CHAPTER TWO

EVALUATION OF PUTTING GREEN SURFACE ORGANIC MATTER MANAGEMENT PROGRAMS: Part I. Changes in Soil Physical Properties.

Abstract

Excessive organic matter (OM) accumulation can degrade the optimum soil physical properties of sand-based rootzones. This multi-year field study documented the changes in rootzone physical properties of a sand-based putting green subjected to five OM management programs for three creeping bentgrass [*Agrostis stolonifera* L. var *palustris* (Huds.) Farw.] cultivars ('A-4', 'L-93', and 'Penncross') maintained at two annual nitrogen levels. The cultural OM management programs were: twice annual core cultivation plus heavy topdressing using either a medium-coarse sand (HTSM) that matched the underlying rootzone or a medium-fine sand (HTSF), the aforementioned programs supplemented with light frequent topdressing (HTFM and HTFF) throughout the growing season, and a non-cultivated control which only received frequent topdressing throughout the growing season with the medium-coarse sand (TOP). Surface OM increased in all treatments compared to the initial level, 23.2 g kg^{-1}. Among management programs, OM accumulated the most in TOP plots (30.2 g kg^{-1}) compared to all aerified programs (26.3-29.6 g kg $^{-1}$). Both treatments receiving the medium-fine sand accumulated more fine sand (0.15-0.25 mm) in the 0-5.7 cm depth at the conclusion of the study with the HTFF treatment accumulating the most. The HTFF treatment also resulted in slightly higher in-situ volumetric water contents at the 0-5.7 cm depth and softer surfaces than all other programs, 0.194 versus 0.170-0.176 m^{3}m^{-3} and 119 versus 122-134 g_{max}, respectively. To maintain optimum rootzone physical properties and prevent excessive OM accumulation, core cultivation with regular topdressing should

be conducted. The practice of topdressing with a medium-fine sand in order to better incorporate sand into a turf canopy should be carefully monitored to avoid excess fines.

Introduction

Modern golf course putting greens are constructed with high sand content (> 85 %) mixtures to provide adequate drainage and resist compaction (Taylor and Blake, 1979). Although sand-based putting greens have optimum physical properties for turfgrass growth, they typically only perform adequately if these properties are maintained. Fine particle migration of silt and clay (0.002-0.05 mm and < 0.002 mm) and organic matter (OM) accumulation in the upper profile are the most destructive changes that occur in the rootzone over time. Both OM (Carrow, 1998) and fine particle accumulations (Habeck and Christians, 1999) decrease aeration pore space and slow internal drainage, thus causing a decline in rootzone performance. Fine particle migration occurs naturally with time and few management practices can be performed to prevent subsequent accumulation. Accumulation of OM, however, is a primary concern of turf managers and is often mitigated through various cultural practices that target both removal, hollow tine core cultivation, and dilution, frequent sand topdressing, of accumulating OM (Beard, 2002).

Numerous researchers have reported improvements in the soil physical properties as a result of OM reductions through various core cultivation practices (Engel and Alderfer, 1967; Engel, 1970; Eggens, 1980; Murphy et al., 1993; Kauffman, 2007). Additionally, several researchers have reported OM accumulation was mitigated through regular sand topdressing applications (Engel and Alderfer, 1967; Eggens, 1980; Cooper and Skogley, 1981; Fermanian et al., 1985; Callahan et al., 1998; Stier and Hollman, 2003; McCarty et al., 2007).

Since the mid-1950's Penncross has been the most widely planted creeping bentgrass [*Agrostis stolonifera* L. var *palustris* (Huds.) Farw.] cultivar on golf course putting greens (Beard, 2002). To meet elevated golfer demands for faster putting surfaces golf course managers now mow lower and fertilize and irrigate less than ever before. In response turfgrass breeders have developed new creeping bentgrass cultivars within the last few decades such as the Penn A and G series that possess greater shoot density, finer texture, and more aggressive upright growth. These high shoot density (HSD) cultivars better persist under low cutting heights and provide superior appearance compared to Penncross (Beard, 1997; Fraser, 1998). Many of these HSD cultivars however, have been reported to have more OM accumulation than Penncross (Ervin, 2000; Landry and Schlossberg, 2001; Stier and Hollman, 2003). Not surprisingly, anecdotal evidence suggests that they require more intensive cultivation and sand topdressing for OM management (Fraser, 1998). The majority of the research involving cultivation and sand topdressing programs however, have been performed on older, less dense cultivars such as Penncross.

Engel (1967) reported that bentgrass putting greens that receive high nitrogen (N) fertility and have a vigorous growth habit can result in rapid OM accumulation. Applications of 122-244 kg N $ha^{-1}yr^{-1}$ have generally produced dense, healthy bentgrass putting greens (Beard, 2002). Accumulation of OM reportedly has been greater for HSD cultivars compared to Penncross when receiving between 170-200 kg N ha^{-1} yr^{-1} (Landry and Schlossberg, 2001; Stier and Hollman, 2003). It has been theorized, however, that HSD cultivars will perform best with slightly lower annual N-regimes (Beard, 2002). Documentation of OM accumulation of HSD cultivars maintained at ultra-low ($\leq$ 112 kg N $ha^{-1}yr^{-1}$) N levels commonly adopted in an attempt for longer ball roll distances does not exist.

Agronomists recommend that a successful sand topdressing program requires applying topdressing frequently enough to match OM accumulation rates, and using a material that matches the particle size distribution (PSD) of the underlying rootzone (Beard, 1973; O'Brien and Hartwiger, 2003). Therefore, more frequent sand topdressing may be required for HSD cultivars. The extreme density and lower cutting heights associated with these HSD cultivars may cause sand particle incorporation challenges (Engelke, 2000; Fraser, 1998; Stier and Hollman, 2003). Golf course managers may switch to a topdressing sand with a higher amount of fines (0.15-0.25 mm) to ease particle migration into the dense canopies of HSD cultivars or when mowing at ultra-low heights. This will likely create a layer finer sand at the surface, commonly referred to as a perched water table, which slows drainage from moving freely through sand-based rootzones (Hillel, 2004). This unintentionally created perched water table will cause similar negative effects to the rootzone hydraulic properties compared to layers created with excessive OM accumulation and fine particle migration, perhaps at a more rapid pace.

Core cultivation and sand topdressing practices used properly can effectively prevent excessive OM accumulation and maintain good soil physical properties in the rootzone. If proper sand topdressing and core cultivation strategies are abandoned to ease management practices and reduce golfer inconvenience, a decline in the soil physical properties is likely. The objective of this study was to document changes in rootzone physical properties over time for a sand-based putting green subjected to five OM management programs which included varying sand particle size and application frequency.

Materials and Methods

A field experiment was conducted from Aug. 2004 through Nov. of 2007 on a sand-based (80 sand: 20 peat mixture) research green built to United States Golf Association (USGA) construction specifications with > 90 % of the sand particles between 0.1 - 1.0 mm size (USGA Green Section Staff, 1993) at the Purdue University, W.H. Daniel Turfgrass Research and Diagnostic Center, West Lafayette, Indiana. The rootzone was an 80:20 (v:v) sand and sphagnum peat mixture, which has a pH of 7.5 and a CEC of < 2 cmol$_c$ kg^{-1}. All construction materials were tested by an accredited lab (Hummel & Co, Inc., Trumansburg, NY) and met USGA specifications for putting green construction (Table A-9) (USGA Green Section Staff, 1993). The base sand was a locally available and widely used calcareous sand (Shelby Materials, Shelbyville, IN).

General Plot Maintenance

Three widely planted creeping bentgrass cultivars, A-4, L-93, and Penncross, were seeded on 5 August 2003 in 1.5 x 1.5 m plots at a rate of 73 kg seed ha^{-1}. A seeding box (1.5 x 1.5 m) was used to prevent cultivar seed contamination. A granular starter fertilizer (0-46-0) was applied at 73 kg P_2O_5 ha^{-1} to the rootzone prior to seeding and other nutrients were applied according to soil test recommendations. The study site was located in full-sun with no surrounding obstructions, which was conducive to rapid drying of the canopy in the early morning hours. Irrigation was used to supplement rainfall and promote plant growth during the growing months (Apr. - Nov.). In the absence of a significant ($\geq$ 13 mm) rainfall event, overhead irrigation was applied approximately 5 mm nightly to achieve 35 mm wk^{-1}. Irrigation was reduced to once per week (5 mm wk^{-1}) from 21 July to 15 Aug. 2006 and from 9 Aug. to 30 Aug. 2007. Plots were mowed (3.6 mm) six days per week using a triplex reel mower (Toro Greensmaster 3100, The Toro Company, Bloomington, MN) with clippings removed. Fungicides (chlorothanonil, propiconazole, thiophanate-methyl, and flutolonil) were applied curatively 2004 - 2006 and preventatively in 2007 during periods of active disease pressure, primarily for dollar spot (*Sclerotinia homoeocarpa* F.T. Bennett) and brown patch (*Rhizoctonia solani* Kuhn.) control.

Nitrogen Applications

Two fertility regimes designated as "low" and "high" were used to assess the varying range of N applied to golf course putting greens. Initially in 2004 and 2005 N regimes were 146 versus 293 kg N ha^{-1}yr^{-1} for the low and high N-levels respectively. Slightly higher N-levels were used during "grow-in" to ensure maximum turf coverage. In 2006, fertility was lowered (112 vs. 196 kg N ha^{-1}yr^{-1}) to adjust N-rates to those commonly applied by golf course managers in the cool-humid region. Nitrogen was applied either as liquid or granular formulations depending on application rates and dates (Table A-9). Granular applications for the "low" treatment were applied with a broadcast rotary spreader. "High" treatment plots receiving additional granular N-applications were applied evenly over individual plots using a hand shaker with a pre-weighed amount of fertilizer. Granular applications were made in mid-Apr., mid-Sept., and Oct. (depending upon annual N-regime) at 24 kg N ha^{-1}. Liquid applications were applied using a 2 m wide hand held boom sprayer with an 8010E TeeJet XR nozzle attached to an 11.4 L hand-pump back-pack container for "low" treatments. Additional liquid N-applications for "high" treatments were applied using a pressurized (242 kPa) CO_2 back-pack sprayer equipped with an 8010E TeeJet XR nozzle with 820 L ha^{-1} spray volume.

Liquid applications of 10 kg N ha^{-1} were made every 14 days for the "high" treatment monthly for the "low" treatment (excluding Aug.) from May to Oct.

