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Soil Physical Responses of a Compacted Sports Field Following Various Core Aerification Techniques

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Authors' contributions

This work was carried out in collaboration between all authors. Authors LBM, VLQ and PJB designed the study and wrote the protocol. Author JLA wrote the first draft of the manuscript and managed the literature searches. Author PJB conducted the in field research, data collection, and analysis. All authors read and approved the final manuscript.

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ABSTRACT

Aims: Soil compaction is detrimental to turfgrass health and potentially hazardous to users of sports field participants. Previous research has evaluated numerous core aeration programs and their effects on water infiltration and thatch levels in a myriad of soil series under various management programs. The goal of this study was to identify detailed soil responses of a highly compacted, multi-purpose sports field to different soil aerification techniques while minimizing the negative impact of core removal on turfgrass quality.
Study Design: The study was designed as a randomized complete block with 4 replications and a 2 × 2 factorial treatment arrangement.
Place and Duration of Study: The study was conducted over two years on Clemson University's band practice field, Clemson, SC, USA.
Methodology: The study evaluated deep (17.8 cm) and shallow (7.6 cm) tine core aerification and number of yearly aerification events on several soil and turf parameters. Extracted cores were either removed or incorporated back into the plots.

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Results: Little effect on turfgrass quality was observed due to mowing height (2.65 cm) masking any reduction in turfgrass density. Deep tine aerification lowered bulk density 5% in the first year compared to shallow tine aerification. In year one, infiltration was increased 29% after deep tine core aeration and 34% when cores were removed after aerification.
Conclusion: Treatment effects were not as drastic as studies conducted in sand based soils, reflecting the necessity of a perpetual soil aerification program in clay-based soils.

Keywords: Soil compaction; turfgrass; bulk density; clegg impact value; turfgrass quality; aerification.

ABBREVIATIONS

BD: Bulk density; CIV: Clegg impact value; TQ: Turfgrass quality.

1. INTRODUCTION

Soil compaction is a potentially serious problem for turfgrass managers and users of sports fields. The soil physical properties of a compacted soil can adversely influence plant growth, efficiency of an irrigation program [1] and decrease player safety as surface cushioning will not be adequate to prevent injury during use. Compaction is most problematic in high traffic areas [2].

Soil compaction is the reduction of macro-porosity by the pressing together of soil particles, resulting in a more dense soil mass with less aeration porosity, increased bulk density, increased soil strength, and altered pore size distribution [1]. Compaction also often results in destruction of soil structure [3]. In turfgrass systems, soil compaction discourages root and shoot growth, slows replenishment of carbohydrate reserves, and eventually causes a decline in overall plant health.

In commercial turfgrass, soil aerification is typically performed with vertically operating hollow tine core aeration units, which selectively remove soil cores from the soil profile [3]. More recently, soil aerification with solid tines has gained in popularity as they typically cause less surface disruption and have lower labor costs due to less post-aerification cleanup compared to hollow tine aerification [3]. However, solid tine core aeration may create an impermeable layer at the bottom of the aerification zone and directly adjacent to coring holes [4].

Previous research has evaluated numerous core aeration programs and their effects on water infiltration and thatch levels in a myriad of soil series under various management programs. Detailed soil responses to various cultivation techniques such as deep tine and shallow tine aerification have received limited attention. The goal of this study was to identify detailed soil responses to different soil aerification techniques in a highly compacted, multi-purpose sports field while minimizing the negative impact of core removal on turfgrass quality.

2. MATERIALS AND METHODS

2.1 Site Description

A two-year field study was conducted between 2002 & 2003 to evaluate various aerification techniques on soil physical properties on the Clemson University band practice field in Clemson, SC. The field presented a worst-case-scenario combination of frequent soil compression from a variety of sources and a Cecil soil series [Cecil sandy clay loam (fine, kaolinitic, thermic Typic Kanhapludults)] that is highly susceptible to compaction, particularly after catastrophic disruption to existing soil structure which likely occurred during shaping of the field surface and subsequent daily use. Prior to this study, no known core aerification was performed on this field. The field was exposed to daily band practice and was also used as an overflow parking lot on home football games. The site was planted with common bermudagrass (*Cynodon dactylon* L.) and maintained by the Clemson University Facilities and Landscape Service Department. In the absence of rain, the field was irrigated with ~1.25 cm every 3 d, mowed once weekly at 2.65 cm using a reel mower, fertilized with at 45 kg N ha-1 monthly during the growing season to total 270 kg N ha-1 annually, and limed as recommended by soil tests. The field was not overseeded to provide green turf during winter dormancy.

