, including core aeration, and high intensity of foot traffic (CA-HT),
2) regular management practices, but no core aeration, and high intensity of foot traffic (NCA-HT), and
3) limited number of management practices, no core aeration, and low intensity of foot traffic (NCA-LT). The pressures imposed by the management practices and foot traffic on this treatment were much lower than normally found on sand-based putting greens.

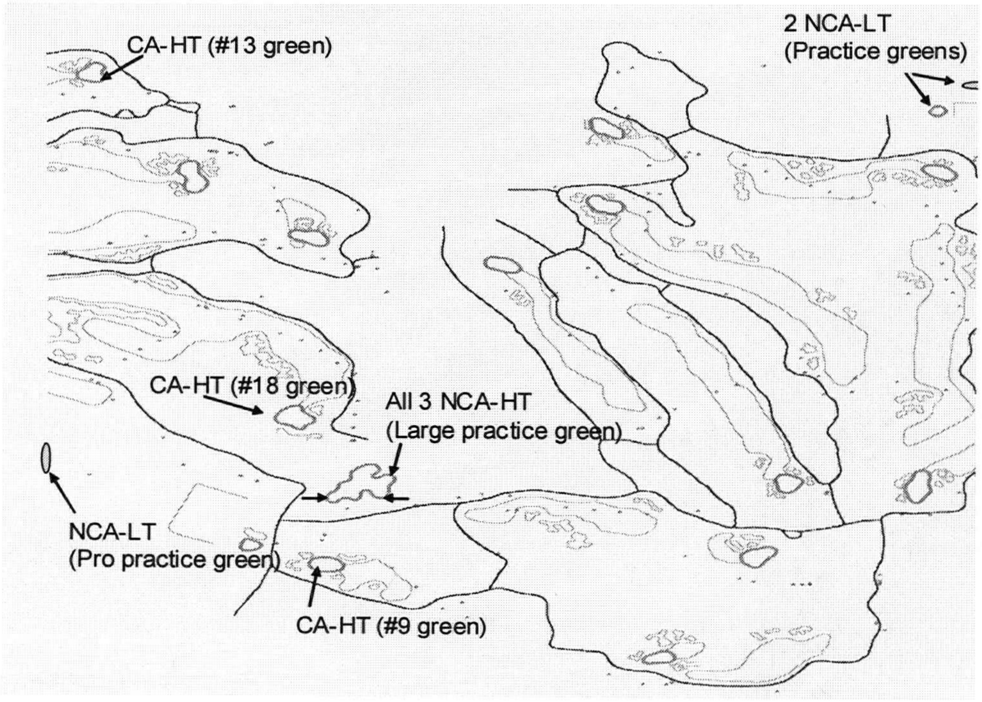

Figure 3.3. Experimental layout at the Northview Golf and Country Club Ltd. in Surrey, BC

All study plots were located on a similar slope and were about 100 m^2 in size. All study plots received core aeration in September 2001, i.e. six months before the beginning of the study. This practice impacted 7% of the surface on all plots except for two out of three replications of the NCA-LT plots for which the impact was 14%. From 1996 until the beginning of the study in March 2002 the NCA-HT and CA-HT treatments received 17 core aerations, while the NCA-LT was core aerated 10 times.

During the study, core aeration on the CA-HT treatment was carried out on March 28 and September 29, 2002, and March 31 and August 24, 2003 (Table 3.1). A Toro Greens Aerator (Figure 3.4) with 13 mm outside diameter hollow tines arranged in a spacing of 50 × 65 mm was used for core aeration (Figure 3.5). The tines were inserted to 7.5 cm depth. About 7% of the total surface area was affected by removing cores of sand and turf from the putting greens. Immediately after core aeration the holes were filled with 1.0 mm sand during sand topdressing. The Toro Greens Aerator has a vibrating movement, which may result in sand settling (i.e., close packing) below the depth of core aeration penetration. In 2004, deep-tine aeration replaced the spring core aeration. Deep-tine aeration was done on April 4, 2004 using 4720 John Deere Tractor and a soil reliever aerator with 1.9 cm solid tines arranged in a spacing of 10 x 10 cm. The tines were inserted to a 30 cm depth and affected about 5% of the surface. There was no core removal during deep solid-tine aeration.

Table 3.1. Dates for core aeration and sampling for soil bulk density, penetration resistance, water content, water infiltration, organic matter, and root biomass in 2002, 2003, and 2004.

Year / event	Dates							
2002 sampling	Mar 27		Apr 24^Z	Jun 15^Y	Aug 18^Y	Sep 22		Oct 20
2002 core aeration		Mar 28					Sep 29	
2003 sampling	Mar 29		Apr 28	Jun 18^Y	Aug 20^X		Sep 25	
2003 core aeration		Mar 31				Aug 24		
2004 sampling	Apr 1		May 1					
2004 deep-tine aeration		Apr 4^W						

^{Z}No sampling for bulk density, organic matter, root biomass, and no penetration resistance.

^{Y}No sampling for organic matter, root biomass, and no soil penetration resistance.

^{X}Two (out of three) replications of the NCA-LT treatment were eliminated by the golf course management.

^{W}Core aeration was replaced with the deep-tine aeration.

Figure 3.4. Core aeration machine.

Foot (or play) traffic during peak season on the CA-HT and NCA-HT treatments consisted of 1,000 to 1,100 rounds of play per week. The NCA- LT received zero rounds of play per week.

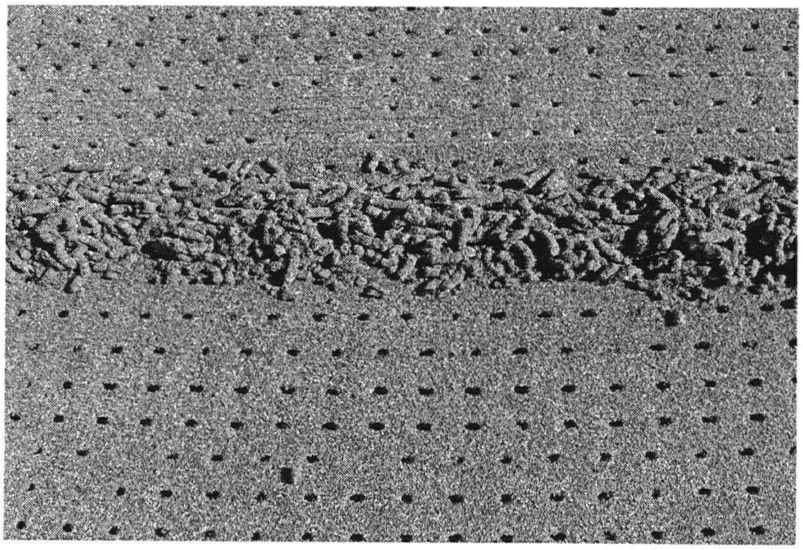

Figure 3.5. Putting green surface disruption caused by core aeration.

Regular management practices carried out on both CA-HT and NCA-HT treatments included mowing, fertilizer application, irrigation, verti-cutting, Aer-way aeration, sand topdressing (done on CA-HT after both core aeration and verti-cutting, on NCA-HT after verti-cutting), brushing, and rolling (Table 3.2; Table A.1). Turfgrass mowing was done daily during growing season (i.e., from April to October) and grass cuttings were removed from the putting greens. Fertilizer application was done every 10-14 days during growing season at a rate of 4.9 kg N ha^{-1} (0.1 lbs N 1000 ft^{-2}). In 2002 annual application rates were 220 kg N ha^{-1} (4.5 lbs N 1000 ft^{-2}), 98 kg P ha^{-1} (2.0 lbs P 1000 ft^{-2}), and 307 kg K ha^{-1} (6.3 lbs K 1000 ft^{-2}), while in 2003 these rates were 180 kg N ha^{-1} (3.7 lbs N 1000 ft^{-2}), 59 kg P ha^{-1} (1.2 lbs P 1000 ft^{-2}), and 278 kg K ha^{-1} (5.7 lbs K 1000 ft^{-2}). Depending on weather conditions during summer irrigation was applied at a rate of approximately 15-30 mm every 7-10 days. Turfgrass brushing was done once per month during the growing season. Rolling was done 22 times in 2002 and 35 times in 2003. All rolling practices were carried out between May and September. In 2004 there was no rolling before the last sampling date. Even though the NCA-HT treatment did not receive any core aeration other cultivation practices (as described in Table 3.2) were done on this treatment.

Table 3.2. Cultivation practices applied during the study on the CA-HT and NCA-HT treatments.

Cultivation	Description	Timing
Core aeration	***Done on CA-HT***. A Toro Greens Aerator[z] (Figure 3.4) was used. It has hollow tines (13 mm outside diameter) arranged in a spacing pattern of 50 x 65 mm (Figure 3.5).	In March and September 2002. In March and August 2003. In April 2004, deep-tine aeration replaced core aeration.
Verti-cutting	***Done on CA-HT and NCA-HT***. This is a vertical mowing of turfgrass that cuts horizontally growing leaf blades. The cutting blades were set at 3 mm below surface to stimulate growth and improve incorporation of sand added during topdressing.	Bi-monthly from May to September In 2002 it was done 10 times, while in 2003 due to weather limiting conditions verti-cutting was done 6 times.
Deep-tine aeration	***Done on CA-HT***. Deep-tine aeration inserts a solid-tine (19 mm diameter) to a depth of 30 cm. A 10 x 10 cm square spacing pattern was used.	On Apr 4, 2004, deep-tine aeration replaced core aeration to penetrate through a compaction pan.
Aer-way[z] aeration	***Done on CA-HT and NCA-HT***. Slices turf with triangular blades (5 mm thick and 60 mm in width) to the 10-12 cm depth. A 15 x 30 cm spacing pattern was used.	Done on Oct 5, 2003, to enhance water infiltration before the beginning of winter season.

[z]Trade name is used for convenience of the reader and does not imply endorsement over similar products.

On the NCA-LT treatment a limited number of management practices was applied, including only mowing, fertilizer application, and irrigation. Those practices were carried out as described above for CA-HT and NCA-HT treatments.

3.2. Sampling and Analyses

Dates for soil sampling and core aeration (or deep-tine aeration) applications during the study period are shown in Table 3.1. Soil sampling and measurements were carried on the NCA-LT treatment until August 2003, when this treatment was eliminated due to golf course reconstruction imposed by the golf course management.

3.2.1. Soil Organic Matter and Root Weight Density

In 2002, samples for soil organic matter and root biomass determination were collected before spring core aeration (Mar 27) and before (Sep 22) and after (Oct 20) fall core aeration. In 2003, samples were collected before (Mar 29) and after (Apr 28) spring core aeration and before (Aug 20) and after (Sep 25) fall core aeration. In 2004, samples were taken before (Apr 1) and after (May 1) spring deep-tine aeration. Samples were taken using a standard putting greens cup cutter with a 10.8-cm diameter core. Only the mat layer was sampled for soil organic matter and root biomass. The exception was March 27, 2002 when sampling was done for the 0-17.5 cm layer. One sample was taken per plot.

Soil organic matter content was determined by the loss-on-ignition method (Nelson and Sommers, 1996) after roots were removed from the sample.

Initial separation of roots from sand and organic matter particles (Figure 3.6) was done by washing samples over a set of sieves (1 mm, 600 μm, and 53 μm). This was followed by drying in a forced-air oven at 70-80°C for 18 hours. After drying, final separation of roots from sand and organic matter particles was done by using tweezers; roots were then weighed. Total root weight was converted to root weight density because depth of the mat layer varied among samples. Depths of mat layer were recorded for each sample and the conversion was done by dividing root weights by the specific core volume from which the roots were removed.

Figure 3.6. Initial root separation by washing - a fine stream of water removes sand and organic matter particles from roots.

3.2.2. Soil Water Content and Water Retention

In 2002, samples for soil water content determination (Table 3.1) were collected before (Mar 27) and after (Apr 24, Jun 15, Aug 18) spring core aeration and before (Sep 22) and after (Oct 20) fall core aeration. In 2003, samples were collected before (Mar 29) and after (Apr 28, Jun 18) spring core aeration, and before (Aug 20) and after (Sep 25) fall core aeration. In 2004, samples were taken before (Apr 1) and after (May 1) spring deep-tine aeration. During 2002, samples were collected from the 0-17.5 cm depth, while during 2003 and 2004 samples were collected separately from mat and sand layers. One sample per plot was taken in 2002, while two samples per plot were taken in 2003 and 2004. Soil water content was determined gravimetrically (Gardner, 1986). Sampling was usually done two days after irrigation.

Cores (5.3 cm diameter by 3 cm height) of undisturbed soil were collected using a drop-hammer sampler for water retention analysis. Undisturbed core samples were taken at 0-3 cm depth on Mar 27 and Oct 20, 2002, Mar 29, 2003, and May 1, 2004. At each sampling date one core per plot was taken. Samples were analyzed to determine water content at 0, 3, 8, 20, 60, 90, 180, and 300 kPa with a pressure plate apparatus (Klute, 1986). Equilibrium was reached for each pressure after three days or when water evaporation from the collection beaker exceeded water coming in from pressure chamber.

3.2.3. Soil Bulk Density

In 2002, samples for soil bulk density determination (Table 3.1) were collected before (Mar 27) and after (Jun 15, Aug 18) spring core aeration, and before (Sep 22) and after (Oct 20) fall core aeration. In 2003 samples were collected before (Mar 29) and after (Apr 28, Jun 18) spring core aeration, and before (Aug 20) and after (Sep 25) fall core aeration. In 2004, samples were taken before (Apr 1) and after (May 1) spring deep-tine aeration. Intact soil core samples for bulk density determination (Blake and Hartge, 1986) were taken with a standard putting greens cup cutter with a 10.8-cm diameter core. During 2002 one sample per plot was taken, while during 2003 and 2004 two samples were taken per plot. Samples were collected from 0-17.5 cm depth during 2002. Mat and sand layers were sampled separately during 2003 and 2004. Depths of mat and sand layers were recorded for each core sample and specific depths were used to calculate bulk density. Samples were dried to constant weight in a forced-air oven at 105°C for 48 hours and weight.

3.2.4. Soil Penetration Resistance

In 2002, measurements of soil penetration resistance (Bradford, 1986) were done before (Mar 27) spring core aeration, and before (Sep 22) and after (Oct 20) fall core aeration (Table 3.1). In 2003, measurements were done before (Mar 29) and after (Apr 28) spring core aeration, and before (Aug 20) and after (Sep 25) fall core aeration. In 2004, measurements were done before (Apr 1) and after (May 1) spring deep-tine aeration. Measurements were carried out about 50 cm away from the spot where soil bulk density and water content samples were obtained. Soil penetration resistance was measured to 18 cm depth at intervals of 1.5 cm, using a hand-pushed 13-mm diameter cone (30°) penetrometer with data logger (Agridry Rimik PTY Ltd., Toowoomba, QLD, Australia). At each sampling date five soil penetration resistance measurements were taken per plot.

