4.4 RESULTS AND DISCUSSION

4.4.1 Measurement and Analysis of Soil Quality Indicators

The intent of this project was to measure and analyze the status of numerous soil quality indicators. Golf courses are highly managed ecosystems that receive numerous applications of fertilizer, pesticides, and irrigation water on a monthly basis. There was no control over the overall management of the research areas. Logbooks containing application rates of fertilizers and pesticides were not reviewed and can be accessed to cross check the influence they may have had on various indicators. With the numerous inputs and management practices, the results of this study will be analyzed using control charts. Using control charts and relating the data to their position relative to the upper and lower control limits, allows for general interpretation since statistical analysis is not allowable in this situation. The use of control charts to interpret the results allows for easy application and conversion to spider/radar graphs, which can reflect the status of numerous soil quality indicators. Table 4.2 is a summary of the established control limits used in this chapter. Additionally, for some soil quality indicators, little if any literature exists to establish upper and/or lower threshold values. For the establishment of the spider radar graphs presented later in this chapter, upper and lower threshold values are arbitrary chosen and were based on the measured results. All soil quality indicators were monitored over a two-year period from October 1999 to October 2001. Microbial analyses represents data collected from samples taken 1997-1998 through October 2001 with the exception of potential mineralizable C and N which was measured in 1997-1998 (pre-construction), July 2000 (undisturbed sites) and October 2000 (post construction).

Table 4.2. Physical, chemical, and biological soil quality indicators measured and the referred method.

Property	Zoysiagrass Silt Loam/Clay Loam Lower Limit	Upper Limit	Reference
Physical properties			
Bulk density (g cm^{-3})	1.30	1.70	Waltz et al. (2000)
Porosity (%)	36	51	Waltz et al. (2000)
Aggregate Stability (MWD, mm)	1.0	6.4	Kemper & Rosenau (1984)
Biological properties			
Microbial biomass C (μg C g-1)	50	800	N/A†
Microbial biomass N (μg N g-1)	50	200	N/A
MBM C/Total C (%)	1	4	Rice et al. (1996)
MBM N/Total N (%)	2	6	Rice et al. (1996)
Mineralizeable C (μg C g^{-1})	0	300	N/A
Mineralizeable N (μg N g^{-1})	0	50	N/A
Chemical properties			
Total Carbon (g C kg^{-1})	10.0	50.0	N/A
Total Nitrogen (g C kg^{-1})	0.5	4.5	N/A
Elec. cond. (mmho cm^{-1})	0	3	Carrow (1995)
CEC (cmol kg^{-1})	15	30	Carrow (2001)
pH	4.5	7	Duncan & Carrow (1993); Musser (1950)
Mg - Mg/CEC (%)	10	20	Skorulski (2001); Christians (1993)
K - K/CEC (%)	2	7	Skorulski (2001); Christians (1993)
Ca - Ca/CEC (%)	60	85	Skorulski (2001); Christians (1993)
Free $CaCO_3$	0	2	Carrow (2001)
Na - Na/CEC (%)	0	15	Carrow (1995); Mitra (2001)

†No reference was found for these indicators under the specific soil and turf conditions.
The values were chosen based on values reported for similar soil types or under similar management.

4.4.2 Pre-Construction (1997-1998) and Undisturbed (July 2000) Analysis of Soil Quality

Sampling of the native prairie soils was conducted in 1997 and 1998 before initial construction. The native vegetation of the development area was tall grass prairie. Nine soils reflecting seven different soil types were identified and analyzed for chemical and biological properties (Figure 4.2). Kansas soils typically have a high base saturation with high levels of Ca and Mg (Table. 4.3). When these elements are found in high concentrations, it is not uncommon for these soils to have excess carbonates and a soil pH above 8.0 (Table 4.4). Prairie soils typically have a high inherent organic carbon and organic matter content. The C:N ratio of these soils is quite low as a result of the high amount of nitrogen in the surface (A) horizon (Table 4.4). The high C and N content in prairie soils also tend to promote healthy and abundant microbial activity and diversity (Table 4.5 and Table 4.6). Microbial biomass C and N (MBC, MBN) in these soils ranges from 0.72 to 1.10 g C kg^{-1} and 0.22 to 0.36 g N kg^{-1} respectively (Table 4.5). The MBC and MBN pools accounted for approximately 2 to 4% and 8 to 11% respectively, of the total C and N pools, respectively (Table 4.6). Potentially mineralizable carbon and nitrogen (PMC, PMN) ranged from 3.72 to 6.25 g C kg^{-1} and 0.00 to 0.80 g N kg^{-1} respectively (Table 4.5). These pools accounted for 9 to 14% and 8 to 17% of the total C and N pools, respectively (Table 4.6).

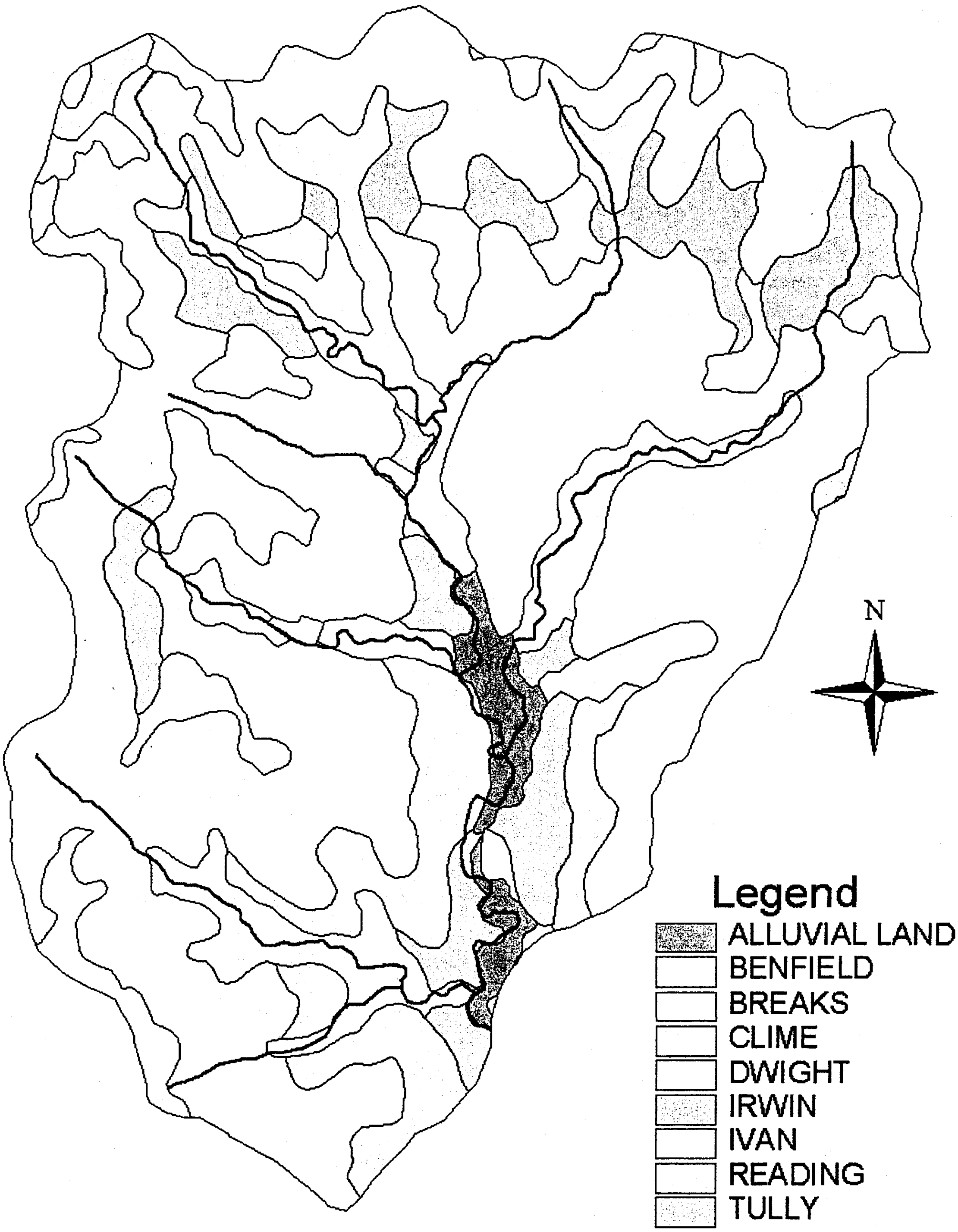

Figure 4.2. Soil map for development site of Colbert Hills Golf Course (taken from Su, 2002).

Table 4.3. Extractable cations for soils sampled before construction at Colbert Hills Golf Course

		Extractable Cations (cmol kg^{-1})							
	Depth						Sum	Sum	Base (sat.)
Soil Series (Site)	(cm)	H	Ca	Mg	K	Na	Bases	Cations	(%)
Tully (Pit 31)	0-12	6.1	12.6	2.61	2.48	0.15	17.9	23.9	74.67
Tully (Pit 32)	0-15	3.7	13.3	3.42	0.87	0.06	17.6	21.3	82.76
Kahola (Pit 33)	0-13	1.3	19.1	2.34	0.83	0.04	22.3	23.6	94.51
Kahola (Pit 34)	0-9	1.1	20.9	2.68	1.17	0.03	24.8	25.9	95.83
Konza (Pit 35)	0-10	7.1	11.1	4.38	0.93	0.25	16.6	23.8	69.99
Clime (Pit 36)	0-11	--	--	--	--	--	--	--	--
Tuttle (Pit 47)	0-15	--	--	--	--	--	--	--	--
Florence (Pit 48)	0-10	14.6	13.2	3.01	1.69	0	17.9	32.5	55.1
Benfield (Pit 49)	0-9	12	23.3	4.01	1.06	0.08	28.5	40.5	70.33

Table 4.4. Chemical data for soils sampled before construction of Colbert Hills Golf Course

		pH		Total	Total		Carbonates
	Depth	H_2O	$CaCl_2$	Nitrogen	Carbon	C:N	CCE
Soil Series (Site)	(cm)	(1:1)	(2:1)	(g kg^{-1})	(g kg^{-1})	Ratio	(%)
Tully (Pit 31)	0-12	6.2	5.6	2.71	33.8	12	1.5
Tully (Pit 32)	0-15	6.4	5.6	2.05	27.6	13	1.5
Kahola (Pit 33)	0-13	7.3	6.7	2.36	28.6	12	1.5
Kahola (Pit 34)	0-9	8.1	6.9	2.41	28.9	12	3.4
Konza (Pit 35)	0-10	6.1	5.2	2.57	32.8	13	1.8
Clime (Pit 36)	0-11	7.8	7.5	3.39	46.2	14	2.5
Tuttle (Pit 47)	0-15	8.1	7.6	3.93	60.4	15	18.3
Florence (Pit 48)	0-10	6.0	5.5	4.04	49.6	12	1.5
Benfield (Pit 49)	0-9	5.6	5.8	2.81	36.2	13	0.0

Table. 4.5. Levels of C and N in the soil organic matter, microbial biomass, and mineralizeable fractions for the native prairie soils at the Colbert Hills Golf Course

Soil Series (Site)	Depth	TC	PMC	MBC	TN	PMN	MBN
1997-1998		---- g C kg^{-1} ----			---- g N kg^{-1} ----		
Tully (Pit 31)	0-12	27.8	3.72	1.10	2.59	0.32	0.29
Kahola (Pit 33)	0-13	--	4.43	0.72	--	0.80	0.31
Konza (Pit 35)	0-10	29.4	4.11	0.73	2.72	0.23	0.22
Clime (Pit 36)	0-11	44.7	6.25	1.06	3.84	0.00	0.36
Benfield (Pit 49)	0-9	40.2	3.55	0.84	3.29	0.57	0.34

Table 4.6. Relationship between potential mineralizable C (PMC), N (PMN), microbial biomass C (MBC) and N (MBN), stable organic C (SOC) and N (SON), and total C (TC), and N (TN) on the native soils at Colbert Hills Golf Course

Soil Series (Site)	Depth	PMC/TC	MBC/TC	SOC/TC	PMN/TN	MBN/TN	SON/TN
1997-1998			%			%	
Tully (Pit 31)	0-12	0.13	0.04	0.83	0.12	0.11	0.77
Kahola (Pit 33)	0-13	--	--	--	--	--	--
Konza (Pit 35)	0-10	0.14	0.02	0.84	0.08	0.08	0.83
Clime (Pit 36)	0-11	0.14	0.02	0.84	--	0.09	--
Benfield (Pit 49)	0-9	0.09	0.02	0.89	0.17	0.10	0.72

TC = total carbon; PMC = potentially mineralizable carbon; MBC = microbial biomass carbon; TN = total nitrogen PMN = potentially mineralizable nitrogen; MBN = microbial biomass nitrogen; SOC = stable organic carbon fraction; SON = stable organic nitrogen fraction

Changes in the design of the course caused construction to encroach onto sites that were originally sampled as undisturbed. Sampling sites were moved and re-tested in July of 2000. Since these soils were in similar condition to the soils tested before construction, most of the chemical and biological properties were similar. Total C and N, pH, and carbonate percentage levels were similar to the respective soil analyzed before construction (Tables 4.7 and 4.8). However, some additional physical and chemical properties such as bulk density, porosity, aggregate stability and electrical conductivity were analyzed in the July 2000 sampling. Prairie soils are characterized by their low bulk density (< 1.23 g cm^{-3}) and high soil porosity ($> 53.3\%$). Additionally, these soils have a very low soluble salt content with EC measurements below 0.61 dS m^{-1} (Table 4.8).

Aggregate stability expressed as either the mean weight diameter (MWD) or geometric mean diameter (GMD) was moderate compared to soils exposed to tillage and used in agriculture (Wright et al., 1999). In the undisturbed soils, aggregate stability ranged from 2.51 to 5.53 mm and 1.23 to 5.79 mm for the MWD and GMD respectively.

