ABSTRACT

GOODMAN, HAROLD DAVID. Organic Matter Accumulation Beneath Maintained Turfgrass Systems. (Under the direction of Dr. Thomas W. Rufty.)

The first objective focused on excessive organic matter (OM) accumulation in creeping bentgrass (*Agrostis stolonifera* L.) putting greens, which is one of the more important problems in golf course management. Detrimental effects of OM accumulation are particularly acute in the transition zone in the southeastern U.S. In this study, temporal and spatial aspects of OM accumulation that are keys for understanding the bentgrass system were investigated. Root zone samples were collected from 49 golf course greens of different ages. The analyses indicated that (OM) accumulated very rapidly in the top 2.54 cm, typically exceeding critical levels of 40 g kg^{-1} within five years. Accumulation over time was best described by a hyperbolic curve, with rates declining to minimal levels within 15 to 20 years. Accumulation at a depth of 2.54 to 7.68 cm was much slower and linear over time, and critical levels were not reached even after 20 years. In field studies on bentgrass plots exposed to different nitrogen treatments, higher nitrogen fertilization led to more rapid OM accumulation, especially near the soil surface. Hyperbolic OM accumulation suggests that the relationship between below-ground bentgrass growth and soil microbial activity changes with time as greens age, although no mechanistic explanation is available. Rapid accumulation in early years after establishment indicates that it may be unrealistic to expect that OM accumulation can be controlled entirely, but it is clearly essential to intensively manage the system and maintain gas exchange into the rhizosphere throughout the life of a bentgrass putting green. Correct sampling for organic matter levels should be focused near the top of the soil profile.

In the second study, we examine the extent that C can be accumulated in soil beneath turfgrass systems. Since substantial evidence indicates that increases in world temperatures are being driven by accumulation of ‘greenhouse’ gases in the earth’s atmosphere, the most important of which is carbon dioxide (CO_2), the need to limit or reduce CO_2 emissions of has become the most important. It has also been proposed that release of CO_2 could be offset by carbon (C) sequestration in long-term storage pools. Recent literature suggests this might be the case, but only one data set has been published and it was from work done in Colorado. For this study, samples were taken from bermudagrass (*Cynodon* spp.) fairways on 59 golf courses of

varying ages North and South Carolina. The samples were analyzed initially using the ashing method. After a series of tests, it was discovered that the ashing method did not accurately measure soil C levels in clay soils, but did closely predict C in sandy soils. Accumulation over the first 20 years is about 31.0 Mg ha^{-1} or 1,400 lbs per acre in sandy soils and about 17.5 Mg ha^{-1} or 780 lbs per acre in clay soils. The potential C sequestration beneath turfgrasses in the Southeast raises the possibility of substantial carbon credits for the turfgrass industry in this region.

Lastly, in a series of hydroponic experiments, we study how four bentgrass cultivars respond to nitrogen (N) fertility. These experiments clearly show that there is a 'range' in N fertilization where shoot growth responds with minimal effects on root growth. It is not possible to relate exact concentrations in solution with fertilization rates in the field, but it is logical to think the target 'range', which was about 0.6 mM in our treatments, is similar to that being used with the frequent applications or 'spoon feeding' in the field. If fertilization is kept within a 'target window' like that identified in these experiments (0.6 mM), the possibility for negative environmental leaching effects is minimized.

Organic Matter Accumulation Beneath Maintained Turfgrass Systems

by
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BIOGRAPHY

David Goodman was born in Salisbury, North Carolina on March 26, 1976. He graduated from Salisbury High School in 1994 and then chose to attend Appalachian State University. During his four years at ASU he maintained a golf scholarship on the men's golf team. He earned MVP honors during his junior year and was named captain of the team during his senior year. After graduating from ASU in December 1998 with a degree in Management, he worked for two years as an assistant golf professional in the mountains of North Carolina. In 2001 he returned to school at North Carolina State University to pursue an Associated of Applied Science in Turfgrass Management and Ornamentals and Landscape Technology degree. He graduated from this program with high honors and began working as a research technician for Dr. Tom Rufty in the Department of Crop Science. After working in the research program for several months he decided to pursue an MS in Crop Science at NCSU. In the summer of 2009 he defended his thesis, and received his Master's degree in Crop Science in December 2009.

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I would not have been able to attain this Master’s degree without the guidance, support, and patience of my major professor, Dr. Tom Rufty, and director of research in NCSU’s plant physiology research program, Dr. Danesha Seth-Carley. I am also grateful to the other members of my Thesis Committee, Lane Tredway, Charles Peacock, and Fred Yelverton for their input and guidance. It should also be noted that this research project would not have been possible without the cooperation and support from many golf course superintendents who are members of the Carolinas Golf Course Superintendents Association of America section.

Lastly, and most importantly, I would like to thank my parents and family for their unconditional love, support, and guidance they have provided over the years.

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CHAPTER 1

Organic Matter Accumulation in Bentgrass Greens: A Chronosequence with Management Implications

ABSTRACT

Excessive organic matter accumulation in creeping bentgrass (*Agrostis stolonifera* L.) putting greens is one of the more important problems in golf course management. Detrimental effects of organic matter accumulation are particularly acute in the transition zone in the southeastern U.S. where ‘summer bentgrass decline’ is common. In this study, temporal and spatial aspects of organic matter accumulation that are keys for understanding the bentgrass system were investigated. Root zone samples were collected from 50 golf course greens of different ages. The analyses indicated that organic matter accumulated very rapidly in the top 2.54 cm, typically exceeding critical levels of 40 g kg^{-1} within five years. Accumulation over time was best described by a hyperbolic curve, with rates declining to minimal levels within 15 to 20 years. Accumulation at a depth of 2.54 to 7.68 cm was much slower and linear over time, and critical levels were not reached even after 20 years. In bentgrass plots exposed to different nitrogen treatments, higher nitrogen fertilization led to more rapid organic matter accumulation, especially near the soil surface. Surprisingly, there was no indication that the organic matter accumulation restricted gas exchange into the root zone, as rhizosphere oxygen levels were relatively stable. The results have a number of implications for the field. Hyperbolic organic matter accumulation suggests that the relationship between below-ground bentgrass growth and soil microbial activity changes with time as greens age, although no mechanistic explanation is available. Rapid accumulation in early years after establishment indicates that it may be unrealistic to expect that organic matter accumulation can be controlled entirely, but it is clearly essential to intensively manage

the system and maintain gas exchange into the rhizosphere throughout the life of a bentgrass putting green. Correct sampling for organic matter levels should be focused near the top of the soil profile.

INTRODUCTION

One of the biggest problems in turfgrass management on golf courses is the accumulation of excessive amounts of organic matter on creeping bentgrass (*Agrostis stolonifera* L.) putting greens. The aggressive lateral growth of bentgrass produces a dense, even surface and allows rapid closure of gaps after surface disruptions. The same growth properties, however, lead to the build-up of soil organic matter. An elaborate group of management techniques has been developed for controlling organic matter. It is common for bentgrass putting greens to be core and solid tine aerated, top-dressed, and verticut on regular schedules each year (O’Brien and Hartwiger, 2003; McCarty et al., 2005; Landreth et al., 2008). The management intensity, of course, comes with large financial costs.

A the present time, the dominant view emerging from USGA Green Section research is that the critical level for organic matter accumulation is in the range of 35 to 40 g kg^{-1} of soil (Carrow, 2003; 2004). Once accumulation reaches the critical range, soil macropores become obstructed, restricting drainage and air exchange in the root zone. The evidence cited for the critical range primarily comes from the work of Murphy et al. (1993) in New Zealand.

Detrimental effects of organic matter accumulation appear to be relatively severe in the transition zone in the southeastern U.S. Macropore obstructions can be accompanied by chemical transformations in the high heat of summer, which results in ‘sealing’ of pore spaces near the soil surface and an increased likelihood of restricted gas exchange into the root zone (Carrow, 2003). These negative effects from organic matter, together with those from direct heat stress on bentgrass biochemistry (Huang et al., 1998) and increased fungal disease infestations (Dernoeden, 2002), lead to decreasing bentgrass health, i.e. ‘summer bentgrass decline’ (Carrow, 1996).

Despite its importance in the bentgrass system, many aspects of organic matter accumulation are not well understood. In this study examined organic matter accumulation and its underlying processes *in situ*. This was to answer the following two basic questions: 1) What is the rate of organic matter accumulation in the soil profile beneath bentgrass greens as they age? 2) Is there evidence that accumulation of organic matter above critical levels is causing detrimental effects on root zone gas exchange and bentgrass health?

Research of this type is inherently difficult because organic matter accumulation is time dependent, and there is considerable variation in the field. Our approach was to collect root zone samples from 50 golf courses of different ages and from young, managed field plots, which allowed development of a chronosequence describing organic matter accumulation over time. We were particularly interested in the possibility of changes in accumulation rate, as accumulation reflects interactions between plant growth below ground and soil microbial activity that transform and degrade plant tissues. Organic matter accumulation profiles could provide insights into shifts in the two processes and whether they are linked to the potential for root zone permeability problems.

MATERIALS AND METHODS

Samples were collected from putting greens of 50 golf courses in North Carolina (Table 1-1). The sampling was done primarily in summer and fall in 2005 and 2006. The golf courses were selected for geographical and age diversity. They were located throughout the state, in mountain, piedmont, and coastal regions. Green ages ranged from less than one to 39 years old (Appendix Table 1.1). The great majority of the greens had been built according to USGA specifications. The bentgrass cultivars included ‘A-1’, ‘A-4’, ‘L-93’, ‘G-2’, ‘G-6’, ‘Penncross’, ‘Crenshaw’, and ‘Cato’, as well as various blends of these cultivars.

In general, soil samples were taken from putting greens that had been chosen randomly on each course. Greens identified by the golf course superintendent as ‘abnormal’ for the golf course, e.g. those with too much shading or low air circulation, were excluded from the selection process. Sampling was always delayed until at least four weeks after major core aeration events, and if core holes could be identified, samples were taken from spaces between core holes. Samples were removed from a minimum of four greens at each golf course, two on the first nine holes and two on the back nine. Sampling involved removal of four soil cores from designated quadrants on each green using a one inch diameter soil probe (Oakfield Apparatus Co., Oakfield, WI). The intact cores were placed on a cutting board and shoot tissues and verdure removed with a knife at the soil surface. The remaining soil material was separated into the top 2.54 cm and 2.54 – 7.68 cm from the soil surface, and placed into separate plastic bags. The four samples from each green were combined. With courses where organic matter levels were examined at greater depths, sections were dissected and saved separately.

Soil organic matter was determined by the combustion method (Storer, 1984). The samples were thoroughly homogenized and dried at 105 °C until samples maintained a constant weight. Samples were then transferred to a muffle furnace (Thermolyne, Dubuque, IA) and ashed for 12 hrs at 500 °C. Percent soil organic matter was then calculated as (soil dry mass – soil mass after ashing) / (soil dry mass).

Soil oxygen and carbon dioxide were measured on 14 of the golf courses, selected for different ages. Measurements occurred at the same time as soil sampling. The gases were measured using a soil gas analyzer (RKI Industries, Hayward, CA). The analyzer probe was inserted to a depth of 7.62 cm. Because the golf courses were located at different elevations above sea level, it was necessary to measure ambient gas content in the above ground atmosphere before the sensing probe was inserted into the soil. Oxygen data are reported in the Results as the decline in content relative to ambient values. Saturated hydraulic conductivity was measured using a single walled metal lysimeter measuring 27.40 cm in diameter inserted to a depth of 7.62 cm. Water was poured into the lysimeter and allowed to saturate the soil for at least 10 minutes. Then the lysimeter was re-filled with water and the rate of downward water movement determined.

Once soil organic matter had been measured at the 50 courses, putting greens at eight of the courses were sampled in greater detail to define organic matter changes with depth in the soil profile. In these cases, soil cores were divided into 0 to 2.54 cm, 2.54 to 5.08 cm, 5.08 to 7.62 cm, 7.62 to 10.16 cm, and 10.16 to 15.24 cm sections from the soil surface. The organic matter in each section was determined using methods described above.

Organic Matter Accumulation in Managed Field Plots

In a separate experiment, on soil organic matter accumulation was examined over a two year period from 2005 to 2007. The plots were treated with different levels of nitrogen fertility to alter plant growth rates and, potentially, the rate of organic matter buildup. The experiment was conducted in field plots established on a two year old research green planted with ‘Penn A-1’ creeping bentgrass at the Turfgrass Research Laboratory at N.C. State University. The green was constructed to USGA specifications, with a root-zone mix consisting of a 90 sand:10 peat (volume:volume) mixture. The bentgrass was maintained at a height of cut ranging from 0.30 – 0.46 cm, with greater height implemented during environmentally stressful periods in summer. Irrigation was provided throughout the study as needed. Herbicides, fungicides, and insecticides were applied regularly for preventative and curative control of weeds, fungal pathogens and insects.

The research plots were arranged in a randomized complete block, strip split-plot design with four replicates. Each 22.3 m^2 block consisted of two levels of a main plot factor (topdressing versus no topdressing) applied in 11.2 m^2 strips, and four levels of a subplot factor (annual N application rates of 0, 1.81, 2.27, 2.84 kg N 92.9 m^2 yr^{-1}) randomly arranged within each main plot. Each of the eight subplots within a block measured 2.8 m^2. Topdressing sand was applied with a drop spreader (Gandy, Owatonna, MN) every 2-3 weeks from March through November at a rate of 5.38 m^3 ha^{-1}(based on USGA recommendations). Following application, a push broom was used to incorporate the topdressing sand into the turf canopy.

Fertility treatments were applied to plots as a liquid fertilizer on a bi-weekly basis from June through September using a 20-20-20 fertilizer and a backpack sprayer (Pro-spray, Cleveland, OH). A granular 15-15-15 IBDU was applied in October, November, February, March, and April using a hand-held shaker. A 55.9 cm (22”) walk behind greens mower (Deere and Company, Moline, IL) was used to periodically collect clippings from each plot. Clippings were oven dried and dry weights recorded. Clippings were then ground using a Geno Grinder (SPEX Certiprep, Metuchen, NJ) and analyzed for percent N using an automated N analyzer (Thermo Finnigan, Waltham, MA). Soil samples were taken seasonally over the two year experiment and analyzed for organic matter using the methods described previously.

RESULTS

Data from field samples like these are inherently variable. Different golf course superintendents use different management strategies, and strategies may be changed from year to year depending on the weather and new products entering the market. Moreover, we found that record keeping was rarely in place for extended time periods, so it was not possible to trace reliable management histories. Nonetheless, using samples from the large number of courses, a pattern of organic matter accumulation over time was clearly discernable.