Treatments consisted of an nontreated control, deep hollow tine (17.8 cm depth, 1.6 cm diameter) aerification with a tractor mounted aerification unit (Southern Green, Zachary, LA 70791) with cores removed; deep hollow tine aerification without core removal; shallow hollow tine (7.6 cm depth, 1.3 cm diameter) aerification with a walk-behind aerification unit (Ryan Manufacturers, Lincoln, NE 68504) with cores removed; and, shallow hollow tine aerification without cores removed (Table 1). All treatments were applied on 5 x 5 cm centers. Treatments were made 2 d after an irrigation or rainfall event to ensure uniform soil moisture. Treatments were applied to the same plots for both years of the study.

For treatments with cores removed, cores were swept into the middle of the plot using a stiff shop broom then collected using a flat-head shovel and discarded. In treatments with cores re-incorporated, cores were allowed to dry on the soil surface and then crumbled to reincorporate back into the soil profile using a shop broom in several directions until cores disintegrated into aerification holes. The design was a randomized complete block with 4 replications and a 2 × 2 factorial treatment arrangement.

2.2 Variables Measureds

2.2.1 Turfgrass quality

Visual turfgrass quality (TQ) ratings were based on color, shoot density, and uniformity of stand using a scale of 1 to 9 with 1 representing dead turf and 9 representing dark green, dense turf. Visual TQ was evaluated monthly from May to October during each year.

2.2.2 Bulk density

Soil BD was measured 15 d after the final treatment by removing a 154.4 cm3 soil core between 2 and 8 cm below the turf surface from each plot using an A-145 Soil Core Sampler (ELE International, Lake Bluff, IL). Cores were dried in a forced air oven for 48 h at 105ºC, then weighed (g). Bulk density (g cm^{-3}) was determined by dividing dry soil core mass by total soil core volume.

2.2.3 Surface hardness

Surface hardness was assessed 14 d after each aerification event using a Clegg impact soil tester (Lafayette Instrument Co., Lafayette, IN) where a 2.25 kg weight was dropped from a height of 45 cm. Upon impact with the ground, the tester measured deceleration of the weight, or Clegg impact value (CIV), to indicate a relative surface hardness value. The CIVs were multiplied by 10 to convert to gmax (peak deceleration in gravities). Measurements were made 2 d following irrigation to ensure uniform soil moisture content. Two readings were taken per plot during each assessment and averaged before statistical analysis.

2.2.4 Infiltration rate

Infiltration rate was measured using a double ring infiltrometer (IN5-W, Turf-Tec International, Tallahassee, FL) with an outer ring diameter of 30.5 cm, and inner ring diameter of 15.2 cm. Measurements were taken 15d (+5 d) after the final treatment and 2 d following irrigation to ensure uniform soil moisture. Rings were randomly placed within each plot and inserted 2 cm below soil surface. Water was added in both rings to the top of the infiltrometer. Infiltration (cm h-1) was calculated as the drop in water level after 10 min from an initial height of 8 cm in the inner ring and converted to cm hr-1.

Table 1. Treatment list comparing deep (17.8 cm) and shallow (7.6 cm) hollow tine core aerification with cores removed or incorporated. Treatments were applied either 1, 2, or 4X per year in Clemson, South Carolina

Aerification depth	Cores removed	Aerification timing
cm		
17.8	yes	June
17.8	no	June
17.8	yes	June & Sept.
17.8	no	June & Sept.
17.8	yes	June, July, August, & Sept.
17.8	no	June, July, August, & Sept.
7.6	yes	June
7.6	no	June
7.6	yes	June & Sept.
7.6	no	June & Sept.
7.6	yes	June, July, August, & Sept.
7.6	no	June, July, August, & Sept.

