# CHAPTER THREE

## Hollow Tine and Water Injection Cultivation of a Compacted Kentucky Bluegrass Turf

### ABSTRACT

A regular core cultivation program is frequently recommended on general turf sites receiving high levels of traffic. Few studies have evaluated cultivation of general turf subjected to regular compaction stress. This study was initiated on a six-year-old 'Cheri' Kentucky bluegrass (*Poa pratensis* L.) turf growing on a sandy loam soil (fine-loamy, mixed, mesic, Typic Hapludalf) to evaluate cultivation with vertically operating hollow tines (HTC) and pulse injection of highly pressurized water (WIC). A prototype of the commercial water injection unit was furnished by the Toro Company, Minneapolis, MN. Compaction stress was applied with a water-filled vibrating roller (51 kPa static pressure). Soil bulk density was decreased and aeration porosity was increased with HTC, but not by WIC. WIC increased saturated hydraulic conductivity more than HTC due to the deeper channels created with WIC. Clipping yield was decreased by HTC on several dates in 1988 and 1989 following treatment application. WIC had no effect on clipping yield. Thatch/mat weights were reduced after two years (six treatments) of both HTC and WIC. HTC reduced thatch/mat weight more than WIC, but this was offset by a loss in stand density with HTC. WIC appeared to

be a less damaging cultivation practice than HTC and should be a better cultivation technique for improving soil water movement when turf will not tolerate excessive mechanical injury and be slow to recover.

# INTRODUCTION

Core cultivation is often recommended as a routine cultural practice to improve turfgrass growth and soil conditions on general turf areas subjected to regular compaction stress. Core cultivation research on general turf has been limited primarily to evaluation of thatch control, turfgrass quality, and water infiltration. Core cultivation of a 'Meyer' zoysiagrass (*Zoysia japonica* Steud.) turf reduced turf quality and thatch (Weston and Dunn, 1985). Carrow et al. (1987) reported that core cultivation once and twice a year reduced stand density but did not lower thatch accumulation of a 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* (Burtt-Davis)] homelawn turf. Murray and Juska (1977) observed core cultivation had no impact on common Kentucky bluegrass (*Poa pratensis* L.) thatch during the first five years, but after the sixth year thatch-organic matter weight was reduced and turf quality increased with core cultivation. Cultivation with spoon tines lowered the quality of a Colonial bentgrass (*Agrostis tenuis*) turf receiving minimal traffic (Engel, 1951a). Engel and Alderfer (1967) found water infiltration was unaffected with spoon type cultivation.

A limited number of studies have evaluated cultivation on general turf sites under compacted conditions. Engel (1951a) reported that spoon tine cultivation (eight applications over three seasons) did not affect the quality of a golf course fairway comprised of Kentucky bluegrass and annual bluegrass (*Poa annua* L.). Based on pasture work, Engel (1951b) speculated that cultivation may be harmful to Kentucky bluegrass turf. Core cultivation was reported to enhance recovery of 'Merion' Kentucky bluegrass following simulated foot traffic (Cordukes, 1968). Core cultivation of a heavily compacted Kentucky bluegrass turf decreased runoff but did not increase turf growth compared to noncultivated plots (Alderfer, 1954). Byrne et al. (1965) found no change in infiltration of a compacted putting green following core cultivation; only coring holes dug manually to 150 mm improved infiltration. Core cultivation has increased water infiltration rates (Waddington et al., 1974) of compacted soils, particularly soils with large sand volumes.

High pressure water injection has recently been introduced as a new method to cultivate compacted turf soils. A prototype high pressure water injection unit was provided by the Toro Company, Minneapolis, MN. This study compared water injection and hollow tine cultivation as a routine management practice on a 'Cheri' Kentucky bluegrass turf subjected to compaction stress.

## MATERIALS AND METHODS

The study was initiated on a six-year-old 'Cheri' Kentucky bluegrass turf growing on a sandy loam soil (fine-loamy, mixed, mesic, Typic Hapludalf). Compaction treatments were initiated in July 1987 and performed throughout the study with a vibrating water-filled roller (50 kPa); 120 passes between 27 July and 31 Aug. 1987; 132 passes between 10 Apr. and 30 Sept., 1988; and 134 passes between 29 Apr. and 1 Oct., 1989.