The golf courses included in this study are generally well managed and intensive management is used on bentgrass putting greens (Table 1.1; Appendix Table 1.1). At the time of sampling, the quality of all bentgrass greens was judged to be acceptable.

The analyses indicated that organic matter accumulation was very different near the soil surface (0 – 2.54 cm) from that just below it (2.54 – 7.68 cm) (Fig. 1.1; Appendix Fig. 1.1a). Accumulation was much faster near the surface and best described by a hyperbolic equation (Fig. 1.1a; $p \leq 0.001$). Levels of 40 to 50 g kg^{-1} were reached within about five years. As greens aged beyond five years, the variability became greater; some courses were controlling organic matter well while others were not. From the hyperbolic model, it can be estimated that rate of organic matter accumulation declined over time. The rate during the first five years was 8.8 g kg^{-1} yr^{-1}, during the five to 10 year period 2.2 g kg^{-1}, during 10 to 15 years 1.6 g kg^{-1}, and it was down to 0.6 g kg^{-1} during years 15 to 20 (data not shown).

The kinetics of organic matter accumulation were different at the 2.54 to 7.68 cm depth. Accumulation occurred more slowly and increased linearly over time (Fig. 1.1b; $p \leq 0.001$; Appendix Fig. 1.1b). At five years levels were just over 10 g kg^{-1} and they were still below 40 g kg^{-1} in greens that were greater than 20 years old. The rate of increase was about 0.98 g kg^{-1} yr^{-1}.

At 14 of the courses (56 total putting greens), selected for a range of different ages, and root-zone oxygen and carbon dioxide were measured at the time of soil sampling. No statistical differences or consistent patterns of change could be detected among the courses with any of the parameters. The mean oxygen differential between ambient air and the root zone was 1.31 +/- 0.1 mg l^{-1} and the mean carbon dioxide concentration was 1.2 +/- 0.1 mg l^{-1}. Plots are included in the Appendix (Figs. 1.2 and 1.3).

After the initial survey was completed, eight courses were selected for more detailed examination of changes in soil organic matter with depth in the soil profile. The sampling sites represented a range of soil organic matter levels and ages (Table 1.2). Regardless of age, organic matter declined sharply below the soil surface. As shown by the statistical analyses, some elevation was present at the 2.54 to 5.08 cm depth after greens reached three years of age, but no differences could be resolved at greater depths. The lone exception was a decline at the 5.08 to 7.62 cm depth in the greens that were 17 years old. The degree of the decline with depth can be seen in a summary graph with the courses grouped by statistical differences in organic matter levels with depth (Fig. 1.2).

Nitrogen fertility and organic matter accumulation

Creeping bentgrass plots were two years old at the beginning of the fertility treatments in August 2006, and treatment effects were first detected the following spring, eight months later in April 2007. After that time, until the end of the experiment in June 2008, there were no significant statistical differences among sample dates or between plots that were top-dressed and those that were not. Thus, data were pooled and presented as means. Data were analyzed using PROC GLM, and means separation tests were run using Fisher's Protected Least Significant Difference (SAS Systems software, Cary, NC).

Nitrogen fertilization rates had a clear impact on bentgrass growth and organic matter accumulation (Table 1.3). Clipping weights increased more than three-fold as N fertility was increased from 0 to 2.84 kg N m^{-2}, and N in the tissue increased from about 31.9 g kg^{-1} of dry weight to about 41.3 g kg^{-1}. The increases in N fertilization and bentgrass growth were accompanied by distinct increases in organic matter in the top 2.56 cm of the soil profile. The increases were most apparent with treatments up to 2.27 kg m^{-2}, as organic matter increased from 23 to 37 g kg^{-1}. Significant differences in organic matter accumulation could also be seen at a depth of 2.54 to 7.62 cm, even though they were smaller quantitatively.

DISCUSSION

A main purpose of this study was to define the rate of organic matter accumulation within the soil profile beneath bentgrass putting greens. This is the first study in the eastern transition zone which has attempted to characterize organic matter accumulation in detail, even though it has been implicated as a key driver of 'summer bentgrass decline' (Carrow, 2003).

The analyses clearly showed that organic matter accumulated rapidly near the soil surface, where one would expect production of stolons and roots to be greatest. Calculations indicated that levels exceeded 40 g kg^{-1} within five years. A similar rate of accumulation evidently occurred in the fertility study, where levels above 40 g kg^{-1} were reached with higher N fertilization treatments in putting greens that were four years old at the end of the experiment (Table 1.3). The results indicate that a steady progression of organic matter accumulation occurs over time near the soil surface, despite efforts to control it using current management strategies. Importantly, because permeability of a soil column is determined by the soil layer with the most resistance, within five years after establishment, the potential existed for substantial negative effects on below ground root function and health of the bentgrass.

Even through organic matter rapidly accumulated to levels that exceed the apparent ‘critical range’ (Carrow, 2003; 2004), there was no indication of widespread bentgrass green failure on courses that were older than five years. All of the golf courses included in the study are well known in the North Carolina area and bentgrass quality always was judged to be acceptable. Also, a negative relationship between organic matter level and oxygen content in the root zone could not be detected. Furthermore, searching the bentgrass literature for the transition zone, we cannot find examples where build up of organic matter was related to measured low oxygen levels. A study similar to ours in New Zealand by Glasgow et al. (2005) did find that organic matter accumulation to high levels was associated with decreased water infiltration, and by inference, gas exchange. How might the apparent inconsistency between our observations from the transition zone and the ‘critical’ level concept be explained?

The proposition that 35 to 40 g kg^{-1} is a ‘critical’ level for organic matter accumulation appears sound. Examination of soil physical properties where organic matter was added to sand media found that permeability was noticeably decreased when levels approached 4 to 5 g kg^{-1} (Adams, 1986; McCoy, 1992). Experiments in columns with different organic matter contents in soil pinpointed the 35 to 40 g kg^{-1} range (Murphy et al., 1993). While those results show a decline in permeability occurs in the ‘critical’ range, they are much less conclusive about the degree that permeability is impacted at or above the critical point, and whether permeability of water is affected similarly to diffusion of gases.

The uncertainties about organic matter level and gas exchange notwithstanding, a likely explanation for the ability golf courses to sustain bentgrass health in older greens with high organic matter is that main concentration of organic matter is near the soil surface and the golf course superintendents are successfully managing that zone. It is widely accepted that, with the climate in the transition zone, superintendents risk severe damage to bentgrass, particularly in summer, if they do not intensively manage the putting greens. Although it was not possible to document management histories, all of the courses in our study were currently using aeration and top-dressing techniques that facilitate gas exchange through the soil layers near the soil surface and into the root zone. Organic matter accumulating deeper in the soil horizon, even at the relatively shallow 2.54 to 7.68 cm depth, did not appear to be a problem, as the 40 g kg^{-1} range was not approached until about 20 years.

The observation that organic matter accumulation is a problem primarily at the soil surface seems so fundamental; why has it not been shown and emphasized in other studies? Few published experiments have attempted to define organic matter in the soil profile in detail, although a couple have appeared fairly recently. In a survey of golf courses in New Zealand (Glasgow et al., 2005) and work conducted for the Netherlands Golf Federation (cited by Baker, 2008), it was found that organic matter accumulation was greatest near the soil surface and progressively decreased with depth. Similar to our results, those reports also indicated that organic matter accumulated much faster than previously expected in newly constructed greens. As opposed to our results, however, high levels were often associated with poor infiltration. As indicated above, the absence of large changes in infiltration and rhizosphere gas levels in the transition zone likely reflect the extremely aggressive management that minimizes permeability problems.

One of the most interesting aspects of the organic matter accumulation profiles in our study was that the rate of accumulation in the top 2.54 cm steadily decreased with time. A hyperbolic pattern of accumulation should not be surprising. It has been observed previously by others measuring soil organic matter or organic N accumulation in different climates in the U.S. In bentgrass greens in the Colorado area, for example, accumulation was rapid in early years and slowed to minimum rates after about 30 to 40 years (Qian and Follett, 2002). Organic matter accumulation beneath fairways in the same area slowed progressively to minimal net accumulation within 20 to 25 years (Qian and Follett, 2002), and beneath grass systems in New England, organic N accumulated rapidly initially and then slowed to a minimum after about 30 years (Porter et al., 1980; Pertrovic, 1990).

Mechanistically, net accumulation of organic matter reflects the balance between generation by the plant and microbial degradation. From interviews with superintendents and field observations of bentgrass plots at our University field stations, we have had no indication that bentgrass growth rates or health systematically decline over time in the transition zone climate. Bentgrass growth and quality are maintained as long as intensive management continues. The implication is that changes in soil microbial activity are the controller of declining rates of organic matter accumulation over time. It is known that soil organic matter, and presumably the supply of carbon substrate, enhances microbial communities in putting greens (Elliot et al., 2003; 2004) and in turfgrasses in general (Zhou et al., 2002; Shi et al., 2007), and that microbial activity is highest in the top portion of the soil profile (Mancino et al., 1993). We cannot find, however, any experimental evidence in the literature that would indicate shifts in microbial community structure or activity over the long term. An alternative hypothesis is that increased microbial activity over time reflects a change in soil organic matter properties near the soil surface. Soil organic matter is heterogeneous, with a diverse structure and chemistry. Some forms are “labile”; they can accumulate and be degraded rapidly, while other forms are more stable or ‘recalcitrant’ and break down slower. Accordingly, the decreasing rate of organic matter accumulation could is that the labile forms are the dominant carbon form during the first few years after putting green establishment, and slower accumulation over time reflects an increasing presence of more stable, recalcitrant forms.

Our results have a number of implications for management of organic matter in bentgrass greens. The sustained accumulation suggests that it may be unrealistic to expect that accumulation of organic matter in bentgrass greens can be controlled entirely. The key in maintaining bentgrass health clearly is to keep pores open in the top 2.54 cm of the soil profile. The results also indicate that proper soil sampling to monitor organic matter would focus on the top 2.54 cm. Anything deeper will dilute the 2.54 cm levels with lower organic matter from below, leading to the conclusion that organic matter is not a problem and management intensity might be relaxed. Once putting greens in the transition zone reach an age of about five years, the potential for macropore blockage is present and greens are in progressively greater danger over time. To the contrary, the physical conditions are present for the greens to suffer, and perhaps fail, if they are not kept open for gas exchange into the root zone.

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Table 1.1. List of North Carolina golf courses that participated in the organic matter study.

Golf Course Name

Blowing Rock Country Club	North Ridge Country Club - Oaks
Cape Fear Country Club	Old Chatham Golf Club
Chapel Hill Country Club	Pine Valley Country Club
Charlotte Country Club	Pinehurst No. 1
Country Club of Landfall - Marsh	Pinehurst No. 2
Country Club of Landfall - Ocean	Pinehurst No. 3
Country Club of Landfall - Pines	Pinehurst No. 4
Country Club of Salisbury	Pinehurst No. 5
Crescent Golf Club	Pinehurst No. 6
Eagle Point Golf Club	Pinehurst No. 7
Elk River Club	Pinehurst No. 8
Governors Club - Championship 18	Prestonwood Country Club - Fairways
Governors Club - Upper 9	Prestonwood Country Club - Meadows
Grandfather Golf and Country Club	Providence Country Club
Greensboro Country Club	Raleigh Country Club
Heritage Golf Club	Raleigh Golf Association
Jefferson Landing	Sapona Country Club
Kinston Country Club	Sedgefield Country Club
Linville Ridge	St. James Plantation - Founders
MacGregor Downs Country Club	St. James Plantation - Members
Magnolia Greens Golf Plantation	St. James Plantation - Players
Mimosa Hills Country Club	St. James Plantation - Reserve
Myers Park Country Club	The Club at Longview
NCSU Short Game Facility	UNC Finley Golf Course
North Ridge Country Club - Lakes	Wakefield Plantation

Table 1.2. Organic matter present at different depths below the soil surface in creeping bentgrass putting greens. The greens had been in place at different ages ranging from one to 17 years.§

Depth (cm)	**Course Age (yrs)**								
	1	**2**	**3**	**4**	**6**	**7**	**8**	**16**	**17**
0.00-2.54	2.55 a	3.72 a	3.52 a	4.14 a	3.77 a	7.78 a	4.38 a	3.23 a	5.98 a
2.54-5.08	0.59 b	1.24 b	1.67 b	1.09 b	2.39 b	1.16 b	3.32 b	1.83 b	2.79 b
5.08-7.62	0.51 b	1.13 b	0.71 c	0.80 c	0.92 c	0.35 c	0.69 c	0.85 c	0.92 c
7.62-10.16	0.43 b	1.11 b	0.62 c	0.72 c	0.61 d	0.24 c	0.49 c	0.82 c	0.60 d
10.16-15.24	0.43 b	1.11 b	0.59 c	0.67 c	0.55 d	0.18 c	0.49 c	0.55 c	0.52 d
LSD	0.19	0.34	0.19	0.23	0.26	0.56	0.64	0.40	0.27

§ Means within a column followed by the same letter are not significantly different according to Fisher's Protected Least Significant Difference test at 0.05 probability level.