2.3 Statistical Analysis

All data were analyzed using ANOVA to test for overall treatment effects and interactions, and Fisher's protected LSD to test for specific differences among pairs of treatment levels. Analyses focused on the effects of aerification depth and aerification frequency, and interactions of these on parameters measured. All tests were performed at a significance level of 0.10. This level was chosen to avoid type II errors that could occur due to the inherent variability of soil measurements [5]. The General Linear Model procedure of SAS [6] was used for all calculations.

3. RESULTS AND DISCUSSION

Treatment effects of core aeration depth, frequency, and core removal or incorporation varied between measured parameters and years (Table 2). Because of main effect-by-year interaction, main effects will be discussed for each parameter, separated by year, and further interaction effects discussed where appropriate.

3.1 Turf Quality

A certain degree of disruption to TQ should be expected to improve soil physical properties through core aeration. Frequent core aeration may reduce the amount of time a field is in acceptable playing condition, often during periods of heavy use. Minimizing surface disruption is an important consideration when developing a balanced, effective core aeration program.

Much of the previous research evaluating core aeration programs was conducted on turfgrass stands maintained at <0.66 cm (0.25 in) mowing height [3,7-10] Typically at lower mowing heights, reducing the number of core aerations per growing season limits thinning of turf cover and subsequent healing period necessary to return to pre-core removal turfgrass density [7]. The taller mowing height in this study (2.65 cm) helped mask any reduction in turfgrass density following core aeration. Variation between experiments in turfgrass stands of similar mowing height may be attributed in part to differences in turfgrass cultivar, soil fertility, water, or light availability, among other differences in environmental conditions effecting speed of recovery, turfgrass color, and density.

In this study, TQ values do not necessarily reflect TQ at the end of the experiment; rather, they reflect mean TQ across the experiment duration. In year one, significant treatment effects ($P < 0.05$) were limited to treatments core aerated 4 times per year (Table 3). In these treatments, deep tine core aeration improved TQ 4.7% compared to shallow tine core aeration. Additional variance in TQ values could not be attributed to other treatment effects (Table 2).

In year two, TQ was 2-3% higher in treatments aerified once yearly compared to treatments aerified 2 or 4 times yearly and the untreated

Table 2. Analysis of variance among aerification depth (17.8 vs. 7.6 cm), core removal, and aerification events (0, 1, 2 or 4X), on turfgrass quality and soil physical properties in Clemson, SC

Source	df	Year 1				Year 2			
		Turfgrass quality	Bulk density	Surface hardness	Infiltration	Turfgrass quality	Bulk density	Surface hardness	Infiltration
Depth (D)	1	ns†	*	*	*	ns	ns	*	ns
Cores Removed (CR)	1	ns	*	ns	*	ns	*	*	*
Aerification Events (AE)	3	ns	*	ns	*	*	*	*	*
D x CR	1	ns	*	*	ns	ns	*	*	*
D x AE	3	*	*	ns	*	*	ns	*	ns
CR x AE	3	ns	*	*	ns	ns	*	*	*
D x CR x AE	3	*	*	*	ns	*	*	*	ns

**Significance at α = 0.10 level, † ns, not significant*

(Table 4). Frequent removal of turf cover through core aerification can result in an overall decrease in season-long TQ if turfgrass density is a consideration in this measurement [7]. Treatment effects of aerification depth and core removal or incorporation were not significant in year two (Table 2).

In previous research, the overall effect of core aeration on turfgrass quality has been inconsistent. Turf quality improved from core aeration in some studies [3,11-13] and declined in others [14,15]. Numerous factors are responsible for the overall effect of core aeration on turfgrass quality. Site history and soil type determine the amount of aerification necessary while turf cultivar, fertilization, irrigation, and other cultural practices determine speed of recovery after core aeration. Short-term studies may not fully capture long-term effects of core aeration on turfgrass quality. Depending on existing conditions, multiple years of a consistent soil aerification program may be necessary before appreciable improvements to turfgrass quality will be attained. Additional evaluations of long-term core aeration programs are necessary to separate the short-term effects of core aeration on turfgrass density from the long-term impact of core aeration on overall plant health.