Topdressing Sand

Two different sand sizes were applied as topdressing: a predominantly medium-coarse (0.25-1 mm) sand that matched the underlying rootzone, and a predominantly medium-fine (0.15-0.5 mm) sand. The medium-fine sand was selected because it is typical of sands chosen to easily filter into dense turf canopies. Particle size analysis was conducted (Table A-2) to determine sand sizes in relation to USGA specifications. The medium-coarse sand, which matched the underlying rootzone, fell within USGA specifications for rootzone construction while the medium-fine sand did not meet USGA specifications (USGA Green Section Staff, 2004). The medium-fine sand had approximately 650 g kg^{-1} in the fine sand category. Both sands were stored indoors to keep them dry and weed free.

Topdressing Applications

Topdressing applications began in May of 2004 and were applied using a 1 m wide drop-spreader (LESCO Drop Spreader, Cleveland, OH). Light applications consisted of 0.03 m^3 sand 100 m^2 applied every 7-10 days during periods of active growth. During periods of severe high temperature stress light topdressing was applied every 10-14 days. Heavy sand topdressing (0.13 m^3 100 m^2) was applied twice annually to back-fill aerification channels. Additionally, moderate (0.06 m^3 100 m^2) applications were made during periods of optimum growing conditions (Tables A-3, A-4, A-5, and A-6). Following all topdressing applications, sand was brushed into the turf canopy using a stiff bristle push broom in perpendicular directions.

Core Cultivation

Core cultivation (1.6 cm diam. x 8 cm depth x 5 cm spacing) (Toro Greens 09120 Aerator, The Toro Company, Bloomington, MN) was performed in mid-Apr. and mid-Sept. from 2005 to 2007. Cores were removed following cultivation and channels backfilled with the appropriate sand size. One OM management program did not receive any core cultivation at any time during the study, and was included as the control treatment to compare frequent topdressing in place of core cultivation.

Surface Organic Matter and Sand Particle Size Distribution

Surface OM content and PSD was determined for all treatments at the end of each growing season in 2006 and 2007. Organic matter by weight was quantified using the loss on ignition (LOI) method (Dane and Topp, 1986). Four cores (1.9 cm diam. x 5.7 cm length) were removed from each sub-plot and combined to form a composite sample using a soil probe. Verdure was removed from the cores prior to processing. Cores were dried at 105°C for 2 h and weighed. Samples were then placed in a muffle furnace at 400 °C for 18 h to burn of all OM. Organic matter (g kg^{-1}) was determined as the difference between these two measurements. After OM was quantified, the remaining sand (> 60 g) was sieved using a vibratory plate (Fritsch Analysette Laboratory, Idar-Oberstein, Germany) for five minutes (ASTM F 1632-03). Samples were passed through sieves in the following order: 10-mesh (2000μm), 18-mesh (1000 μm), 35-mesh (500 μm), 60-mesh (250 μm), 100-mesh (150 μm), 140-mesh (100 μm), 270-mesh (53 μm), and pan. Each sand fraction was weighed as well as the residual silt and clay collected in the pan.

Volumetric Water Content

Volumetric water content (VWC) at the rootzone surface (0-5.7 cm depth) was measured every 14 to 28 days using a portable soil moisture probe equipped with time domain reflectometry (TDR) (POGO Soil Sensor, Stevens Water Monitoring Systems, Beaverton, OR) throughout the growing season in 2006 and 2007. A systematic grid pattern that measured the four corner and centers regions of each plot was used and measurements were pooled together and averaged to one number for statistical analysis.

Surface Hardness

A Clegg Impact Soil Tester (0.5 kg model, Lafayette Instrument Co., Lafayette, IN) was used to measure surface hardness (SH). The Clegg impact hammer is a commonly accepted method of measuring SH (Lush, 1985; Linde, 2005). Readings were taken nine times throughout 2006 and 2007. The hammer was dropped from 0.46 m three times per location and the third value was recorded. Two locations were measured per sub-plot and averaged to one value. Units were recorded in Clegg Impact Values (CIV's) which were converted to g_{max} (peak deceleration) using the following equation, (Bregar and Moyer, 1990).

Accerlation Due to Gravity

$$g_{max} = 10(CIV)$$

Infiltration Rate

A double ring Turf-Tec Infiltration Ring (model IN5-W, Turf-Tec International, Coral Springs, FL) was used to measure field infiltration rates. The double ring infiltrometer measured 30 cm on the outside ring and 15 cm on the inside ring. The infiltrometer was forced into the turf 2 cm deep using a rubber mallet. Each plot was evaluated for infiltration rates. Water was poured into the center ring until it filled the infiltrometer (10 cm), and following steady state of flow, infiltration rates (cm h^{-1}) were recorded as water vacated the center ring (Gregory et al., 2005).

Experimental Design and Statistical Analysis

The statistical design separated OM management programs in a randomized complete block with four replications (Figures A-9 and A-10). Main plots were separated in a two by two plus one factorial with two sand sizes and two application frequencies plus an non-cored topdressed only control. Five main plots (4.5 m x 3.0 m) determine management program (sand topdressing and core cultivation treatments) and were separated with 0.6 m borders. Management programs were:

1. Hollow tine aerification plus seasonal topdressing with a medium-coarse sand (HTSM)
2. Hollow tine aerification plus frequent topdressing with a medium-coarse sand (HTFM)

3. Hollow tine aerification plus seasonal topdressing with a medium-fine sand (HTSF)
4. Hollow tine aerification plus frequent topdressing with a medium-fine sand (HTFF)
5. Frequent topdressing only with a medium-coarse sand (TOP)

Subplots (1.5 m x 1.5 m) were separated in a three by two factorial containing cultivar and N treatments and were arranged in a completely randomized design within each main plot. All data was subjected to analysis of variance (ANOVA) using the general linear models procedure in SAS (SAS Institute, Cary, NC) and treatment means for management program, cultivar, and annual N-regime separated using Fisher's protected least significant difference (P=0.05). For each ANOVA table, a two by two plus one factorial was used which excluded the TOP (control) program.

Results and Discussion

Overall, OM management program had the biggest influence on surface OM, PSD, VWC, SH, and field infiltration rate. The effects of bentgrass cultivar and annual N-regime were more minor.

Surface organic matter (SOM)

Surface OM, measured once annually at the end of each growing season was significantly affected by management program, cultivar, and annual N-regime (Table 2-1). Prior to establishment, rootzone OM was 23.2 g kg^{-1}. In Nov. 2006, only three years after establishment, the mean OM values across cultivar and N-regime ranged from 26.3 to 28.9 with the TOP plots having the highest OM of all management programs most likely due to the lack of core removal. This program, however, was not statistically different from the HTSM and HTFF programs. Plots receiving core cultivation plus seasonal or frequent topdressing with either sand were similar for OM levels. Among cultivars, A-4 and L-93 had significantly more (28.8 and 28.3 g kg^{-1} respectively) OM than Penncross (26.3 g kg^{-1}) when averaged across management program and N-regime. Stier and Hollman (2003) found similar results in OM (201 versus 179 mg cm^{-3}) when comparing A-4 and Penncross. Additionally, increasing N from 112 to 196 kg N $ha^{-1}yr^{-1}$ significantly increased OM from 27.1 to 28.5 g kg^{-1} when averaged across cultivars and management programs in 2006 and 26.9 to 29.4 g kg^{-1} in 2007.

Similar OM trends were measured in 2007, with values ranging from 26.2 to 30.2 g kg^{-1}. Among management programs, TOP plots again had the most (30.2 g kg^{-1}) OM, which was similar to the HTSM (29.6 g kg^{-1}) program. The remaining programs had significantly less OM ranging from 26.3 to 27.4 g kg^{-1}. The HTSM and TOP programs had significantly more OM in 2007 than 2006. The HTFM and HTFF management programs had significantly less OM than the TOP plots. When evaluating the effects of each individual OM management program for each cultivar and N-regime the OM ranged from 22.6 to 34.3 g kg^{-1}. Additionally, when evaluating the individual years there were fewer effects of cultivar and N-regime in 2006 (Table 2-2). In 2007, however, there was much greater separation of treatments and in general for most OM management programs there was a trend with higher OM being associated with A-4 at either N-level and Penncross having less OM.

These data indicate that OM was best managed with seasonal OM removal (core cultivation) combined with frequent, light topdressing throughout the growing season. Additionally, these findings are consistent with current putting green OM management recommendations (Beard, 2002).

The magnitude of difference between cultivars for OM was more dramatic in 2007 with A-4 having the highest (30.2 g kg^{-1}) OM compared to Penncross (26.2 g kg^{-1}), which had the least, while L-93 (28.0 g kg^{-1}) was intermediate. Among cultivars, however, A-4 was the only cultivar to have significantly more OM in 2007 than 2006. Surface OM differences between an A series bentgrass and L-93 compared to Penncross were similar as to those reported by Landry and Schlossberg (2001). Their values, which were larger than our results, may have had more OM because of the maturity of the cultivars compared to our plots. Sifers et al. (2001) found that A and G series bentgrasses fertilized at 300 kg N ha^{-1} yr^{-1} had substantially more surface OM and canopy biomass than Penncross. Our study did not have as high annual N fertilization, which is influential in OM accumulation. A more pronounced numerical difference in OM among annual N-regime was also measured in 2007, although actual results were statistically similar to 2006. Across management program and cultivar, as annual N increased from 112 to 196 kg N ha^{-1} yr^{-1}, OM increased 26.9 and 29.4 g kg^{-1}.

From 2003 to 2007, OM increased 7.0 g kg^{-1} from 23.2 g kg^{-1} in TOP plots, compared to 5.3 g kg^{-1} in seasonal topdressed plots (HTSM and HTSF) and 3.6 g kg^{-1} in frequent topdressed (HTFM and HTFF) plots. Sand size did not dramatically affect OM levels. The rather rapid increase in OM from 2006 to 2007 in A-4 indicate that the management practices being employed were not slowing OM compared to L-93 and Penncross. Therefore, perhaps slightly more intensive management practices may be required to sufficiently keep OM below the 40 g kg^{-1} which has been suggested to avoid serious deleterious effects on rootzone performance (Carrow, 2003) for this cultivar. A correlation between shoot density (Tables 4-1 and 4-2) and OM (Figure 2-2: $R^2 = 0.731$) supports the general observation that HSD are more prone to OM accumulation. As OM continues to accumulate, the functionality and persistence of the putting green turf may eventually deteriorate. Additionally, increasing N from 112 to 196 kg N $ha^{-1}yr^{-1}$ seems to demand more aggressive OM management to mitigate further accumulation.