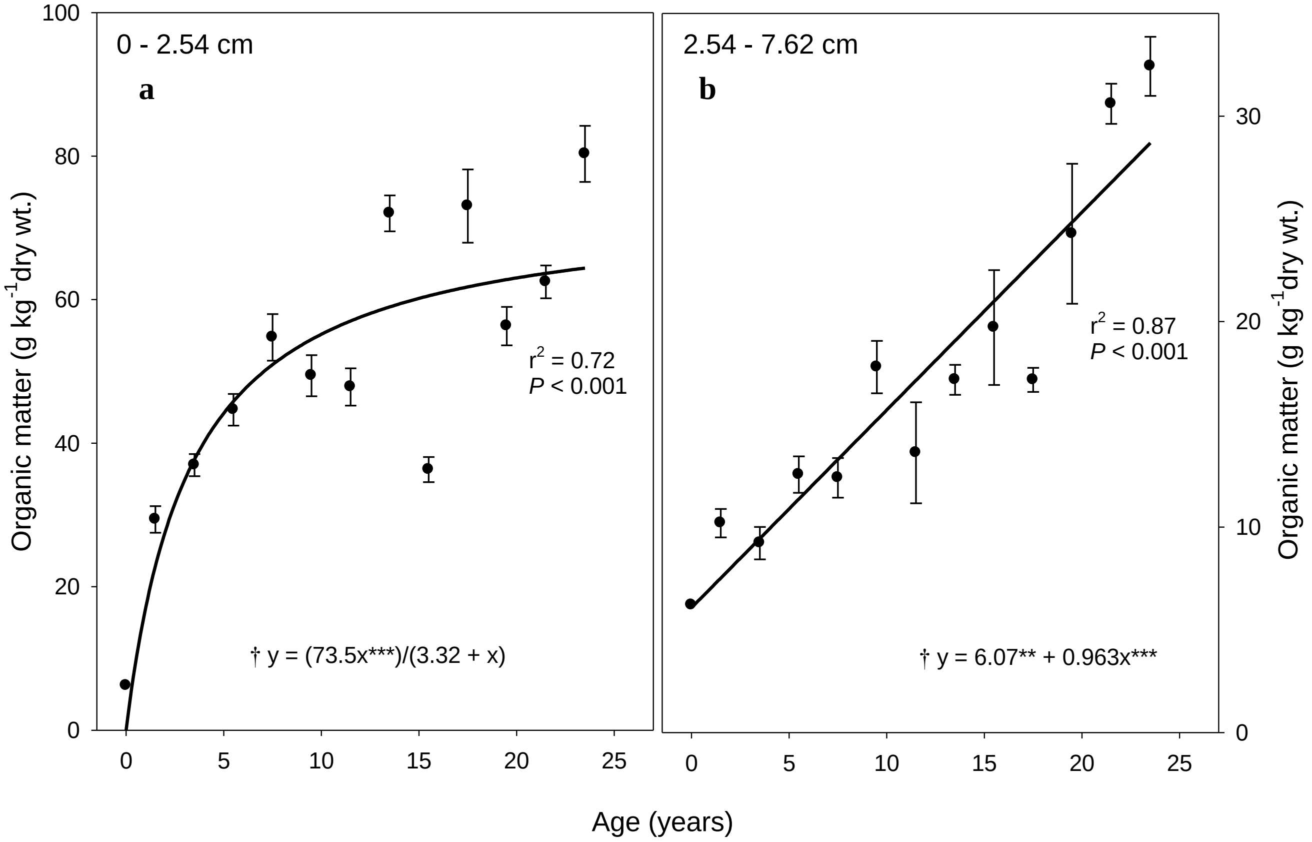
Table 1.3. Differences in various factors for four different fertility treatments. §

	Nitrogen fertility (kg 92.9 m^{-2})				
	0.0	**1.81**	**2.27**	**2.84**	**LSD**
Clipping weight (g)*	2.41 a	4.10 b	5.50 c	6.72 d	0.39
Nitrogen in tissue (g kg^{-1})*	31.9 a	35.6 b	38.1 c	41.3 d	1.80
Soil organic matter (g kg^{-1}) ** 0-2.54 cm	2.30 a	3.31 b	3.72 cd	4.08 d	0.50
Soil organic matter (g kg^{-1}) ** 2.54-7.62 cm	0.80 a	0.90 b	0.97 c	1.00 c	0.04
Infiltration rate (cm/hr)*	52.6 a	50.3 a	58.2 b	64.0 c	1.99
Carbon dioxide level (volumetric)*	0.33 a	0.44 b	0.54 c	0.55 c	0.05
Oxygen level (volumetric)*	0.27 a	0.36 b	0.44 c	0.45 c	0.04

§ Means within a row followed by the same letter are not significantly different according to Fisher's Protected Least Significant Difference test at 0.05 probability level.

*Data averaged over six sampling dates.

**Data averaged over seven sampling dates.



† Regression parameter estimate significant at $P = 0.01^{**}$ or 0.001^{***} level, respectively, based on analysis of variance and *t*-tests.

Figure 1.1 (a and b). A chronosequence of organic matter accumulation in creeping bentgrass putting greens at two depths (0-2.54 cm and 2.54-7.62 cm) below the soil surface. Fifty courses were sampled. The data are means of data from two year periods.

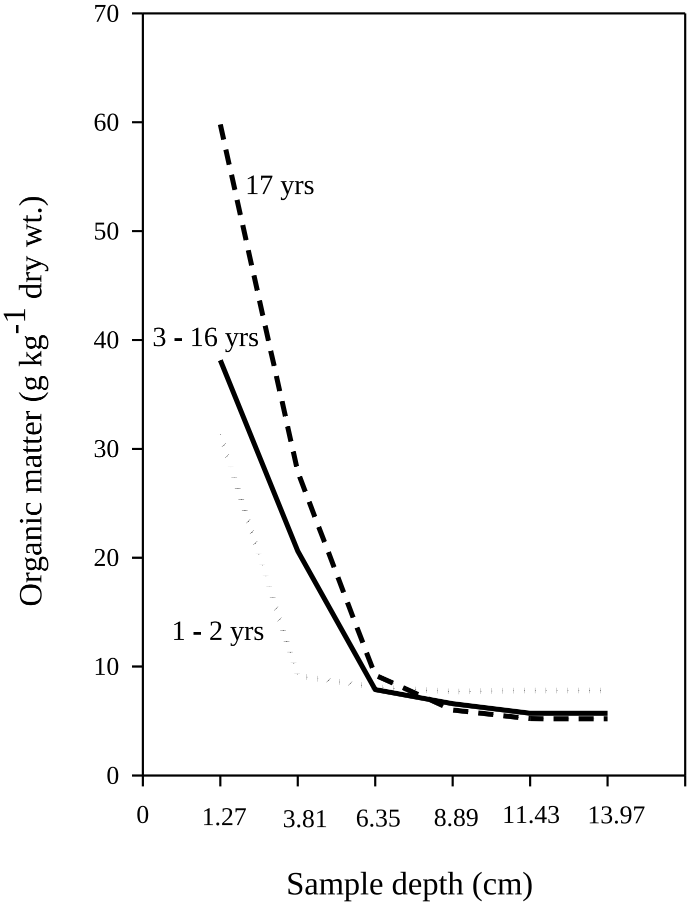


Figure 1.2. Organic matter accumulation at different depths from the soil surface. Data from greens in different age groups (refer to Table 1.2) were averaged for each depth.

CHAPTER 2

Carbon Accumulation in Soil Beneath Bermudagrass Fairways

ABSTRACT

Substantial evidence indicates that increases in world temperatures are being driven by accumulation of ‘greenhouse’ gases in the earth’s atmosphere. One of the most important is CO_2, which is a product of burning fossil fuels in industrialized countries. Many steps are being considered to control the generation of CO_2. The most obvious and the most important step is to limit or reduce CO_2 emissions. But, it has also been proposed that release of CO_2 could be offset by carbon (C) sequestration in long-term storage pools. In this study, we examine the extent that C can be accumulated in soil beneath turfgrass systems. Recent literature suggests this might be the case, but only one data set has been published and it was from work done in Colorado. The dynamics of turfgrass growth and microbial activity dictate soil C accumulation patterns, and the two processes vary greatly among geographic regions.

Samples were taken from bermudagrass (*Cynodon* spp.) fairways on 59 golf courses in the Piedmont and Coastal Plain of North Carolina and the upper Coastal Plain of South Carolina that were of differing ages. The samples were analyzed initially using the ashing method, which is a typical technique used in the past for estimating C content of soils. After a series of tests, it was discovered that the ashing method did not accurately measure soil C levels in clay soils. Logical declines in C with soil depth were not evident and subsequent parallel analyses using a C analyzer yielded very different values. The inaccuracies resulted from water retention by the clay soil during the initial drying process at 110 °C. On the other hand, ashing did closely predict C in sandy soils, particularly when values were adjusted by a model based on direct C analysis.

The results provide the first quantitative estimates of C accumulation in soils beneath turfgrass systems in the southeastern U.S. Carbon accumulates in soil in a hyperbolic manner with age. Accumulation over the first 20 years is about 31.0 Mg ha^{-1} or 1,400 lbs per acre in sandy soils and about 17.5 Mg/ha or 780 lbs per acre in clay soils. The higher values for sandy soils reflect more rapid deposition throughout the soil profile and to a greater depth. It is

speculated that greater macro-pore space, drainage, and gas exchange in sandy soils, along with a longer growing season, enhance root and whole plant development, which lead to greater C accumulation.

The results of our study indicate that C accumulates more rapidly in the sandy soils of the Southeast and accumulation in clay soils is roughly equivalent to the accumulation occurring in the Colorado region with Kentucky bluegrass (*Poa pratensis* L.). The potential C sequestration beneath turfgrasses in the Southeast raises the possibility of substantial carbon credits for the turfgrass industry in this region.

INTRODUCTION

Climate change has been a focus of research since the mid- 20th century. The Intergovernmental Panel on Climate Change (IPCC) concluded that global temperatures have increased by 0.6 °C over the past century and the rate of increase is accelerating (IPCC Report, 2008). Models now predict that the increases in surface temperatures in the decades ahead could reach 3.3 to 3.9 °C.

It is widely agreed that the increases in world temperatures are being driven by accumulation of ‘greenhouse’ gases in the earth’s atmosphere. The greenhouse gases include carbon dioxide (CO_2), chlorofluorocarbons, nitrous oxide, and methane, which are largely the result of human activities. In particular, atmospheric levels of CO_2 have been closely monitored since the middle of the 20th century at Mauna Loa, HI. The data show that CO_2 concentrations have increased from 315 ppm to 370 ppm from 1958 to 2005 (Lutgens, 2007), and it is projected they will increase to levels that range from 550 to 1000 ppm over the course of the next century. From these measurements and others from physical sources like ice cores, it is known that the current increases in CO_2 concentrations began at the time of the industrial revolution and appear linked with burning of fossil fuels and deforestation.

The ‘greenhouse effect’ is a result of short wavelength solar radiation entering the atmosphere from the sun, then reflecting back off of the earth’s surface as longer wavelengths. The longer wavelengths then strike the CO_2 molecules, causing their bonds to bend and vibrate. The resulting increase in kinetic energy is then transferred to other molecules, resulting in an increase in atmospheric temperature.

Historically, the greenhouse effect is part of a feedback loop that has kept the earth within a temperature range suitable for life. It is likely that increasing CO_2 coupled with an increase in global temperatures will result in climate changes that will adversely impact society by causing drastic changes in energy use, water supplies, agriculture, disease distributions, and flooding of coastal and island communities.

A number of steps are being considered to mitigate the changes in atmospheric CO_2 and climate. The most obvious and the most important step is to limit or reduce CO_2 emissions. Governments are in the process of regulating CO_2 emissions which, if successful, is likely to have a large impact on the economy of industrialized and developing countries. A supplementary strategy for helping to control atmospheric CO_2 levels is to increase carbon (C) sequestration in long-term storage pools as above ground biomass and in soil organic matter (Lal, 2004; Jackson and Schlesinger, 2004). Amounts of carbon sequestered vary by ecosystem, but it is known that forests can store a great deal of carbon above ground. Soil also can act as an effective carbon sink. The soil carbon pool is 3.3 times the size of the atmospheric pool (760 Gt) and 4.5 times the size of the biotic pool (Lal, 2004). Once sequestered, carbon remains in the soil as long as restorative land use, no-till farming, and other recommended management practices are followed, potentially offsetting as much as 20% of CO_2 generated annually (Lal, 2004).

Recent research has revealed that turfgrass systems have significant potential for long-term storage of carbon below ground. Turfgrasses occupy increasingly large acreages in the continental U.S. - about 165,000 km^2 (Bandaranayake et al., 2003; Brown et al., 2005; Milesi et al., 2005) primarily due to urbanization and its associated lawns, roadsides, and recreational areas. If maintained, turfgrasses can grow rapidly, fixing CO_2 from the atmosphere, and sustain large organic matter pools in soil (Qian and Follett, 2002). From studies in the Colorado area, it is estimated that as much as 30 to 40 Mg ha^{-1} of carbon can be stored beneath turfgrass systems (Qian and Follett, 2002; Qian et al., 2003). Net carbon accumulation reflects organic matter generation by plant growth and its degradation by soil microbes. The activities of the two processes are strongly influenced by the environment, and thus will vary among geographical regions, and even soil types. At the current time, no data are available that estimate carbon storage beneath turfgrasses in the southeastern. U.S.

In this study, we will evaluate the carbon storage capacity of turfgrasses in the transition states of North and South Carolina. In this initial study, samples were taken from bermudagrass on golf course fairways, most of which are intensively managed with frequent applications of fertilizers, pesticides, and supplemental irrigation.

It should be emphasized that limiting or reducing the amount of CO_2 emissions is one of the most important steps in maintaining sustainable levels of atmospheric CO_2. Governments of many countries around the world are in the process of regulating CO_2 emissions which, if successful, is likely to have a significant impact on the economy of industrialized and developing countries. One of the societal and economic benefits of soil C is the trading of C credits. These trading markets have existed in Europe since 2002 (Lal, 2004). Carbon management policies like these are an important step in beginning to control CO_2 on a global scale. The purpose of this project was to begin to establish a scientific basis for understanding carbon sequestration potential and provide reliable data that can be used by carbon credit and trading programs as they evolve.

MATERIALS AND METHODS

Overview

Soil samples were collected from spring 2008 through summer 2009 from fairways on 59 golf courses from across the state of North Carolina and the northeastern coastal region of South Carolina (Table 2.1 and Fig. 2.1). In general, all courses sampled were well maintained and sound management practices were in place. The turfgrass on all fairways was bermudagrass (*Cynodon* spp.). Samples were taken at different depths in the different phases of the research in attempts to understand patterns of C accumulation and analytical problems, as explained below.

Sampling involved removal of four cores at each fairway sampling site and removal of leaf tissue as close to the crown as possible. Cores were removed using a 2.54 cm diameter, 30.48 cm long soil probe (Oakfield Apparatus Company, Oakfield, WI). Cores at each site were then cut at a specific depth on a marked cutting board, and then mixed and stored together in a labeled zip-lock bag.

In the fairway sites, existing soils were subjected to shaping and topsoil replacement during course establishment and building, but courses fell into general soil classification categories (Appendix Table 2.1.). These soil series, surface textures, and taxonomic classifications were obtained from soil series maps of North and South Carolina.

Phase 1. The first study involved sampling at 47 golf courses in piedmont and coastal regions in NC and northeastern SC. Four fairway sites were sampled to a 7.62 cm (3”) depth at each course - two holes on the front nine and two holes on the back nine. Percent organic matter by weight was calculated for all sampling sites using the combustion method. Percent C was also measured at four of these golf courses using a carbon/nitrogen (CN) flash analyzer (Thermo Finnigan, Flash EA 1112 series).