3.2 Bulk Density

In a compacted soil with high bulk density, gas exchange and water holding capacity are low, water binds tightly to micro pores and the resistance roots face to growth is increased which discourages rhizosphere development for more efficient utilization of soil available water and nutrients [1]. In a clay to clay-loam soil, a bulk density value of 1.0 to 1.6 g cm^{-3} is recommended to balance water retention with drainage and soil gas exchange [16]. Core aeration aims to reduce bulk density of compacted soil by reducing the amount of soil mass per given soil volume.

Table 3. Turfgrass quality, soil bulk density, surface hardness, and infiltration responses to deep tine (17.8 x 1.6 cm) and shallow tine (7.6 x 1.3 cm) aerification in all plots receiving four aerifications yearly in Clemson, SC

Aerification depth	Year1				Year2			
	Turfgrass quality†	Soil bulk density	Surface hardness	Infiltration	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration
cm	1 - 9	g cm^{-3}	g_{max}‡	mm hr^{-1}	1 - 9	g cm^{-3}	g_{max}	mm hr^{-1}
17.8	7.02a§	1.16b	79.24a	21.75a	6.82a	1.24a	95.39c	14.25a
7.6	6.70b	1.27a	81.49a	21.75a	6.89a	1.25a	100.24a	17.25a
Nontreated	6.79ab	1.28a	79.29a	14.81b	6.88a	1.28a	98.82b	17.63a
p-value	0.06	0.05§	<0.01	1.00	0.61	0.55	<0.01	0.37
LSD (0.1)	0.28	0.09	2.35	5.79	0.23	0.05	0.21	5.56

†Visual turfgrass quality ratings were based on a scale of 1 to 9 where 1 = brown dead turfgrass and 9 = green healthy turfgrass, ‡Relative surface hardness value quantifies deceleration of 2.25 kg weight dropped from height of 45 cm, §Means followed by the same letter within a column are not significantly different at the 0.10 significant level

Table 4. Turfgrass quality, soil bulk density, surface hardness, and infiltration responses to one, two, or four core aeration events per year in Clemson, SC

Aerification event yr^{-1}	Year 1				Year 2			
	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration
	1 - 9†	g cm^{-3}	g_{max}‡	mm hr^{-1}	1 - 9	g cm^{-3}	g_{max}	mm hr^{-1}
0	6.79a	1.28a§	79.29a	14.81a	6.88ab	1.28a	98.82ab	9.88a
1	6.91a	1.23ab	79.68a	17.25a	7.02a	1.29a	98.29b	9.83a
2	6.96a	1.24ab	79.60a	16.69a	6.80b	1.27ab	100.09a	10.01a
4	6.86a	1.21b	79.29a	14.81a	6.86b	1.25b	97.87b	9.78a
p-value	0.75	0.74	0.14	0.02	0.14	0.14	0.07	0.35a
LSD (0.1)	0.25	0.06	2.35	3.74	0.16	0.03	0.15	3.75

†Visual turfgrass quality ratings were based on a scale of 1 to 9 where 1 = brown dead turfgrass and 9 = green healthy turfgrass, ‡Relative surface hardness value quantifies deceleration of 2.25 kg weight dropped from height of 45 cm, § Means followed by the same letter within a column are not significantly different at the 0.10 significant level

Bulk density values are often inconsistent from year-to-year as a reflection of changing levels of traffic, cultivation, and soil moisture content throughout the year. Also for these reasons, treatment effects in this study were inconsistent between years (Table 2). In year one, deep tine core aeration reduced BD ~5% compared to the untreated and shallow tine core aeration (1.28 and 1.26 to 1.20 g cm^{-3}, respectively). Deep tine core aeration did not further reduce BD in year two; however, BD remained below pre-study levels. Shallow tine core aeration did not affect BD compared to the untreated in either year (Table 5).