Particle Size Distribution

Marked differences in PSD of management programs were measured each year (2006 and 2007). The exact PSD for the original sand-based rootzone contained in the appendix (Table A-1) but contained 279 g kg^{-1} coarse sand (1.0-0.5 mm), 533 g kg^{-1} medium sand (0.5-0.25 mm), and 149 g kg^{-1} fine sand (0.25-0.15 mm). In 2006, considerable changes in the PSD of plots topdressed with the medium-fine sand occurred, specifically the coarse (0.5-1.0 mm) and medium (0.25-0.5 mm) particles decreased, and fine (0.15-0.25 mm) particles increased (Table 2-3). Similar PSD values were measured in 2007. A bigger separation in PSD in HTFF and HTSM were measured compared to all other management programs, with decreases in coarse and medium particles while fine particles increased (Table 2-4). The HTFF and HTSF programs had 87 and 29 g kg^{-1} increase and 149 and 50 g kg^{-1} increases in fine particles compared to all other management programs in 2006 and 2007, respectively. If accumulation of fine sand continues at this pace for the HTFF treatment (≈ 118 g kg^{-1} yr^{-1}), the 0-5.7 cm depth could completely transition to fine sand in approximately six years. The TOP, HTSM, and HTFM programs all had similar PSD values at all sieve sizes in each measurement year.

When the PSD of each management program was compared to USGA specification PSD for a rootzone mix, HTFF plots (236 and 298 g kg^{-1}) no longer met specifications (<200 g kg^{-1} in the fine sand category), and HTSF plots (178 and 199 g kg^{-1}) were noticeably closer to the maximum allowable values in the fine sand category in 2006 and 2007 respectively.

Stier and Hollman (2003) reported difficulties incorporating coarse sand particles into the dense canopy of A-4. Therefore, it is theorized that A-4 putting surfaces might accumulate more fine particles compared to L-93 and Penncross due to coarse sand particles removed from mower pick-up (Table A-8). Stier and Hollman (2003) observed minor significant differences in PSD of sand pick-up following topdressing of two HSD cultivars compared to Penncross. They found that A-4 and 'G-2' had approximately 30 g kg^{-1} more of the larger sized (1.0-2.0 mm) particles removed compared to Penncross. They concluded however, that this difference was likely unsubstantial in the long-term performance of the rootzone. However, they applied annual topdressing amounts perhaps lower than what is performed on golf courses in warmer locations in the cool-humid region. A higher annual amount could result in a more substantial PSD change of the upper profile of a sand-based putting green.

Each core cultivation event affected roughly eight percent of the plot surface area. The back-filling of the aeration channels added a large amount of the medium-fine sand into the upper rootzone of HTSF plots. This is likely the cause of the increasing amount of fines in the PSD of this management program. In addition to the back-filling with the fine sand, HTFF plots also were lightly (0.03 m^3 100 m^2) topdressed 16-23 times each year with the medium-fine sand (Tables A-3, A-4, A-5, and A-6). The combination of the two practices explains the significant and abrupt changes in PSD for this management program. The increased amount of fine sand in the upper profile of HTSF and HTFF plots altered rootzone hydrology, which may have affected numerous functional and visual characteristics.

Volumetric Water Content

Mean annual VWC was influenced by management program throughout 2006 and 2007. For the study mean, HTFF plots held more (0.194 m^3m^{-3}) moisture compared to all other management programs, with values ranging from 0.170-0.176 m^3m^{-3} (Table 2-5). For the study mean, VWC values for HTSM, HTFM, HTSF, and TOP were 0.175, 0.174, 0.176, and 0.170 m^3m^{-3}, respectively.

In 2006, weather patterns were somewhat unstressful for cool-season turf with moderate summer temperatures and regular rainfall (Figure A-1). The HTFF program (0.197 m^3m^{-3}) had a higher annual VWC than all management programs, although statistically equal to TOP plots (0.186 m^3m^{-3}). Sand size significantly affected VWC on all measurement dates.

In 2007, further separation among the management programs occurred under more stressful summer temperatures and lower total rainfall amounts (Figure A-1). The HTFF program held more (0.191 m^3m^{-3}) VWC than all other management programs and substantially more VWC than TOP plots (0.159 m^3m^{-3}). This could be a result of rapid drying that occurs in thatch/mat layers under hot and dry conditions, although OM did not strongly correlate (Figure 2-2: R^2 =0.224) with VWC. Sand size less strongly affected VWC in 2007 (Table 2-7a). Conversely, application frequency was more common.

In Aug. of each year, during a dry-down cycle with supplemental irrigation reduced to once per week (5 mm wk^{-1}), slightly lower VWC values were commonly measured for all management programs. The HTFF program, however, still had slightly higher VWC than all other management programs. The incorporation of more fine sands (0.15-0.25 mm) in the upper (0-5 cm depth) profile is likely the explanation for increased VWC in HTFF plots because finer textured sands hold more water (Hillel, 2004). Cultivar and annual N-regime did not influence VWC in this study. Excess surface OM accumulation as a result of numerous factors (i.e. no core cultivation, an aggressively growing cultivar, or an excessively growing turf) could lead to VWC increases.

Surface Hardness

Soft putting green conditions increase the likelihood of mechanical damage and inconsistent ball roll. Wetter, softer putting surfaces may also be prone to increased ball mark damage (Bigelow et al., 2008). Surface hardness was measured on nine dates, with distinct differences measured among management program, cultivar, and annual N-regime, with values ranging from 104 to 154 g_{max} when averaged across management programs (Tables 2-8 and 2-9). The HTFF plots yielded the softest surfaces among all management programs on all nine measurement dates. The HTSF plots were in the lowest statistical category on seven of the nine measurement dates. While the TOP plots had the firmest surfaces on six of the nine measurement dates. Among cultivars, Penncross had significantly firmer surfaces compared to A-4 and L-93 on all nine measurement dates. Increasing annual N from 112 to 196 kg N ha^{-1} yr^{-1} resulted in significantly softer surfaces on all dates and resulted in 124 versus 128 g_{max} for the study mean (Table 2-10).

The softer surfaces measured throughout the study in HTFF plots may be related (Figure 2-3: $R^2 = 0.519$) with higher VWC (Table 2-5). Previous research by Bunnell et al. (2001) and McCarty et al. (2007) demonstrated that core cultivation decreases SH, which explains why decreased values were measured on 27 Sept. and 25 Oct., 2007 following core cultivation (18 Sept.). Contrary to what Kauffman (2007) reported, TOP plots generally had firmer surfaces than plots receiving core cultivation. This is likely the result of the absence of soft surfaces that core cultivation practices generally produce. Consistent with other reports (Engel, 1967), increasing N-level can result in soft putting greens, potentially from excess OM accumulation. However, no relationship (Figure 2-4: $R^2 = 0.177$) between OM and SH was measured.

Infiltration Rate

Field infiltration rate was measured twice each study year and significantly influenced by management program (Table 2-11). Infiltration rates were highest on 30 June, 2006, ranging from 58.5 to 94 cm hr^{-1}. Among management programs, HTFF plots were in the lowest statistical category on all measurement dates. Similarly, TOP plots were in the lowest statistical category on three of the four measurement dates. Conversely, HTSM plots were in the highest statistical category on each measurement dates. All other management programs were intermediate. There was a significant decline over time with infiltration rates ranging from 42.2 to 54.0 cm hr^{-1} on 24 Aug., 2007. On average, infiltration rate declined 45 percent in HTSM plots, 30 percent in HTFF plots, and 28 percent in TOP plots. All infiltration rates however, were well above USGA rootzone specification guidelines (USGA Green Section Staff, 2004). One reason for the rapid infiltration rates in our study may be a result of the relatively young sand-based rootzone, and somewhat uniform PSD.

Several studies have reported increased infiltration as a benefit of core cultivation (Engel and Alderfer, 1967; Bunnell et al., 2001; Carrow, 2003; McCarty et al., 2005; McCarty et al., 2007). As a result, it is not surprising that TOP plots had slower infiltration rates. Management programs with core cultivation always had higher infiltration rates than the TOP program except when topdressed frequently with the fine sand. Core cultivation occurred in mid-Apr. of each year. Measurements were not conducted until late June to early-July and mid-Aug. of each year. As a result, only subtle increases in infiltration rates in plots receiving cultivation compared to TOP plots were observed. Carrow (2003) reported the benefit of increased infiltration from core cultivation only lasted five to eight weeks. Therefore, larger increases in infiltration rates would likely be realized if measurements were conducted shortly after core cultivation. A layer of fine sand (0.15-0.25 mm) particles, with more water holding capacity, accumulated in the upper profile of HTFF plots slightly correlated with VWC (Figure 2-5: $R^2 = 0.437$). This layer of fine sand may have created a perched water table and restricted drainage because water infiltrating into the profile will not percolate into lower depths of the rootzone until enough hydraulic pressure accumulates for water to move through the upper fine layer (Hillel, 2004). There was no effect of cultivar and N-regime on infiltration rate during this study.

Summary

To maintain optimum rootzone physical properties and prevent excessive OM accumulation, core cultivation with regular topdressing should be conducted. This study demonstrated that there were significant differences in the soil physical properties among OM management programs, cultivar, and annual N-regime. After four years of implementing the management programs, the most OM accumulated in the TOP treatment. Most likely due to the lack of OM removal from core cultivation. Among cultivars, OM was higher in the HSD cultivar A-4 than Penncross. Additionally, increasing N from 112 to 196 kg N ha^{-1} yr^{-1} resulted in more OM accumulation over time when averaged across OM management program and cultivar.

Significant changes in the rootzone PSD among management programs were documented in both measurement years. The HTFF program had a PSD that no longer met USGA rootzone specifications because it exceeded 200 g kg^{-1} for the fine sand category (0.15-0.25 mm). Similarly, HTSF plots had substantially more fines than the original rootzone sand and will likely exceed USGA rootzone specifications within the next year if management practices are continued. The effects of these considerable increases in fine sands in the upper profile of HTFF plots were manifested in significant differences in VWC. Although VWC was generally only one to three percent higher in HTFF plots compared to all other management programs, it was enough to affect functional characteristics like SH. Additionally, in-situ infiltration rates declined 28 - 45 % over time for all management programs, with the HTFF program having the slowest infiltration rates on all measurement dates.