Phase 2. The possibility of some variation problems appeared in Phase 1, so a set of samples were taken with the soil probe as before from 12 golf courses in Phase 2 at a 15.24 cm depth (6”). The samples were collected from courses in clay soils in the piedmont and sandy soils in coastal regions of NC. Some of the courses were repeats. The number of sampling sites was increased from four to six - three holes on the front nine and three holes on the back nine. All samples were analyzed using both the combustion and automated C analyzer.

Phase 3. To define changes in C with depth, soil samples were divided into increments. The samples were collected from three courses located on clay soils in the Piedmont to a 15.24 cm depth using the same soil probe as before and two courses in the sandy soils of coastal areas to a 30.48 depth using a 48.26 cm long soil probe. Four fairways were sampled at each golf course with clay and six on courses with sandy soil. The depth increments are described in the Results section. All samples were analyzed using both combustion and direct C analysis.

Measurement of soil carbon

Soil samples were transferred from zip-lock storage bags to ceramic crucibles (Coors Tek, Golden, CO) and oven dried at 105 °C until samples maintained a constant weight. Organic matter (OM) was determined by weight loss after combustion (Storer, 1984) for 12 hrs at 500 °C using a muffle furnace (Thermolyne, Dubuque, IA). Percent soil organic matter was then calculated as (soil dry mass – soil mass after ashing) / (soil dry mass), and carbon calculated as 52% of the organic matter. Carbon content was also measured using an automated flash combustion gas analyzer configured for C and N determination. Soil samples were oven dried at 105 °C as before and then thoroughly homogenized using a flail soil grinder. Sub-samples of 20 – 30 mg were taken from the bulk oven dried samples and placed into tin capsules, and then analyzed.

Data Analysis

Nonlinear regression analysis was used to evaluate changes in soil C contents. Because samples were collected from courses of different ages, a chronosequence could be established describing C accumulation with age. SAS programs were used to establish statistical differences where appropriate.

RESULTS AND DISCUSSION

Analytical issue with ashing

Throughout the sampling phases, unexpected C accumulation patterns were found, especially in clay soils, when the combustion analytical method was used. From research by Qian and Follett (2002), Qian et al. (2003), and our research on organic matter accumulation in bentgrass greens (Chapter 1, Goodman thesis), it was inferred that C would accumulate hyperbolically with age. One could not detect this type of pattern using ashing (combustion). Also, direct comparisons of C using standard ashing analysis techniques produced higher values than that measured directly using more arduous sample preparation techniques and direct C analysis.

Three examples demonstrate the point. First is a plot of soil C against fairway age (Fig. 2.2). No age effect could be detected statistically, and ashing resulted in much higher C estimates than actual C measurements on specific samples where they were compared. As is normally the case when using ashing, C in organic matter was calculated using an estimated %C value (49.9% of OM total; see below). A second example can be seen in depth analyses for three courses that have clay soils (Fig. 2.3). Using combustion, C decreased with depth as expected, but leveled off at 18 %C at depths between 7.62 and 12.7 cm. This level was much higher than measured C values. A third example is from depth analyses with sandy soils (Fig. 2.4). In this case, C estimates from ashing were much closer to actual C values than in the clay soils, but they still over-estimated soil C at the top of the soil profile where OM levels were highest.

From these results, the ashing method was clearly generating artificially high C values, even though the technique is widely used for that purpose (Storer, 1984). The most likely problem is with water retention by the soils during the 105 °C drying process. For ashing analysis, soils are dried at this level to drive off water and then weighed. If microscopic water held tightly to soil surfaces was retained, then estimates of OM and the C associated with it would be over-estimated. It is logical that clay would hold higher amounts of water than sand because of the extensive surface area and charged surfaces, which would lead to the distorted C levels. With sand, water retention by OM could explain the somewhat smaller elevation in C values at the top of the soil profile.

Based on these observations, it was determined that a) C estimates from ashing of clay soils would be unacceptably inaccurate and unpredictable, and b) while also tending to be elevated, C estimates using sandy soil ashing were predicable with an adjustment. A plot of all sandy soil samples where C values were processed by ashing and actual C measurements revealed an adjustment equation that could be used to accurately predict soil C values (Fig. 2.5a). The equation coefficient of 0.499 indicates that carbon is approximately 50% of the OM total, which is close to the 0.56 previously accepted in the literature (Qian and Follett, 2002). It should be stressed that the reason for using adjusted ashing C is to allow inclusion of the many samples taken early on in the study and because direct C measurements must include exhaustive sample preparation that precludes processing of large sample numbers. Because of the inaccuracy and variability in ashing results with clay, as shown above, a statistical relationship could not be resolved between OM and C content of clay soils (Fig. 2.5b).

Carbon accumulation over time

The construction of a chronosequence from the soils beneath the golf course fairways shows that C accumulation is best described by a hyperbolic equation (Fig. 2.6a). The soils in the North and South Carolina region are typically classified as ultisols which, characteristically, have low OM (Buol et al., 2003) levels of < 0.5 %. This equates with about 5 Mg C ha^{-1}. From that starting point, soils beneath bermudagrass fairways accumulated C to about 38 Mg ha^{-1} over a 20 year period in sandy soils and about 26 Mg ha^{-1} in clay soils. Because the accumulation was hyperbolic, the rate of C accumulation decreased progressively over time (Fig. 2.6b). The highest rate in sandy soils was about 8.5 Mg ha^{-1} and in clay soils 6 Mg ha^{-1} yr^{-1}. The rates decreased to less than 0.5 Mg ha^{-1} yr^{-1} within 20 years.

Few studies have examined C accumulation beneath managed turfgrass areas. In perhaps the most often cited, Qian and Follet (2002) and Qian et al. (2003) estimated that C accumulation in the Colorado area was 0.9 Mg ha^{-1} yr^{-1} over a 25 year period. For the same time period, C accumulation in sandy soils in our study was about 1.3 Mg ha^{-1} yr^{-1} (41 Mg at 25 years – 8.5 Mg at time 0, Figure 2.6a). In clay soils, the C accumulation was lower for the same time period at about 0.7 Mg ha^{-1} yr^{-1}. Again, it should be emphasized that the rates steadily decrease over time (Fig. 2.6b), so the long-term averages include the very low rates that occur towards the end of the 25 yr period.

Although comparisons with Qian and Follet are instructive (their data is the current benchmark), one difference between our hypobolic curve and theirs' is that the low rates of accumulation occur a slight bit earlier in our study in the Southeast. In other words, the C accumulation process tends to plateau somewhat sooner. If the comparison of C accumulation is backed up to 20 years, then rates become 1.6 Mg ha^{-1} yr^{-1} in sandy soil and 0.9 Mg ha^{-1} yr^{-1} in clay. The sandy soil rate equates with 1.4 lbs ac^{-1} yr^{-1}, and the clay value is 780 lbs ac^{-1} yr^{-1}.

Qian and Follet found 800 lbs ac^{-1} yr^{-1}. These differences become important when potential 'carbon credits' are considered (see below).

One has to ask 'why does the rate of C accumulation decrease over time?'. The answer is elusive. This type of accumulation appears typical of OM in soil with maintained turfgrass, as shown in the previous Chapter with bentgrass putting greens and was true in the Qian studies cited previously. Mechanistically, net C accumulation will reflect C generation by growth and its degradation by microbial activity. Because the bermudagrass clippings are left in place, soil C will be influenced by total turfgrass growth and not simply that occurring below ground. We know of no evidence indicating that growth decreases steadily over time in turfgrass systems, or that there is an orderly shift to less below ground OM production that might be less available for microbial degradation over many years. Thus, the most probable controller for the decreasing rate of OM and C accumulation is that the microbial activity progressively increases. Indeed, studies have shown that microbial populations increase as OM levels increase as turfgrass systems age (Kerek et al., 2002; Shi et al., 2007).

There is no evidence available at this time which allows understanding of the higher rates of net C accumulation in sandy soils. But based on previous reasoning, it is expected that the growth to degradation balance shifts favoring growth processes. A key may be the better permeability that accompanies more macropores, allowing more extensive root development. The other side to this suggestion is that clay soils have physical and chemical barriers to root development. During construction and with traffic, the clay soils can have very high bulk densities that inhibit downward root penetration. Also, because of their genesis from alumino-silicate parent material, clay soils typically have high levels of aluminum (Al). Aluminum in acid conditions is toxic to plants, strongly inhibiting downward root extension (Taylor, 1988; Kochian, 1995; Von Uexkull and Mutert, 1995). Grasses have higher Al tolerance than crop plants, but tolerance is still well below that found in species like pines (Moyer-Henry et al., 2005) that dominate successional landscapes. Also, liming is the general management practice for controlling Al toxicity (Adams, 1984), and liming has only slow impacts in turfgrass systems because they are cannot be cultivated once established. The end result is that in clay soils, both because of physical and chemical barriers, root development may be restricted, limiting C deposition.

Carbon sequestration and carbon credits

The ability of turfgrasses to store C below ground may result in a monetary value in the future. The Obama Administration recently announced it would be pursuing a 'cap' on the amount of CO_2 released in the U.S. Most other industrialized countries adopted caps years ago in an attempt to control CO_2 emissions. If a CO_2 cap were put into place, it would be accompanied by a national trading system where carbon credits are bought and sold, much like the commodities market.

It would be expected that a U.S. system would be similar to the one established in the European Union, the European Climate Exchange. The EU placed caps on CO_2 emissions by energy-intensive industries. If companies exceed caps, stiff penalties can be avoided only if they purchase 'allowances' or 'credits' in the market. A similar voluntary system already is in place in the U.S. – The Chicago Climate Exchange (CCX). Importantly for the turfgrass industry, the CCX includes a 'carbon offset' program. Carbon sequestration contracts are bought and sold. If caps on CO_2 emissions are put into place in the years ahead by federal legislation, biomass and soil carbon will qualify as credits and have a value that could be traded in a commodity market.

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Table 2.1. List of North and South Carolina golf courses and their ages that participated in the carbon sequestration study.

Golf Course Name	Age	Golf Course Name	Age
Lonnie Poole - NCSU	1	Myrtle Beach National - Southcreek	17
Ocean Ridge Plantation - Leopards Chase	1	St. James Plantation - Founders	17
St. James Plantation - Reserve	2	Ocean Ridge Plantation - Lions Paw	20
Hasentree	3	Pinehurst No. 5	20
NCSU Short Game Facility	4	Pinehurst No. 3	21
The Club at Longview	5	Pinehurst No. 2	22
Eagle Ridge Golf Club	7	Pinehurst No. 7	23
Barefoot Resort - Fazio	8	Pinehurst No. 6	29
Barefoot Resort - Love	8	Jamestown Park	34
Barefoot Resort - Norman	8	Myrtle Beach National - West	34
Ocean Ridge Plantation - Tigers Eye	8	Keith Hills I - Creek	35
TPC Wakefield	8	Croasdaile Country Club	40
Barefoot Resort - Dye	9	North Ridge Country Club - Lakes	40
Eagle Point Golf Club	9	North Ridge Country Club - Oaks	40
Heritage Golf Club	9	MacGregor Downs Country Club	41
Keith Hills II - River	9	Carmel Country Club - North	45
Pinehurst No. 4	9	Carmel Country Club - South	45
UNC Finley Golf Club	9	Chapel Hill Country Club	45
UNC Finley Golf Course	9	Greensboro Country Club - Farm	45
Bentwinds Country Club	10	Duke University Golf Club	52
Carolina National	10	Raleigh Country Club	60
River Ridge Golf Club	10	Alamance Country Club	63
Grandover Resort West Course	11	Hope Valley Country Club	83
St. James Plantation - Players	11	Carolina Country Club	90
Grandover Resort East Course	12	Greensboro Country Club - Irving Park	99
Myrtle Beach National - Kings North	12	Cape Fear Country Club	103
Ocean Ridge Plantation - Panthers Run	13	Pinehurst No. 1	110
Pinehurst No. 8	13		

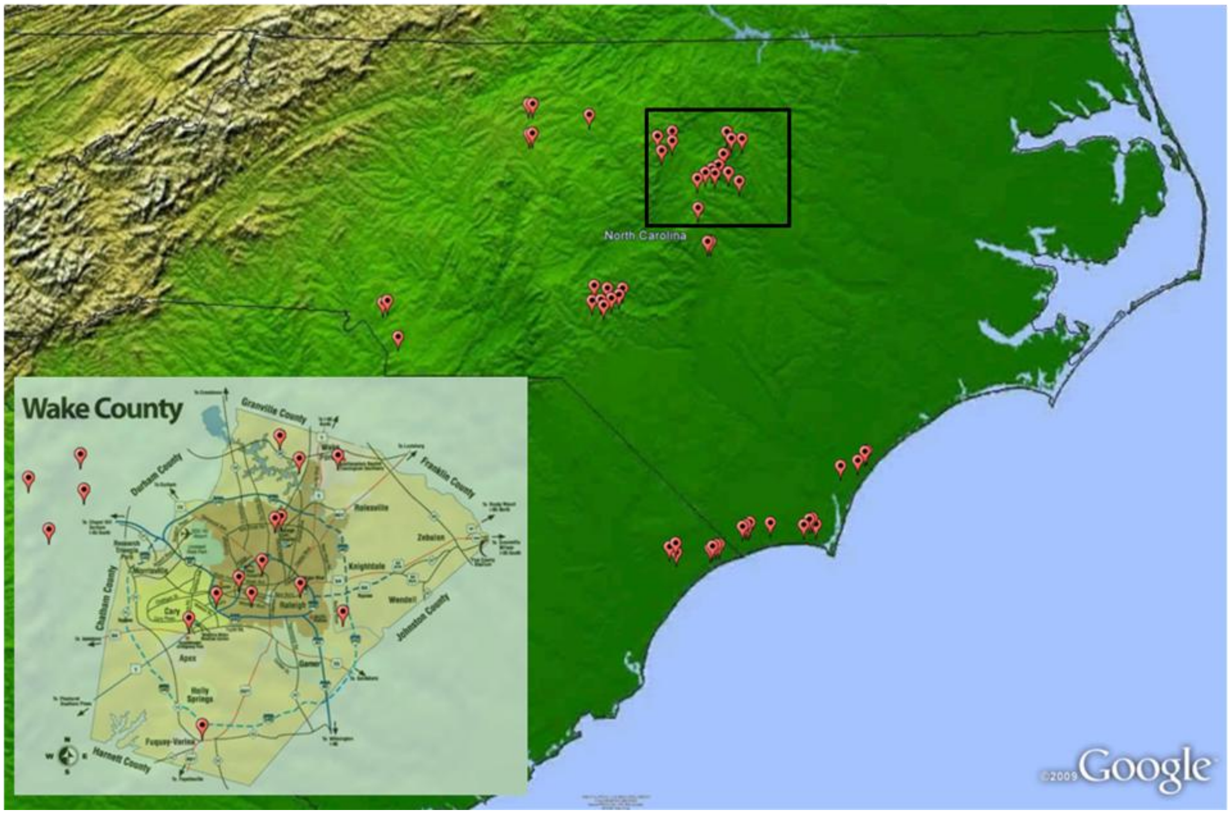

Figure 2.1. Map showing golf course locations in North and South Carolina where soil samples were taken from beneath bermudagrass fairways.