Table 4.7. Chemical data for undisturbed soils at Colbert Hills Golf Course

Soil Series (Site)	Depth (cm)	Total Nitrogen ($g\ kg^{-1}$)	Total Carbon ($g\ kg^{-1}$)	$CaCO_3$ CCE (%)	Cation Saturation Ca Sat. (%)	Mg Sat. (%)	K Sat. (%)	Na Sat. (%)	CEC $cmol\ kg^{-1}$
Tully (Pit 31)	0-12	2.72	30.8	0.0	55.0	14.7	5.1	0.6	22.6
Kahola (Pit 33)	0-13	2.51	28.0	2.3	113	9.2	3.1	1.3	21.2
Konza (Pit 35)	0-10	2.58	29.9	0.2	53.2	17.2	3.7	1.7	19.2
Clime (Pit 36)	0-11	2.93	38.4	0.4	60.3	12.7	3.7	0.5	25.4
Tuttle (Pit 47)	0-15	4.17	53.5	0.7	97.5	3.8	3.0	0.4	31.1
Florence (Pit 48)	0-10	4.16	44.5	1.3	67.1	13.4	6.5	0.5	25.3
Benfield (Pit 49)	0-9	4.00	54.4	1.1	98.8	3.9	4.5	0.4	33.9

Table 4.8. Physical and chemical data for undisturbed soils at Colbert Hills Golf Course

Soil Series (Site)	Depth (cm)	Bulk Density ($g\ cm^{-3}$)	Porosity (%)	Aggregate Stability MWD (mm)	GMD (mm)	pH H_2O (1:1)	$CaCl_2$ (2:1)	Elec. Cond. $dS\ m^{-1}$
Tully (Pit 31)	0-12	1.12	57.6	4.78	3.88	6.2	5.7	0.38
Kahola (Pit 33)	0-13	1.22	53.8	2.51	1.23	7.7	7.2	0.52
Konza (Pit 35)	0-10	1.23	53.3	3.12	1.67	6.3	5.8	0.46
Clime (Pit 36)	0-11	1.17	55.8	5.26	4.64	6.5	5.8	0.44
Tuttle (Pit 47)	0-15	1.07	59.5	5.05	4.41	7.8	7.4	0.45
Florence (Pit 48)	0-10	1.18	55.4	3.40	1.96	6.3	5.9	0.44
Benfield (Pit 49)	0-9	1.02	61.4	5.53	5.79	7.9	7.4	0.61

The high amount of inherent organic matter, similar to the soils sampled before construction, contributed to high amounts of PMC and PMN. The PMC and PMN ranged from 5.14 to 8.13 g C kg^{-1} and 0.39 to 1.13 g N kg^{-1} (Table 4.9) respectively. The PMC and PMN pools accounted for 14 to 25 % and 14 to 28 %, respectively, of the total organic C and N pools, respectively (Table 4.10). The conditions of these soils were fairly similar to the soils sampled before construction, however, MBC was lower in the undisturbed samples compared to the pre-construction samples. The MBC and MBN ranged from 0.25 to 0.49 g C kg^{-1} and 0.14 to 0.29 g N kg^{-1} (Table 4.9) respectively. Microbial biomass carbon and MBN accounted for 1 % and 6 to 8%, respectfully, of the total organic C and N pools, respectively (Table 4.10).

Table. 4.9. Levels of C and N in the soil organic matter, microbial biomass, and mineralizeable fractions for the undisturbed soils at the Colbert Hills Golf Course

Soil Series (Site)	Depth	TC	PMC	MBC	TN	PMN	MBN
1997-1998	(cm)		--- g C kg^{-1} ---			--- g N kg^{-1} ---	
Tully (Pit 31)	0-12	30.8	7.27	0.25	2.72	0.39	0.23
Kahola (Pit 33)	0-13	28.0	5.14	0.25	2.51	0.56	0.14
Konza (Pit 35)	0-10	29.9	7.51	0.30	2.58	0.46	0.16
Clime (Pit 36)	0-11	38.4	5.83	0.39	2.93	0.77	0.21
Tuttle (Pit 47)	0-15	53.5	8.11	0.49	4.17	0.90	0.28
Florence (Pit 48)	0-10	44.5	6.44	0.32	4.16	0.72	0.23
Benfield (Pit 49)	0-9	54.4	8.13	0.48	4.00	1.13	0.29

Table 4.10. Relationship between potential mineralizable C (PMC), N (PMN), microbial biomass C (MBC) and N (MBN), stable organic C (SOC) and N (SON), and total C (TC), and N (TN) on the undisturbed soils at Colbert Hills Golf Course

	Depth	PMC/TC	MBC/TC	SOC/TC	PMN/TN	MBN/TN	SON/TN
Soil Series (Site)	(cm)		%			%	
Tully (Pit 31)	0-12	0.24	0.01	0.76	0.14	0.08	0.77
Kahola (Pit 33)	0-13	0.18	0.01	0.81	0.22	0.06	0.72
Konza (Pit 35)	0-10	0.25	0.01	0.74	0.18	0.06	0.76
Clime (Pit 36)	0-11	0.15	0.01	0.84	0.26	0.07	0.67
Tuttle (Pit 47)	0-15	0.15	0.01	0.84	0.22	0.07	0.72
Florence (Pit 48)	0-10	0.14	0.01	0.85	0.17	0.06	0.77
Benfield (Pit 49)	0-9	0.15	0.01	0.84	0.28	0.07	0.65

TOC = total carbon; PMC = potentially mineralizable carbon; MBC = microbial biomass carbon; TN = total nitrogen PMN = potentially mineralizable nitrogen; MBN = microbial biomass nitrogen; SOC = stable organic carbon fraction; SON = stable organic nitrogen fraction

4.4.3 Post-Construction Analysis of Soil Quality Indicators

4.4.3.1 Physical Soil Quality Indicators

4.4.3.1.1 Bulk Density

Bulk density is an important physical soil quality indicator of human-induced soil compaction. High bulk densities can negatively impact root penetration, water infiltration and percolation and gas transfer. The ideal bulk density for healthy turf growth is between 1.30 g cm^{-3} and 1.70 g cm^{-3} (Waltz et al., 2000). Bulk density measurements only reflect sampling periods after construction was complete.

All soils were within the control limits with the exception of the fairway on hole 13, which, was below the lower control limit throughout the post construction (Figure 4.3). While the values were below the lower control limit, this situation does not pose as much threat as values above the upper control limit. Soils with a very low bulk density could be sensitive to compaction, especially when wet, from foot and vehicle traffic. Despite values within the control limits, an overall increase in bulk density has occurred compared to the undisturbed soils (native prairie soils) within the area. These soils had bulk density values ranging from 1.02 g cm^{-3} to 1.23 g cm^{-3} (Table 4.8). The soils on the 13^{th} fairway were the only site within this range.

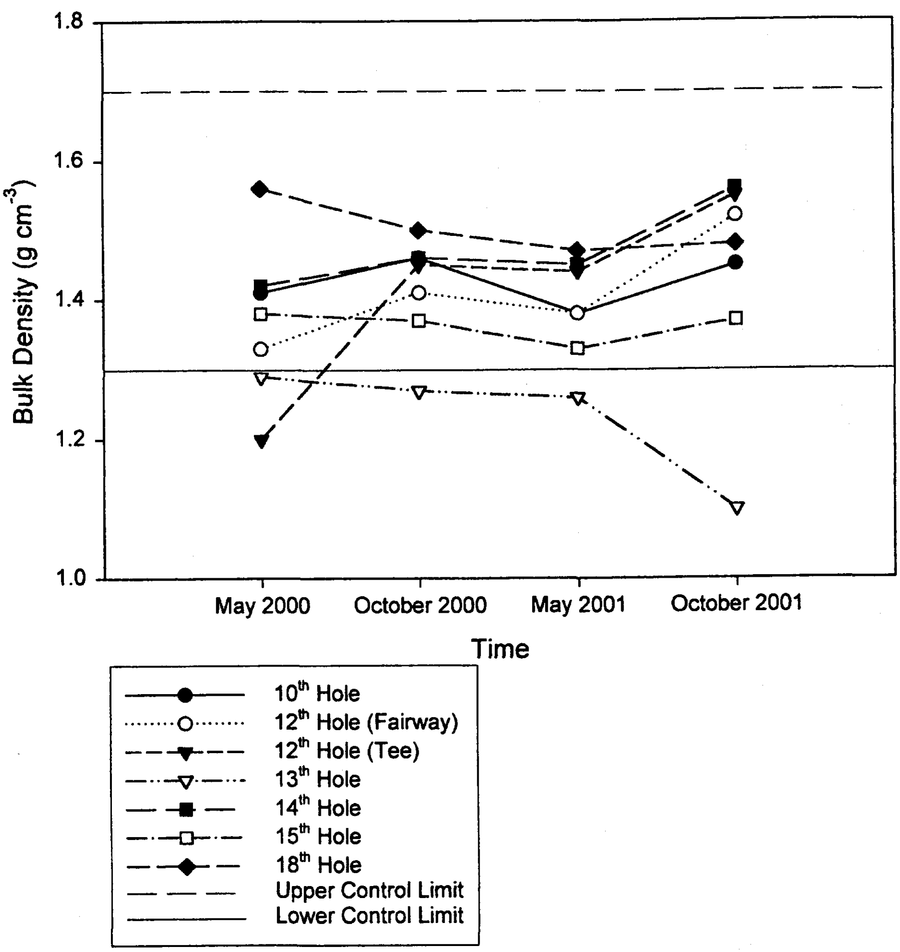

Figure 4.3. Bulk density of fairway soils at Colbert Hills Golf Course.

4.4.3.1.2 Porosity

Porosity, like bulk density, is a physical soil property responsive of human-induced soil compaction. Control limits for soil porosity range from 36% to 51%. Extremely low porosity values can reduce gas flow, water movement, and root development. Extremely high porosity values can indicate potential for compaction. Turf soils receive a considerate amount of irrigation and over irrigation on soils with high porosity can increase the potential for compaction and anaerobic conditions. Soil porosity was determined using the following relationship:

$$\%P.S. = 100-(\frac{B.D.}{P.D.}*100)$$

where B.D. is bulk density, P.D. is particle density (assumed to be 2.65 g cm^{-3}) and %.P.S. is percent pore space.

Ideally, soil porosity is near 50%, which is near the upper control limit. All areas were within the control limits except for hole 13 which had porosity values exceeding the upper control limit of 51% (Figure 4.4). While this is outside the establish range for sustainability, extremely low porosity values would be more harmful to soil functions than a high porosity. Low porosity values would restrict water flow and root development preventing the establishment of a health turf. The high porosity values on hole 13 should be monitored as significant compaction can occur in a short period of time especially under wet conditions, when soils have a greater degree of potential compactability (Hillel, 1980).

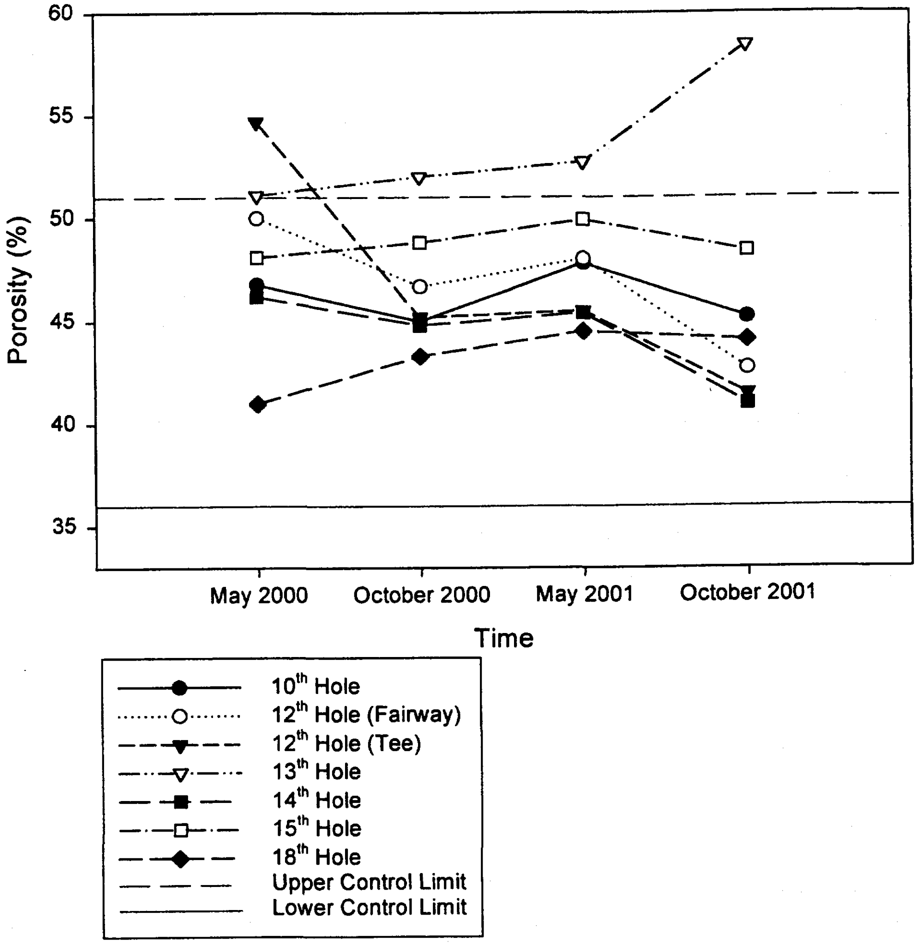

Figure 4.4. Soil porosity of fairway soils at Colbert Hills Golf Course.

4.4.3.1.3 Aggregate Stability

An aggregate is defined as a group of primary particles that cohere to each other more strongly than to other surrounding particles (Kemper & Rosenau, 1986). Soils high in organic matter and/or clay content tend to have more stable aggregates. An aggregate is considered to be stable if the cohesive forces between particles can withstand an applied disruptive force such as compaction, erosion (wind or water), and anthropogenic forces. While ideal conditions (upper and lower limits) are not known for turf soils, soils with a low aggregate stability tend to be sensitive to the formation of soil crusts and erosion from wind and/or water. Soils with greater stability can resist the forces of erosion, especially water erosion and usually have improved porosity and microbial activity compared to those with poor stability (Wright et al., 1999). Forces involved in the determination of aggregate stability include impact and shearing forces during preparation of samples, abrasive and impact forces during sieving, and/or forces involved from the entry of water into the aggregate (Kemper & Rosenau, 1986). While these forces represent those expected in the field, the analysis does not duplicate field conditions. A sieving apparatus was used to move a set of five sieves within a container of water for 10 minutes. The amount of soil left on each sieve was measured and then subjected to further disruption through mechanical and chemical separation to measure the amount of sand particles on each sieve. The sieves used are detailed in Table 4.1.

Aggregate stability can be expressed by determination of the mean weight diameter (MWD) or the geometric mean diameter (GMD). The MWD provides a weighting factor that is proportional to the size of the aggregate and is the most commonly used to express aggregate stability and aggregate size distribution. The MWD is expressed as:

$$\text{MWD} = \sum_{i=1}^{n} \bar{x}_i w_i$$

where $\bar{x}_i$ is the mean diameter of each size fraction and w_i is the total sample weight occurring in the corresponding size fraction. Often, aggregate stability is represented by the GMD on the basis that aggregate size distribution is approximately log-normal rather than normal. The GMD is expressed as:

$$\text{GMD} = \exp\left[\frac{\sum_{i=1}^{n} w_i \log \bar{x}_i}{\sum_{i=1}^{n} w_i}\right]$$

where w_i is the weight of aggregates in a particular size class with an average diameter x_i and $\sum_{i=1}^{n} w_i$ is the total weight of the sample. This calculation allows for the description of aggregation size distribution with two parameters, the geometric mean diameter and the log standard deviation (Gardner, 1956).