High sand content (> 85 %) rootzones provide rapid drainage and resist compaction. The optimum soil physical properties, such as good aeration pore space must remain intact to sustain high quality putting surfaces. To maintain optimum rootzone physical properties and prevent excessive OM accumulation, core cultivation with regular sand topdressing should be conducted. The practice of topdressing with a medium-fine sand in order to better incorporate sand into a turf canopy should be carefully monitored.

References

ASTM F 1632-03. Standard test method for particle size analysis and sand shape grading of golf course putting green and sports field rootzone mixes. Amer. Soc. for Testing and Materials.

Beard, J. B. 1973. Turfgrass science and culture. Prentice-Hall, Englewood Cliffs, NJ.

Beard, J.B. 2002. Turf management for golf courses. 2nd ed. Ann Arbor Press. Chelsea, MI.

Beard, J.B., and S.I. Sifers. 1997. Bentgrasses for putting greens. Golf Course Manage. 5:54-69.

Bigelow, C.A., J.R. Nemitz, A.C. Moeller. 2008. Creeping bentgrass golf ballmark recovery as affected by various tools on two sand-based research putting green areas with varying surface firmness and moisture contents, 2007. Purdue Univ. Ann. Rep. Available at: http://www.agry.purdue.edu/turf/. (verified 28 February 2008).

Bregar, M. J., and W. W. Moyer. 1990. An automated system for field testing and soil impact analysis. *In*: Natural and Artificial Playing Fields: Characteristics and Safety Features. Ann Arbor, MI: Am. Soc. for Testing and Materials.

Bunnell, B.T., L.B. McCarty, and H.S. Hill. 2001. Summer cultivation effects on a sand based creeping bentgrass golf green. Int. Turfgrass Soc. Res. J. 9: 843-849.

Callahan, L.L., W.L. Sanders, J.M. Parham, C.A. Harper, L.D. Lester, and E.R. McDonald. 1998. Cultural and chemical controls of thatch and their influence on rootzone nutrients in a bentgrass green. Crop Sci. 38(1):181-187.

Carrow, R. 1998. Organic matter dynamics in the surface zone of a USGA green: Practices to alleviate problems. Turfgrass Environ Res. Summ. p. 15-17.

Carrow, R. N. 2003. Surface organic matter in bentgrass greens. [Online] USGA Turfgrass and Environ. Res. Online. 2(17):1-12.

Cooper, R. J. and C.R. Skogley. 1981. An evaluation of several topdressing programs for *Agrostis palustris* Huds. and *Agrostis canina* L. putting green turf. Int. Turfgrass Soc. Res. J. 4:129-136.

Dane, J.H., and G.C. Topp. 2002. Methods of Soil Analysis: Part 4 - Physical Methods. (eds.) xli, 1692 pp. Madison, Wisconsin: Soil Sci. Soc. of Am.

Eggens, J.L. 1980. Thatch control on creeping bentgrass turf. Can. J. Plant Sci. 60:1209-1213.

Engel, R.E. 1967. A note on the development of puffiness in quarter inch bentgrass turf with varied nitrogen fertilization. New Jersey Ag. Exp. Station Bull. 818:46-49.

Engel, R. E. 1970. Thatch, cultivation and topdressing of closely-cut turf. Proc. Int. Turfgrass Res. Conf. 1:496-501.

Engel, R.E., and R.B. Alderfer. 1967. The effect of cultivation, topdressing, lime, nitrogen and wetting agent on thatch development in ¼ inch bentgrass turf over a ten-year period. New Jersey Agriculiture Experimental Station Bulletin. 818:32-45.

Engelke, M.G. 2000. Bentgrass management and rootzone maintenance. GCSAA Seminar Booklet, Lawrence, KS.

Ervin, E.H., S. Frame, A. Smith, and A. Zelko. 2000. Turfgrass: 2000 Research & Information Report [Missouri]. p. 13-14. [Online]. http://agebb.missouri.edu/pdc/turf/report00.pdf (verified 13 Nov. 2007).

Fermanian, T.W., J.E. Haley, and R.E. Burns. 1985. The effects of sand topdressing on a heavily thatched creeping bentgrass turf. Int. Turfgrass Soc. Res. J. p. 439-448.

Fraser, M.L. 1998. Managing the new cultivars of creeping bentgrass. Golf Course Mgt. 66(8):53-56.

Gregory, J.H., M.D. Dukes, G.L. Miller, and P.H. Jones. 2005. Analysis of double-ring infiltration techniques and development of a simple automatic delivery system. Available at www.plantmanagementnetwork.org/pub/ats/guide/2005/ring/ (verified 3 Jan 2008)

Habeck, J., and N. Christians. 1999. Soil physical characteristics in golf course greens of varying age. M.S. Non-thesis. Iowa State University, Ames, Iowa.

Hillel, D. 2004. Introduction to environmental soil physics. Academic Press, Inc. San Diego, CA.

Kauffman, J.M. 2007. Long-term cultivation effects on rootzone properties of a sand-based putting green. M.S. Thesis. Univ. of Arkansas, Fayetteville.

Landry, G., and M. Schlossberg. 2001. Bentgrass (*Agrostis* spp.) cultivar performance on a golf course putting green. Int. Turfgrass Soc. Res. J. 9:886-891.

Linde, D. 2005. Assessing golf course conditions in New Zealand. Golf Course Manage. 73(2):110-113.

Lush, W.M. 1985. Objective assessment of turf cricket pitches using an impact hammer. J. of Sports Turf Res. Institute. 61:71-79

McCarty, L.B., M.F. Gregg, and J.E. Toler. 2007. Thatch and mat management in an established creeping bentgrass golf green. Agron. J. 99:1530-1537.

Murphy, J.A., P.E. Rieke, and A.E. Erickson. 1993. Core cultivation of a putting green with hollow and solid tines. Agron. J. 85(1):1-9.

O'Brien, P., and C. Hartwiger. 2003. Aeration and topdressing for the 21st century. USGA Green Section Record. 41(2):1-7.

SAS Institute. 1999. SAS OnlineDoc. Version 8. SAS Inst., Cary, NC.

Sifers, S.I., J.B. Beard, and M.L. Fraser. 2001. Botanical comparisons of twelve *Agrostis* cultivars in a warm-humid climate. Int. Turfgrass Soc. Res. J. 9:213-217.

Stier, J.C., and A.B. Hollman. 2003. Cultivation and topdressing requirements for thatch management in A and G bentgrasses and creeping bluegrass. HortSci. 38(6):1227-1231.

Taylor, D.H., and G.R. Blake. 1979. Sand content of sand-soil-peat mixtures for turfgrass. Soil Sci. Soc. Am. J. 43:394-398.

USGA, Green Section Staff. 1993. USGA's recommendations for a method of putting green construction. USGA Green Section Record 31(2):1-33.

USGA, Green Section Staff. 2004. Revising the USGA recommendations for a method of putting green construction. USGA Green Section Record. 42(3).

Table 2-1. Summary of main effects for sand-based rootzone mean surface (0-5.7 cm) soil organic matter (OM) content as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes.

Management program ‡	Sand particle size	Soil organic matter †	
		2006	2007
		---------- g kg^{-1} ----------	
HT + Seas. Top.	Medium-coarse	28.0 abB[§]	29.6 aA
HT + Freq. Top.	Medium-coarse	27.1 bA	26.3 bA
HT + Seas. Top.	Medium-fine	26.9 bA	27.4 bA
HT + Freq. Top.	Medium-fine	28.0 abA	27.3 bA
Freq. Top. Only	Medium-coarse	28.9 aB	30.2 aA
Cultivar			
A-4		28.8 aB	30.2 aA
L-93		28.3 aA	28.0 bA
Penncross		26.3 bA	26.2 cA
Annual N regime			
112 kg N ha^{-1} yr^{-1}		27.1 bA	26.9 bA
196 kg N ha^{-1} yr^{-1}		28.5 aA	29.4 aA

† Organic matter was measured using the loss on ignition method.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept. in 2006 and 13 Apr. and 18 Sept. in 2007.

§ Means in the same column followed by the same lower case letter are not significantly different, means in the same row followed by the same upper case letter are not significantly different, according to Fisher's protected LSD t-test ($p=0.05$).

Table 2-1a. ANOVA table of soil organic matter as affected by various factors, 2006-2007.

ANOVA	Soil organic matter †	
	2006	2007
Sand Size (S)	NS	NS
Application frequency (F)	NS	**
S x F	NS	**
Cultivar (C)	*	***
F x C	NS	NS
S x C	NS	NS
S x F x C	NS	NS
Nitrogen (N)	*	***
F x N	NS	NS
S x N	NS	NS
S x F x N	NS	NS
C x N	NS	NS
F x C x N	NS	NS
S x C x N	NS	NS
S x F x C x N	NS	NS

† Organic matter was measured using the loss on ignition method.

*, **, ***, and NS refer to significant at the 0.05, 0.01, 0.001, and non-significant respectively.

Table 2-2. Soil organic matter by weight as affected by each organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2006 and 2007.

			Soil organic matter †	
Management program ‡	Cultivar	Annual N regime	2006	2007
		--- kg N ha^{-1} yr^{-1} ---	--------- g kg^{-1}---------	
HTSM	A-4	112	28.2 bc[§]	30.1 bc
	L-93	---	27.4 bc	26.6 d
	Penncross	---	25.3 c	26.6 d
	A-4	196	31.3 a	34.3 a
	L-93	---	29.3 ab	32.2 ab
	Penncross	---	26.8 bc	27.8 cd
	Mean		28.0 AB	29.6 A
HTFM	A-4	112	26.7 ab	27.0 ab
	L-93	---	26.3 b	24.9 b
	Penncross	---	25.4 b	23.8 b
	A-4	196	29.8 a	29.2 a
	L-93	---	27.5 ab	27.1 ab
	Penncross	---	27.0 ab	25.9 ab
	Mean		27.1 B	26.3 B
HTSF	A-4	112	27.0 a	29.1 a
	L-93	---	25.7 a	25.2 b
	Penncross	---	25.3 a	22.6 b
	A-4	196	28.3 a	29.5 a
	L-93	---	29.4 a	29.0 a
	Penncross	---	25.8 a	29.2 a
	Mean		26.9 B	27.4 B
HTFF	A-4	112	27.0 a	26.7 ab
	L-93	---	30.3 a	26.5 ab
	Penncross	---	26.0 a	24.1 b
	A-4	196	28.6 a	30.5 a
	L-93	---	27.9 a	27.8 ab
	Penncross	---	27.9 a	27.9 ab
	Mean		28.0 AB	27.3 B
Freq. Top. Only	A-4	112	29.6 bc	33.0 a
	L-93	---	29.9 ab	29.7 bc
	Penncross	---	25.8 d	27.6 cd
	A-4	196	31.4 a	33.0 a
	L-93	---	29.3 bc	31.2 ab
	Penncross	---	27.8 c	26.9 d
	Mean		28.9 A	30.2 A

† Organic matter was measured using the loss on ignition method.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept. and 13 Apr. and 18 Sept. in 2006 and 2007 respectively.