Since soil penetration resistance is strongly affected by the soil water content at the time of measurement, correction to a reference soil water content was done using the method proposed by Busscher and Sojka (1987). This method assumes that penetration resistance (PR) depends on bulk density (ρ_b) and gravimetric water content (W) as follows:

$$PR = c\,\rho_b^{\,a}\,w^b \qquad (3.1)$$

where *c* is a constant.

$$PR_1 = (w_1 / w_2)^b\,PR_2 \qquad (3.2)$$

Where subscripts 1 and 2 indicate corrected and uncorrected conditions, respectively.

The coefficient *b* was determined by measuring PR, ρ_b , and *w* in the laboratory using a repacked soil that had been sieved through a 2 mm sieve in 7.3 cm diameter by 7.5 cm height cores. The cores with various soil bulk densities were saturated from the bottom up by raising the water slowly up to 2 cm below the surface of the core. The water in the soil cores was allowed to evaporate, and soil penetration resistance was measured at various water contents, representing the seasonal variation in the field. All data were substituted into the Busscher-Sojka model, giving a *b* coefficient of -0.03 (Table 3.3). Corrections were adjusted to a reference water content of 0.15 kg kg^{-1}, an average value for the three putting greens at the time of penetration resistance measurements.

Table 3.3. Parameters in equation $PR = c\,\rho_b^{\,a}\,w^b$ as determined by laboratory measurements

Depth (cm)	Equation	n	r^2	*P*
0-17.5	$\log(PR) = 8.24 \log(\rho_b) - 0.03 \log(w) + 1.39$	65	0.914	0.0001

3.2.5. Water Infiltration Rate

Water infiltration rates were determined using a small (Turf-Tec International, Coral Springs, Florida, USA) and large constant head double-ring infiltrometers (Bouwer, 1986). In 2002, the small double ring infiltrometer with an inner diameter of 6.4 cm and outer diameter of 11.0 cm was used. The unit was inserted 5 cm deep into the ground. The change in water depth inside of the inner cylinder of small infiltrometer was measured over a period of 15 min. One measurement was done per plot. In 2003 and 2004, infiltration measurements were carried out with both the small and large double ring infiltrometers. The larger infiltrometer had an inner diameter of 28 cm (30 cm height) and an outer diameter of 56 cm (30 cm height). The large double ring cylinders were inserted 5 cm deep into the ground using a 4.5 kg hammer to form a watertight seal with the turf surface. For both infiltrometers the change in water depth of the inner cylinder was measured over a period of one hour at time intervals of five minutes. A water head of 10-15 cm was maintained by recharging every five minutes (true for both infiltrometers). One measurement per plot was done with each infiltrometer. Measurements were usually done two days after irrigation application.

In 2002, measurements of water infiltration rate (Table 3.1) were done before (Mar 27) and after (Apr 24, Jun 15, Aug 18) spring core aeration, and before (Sep 22) and after (Oct 20) fall core aeration. In 2003, measurements were done before (Mar 29 - only with small infiltrometer) and after (Apr 28, Jun 18) spring core aeration, and before (Aug 20) and after (Sep 25) fall core aeration. In 2004, measurements were done before (Apr 1) and after (May 1) spring deep solid-tine aeration.

3.3. Statistical Analysis

Data were analyzed as randomized complete block design with three replications. Soil data were analyzed separately for each depth of sampling. The JMPin Fit model procedure was used (SAS Institute Inc., 2001) and an α value of 0.05 was considered significant. The Tukey multiple comparison test was used to determine if differences existed among treatments.

Data collected with small and large double ring infiltrometers were subjected to simple correlation and linear regression analysis using Sigma Plot (SPSS Inc., Chicago, IL).

4. RESULTS AND DISCUSSION

4.1. Soil Organic Matter and Root Weight Density

Content of soil organic matter was similar on all treatments throughout the 27-month study period (Table 4.1). The only exception was March 27, 2002 (before the spring core aeration) when soil organic matter on NCA-LT was lower than on NCA-HT treatment. Six months before the initiation of this study (i.e., in September 2001), two out of three replications of the NCA-LT putting greens received double core aeration, which impacted 14% of the total surface area and removed a substantial amount of organic matter and root biomass. As a result, six months latter organic matter on NCA-LT was lower than on NCA-HT. Even though core aeration carried out in September 2001 reduced soil organic matter in the NCA-LT, difference observed on March 27, 2002 disappeared later in 2002 as root growth re-established organic matter levels. Similarly, a three-year long study by Murphy et al. (1993) showed that core aeration applied two times per year on sand-based putting greens (at a five percent surface area impact) did not reduce organic matter content within the mat layer relative to non-core aerated treatment. Smith (1979) reported that organic matter content of a bermudagrass loamy fine sand putting green in Florida was only reduced when the number of core aeration applications was increased from two times per year to monthly in a seven-month study.

In my study regardless of the sampling date, core aeration did not significantly reduce organic matter content on CA-HT relative to other two treatments without this cultivation practice. Lack of organic matter reduction on the treatment with core aeration is most likely due to the small size of the hollow tines used (13 mm outside diameter) that resulted in the relatively low impact of 7% of the total surface area of the putting greens.

According to the USGA recommendations the root zone of sand-based putting greens should have less than 3% organic matter by weight (Curtis and Pulis, 2001), since above this limit it is difficult to balance appropriate soil water retention and aeration (Carrow, 2004, O'Brien and Hartwiger, 2003). In my study at six out of nine sampling dates organic matter content on NCA-HT was greater than 3%. Conversely, organic matter on CA-HT was above the critical value only at two dates (August 20 and September, 25 2003) indicating that two core aeration applications per year maintained soil organic matter content at an adequate level in the humid maritime climate of lower Fraser Valley.

Table 4.1. Soil organic matter content in the mat layer under three management treatments in 2002-2004.

Date	Treatment			P (F-test)
	NCA-LT	NCA-HT	CA-HT	
	2002 (%)			
Mar 27	2.1a (0.12) [Z]	2.9b (0.17)	2.5ab (0.16)	0.038
Sep 22	2.7a (0.38)	2.9a (0.16)	2.5a (0.07)	0.547
Oct 20	3.1a (0.53)	2.8a (0.20)	2.9a (0.20)	0.722
	2003 (%)			
Mar 29	2.7a (0.46)	3.5a (0.36)	3.0a (0.11)	0.173
Apr 28	2.6a (0.57)	3.7a (0.11)	2.9a (0.38)	0.137
Aug 20	N/A [Y]	4.0a (0.69)	3.7a (0.19)	0.960
Sep 25	N/A	4.0a (0.49)	3.1a (0.29)	0.118
	2004 (%)			
Apr 1	N/A	3.3a (0.23)	2.8a (0.05)	0.151
May 1	N/A	3.0a (0.04)	2.8a (0.07)	0.105

[Z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the same sampling date are not significantly different (P>0.05).

[Y]Data were not obtained since two replications were removed by the golf course management.

Root weight density (i.e., root weight per unit soil) data were similar among treatments (Table 4.2). Even on sampling dates about a month after core aeration root weight density was similar on treatments with and without this practice, indicating that new roots of annual bluegrass and creeping bentgrass were able to quickly re-establish within the holes created by core aeration. Similarly, in the warm and humid climate of Florida root biomass of Bermuda grass was not reduced by core aeration even when it was increased from two times per year to once per month over a period of seven months

(Smith, 1979). Only when core aeration was applied two times per month was root weight decreased by 8.5%. A study by Murphy et al. (1993) showed that two core aeration events per year (each impacting 5% of surface area) did not reduce root weight density in the 0-7.6 cm soil layer relative to treatment without core aeration on "Penneagle" creeping bentgrass grown on a loamy-sand putting greens in Michigan.

Table 4.2. Root weight density in the mat layer under three management treatments in 2002-2004.

Date	Treatment			*P* (F-test)
	NCA-LT	NCA-HT	CA-HT	
	------2002 ($g\ cm^{-3}$)------			
Mar 27	0.003a (0.0004)[Z]	0.001b (0.0002)	0.001a (0.0001)	0.049
Sep 22	0.007a (0.002)	0.004a (0.001)	0.003a (0.001)	0.361
Oct 20	0.014a (0.002)	0.006a (0.002)	0.007a (0.002)	0.135
	------2003 ($g\ cm^{-3}$)------			
Mar 29	0.009a (0.003)	0.009a (0.005)	0.011a (0.001)	0.863
Apr 28	0.010a (0.003)	0.014a (0.003)	0.008a (0.001)	0.391
Aug 20	N/A[Y]	0.022a (0.007)	0.028a (0.004)	0.632
Sep 25	N/A	0.014a (0.004)	0.011a (0.004)	0.196
	------2004 ($g\ cm^{-3}$)------			
Apr 1	N/A	0.006a (0.001)	0.007a (0.001)	0.833
May 1	N/A	0.006a (0.001)	0.004a (0.001)	0.357

[Z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the same sampling date are not significantly different (P>0.05).

[Y]Data were not obtained since two replications were removed by the golf course management.

In my study, root weight density data varied over time increasing from spring to summer and decreasing till the fall (Table 4.2). This is not surprising since root growth is strongly affected by soil temperature (Hannaford and Baker, 2000). The greatest root growth of creeping bentgrass and annual bluegrass occurs when spring and fall soil temperatures are about 12-13°C, while the root growth is inhibited at soil temperature above 24°C (McCarty, 2001). The frequent turf mowing and verti-cutting practices that were carried out on the putting greens in this study removed all aboveground biomass, hence root biomass was the main source of soil organic matter. For that reason, annual changes of the root weight density closely matched changes in soil organic matter. The greatest increase in root weight density (0.020 g cm^{-3}) was observed from April to August 2003 on the CA-HT treatment, which corresponded to the greatest increase of soil organic matter (0.8%). During the same period an increase in root weight density also occurred on the NCA-HT treatment (0.014 g cm^{-3}) corresponding to an increase of 0.3% in soil organic matter.

4.2. Soil Water Content and Water Retention

Soil water content data obtained during the first year (2002) of the study showed no difference among the three treatments, with exception of March 27, 2002, when soil water content on NCA-HT was greater than on the other two treatments (Table 4.3). Wetter soil on NCA-HT was in agreement with greater amount of organic matter observed on the same sapling date (Table 4.1) relative to two other treatments. Average soil organic matter calculated for all dates of sampling were 3.3, 2.9, and 2.6% on NCA-HT, CA-HT, and NCA-LT, respectively (Table 4.1). Since organic matter can hold up to 20 times its weight in water (Sparks, 1995), a relatively small increase of 0.4-0.7% in organic matter as observed in the NCA-HT treatment increased its water holding capacity relative to the other two treatments. A study by Habeck and Christians (2000) carried out in Colorado on bentgrass sand-based putting greens showed that water retention after the first year of turf growth (i.e., after turf establishment) increased from 13.1 to 20.0% even though organic matter content (by mass) increased by 0.5%. The increase in water retention was partially attributed to the increase of the soil organic matter in the root zone (through root and shoot die-off) and partially to an increase of clay content (from 0.4 to 3.7%) through either wind deposition or topdressing application.

Table 4.3. Soil water content at 0-17.5 cm depth on three management treatments during 2002.

Date	Treatment			*P* (F-test)
	NCA-LT	NCA-HT	CA-HT	
	---------------------------------(%, weight)---------------------------------			
Mar 27	0.13a (0.011)[z]	0.17b (0.012)	0.14a (0.012)	0.001
Apr 24	0.14a (0.012)	0.23a (0.032)	0.17a (0.021)	0.210
Jun 15	0.12a (0.008)	0.13a (0.013)	0.09a (0.015)	0.056
Aug 18	0.12a (0.023)	0.14a (0.007)	0.11a (0.015)	0.538

[z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the same sampling date are not significantly different (P>0.05).

When core samples were divided into mat and sand layer (starting on September 22, 2002) NCA-HT soil water content of the mat layer was significantly greater relative to the other two treatments on four out of nine sampling dates (Table 4.4). Core aeration removed soil and turf organic matter, while sand topdressing (which always followed core aeration application) added sand into the mat layer. This improved water movement and resulted in drier soil conditions on the CA-HT treatment relative to treatments without core aeration. The effects of core aeration on soil water content were temporary and disappeared two (June 18, 2003) months following the core aeration application when comparing the two high traffic treatments. According to Carrow (2004) core aeration improves surface drainage and consequently reduces water holding capacity only for five to eight weeks before roots grow back into the core aeration holes plugging up soil pores. The data collected in my study were similar to Carrow (2004) in that water content from the two high traffic treatments were significantly different until two months later when the two treatments were similar. This was not the case when comparing the low traffic treatment to the high traffic treatments. Differences among the low and high traffic treatments were not similar until five months later (August 20, 2003).

Table 4.4. Soil water content of the mat layer on three management treatments from September 2002 to May 2004.

Date	Treatment			P (F-test)
	NCA-LT	NCA-HT	CA-HT	
	--------2002 (%, weight)--------			
Sep 22	0.15a (0.036)[Z]	0.25a (0.027)	0.18a (0.016)	0.169
Oct 20	0.15a (0.027)	0.26b (0.031)	0.22c (0.015)	0.002
	--------2003 (%, weight)--------			
Mar 29	0.29a (0.032)	0.39a (0.053)	0.32a (0.028)	0.439
Apr 28	0.17a (0.026)	0.28b (0.017)	0.21a (0.019)	0.001
Jun 18	0.10a (0.009)	0.21b (0.028)	0.15b (0.012)	0.001
Aug 20	0.18a (0.028)	0.24a (0.026)	0.20a (0.024)	0.102
Sep 25	N/A[Y]	0.26b (0.012)	0.16a (0.008)	0.001
	--------2004 (%, weight)--------			
Apr 1	N/A	0.27a (0.022)	0.24a (0.024)	0.417
May 1	N/A	0.24a (0.05)	0.17a (0.002)	0.421

[Z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the same sapling date are not significantly different (*P*>0.05).

[Y]Data were not obtained since two out of three replications were removed by the golf course management.