In all soils, there was a significant increase in aggregate stability from October 1999 to October 2001 with a decrease observed in May 2001(Figures 4.5 and 4.6). The extremely low stability in the fall of 1999 reflects the condition of the soil during construction. At this time, soil was brought in from areas around Kansas to form a 15 to 30 cm layer on each hole. Soil was disturbed through anthropogenic events and had no vegetative cover until the following spring. This situation is similar to conditions where soils are exposed to tillage practices. Once sod was in place and established, aggregate stability increased from better vegetative cover and improvements in microbial activity and organic matter content. Eash et al. (1994) reported an increase in MWD of soils in soils receiving additions of fungal inoculum. Aggregate stability increased significantly from October 1999 to May 2000 as turf was put in place and microbial activity was improved. Since this time, aggregate stability decreased in May 2001 and increased in October 2001. The decreased observed in the May 2001 sampling may be from freezing and thawing experienced from the previous winter. The aggregate stability reported in October 2001 is fairly similar to the undisturbed soils reported in Table 4.8.

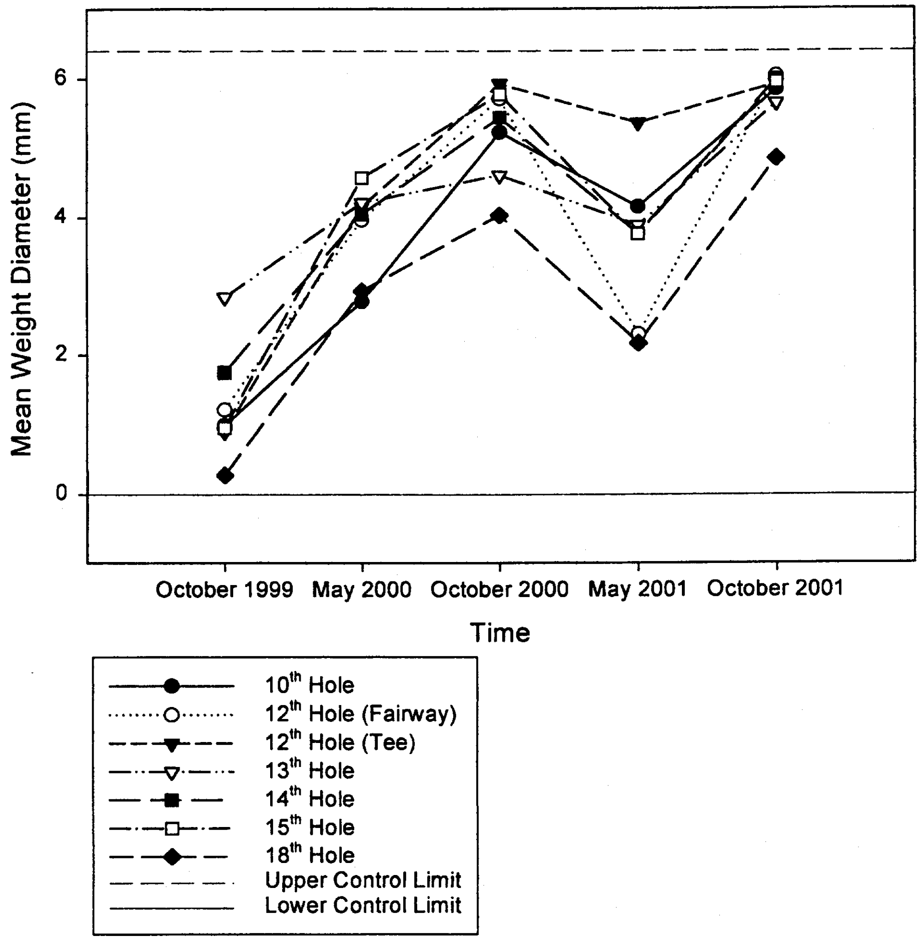

Figure 4.5. Aggregate stability and size distribution (MWD) of fairway soils at Colbert Hills Golf Course.

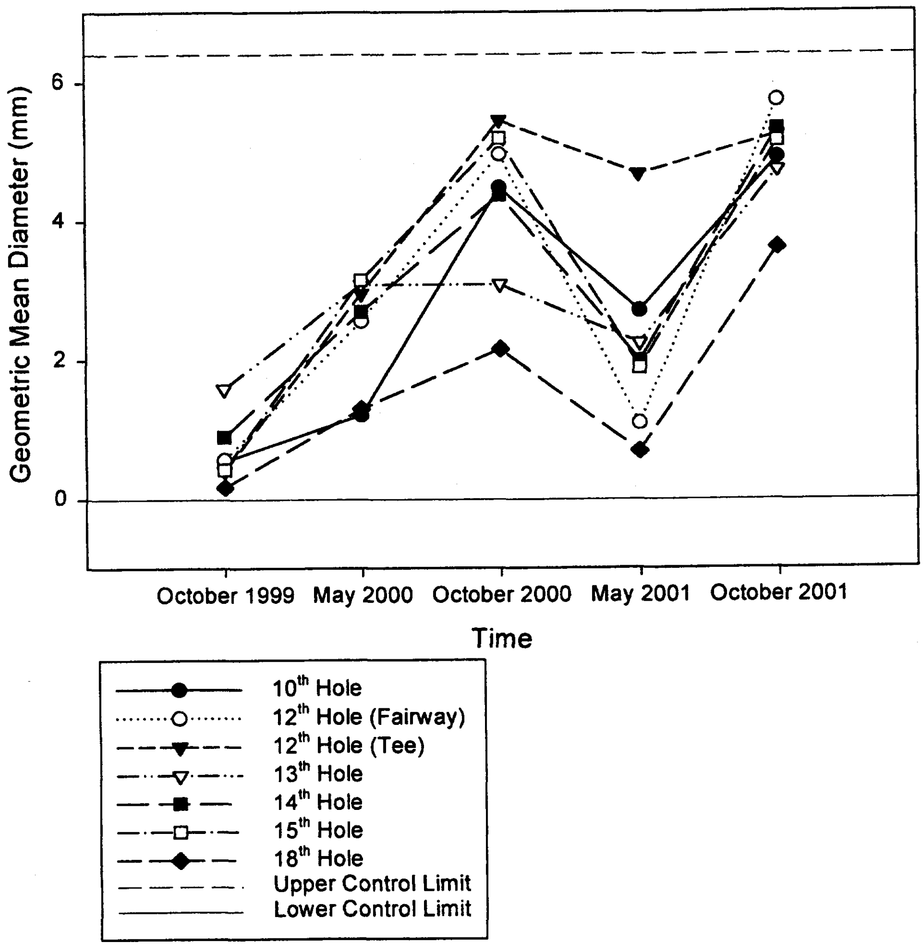

Figure 4.6. Aggregate stability and size distribution (GMD) of fairway soils at Colbert Hills Golf Course.

4.4.3.2 Chemical Soil Quality Indicators

4.4.3.2.1 Sodium Saturation

Sodium saturation (Na) is the proportion of exchange sites (CEC) filled with Na. This property is slightly different from exchangeable sodium percentage (ESP), which also describes the proportion of exchange sites on soil colloids occupied by sodium, (Mitra, 2000). ESP can be determined by the following equation:

$$ESP (\%) = [\text{Exchangeable sodium} \div \text{cation exchange capacity (CEC)}] \times 100$$

Exchangeable sodium is calculated by subtracting the water-soluble sodium from the amount of extractable sodium. Sodium saturation is calculated using the following equation.

$$Na_{sat} (\%) = [\text{Extractable sodium} \div \text{cation exchange capacity (CEC)}] \times 100$$

where extractable Na and CEC is represented in meq $100g^{-1}$ or cmol kg^{-1}. Typically, ESP values greater than 15% produce sodic conditions, a degraded soil physical condition that reduces water uptake and permeability. ESP values between 3.0 and 15.0 are warning signs of an increasing problem with sodium (Carrow, 1995). The same control limits will be used for sodium saturation, however, these values are only an estimate of ESP and are likely to be higher than actual ESP values since soluble sodium was not considered in the calculation.

Sodium saturation was well within the control limits through the two years after construction (Figure 4.7). At times the sodium saturation for the 10^{th}, 14^{th} and 18^{th} fairways did reach above 3 %, which is a possible cause for concern, however, these values are slightly elevated since water-soluble sodium was not accounted for in the calculation.

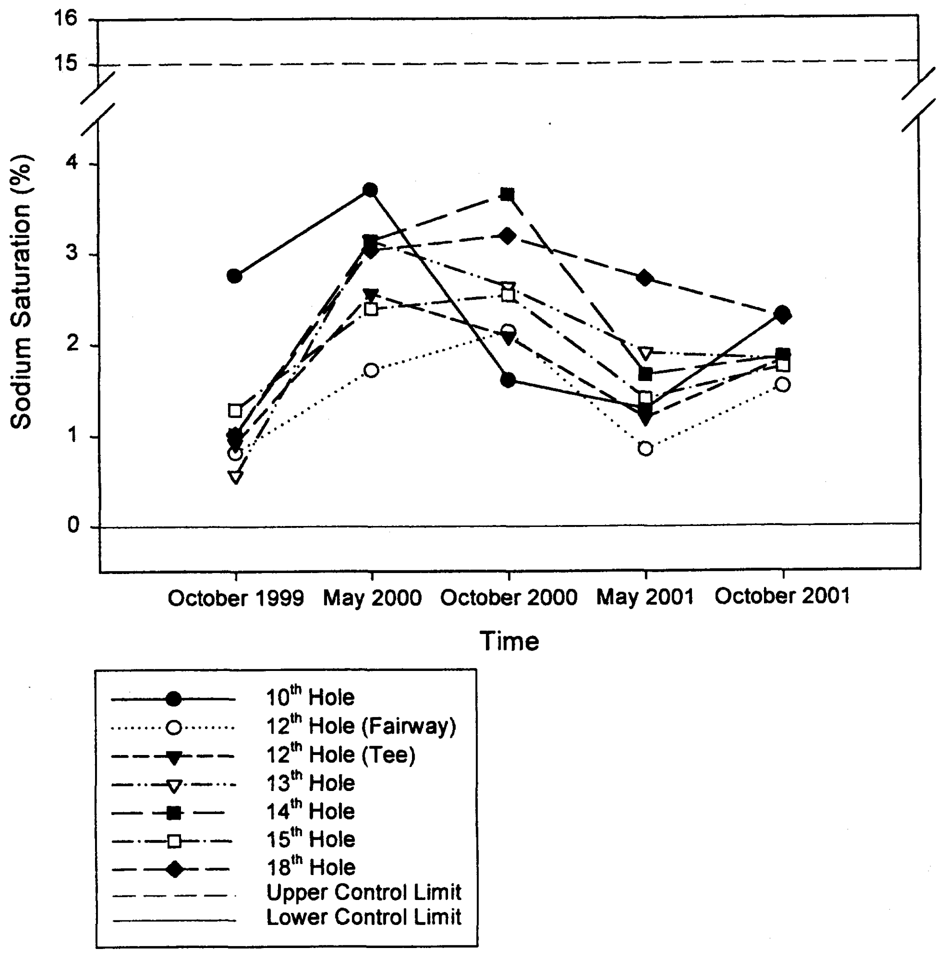

Figure 4.7. Sodium saturation of fairway soils at Colbert Hills Golf Course.

4.4.3.2.2 Electrical Conductivity (EC)

Electrical conductivity measures the amount of dissolved salts present in the soil solution. As previously stated, a measurement of 4 dS m^{-1} or greater would indicate saline conditions. An upper control limit of 3 dS m^{-1} is often used to identify potential problems with salinity before they exceed the limit required for saline conditions. Saline conditions impair the growth and development of turf by increasing the osmotic tension of water, which, in turn, increases the energy plants expand to extract water from the soil (Carrow, 1995). Excess salts inhibit water uptake and cause wilting, even in moist or wet soils (Duncan et al., 2000). Zoysiagrass is highly salt tolerant and can withstand EC values as high as 11 dS m^{-1} (Mitra, 2001). While this grass species can tolerate high salt contents, it is more desirable to keep salt levels below 3 dS m^{-1}.

Electrical conductivity increased considerably over time compared to the soils that were not disturbed (Figure 4.8). Electrical conductivity was within the control limits after construction except in October 1999 for the 2nd fairway sampling site on hole 12 at 3.17 dS m^{-1}. An across-the-board increase in EC was observed from May 2000 to October 2000 with an across-the-board decrease in EC from October 2000 to May 2001.

Soil salinity should be monitored carefully on turf soils as increases in salt content often occur over a short period of time. The use of fertilizers and frequent irrigation are often the source of salts found in turf soils. Appendix F contains the chemical characterization of the Manhattan City water supply. A portion of the irrigation water at Colbert Hills Golf Course comes from city water system.

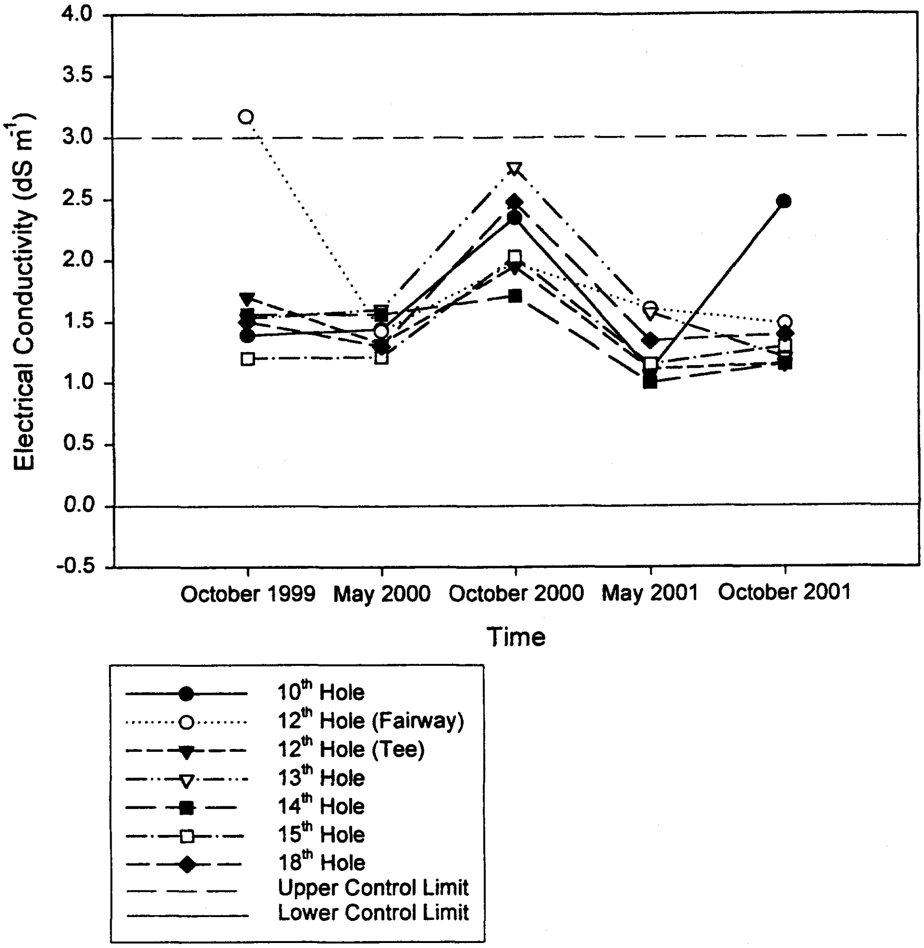

Figure 4.8. Electrical conductivity of fairway soils at Colbert Hills Golf Course.