§ Means in the same column of the same management program followed by the same letter are not significantly different according to Fisher's protected LSD t-test (p=0.05).

HT = hollow tine cultivation; SM = seasonal topdressing with med-coarse sand; FM = frequent topdressing with med-coarse sand; SF = seasonal topdressing with med-fine sand; FF = frequent topdressing with med-fine sand; Freq. Top. Only = frequent topdressing only with med-coarse sand without hollow tine core cultivation.

Table 2-3. Particle size distribution as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2006.

		Sieve fraction sand particle diameter (mm) †							
Management program ‡	Sand particle size	F. Gravel 2.0	V. Coarse 1.0	Coarse 0.5	Medium 0.25	Fine 0.15	V. Fine 0.10	V. Fine 0.05	Silt/Clay < 0.05
		g kg^{-1}							
HT + Seas. Top.	Medium-coarse	6.4 a§	56.7 a	277 a	500 ab	130 c	12.0 b	10.6 b	5.7 c
HT + Freq. Top.	Medium-coarse	5.7 ab	50.7 bc	261 b	502 a	146 c	15.1 b	12.7 b	5.8 c
HT + Seas. Top.	Medium-fine	5.3 bc	47.6 c	236 c	486 b	178 b	21.1 a	19.0 a	8.2 a
HT + Freq. Top.	Medium-fine	4.6 c	43.9 d	208 d	460 c	236 a	21.1 a	19.5 a	7.4 ab
Freq. Top. Only	Medium-coarse	5.0 bc	52.8 b	270 ab	507 a	133 c	15.1 b	10.9 b	6.5 bc
Cultivar									
A-4		5.4 a	49.9 a	247 a	491 a	168 a	17.3 a	14.8 a	6.4 a
L-93		5.5 a	51.3 a	254 a	493 a	158 a	17.0 a	14.1 a	7.0 a
Penncross		5.3 a	49.9 a	250 a	489 a	168 a	16.4 a	14.8 a	6.8 a
Annual N regime									
112 kg N ha^{-1} yr^{-1}		5.4 a	49.9 a	252 a	491 a	165 a	16.0 a	14.6 a	6.6 a
196 kg N ha^{-1} yr^{-1}		5.5 a	50.7 a	249 a	492 a	164 a	17.8 a	14.4 a	6.8 a

† Samples (> 60 g) were passed through a collection of sieves and separated using a vibratory shaker for 5 minutes (ASTM F 1632-03).

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test (p=0.05).

Table 2-3a. ANOVA table of particle size distribution as affected by various factors, 2006.

	Sieve fraction sand particle diameter (mm) †							
ANOVA	F. Gravel 2.0	V. Coarse 1.0	Coarse 0.5	Medium 0.25	Fine 0.15	V. Fine 0.10	V. Fine 0.05	Silt/Clay < 0.05
Sand Size (S)	***	***	***	***	***	***	***	***
Application frequency (F)	*	***	***	NS	***	NS	NS	NS
S x F	NS	NS	NS	*	*	NS	NS	NS
Cultivar (C)	NS	NS	NS	NS	NS	NS	NS	NS
F x C	NS	NS	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS	NS	NS
S x F x C	NS	NS	NS	NS	NS	NS	NS	NS
Nitrogen (N)	NS	NS	NS	NS	NS	NS	NS	NS
F x N	NS	NS	NS	NS	NS	NS	NS	NS
S x N	NS	NS	NS	NS	NS	NS	NS	NS
S x F x N	NS	NS	NS	NS	NS	NS	NS	NS
C x N	NS	NS	NS	NS	NS	NS	NS	NS
F x C x N	NS	NS	NS	NS	NS	NS	NS	NS
S x C x N	NS	NS	NS	NS	NS	NS	NS	NS
S x F x C x N	NS	NS	NS	NS	NS	NS	NS	NS

† Samples (> 60 g) were passed through a collection of sieves and separated using a vibratory shaker for 5 minutes (ASTM F 1632-03).

*, ***, and NS refer to significant at the 0.05, 0.001, and non-significant respectively.

Table 2-4. Particle size distribution as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2007.

		Sieve fraction sand particle diameter (mm) †							
Management program ‡	Sand particle size	F. Gravel 2.0	V. Coarse 1.0	Coarse 0.5	Medium 0.25	Fine 0.15	V. Fine 0.10	V. Fine 0.05	Silt/Clay < 0.05
		$g\ kg^{-1}$							
HT + Seas. Top.	Medium-coarse	6.4 a§	56.5 a	296 a	482 bc	133 c	8.3 a	13.6 b	3.8 c
HT + Freq. Top.	Medium-coarse	4.7 b	42.8 b	269 b	502 a	153 c	9.3 a	14.6 b	3.6 c
HT + Seas. Top.	Medium-fine	4.6 b	42.7 b	234 c	474 c	199 b	12.6 a	18.7 a	6.1 a
HT + Freq. Top.	Medium-fine	3.8 b	33.1 c	176 d	455 d	298 a	10.9 a	18.6 a	4.8 b
Freq. Top. Only	Medium-coarse	4.6 b	42.3 b	272 b	498 ab	149 c	15.4 a	13.7 b	4.3 bc
Cultivar									
A-4		4.7 a	42.6 a	248 a	483 a	190 a	10.9 a	16.3 a	4.6 a
L-93		5.0 a	44.5 a	254 a	485 a	190 a	10.1 a	16.0 a	4.3 a
Penncross		4.8 a	43.3 a	248 a	478 a	180 a	12.8 a	15.4 a	4.7 a
Annual N regime									
$112\ kg\ N\ ha^{-1}\ yr^{-1}$		5.0 a	43.7 a	249 a	482 a	189 a	12.2 a	15.4 a	4.6 a
$196\ kg\ N\ ha^{-1}\ yr^{-1}$		4.7 a	43.3 a	251 a	483 a	184 a	10.4 a	16.3 a	4.4 a

† Samples (> 60 g) were passed through a collection of sieves and separated using a vibratory shaker for 5 minutes (ASTM F 1632-03).

‡ Hollow tine core cultivation occurred on 13 Apr. and 18 Sept.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test (p=0.05).

Table 2-4a. ANOVA table of particle size distribution as affected by various factors, 2007.

	Sieve fraction sand particle diameter (mm) †							
ANOVA	F. Gravel 2.0	V. Coarse 1.0	Coarse 0.5	Medium 0.25	Fine 0.15	V. Fine 0.10	V. Fine 0.05	Silt/Clay < 0.05
Sand Size (S)	***	***	***	***	***	**	***	***
Application frequency (F)	***	***	***	NS	***	NS	NS	*
S x F	NS	NS	*	***	***	NS	NS	NS
Cultivar (C)	NS	NS	NS	NS	NS	NS	NS	NS
F x C	NS	NS	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS	NS	NS
S x F x C	NS	NS	NS	NS	NS	NS	NS	NS
Nitrogen (N)	NS	NS	NS	NS	NS	NS	NS	NS
F x N	NS	NS	NS	NS	NS	NS	NS	NS
S x N	NS	NS	NS	NS	NS	NS	NS	NS
S x F x N	NS	NS	NS	NS	NS	NS	NS	NS
C x N	NS	NS	NS	NS	NS	NS	NS	NS
F x C x N	NS	NS	NS	NS	NS	NS	NS	NS
S x C x N	NS	NS	NS	NS	NS	NS	NS	NS
S x F x C x N	NS	NS	NS	NS	NS	NS	NS	NS

† Samples (> 60 g) were passed through a collection of sieves and separated using a vibratory shaker for 5 minutes (ASTM F 1632-03).
*, ***, and NS refer to significant at the 0.05, 0.001, and non-significant respectively.

Table 2-5. Volumetric water content as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2006-2007.

		Volumetric water content †		
Management program ‡	Sand particle size	2006	2007	Study Mean
		$m^3 m^{-3}$		
HT + Seas. Top.	Medium-coarse	0.178 b[§]	0.173 b	0.175 b
HT + Freq. Top.	Medium-coarse	0.177 b	0.173 b	0.174 b
HT + Seas. Top.	Medium-fine	0.184 b	0.171 b	0.176 b
HT + Freq. Top.	Medium-fine	0.197 a	0.191 a	0.194 a
Freq. Top. Only	Medium-coarse	0.186 ab	0.159 b	0.170 b
Cultivar				
A-4		0.184 a	0.172 a	0.176 a
L-93		0.185 b	0.174 a	0.179 a
Penncross		0.184 a	0.174 a	0.178 a
Annual N regime				
112 kg N ha^{-1} yr^{-1}		0.183 a	0.172 a	0.176 a
196 kg N ha^{-1} yr^{-1}		0.186 a	0.174 a	0.179 a

† Volumetric water content was measured (0-2.25 cm depth) using time domain reflectometry.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept. in 2006 and 13 Apr. and 18 Sept. in 2007.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test ($p=0.05$).

Table 2-5a. ANOVA table of volumetric water content as affected by various factors, 2006-2007.

ANOVA	Volumetric water content †		
	2006	2007	Study Mean
Sand Size (S)	*	NS	*
Application frequency (F)	NS	NS	NS
S x F	NS	*	*
Cultivar (C)	NS	NS	NS
F x C	NS	NS	NS
S x C	NS	NS	NS
S x F x C	NS	NS	NS
Nitrogen (N)	NS	NS	NS
F x N	NS	NS	NS
S x N	NS	NS	NS
S x F x N	NS	NS	NS
C x N	NS	NS	NS
F x C x N	NS	NS	NS
S x C x N	NS	NS	NS
S x F x C x N	NS	NS	NS

† Volumetric water content was measured (0-2.25 cm depth) using time domain reflectometry.
* and NS refer to significant at the 0.05 and non-significant respectively.