Generally, the NCA-LT treatment was the driest (Table 4.4) and had the lowest organic matter content (Table 4.1) among the study treatments. The NCA-LT had no foot or play traffic and a very limited number of management practices hence it is possible that organic material on this treatment consisted of relatively larger particles that were not crushed by constant traffic. It has been observed that high play traffic on sand-based athletic fields tends to reduce size of organic material within the root zone consequently increasing surface area and enhancing water holding capacity (Schreier personal communication, 2004).

In 2004 the core aeration practice was replaced with deep solid-tine aeration during which there was no core removal from the putting green surface. Soil water content obtained one month after deep solid-tine aeration (May 1, 2004) was similar on CA-HT and NCA-HT treatments regardless of the depth of measurement (Tables 4.5 and 4.6). This indicates that when there is no removal of organic matter during cultivation sand-based putting greens will have water holding capacity and content similar to greens without cultivation.

Soil water content in the sand layer was significantly affected by the treatments on three out of nine sampling dates (Table 4.5). On March 29, 2003 CA-HT had drier soil than NCA-LT, on April 28, 2003 the soil water content of the NCA-LT treatment was greater than on the NCA-HT and CA-HT treatments, while on April 1, 2004 CA-HT was drier than NCA-HT. Despite these differences the soil water content in the sand layer should have a limited impact on root growth since roots did not penetrate into this layer.

Average water contents for all treatments during the period September 2002 – May 2004 were 22% for the mat layer and 9% for the sand layer. At all nine sampling dates of this study the mat layer consistently had significantly greater soil water content relative to the sand layer (Table 4.6). Accumulation of organic matter in the mat layer was the main reason for greater water content relative to the sand layer. Baker et al. (1999) found that organic matter content in the 0-2 cm layer was 7%, while it was 3% for the 2-8 cm layer. They observed that water contents in the surface layer were twice as great as in the lower (2-8 cm) layer.

Table 4.5. Soil water content of the sand layer on three management treatments from September 2002 to May 2004.

Date	Treatment			P (F-test)
	NCA-LT	NCA-HT	CA-HT	
	2002 (%, weight)			
Sep 22	0.09a (0.002)[Z]	0.08a (0.006)	0.07a (0.002)	0.086
Oct 20	0.08a (0.008)	0.08a (0.004)	0.08a (0.002)	0.595
	2003 (%, weight)			
Mar 29	0.10a (0.003)	0.09ab (0.006)	0.08b (0.003)	0.024
Apr 28	0.10a (0.002)	0.09b (0.002)	0.08c (0.002)	0.0001
Jun 18	0.09a (0.009)	0.08a (0.007)	0.07a (0.002)	0.115
Aug 20	0.09a (0.006)	0.09a (0.005)	0.08a (0.009)	0.232
Sep 25	N/A[Y]	0.09a (0.007)	0.07a (0.001)	0.071
	2004 (%, weight)			
Apr 1	N/A	0.10b (0.002)	0.09a (0.003)	0.024
May 1	N/A	0.08a (0.009)	0.07a (0.005)	0.556

[Z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the same sapling date are not significantly different (P>0.05).

[Y]Data were not obtained since two out of three replications were removed by the golf course management.

Table 4.6. Average soil water content of mat and sand layers during 2002-2004.

Date	Layer		*P* (F-test)
	Mat	Sand	
	---(%, weight)---		
Sep 22, 2002	0.19 (0.02)[z]	0.08 (0.03)	0.0004
Oct 20, 2002	0.21 (0.02)	0.08 (0.03)	0.0001
Mar 29, 2003	0.34 (0.016)	0.09 (0.003)	0.0001
Apr 28, 2003	0.22 (0.016)	0.09 (0.020)	0.0001
Jun 18, 2003	0.16 (0.015)	0.08 (0.004)	0.0024
Aug 20, 2003	0.20 (0.015)	0.10 (0.004)	0.0023
Sep 25, 2003	0.20 (0.021)	0.08 (0.007)	0.0006
Apr 1, 2004	0.26 (0.017)	0.10 (0.003)	0.0001
May 1, 2004	0.21 (0.028)	0.07 (0.006)	0.0011

[z]Standard error of the mean in the parentheses (n=9).

Since soil water content affects various soil properties and processes (e.g., soil strength which determines root penetration) measuring soil water content is needed in any type of soil management study. Soil water content is a dynamic parameter that changes with time and space depending on a combination of numerous factors such as texture, structure, cropping practice, organic matter. Even though soil water content is a commonly measured parameter it does not directly indicate how much water is available for plant growth unless information is available on how strongly the water is held by the soil. In other words, amount of plant-available water in a soil is dependant on soil water potential. However, water potential is much more difficult to determine and soil water content is often used as an indicator of the state of water in soil. Measurements of soil water content on sand-based putting greens may provide an indication of surface softness following irrigation or precipitation. This in turn indicates how well the surface of the putting green (i) accepts and removes water by drainage and (ii) withstands traffic without becoming overly bumpy.

Water retention measurements at 0, 3, 8, and 20 kPa obtained on samples collected before spring core aeration (March 27, 2002) were similar among the three treatments (Figure 4.1). On the other hand, measurements obtained at higher pressures (i.e., 60, 90, 180, and 300 kPa) were significantly greater on NCA-HT than NCA-LT. These higher pressures were above field capacity (corresponds to 10 to 30 kPa) but still represented plant-available soil water. Organic matter content on NCA-HT treatment was 0.8% greater than on the NCA-LT (Table 4.1), which probably contributed to greater water retention on the NCA-HT treatment. Similarly, a study by Habeck and Christians (2000) carried out on sand-based putting greens in Colorado showed that (when measured at 40 cm tension) a putting green with 0.5% organic matter had water content of 20%, while a putting green with 1.4% organic matter had a water content of 31%.

Differences in water retention between NCA-HT and NCA-LT observed at the first sampling date in 2002 disappeared by the last sampling date in the season (Figure 4.2). On October 20, 2002 (three weeks after fall core aeration) organic matter content of the mat layer was similar on all treatments ranging from 2.8 to 3.1% (Table 4.1), which resulted in similar water retention on all three treatments.

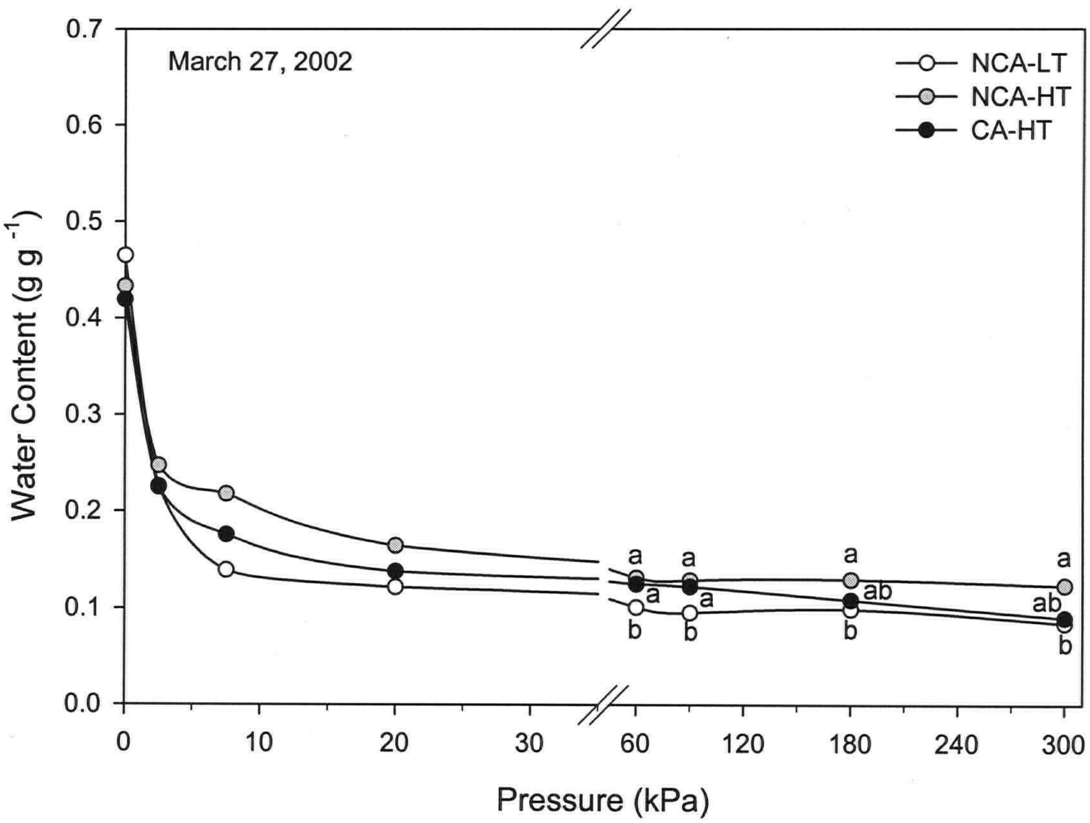

Figure 4.1. Water retention for three management treatments on March 27, 2002 (before spring core aeration). Means followed by the same letter within the same pressure are not significantly different (*P*>0.05). Letters are only shown at pressures where treatments had a significant effect on water retention.

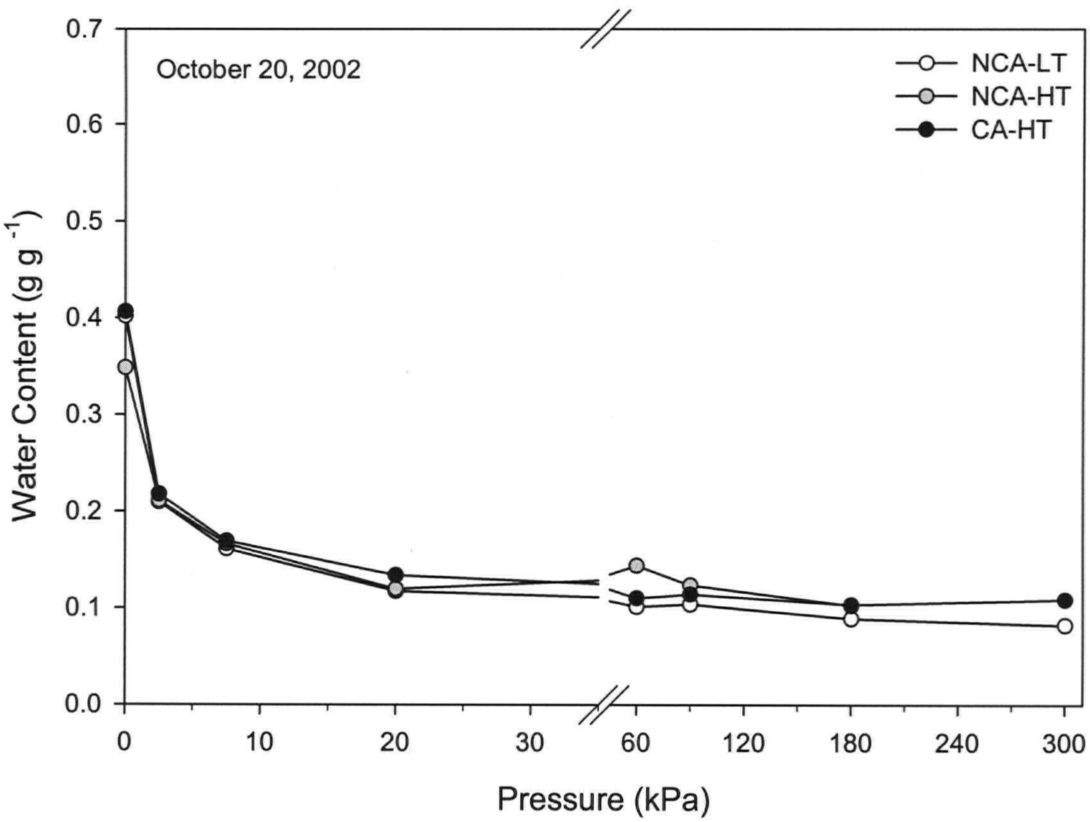

Figure 4.2. Water retention for three management treatments on October 20, 2002 (three weeks after fall core aeration).

At two subsequent measurement dates (March 29, 2003 –before spring core aeration and May 1, 2004 – one month after spring core aeration) water retention was similar among the treatments (Figures 4.3 and 4.4), which was in agreement with the similar organic matter contents among the treatments (Table 4.1).

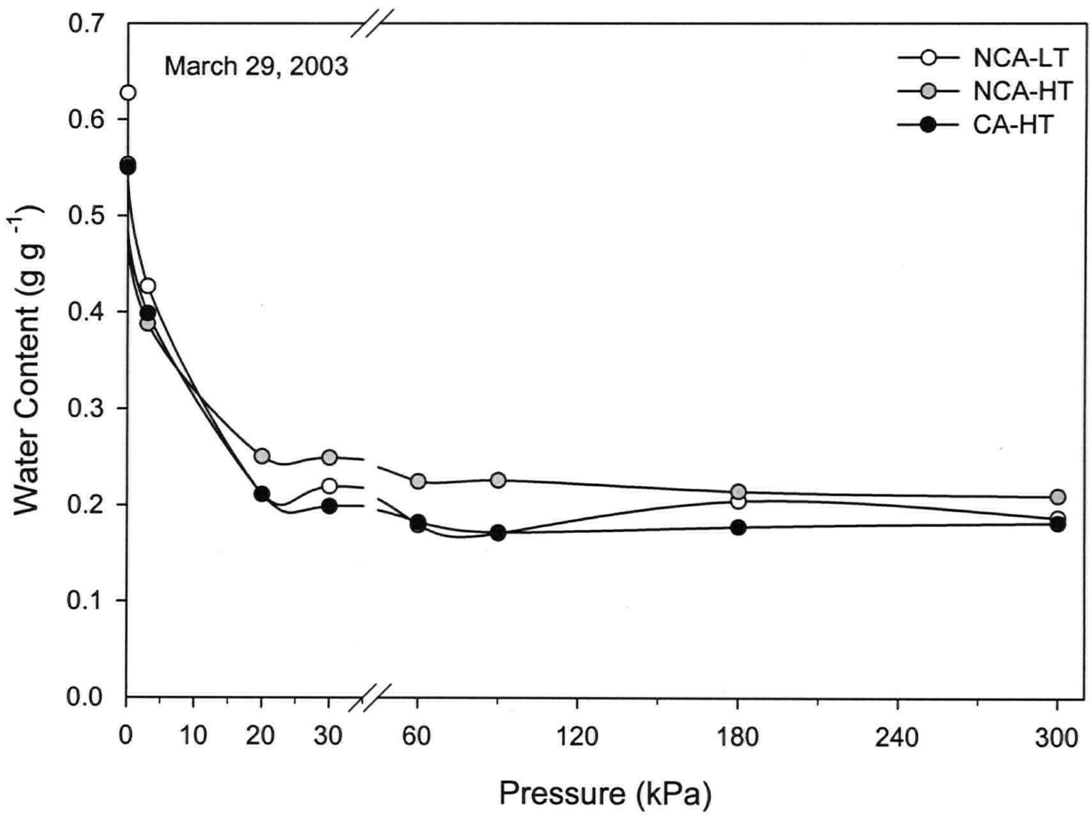

Figure 4.3 Water retention for three management treatments on March 29, 2003 (just before spring core aeration).