Cultivation treatments consisting of no cultivation (check), hollow tine cultivation (HTC), and high pressure water injection cultivation (WIC) were arranged in a randomized complete block design with three replications. HTC was performed with a TORO greens aerator equipped with 13 mm hollow tines reaching maximum depth of 75 mm. WIC was applied using 19.3 to 22.1 MPa line pressure through 13 injections nozzles spaced 76 mm apart which cut small diameter channels to an average 110 mm depth. Cultivation treatments were applied on 6 July, 10 Aug., and 28 Sept., 1988; and 7 Aug., 12 Sept., and 7 Oct., 1989. Soil brought to the surface with HTC was removed with a flat shovel. All plots were then leaf-raked to remove remaining debris. No soil was brought to the surface with WIC. Nitrogen was applied at 142 and 134 kg $ha^{-1}$ in 1988 and 1989, respectively. Dates of application were 5 July, 16 Aug., and 5 Oct., 1988, and 6 May, 10 July, 23 Aug., 1989. Phosphorus and potassium were applied according to soil test recommendations. Supplemental irrigation was applied to avoid wilt.

Clippings were collected from a 1.4 $m^2$ swath, dried, and weighed for selected growth periods in 1988 and 1989. Soil moisture use was estimated by tensiometer in 1988 and 1989, and time-domain reflectometry (Topp and Davis, 1985) in 1989. Two tensiometers per plot were installed in the 25 to 75 mm and 100 to 150 mm soil depth zones. Volumetric water contents were interpolated from soil moisture characteristic curves developed from 76 mm i.d. soil cores taken from the 0 to 76 and 76 to 152 mm soil depth zones. Two waveguides for the time-domain reflectometry (TDR) measurements were installed in each plot at the 0 to 100 and 0 to 200 mm depth zones. Measurements for the 100 to 200 mm were determined by subtraction. TDR volumetric water contents were calculated using the equations of Topp and Davis (1985).

Sampling for shoot tissue, thatch/mat, and roots was performed November 1988, and June and November 1989. Shoot tissue was considered to be any aerial tissue above the depth in the canopy where green color was no longer found. Thatch/mat consisted of the material below the shoot tissue harvest down to the soil depth where rhizomes were no longer present (25 mm). Root material was sampled from the soil below the thatch/mat layer. Soil cores 102 mm in dia. were excavated. The first 25 mm of the core, comprised of the thatch/mat zone, was cut from the core. The soil was sectioned into 0 to 50, 50 to 100, and 100 to 200 mm soil depth intervals. Shoot, thatch/mat, and root tissue were separated from any soil present using a hydropneumatic elutriation method (Smucker et al., 1982), dried overnight at 60° C, and weighed.

Soil sampling was performed November 1988, and August and November 1989 using 76 i.d. by 76 mm high cores. Samples were taken at the 0 to 76 and 76 to 152 mm soil depth zone (below the 25 mm thatch/mat zone) for bulk density, soil porosity, and saturated hydraulic conductivity measurements.

Analysis of variance was performed on all data and means were separated using Fisher's protected LSD procedure at the 0.05 level of probability (Steel and Torrie, 1980).

## RESULTS AND DISCUSSION

Soil Physical Properties. Table 3.1 presents soil bulk density, total porosity, aeration porosity (0 to -6 kPa), and hydraulic conductivity data for the different sampling dates and depth zones in 1988 and 1989. After the initial three treatment applications in 1988, soil bulk density was decreased, and total porosity and aeration porosity were increased with HTC compared to noncultivated plots, while WIC had no measurable effect. Since WIC removed no soil, neither density nor overall porosity measurements were affected on these plots

Table 3.1. The influence of cultivation on soil physical properties at the 0 to 76 and 76 to 152 mm soil zones sampled 1988 and 0 to 76 mm zone sampled 1989.

| | Bulk Density | Total Porosity | Aeration Porosity | K Sat |
|---|---|---|---|---|
| October 1988 (3 weeks after treatment) | | | | |
| | Mg m$^{-3}$ | — m$^3$ 100m$^{-3}$ — | | mm hr$^{-1}$ |
| 0 to 76 mm zone | | | | |
| Check | 1.66 a[+] | 37.7 b | 6.4 b | 11 b |
| Hollow Tine | 1.60 b | 39.6 a | 8.4 a | 24 ab |
| Water Injection | 1.64 ab | 38.1 b | 6.7 b | 41 a |
| 76 to 152 mm zone | | | | |
| Check | 1.67 a | 35.4 a | 7.2 a | 7 a |
| Hollow Tine | 1.68 a | 35.1 a | 7.0 a | 15 a |
| Water Injection | 1.69 a | 34.7 a | 6.6 a | 7 a |
| August 1989 (47 weeks after treatment) | | | | |
| 0 to 76 mm zone | | | | |
| Check | 1.67 a | 35.3 b | 4.4 a | nd |
| Hollow Tine | 1.65 a | 36.2 a | 5.2 a | nd |
| Water Injection | 1.65 a | 35.8 ab | 4.7 a | nd |
| November 1989 (6 weeks after treatment) | | | | |
| 0 to 76 mm zone | | | | |
| Check | 1.64 a | 35.8 b | 5.6 b | 13 a |
| Hollow Tine | 1.63 a | 36.9 a | 7.0 a | 16 a |
| Water Injection | 1.63 a | 36.2 ab | 5.9 b | 41 a |