4.4.3.2.3 Cation Exchange Capacity (CEC)

The CEC, as previously defined, is the quantity of cations reversibly adsorbed and is expressed as moles of positive charge per unit weight of soil (McBride, 1994). An increase in CEC allows for higher retention of nutrients and other chemicals such as xenobiotics. An increase in CEC can influence the buffering capacity of a soil preventing sharp changes in soil pH due to various management practices. Soils with low cation retention often show deficiencies in nutrients such as N, K, Mg, Mn, and Ca (Carrow et al., 2001). Typically, CEC for silt loam texture soils range between 10 and 25 cmol kg^{-1}. Clay and clay loams have a CEC between 20 and 50 cmol kg^{-1}. The soils on the fairways have textures between silt loam and clay loam. An ideal CEC for soils of this texture would be between 15 and 30 cmol kg^{-1} (Carrow et al., 2001).

Overall, all soils had CEC values within the control limits with the exception of the May 2000 measurement on the 10th fairway (Figure 4.9). This value looks to be an outlier or a pocket containing a high amount of silt and little clay. Dramatic decreases in CEC are not common on golf course soils unless bare-soil is exposed and lost from erosion or poor management. However, CEC values can be used to determine fertilizer, liming, and pesticide application rates to improve turf quality.

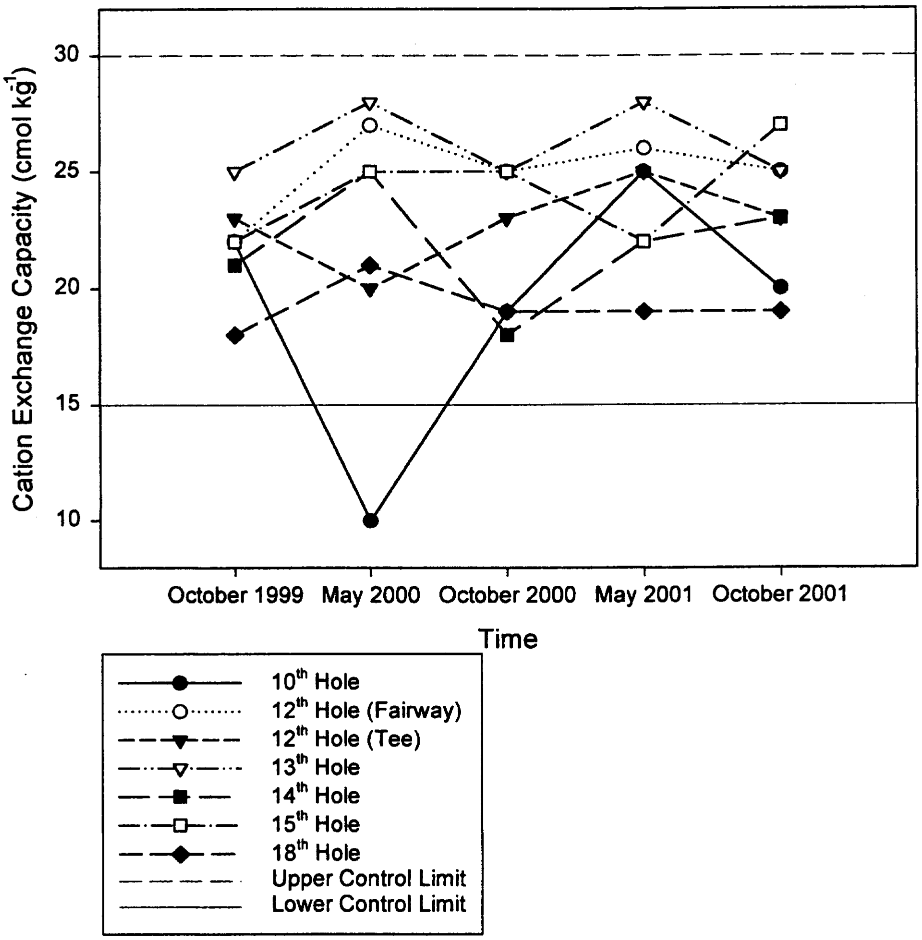

Figure 4.9. Cation exchange capacity of fairway soils at Colbert Hills Golf Course.

4.4.3.2.4 Calcium Saturation

Ca is an important macronutrient necessary for successful turf growth. A considerable amount of Ca is located within cell wall structures and organizes membrane proteins in plant tissues by binding proteins together (Carrow et al., 2001). It is also an important element in the buffering of soil pH and maintenance of soil tilth. Soils with a high amount of Ca tend to have a soil pH near neutral to 8.0. However, extremely high levels of Ca or free $CaCO_3$ can complex with elements such as phosphorus, preventing plant uptake (Duble, 2000). High levels of Ca in the form of soluble salts can contribute to soil salinity (Duncan et al., 2000). Calcium saturation was determined using the same equation used to determine sodium saturation.

Often, a Ca saturation percentage of 65 to 85 % on the CEC sites is considered ideal. However, as long as Na, Al, or Mn ions are not predominant on the exchange sites and there is not an overabundance of Ca compared to Mg and K, Ca saturation values can vary without posing a problem. Generally, ratios of less than 8.5:1 for Ca:Mg and 15:1 for Ca:K are considered ideal. The soils sampled on the 14^{th} and 15^{th} fairways were the only two to have calcium saturation levels within the control limits (Figure 4.10). A Ca saturation of 98% was reported for hole 14 in October 2000. The soils on the 18^{th} fairway were the only ones to be consistently above the upper control limit and exceeded 100%. This indicates the possible presence of free $CaCO_3$. The extremely high amounts of Ca could be the result of the limestone base layer used in construction of the golf course or may be the result of high amount of Ca present in the soils brought in from around Kansas (Mitra, 2001). Calcium toxicities are not common for turf grasses except as a foliar burn when a soluble form of Ca has been applied at a high rate (Carrow et al., 2001). However, high Ca levels can prevent and reduce Mg and K uptake. Thus, turf soils high in Ca should be monitored for K or Mg deficiencies.

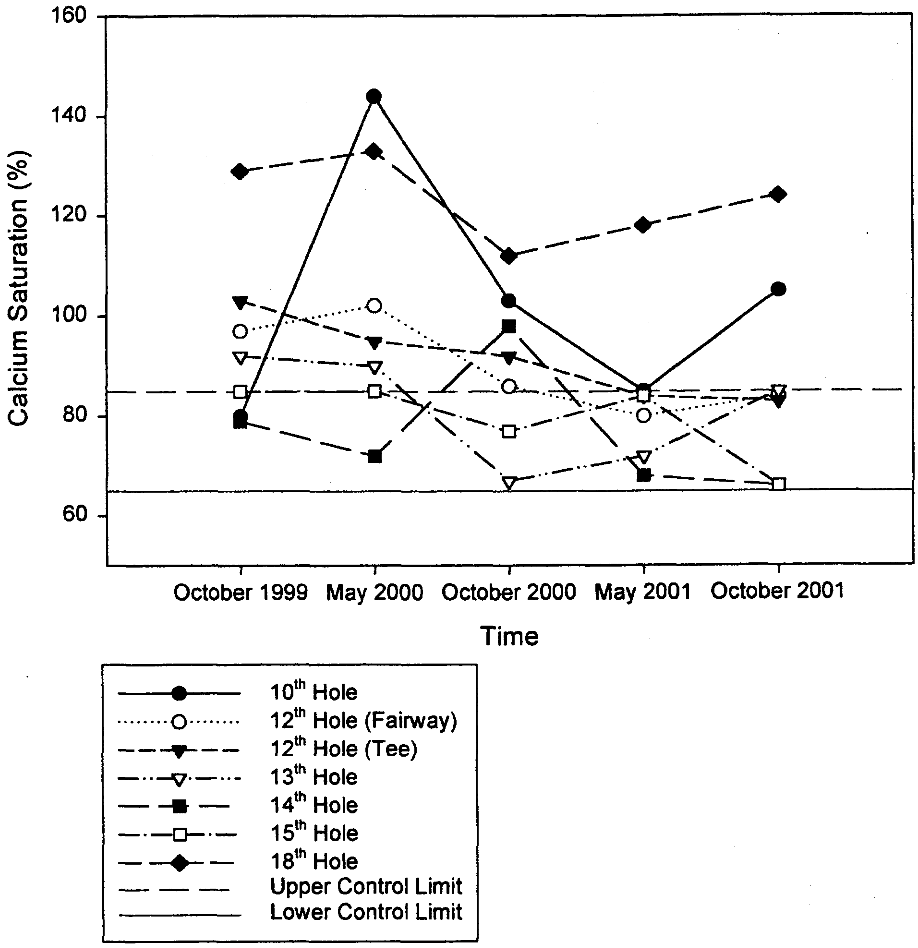

Figure 4.10. Calcium saturation percentage of fairway soils at Colbert Hills Golf Course.

4.4.3.2.5 Free Calcium Carbonate ($CaCO_3$) Content

Along with calcium concentration/saturation, the presence or absence of free calcium carbonate ($CaCO_3$) can be an important soil quality indicator. A soil with excess $CaCO_3$ is termed calcareous and will have a greater pH buffering capacity. Sulfur applications are often required in soils with free $CaCO_3$. It takes roughly 15 kg of S to neutralize 45 kg of $CaCO_3$ (Carrow et al., 2001). A soil with 2 or 3% $CaCO_3$ would require a very high application rate of S to eliminate the excess Ca. The source of free $CaCO_3$ on turf soils is often the result of poor quality irrigation water, especially during the establishment of turf (Duncan et al., 2000).

The soil sampled on the 18th fairway was the only soil to exceed the 2% $CaCO_3$ upper control limit (Figure 4.11). This problem could be foreseen from the high Ca saturation and excessive Ca:K ratios (Figures 4.10 and 4.15). This area also had an excessively high pH compared to the other sampling sites. To lower the soil pH on the 18th fairway from 7.5-8.0 to 6.5 an application of 11-16 kg S per 100 m^2 should be incorporated down to a 25 cm depth. When $CaCO_3$ is present, the S requirement should be increased 60 kg per 1,00 m^2 for every 1% $CaCO_3$ down to a 15 cm depth (Carrow et al., 2001). This application treatment will only work on soils with no established turf. A soil with established or matured turf should receive lower rates of elemental S frequently (2-4 times weekly) over a long period of time (annually).

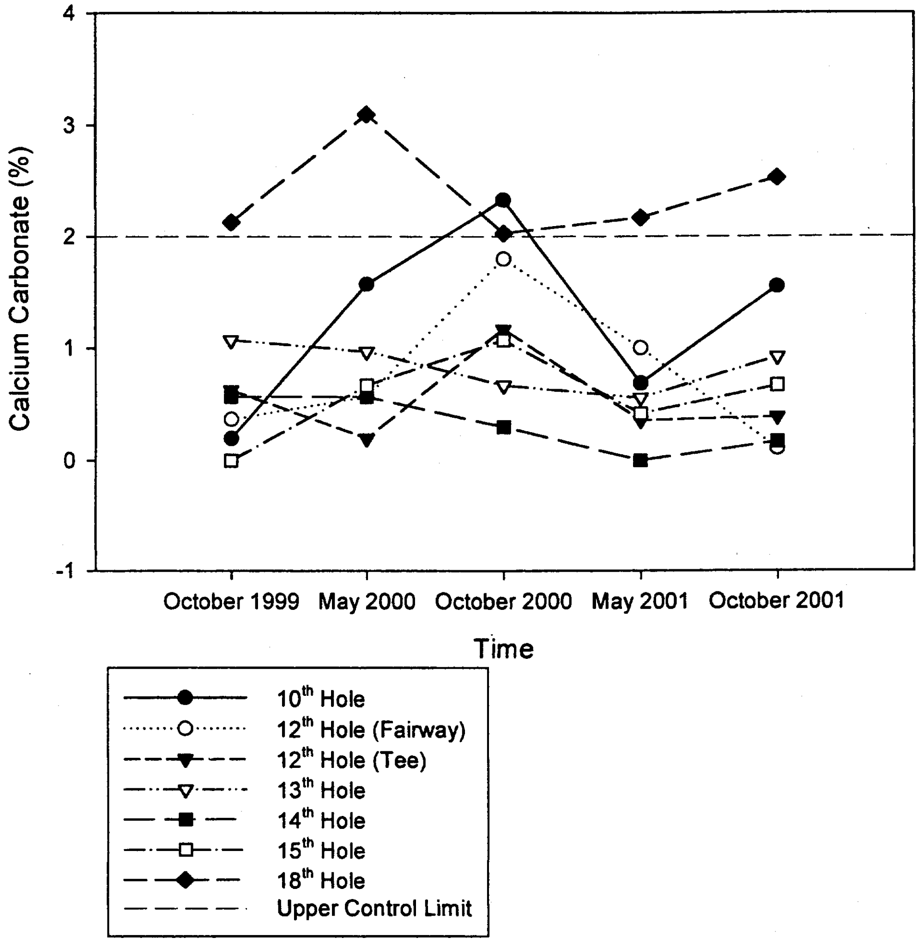

Figure 4.11. Free $CaCO_3$ on fairway soils at Colbert Hills Golf Course.

4.4.3.2.6 Magnesium Saturation

Magnesium is an important nutrient because of its presence in chlorophyll and various enzymatic processes (Carrow et al., 2001; Christians, 1993). Similar to elements like Ca, Mg can influence pH and pH buffering capacity in soils. Magnesium deficiency is common in acidic soils, soils with high amounts of Ca and Na from irrigation water, and those receiving substantial K fertilization. Similar to Ca, Na and K, Mg concentration will be expressed as Mg saturation. Typical values for Mg saturation range between 10 and 20%. Using the equation described for sodium saturation, the saturation of extractable Mg on exchange sites was determined. The ratio of Ca:Mg were also calculated for the fairway soils and are presented in Figure 4.13.

All soils were within the control limits except the soil sampled on the 10th fairway, which had Mg saturation outside the upper control limit in October 1999 and May 2000 (Figure 4.12). Magnesium saturation was also increasing gradually from October 2000 near to the upper control limit. The Ca:Mg ratios for all fairway soils have been consistently below the upper control limit of 8.5:1 (Figure 4.13).