The water retention curves (sometimes referred to as desorption curves) indicate how much water is retained by the soil at each successively lower matric potential (Topp et al. 1993). These measurements can be used to characterize some other soil physical properties such as pore size distribution (and associated water availability to plants) and water infiltration. My data indicate that organic matter was the driving force for soil water retention on the sand-based putting greens and changes in water retention closely matched changes in organic matter. Distribution of macropores (as indicated by the measurements at low pressures) was similar on all three treatments, while distribution of mesopores (as indicated by measurements at high pressures) was increased with increasing organic matter content on NCA-HT. Allowing organic matter to accumulate above 3-4% on treatments without core aeration may result in wetter soil conditions not favorable for a healthy turf growth.

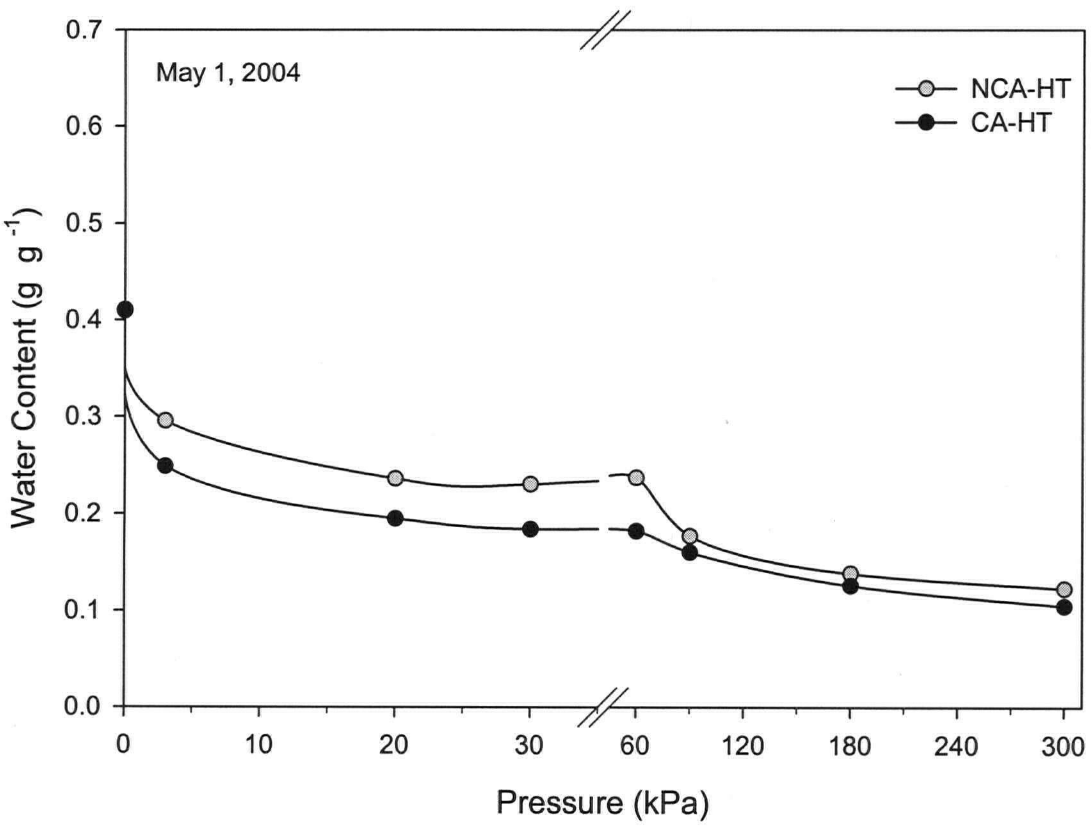

Figure 4.4. Water retention for two management treatments on May 1, 2004 (one month after spring deep solid-tine aeration).

4.3. Soil Bulk Density

During 2002 soil bulk density was significantly affected by the treatments on two out of five sampling dates (Table 4.7). On March 27, 2002 (before spring core aeration), NCA-LT soil bulk density was lower relative to two other treatments as a result of double core aeration carried out six months before the beginning of this study. That practice removed root biomass and organic matter and sand from 14% of the total surface area, lowering the bulk density on NCA-LT. On August 18, 2002 (five months after spring aeration), bulk density was still lower on NCA-LT than for CA-HT. The NCA-LT treatment had low impacts of management practices and virtually no play traffic, so it was able to maintain low bulk density relative to the CA-HT treatment that was continuously exposed to pressures of numerous management practices (mowing, fertilizer application, rolling, etc.).

When samples were collected separately from the mat and sand layers, NCA-LT bulk density of the mat layer obtained three weeks after fall core aeration (October 20, 2002) was lower relative to two the other treatments (Table 4.8). In addition, NCA-LT bulk density was also lower than CA-HT on June 18, 2003 (three months after spring core aeration). The most likely reason was due to a greater increase in soil organic matter on the NCA-LT treatment in 2002 relative to the high traffic treatments (Table 4.1) in association with no traffic to reduce the size of organic matter particles both contributing to a reduction of soil bulk density in October 2002.

Bulk densities of the mat layer on two treatments having high traffic were significantly different only on one (June 18, 2003) out of nine sampling dates. On June 18, 2003 (three months after core aeration), NCA-HT soil bulk density was lower than for CA-HT. On April 4, 2004 deep solid-tine aeration, which did not remove cores of sand and turf, was used instead of core aeration. One month after deep solid-tine aeration there were no differences in soil bulk density (in either the mat or sand layers) between the treatments (Tables 4.8 and 4.9).

Similar to findings of my study, core aeration did not lower soil bulk density relative to the control treatment without this practice in a study by Murphy et al. (1993) carried out on creeping bentgrass grown on sand-based putting greens with 83% sand, 11% silt, and 6% clay in Michigan.

Table 4.7. Soil bulk density obtained in the 0-17.5 cm layer for three management treatments during 2002.

Date	Treatment			*P* (F-test)
	NCA-LT	NCA-HT	CA-HT	
	----------(Mg m^{-3})----------			
Mar 27	1.42a (0.008)[Z]	1.47b (0.005)	1.47b (0.012)	0.033
Jun 15	1.44a (0.032)	1.48a (0.037)	1.49a (0.014)	0.693
Aug 18	1.44a (0.012)	1.48ab (0.022)	1.54b (0.017)	0.029
Sep 22	1.44a (0.021)	1.47a (0.013)	1.48a (0.006)	0.572
Oct 20	1.46a (0.016)	1.47a (0.004)	1.48a (0.002)	0.632

[Z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the sampling date are not significantly different (*P*>0.05).

Table 4.8. Soil bulk density obtained from the mat layer on study treatments from September 2002 to May 2004.

Date	Treatment			*P* (F-test)
	NCA-LT	NCA-HT	CA-HT	
	------------------------2002 ($Mg\ m^{-3}$)------------------------			
Sep 22	1.34a (0.021)[Z]	1.37a (0.034)	1.38a (0.027)	0.930
Oct 20	1.28a (0.063)	1.38b (0.05)	1.41b (0.023)	0.019
	------------------------2003 ($Mg\ m^{-3}$)------------------------			
Mar 20	1.27a (0.047)[Y]	1.28a (0.040)	1.33a (0.038)	0.812
Apr 28	1.38a (0.051)	1.37a (0.019)	1.39a (0.016)	0.348
Jun 18	1.35a (0.033)	1.35a (0.031)	1.45b (0.013)	0.028
Aug 20	1.33a (0.030)	1.37a (0.037)	1.41a (0.019)	0.269
Sep 25	N/A[X]	1.38a (0.024)	1.37a (0.020)	0.990
	------------------------2004 ($Mg\ m^{-3}$)------------------------			
Apr 1	N/A	1.37a (0.031)[Z]	1.41a (0.047)	0.169
May 1	N/A	1.36a (0.038)	1.40a (0.015)	0.277

[Z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the sampling date are not significantly different (P>0.05).

[Y]Standard error of the mean in the parentheses (n=6).

[X]Data was not obtained since two study replications were removed by the golf course management.

Bulk densities of the sand layer for the NCA-LT treatment (Table 4.9) was lower than on two other treatments on two (April 28 and August 20, 2003) out of nine sampling dates. Similarly as for the mat layer, bulk densities of the sand layer were not statistically different for the NCA-HT and CA-HT treatments regardless of the sampling date.

Table 4.9. Soil bulk density obtained from the sand layer on study treatments from September 2002 to May 2004.

Date	Treatment			*P* (F-test)
	NCA-LT	NCA-HT	CA-HT	
	------2002 ($Mg\ m^{-3}$)------			
Sep 22	1.54a (0.057)[Z]	1.54a (0.030)	1.56a (0.032)	0.964
Oct 20	1.63a (0.015)	1.53a (0.037)	1.53a (0.018)	0.136
	------2003 ($Mg\ m^{-3}$)------			
Mar 29	1.48a (0.032)[Y]	1.50a (0.012)	1.49a (0.024)	0.805
Apr 28	1.42a (0.028)	1.53b (0.010)	1.52b (0.015)	0.010
Jun 18	1.58a (0.019)	1.59a (0.015)	1.60a (0.014)	0.068
Aug 20	1.44a (0.020)	1.50b (0.021)	1.52b (0.011)	0.024
Sep 25	N/A[X]	1.62a (0.024)	1.67a (0.028)	0.719
	------2004 ($Mg\ m^{-3}$)------			
Apr 1	N/A	1.49a (0.012)[Z]	1.51a (0.012)	0.145
May 1	N/A	1.47a (0.022)	1.52a (0.007)	0.386

[Z]Standard error of the mean in the parentheses (n=3). Means followed by the same letter within the sampling date are not significantly different (P>0.05).

[Y]Standard error of the mean in the parentheses (n=6).

[X]Data was not obtained since two study replications were removed by the golf course management.

For sampling dates when soil bulk density was obtained separately for the mat and sand layers data were averaged over the treatments (Table 4.10). The mat layer with accumulation of organic matter had consistently lower bulk density (1.37 $Mg\ m^{-3}$) relative to the sand layer (1.53 $Mg\ m^{-3}$) with very little organic matter. Core aeration on the study sites was consistently applied at the same depth (7.5 cm) since 1996 creating a compaction pan at depth just below tine penetration. Studies by Petrovic (1979), Murphy et al. (1993), and Guertal and Han (2002) also reported creation of compaction pan after years of cultivation carried out at the same depth. In my study there was an additional factor that could have contributed to compaction of the sand layer. The vibrating action of the "Toro Greens Aerator" may have facilitated close packing of sand particles, especially since the sand layer had low aggregation and low cohesive properties during times when core aeration was applied. Eight years of consistent depth of core aeration accompanied with vibrating action of the core aerator resulted in a bulk density of the sand layer that may have been restrictive for root penetration.

Bulk densities within the range of 1.2 to 1.6 Mg m^{-3} are considered to be non restrictive for root growth of majority of turf species (USGA, 1993). Mat layer in my study had bulk density well within the acceptable range, while on couple of dates bulk density of the sand layer exceeded 1.6 Mg m^{-3}.

Table 4.10. Average soil bulk density for mat and sand layers in 2002-2004.

Date	Layer		*P* (F-test)
	Mat	Sand	
	------------------------------(Mg m^{-3})------------------------		
Sep 22, 2002	1.37 (0.015)[Z]	1.55 (0.019)	0.0001
Oct 20, 2002	1.36 (0.032)	1.56 (0.021)	0.0001
Mar 29, 2003	1.29 (0.024)	1.49 (0.013)	0.0001
Apr 28, 2003	1.38 (0.018)	1.49 (0.015)	0.0003
Jun 18, 2003	1.39 (0.019)	1.59 (0.009)	0.0001
Aug 20, 2003	1.37 (0.018)	1.48 (0.013)	0.0001
Sep 25, 2003	1.37 (0.015)	1.64 (0.019)	0.0001
Apr 1, 2004	1.39 (0.027)	1.50 (0.009)	0.015
May 1, 2004	1.38 (0.021)	1.50 (0.016)	0.008

[Z]Standard error of the mean in the parentheses (n=9).

4.4. Soil Penetration Resistance

During the first year of the study (i.e., 2002) NCA-LT consistently had the lowest soil penetration resistance at depths between 3 and 18 cm (Figure 4.5). The NCA-LT lower soil penetration resistance on March 27, 2002 (i.e., before spring core aeration), was a result of double core aeration applied in September 2001 on two out of three replications of NCA-LT. This treatment had minimal overall mechanical disturbance, hence, continued to exhibit the lowest soil penetration resistance at two other dates of measurement in 2002. Before the spring core aeration (March 27, 2002) NCA-HT and CA-HT had similar soil penetration resistance throughout most of the soil profile, with the exception of the 7.5-10.5 cm layer where NCA-HT had greater soil penetration resistance than CA-HT. Six months after spring core aeration application (September 22, 2002) NCA-HT and CA-HT treatments still had similar soil penetration resistances. Fall core aeration lowered soil penetration resistance for CA-HT relative to NCA-HT as indicated by measurements that were done three weeks after fall core aeration (October 20, 2002).

During 2003, soil penetration resistance below the 3 cm depth for NCA-LT was the lowest among the three treatments (Figure 4.6) indicating that sand-based putting greens remain relatively non-compacted when mechanical disturbance (either by management practices and/or play traffic) is reduced to a minimum. When soil penetration resistance measurements were done before the spring core aeration (March 29, 2003) CA-HT was still less compacted than NCA-HT treatment indicating that the fall core aeration done on September 29, 2002 was still noticeable. This may be due to reduced traffic (i.e., management and player traffic similar to the NCA-LT treatment) from mid October to mid March having less compaction effect on the root zone than high traffic during peak golfing seasons. As expected, one month after spring core aeration in 2003 (April 28) CA-HT had lower soil penetration resistance than NCA-HT for the 6-9 cm layer. Five months after spring core aeration (August 20, 2003) soil penetration resistance on CA-HT was greater than for NCA-HT in the 3-11.5 cm soil layer. It is unclear why this was the case. The fall application of core aeration brought soil penetration resistance on CA-HT and NCA-HT treatments to a similar level when measurements were done a month after core aeration (September 25, 2003).