[+] Within each column and depth zone, numbers with the same letter are not significantly different based on Fisher's protected LSD at the 0.05 level of probability.

nd designates not determined.

receiving compaction. However, porosity distribution measurements (Table 3.2) showed both HTC and WIC increased the very large macropores (0 to -1 kPa) within the 0 to 76 mm zone. HTC was better at increasing this range of porosity because of the removal of soil.

Hydraulic conductivity increased 273% following WIC and 118% with HTC compared to noncultivated checks sampled November 1988. The deep channels cut with WIC had a dramatic influence on conductivity. Random measurement of 20 channels cut with WIC in each plot on 6 July, 1988 showed the depth ranged from 60 to 175 mm and averaged 110 mm.

Soil data in August 1989 (prior to 1989 treatments) showed that improvements in density and porosity achieved with HTC and WIC had dissipated. This response illustrates the need for a regular cultivation program on turf where routine traffic re-compacts the soil. Others have observed that the improvement in soil density and macroporosity following cultivation was lost after treatment (Roberts, 1975; Lee, 1989).

After continued cultivation treatment in 1989, total and aeration porosity were increased with HTC compared to noncultivated and WIC plots (Table 3.1). WIC had no effect on these measurements compared to the check plots due to the lack of soil removal. Porosity distribution in November 1989 showed the large macropores (0 to -1 kPa) were greater after three additional HTC and WIC treatments compared to the checks (Table 3.2). A significant decline in the remaining macroporosity (1 to 10 -kPa) was found suggesting that HTC and WIC were resulting in some compaction effects in the 0 to 76 mm soil zone.

Table 3.2. The influence of cultivation on soil porosity distribution between selected moisture potentials in the 0 to 76 and 76 to 152 mm soil zones sampled 1988 and 0 to 76 mm soil zone in 1989.

| | Moisture Potential Ranges (- kPa) | | | |
|---|---|---|---|---|
| | 0 to 1 | 1 to 10 | 10 to 100 | 100 to OD |
| October 1988 (3 weeks after treatment) | | | | |
| 0 to 76 mm zone | $m^3$ 100 $m^{-3}$ | | | |
| Check | 3.5 c[+] | 3.7 a | 3.5 a | 26.9 b |
| Hollow Tine | 5.4 a | 3.9 a | 3.1 a | 27.1 ab |
| Water Injection | 4.3 b | 3.2 a | 3.0 a | 27.7 a |
| 76 to 152 mm zone | | | | |
| Check | 3.1 a | 5.2 a | 3.8 a | 23.2 a |
| Hollow Tine | 3.2 a | 4.8 a | 3.5 a | 23.5 a |
| Water Injection | 3.2 a | 4.3 a | 3.6 a | 23.5 a |
| August 1989 (47 weeks after treatment) | | | | |
| 0 to 76 mm zone | | | | |
| Check | 2.3 a | 3.9 a | 4.2 a | 25.0 a |
| Hollow Tine | 2.9 a | 4.1 a | 4.0 a | 25.1 a |
| Water Injection | 2.6 a | 3.7 a | 4.6 a | 24.9 a |
| November 1989 (6 weeks after treatment) | | | | |
| 0 to 76 mm zone | | | | |
| Check | 2.5 c | 4.1 a | 2.8 a | 26.4 a |
| Hollow Tine | 4.5 a | 3.2 b | 2.8 a | 26.3 a |
| Water Injection | 3.7 b | 3.1 b | 3.2 a | 26.2 a |

[+] Within each column and depth zone, numbers with the same letter are not significantly different based on Fisher's protected LSD at the 0.05 level of probability.

Hydraulic conductivity, although not significant in November 1989, still remained highest in the WIC plots. Hydraulic conductivity was highly variable in November 1989 due to considerable earthworm activity in all plots. Numerous soil cores had to be discarded and some re-excavated to avoid obvious earthworm activity.