Within treatments, removal or incorporation of cores back into the soil profile after core aeration did not affect BD in year one. In year two, core removal reduced bulk density 5% from 1.33 to 1.26 g cm^{-3} compared to incorporating cores back into the soil profile (Table 6). Although incorporation of soil back into the profile following core aeration does not drastically reduce the amount of soil mass per given soil volume per se, re-incorporated soil is likely loosely packed and a portion of removed soil will invariably remain on the soil surface. The additional reduction in soil mass by core removal following core aeration may not be sufficient to consistently reduce bulk density compared to reincorporating loosely packed soil material into core aeration holes.

Treatment effects were more consistent when analyzed by number of core aerations performed per year. Treatments with four core aerifications per year lowered bulk density 5% compared to the untreated in year one from 1.28 to 1.21 g cm^{-3} and 2% in year two from 1.28 to 1.25 g cm^{-3} (Table 4). Multiple core aerations have been necessary to reduce bulk density relative to the untreated in similar studies [7,10]. Only performing one core aeration within a year may not disrupt a large enough percentage of total soil volume to impact BD. Calculated at a soil depth of 17.8 cm, deep tine core aeration (17.8 cm) impacted 8% of total soil volume and shallow tine core aeration (7.6 cm) impacted only 2% of total soil volume. Impacting a higher percentage of total soil volume through multiple core aerations may be necessary to significantly affect soil bulk density, especially in dense clay-based soils.

Table 5. Turfgrass quality, soil bulk density, surface hardness, and infiltration responses to deep tine (17.8 x 1.6 cm) and shallow tine (7.6 x 1.3 cm) aerification in Clemson, SC

Aerification depth	Year 1				Year 2			
	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration
cm	1 - 9†	g cm^{-3}	g_{max}‡	mm hr^{-1}	1 - 9	g cm^{-3}	g_{max}	mm hr^{-1}
17.8	6.92a	1.20b‡	77.50b	19.13a	6.83a	1.27a	97.06c	15.25a
7.6	6.89a	1.26a	80.34a	18.00ab	6.96a	1.27a	100.04a	15.88a
Nontreated	6.79a	1.28a	79.29ab	14.81b	6.88a	1.28a	98.82b	17.63a
p-value	0.76	0.08§	<0.01	0.12	0.25	0.7	<0.01	0.51
LSD (0.1)	0.25	0.05	2.35	3.36	0.14	0.03	0.13	3.32

†Visual turfgrass quality ratings were based on a scale of 1 to 9 where 1 = brown dead turfgrass and 9 = green healthy turfgrass, ‡Relative surface hardness value quantifies deceleration of 2.25 kg weight dropped from height of 45 cm, § Means followed by the same letter within a column are not significantly different at the 0.10 significant level

Table 6. Turfgrass quality, soil bulk density, surface hardness and infiltration response to removing or reincorporating cores removed during core aeration in Clemson, SC

Cores removed	Year 1				Year 2			
	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration
	1 - 9†	g cm^{-3}	g_{max}‡	mm hr^{-1}	1 - 9	g cm^{-3}	g_{max}	mm hr^{-1}
Nontreated	6.79a	1.28a‡	79.29a	14.81b	6.89a	1.29ab	98.82b	17.25a
No	6.92a	1.23b	79.19a	17.25ab	7.00a	1.33a	100.08a	11.25b
Yes	6.89a	1.23b	78.65a	19.88a	7.04a	1.26c	96.50c	16.50a
p-value	0.76	0.79§	0.82	0.05	0.77	0.04	<0.01	0.07
LSD (0.1)	0.25	0.05	2.38	3.34	0.2	0.06	0.2	4.68

†Visual turfgrass quality ratings were based on a scale of 1 to 9 where 1 = brown dead turfgrass and 9 = green healthy turfgrass, ‡Relative surface hardness value quantifies deceleration of 2.25 kg weight dropped from height of 45 cm, § Means followed by the same letter within a column are not significantly different at the 0.10 significant level

3.3 Surface Hardness

Clegg impact values (CIV) are a surface barometer of soil strength. A firm surface will slow water infiltration and effect playability and user safety by reducing the amount of surface cushioning. The degree of surface hardness is a cumulative effect of soil texture, density, and moisture level, among other factors.