Table 2-6. Volumetric water content as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2006.

Management program ‡	Sand particle size	Volumetric water content †				
		3 May	19 May	14 June	17 July	13 Aug
		m^3 m^{-3}				
HT + Seas. Top.	Medium-coarse	0.175 b§	0.186 c	0.197 bc	0.168 b	0.168 b
HT + Freq. Top.	Medium-coarse	0.175 b	0.184 c	0.191 c	0.164 b	0.170 b
HT + Seas. Top.	Medium-fine	0.184 ab	0.192 bc	0.200 abc	0.172 b	0.173 b
HT + Freq. Top.	Medium-fine	0.194 a	0.205 a	0.211 a	0.186 a	0.190 a
Freq. Top. Only	Medium-coarse	0.192 a	0.198 ab	0.205 ab	0.169 b	0.166 b
Cultivar						
A-4		0.180 a	0.192 a	0.206 a	0.173 a	0.170 a
L-93		0.184 a	0.194 a	0.201 ab	0.174 a	0.174 a
Penncross		0.188 a	0.192 a	0.196 b	0.169 a	0.176 a
Annual N regime						
112 kg N ha^{-1} yr^{-1}		0.186 a	0.192 a	0.199 a	0.167 b	0.171 a
196 kg N ha^{-1} yr^{-1}		0.183 a	0.194 a	0.202 a	0.177 a	0.176 a

† Volumetric water content was measured (0-2.25 cm depth) using time domain reflectometry.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test (p=0.05).

Table 2-6a. ANOVA table of volumetric water content as affected by various factors, 2006.

ANOVA	Volumetric water content †				
	3 May	19 May	14 June	17 July	13 Aug
Sand Size (S)	**	**	*	*	*
Application frequency (F)	NS	NS	NS	NS	NS
S x F	NS	NS	NS	NS	NS
Cultivar (C)	NS	NS	NS	NS	NS
F x C	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS
S x F x C	NS	NS	NS	NS	NS
Nitrogen (N)	NS	NS	NS	*	NS
F x N	NS	NS	NS	NS	NS
S x N	NS	NS	NS	NS	NS
S x F x N	NS	NS	NS	NS	NS
C x N	NS	NS	NS	NS	NS
F x C x N	NS	NS	NS	NS	NS
S x C x N	NS	NS	NS	NS	NS
S x F x C x N	NS	NS	NS	NS	NS

† Volumetric water content was measured (0-2.25 cm depth) using time domain reflectometry.

*, **, and NS refer to significant at the 0.05, 0.01, and non-significant respectively.

Table 2-7. Volumetric water content as affected by organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2007.

Management program ‡	Sand particle size	Volumetric water content †							
		20 May	7 June	20 June	10 July	25 July	11 Aug	2 Sept	17 Sept
		---------- $m^3 m^{-3}$ ----------							
HT + Seas. Top.	Medium-coarse	0.157 b§	0.198 ab	0.218 b	0.208 ab	0.223 b	0.144 bc	0.104 b	0.129 bc
HT + Freq. Top.	Medium-coarse	0.158 b	0.186 bc	0.207 b	0.199 bc	0.218 bc	0.153 ab	0.121 a	0.133 b
HT + Seas. Top.	Medium-fine	0.156 b	0.201 bc	0.216 b	0.201 bc	0.226 ab	0.144 bc	0.097 b	0.129 bc
HT + Freq. Top.	Medium-fine	0.179 a	0.219 a	0.234 a	0.212 a	0.237 a	0.166 a	0.122 a	0.165 a
Freq. Top. Only	Medium-coarse	0.149 b	0.192 b	0.205 b	0.192 c	0.210 c	0.135 c	0.096 b	0.109 c
Cultivar									
A-4		0.157 a	0.192 a	0.215 a	0.203 a	0.224 a	0.147 a	0.107 a	0.128 a
L-93		0.161 a	0.197 a	0.217 a	0.203 a	0.222 a	0.149 a	0.110 a	0.135 a
Penncross		0.162 a	0.195 a	0.216 a	0.204 a	0.222 a	0.150 a	0.106 a	0.136 a
Annual N regime									
112 kg N ha^{-1} yr^{-1}		0.160 a	0.192 a	0.214 a	0.199 a	0.218 a	0.147 a	0.109 a	0.139 a
196 kg N ha^{-1} yr^{-1}		0.160 a	0.197 a	0.219 a	0.208 a	0.228 b	0.150 a	0.107 a	0.127 a

† Volumetric water content was measured (0-2.25 cm depth) using time domain reflectometry.

‡ Hollow tine core cultivation occurred on 13 Apr. and 18 Sept.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test (p=0.05).

Table 2-7a. ANOVA table of volumetric water content as affected by various factors, 2007.

	Volumetric water content †							
ANOVA	20 May	7 June	20 June	10 July	25 July	11 Aug	2 Sept	17 Sept
Sand Size (S)	NS	*	*	NS	*	NS	NS	NS
Application frequency (F)	NS	*	**	NS	NS	*	***	*
S x F	NS	NS	NS	**	NS	NS	NS	*
Cultivar (C)	NS	NS	NS	NS	NS	NS	NS	NS
F x C	NS	NS	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS	NS	NS
S x F x C	NS	NS	NS	NS	NS	NS	NS	NS
Nitrogen (N)	NS	NS	NS	*	*	NS	NS	NS
F x N	NS	NS	NS	NS	NS	NS	NS	NS
S x N	NS	NS	NS	NS	NS	NS	NS	NS
S x F x N	NS	NS	NS	NS	NS	NS	NS	NS
C x N	NS	NS	NS	NS	NS	NS	NS	NS
F x C x N	NS	NS	NS	NS	NS	NS	NS	NS
S x C x N	NS	NS	NS	NS	NS	NS	NS	NS
S x F x C x N	NS	NS	NS	NS	NS	NS	NS	NS

† Volumetric water content was measured (0-2.25 cm depth) using time domain reflectometry.

*, **, and NS refer to significant at the 0.05, 0.01, and non-significant respectively.

Table 2-8. Surface hardness as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2006.

Management program ‡	Sand particle size	Surface hardness †			
		24 May	29 June	31 Oct	Mean
		g_{max}			
HT + Seas. Top.	Medium-coarse	109 b[§]	129 a	121 b	120 b
HT + Freq. Top.	Medium-coarse	104 c	120 c	114 cd	113 d
HT + Seas. Top.	Medium-fine	107 bc	124 b	117 c	116 c
HT + Freq. Top.	Medium-fine	104 c	119 c	112 d	112 d
Freq. Top. Only	Medium-coarse	115 a	129 a	134 a	126 a
Cultivar					
A-4		103 c	118 c	116 b	112 c
L-93		107 b	122 b	119 b	116 b
Penncross		112 a	132 a	124 a	123 a
Annual N regime					
112 kg N ha^{-1} yr^{-1}		109 a	126 a	120 a	119 a
196 kg N ha^{-1} yr^{-1}		106 b	122 b	119 b	116 b

† Surface hardness was measured using a Clegg Impact Soil Tester (0.5 kg model) at two locations per sub-plot and averaged to one value.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test ($p=0.05$).

Table 2-8a. ANOVA table of surface hardness as affected by various factors, 2006.

	Surface hardness †			
ANOVA	24 May	29 June	31 Oct	Mean
Sand Size (S)	NS	NS	*	*
Application frequency (F)	*	NS	***	***
S x F	NS	NS	NS	NS
Cultivar (C)	***	***	***	***
F x C	NS	NS	NS	NS
S x C	NS	NS	NS	NS
S x F x C	NS	NS	NS	NS
Nitrogen (N)	NS	**	NS	**
F x N	NS	NS	NS	NS
S x N	NS	NS	NS	NS
S x F x N	NS	NS	NS	NS
C x N	NS	NS	NS	NS
F x C x N	NS	NS	NS	NS
S x C x N	NS	NS	NS	NS
S x F x C x N	NS	NS	NS	NS

† Surface hardness was measured using a Clegg Impact Soil Tester (0.5 kg model) at two locations per sub-plot and averaged to one value.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept.

*, **, ***, and NS refer to significant at the 0.05, 0.01, 0.001, and non-significant respectively.

Table 2-9. Surface hardness as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2007.

		Surface hardness †						
Management program ‡	Sand particle size	24 May	21 June	23 July	22 Aug	27 Sept	25 Oct	Mean
		g_{max}						
HT + Seas. Top.	Medium-coarse	129 b§	137 a	145 a	150 a	127 b	145 b	138 a
HT + Freq. Top.	Medium-coarse	125 bc	128 b	131 cd	134 bc	123 bc	136 c	128 b
HT + Seas. Top.	Medium-fine	126 b	131 b	137 b	137 b	123 bc	136 c	131 b
HT + Freq. Top.	Medium-fine	121 c	123 c	127 d	131 c	119 c	130 d	124 c
Freq. Top. Only	Medium-coarse	134 a	132 b	134 bc	139 b	154 a	152 a	139 a
Cultivar								
A-4		125 b	126 b	132 b	134 b	127 b	136 b	129 b
L-93		126 b	128 b	132 b	135 b	127 b	138 b	130 b
Penncross		131 a	137 a	140 a	145 a	134 a	145 a	137 a
Annual N regime								
112 kg N ha^{-1} yr^{-1}		129 a	133 a	137 a	141 a	129 a	141 a	134 a
196 kg N ha^{-1} yr^{-1}		125 b	127 b	132 b	135 b	130 a	138 a	130 b

† Surface hardness was measured using a Clegg Impact Soil Tester (0.5 kg model) at two locations per sub-plot and averaged to one value.

‡ Hollow tine core cultivation occurred on 13 Apr. and 18 Sept.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test ($p=0.05$).

Table 2-9a. ANOVA table of surface hardness as affected by various factors, 2007.

	Surface hardness †						
ANOVA	24 May	21 June	23 July	22 Aug	27 Sept	25 Oct	Mean
Sand Size (S)	*	***	***	***	NS	***	***
Application frequency (F)	**	***	***	***	NS	***	***
S x F	NS	NS	NS	*	NS	NS	NS
Cultivar (C)	*	***	***	***	*	***	***
F x C	NS	NS	NS	NS	NS	NS	NS
S x C	NS	NS	NS	NS	NS	NS	NS
S x F x C	NS	NS	NS	NS	NS	NS	NS
Nitrogen (N)	**	***	**	***	NS	*	**
F x N	NS	NS	NS	NS	NS	NS	NS
S x N	NS	NS	NS	NS	NS	NS	NS
S x F x N	NS	NS	NS	NS	NS	NS	NS
C x N	NS	NS	NS	NS	NS	NS	NS
F x C x N	NS	NS	NS	NS	NS	NS	NS
S x C x N	NS	NS	NS	NS	NS	NS	NS
S x F x C x N	NS	NS	NS	NS	NS	NS	NS

† Surface hardness was measured using a Clegg Impact Soil Tester (0.5 kg model) at two locations per sub-plot and averaged to one value.