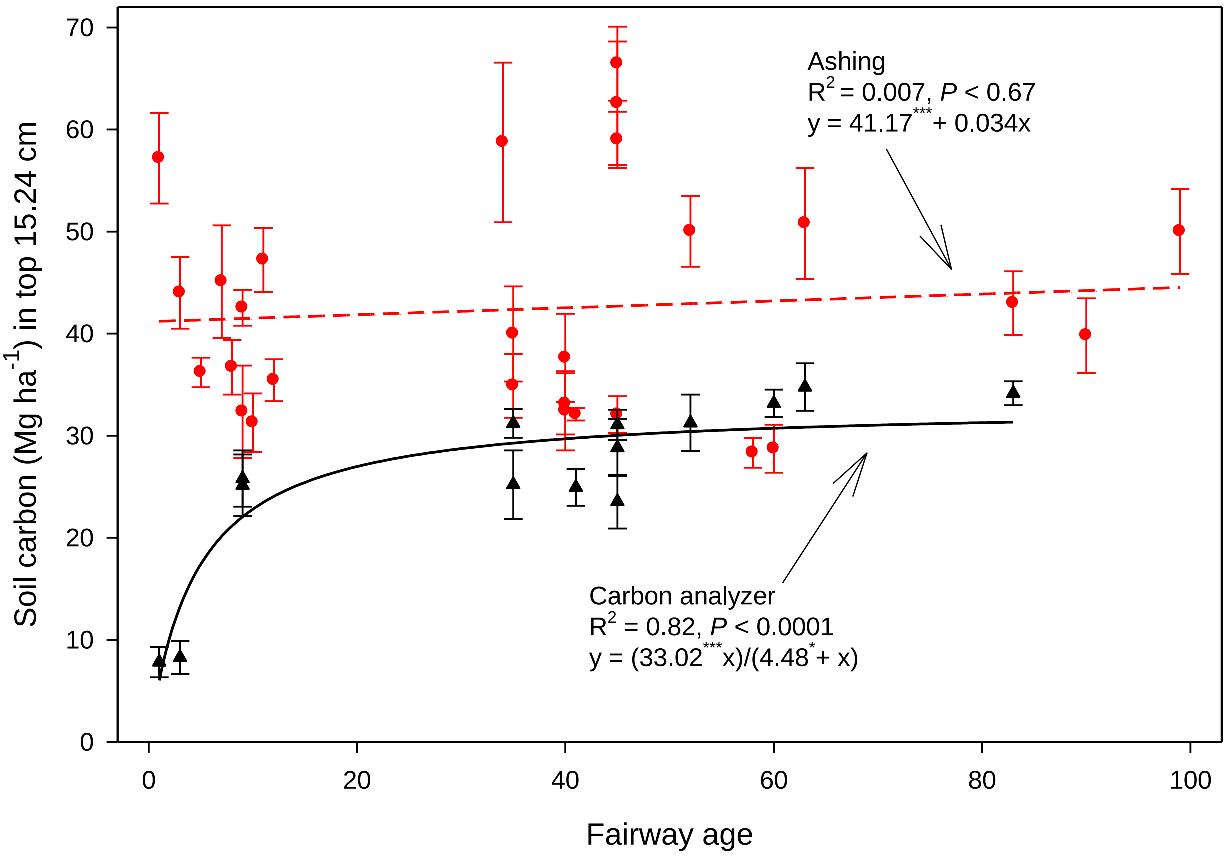

Figure 2.2. Carbon contents of soils beneath bermudagrass fairways on golf courses of different ages with clay soils. Circles and dotted lines represent analysis with the ashing method (C as 50% of the organic matter). Triangles and solid line are direct carbon analysis.

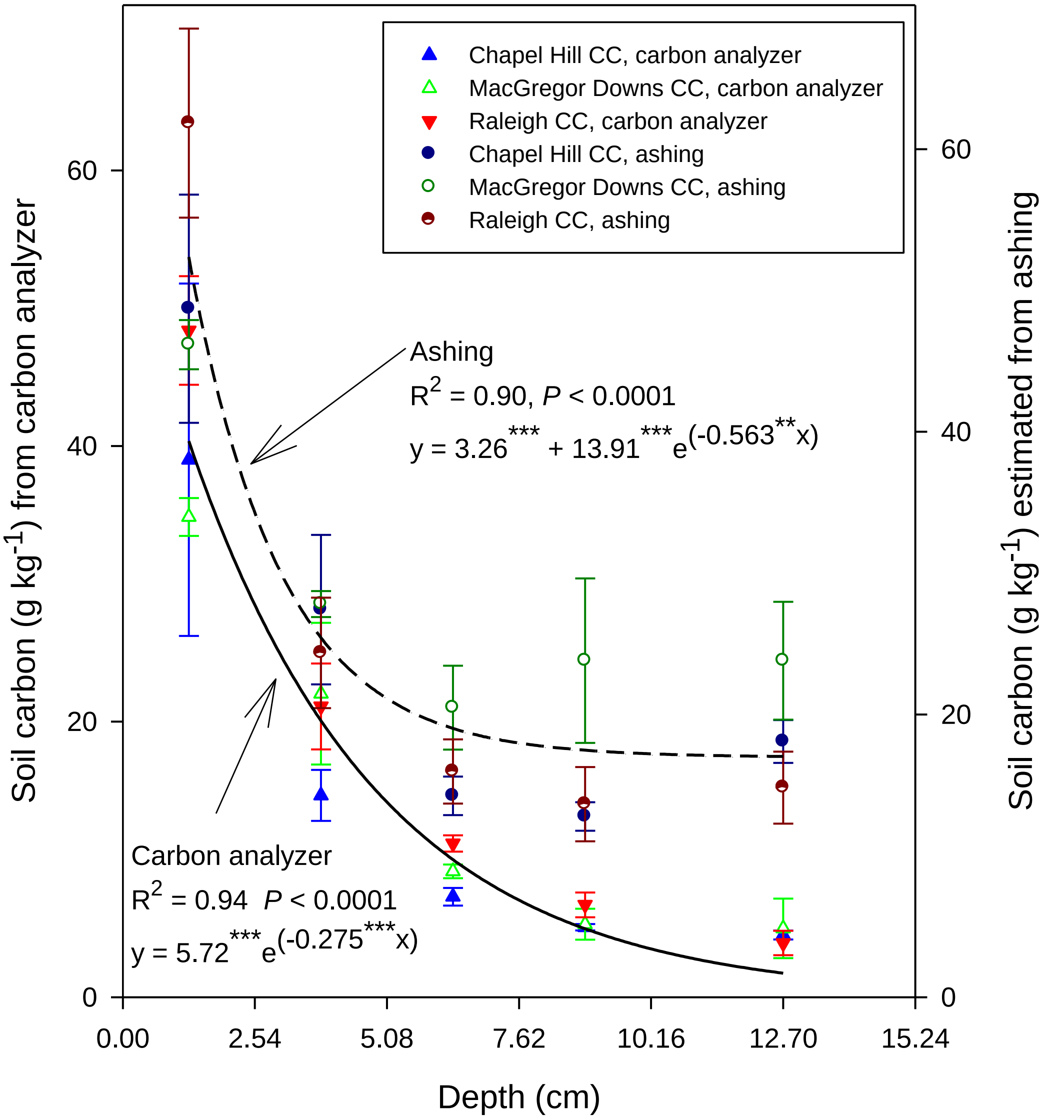

Figure 2.3. Changes in carbon content of soils at different depths from the surface. Sampling sites were bermudagrass fairways on three North Carolina golf courses with clay soils.

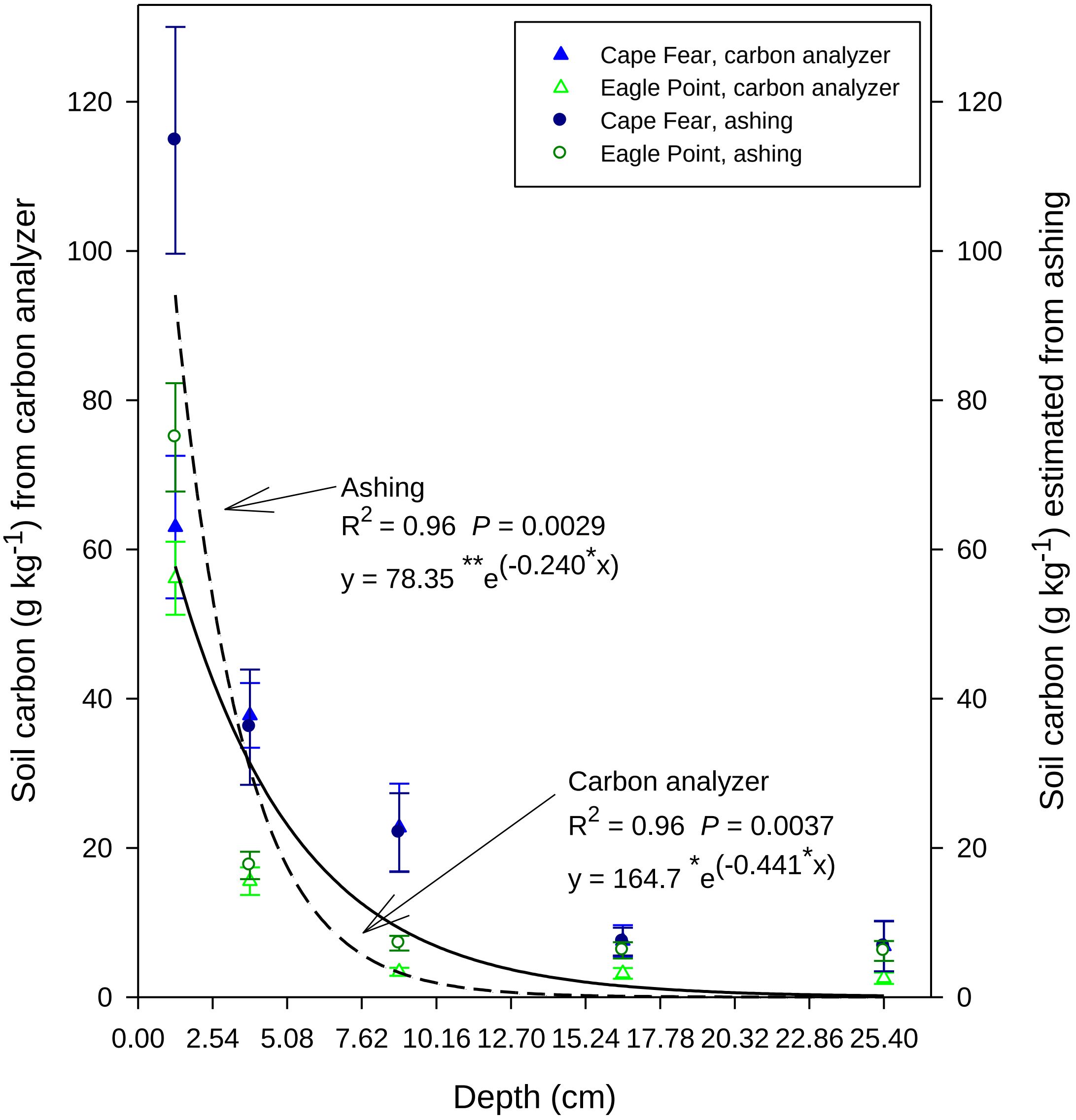

Figure 2.4. Changes in carbon content of soils at different depths from the surface. Sampling sites were bermudagrass fairways on two North Carolina golf courses with sandy soils.

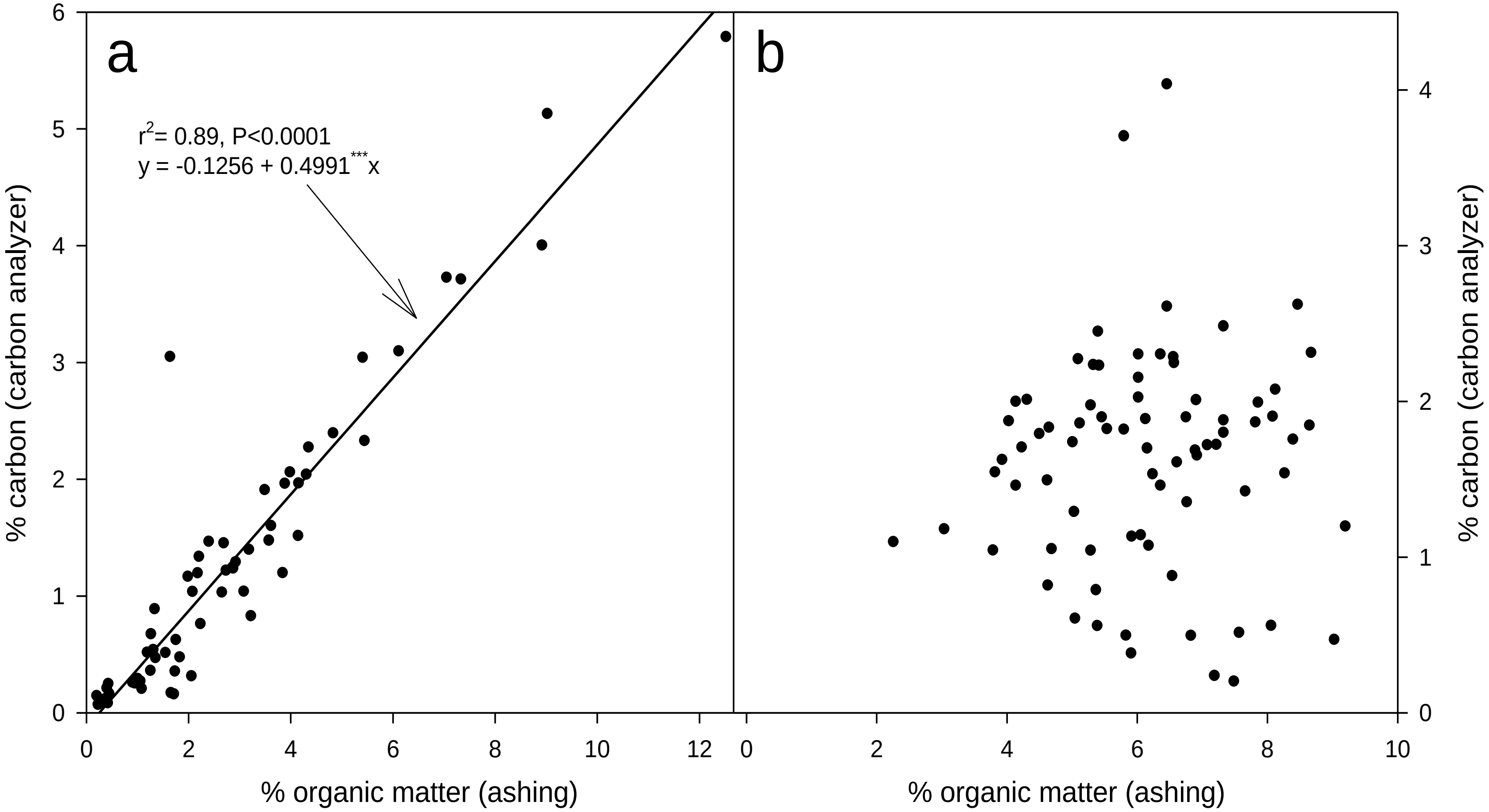

Figure 2.5 (a and b). Relationship between % organic matter determined by ashing procedure and % C determined by C analyzer in a) sandy soils and b) clay soils.