No effect of cultivation was observed in 76 to 152 mm depth zone sampled November 1988. No soil measurements were made in the 76 to 152 mm zone in 1989.

Shoot Tissue and Thatch/Mat. Both HTC and WIC had no consistent effect on shoot and thatch/mat weight until November 1989 (Table 3.3). Weston and Dunn (1985) observed cultivation required two years of treatment to affect thatch depth of 'Meyer' zoysiagrass turf. Shoot tissue of the Kentucky bluegrass turf in this study was decreased with HTC compared to noncultivated plots, in November 1989. WIC had no effect on shoot tissue compared to check plots. By November 1989, HTC and WIC decreased thatch/mat weight by 24 and 15%, respectively compared to noncultivated plots. This decrease in thatch/mat weight illustrates the mechanical removal and injury of plant tissue within the thatch/mat zone via cultivation. Smith (1979) partially attributed decreased thatch to the physical removal by mechanical cultivation. The loss in shoot tissue with HTC suggested that HTC was more damaging to the turf than WIC.

Rooting. No influence on root growth was observed on any sampling or depth zone (Tables 3.3 and 3.4). This may have been due in part to the thickness of the thatch mat zone (approximately 25 mm). The data show that HTC had a marked influence on thatch/mat weights indicating HTC has a considerable effect at the surface. At maximum tine

Table 3.3. The influence of cultivation on shoot tissue, thatch/mat, and total root weights of Kentucky bluegrass turf sampled in 1988 and 1989.

| | Shoot Tissue | Thatch/Mat | Total Root Weight |
|---|---|---|---|
| November 1988 (4 weeks after treatment) | | | |
| | | kg $m^{-2}$ | |
| Check | 0.36 | 1.29 | 0.11 |
| Hollow Tine | 0.28 | 1.23 | 0.12 |
| Water Injection | 0.34 | 1.26 | 0.12 |
| LSD (0.05) | NS | NS | NS |
| June 1989 (32 weeks after treatment) | | | |
| Check | 0.19 | 0.94 | 0.19 |
| Hollow Tine | 0.16 | 0.86 | 0.22 |
| Water Injection | 0.16 | 0.78 | 0.19 |
| LSD (0.05) | NS | NS | NS |
| November 1989 (4 weeks after treatment) | | | |
| Check | 0.34 | 1.08 | 0.11 |
| Hollow Tine | 0.27 | 0.82 | 0.12 |
| Water Injection | 0.30 | 0.92 | 0.12 |
| LSD (0.05) | 0.05 | 0.14 | NS |

NS denotes not significant.

Table 3.4. The influence of cultivation on root weight densities of a Kentucky bluegrass turf sampled in 1988 and 1989.

| | Root Weight Density Zones (cm) | | |
|---|---|---|---|
| | 0 to 5 | 5 to 10 | 10 to 20 |
| November 1988 (4 weeks after treatment) | | | |
| | | kg $m^{-3}$ | |
| Check | 1.38 | 0.35 | 0.19 |
| Hollow Tine | 1.57 | 0.36 | 0.19 |
| Water Injection | 1.57 | 0.39 | 0.21 |
| LSD (0.05) | NS | NS | NS |
| June 1989 (32 weeks after treatment) | | | |
| Check | 2.68 | 0.60 | 0.26 |
| Hollow Tine | 2.74 | 0.65 | 0.26 |
| Water Injection | 2.54 | 0.63 | 0.27 |
| LSD (0.05) | NS | NS | NS |
| November 1989 (4 weeks after treatment) | | | |
| Check | 1.50 | 0.36 | 0.14 |
| Hollow Tine | 1.69 | 0.43 | 0.15 |
| Water Injection | 1.62 | 0.46 | 0.14 |
| LSD (0.05) | NS | NS | NS |

NS denotes not significant.

penetration, only the surface 50 mm of soil would be affected with HTC. Since full tine penetration is not always reached due to stones and varying soil strength, the depth of soil affected on average would be less than 50 mm. The depth of penetration with HTC appeared to be inadequate to have any influence on root weight. Engel (1951a) found spoon tine cultivation (eight treatments over three seasons) had no statistically consistent effect on rooting of a golf course fairway turf, although root weight was 8% greater in cultivated plots compared to noncultivated plots. Carrow (1988) observed increased rooting of bermudagrass at the 200 to 600 mm depth as a result of cultivation.