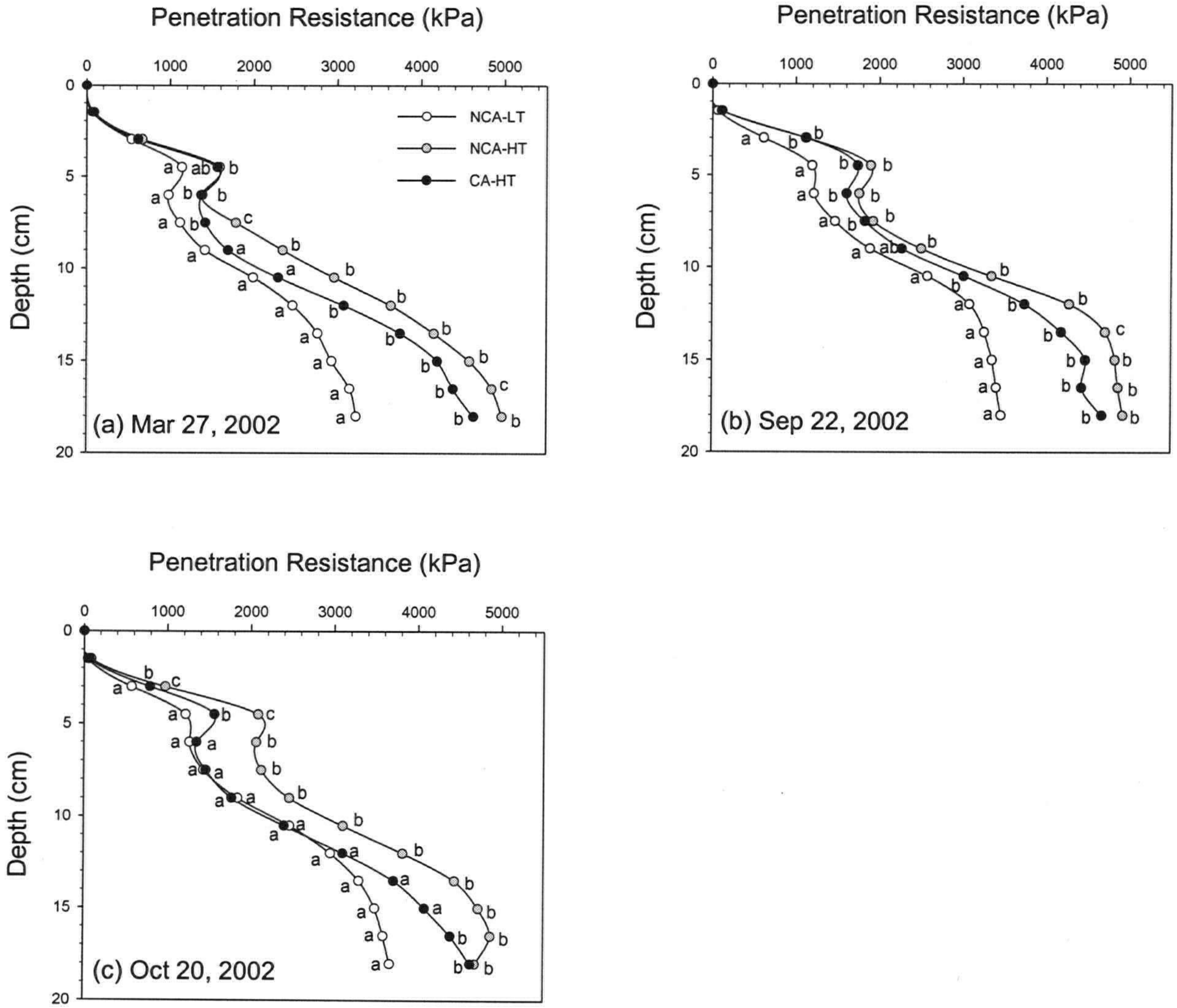

Figure 4.5. Soil penetration resistance obtained on three management treatments on (a) March 27, (b) September 22, and (c) October 20, 2002. Means followed by the same letter within the same depth are not significantly different (*P* >0.05) (n=15). Letters are only shown at depths where treatments had a significant effect on soil penetration resistance.

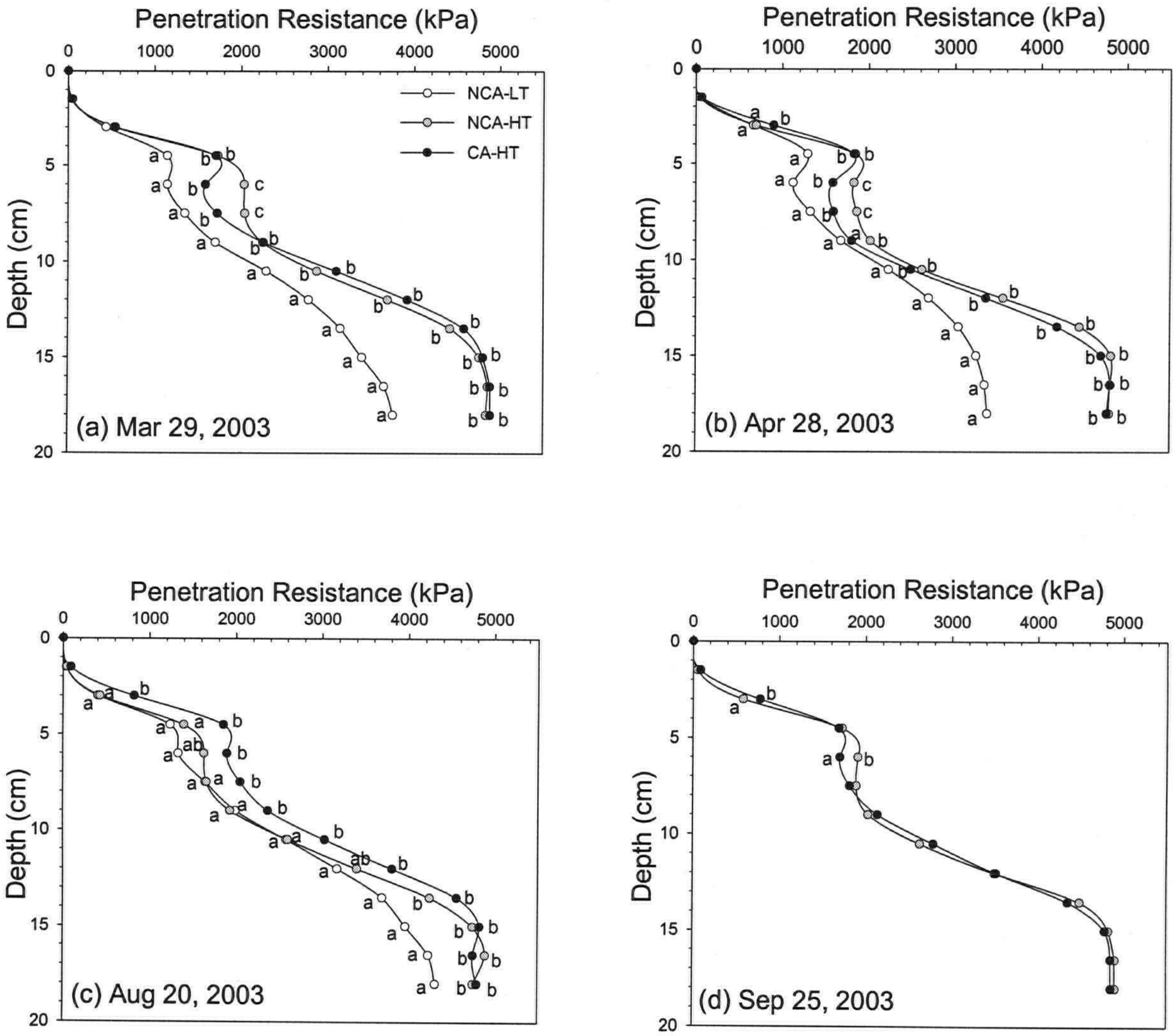

Figure 4.6. Soil penetration resistance obtained on three management treatments on (a) March 29, (b) April 28, (c) August 20, and (d) September 25, 2003. Means followed by the same letter within the same depth are not significantly different (*P* >0.05) (n=15). Letters are only shown at depths where treatments had a significant effect on soil penetration resistance.

Soil penetration resistance for CA-HT and NCA-HT remained similar for the 0-11.5 cm layer before spring cultivation of 2004 (April 1, 2004), while at depths below 11.5 cm NCA-HT had lower soil penetration resistance (Figure 4.7). On April 4, 2004, core aeration was replaced with deep solid-tine aeration that did not remove soil and turf cores. The switch to deep solid-tine aeration was done to reduce compaction below 7.5 cm, i.e. below the usual depth of core aeration. When soil penetration resistance measurements were obtained a month after deep solid-tine aeration CA-HT and NCA-HT treatments had similar soil penetration resistance. According to McCarty (2001) solid-tine aeration may compact soil along the sides and at the bottom of aeration holes, but in my study soil penetration measurements may have been taken too late after deep solid-tine aeration to observe any differences.

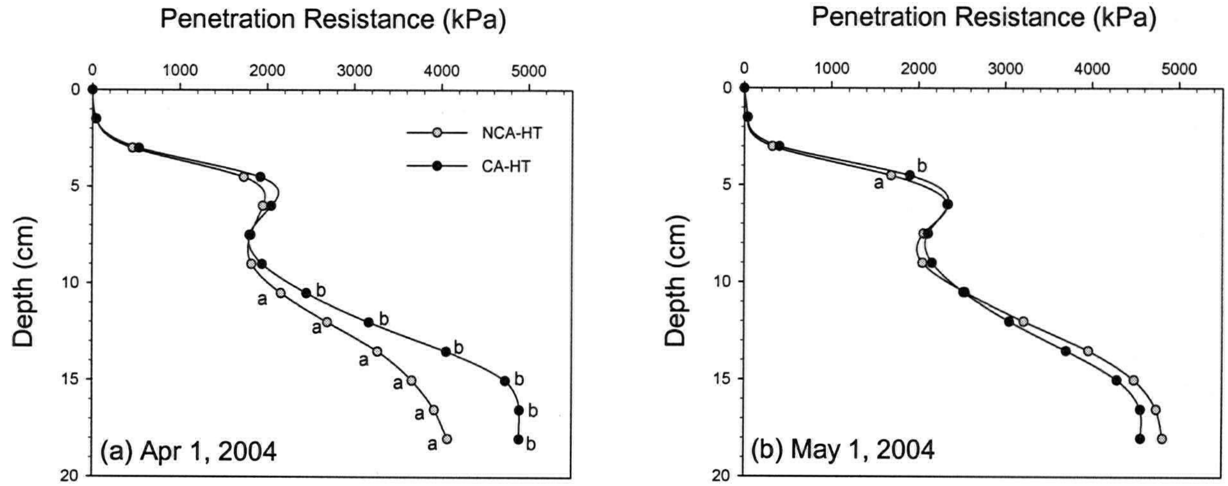

Figure 4.7. Soil penetration resistance in obtained on two management treatments on (a) April 1 and (b) May 1, 2004. Means followed by the same letter within the same depth are not significantly different (P>0.05) (n=10). Letters are only shown at depths where treatments had a significant effect on soil penetration resistance.

Data obtained during my study showed that core aeration generally led to reduction of soil compaction as indicated by soil penetration resistance. This is in agreement with findings of Murphy et al. (1993) who carried out a study on sand-based creeping bentgrass putting greens with 83% sand, 11% silt, and 6% clay in Michigan. They found that cultivation (either core or solid-tine aeration) lowered soil penetration resistance relative to treatment without cultivation. Although soils in the study mentioned above were more compacted compared to my study, soil penetration resistance on core aeration treatments were about 30% lower than on treatment without core aeration. Guertal et al. (2003) found that the effects of core aeration on soil penetration resistance lasted for one to seven weeks on a loamy sand athletic field in Auburn, Georgia. In my study the reduction of soil penetration resistance caused by core aeration lasted for about one month. There was one exception which occurred in spring (March 29, 2003) when penetration resistance at 6 to 7.5 cm on CA-HT was less than NCA-HT indicating that the effect of core aeration lasted from the previous fall application. The most likely reason for this exception was due to reduced traffic during winter months thereby reproducing the effects of the low traffic treatment.

Throughout the 27-month study period NCA-HT and CA-HT soil penetration resistance at depths below 9-10 cm exceeded 2500 kPa, a commonly cited critical value for root growth (Greacen et al., 1969; Busscher et al., 1986; Conlin and van den Driessche, 2000). On the NCA-LT treatment soil penetration resistance exceeded 2500 kPa at depths below 12 cm. This coincided with observations of depth of rooting that rarely exceeded 9 cm for the NCA-HT and CA-HT treatments or 12 cm for the NCA-LT treatment (data not shown). A study by Cook et al. (1996) carried out on *Agrostis* species turfgrass showed that 1400 kPa moderately impeded root penetration, while 2300 kPa severely impeded root growth. The soil penetration resistance data coincide with bulk density data indicating that a compaction pan has developed just below the mat layer.

Even though bulk density is commonly used as a soil compaction indicator either in forest (Froehlich et al., 1986; Cullen et al., 1991; Gomez et al., 2002), agricultural (Pidgeon and Soane, 1977; Blevins et al., 1983; Carter, 1992), or turf ecosystems (Murphy et al., 1993; Baker et al., 1999; USGA, 1993), this static soil property may not completely describe how soil responds to mechanical disturbance or how soil compaction affects plant growth. Sampling for bulk density is destructive, time consuming, and often difficult to carry out. Furthermore, to determine impacts of mechanical disturbance on soil bulk density, a large number of samples are needed particularly on soils with great spatial variability. Findings of this study show that even on relatively homogeneous sand-based putting greens a large number of samples per treatment is needed to capture impacts of mechanical disturbance brought about by core aeration.

On the other hand, impacts of core aeration on soil penetration resistance were observed more often among my study treatments. Measurements of soil penetration resistance are relatively easy to obtain, non-destructive, and can be completed more quickly than bulk density sampling. Consequently, a greater number of measurements per treatment can be taken. Collecting gravimetric soil water content samples concurrently with penetration resistance is necessary to adjust for effects of soil water content. All this allows soil penetration resistance to capture the impacts of mechanical disturbance at various depths throughout the soil profile.