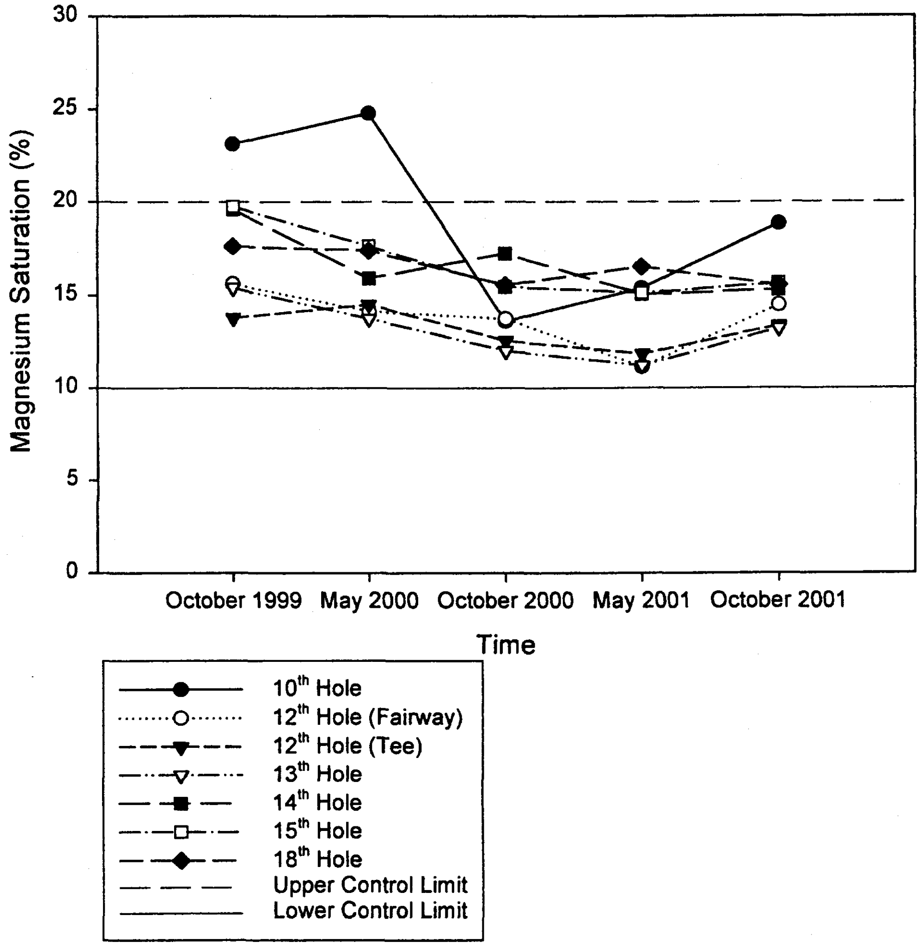

Figure 4.12. Magnesium saturation percentage of fairway soils at Colbert Hills Golf Course.

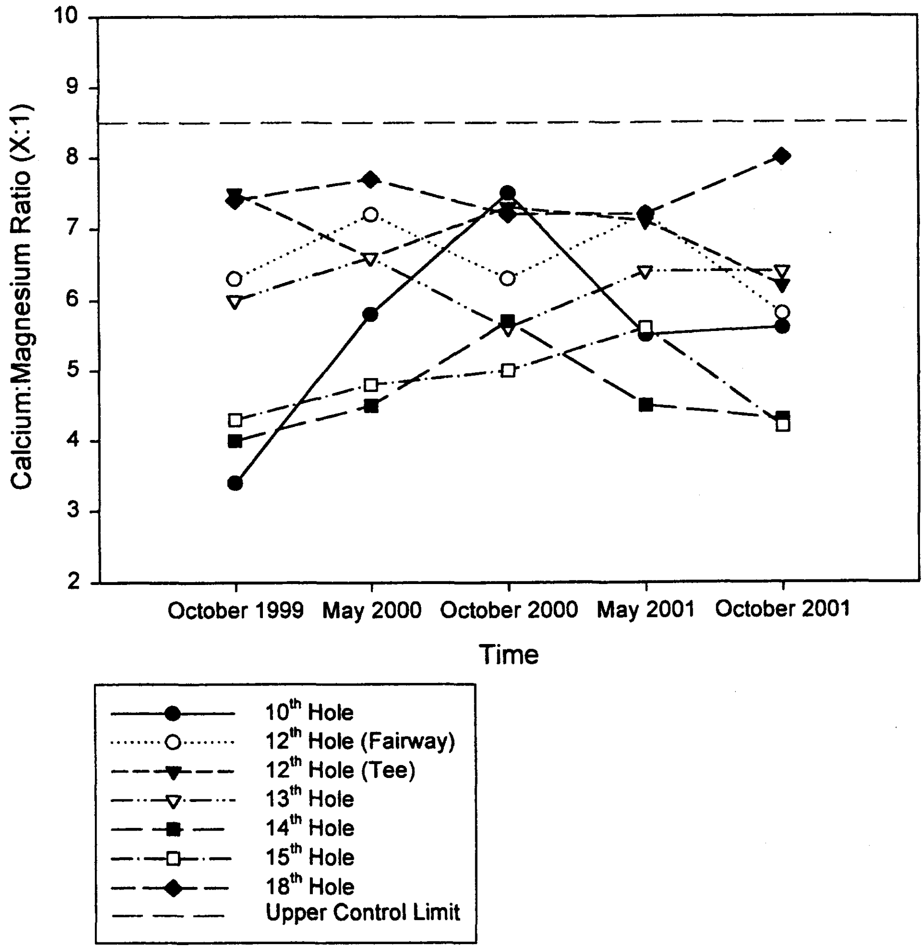

Figure 4.13. The ratio of Ca:Mg on the fairway soils at Colbert Hills Golf Course.

4.4.3.2.7 Potassium Saturation

Potassium is an essential nutrient for healthy turf development. The functions of K in turf include enzyme activation, protein synthesis, the uptake of nitrogen, and disease/stress resistance (Christians et al., 1978; Sartain, 1999). potassium is a critical nutrient in the growth and development of Zoysiagrass. However, Zoysiagrass has a low fertility requirement and can do without frequent fertilization. In some cases excess fertilization can be harmful causing excessive thatch (Brede, 2000). Using the equation described for Na saturation, the saturation of extractable K on exchange sites was calculated.

Potassium saturation was within the control limits for all of the fairway soils (Figure 4.14). Typically, if the Ca:K exceeds a ratio of 15:1, K deficiency is possible. The Ca:K ratio for most of the soils exceeded the upper control limit (Figure 4.15). However, with K saturation values within the control limits, the low fertilization requirement of Zoysiagrass, and no visual symptoms, K deficiency is probably not a problem. If K saturation values do drop and Ca:K ratios remain above the upper control limit this could be a sign of K deficiency. Potassium saturation can also be compared to Mg saturation to obtain an Mg:K ratio. If the ratio of Mg:K is greater than 10:1 K deficiency may occur. All fairway soils had Mg:K ratios less than 10:1 supporting the conclusion that K deficiency is not posing a problem for the Zoysiagrass (Figure 4.16).

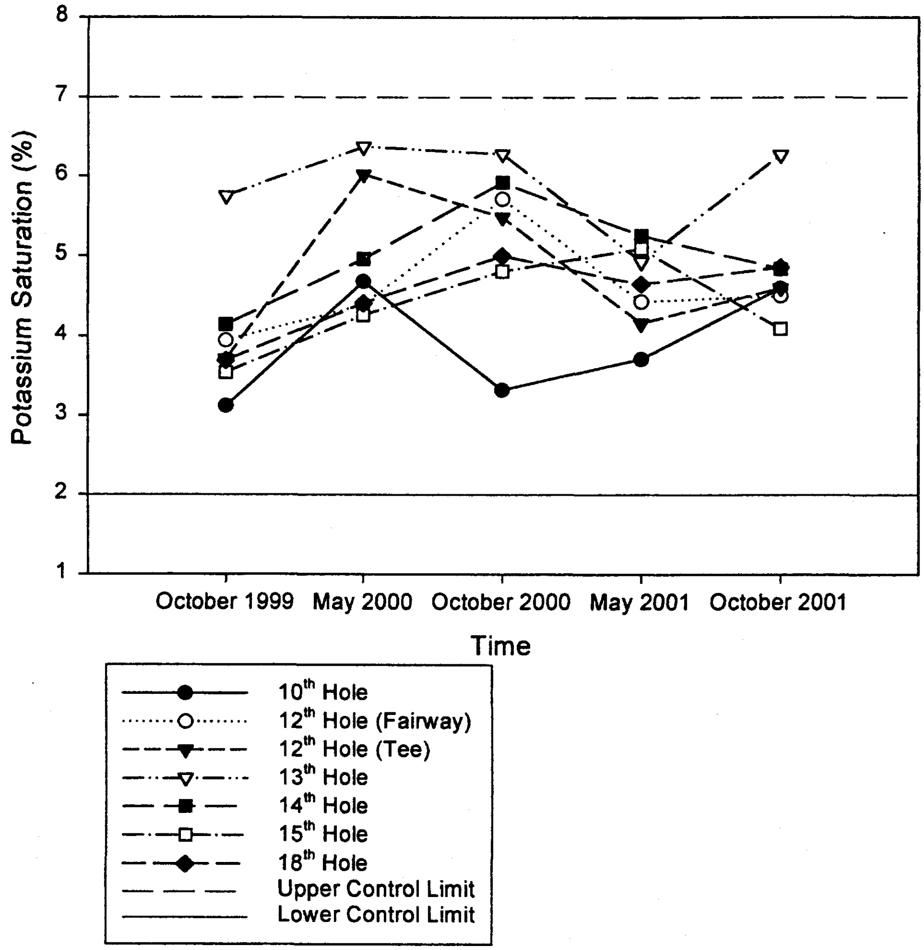

Figure 4.14. Potassium saturation percentage for fairway soils at Colbert Hills Golf Course.

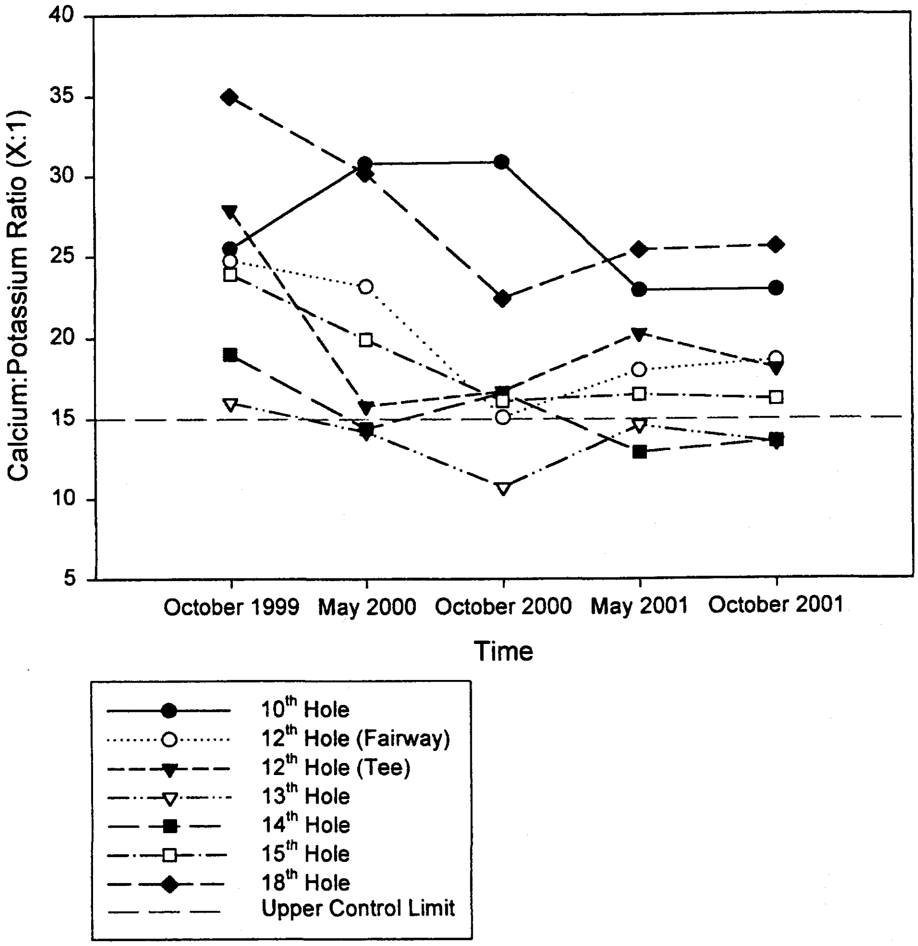

Figure 4.15. The ratio of Ca:K on the fairway soils at Colbert Hills Golf Course.

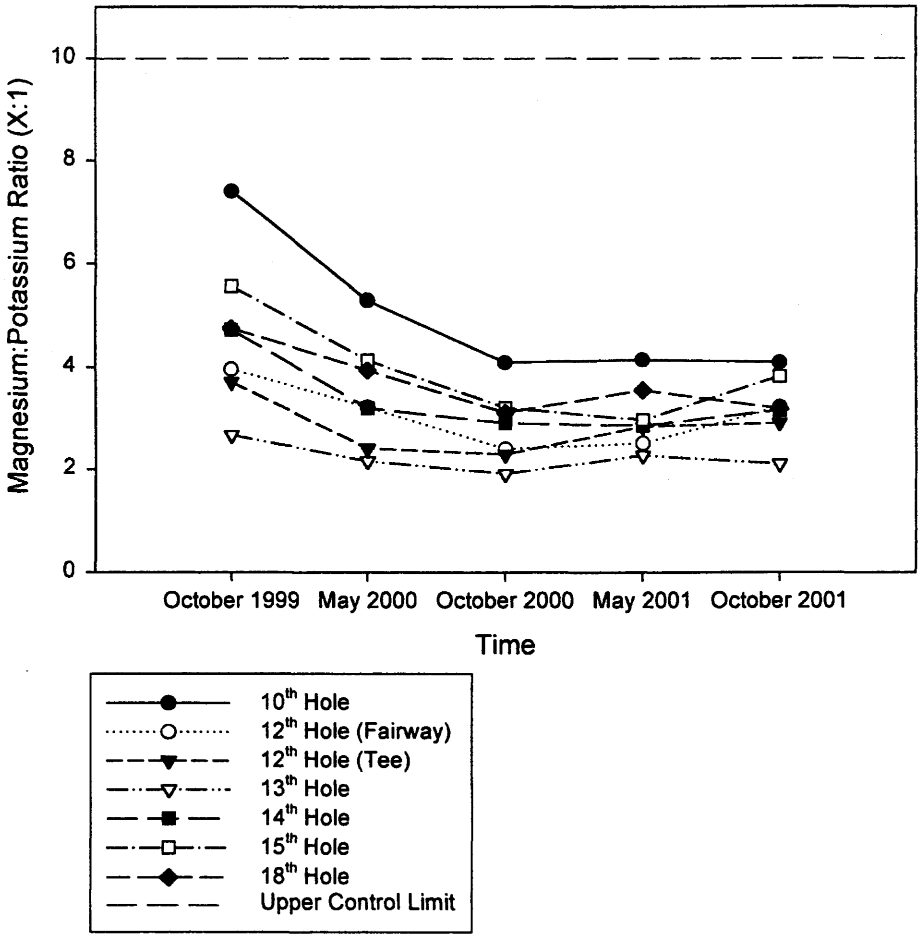

Figure 4.16. The ratio of Mg:K on the fairway soils at Colbert Hills Golf Course.