Clipping Yield. HTC significantly lowered clipping yield compared to WIC and noncultivated plots on 5 and 31 Aug., 1988 (Figure 3.1). A similar response was observed on 25 July and 24 Aug., 1988 ($P<0.10$). Decreased clipping yield with HTC supports the conclusion that HTC injures the turf by physically removing plant tissue. WIC did not decrease clipping yield. Decreased yield during spring green-up was evident on HTC plots sampled 13 May, 1989 (Figure 3.2). However, HTC plots recovered quickly when growth increased in the spring and subsequent yields equaled WIC and check plots. Following the 7 August and 12 September treatment applications in 1989, HTC again decreased clipping yield compared to the check (Figure 3.2). Reductions in clipping yield appeared to be of greater duration in 1988 than 1989 (up to four weeks following HTC treatment). This may have resulted from the extreme high temperature stress which occurred in 1988 coupled with the injury and plant removal associated with HTC. Roberts (1975) reported lower clipping yield of 'Merion' Kentucky bluegrass following core cultivation.

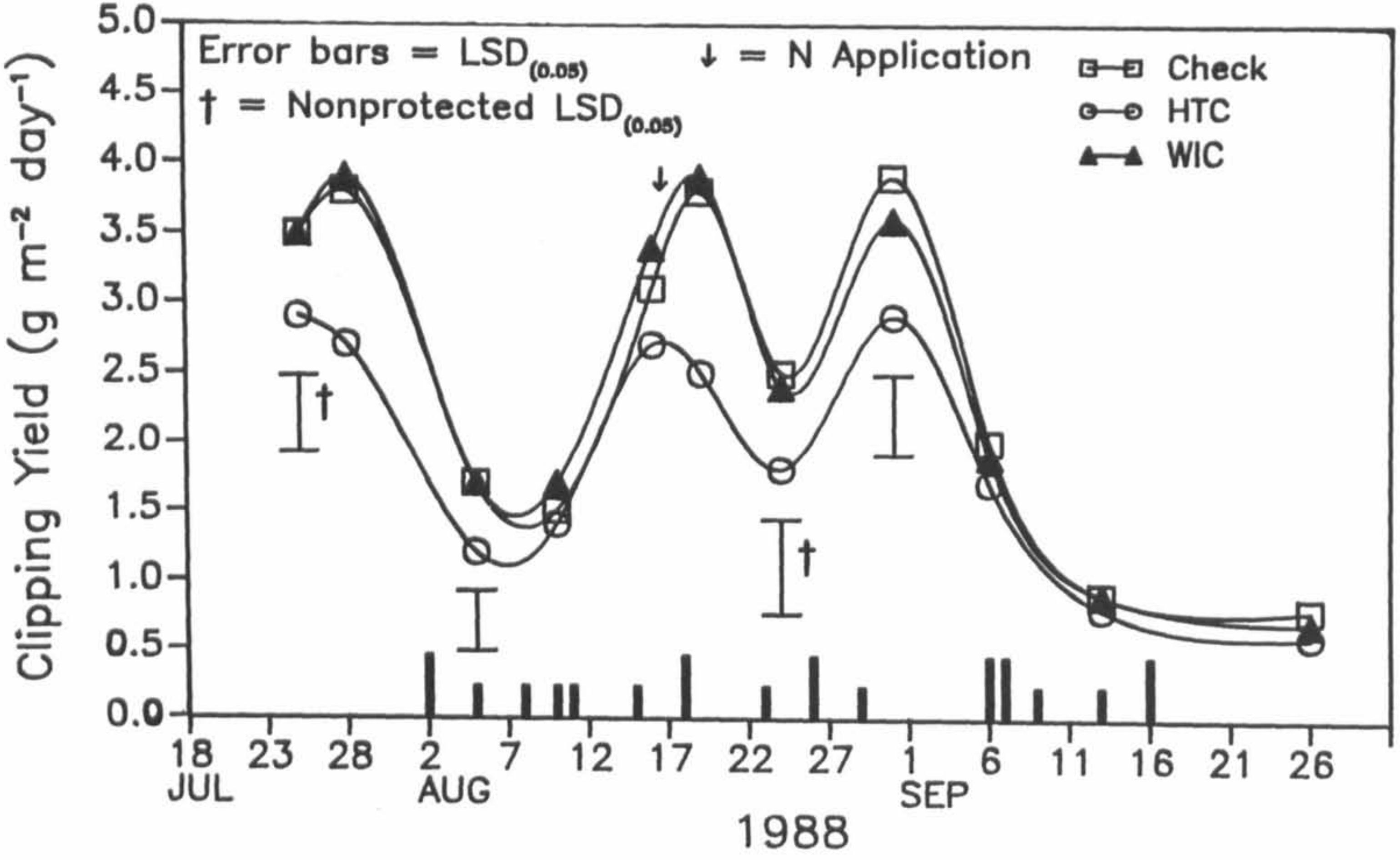

Figure 3.1. Influence of hollow tine (HTC) and water injection (WIC) cultivation on clipping yield of Kentucky bluegrass turf. Solid bars indicate 2 or 4 pass compaction events. Treatments were applied 6 July, 10 August, and 28 September, 1988.