4.5. Water Infiltration Rate

In 2002 when only the small double ring infiltrometer was used water infiltration rate was significantly affected by treatment on four out of six sampling dates (Table 4.11). Water infiltration rate for the NCA-LT was consistently greater than for NCA-HT, while only on one date (October 20, 2002) it was greater relative to CA-HT (Figure 4.8). Two high traffic treatments (NCA-HT and CA-HT) had similar water infiltration rates (Figure 4.8).

Table 4.11. Analysis of variance (*P*-values) for the effect of three management treatments in 2002 on water infiltration rate using a small double ring infiltrometer.

Source of Variation	df	Sampling Dates in 2002					
		Mar 27	Apr 28	Jun 15	Aug 18	Sep 22	Oct 20
Block	2	0.347	0.100	0.878	0.192	0.351	0.411
Treatment	2	0.063	0.029	0.093	0.012	0.024	0.004

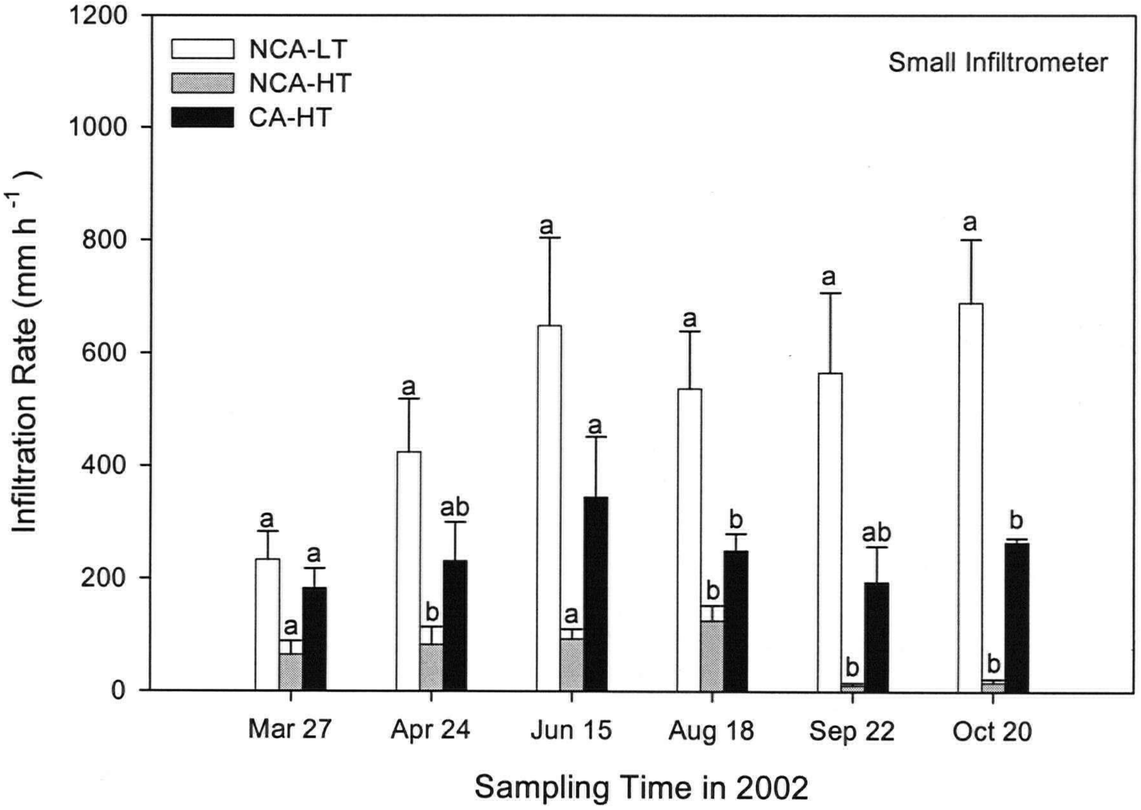

Figure 4.8. Water infiltration rates obtained with a small double ring infiltrometer under three management treatments during 2002. Error bars represent standard error of the mean (n=3). Means followed by the same letter within the same sampling time are not significantly different ($P>0.05$).

In 2003, both the small and large double ring infiltrometers were used to measure water infiltration rates. Water infiltration rates obtained with the small double ring infiltrometer were significantly affected by treatments on only one (August 20, 2003) out of five sampling dates (Table 4.12), when the NCA-LT treatment had greater infiltration rate relative to the other two treatments (Figure 4.9). Similar to 2002, there were no significant differences in water infiltration rates between NCA-HT and CA-HT treatments (Figure 4.9).

Table 4.12. Analysis of variance (*P*-values) for the effect of three management treatments during 2003 on water infiltration rate using a small double ring infiltrometer.

Source of Variation	df	Sampling Dates in 2003				
		Mar 29	Apr 28	Jun 18	Aug 20	Sep 25
Block	2	0.513	0.325	0.573	0.012	0.652
Treatment	2	0.080	0.116	0.089	0.004	0.368

The NCA-LT treatment had higher infiltration (measured with large infiltrometer) relative to NCA-HT on April 28 and June 18, 2003 (Fig. 4.10). For the first time during this study water infiltration rate was significantly different between the two high traffic treatments (Table 4.13). On two post-core aeration sampling dates done about a month after core aeration (i.e., April 28 and September 25, 2003) water infiltration rate was higher on CA-HT relative to NCA-HT treatment. About three and five months after core aeration June 18 and August 20, 2003, respectively improvements of drainage in the mat layer achieved by the core aeration disappeared since infiltration was similar in treatments with and without this cultivation practice.

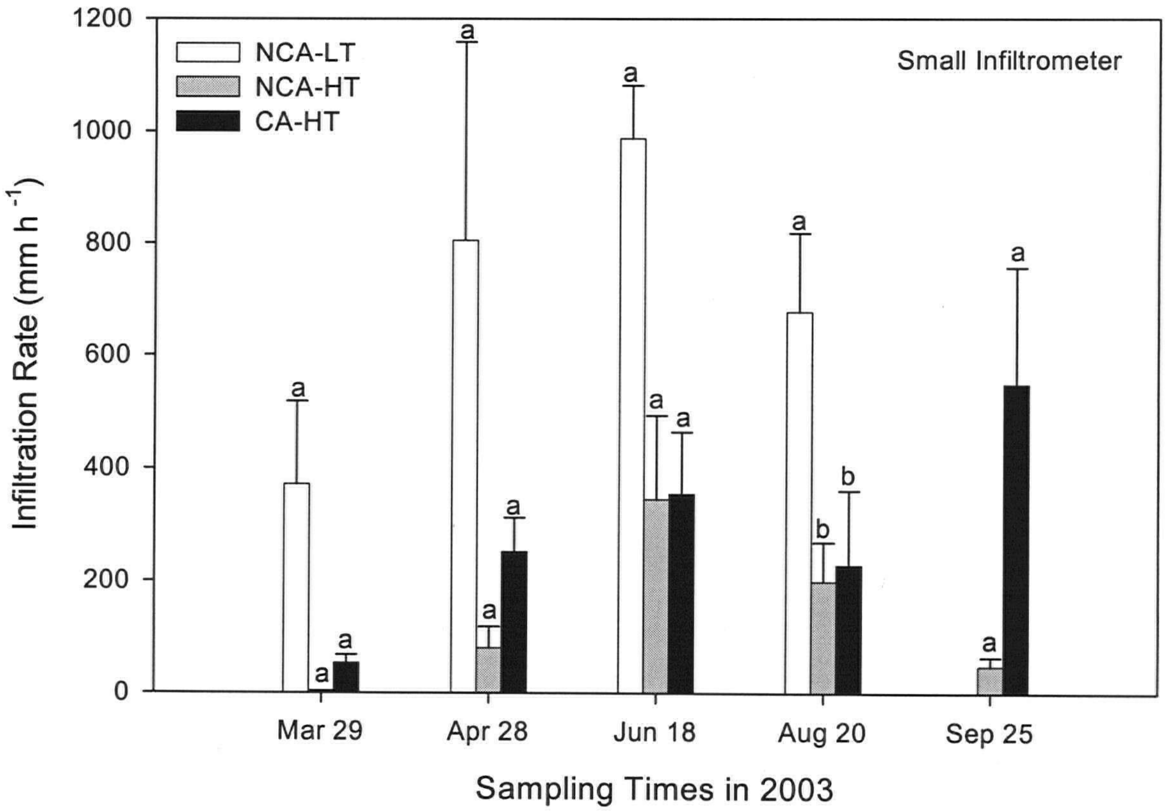

Figure 4.9. Water infiltration rates obtained with a small double ring infiltrometer under three management treatments during 2003. Error bars represent standard error of the mean (n=3). Means followed by the same letter within the same sampling time are not significantly different (*P*>0.05).

Table 4.13. Analysis of variance (*P*-values) for the effect of three management treatments in 2003 on water infiltration rate using a large double ring infiltrometer.

Source of	df	Sampling Times in 2003			
Variation		Apr 28	Jun 18	Aug 20	Sep 25[Z]
Block	2	0.084	0.461	0.145	0.216
Treatment	2	0.003	0.024	0.109	0.035

[Z] Degrees of freedom (df) for treatment on Sep 25, 2003 are 1 (instead of 2).

According to McCarty (2001) infiltration rate on sand-based putting greens should range from 250 to 380 mm h^{-1} for initial construction and should not be lower than 100 mm h^{-1} for mature putting greens (over one to two years old). Average infiltration rates obtained in my study with the large double ring infiltrometer were within the ranges indicated above except for April and September 2003 and April 2004 on the NCA-HT treatment. On August 20, 2003 prior to the fall core aeration, the infiltration rate on NCA-HT was similar to CA-HT, which coincides with similar organic matter content (Table 4.1). Numerous studies have indicated that soil organic matter has a profound effect on infiltration in sand-based putting greens (Hanson, 1969; Baker et al., 1999; Curtis and Pulis, 2001). Habeck and Christians (2000) reported that soil organic matter increased from initial 0.5% at the time of putting greens construction in Colorado to 0.8% decreasing water infiltration from 279 to 79 mm h^{-1}. Additional increase in soil organic matter to 1.4% resulted in water infiltration rate of 64 mm h^{-1}.

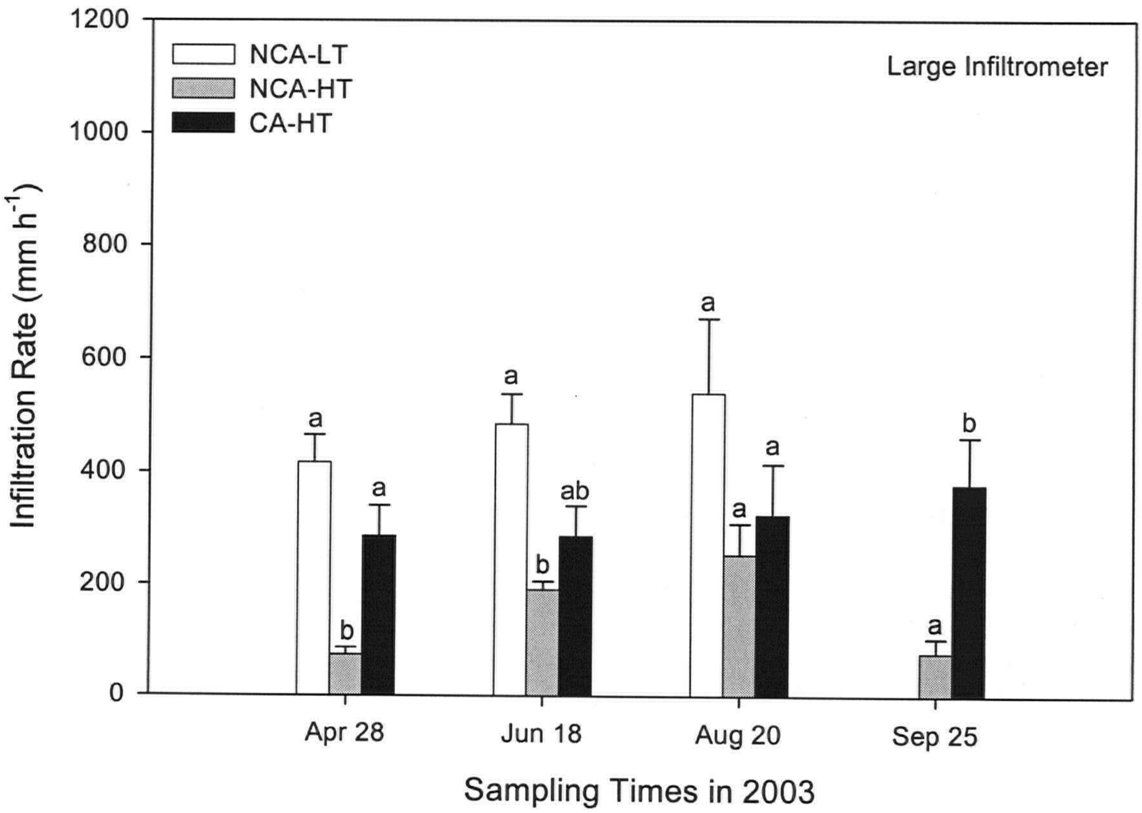

Figure 4.10. Water infiltration rates obtained with a large double ring infiltrometer under three management treatments during 2003. Error bars represent standard error of the means (n=3). Means followed by the same letter within the same sampling date are not significantly different (*P*>0.05).

On April 1, 2004 (i.e., just before the spring deep solid-tine aeration), water infiltration rate obtained with a large infiltrometer was significantly greater on CA-HT than NCA-HT (Table 4.14). At the same date soil organic matter content on NCA-HT was 0.5% greater than on CA-HT treatment (Table 4.1) and exceeded the recommended 3%, which may have led to lower infiltration rate for the NCA-HT treatment (Figure 4.11). On May 1, 2004 (a month after the solid deep-tine aeration), there was no difference between two treatments. This was in agreement with similar soil penetration resistance on NCA-HT and CA-HT treatments. Since deep solid-tine aeration did not remove cores of soil and turf, content of organic matter (Table 4.1) and root weight density (Table 4.3) were similar on CA-HT and NCA-HT treatments creating similar conditions for water infiltration. It is also possible that measurement of water infiltration rate on May 1, 2004 may have been done too late after deep-tine aeration to register any differences between treatments. Guertal et al. (2003) indicated that the effects of aerification on infiltration rate of heavily trafficked athletic fields greens lasted from one to seven weeks on a loamy sand (>80% sand) in Alabama.