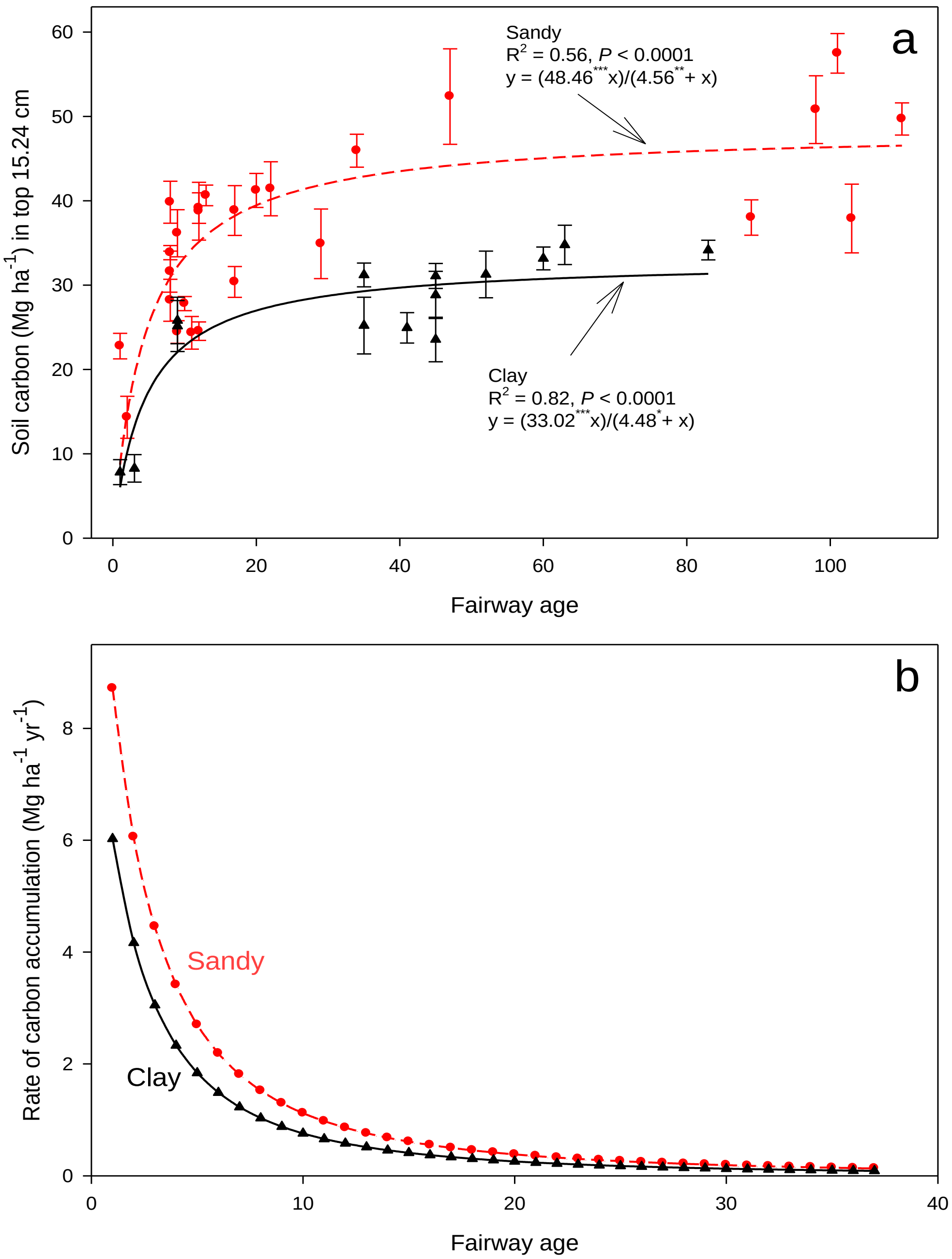

Figure 2.6 (a and b). a) Carbon contents of soils beneath bermudagrass fairways on golf courses of different ages. Different plots are for courses with sandy and clay soils. b) Rates of C accumulation over time, calculated using the hyperbolic equations for sandy and clay soils.

CHAPTER 3

Nitrogen Effects on Bentgrass Growth: A Hydroponics Study

INTRODUCTION

As shown in previous experiments, organic matter accumulates rapidly in creeping bentgrass greens. Also, the controlled field plots indicate bentgrass grows faster and organic matter accumulation is more rapid with increasing nitrogen (N) nutrition. From other research in our group, it is also known that sensitivity to heat increases with high N nutrition. Thus, it is reasonable to think that golf course superintendents should always minimize N fertility, both to minimize the likelihood of excessive organic matter build-up and, particularly in summer months, to minimize damage from heat stress. There is, however, more to N nutrition than its impacts on organic matter and heat sensitivity.

One of the biggest problems for bentgrass in the Southeast is fungal disease. Diseases typically invade unhealthy turfgrass more aggressively, and turfgrass health can be depressed by N stress and improved at higher N nutrition. Also, the expression of disease symptoms in summer months often can be offset if N nutrition is raised (Dernoeden, 1987; Uddin et al., 2009).

One of the new approaches in managing bentgrass is to supply low levels of N (i.e. spoon feeding) on a frequent basis (Radko, 1985; Throssell, 1986). Although responses have never been detailed, the success of frequent fertilization evidently is to produce healthy bentgrass that is growing only at a moderate rate, with minimal production of excessive amounts of organic matter.

In this series of experiments, we attempt to determine how bentgrass cultivars respond to N fertility. There are currently a number of new creeping bentgrass cultivars on the market that are being established on putting greens throughout the Southeast and have superior playing characteristics. The grasses have been observed to have finer texture and greater density. Greater density is associated with more organic matter accumulation, and therefore, requires more intense management. We wanted to determine if the modern cultivars had greater N use efficiencies in the production of dry matter than a traditional type – 'Penncross'. If so, it would indicate that lower nitrogen amounts might be added to the modern types, whether by fertilization or frequent 'spoon feeding'. It also would indicate that analysis of organic matter accumulation in the field would need to be limited to a particular cultivar or group of cultivars that behave similarly.

The experiments were conducted in hydroponics culture, which allowed examination of growth responses in the absence of other stresses. Because solutions could be monitored on a regular basis and depletion minimized, it was possible to establish and precisely maintain different fertility treatments.

MATERIALS AND METHODS

Experiments in hydroponics culture examined growth of four bentgrass cultivars ('A-1', 'A-4', 'G-2', and 'Penncross') at four different N levels (0, 0.2, 0.6, and 2.0 mM). The experiments were conducted in custom built 12 L hydroponics culture units with a rapid solution flow rate, ~ 2.5 L per minute, and with temperature and pH control. Units were housed in an enclosed environmentally controlled walk-in growth chamber programmed for a daytime air temperature of 30 ºC +/- 1º and nighttime air temperature of 26 ºC +/- 1º. Daylight length was 9 hours, while nighttime length was 15 hours. A pH of 6.5 +/- 0.1 and a solution temperature of 26 °C were maintained in each unit. The lighting was provided by 1000-watt metal halide lamps and 100 watt incandescent bulbs at 18 inches above canopy (shoots), which provided approximately 1200 µmol/m^2/sec of photosynthetically active irradiance. The environmental conditions were near optimal for bentgrasses.

The lid on each hydroponic unit contained 16 circular openings and consisted of four replicates of each cultivar per treatment. A polyethylene cup with a fine nylon mesh was placed into each opening so that the bottom touched the solution surface. Each cup with a surface area of 9.62 cm^2 contained 0.04-0.05 g of seed. Prior to germination, the seeds were exposed to solutions containing only 800 µM $CaSO_4$. At the time of radical emergence, additional nutrients (0.6 mM KNO_3, 0.5 mM KH_2PO_4, 2 mM $CaSO_4$, 1 mM $MgSO_4$, and 71.6 µM Fe as 10% chelated iron, 0.61 µM H_3BO_3, 0.12 µM $MnCl_2$, 0.11 µM $ZnSO_4$, 0.13 µM $CuSO_4$, and 0.003 µM Na_2MoO_4) were added, so the seedlings were exposed to a complete nutrient solution.

Plants were allowed to grow for four weeks and then N treatments were established. Nitrogen was added to the solutions from a 1 M KNO_3 stock solution, and N concentrations were monitored several times a week and additional N added when needed to limit depletion to less than 15% of the original concentrations. Entire solutions were replaced every two weeks.

The bentgrass was exposed to the different N treatment solutions for 4 wks, with shoots clipped twice a week. Fresh weights were determined and the clippings then placed in a drying oven (Fischer Scientific, Suwanee, GA) at 60 ºC and dry weights determined after 72 hrs. Root tissues, along with shoot tissue, were harvested and weighed at the end of the experiment. The experiments were repeated twice.

RESULTS

Plants exposed to increasing nitrogen in solution during the treatment period exhibited different shoot and root growth response patterns. The oven dry weights represent the means for total shoot and root tissue harvested two times per week over a four week period. All four cultivars evaluated demonstrated nearly identical shoot growth responses. Shoot growth increased as nitrogen was increased up to 0.6 mM and then remained stable (Fig. 3.1). The average shoot tissue weight at the 0, 0.2, 0.6, and 2.0 mM N treatments were as follows; 0.19 g, 0.63 g, 0.96 g, and 0.93 g, respectively. On the other hand, root growth increased with N addition up to 0.2 mM and then decreased, stabilizing at a relatively low level above 0.6 (Fig. 3.2). The pattern of the cultivar responses was similar, with the average root tissue weight at the 0, 0.2, 0.6, and 2 mM N treatments being 0.22 g, 0.31 g, 0.13 g, and 0.10 g, respectively. Penncross root growth tended to be higher than that for the newer cultivars.

With the different growth responses, the shoot to root growth ratio of the bentgrass cultivars increased sharply as N was increased up to 0.6 mM (Fig. 3.3). There was a tendency for the cultivars to diverge beyond that point. The shoot to root ratio of the newer cultivars (A1, A4, G2) tended to continue increasing as nitrogen was increased up to 2.0 mM, while the S/R ratio of the traditional cultivar Pencross slightly decline as N increased from 0.6 to 2.0 mM.

DISCUSSION

The results of these experiments clearly show that there is a ‘range’ in N fertilization where shoot growth responds with minimal effects on root growth. It is not possible to relate exact concentrations in solution with fertilization rates in the field, but it is logical to think the target ‘range’, which was about 0.6 mM in our treatments, is similar to that being used with the frequent applications or ‘spoon feeding’ in the field. At this level, bentgrass shoot growth has increased to moderate levels, root growth is slowed, and shoot to root growth ratios are beginning to approach maximal values.

We see no evidence that modern bentgrass cultivars use N more efficiently than Pencross. Shoot and root mass increased similarly as the nitrogen treatment level increased. Thus, the results imply that the cultivars would require, physiologically, similar fertilization rates in the field. Within the framework of this research project, it does not seem that field sampling should be confined to a particular bentgrass cultivar. Assuming similar fertilization programs, they will accumulate mass, and by inference soil organic matter, at similar rates.

Even though dry mass differences could not be separated statistically, there was a trend for Penncross shoot to root ratio to be lower than the modern cultivars at high nitrogen levels. Cultivated crop plants developed under high nutrition have often been observed to increase their ‘harvest index’ or above ground biomass at the expense of root growth. In this case, the A and G series bentgrasses, i.e. the modern cultivars, had increased partitioning of dry mass to the shoot compared to Penncross. It is unclear whether this would be an advantage or disadvantage under stress conditions in the field. It seems unlikely that the partitioning differences would greatly change rates of organic matter accumulation. Both stolons and roots can contribute to organic matter build up near the soil surface, the location where permeability is most likely to be restricted (refer to main body of the thesis).

In general terms, it can be speculated that the upper end for fertilization additions with all bentgrass cultivars would be defined by a rate where there is enhanced sensitivity to heat stress, likelihood of environmental degradation due to nitrate losses through leaching. If fertilization is kept within a ‘target window’ like that identified in these experiments (0.6 mM), the possibility for these negative effects is minimized. Another negative, of course, is the lack of root growth, which may predispose plants to drought stress. Most often, however, bentgrass is well irrigated and drought is avoided.