4.4.3.2.8 Soil pH (1:1 – Water)

Soil pH regulates chemical and biological processes within the soil environment. An ideal soil pH for Zoysiagrass is between 4.5 and 7.5. An extremely low pH could lead to micronutrient toxicity (such as Al, Fe, and Cd) and extremely high could be a sign of saline conditions and/or free $CaCO_3$ (Duble, 2000). Zoysiagrasses tend to be tolerant to excessive acidity (pH < 5.0), however, some varieties can be sensitive to pH values between 4.5 and 5.0 (Carrow et al., 2001).

Soil pH was fairly high in all treatments (Figure 4.17). Soils located on the 10^{th}, 12^{th}, and 18^{th} fairways exceeded the upper control limit at times with soils on 18^{th} fairway consistently above the upper control limit. The Ca saturation and free $CaCO_3$ values on this site were probably a contributing factor to the excessively high pH. However, these values were similar to the native soil conditions as pH measurements for the native soils ranged between 5.6 and 8.1 (Table 4.4). The limestone base layer coupled with the use of potentially high calcium concentrated irrigation water could be the source of the high pH. Frequent testing of the irrigation water along with careful monitoring of soil pH, Ca saturation, and free $CaCO_3$ would help identify and rectify this problem.

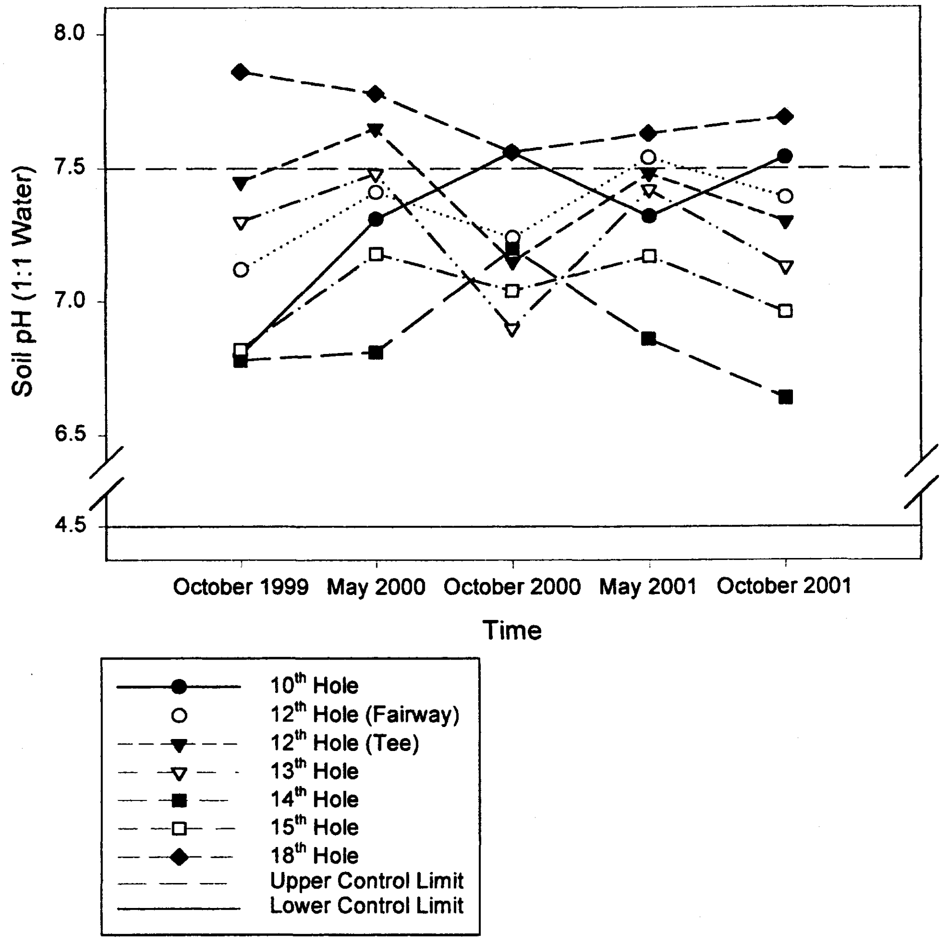

Figure 4.17. Soil pH (1:1 water) for fairway soils on Colbert Hills Golf Course.

4.4.3.2.9 Soil pH (2:1 – $CaCl_2$)

The presence of soluble salts in a soil sample can affect the soil pH and for that reason soil pH is often measured in a mixture of soil and 0.01 *M* $CaCl_2$ at a ratio of 2:1. The excess salt in the solution masks the effects of differential soluble salt concentrations in individual samples. As a result, samples measured with this method tend to have a slightly lower pH than the standard method.

Soil pH values using the 2:1 calcium chloride saturated paste method were slightly lower compared to the 1:1 water method (Figure 4.18). All soils were within the control limits with the fairway soil on hole 18 at or near the upper control limit. This indicates that soluble salts have contributed to soil pH values, however, the low electrical conductivity values previously discussed show no excessive problem is present.

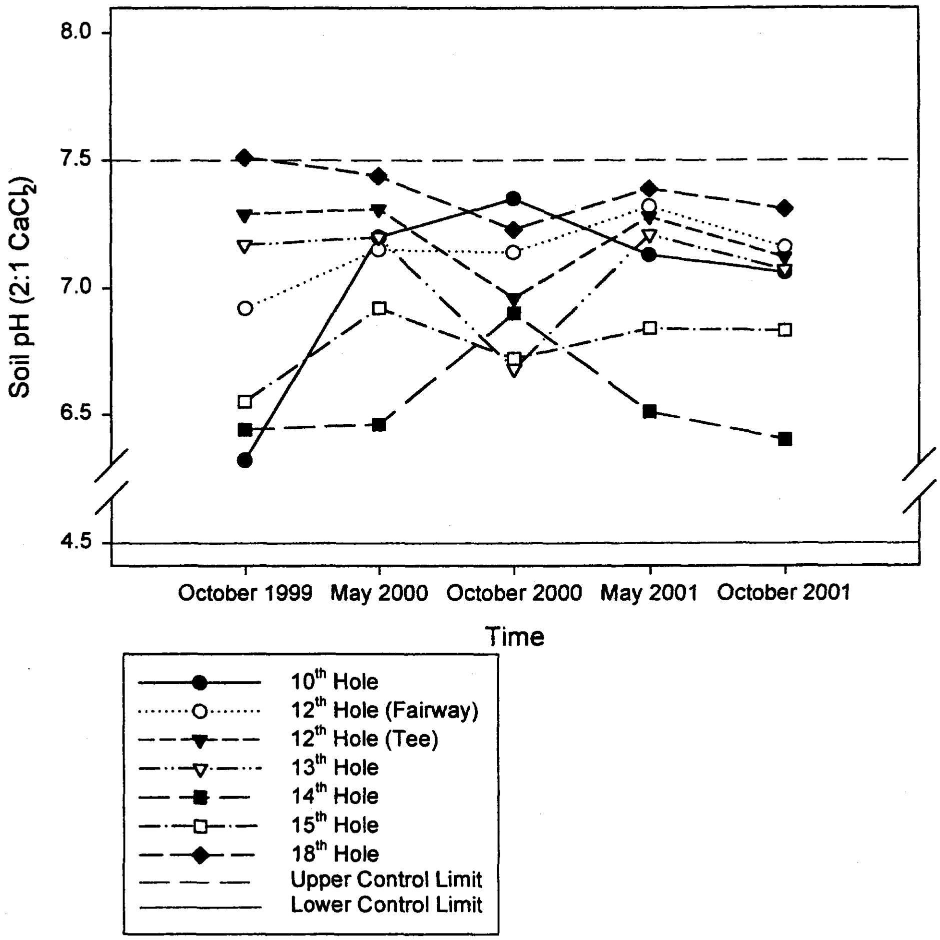

Figure 4.18. Soil pH (2:1 $CaCl_2$) for fairway soils at Colbert Hills Golf Course.

4.4.3.2.10 Total Carbon

The presence of organic matter is critical for chemical sorption of nutrients and development of plant roots. Total C provides a measure of the amount of organic matter present in the soil. An increase in soil organic matter can improve the retention of nutrients, water, and other chemicals as well as provide greater resilience to environmental stress. Typically, fairway soils on golf courses have more inherent organic matter and thus more total C compared to green and tee box soils, which often have a high percentage of sand. A lack of literature and research in turf soils prevents an accurate determination of the upper and lower control limits. Discretionary limits were used and determined from measured values in Figure 4.19.

The soils on the 13th fairway had the highest amount of total carbon while the soils on the 10th and 18th fairway were near the lower control limit. While these trends are shown in Figure 4.19, these statements are not statistically proven. The best comparison with total C for these soils could be with the undisturbed soils. Total C ranged from 28.0 up to 54.4 g C kg^{-1} for these soils (Table 4.7). A significant deviation from the pre-condition or undisturbed soils could be used as a possible indicator of soil degradation. The amount of total C was slightly lower for the fairway soils and ranged from around 10.0 g C kg^{-1} up to near 40.0 g C kg^{-1}. Further research in carbon cycling and carbon dynamics in turf soils would strengthen the relevance of this soil quality indicator.

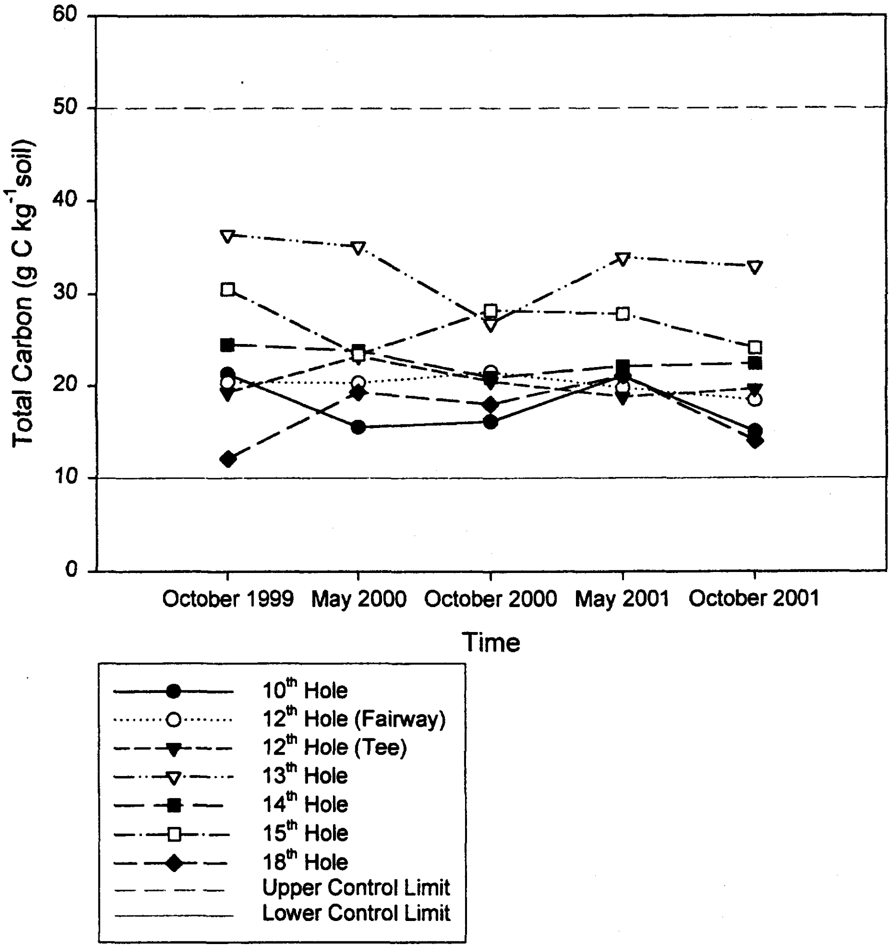

Figure 4.19. Total C in fairway soils at Colbert Hills Golf Course.

4.4.3.2.11 Total Nitrogen

Soil organic matter serves as a storehouse for plant nutrients that are released slowly, particularly nitrogen. The amount of total N and total C provide an estimate as to the amount of organic matter as well as nutrients present for potential plant use. Similar to total C, little literature or research has been conducted as to the ideal range of total N values in turf soils. Discretionary limits were used and determined from measured values in Figure 4.20. Microbial nitrogen percentage (MBM N/Total N) will be used to give a better evaluation of the soil organic matter (Figure 4.26).

Similar to total carbon measurements, the 13th fairway had the highest amount of total N compared to others sampling sites with the soils on the 10th and 18th fairways having the lowest amount of total N (Figure 4.20). Again, these trends are evident in Figure 4.20, however, they were not statistically determined. The high total N on the 13th fairway could indicate a high organic matter content compared to the other soils. This conclusion is further supported by the extremely low bulk density and high porosity reported for this location. Also, the CEC for the 13th fairway was closer to the upper control limit compared to other soils. Organic matter content is known to increase porosity, aggregate stability and CEC along with decreasing bulk density. Further research in carbon and nitrogen cycling in turf soils will help provide a better evaluation of organic matter content and nutrient availability.

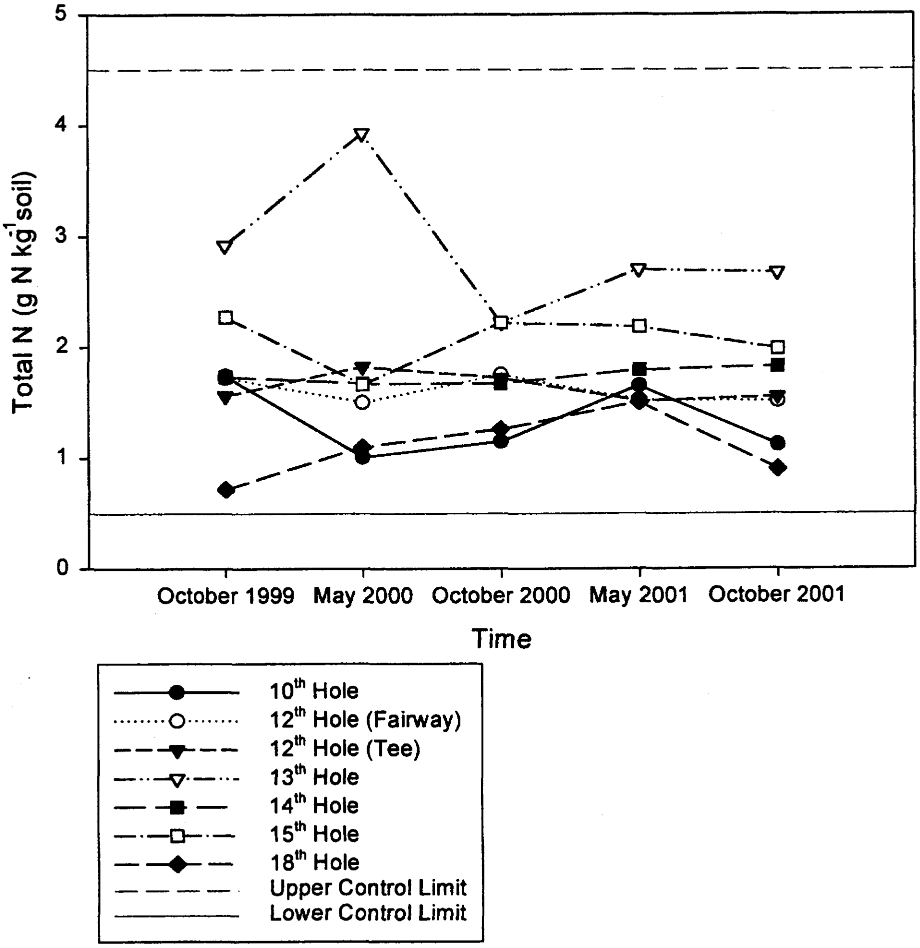

Figure 4.20. Total N for fairway soils at Colbert Hills Golf Course.