‡ Hollow tine core cultivation occurred on 13 Apr. and 18 Sept.

*, **, ***, and NS refer to significant at the 0.05, 0.01, 0.001, and non-significant respectively.

Table 2-10. Surface hardness as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2006-2007.

Management program ‡	Sand particle size	Surface hardness †		
		2006	2007	Study Mean
		g_{max}		
HT + Seas. Top.	Medium-coarse	120 b[§]	138 a	131 a
HT + Freq. Top.	Medium-coarse	113 d	128 b	122 bc
HT + Seas. Top.	Medium-fine	116 c	131 b	125 b
HT + Freq. Top.	Medium-fine	112 d	124 c	119 c
Freq. Top. Only	Medium-coarse	126 a	139 a	134 a
Cultivar				
A-4		112 c	129 b	123 b
L-93		116 b	130 b	125 b
Penncross		123 a	137 a	132 a
Annual N regime				
112 kg N ha^{-1} yr^{-1}		119 a	134 a	128 a
196 kg N ha^{-1} yr^{-1}		116 b	130 b	124 b

† Surface hardness was measured using a Clegg Impact Soil Tester (0.5 kg model) at two locations per sub-plot and averaged to one value.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept. in 2006 and 13 Apr. and 18 Sept. in 2007.

§ Means in the same column followed by the same letter are not significantly different according to Fisher's protected LSD t-test (p=0.05).

Table 2-10a. ANOVA table of surface hardness as affected by various factors, 2006-2007.

	Surface hardness †		
ANOVA	2006	2007	Study Mean
Sand Size (S)	*	***	***
Application frequency (F)	***	***	***
S x F	NS	NS	NS
Cultivar (C)	***	***	***
F x C	NS	NS	NS
S x C	NS	NS	NS
S x F x C	NS	NS	NS
Nitrogen (N)	**	**	***
F x N	NS	NS	NS
S x N	NS	NS	NS
S x F x N	NS	NS	NS
C x N	NS	NS	NS
F x C x N	NS	NS	NS
S x C x N	NS	NS	NS
S x F x C x N	NS	NS	NS

† Surface hardness was measured using a Clegg Impact Soil Tester (0.5 kg model) at two locations per sub-plot and averaged to one value.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept. in 2006 and 13 Apr. and 18 Sept. in 2007.

*, **, ***, and NS refer to significant at the 0.05, 0.01, 0.001, and non-significant respective.

Table 2-11. Infiltration rate as affected by five organic matter management programs, three creeping bentgrass cultivars, and two annual N regimes, 2006-2007.

		Infiltration rate †			
		2006		2007	
Management program ‡	Sand particle size	30 June	16 Aug	6 July	24 Aug
		---------- cm hr^{-1} ----------			
HT + Seas. Top.	Medium-coarse	94 aA[§]	87 aA	71 aB	52 abC
HT + Freq. Top.	Medium-coarse	79 bA	74 bA	61 bB	54 aC
HT + Seas. Top.	Medium-fine	70 cA	72 bA	61 bB	54 aC
HT + Freq. Top.	Medium-fine	58 dA	57 cA	50 cB	42 cC
Freq. Top. Only	Medium-coarse	65 cdB	73 bA	52 cC	45 bcD
Cultivar					
A-4		78 aA	79 aA	59 aB	50 aC
L-93		72 abA	72 abA	59 aB	51 aC
Penncross		69 bA	67 bA	58 aB	48 aC
Annual N regime					
112 kg N ha^{-1} yr^{-1}		73 aA	71 aA	58 aB	47 aC
196 kg N ha^{-1} yr^{-1}		73 aA	74 aA	60 aB	52 aC

† Infiltration rate was measured through time of water to empty from the center ring (10 cm diam.) of a double-ring infiltrometer.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept. in 2006, and 13 Apr. and 18 Sept. in 2007.

§ Means in the same column followed by the same lower case letter are not significantly different, means in the same row followed by the same upper case letter are not significantly different, according to Fisher's protected LSD t-test ($p=0.05$).

Table 2-11a. ANOVA table of infiltration rate as affected by various factors, 2006-2007.

	Infiltration rate †			
	2006		2007	
ANOVA	30 June	16 Aug	6 July	24 Aug
Sand Size (S)	***	***	***	NS
Application frequency (F)	***	***	***	NS
S x F	NS	NS	NS	*
Cultivar (C)	NS	NS	NS	NS
F x C	NS	NS	NS	NS
S x C	NS	NS	NS	NS
S x F x C	NS	NS	NS	NS
Nitrogen (N)	NS	NS	NS	NS
F x N	NS	NS	NS	NS
S x N	NS	NS	NS	NS
S x F x N	NS	NS	NS	NS
C x N	NS	NS	NS	NS
F x C x N	NS	NS	NS	NS
S x C x N	NS	NS	NS	NS
S x F x C x N	NS	NS	NS	NS

† Infiltration rate was measured through time of water to empty from the center ring (10 cm diam.) of a double-ring infiltrometer.

‡ Hollow tine core cultivation occurred on 14 Apr. and 14 Sept. in 2006, and 13 Apr. and 18 Sept. in 2007.

*, ***, and NS refer to significant at the 0.05, 0.001, and non-significant respectively.

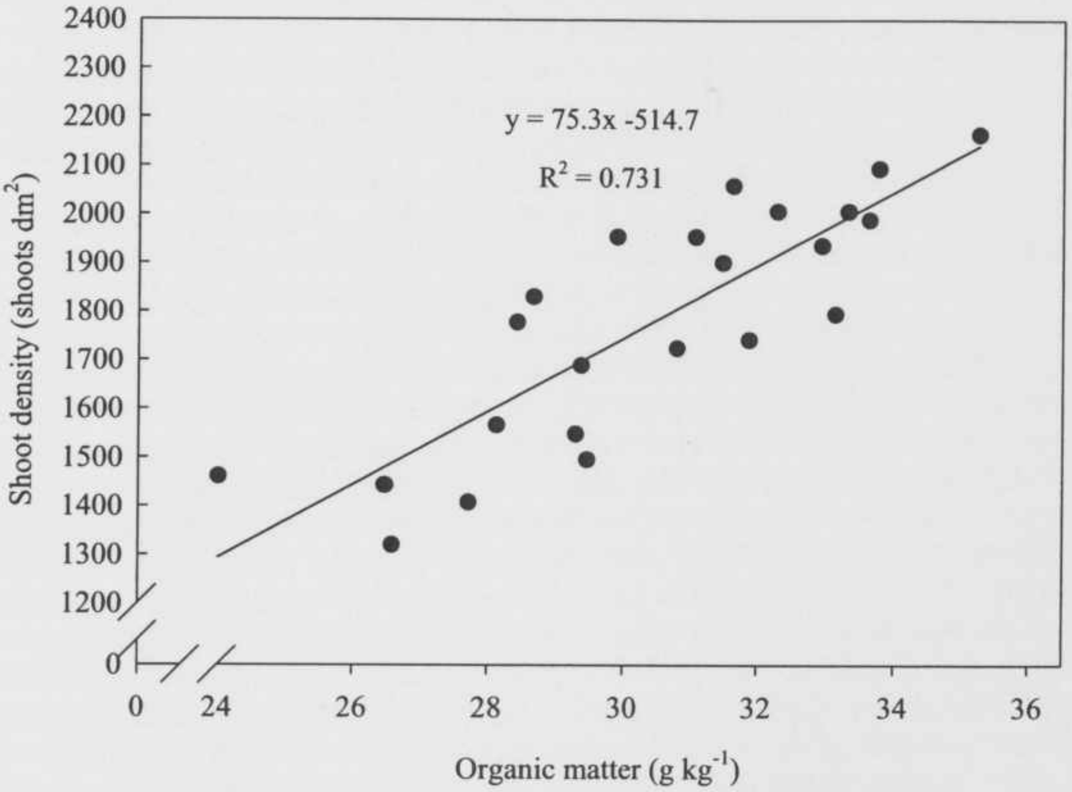

Figure 2-1. Shoot density and organic matter content (May 2007 SD and 2007 OM) of the TOP management program, across three creeping bentgrass cultivars and two annual N regimes.

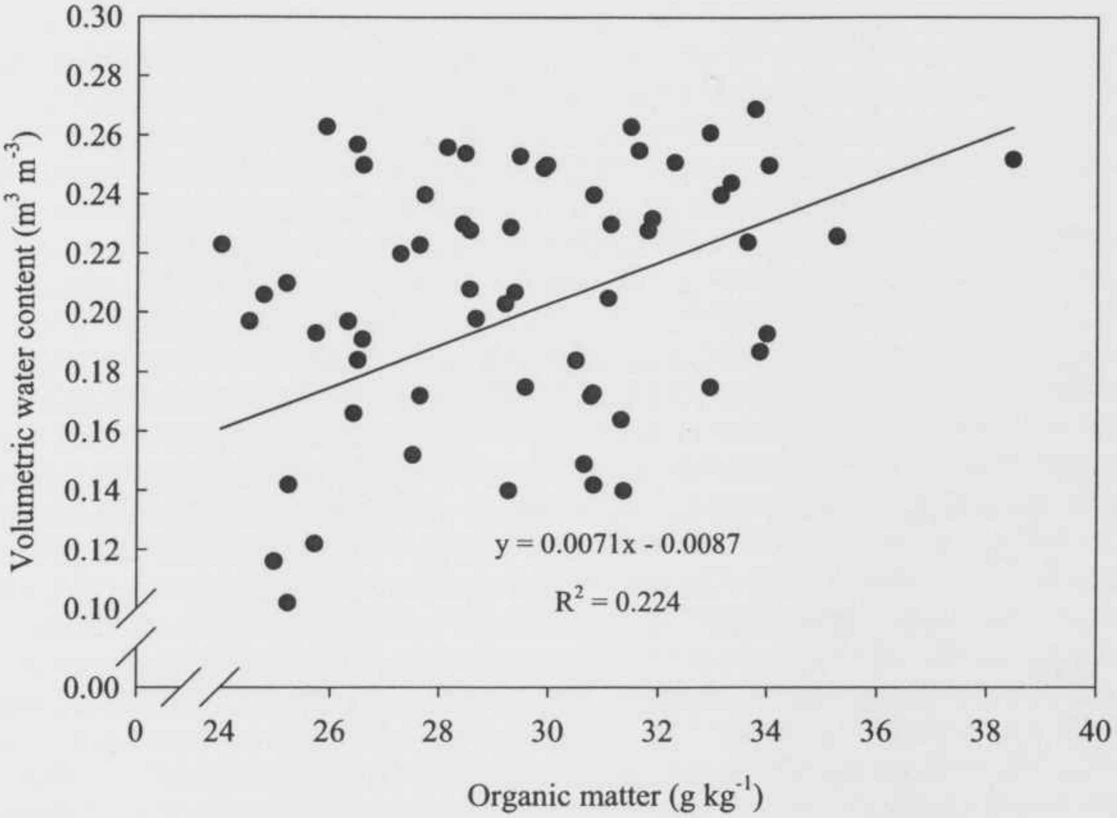

Figure 2-2. Volumetric water content (13 Aug. 2007) and organic matter (2007) of TOP, HTFF, and HTSM plots.