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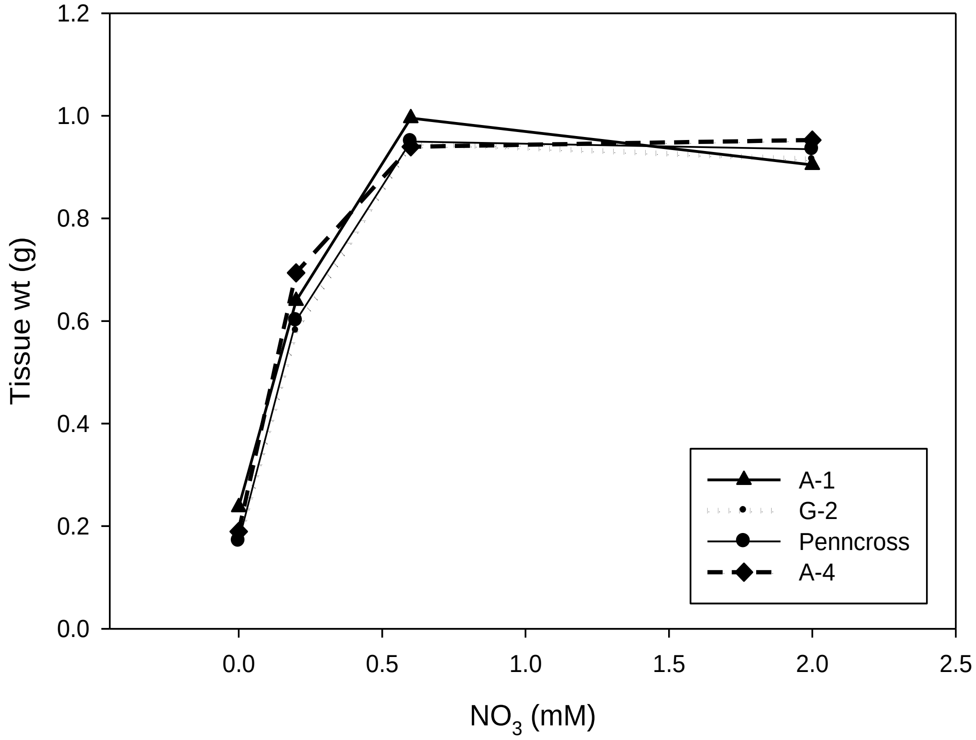


Figure 3.1. Shoot growth response to nitrogen treatment on complete hydroponic solution for four bentgrass cultivars.

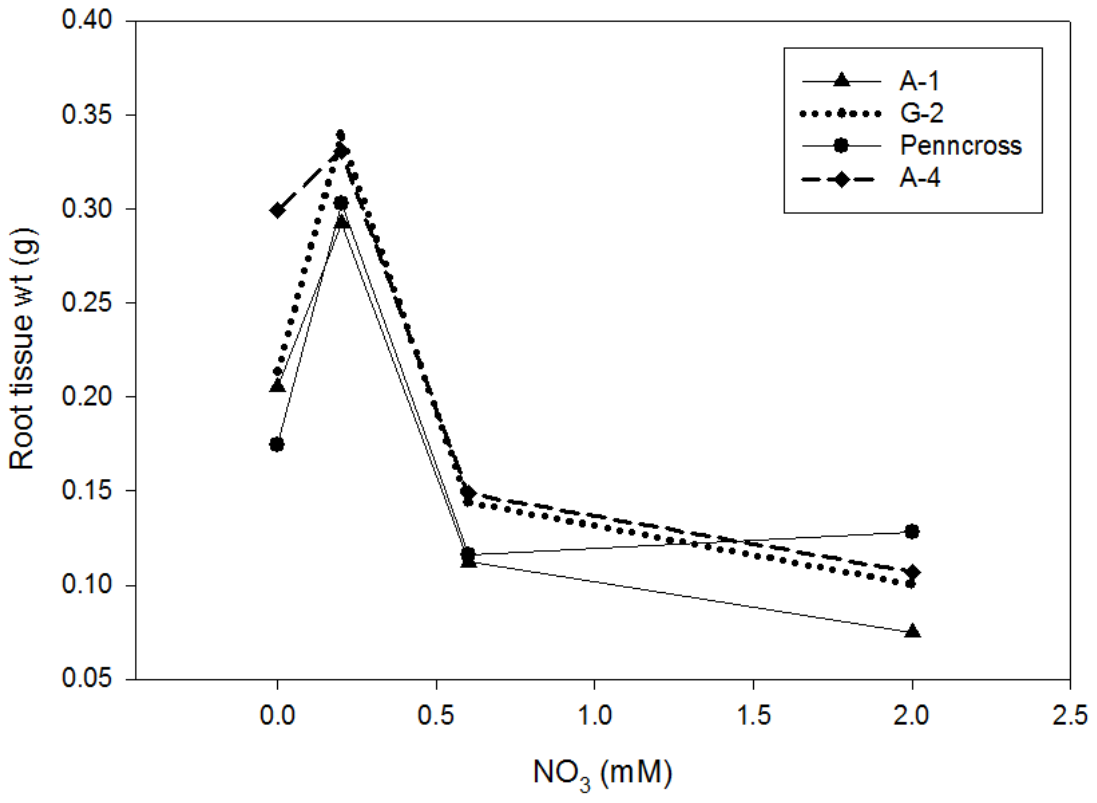


Figure 3.2. Root growth response to nitrogen treatment on complete hydroponic solution for four bentgrass cultivars.

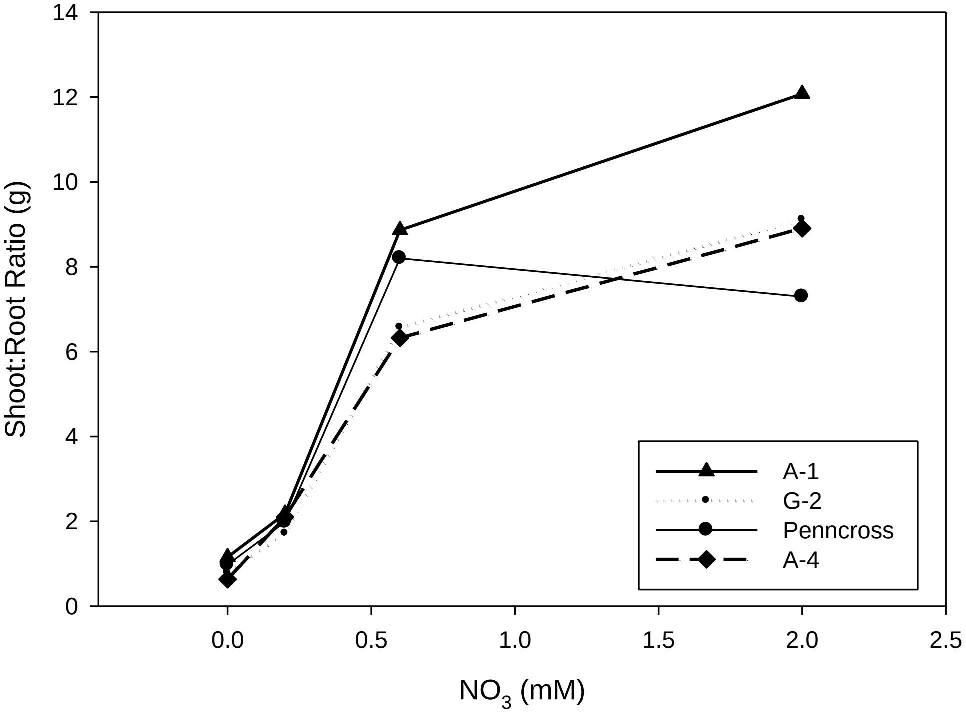
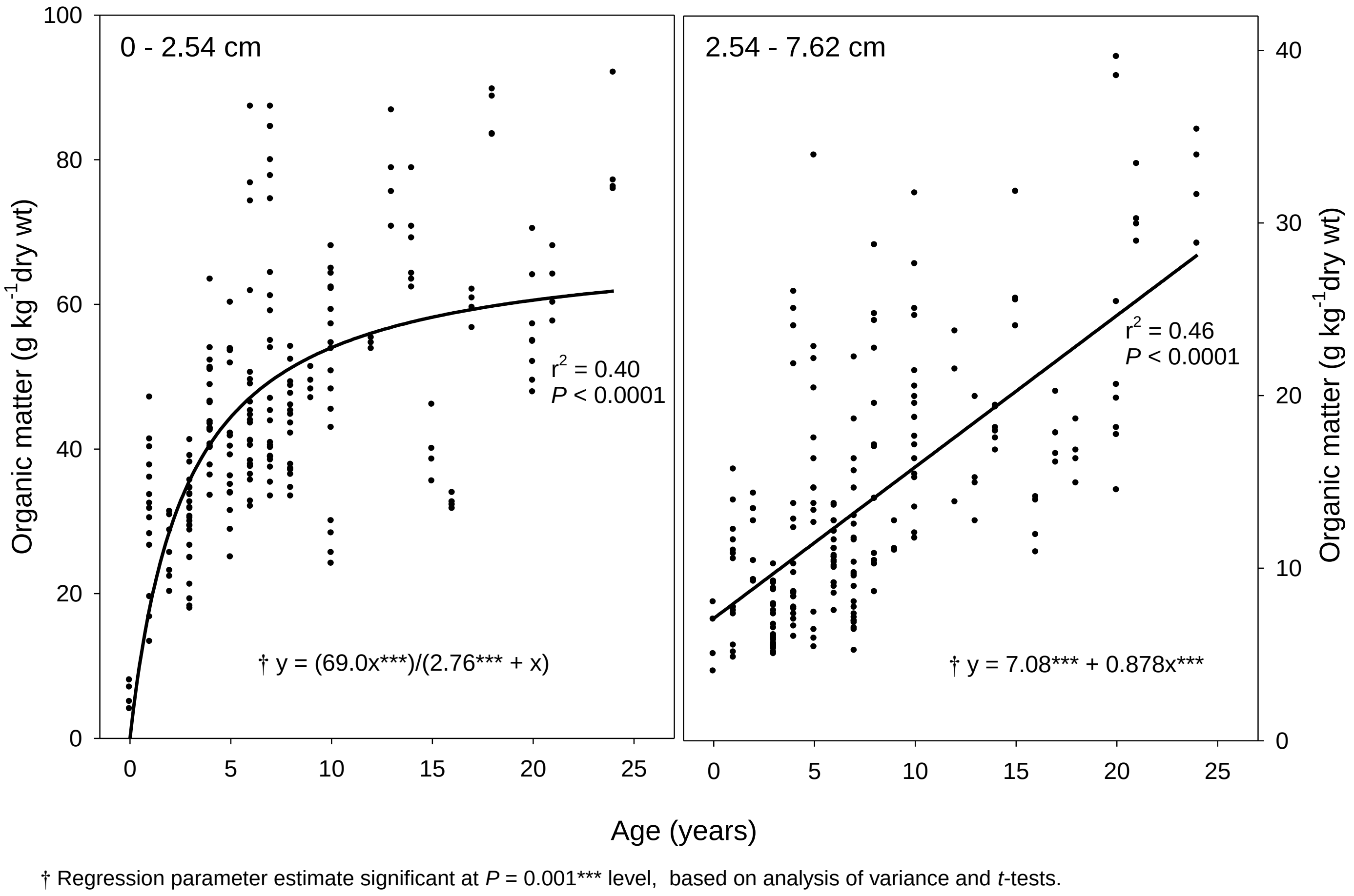


Figure 3.3. Changes in shoot to root growth ratios with increasing nitrogen in hydroponics solution for four bentgrass cultivars.

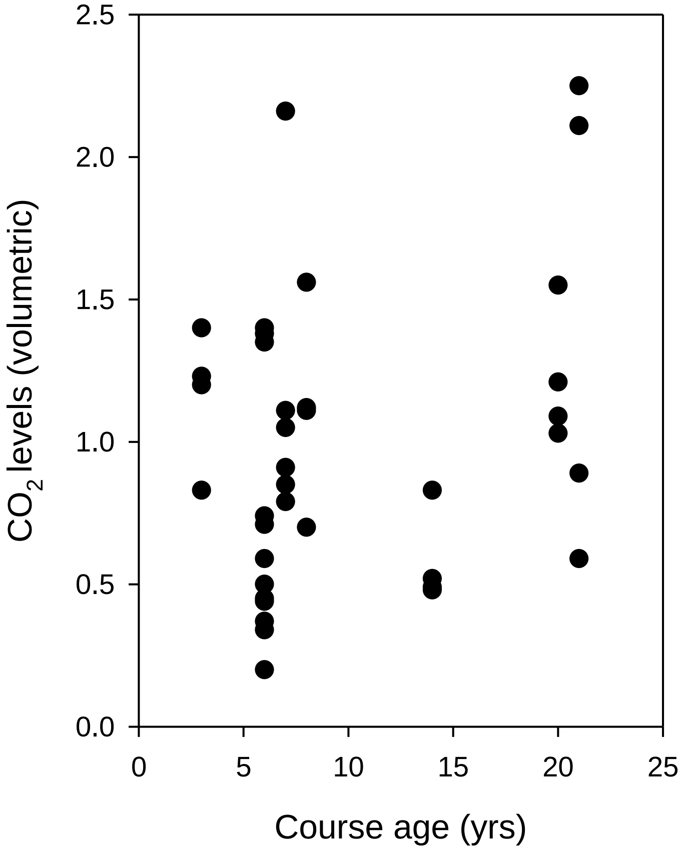
APPENDICES

Appendix Table 1.1. List and age of North Carolina golf courses that participated in the study.