In this study, deep tine core aeration reduced surface hardness 3% compared to shallow tine core aeration; however, no treatment effects were significant compared to the untreated in year one (Table 5). By year two, deep tine core aeration reduced surface hardness 2% compared to the untreated and shallow tine core aeration increased surface hardness 2% compared to the untreated (Table 5). In heavier soils, core aeration has the potential to increase soil strength in the region directly adjacent to the coring hole [4]. Shallow tine core aeration may have produced too little mechanical fracture within the soil profile to overcome any localized increase in soil strength.

Core removal or incorporation did not affect surface hardness in year one; however, in year two core removal reduced surface hardness 4% compared to plots with cores reincorporated (Table 6). In plots core aerated once per year, core removal reduced surface hardness 5% and 4% in year one and two, respectively (Table 7).

The number of core aerations performed per year did not drastically affect surface hardness (Table 4), although previous research has shown surface hardness to be reduced by increasing number of core aeration events [7]. The limited effect of core aeration frequency and other main effects in this study may be related to soil type. In general, surface hardness has decreased in response to core aeration, although the majority of these studies were conducted on sand-based golf course putting greens with inherently less soil strength than clay-based soils [3,7,8,10,17]. The structural integrity of clay-based soil is likely too great to induce a rapid change in surface hardness in response to a single season of core aeration. A consistent, long-term core aeration program may be necessary to realize effects of core aeration on surface hardness in clay-based soils.

3.4 Infiltration Rate

In clay-based soils, water availability is dependent on adequate surface water infiltration after an irrigation or rainfall event to prevent excessive water loss through surface runoff. Clay soil particles can form a tight matrix at the soil surface that prevents water infiltration, especially in compacted soils. Disruption of this matrix through core aeration aims to lower the tortuosity water must overcome at the soil surface by creating channels for water to quickly infiltrate into the soil profile.

Infiltration speed increased an average of 29% after deep tine core aeration and 34% if cores were removed compared to the untreated in year one (Tables 5 and 6). In year two, treatment effects were less pronounced. Incorporation of cores back into the soil profile after core aeration slowed infiltration speed 35% compared to the untreated. Further treatment effects were not significant (Table 2).

The limited effect of core aeration on surface infiltration in this study may be related to soil texture. In sand based systems, surface water infiltration has typically increased following core aeration [7,8,17]. Although core aeration

Table 7. Turfgrass quality, soil bulk density, surface hardness and infiltration response to removing or reincorporating cores removed during core aeration in treatments receiving on core aerification yearly in Clemson, SC

Cores removed	Year1				Year2			
	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration	Turfgrass quality	Soil bulk density	Surface hardness	Infiltration
	1 - 9†	g cm^{-3}	g_{max}‡	mm hr^{-1}	1 - 9	g cm^{-3}	g_{max}	mm hr^{-1}
No	6.91a	1.25a‡	81.54a	16.88a	7.00a	1.33a	100.08a	11.25b
Yes	6.91a	1.22a	77.82c	17.63a	7.04a	1.26b	96.50b	16.50a
p-value	1	0.71§	0.02	0.84	0.77	0.04	<0.01	0.07
LSD (0.1)	0.25	0.12	2.70	6.07	0.20	0.06	0.20	4.68

†Visual turfgrass quality ratings were based on a scale of 1 to 9 where 1 = brown dead turfgrass and 9 = green healthy turfgrass, ‡Relative surface hardness value quantifies deceleration of 2.25 kg weight dropped from height of 45 cm, § Means followed by the same letter within a column are not significantly different at the 0.10 significant level

opens large channels to facilitate movement of water through the soil surface, clay-based soils are likely more sensitive to disruptions in soil structure than sand based systems. Soil fracture and motion from core aeration tines smearing soil particles along the inside of core aeration holes may prevent water from reaching existing channels within the soil structure that facilitate water movement through the soil profile, effectively slowing water infiltration.

The data produced by this study suggests deep tine core aeration and core removal following aeration may be necessary to improve surface water infiltration in heavy soils. Shallow tine core aeration may not penetrate the soil to an adequate depth to encourage movement of water past the uppermost compacted horizon to less compacted horizons. Further, core removal decreases the tortuosity water encounters in newly formed channels while core reincorporation introduces pockets of unstructured soil which may resist water movement.