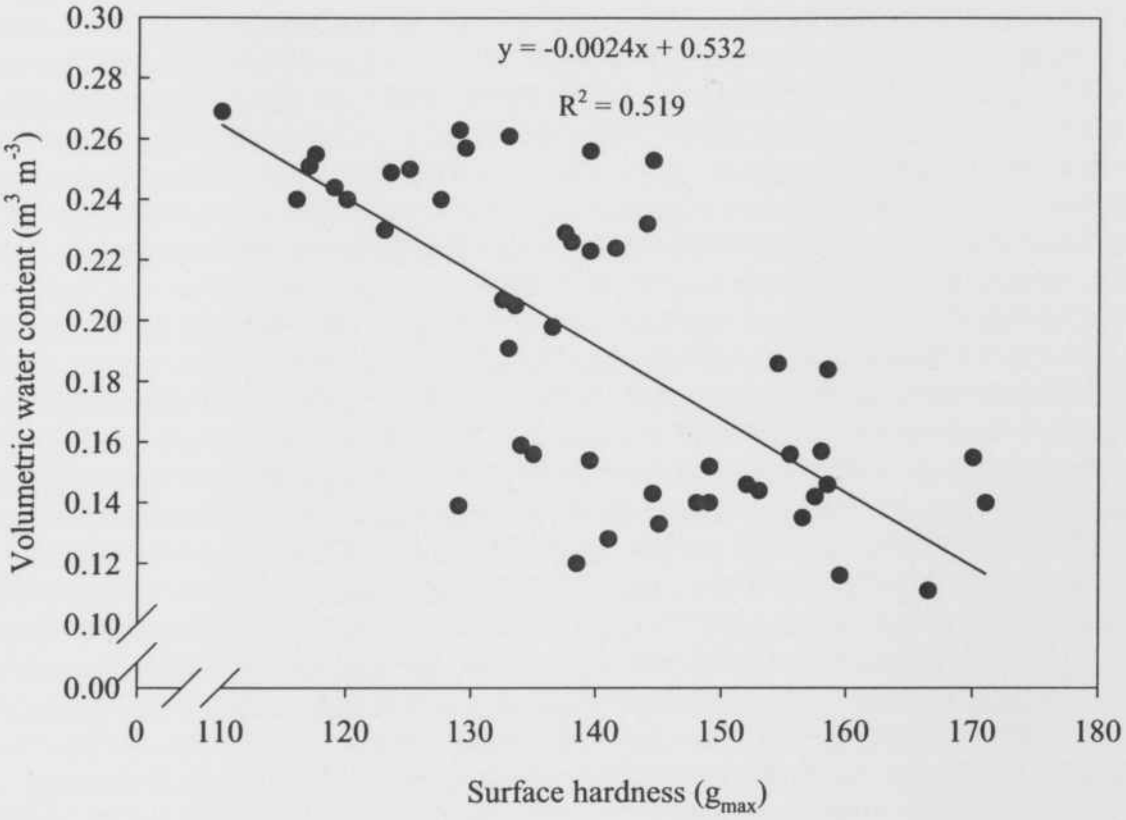

Figure 2-3. Volumetric water content (13 Aug. 2007) and surface hardness (22 Aug. 2007) of TOP, HTFF, and HTSM plots.

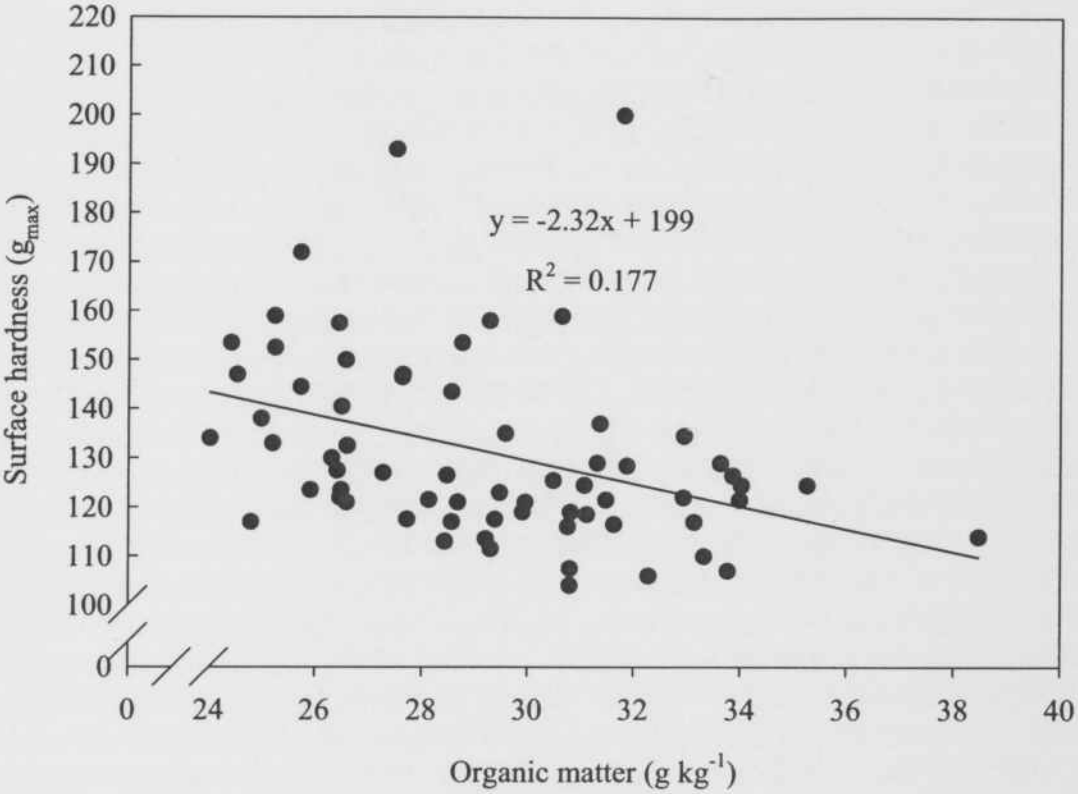

Figure 2-4. Surface hardness (13 Aug. 2007) and organic matter (2007) of TOP, HTFF, and HTSM plots.

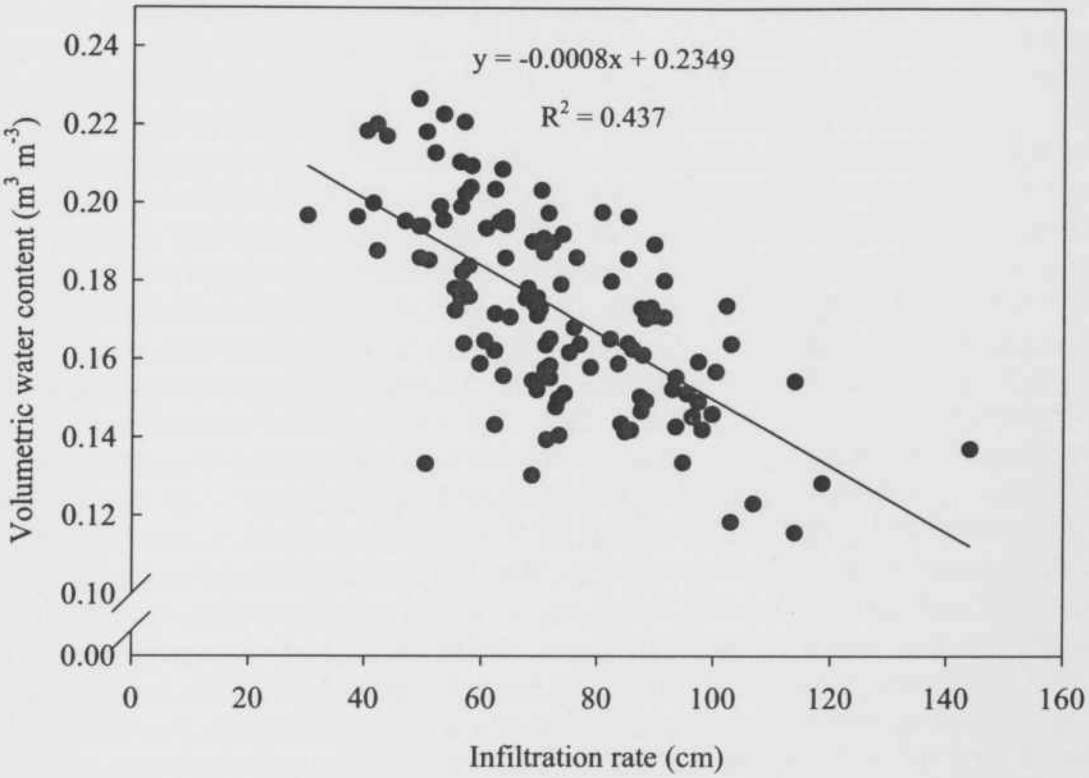

Figure 2-5. Volumetric water content (13 Aug. 2006) and infiltration rate (16 Aug. 2006).

Figure 2-6. Soil profiles of the five organic matter management programs in Sept., 2007, after four years of management practices.