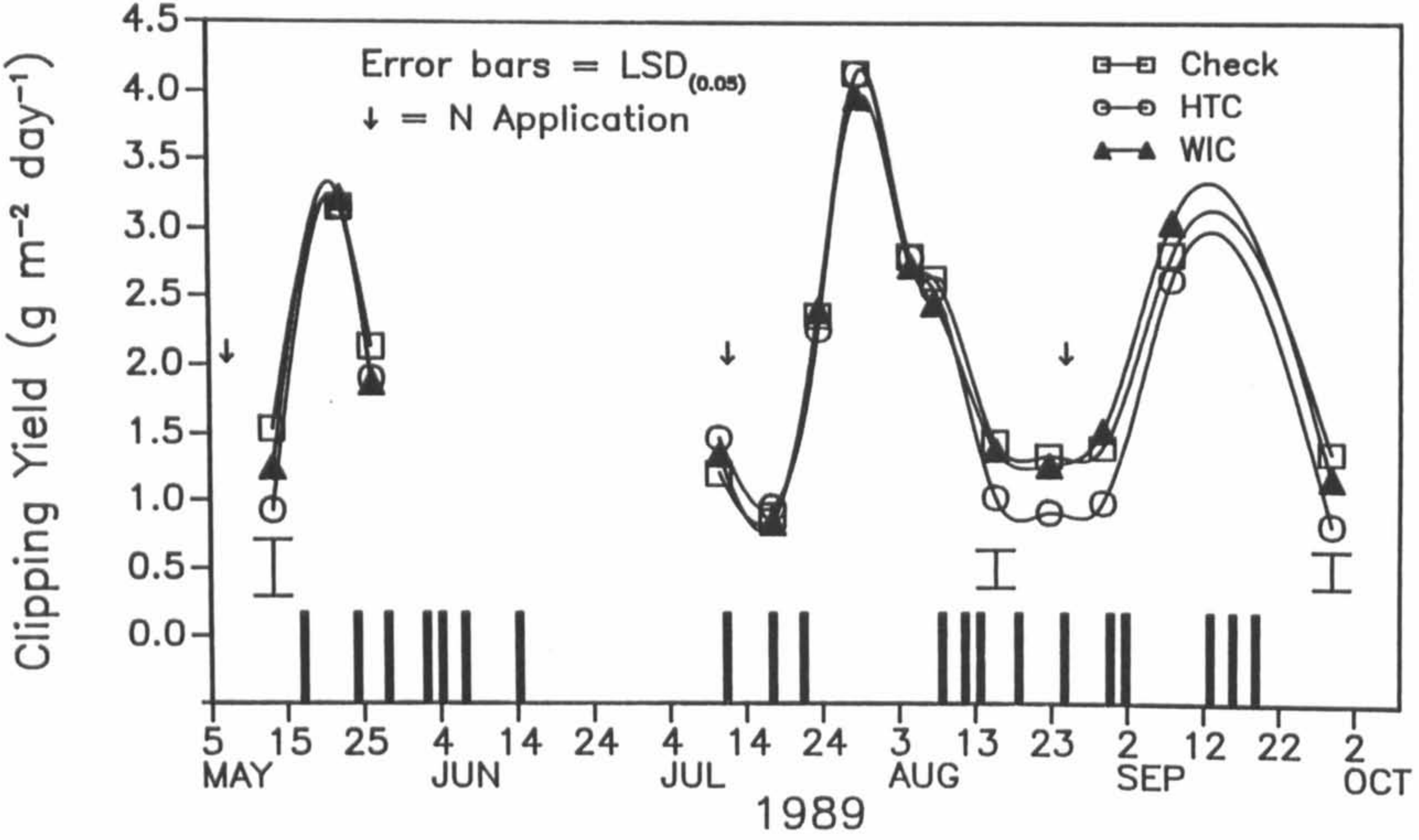

Figure 3.2. Influence of hollow tine (HTC) and water injection (WIC) cultivation on clipping yield of Kentucky bluegrass turf. Solid bars indicate 6 pass compaction events. Treatments were applied 7 August, 12 September, and 7 October, 1989.