Continued core aeration of heavier soils at a consistent depth may further slow surface water infiltration as compacted pockets accumulate at the lower end of the aerification zone, influencing the speed at which water can infiltrate [3]. Formation of a compaction zone was not observed in this study; however, long term evaluation of core aeration programs could further the understanding of this effect.

4. CONCLUSION

Although the data presented here does not reflect a drastic nor immediate response in plant health or soil physical properties after a short-term core aeration program, it is overall supportive of an aerification program that utilizes frequent core aeration to improve soil physical properties in heavily compacted, clay-based soils.

Improvements to soil physical properties after core aeration are often short-lived and require regular aerification to maintain high quality turf. A perpetual core aeration program is recommended to provide sustainable improvements to both TQ and soil physical properties over several growing seasons. In addition, knowledge of the particular soil system under aerification will aid in determining the correct course of action for improvement of soil physical properties.

Most soil aerification studies, including this study, are limited in scope by study duration. Continuing research is needed to fully appreciate the effect of long-term soil aerification programs on soil physical properties and overall plant health, especially as new equipment and technology emerge.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. O'Neil KJ, Carrow RN. Perennial ryegrass growth, water use, and soil aeration status under soil compaction. Agron J. 1983;75: 177-180.
2. Swartz WE, Kardos LT. Effects of compaction on physical properties of sand-soil-peat mixtures at various moisture contents. Agron J. 1963;55:7-10.
3. Murphy JA, Rieke PE, Erickson AE. Core cultivation of a putting green with hollow and solid tines. Agron J. 1993;85:1-9.
4. Petrovic AM. The effects of vertical operating hollow tine (VOHT) cultivation on turfgrass soil structure. Ph.D. diss., Michigan State Univ., East Lansing; 1979.
5. Weicko G, Carrow RN, Karnock KJ. Turfgrass cultivation methods: Influence on soil physical, root/shoot and water relationships. Int Turf Soc Res J. 1993;7: 451-457.
6. SAS Institute. Users guide: Statistics. SAS Inst., Cary, NC; 2004.
7. Atkinson JL, McCarty LB, Bridges WC. Effect of core aerification frequency, area impacted, and topdressing rate on turf quality and soil physical properties. Agron J. 2012;104:1710-1715.
8. Bunnell BT, McCarty LB, Hill HS. Summer cultivation effects on a sand based creeping bentgrass golf green. Int Turf Res J. 2001;9:3-9.
9. Murphy JA, Rieke PE. Comparing hollow and solid-tine cultivation. USGA Green Section Record. 1990;28:7-10.
10. Murphy JA, Rieke PE. High-pressure water injection and core cultivation of a compacted putting green. Agron J. 1994; 86:719-724.
11. Carrow RN, Johnson BJ, Burns RE. Thatch and quality of tifway bermudagrass turf in relation to fertility and cultivation. Agron J. 1987;79:524-530.

12. McWhirter EL, Ward CY. Effect of vertical mowing and cultivation on golf green quality. Rep. 2. Mississippi Agric. For. Exp. Stn. Starkville, Mississippi; 1976.
13. Murray JJ, Juska FV. Effect of management-practices on thatch accumulation, turf quality, and leaf spot damage in common Kentucky bluegrass. Agron J. 1977;69:365-369.
14. Cooper RJ, Skogley CR. An evaluation of several topdressing programs for Agrostis palustris huds. and *Agrostis canina* L. putting green turf. In R.W. Sheard, editor, Proceedings of the 4th International Turfgrass Research Conference, Guelph, Ontario. 198;129-136.
15. Weston JW, Dunn JH. Thatch and quality of meyer zoysia in response to mechanical cultivation and nitrogen fertilization. In F. Lemaire, editor, Proceedings of the 5th International Turfgrass Conference, Avignon, France. 1985;449-457.
16. McCarty LB. 2011. Best golf course management practices. 3rd ed. Upper Saddle River, New Jersey: Pearson Education, Inc; 2011.
17. McCarty LB, Gregg MF, Toler JE. Thatch and mat management in an established creeping bentgrass golf green. Agron J. 2007;99:1530-1537.

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