4.4.3.3 Biological Soil Quality Indicators

4.4.3.3.1 Microbial Biomass Carbon (MBC)

Microbial biomass is the living component of soil organic matter. More than 95% of the total soil organic matter is nonliving and relatively stable, microbial biomass measurements are critical to assessing the quality of a soil (Rice et al., 1996). Microbial biomass represents the fraction of the soil responsible for the energy and nutrient cycling and the regulation of organic matter transformations. The rapid turnover time of microbial biomass is helpful in the evaluation of management practices and environmental stress (Insam et al., 1989). Microbial biomass carbon measurements alone are not as valuable as the relationship between biomass C and total C. Due to lack of research on turf soils, the upper and lower control limits for MBC were chosen based on values reported under similar soil textures and management practices discussed in Chapter 3. The limits were then adjusted to account for the greater amount of organic matter found in the fairway soils

While statistically not proven, the soils on the 14th fairway had the greatest amount of MBC (Figure 4.21). The soils on the 10th, 12th, 15th, and 18th fairways had a decrease in biomass carbon from October 2000 to May 2001. This may be due to stress created from vehicle and foot traffic, application of xenobiotics, or high soil temperatures. The amount of MBC on the 12th and 15th fairways did rebound and increase in the October 2001 sampling. It is difficult to asses if microbial biomass values alone are at sustainable levels. Overall, research in the biological properties of turf soils is limited and with the exception of the amount of biomass C and N in relation to total C and N, little information exists to help evaluate these properties.

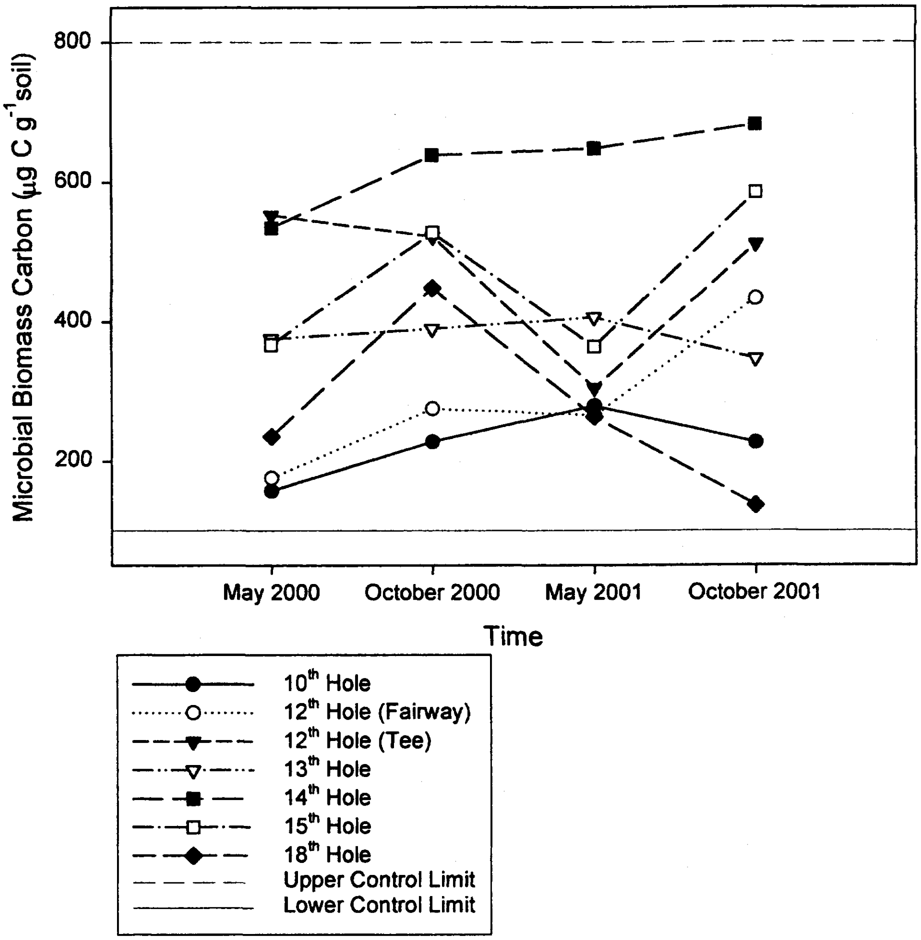

Figure 4.21. Microbial biomass C of fairway soils at Colbert Hills Golf Course.

4.4.3.3.2 Mineralizable Carbon

Mineralizable C is the amount of CO_2-C evolved from metabolizing organisms (Zibilske, 1994). The amount of carbon converted to CO_2 gives a measure of microbial activity and is a gauge used to monitor substrate decomposition and organic matter turnover in soils. Mineralizable C measurements obtained from fumigation-incubation biomass studies reflect the highly labile carbon fraction. Potential mineralizable carbon, which provides a more accurate estimation of carbon mineralization, will also be discussed later in this chapter. Since little information or research has been found on this kind of study in turf soils, the upper and lower threshold limits were chosen based on values reported by Mahmood et al. (1997) discussed in Chapter 3.

While not statistically determined, a seasonal trend was observed in mineralizable C (Figure 4.22). During the fall sampling period mineralizable C decreased and the spring sampling increased. The increase in mineralizable carbon during the May 2001 sampling is inversely related to the microbial biomass carbon measurements during that same time. The high temperatures in the spring may account for the increase in mineralizable carbon and decrease biomass C as microbial activity may have increased. Also, fluctuations in growth patterns or water content could have also contributed to the change in mineralizable C. While, during the fall sampling, the lower temperatures allowed for a decrease in mineralizable C and an increase in microbial biomass.

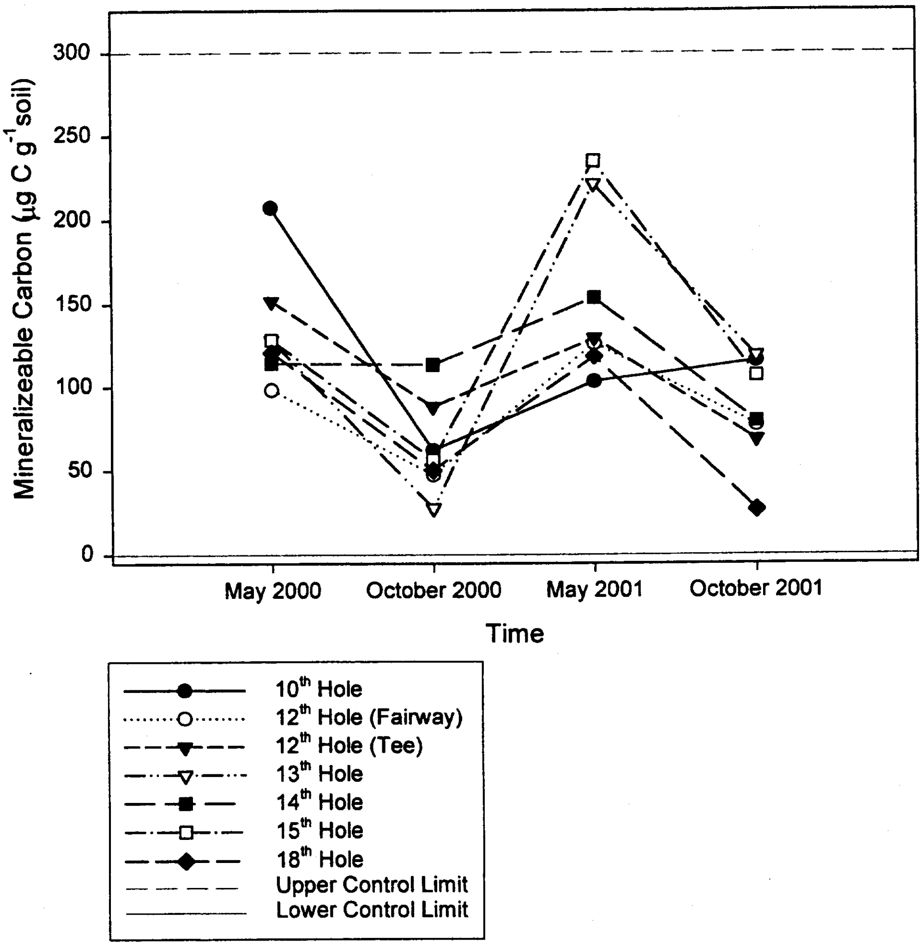

Figure 4.22. Mineralizable C in fairway soils at Colbert Hills Golf Course.

4.4.3.3.3 Microbial Biomass Nitrogen (MBN)

Microbial biomass nitrogen similar to MBC represents the fraction of organic matter responsible for the cycling of nutrients and is critical in the estimation of the biological status or health of a soil (Turco et al., 1994). The effects of tillage, crop rotations, or turf management on nutrient turnover can be assessed by following nutrient pools and microbial activity associated with the microbial biomass (Horwath & Paul, 1994). Microbial biomass nitrogen values for the fairway soils were greater than those of agricultural soils (19 to 160 $\mu g\ N\ g^{-1}$) but less than those of native prairie soils (290 $\mu g\ N\ g^{-1}$) (Rice & Garcia, 1994; Omay et al., 1997). The upper and lower control limits for the fairway soils were set at 200 and 50 $\mu g\ N\ g^{-1}$ respectively (Figure 4.23).

Microbial biomass nitrogen was near the lower control limit for the 10^{th} and 18^{th} fairways and near the upper control limit for the 14^{th} fairway. It is difficult to assess if any specific management practice could be influence microbial biomass N on these soils. Fertilization and xenobiotic applications were not reported and could have some impact on microbial activity. Microbial nitrogen percentage (MBM N/ Total N) provides a better evaluation of nutrient and organic matter dynamics (Figure 4.26).

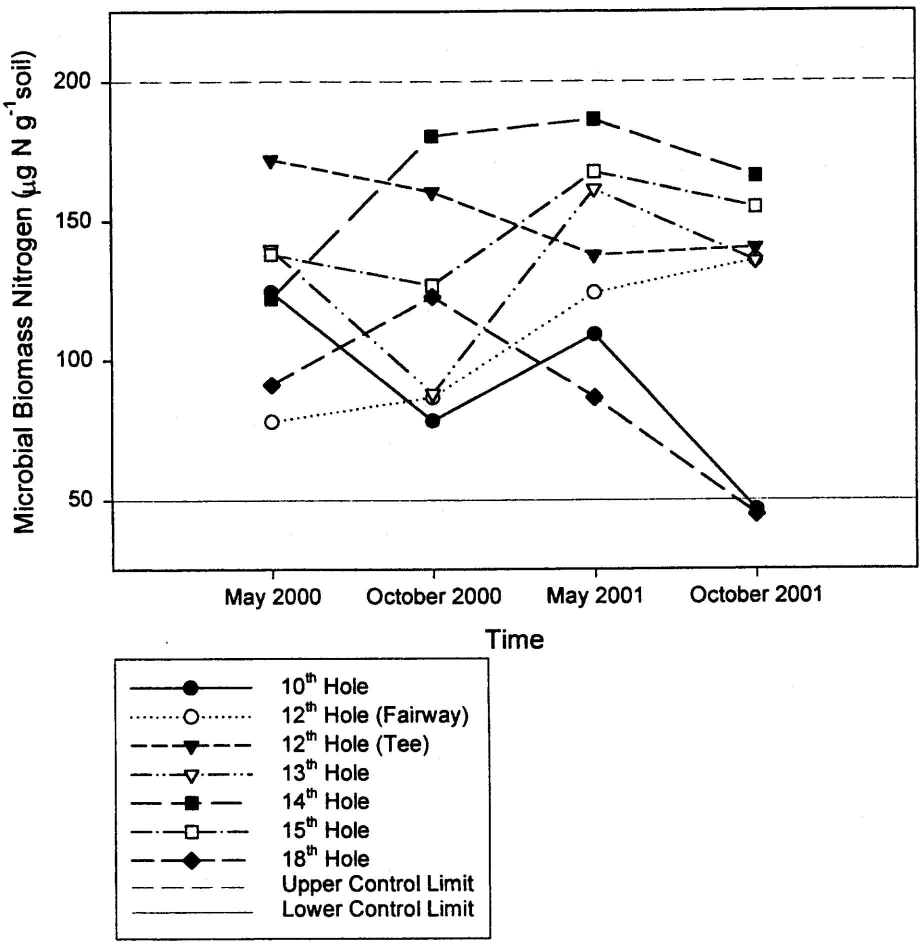

Figure 4.23. Microbial biomass N for fairway soils at Colbert Hills Golf Course.

4.4.3.3.4 Mineralizable Nitrogen

Almost all of the N in soils is present in organic forms that cannot be used by plants. The amount of N mineralized from organic to mineral forms varies based on climatic conditions and inherent soil properties (Drinkwater et al., 1996). The capacity of a soil to supply plant available N is an important indicator of soil quality. Mineralizable N was measured along with microbial biomass C and N and reflects the highly labile fraction of potential mineralizable N (Figure 4.24). The determination of this property is different from potential mineralizable nitrogen, which reflects the labile, active soil C, and N that can be mineralized over the course of a year (Drinkwater et al., 1996). The upper and lower control limits were arbitrarily chosen and were set at 50 and 0 $\mu g\ N\ g^{-1}$.

Mineralizable nitrogen did not change much over the past two years. However, the soil on the 10th fairway increased considerable over the past year. The increase in mineralizable carbon was concurrent with a decrease in microbial biomass N. Little information is available on the use of mineralizable nitrogen measurements in turf soils. Potential mineralizable N determined over a long period of time will provide a better evaluation of the N dynamics on turf soils (Table 4.11).