Stand Density. Stand density ratings were not affected by cultivation treatment until September 1989 (Table 3.5). September and October 1989 ratings showed HTC plots had lowered stand densities compared to noncultivated and WIC plots. Most likely, shoot growth during this period was not great enough for HTC plots to recover from damage caused during treatment in 1989. Weston and Dunn (1985) and Carrow (1987) observed lower quality and density following core cultivation of 'Meyer' zoysiagrass and 'Tifway' bermudagrass turf, respectively. Engel (1952) reported that cultivation improved turf quality only in areas with severe thatch accumulation.

Estimated Water Use. Water use estimates by tensiometry (Table 3.6) and time-domain reflectometry (Table 3.7) did not indicate any increase or decrease in water utilization as a result of cultivation treatment. Carrow (1988) has reported increased water utilization following cultivation treatment on bermudagrass. Possibly the methods used for estimating water use in this study were not precise enough to detect differences between treatments. Also, rainfall events and the limited range of soil moisture sensing with tensiometry resulted in rather short periods of measurement which might not have been long enough to detect differences. The water use rates in this study were low compared to other reported values (Feldhake et al., 1983), but high humidity and heavy dew formation were prevalent during these measurement periods.

## SUMMARY

Hollow tine cultivation (HTC) had a pronounced effect on soil physical properties, such as decreased bulk density and increased

Table 3.5. Effect of hollow tine (HTC) and water injection (WIC) cultivation on visual density estimates of a Kentucky bluegrass turf in 1988 and 1989.

| | 1988 | | | 1989 | | |
|---|---|---|---|---|---|---|
| | 8/10 | 9/28 | 10/18 | 8/7 | 9/8 | 10/14 |
| | Density (9=dense, 6=acceptable, 1=no turf) | | | | | |
| Check | 8.0a+ | 8.0a | 8.0a | 7.7a | 8.7a | 7.3a |
| HTC | 7.7a | 7.7a | 7.3a | 7.7a | 6.7b | 5.7b |
| WIC | 8.7a | 7.3a | 8.0a | 7.7a | 8.3a | 7.7a |

+ Within each column, numbers followed by the same letter are not significantly different based on Fisher's protected LSD test at the 0.05 level of probability.

Treatments were applied 6 July, 10 Aug., and 28 Sept., 1988, and 7 Aug., 12 Sept., and 7 Oct., 1989.

Table 3.6. Influence of cultivation on water use of a Kentucky bluegrass turf as estimated by tensiometers between 8:00 and 20:00 h for a 2 or 3 day period.

| | July 1988 | | July 1989 |
|---|---|---|---|
| | 21 to 23 | 26 to 28 | 6 to 7 |
| | mm | | |
| 0 to 76 mm zone | | | |
| Check | 3.6 a+ | 3.2 a | 2.8 a |
| Hollow Tine | 3.1 a | 3.1 a | 2.6 a |
| Water Injection | 2.4 a | 2.7 a | 2.7 a |
| 76 to 152 mm zone | | | |
| Check | 3.1 a | 3.2 a | 2.3 a |
| Hollow Tine | 2.7 a | 2.5 a | 2.0 a |
| Water Injection | 2.5 a | 2.7 a | 1.8 a |
| 0 to 152 mm | | | |
| Check | 6.7 a | 6.4 a | 5.1 a |
| Hollow Tine | 5.7 a | 5.6 a | 4.6 a |
| Water Injection | 4.9 a | 5.4 a | 4.5 a |

+ Within each column and depth zone, numbers followed by the same letter are not significantly different based on Fisher's protected LSD test at the 0.05 probability level.

Treatments were applied 6 July, 10 Aug., and 28 Sept., 1988, and 7 Aug., 12 Sept., and 7 Oct., 1989.

Table 3.7. Influence of cultivation on water use of a Kentucky bluegrass turf as estimated by time-domain reflectometry from 2 to 5 September, 1989.

| | Depth Zone (mm) | | |
|---|---|---|---|
| | 0 to 100 | 100 to 200 | 0 to 200 |
| | | mm | |
| Check | 4.7 a[+] | 2.0 a | 6.7 a |
| Hollow Tine | 5.9 a | 0.5 a | 6.4 a |
| Water Injection | 4.3 a | 2.5 a | 6.8 a |

[+] Within each column, numbers followed by the same letter are not significantly different based on Fisher's protected LSD test at the 0.05 probability level.