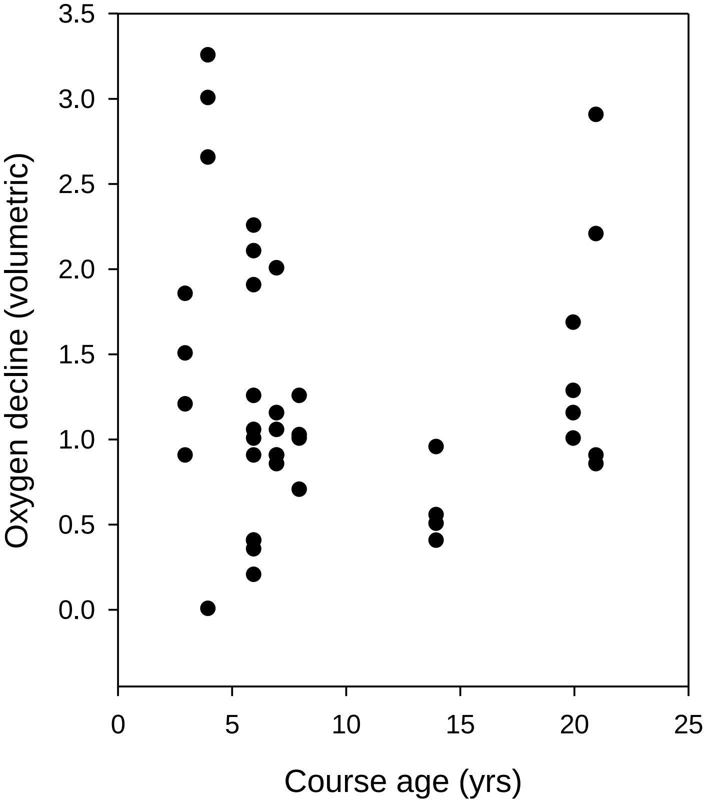
Golf Course Name	**Age**	**Golf Course Name**	**Age**
NCSU Short Game Facility	1	Governors Club - Championship 18	7
Providence Country Club	1	Magnolia Greens Golf Plantation	7
St. James Plantation - Reserve	1	Raleigh Golf Association	7
Country Club of Landfall - Ocean	2	Greensboro Country Club	8
Pinehurst No. 6	2	Pinehurst No. 1	8
Country Club of Landfall - Marsh	3	Pinehurst No. 5	8
Mimosa Hills Country Club	3	St. James Plantation - Players	8
Myers Park Country Club	3	Pinehurst No. 2	9
North Ridge Country Club - Oaks	3	Charlotte Country Club	10
Prestonwood Country Club - Meadows	3	Kinston Country Club	10
The Club at Longview	3	Pine Valley Country Club	10
Heritage Golf Club	4	Pinehurst No. 8	10
Country Club of Landfall - Pines	4	Governors Club - Upper 9	11
Old Chatham Golf Club	4	Prestonwood Country Club - Fairways	12
Pinehurst No. 3	4	Grandfather Golf and Country Club	13
Pinehurst No. 7	4	Jefferson Landing	14
Chapel Hill Country Club	5	St. James Plantation - Founders	15
Eagle Point Golf Club	5	Macgregor Downs Country Club	16
North Ridge Country Club - Lakes	5	Raleigh Country Club	17
St. James Plantation - Members	5	Sedgefield Country Club	18
Country Club of Salisbury	6	Blowing Rock Country Club	20
UNC Finley Golf Course	6	Cape Fear Country Club	20
Pinehurst No. 4	6	Linville Ridge	21
Wakefield Plantation	6	Elk River Club	24
Crescent Golf Club	7	Sapona Country Club	39



Appendix Figure 1.1. A chronosequence of organic matter accumulation in bentgrass putting greens at two depths (0-2.54 cm and 2.54-7.62 cm) below the soil surface. Fifty courses were sampled. The data are means of data from two year periods.



Appendix Figure 1.2. Carbon dioxide levels in the bentgrass root zone for golf courses aged two to 22 years. Data are from 14 courses.



Appendix Figure 1.3. Change in volumetric oxygen levels in bentgrass greens for courses aged two to 22 years. Data are from 14 courses.

Appendix Table 2.1. Predominant soil series with taxonomic classification for each golf course sampled.

Golf Course Name	Age	Series	Description	Taxonomic classification
Lonnie Poole - NCSU	1	CgC2	Cecil gravelly sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		PaF	Pacolet sandy loam, 15 to 45 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
Ocean Ridge Plantation - Leopards Chase	1	Mu	Murville mucky fine sand	Fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults
		Lo	Leon fine sand	Fine-loamy, kaolinitic, thermic Typic Kandiudults
Pinehurst No. 1	1	VaD	Vaucluse loamy sand, 8 to 15 percent slopes	Fine-loamy, kaolinitic, thermic Fragic Kanhapludults
		CaB	Candor sand, 0 to 4 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
Pinehurst No. 6	2	CaB	Candor sand, 0 to 4 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
		VaD	Vaucluse loamy sand, 8 to 15 percent slopes	Fine-loamy, kaolinitic, thermic Fragic Kanhapludults
St. James Plantation - Reserve	2	Lo	Leon fine sand	Sandy, siliceous, thermic Aeric Alaquods
		KrB	Kureb fine sand, 1 to 8 percent slopes	Thermic, uncoated Spodic Quartzipsamments
Hasentree	3	CeD	Cecil sandy loam, 10 to 15 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
		CgC2	Cecil gravelly sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
NCSU Short Game Facility	4	CeC2	Cecil sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		CeB2	Cecil sandy loam, 2 to 6 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
The Club at Longview	5	IrA	Iredell loam, 0 to 3 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
		LdB2	Lloyd clay loam, 2 to 8 percent slopes, moderately eroded	Fine, kaolinitic, thermic Rhodic Kanhapludults
Eagle Ridge Golf Club	7	WmE	Wedowee sandy loam, 15 to 25 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
		AgC2	Appling gravelly sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
Barefoot Resort - Fazio	8	Ec	Echaw sand	Sandy, siliceous, thermic Oxyaquic Alorthods
		Lo	Leon fine sand	Sandy, siliceous, thermic Aeric Alaquods
Barefoot Resort - Love	8	Po	Pocomoke fine sandy loam	Coarse-loamy, siliceous, active, thermic Typic Umbraquults
		We	Witherbee sand	Sandy, siliceous, thermic Aeric Alaquods
Barefoot Resort - Norman	8	Ud	Udorthents and Udipsamments, well drained	n/a

Appendix Table 2.1 (continued).

Golf Course Name	Age	Series	Description	Taxonomic classification
Ocean Ridge Plantation - Tigers Eye	8	GoA	Goldsboro fine sandy loam, 0 to 2 percent slopes	Fine-loamy, siliceous, subactive, thermic Aquic Paleudults
		Fo	Foreston loamy fine sand	Coarse-loamy, siliceous, semiactive, thermic Aquic Paleudults
TPC Wakefield	8	CeB2	Cecil sandy loam, 2 to 6 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		ApC2	Appling sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
Barefoot Resort - Dye	9	Le	Leon fine sand	Sandy, siliceous, thermic Aeric Alaquods
Cape Fear Country Club	9	Be	Baymeade fine sand, 1 to 6 percent slopes	Loamy, siliceous, semiactive, thermic Arenic Hapludults
		Lo	Leon fine sand	Sandy, siliceous, thermic Aeric Alaquods
Heritage Golf Club	9	ApB2	Appling sandy loam, 2 to 6 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		ApB	Appling sandy loam, 2 to 6 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
Keith Hills II - River	9	NoB	Norfolk loamy sand, 2 to 6 percent slopes	Fine-loamy, kaolinitic, thermic Typic Kandiudults
		LnD	Lillington very gravelly sandy loam, 8 to 15 percent slopes	Loamy-skeletal, siliceous, semiactive, thermic Typic Hapludults
Pinehurst No. 4	9	CaB	Candor sand, 0 to 4 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
		VaD	Vaucluse loamy sand, 8 to 15 percent slopes	Fine-loamy, kaolinitic, thermic Fragic Kanhapludults
UNC Finley Golf Course	9	WsB	White Store loam, 2 to 6 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
		CrB	Creedmoor fine sandy loam, 2 to 8 percent slopes	Fine, mixed, semiactive, thermic Aquic Hapludults
Bentwinds Country Club	10	NoB	Norfolk loamy sand, 2 to 6 percent slopes	Fine-loamy, kaolinitic, thermic Typic Kandiudults
		WaC	Wagram loamy sand, 6 to 10 percent slopes	Loamy, kaolinitic, thermic Arenic Kandiudults
Carolina National	10	KrB	Kureb fine sand, 1 to 8 percent slopes	Thermic, uncoated Spodic Quartzipsamments
		BaB	Baymeade fine sand, 1 to 6 percent slopes	Loamy, siliceous, semiactive, thermic Arenic Hapludults
River Ridge Golf Club	10	ApC2	Appling sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		ApB	Appling sandy loam, 2 to 6 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
Grandover Resort West	11	EnB	Enon fine sandy loam, 2 to 6 percent slopes	Fine, mixed, active, thermic Ultic Hapludalfs
		EnC	Enon fine sandy loam, 6 to 10 percent slopes	Fine, mixed, active, thermic Ultic Hapludalfs

Appendix Table 2.1 (continued).

Golf Course Name	**Age**	**Series**	**Description**	**Taxonomic classification**
St. James Plantation - Players	11	Lo	Leon fine sand	Sandy, siliceous, thermic Aeric Alaquods
		Ma	Mandarin fine sand	Sandy, siliceous, thermic Oxyaquic Alorthods
Grandover Resort East	12	EnC	Enon fine sandy loam, 6 to 10 percent slopes	Fine, mixed, active, thermic Ultic Hapludalfs
		EnD	Enon fine sandy loam, 10 to 15 percent slopes	Fine, mixed, active, thermic Ultic Hapludalfs
Myrtle Beach National - Kings North	12	Ec	Echaw sand	Sandy, siliceous, thermic Oxyaquic Alorthods
Ocean Ridge Plantation - Panthers Run	13	BaB	Baymeade fine sand, 1 to 6 percent slopes	Loamy, siliceous, semiactive, thermic Arenic Hapludults
		Lo	Leon fine sand	Sandy, siliceous, thermic Aeric Alaquods
Pinehurst No. 8	13	VaD	Vaucluse loamy sand, 8 to 15 percent slopes	Fine-loamy, kaolinitic, thermic Fragic Kanhapludults
		CaB	Candor sand, 0 to 4 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
Myrtle Beach National - Southcreek	17	Ec	Echaw sand	Sandy, siliceous, thermic Oxyaquic Alorthods
		Ly	Lynn Haven sand	Sandy, siliceous, thermic Typic Alaquods
St. James Plantation - Founders	17	Mu	Murville mucky fine sand	Sandy, siliceous, thermic Umbric Endoaquods
		Tm	Tomahawk loamy fine sand	Loamy, siliceous, semiactive, thermic Aquic Arenic Hapludults
Ocean Ridge Plantation - Lions Paw	20	BaB	Baymeade fine sand, 1 to 6 percent slopes	Loamy, siliceous, semiactive, thermic Arenic Hapludults
		GoA	Goldsboro fine sandy loam, 0 to 2 percent slopes	Fine-loamy, siliceous, subactive, thermic Aquic Paleudults
Pinehurst No. 5	20	VuD	Vaucluse-Urban land complex, 8 to 15 percent slopes	Fine-loamy, kaolinitic, thermic Fragic Kanhapludults
		CbC	Candor-Urban land complex, 2 to 12 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
Pinehurst No. 3	21	CbC	Candor-Urban land complex, 2 to 12 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
		VuD	Vaucluse-Urban land complex, 8 to 15 percent slopes	Fine-loamy, kaolinitic, thermic Fragic Kanhapludults
Pinehurst No. 2	22	CaB	Candor sand, 0 to 4 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
		CaB	Candor sand, 0 to 4 percent slopes	Sandy, kaolinitic, thermic Grossarenic Kandiudults
Pinehurst No. 7	23	VaD	Vaucluse loamy sand, 8 to 15 percent slopes	Fine-loamy, kaolinitic, thermic Fragic Kanhapludults
Jamestown Park	34	ApC	Appling sandy loam, 6 to 10 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
		ApB	Appling sandy loam, 2 to 6 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults

Appendix Table 2.1 (continued).

Golf Course Name	Age	Series	Description	Taxonomic classification
Keith Hills I - Creek	35	OrB	Orangeburg loamy sand, 2 to 6 percent slopes	Fine-loamy, kaolinitic, thermic Typic Kandiudults
		LnB	Lillington very gravelly sandy loam, 2 to 8 percent slopes	Loamy-skeletal, siliceous, semiactive, thermic Typic Hapludults
Croasdaile Country Club	40	WsB	White Store sandy loam, 2 to 6 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
		WsC	White Store sandy loam, 6 to 10 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
North Ridge Country Club - Lakes	40	CeD	Cecil sandy loam, 10 to 15 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
		ApB	Appling sandy loam, 2 to 6 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
North Ridge Country Club - Oaks	40	CeC2	Cecil sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		CeB2	Cecil sandy loam, 2 to 6 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
MacGregor Downs Country Club	41	AgC	Appling gravelly sandy loam, 6 to 10 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
		PaF	Pacolet sandy loam, 15 to 45 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
Carmel Country Club - North	45	WkD	Wilkes loam, 8 to 15 percent slopes	Loamy, mixed, active, thermic, shallow Typic Hapludalfs
		IuB	Iredell-Urban land complex, 0 to 8 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
Carmel Country Club - South	45	MO	Monacan loam	Fine-loamy, mixed, active, thermic Fluvaquentic Eutrudepts
		WkD	Wilkes loam, 8 to 15 percent slopes	Loamy, mixed, active, thermic, shallow Typic Hapludalfs
Chapel Hill Country Club	45	WsB	White Store loam, 2 to 6 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
		WtC2	White Store clay loam, 6 to 15 percent slopes, eroded	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
Greensboro Country Club - Farm	45	PpB2	Poplar Forest clay loam, 2 to 6 percent slopes, moderately eroded	Fine, kaolinitic, mesic Typic Kanhapludults
		PpC2	Poplar Forest clay loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, mesic Typic Kanhapludults
Duke University Golf Club	52	MfC	Mayodan sandy loam, 6 to 10 percent slopes	Fine, mixed, semiactive, thermic Typic Hapludults
		WsE	White Store sandy loam, 10 to 25 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs

Appendix Table 2.1 (continued).

Golf Course Name	Age	Series	Description	Taxonomic classification
Raleigh Country Club	60	ApC2	Appling sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		ApD	Appling sandy loam, 10 to 15 percent slopes	Fine, kaolinitic, thermic Typic Kanhapludults
Alamance Country Club	63	AdB2	Appling sandy loam, 2 to 6 percent slopes, eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		HcB2	Helena sandy loam, 2 to 6 percent slopes, eroded	Fine, mixed, semiactive, thermic Aquic Hapludults
Hope Valley Country Club	83	WsE	White Store sandy loam, 10 to 25 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
		WsC	White Store sandy loam, 6 to 10 percent slopes	Fine, mixed, active, thermic Oxyaquic Vertic Hapludalfs
Carolina Country Club	90	CeC2	Cecil sandy loam, 6 to 10 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
		CeB2	Cecil sandy loam, 2 to 6 percent slopes, moderately eroded	Fine, kaolinitic, thermic Typic Kanhapludults
Greensboro Country Club - Irving Park	99	EuB	Enon-Urban land complex, 2 to 10 percent slopes	Fine, mixed, active, thermic Ultic Hapludalfs
		MuB	Mecklenburg-Urban land complex, 2 to 10 percent slopes	Fine, mixed, active, thermic Ultic Hapludalfs
Eagle Point Golf Club	103	Ke	Kenansville fine sand, 0 to 3 percent slopes	Loamy, siliceous, subactive, thermic Arenic Hapludults