Water infiltration rates obtained in 2004 with a small infiltrometer on the two study treatments were similar. The lack of difference could have been related to the fact that this relatively small infiltrometer sampled areas between the large spacing (10 x 10 cm) of the deep-tine aeration.

Table 4.14. Analysis of variance (*P*-values) for the effect of two management treatments during 2004 on water infiltration rate using small and large double ring infiltrometers.

Sources of Variation	df	Sampling Dates in 2004			
		Large Infiltrometer		Small Infiltrometer	
		Apr 1	May 1	Apr 1	May 1
Block	2	0.586	0.426	0.352	0.533
Treatment	1	0.013	0.177	0.874	0.355

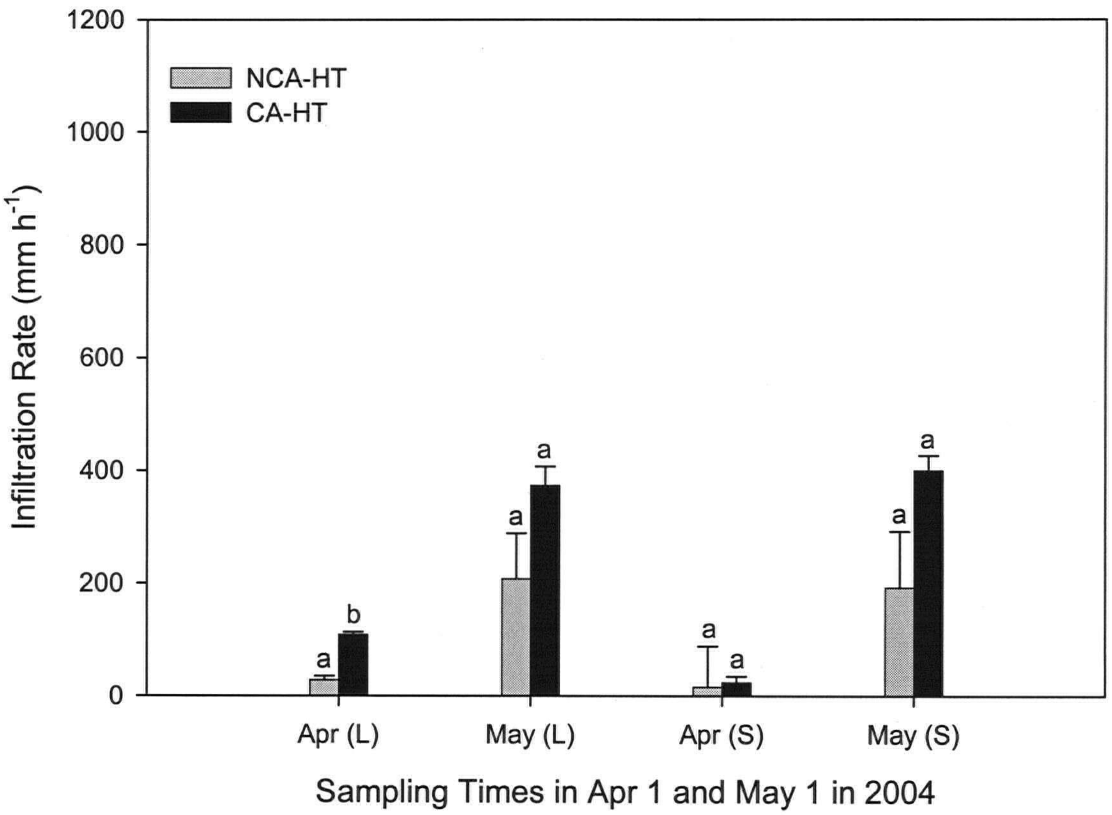

Figure 4.11. Water infiltration rates obtained with large (L) and small (S) double ring infiltrometers under two management treatments during 2004. Error bars represent standard error of the means (n=3). Means followed by the same letter within the same sampling date are not significantly different (P>0.05).

Regression analysis between water infiltration rates obtained by small and large double ring infiltrometers revealed that there was a strong positive linear correlation (r^2=0.74, P=0.01) between the two infiltrometers (Figure 4.12). Based on this preliminary calibration the small infiltrometer overestimates water infiltration rate by a coefficient of 2 (or ~108%). Some additional, more detailed and extensive calibration of the small infiltrometer (commonly used by the golf industry) relative to the large double ring infiltrometer (used in soil science studies) is needed. However, for time being golf course managers can continue to use it and correct the readings by the coefficient mentioned above. This is especially important when a quick estimates are needed (i.e., during play).

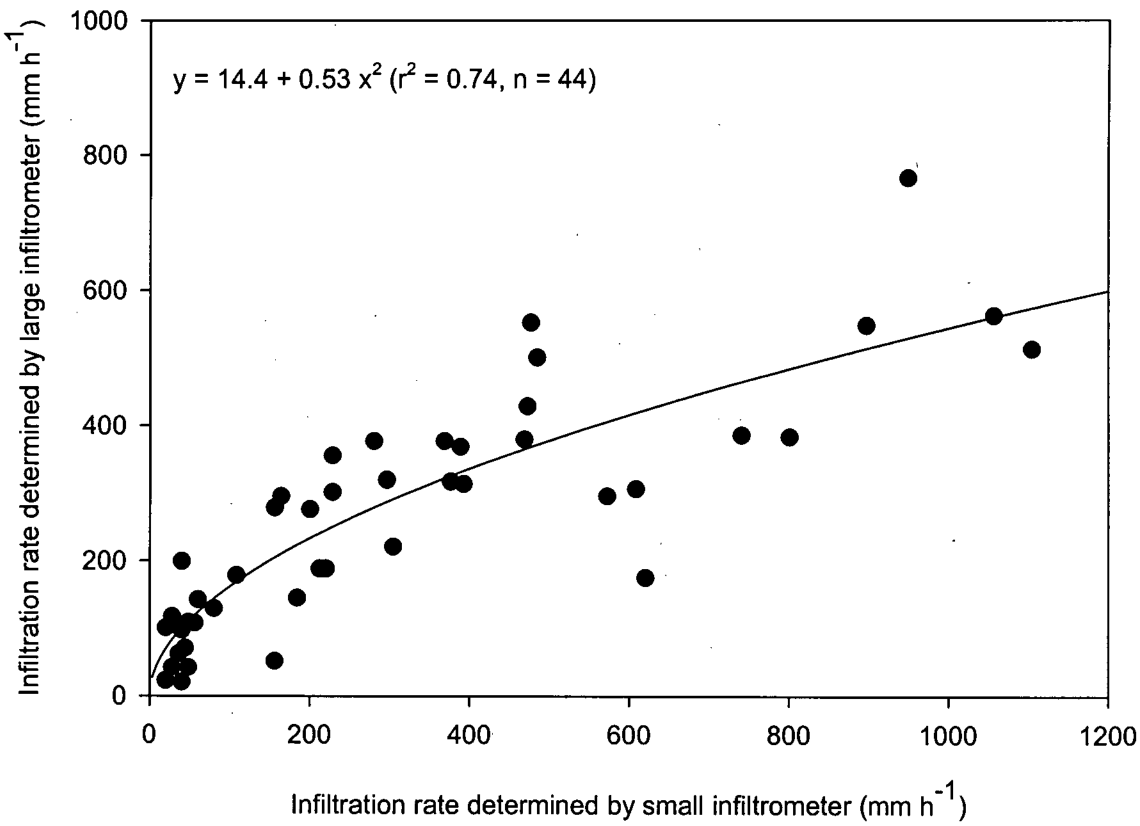

Figure 4.12. Correlation between water infiltration rates obtained with small and large double ring infiltrometers.

In general, determination of water infiltration is non-destructive and relatively easy to obtain (but may take long time to complete). Water infiltration rate can be a valuable indicator of soil compaction, but water infiltration does not indicate the depth at which a compacted layer is present. Hence, it is beneficial to combine water infiltration measurements with soil penetration resistance to assess compaction on sand-based putting greens. Impacts of core aeration on water infiltration rate were observed more often between NCA-HT and CA-HT when the large double ring infiltrometer was used. However, measurements using the small infiltrometer are relatively easy to obtain and can be completed more quickly than using the large double ring infiltrometer. Consequently, a greater number of measurements per treatment can be taken using the small double ring infiltrometer and data should be corrected using the regression correlation between small and large infiltrometers.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Growing good quality turf on areas with high intensity of management practices and high play traffic, such as putting greens, is challenging mainly due to compaction and excessive accumulation of organic matter within the root zone. There is a disagreement either among the golf course managers or in the literature regarding how many core aeration practices should be applied annually to create optimum growing conditions in the root zone.

In this study each core aeration application impacted 7% of the putting greens surface area due to small size of hollow tines used. As a result of the low core aeration impact treatments with and without this cultivation practice ended up having similar organic matter contents. For the most of the 27-month study period soil organic matter content was greater than 3%, a commonly cited critical value for sand-based putting greens, on treatment without core aeration and with high play traffic (NCA-HT) but remained below the critical value on NCA-LT and CA-HT. Root weight density was also similar on all treatments. On sand-based putting greens where all grass clippings are continuously removed, roots are the main source of soil organic matter. Hence, it is not surprising that soil organic matter content closely matched root weight density throughout the study, increasing when root weight density increased and declining when abundance of roots decreased.

About a month after core aeration, soil water content of the mat layer was lower on CA-HT relative to NCA-HT treatment. This was true for three out of four core aeration applications carried out during this study. The impact of core aeration on soil water content was temporary since two months following core aeration water content was similar on all treatments. Mat layer (an upper layer on a golf course or a putting green in which organic matter accumulates) was consistently wetter than the sand layer since the latter had low content of organic matter. Water retention was similar on all study treatments with an exception of March 27, 2002 (a day before spring core aeration) when NCA-HT treatment had greater water retention than NCA-LT and CA-HT at pressures ranging from 60 to 300 kPa. On this same sampling date NCA-HT organic matter was greater for 0.8 and 0.4% than on NCA-LT and CA-HT, respectively.

Soil bulk density was not significantly different among the three treatments with an exception of June 18, 2003 (three months after spring core aeration) when bulk density was greater on CA-HT than

NCA-HT. Soil bulk density of mat layer was consistently lower than of the sand layer. Lack of organic matter in the sand layer accompanied with eight years of core aeration at the same depth of 7.5 cm resulted in development of a compaction pan at depth just below tine penetration. Even though sand-based putting greens of this study had soil bulk densities within the acceptable range Of 1.2 to 1.6 Mg kg^{-3} as specified by the USGA, lack of roots and low organic matter in the sand layer indicate that roots had difficulties penetrating this layer.

The NCA-LT treatment with a limited number of management practices, no core aeration, and almost no play traffic, consistently had the lowest soil penetration resistance at depths between 3 and 18 cm. About one month after core aeration soil penetration resistance was lower for CA-HT than NCA-HT treatment, while this difference disappeared latter on. Deep, solid-tine aeration that replaced core aeration in 2004 did not lower soil penetration resistance on CA-HT treatment relative to the NCA-HT. Soil penetration resistance for all sampling dates on NCA-LT, NCA-HT, and CA-HT treatments exceeded 2500 kPa at depths below about 10 cm indicating presence of root growth limiting conditions within the compaction pan.

Greater water infiltration rates were observed on NCA-LT than on the other two treatments (true for both small and large infiltrometers). This was in agreement with lower soil bulk density, penetration resistance, and organic matter observed on NCA-LT treatment. The lack of significant differences was the result of high data variability associated with the small size of the inner infiltrometer ring of the small infiltrometer that led to either sampling between core aeration holes or encompassing only one or two core aeration holes. Water infiltration rates obtained with the large double ring infiltrometer (commonly used in soil science) showed that about a month after core aeration CA-HT had greater infiltration than NCA-HT. When measurements were taken three and five months after core aeration water infiltration was no longer different on treatments with and without this cultivation practice.

Soil properties such as penetration resistance and water infiltration showed that core aeration reduced compaction on sand-based putting greens, but the effects were temporary and differences observed between treatments with and without core aeration disappeared within several months after application.

5.2. Recommendations

The following recommendations can be made based on the data of this study:

Soil compaction indicators such as soil penetration resistance, water infiltration and conductivity should be monitored continuously. Soil penetration resistance measurements were particularly sensitive to changes in compaction. A double ring infiltrometer that has a large enough inner ring to encompass enough core holes to represent the surface area impacted by core aeration should be used. The double ring infiltrometer should be used throughout the season to establish how water infiltration rates change with time. As infiltration rates decrease, non-damaging management practices such as water injection, needle tine cultivation, and verti-cutting may be used to improve infiltration through the growing season. Accumulation of soil organic matter in the root zone should also be monitored regularly to provide assessments of when core aeration is needed to physically remove soil organic matter.

Core aeration should be used only when needed and should be done at different depths to ensure that a compaction pan does not develop. Core aeration reduces the accumulation of organic matter if applied with high enough surface area impact and may only be needed once per year if enough organic matter is removed.

Future studies on golf course management in the lower Fraser Valley should focus on: (i) the optimum amount of surface area impacted by each core aeration application, (ii) number of core aeration applications per year, and (iii) timing of core aeration.

Core aeration tines vary in size from 9 to 25 mm and on conventional aerating machines are commonly spaced at 5 × 5 cm. Generally, small tines (9.5 mm) are used to decrease the length of time it takes for core aeration holes to heal. This impacts only 4% of the surface area on putting greens, which may be insufficient to reduce the effects of compaction on putting greens. Studies should focus on what levels of impact (5, 10, or 15%) have the greatest benefit to putting greens and how long will it take core aeration holes (formed by different tine sizes) to heal.

Studies showing the effects of different numbers of core aeration applications (one, two, or three) per year are needed. This is especially true, since some of the most recent research has indicated that the effects of core aeration are not long lasting and that non damaging cultivation practices should be used during summer to keep infiltration rates high. The above two studies could also be incorporated into one study where a high level of surface area impact combined with one core aeration application per year may be the most beneficial and economical way of reducing effects of soil compaction on sand-based putting greens.

Generally, two core aeration applications occur per year on most golf courses. Most core aeration applications occur as a matter of convenience when play traffic is reduced during spring and fall, but it is unclear whether these periods are the most beneficial to turf growth. Mid-summer core aeration has never been recommended due to warm air and soil temperatures; however the best time for core aeration has not been established. One would expect that core aeration applied either just before (or during) the period of optimal soil temperatures for root growth would ensure adequate aeration.