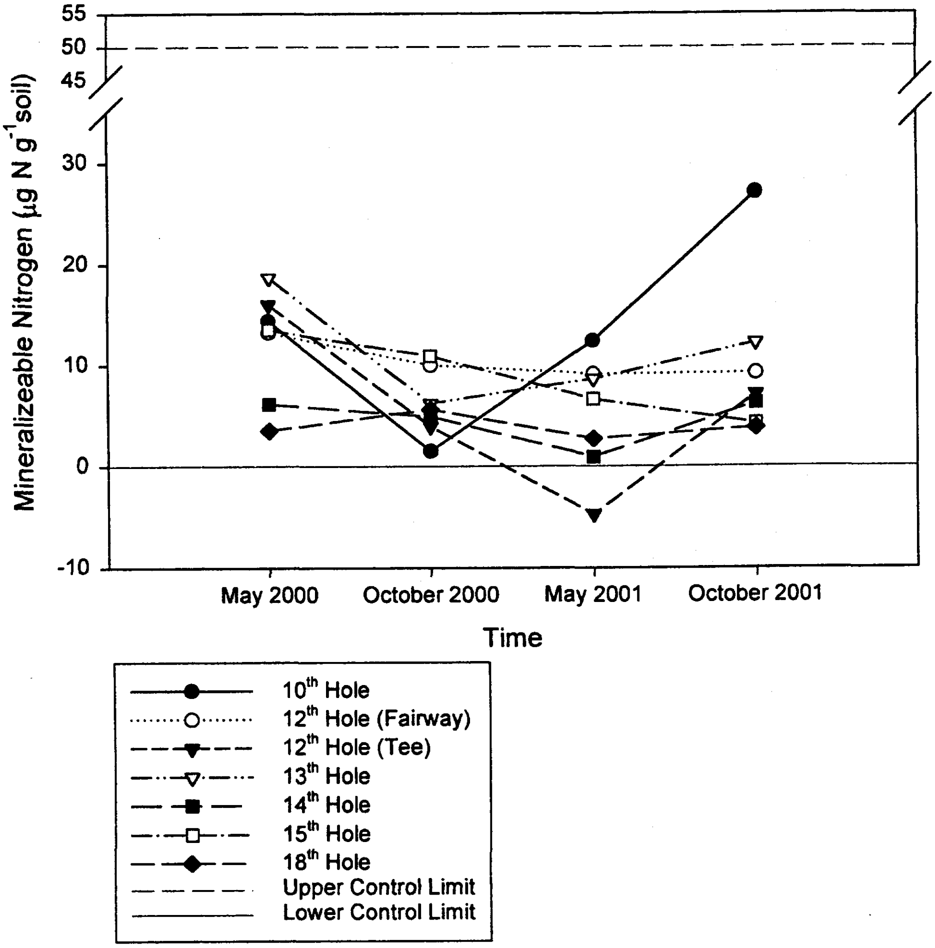

Figure 4.24. Mineralizable N for fairway soils at Colbert Hills Golf Course

4.4.3.3.5 Microbial Biomass C :Total C Ratio (MBC/TOTAL C)

The ratio of MBC to total provides a measure of soil organic matter dynamics and soil quality. The proportion of MBC to total C has been shown to reflect changes in climate, vegetation, and land management (Sparling, 1992). Soil microbial biomass comprises about 1 to 4 % of the total organic C (Sparling, 1992; Rice et al., 1994). Constancy in the ratio between microbial biomass carbon and total carbon has been used as an indication of a system reaching a new equilibrium after disruption. Thus, this measurement is a valuable evaluation of organic matter dynamics in turf soils after construction has been completed.

There was a slight seasonal trend in the ratio of MBC to total C on the fairway soils (Figure 4.25). The MBC:Total C ratio was slightly higher in the fall compared to the spring. This may be due to warmer temperatures and an increase in carbon mineralization (Figure 4.22). The ratio of MBC to total C for soils on the 12th, 13th, and 18th fairways were near the lower control limit throughout the study.

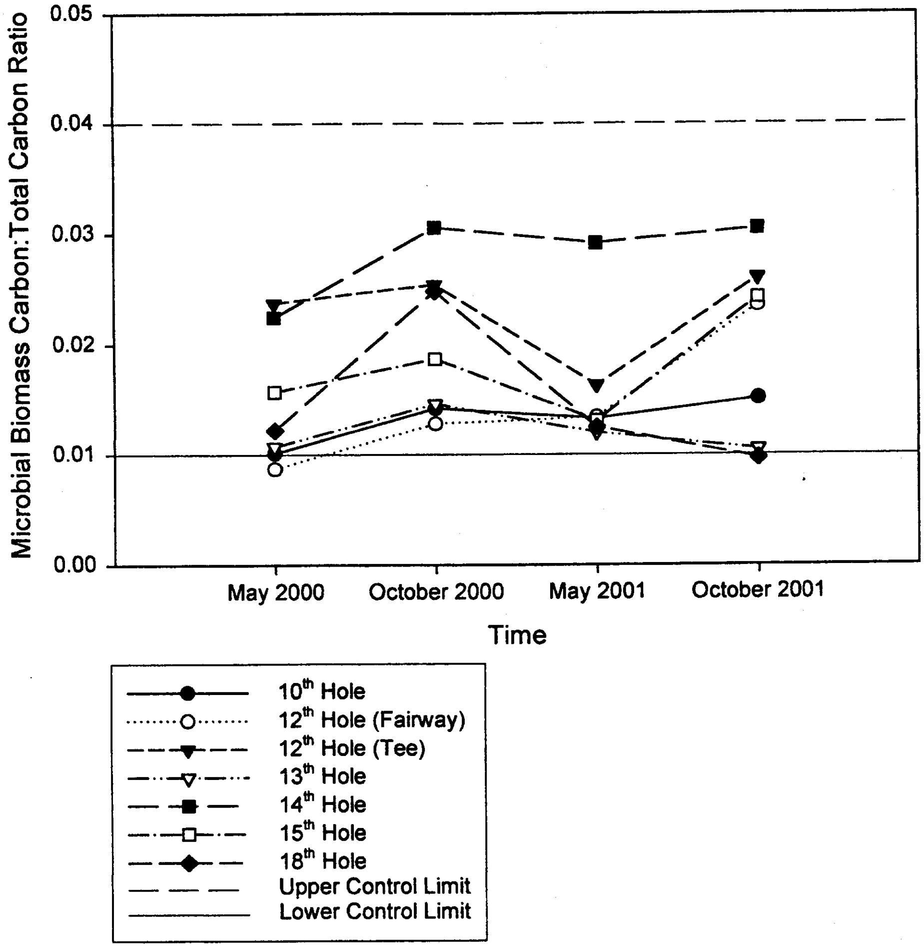

Figure 4.25. Microbial biomass C:Total C Ratio for fairway soils at Colbert Hills Golf Course.

4.4.3.3.6 Microbial Biomass N :Total N Ratio (MBN/TOTAL N)

The ratio of MBN to total N can also be used as a measure of soil organic dynamics and thus soil quality. Soil microbial biomass should be about 2 to 6% of the total organic N (Rice et al., 1996). The ratio of MBN to total N was above the upper control limit throughout the study except for the 13th fairway soil (Figure 4.26). The high levels of microbial biomass N compared to total N may signify more than sufficient nitrogen for turf growth. An increase in available N usually correlates to a darker green color in turf (Brede, 2000). Zoysiagrass, however, usually has a light green color and while increased N may improve turf color it can also cause overgrowth (Brede, 2000; Carrow, 2001). One disadvantage of Zoysiagrass is that it can produce a thatch layer that will literally drown itself and die (Soper et al., 1988). An increase in available N can potentially increase thatch production. Monitoring available N in the future will be pivotal in the prevention of thatch production and improving turf quality.

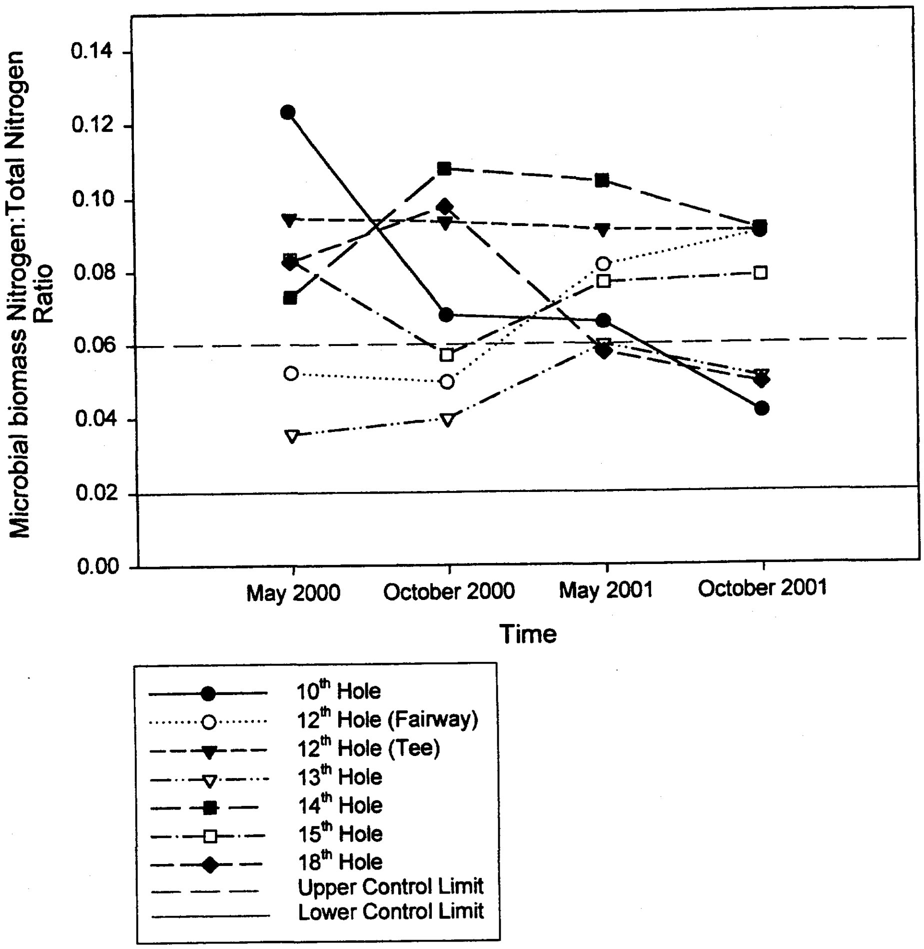

Figure 4.26. Microbial biomass N:Total N ratio for fairway soils at Colbert Hills Golf Course.

4.4.3.3.7 Potential Mineralizable Carbon and Nitrogen

Potential mineralizable carbon and nitrogen (PMC, PMN) can offer a significant understanding of soil organic matter turnover (Rice & Garcia, 1994). The PMC and PMN reflect the biologically active pool of organic matter and are useful in conjunction with total N or soil C as an indicator of soil organic matter quality (Drinkwater et al., 1996).

The PMC and PMN measured in October 2000 were considerably lower than the undisturbed soils measured in July 2000 (Table 4.11). The amount of PMC and PMN ranged from 2.66 to 5.45 g C kg^{-1} and 0.19 to 0.31 g N kg^{-1} respectively and were below values reported by Rice & Garcia (1994) for an unburned tallgrass prairie. This could be due to a loss or reduction of organic matter in the soils brought in to form the golf course compared to the pre-construction conditions. Potentially mineralizable carbon and PMN accounted for 14 to 23% and 11 to 20% of total C and N pools respectively (Table 4.12). Compared to the undisturbed soils measured in July 2000, the fairway soils contained a similar amount of PMC compared to total C however, fairway soils contained slightly less PMN of the total N pool compared to the undisturbed soils. Rice & Garcia (1994) reported that the PMC and PMN pools accounted for 30% and 7% of the total C and N respectively in an unburned prairie soil. While the fairway soils had less PMC and PMN compared to prairie soils, the amount of PMC compared to total C was greater in the unburned prairie while the amount of PMN compared to total N was greater in the fairway soil.

The construction and use of a golf course in the short-term has shown to have an impact on PMC and PMN as well as MBC and MBN. The increase in PMN on the fairway soils, especially if there is a reduction in plant uptake, could be an indicator of potential N losses through leaching (Drinkwater et al., 1996). A loss in PMC could be a sign of eventual degradation in aggregate stability and organic matter content (Tisdall & Oades, 1982). Continual research and sampling will help provide further information on the resilience and stability of soil microorganisms in golf course soils.

Table. 4.11. Levels of C and N in the soil organic matter, microbial biomass, and mineralizeable fractions on the fairway soils at Colbert Hills Golf Course

Sampling Site	Depth	TC	PMC	MBC	TN	PMN	MBN
2000	(cm)		---- $g\ C\ kg^{-1}$ ----			---- $g\ N\ kg^{-1}$ ----	
CH-10	0-6	16.1	3.74	0.23	1.15	0.23	0.08
CH-12F	0-6	21.5	2.91	0.28	1.75	0.19	0.09
CH-12T	0-6	20.5	4.75	0.52	1.72	0.31	0.16
CH-13	0-6	26.8	5.45	0.39	2.22	0.28	0.09
CH-14	0-6	20.9	3.93	0.64	1.67	0.21	0.18
CH-15	0-6	28.2	5.28	0.53	2.22	0.28	0.13
CH-18	0-6	18.0	2.66	0.45	1.26	0.17	0.12
Tallgrass Prairie*	0-5	31.0	8.86	0.98	2.69	0.35	0.29

*Data for unburned tallgrass prairie soil (from Rice & Garcia, 1994)

TOC = total carbon; PMC = potentially mineralizable carbon; MBC = microbial biomass carbon; TN = total nitrogen

PMN = potentially mineralizable nitrogen; MBN = microbial biomass nitrogen

Table 4.12. Relationship between potential mineralizable C (PMC), N (PMN), microbial biomass C (MBC) and N (MBN), stable organic C (SOC) and N (SON), and total C (TC), and N (TN) on the fairways at Colbert Hills Golf Course

	Depth	PMC/TC	MBC/TC	SO/TC	PMN/TN	MBN/TN	SO/TN
Sampling Site	(cm)		%			%	
CH-10	0-6	0.23	0.01	0.75	0.20	0.07	0.73
CH-12F	0-6	0.14	0.01	0.85	0.11	0.05	0.84
CH-12T	0-6	0.23	0.03	0.74	0.18	0.09	0.73
CH-13	0-6	0.20	0.01	0.78	0.13	0.04	0.83
CH-14	0-6	0.19	0.03	0.78	0.13	0.11	0.77
CH-15	0-6	0.19	0.02	0.79	0.13	0.06	0.81
CH-18	0-6	0.15	0.03	0.83	0.14	0.10	0.77
Tallgrass Prairie*	0-5	0.30	0.04	0.7	0.07	0.11	0.82

*Data for unburned tallgrass prairie soil (from Rice & Garcia, 1994)

TOC = total carbon; PMC = potentially mineralizable carbon; MBC = microbial biomass carbon; TN = total nitrogen

PMN = potentially mineralizable nitrogen; MBN = microbial biomass nitrogen; SO = stable organic fraction