Treatments were applied 6 July, 10 Aug., and 28 Sept., 1988, and 7 Aug., 12 Sept., and 7 Oct., 1989.

porosity compared to water injection cultivation (WIC). However, WIC resulted in better water conductivity than HTC illustrating the benefit of deeper cultivation channels with WIC.

Even though soil properties were improved with HTC, clipping yield of the Kentucky bluegrass turf was reduced up to four weeks following HTC treatment. This response was attributed to the removal of plant tissue during HTC and appeared to be more pronounced during 1988, a year of high temperature and low rainfall. WIC had no effect on clipping yield of this turf.

Shoot tissue and thatch/mat weights were not affected until after the second year of treatments. Both HTC and WIC lowered thatch/mat weight while only HTC lowered shoot tissue. Decreased shoot tissue on HTC plots was reflected in a decline in stand density on HTC plots.

Root weight was not measurably affected by either HTC or WIC. Estimated water use also failed to show any influence of HTC or WIC treatment.

The data suggested that an aggressive program of core cultivation can be used to improve soil physical conditions and reduce thatch/mat accumulation as observed at the end of the second year. However, these benefits may be offset by the injury imparted during core cultivation which can lead to a decline in stand density and quality. This may be of greatest importance on turfs which are dormant or growing slowly due to environmental stress. Water injection cultivation appears to be a superior cultivation method to improve soil water movement during periods where the turf may not recover quickly from mechanical injury caused by HTC.

# LIST OF REFERENCES

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Alderfer, R.B. 1954. Effects of soil compaction on bluegrass turf. Penn. State College Turfgrass Conf. 23:31-32.

Byrne, T.G., W.B. Davis, L.J. Booker, and L.F. Werenfels. 1965. A further evaluation of the vertical mulching method of improving old greens. Calif. Agric. 19:12-14.

Carrow, R.N. 1988. Cultivation methods on turfgrass water relationships and growth under soil compaction. 1988 U.S.G.A. Green Section Turfgrass Summary. p.14.

Carrow, R.N., B.J. Johnson, and R.N. Burns. 1987. Thatch and quality of Tifway bermudagrass turf in relation to fertility and cultivation. Agron. J. 79:524-530.

Cordukes, W.E. 1968. Compaction. The Golf Superintendent. 36:20-24.

Engel, R.E. 1951a. Studies of turfgrass cultivation. Ph.D. diss. Rutgers Univ. 100 pp.

Engel, R.E. 1951b. Some preliminary results from turf cultivation. Rutgers Univ. Annual Short Course in Turf Management. 19:17-22.

Engel, R.E. 1952. Turf cultivation. Rutgers Univ. Annual Short Course in Turf Management. 20:9-11.

Engel, R.E., and R.B. Alderfer. 1967. The effect of cultivation, topdressing, lime, nitrogen and wetting agent on thatch development in 1/4-inch bentgrass turf over a ten-year period. New Jersey Agric. Exp. Stn., Bul. 818:32-45.

Feldhake, C.M., R.E. Danielson, and J.D. Butler. 1983. Turfgrass evapotranspiration. I. Factors influencing rate in urban environments. Agron. J. 75:824-830.

Lee, D.K. 1989. Effects of soil cultivation techniques on rooting of Kentucky bluegrass sod. M.S. thesis. Mich. State Univ. 62 pp.

Murray, J.J., and F.V. Juska. 1977. Effects of management practices on thatch accumulation, turf quality and leaf spot damage in common Kentucky bluegrass. Agron. J. 69:365-369.

Roberts, J.M. 1975. Some influences of cultivation on the soil and turfgrass. M.S. thesis. Purdue Univ. 60 pp.

Smith, G.S. 1979. Nitrogen and aerification influence on putting green thatch and soil. Agron. J. 71:680-684.

Smucker, A.J.M., S.L. McBurney, and A.K. Srivastava. 1982. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. Agron. J. 74:500-503.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics. Second Ed. McGraw-Hill, New York, NY. 633 pp.

Topp, G.C., and J.L. Davis. 1985. Measurement of soil water content using time-domain reflectometry (TDR): A field evaluation. Soil Sci. Soc. Am. J. 49:19-24.

Weston, J.B., and J.H. Dunn. 1985. Thatch and quality of Meyer zoysia in response to mechanical cultivation and nitrogen fertilization. Proc. Fifth Int. Turfgrass Res. Conf. pp. 449-458.

Waddington, D.V., T.L. Zimmerman, G.L. Shoop, L.T. Kardos, and J.M. Duich. 1974. Soil modification for turfgrass areas. Penn. Agric. Exp. Stn. Progress Rep. No.337. 96 pp.