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APPENDICES

Table A.1. Description of some of the most common turf management practices

Management Practice	Description
Mowing	On PG mowing occurs almost every day through the growing season (April-October). It is done with Toro 1000 walker mowers at a height of 3-3.5 mm. From November to March mowing was done with a Jacobsen IV ride-on mower at a height of 3.5 mm once per week.
Fertilizing	Fertilizing occurred every 10-14 days at a rate of 0.045 kg of nitrogen per 100 m^2, during the growing season (referred to as "spoon feeding"). The use of liquid fertilizer was the most common method to apply nutrients to turfgrass from April to October. From November to March slow release granular fertilizer was applied. The annual application of fertilizer was: 2002 (4.5 N, 2.0 P, 6.3 K kg 100 m^{-2}) 2003 (3.7 N, 1.2 P, 5.7 K kg 100 m^{-2}) Micronutrients and soil amendments were applied when necessary.
Irrigation	Depending on environmental conditions irrigation was applied at a rate of approximately 15-30 mm every 7-10 days during summer. Water was applied via a Rainbird "Cirrus" irrigation control system.
Sand Topdressing	Sand topdressing was done bi-monthly through the growing season at a rate of 1.1-1.4 m^{-3} per 100 m^{-2} using 1.0 mm sand. Sand topdressing usually followed turf cultivation.
Rolling	Rolling was preformed in 2002 (22 times), in 2003 (35 times) from May to September. In 2004 no rolling was done before the last sample date.
Brushing	Turfgrass brushing was done monthly to promote a more vertical growth habit of leaf tissue.
Fungicides	Applied only when disease was active on the plant from April to October or prior to onset of environmental conditions during November to March that are conducive to fusarium patch.
Wetting Agents	Applied twice during the growing season to combat dry patch or hydrophobic soil conditions.

Table A.2. Methods of soil analysis used for site characterization (soil samples were collected in September 2002).

Soil property	Method of Analysis	Reference
Particle size analysis	Hydrometer method	Gee and Bauder, 1986
Cation exchange capacity	Ammonium acetate (pH 7)	Sumner and Miller, 1996
Electrical conductivity	1:2 (v/v) soil : water extract	Rhoades, 1996

Detailed Description of the Soil Sampling Procedure

Samples from each replicate were taken from the center of the plot starting in March 2002. After removing a core sample each hole was replaced with a core of turf from the nursery area. To ensure that later samples were not removing a nursery replacement core, each date for sampling required a different sample location within the plot. The soil measurements taken in April (2002) were one meter north of the March (2002) sample position. Each later sampling date (June, August, September, and October) were taken one meter away (on a compass bearing) from the center (March 2002) sample location.

To ensure that the initial (center) sampling position could be located again, permanent reference points were established on all treatment replicates. The center position for Control-1 was located 10 meters east of irrigation sprinkler head (station 15) and for Control 2 was located 10 meters north from irrigation sprinkler head (station 2) and for Control 3 was located 10 meters southwest from the irrigation control panel (322). The center position of NCA 1 was located 12 meters north from irrigation sprinkler head (station 12) and for NCA 2 was located 10 meters south from irrigation sprinkler head (station 14) and for NCA 3 was located 10 meters south from irrigation sprinkler head (station 8). The center position for CA 1 was located 10 meters south from irrigation sprinkler head (station 14) and for CA 2 was located 10 meters northwest from irrigation sprinkler head (station 9) and for CA 3 was located 10 meters northwest from irrigation sprinkler head (station 16).

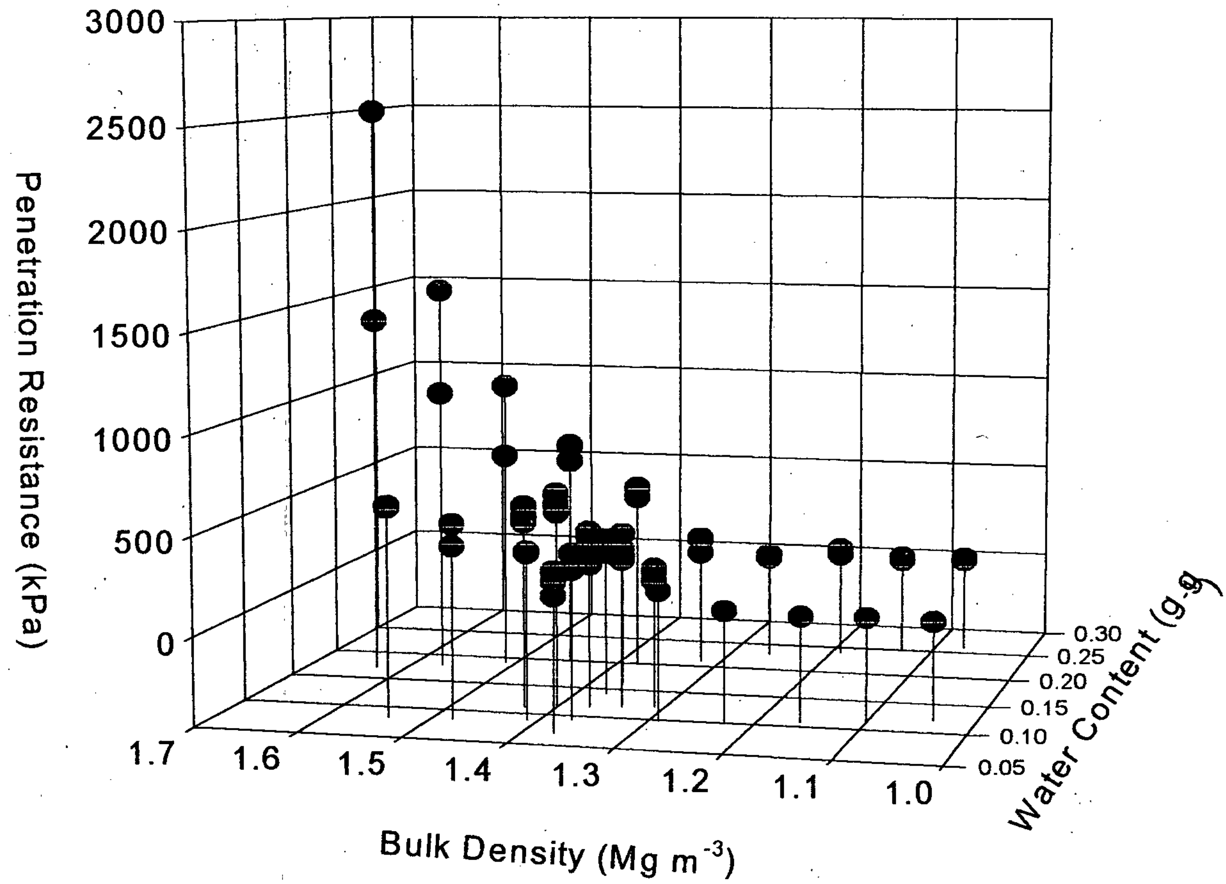

Figure A.1. Graphical relationship among soil penetration resistance, bulk density, and water content used to correct field measurements of the soil penetration resistance.

Table A.3. Analysis of variance (F-ratios) for the effect of three management treatments in 2002 on soil bulk density.

Source of	df	Sampling Times in 2002				
Variation		Mar 27	Jun 15	Aug 18	Sep 22	Oct 20
Block	2	2.46	0.50	0.90	0.17	0.00
Treatment	2	13.82*	0.67	9.26*	0.10	0.08

*Significant at the 0.05 probability level.

Table A.4. Analysis of variance (F-ratios) for the effect of three management treatments in 2002 and 2003 on soil bulk density of the mat layer.

Source of	df	Sampling Times in 2002 and 2003						
Variation		Sep 22	Oct 20	Mar 29	Apr 28	Jun 18	Aug 20	Sep 25[z]
Block	2	0.07	0.04	2.43	1.35	0.92	1.00	0.05
Treatment	2	0.34	1.43	2.63	0.34	2.36	1.36	0.0003

[z] Degrees of freedom for the September 25 sampling time for Treatment is 1.

Table A.5. Analysis of variance (F-ratios) for the effect of deep-tine aeration in 2004 on soil bulk density of the mat (M) and sand (S) layers.

Source of	df	Sample Times in 2004			
Variation		Apr 1(M)	Apr 1(S)	May 1(M)	May 1(S)
Block	2	6.10	16.20	0.50	0.60
Treatment	1	0.39	8.60	0.04	0.14

Table A.6. Analysis of variance (F-ratios) for the difference in soil bulk density between mat and sand layers.

Source of Variation	df	Sampling in 2002, 2003 and 2004							
		Sep	Oct	Mar	Apr	Aug	Sep	Apr	May
Between groups	1	79.95**	28.86**	138.60**	38.23**	21.85**	111.12**	23.56**	18.59**

**Significant at the 0.01 probability level.

Table A.7. Analysis of variance (F-ratios) for the effect of three management treatments in 2002 on water infiltration rate using a small double ring infiltrometer.

Source of Variation	df	Sampling Times in 2002					
		Mar 27	Apr 28	Jun 15	Aug 18	Sep 22	Oct 20
Block	2	1.45	4.30	0.15	2.57	1.38	1.12
Treatment	2	5.99	12.64*	4.57	16.68**	11.04**	28.44**

*, ** Significance at the 0.05 and 0.01 probability level, respectively.

Table A.8. Analysis of variance (F-ratios) for the effect of three management treatments in 2003 on water infiltration rate using a small double ring infiltrometer.

Source of Variation	df	Sampling Times in 2003			
		Apr 28	Jun 18	Aug 20	Sep 25
Block	2	2.24	0.50	5.78	1.30
Treatment	2	6.11	9.00*	25.12**	4.64

*, ** Significant at the 0.05 and 0.01 probability level, respectively.

Table A.9. Analysis of variance (F-ratios) for the effect of three management treatments in 2003 on water infiltration rate using a large double ring infiltrometer.

Source of	df	Sampling Times in 2003			
Variation		Apr 28	Jun 18	Aug 20	Sep 25^{z}
Block	2	4.91	0.94	3.26	3.64
Treatment	2	38.18**	10.98*	4.06	27.02*

*, ** Significant at the 0.05 and 0.01 probability level, respectively.

^{z} Degrees of freedom (df) for treatment on Sep 25, 2003 are 1 (instead of 2).

Table A.10. Analysis of variance (F-ratios) for the effect of three management treatments in 2002 on soil water content.

Source of	df	Sampling Times in 2002				
Variation		Mar 27	Jun 15	Aug 18	Sep 22	Oct 20
Block	2	54.2**	5.01	1.01	3.36	27.5**
Treatment	2	60.5**	6.91	0.79	4.35	49.3**

** Significant at the 0.01 probability level respectively.

Table A.11. Analysis of variance (F-ratios) for the effect of three management treatments in 2003 on soil water content of the mat layer.

Source of	df	Sampling Times in 2003				
Variation		Mar 29	Apr 28	Jun 18	Aug 20	Sep 25^{z}
Block	2	3.07	2.38	2.86	1.46	2.82
Treatment	2	6.29	4.52	7.21*	1.61	147.30**

*, **Significance at the 0.05 and 0.01 probability level, respectively.

^{z}Degrees of freedom for treatments on Sep 25, 2003 is one.

Table A.12. Analysis of variance (F-ratios) for the effect of deep-tine aeration in 2004 on soil water content in the mat (M) and sand (S) layers.

Source of	df	Sampling Times in 2004			
Variation		Apr 1(M)	Apr 1(S)	May 1(M)	May 1(S)
Block	2	1.66	0.43	1.05	0.45
Treatment	1	1.34	5.33	2.48	1.94

U=upper or matt layer and L=lower or sand layer

Table A.13. Analysis of variance (F-ratios) for the effect of three management treatments on water retention of the mat layer on March 27, 2002.

Source of	df	Pressure (kPa)							
Variation		0	3	8	20	60	90	180	300
Block	2	0.8	0.1	1.5	4.2	4.1	5.7	5.6	11.9*
Treatment	2	1.5	0.9	8.9	8.3	10.9*	13.1*	10.0*	14.4*

*Significant at the 0.05 probability level.

Table A.14. Analysis of variance (F-ratios) for the effect of three management treatments on water retention of the mat layer on October 20, 2002.

Source of	df	Pressure (kPa)							
Variation		0	3	8	20	60	90	180	300
Block	2	3.01	1.36	0.77	1.63	1.92	1.58	1.12	5.45
Treatment	2	1.15	0.08	0.04	0.36	4.22	0.48	0.29	3.22
P Values		0.248	0.622	0.801	0.502	0.152	0.488	0.628	0.180

Table A.15. Analysis of variance (F-ratios) for the effect of three management treatments on water retention of the mat layer on March 29, 2003.

Source of Variation	df	Pressure (kPa)							
		0	3	20	30	60	90	180	300
Block	2	5.93	1.01	1.82	0.76	1.61	1.29	0.72	0.55
Treatment	2	0.14	1.22	2.49	1.14	1.61	4.75	1.12	0.52
P Values		0.154	0.460	0.238	0.518	0.327	0.155	0.533	0.719

Table A.16. Analysis of variance (F-ratios) for the effect of three management treatments on water retention of the mat layer on May 1, 2004.

Source of Variation	df	Pressure (kPa)							
		0	3	20	30	60	90	180	300
Block	2	0.13	0.98	3.78	1.55	2.86	6.44	16.1*	2.02
Treatment	2	0.02	1.31	2.02	1.42	2.55	3.60	3.37	0.95
P Values		0.959	0.511	0.247	0.423	0.285	0.158	0.079	0.397

*Significant at the 0.05 probability level.

Table A.17. Analysis of variance (F-ratios) for the effect of three management treatments in 2002 on soil organic matter content.

Source of Variation	df	Sampling Times in 2002		
		Mar 27	Sep 22	Oct 20
Block	2	0.99	0.51	3.13
Treatment	2	8.23*	0.70	0.35

* Significant at the 0.05 probability level.

Table A.18. Analysis of variance (F-ratios) for the effect of three management treatments in 2003 on soil organic matter content.

Source of	df	Sampling Times in 2003			
Variation		Mar 29	Apr 28	Aug 18	Sep 22
Block	2	3.55	2.56	0.32	11.24
Treatment	2	2.80	3.40	0.03	6.99

Degrees of freedom for treatments in August and September 2003 were one.

Table A.19. Analysis of variance (F-ratios) for the effect of two management treatments in 2004 on soil organic matter content.

Source of Variation	df	Sampling Times in 2004	
		Apr 1	May 1
Treatment	2	2.61	3.50