CHAPTER TWO

High Pressure Water Injection and Hollow Tine Cultivation of a Compacted Creeping Bentgrass Green

ABSTRACT

Traditional core cultivation practices are performed in spring and/or fall to alleviate problems associated with soil compaction on golf course putting greens. Mid-season cultivation is rarely done because of the costs involved with closing the course to play and the objection of players to an uneven putting surface. Short-time pulse injection of highly pressurized water has been introduced as a means to relieve soil compaction while limiting playing surface disturbance. This study evaluated the response of a 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) growing on a loamy sand soil (modified fine-loamy, mixed, mesic, Typic Hapludalf) to hollow tine cultivation (HTC) and high pressure water injection (WIC). Cultivation treatments were applied three and two times in 1988 and 1989, respectively, on a putting green receiving compaction from 0.68 t rollers. WIC was equal or superior to HTC in improving soil bulk density, porosity, and saturated hydraulic conductivity in the 0 to 76 mm depth zone. HTC loosened the surface 30 mm of soil more than WIC, but only WIC provided a significant loosening of the soil from the 60 to 100 mm depth. WIC stimulated creeping bentgrass shoot growth after treatment over that

achieved with HTC. HTC lowered thatch/mat weight sooner and to a greater extent than WIC. HTC reduced surface (0 to 100 mm) root weights as well as root numbers observed along minirhizotrons compared to the check and WIC plots. Root damage and removal during HTC cultivation was the reason for this response. Minirhizotron root observations revealed increased rooting below 200 mm for both HTC and WIC plots compared to the check. Deep rooting was greater in WIC plots than HTC plots. Increased rooting below 200 mm may account for decreased water extraction at the 0 to 100 mm zone in WIC plots with a larger portion of water consumption occurring deeper in the soil. WIC offers the potential for routine cultivation during periods of high site usage and environmental stresses.

INTRODUCTION

Golf course putting greens are subjected to intense levels of traffic which can lead to many problems associated with soil compaction, such as poor water infiltration and percolation, reduced soil aeration, restricted root development, and hard playing surfaces (Madison, 1971). Typically, cultivation practices are performed during the spring and/or fall to relieve soil compaction problems. However, the most severe soil compaction problems occur during mid-season when play and the demand for a quality putting surface are at their highest.

The conventional hollow tine cultivation (HTC) technique creates an uneven putting surface because of the removal of turf/soil cores and is not widely used as mid-season cultivation tool. Research regarding the ability of HTC to alleviate soil compaction has been limited and some results are conflicting. Water infiltration rates have increased (Waddington et al, 1974), decreased (Roberts, 1975), or remained unchanged (Byrne et al., 1965; Engel and Alderfer, 1967). Murphy (1986) observed that saturated hydraulic conductivity decreased with cultivation in noncompacted soil and was unaffected by cultivation in compacted soil. HTC has decreased (Murphy, 1986) or increased (Goss, 1984) soil bulk density. Carrow (1988) and Murphy (1986) found HTC reduced penetrometer resistance.

Solid tine cultivation (STC) with small diameter tines has greater acceptance as a mid-season cultivation tool but receives considerable criticism for its potential to develop a cultivation pan. Murphy (1986) found STC increased aeration porosity at the 0 to 76 mm depth but to a smaller extent than HTC. Murphy and Rieke (1987) reported that penetrometer resistance was decreased in the soil surface, but resistance just below the tine depth suggested a compacted layer was forming with STC compared to HTC plots. Goss (1984) reported increased bulk density and decreased infiltration following STC. HTC has enhanced bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* (Burtt-Davis)] rooting and water extraction, but STC had no effect (Carrow, 1988).

A recently developed technique using high pressure water injection shows considerable promise as a tool for mid-season cultivation. This technique uses high velocity streams of water to cut small diameter channels in the soil while minimizing surface disruption. A prototype water injection cultivator was provided by the Toro Company (Minneapolis, MN).

This study was designed to compare hollow tine cultivation (HTC) and high pressure water injection cultivation (WIC) based on the ability to improve soil physical conditions and turf growth of a 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) putting green.

MATERIALS AND METHODS

The study was initiated on a 5-year old 'Penncross' creeping bentgrass green maintained at a 6 mm cutting height and grown on a modified loamy sand soil (original soil was a fine-loamy, mixed, mesic, Typic Hapludalf). Compaction was initiated on 16 June, 1986 with water-filled rollers (approximately 50 kPa). The entire plot area received 70 passes of compaction between 16 June and 16 Sept., 1986; 54 passes between 18 June and 31 Aug., 1987; 120 passes between 8 Apr. and 7 Oct., 1988, and 120 passes between 6 Apr. and 29 Sept., 1989.

Cultivation treatments were initiated on 9 July, 1988 in a randomized complete block design with five replications. Additional cultivation treatments were applied on 19 Aug. and 3 Oct., 1988, and 14 Aug. and 2 Oct., 1989. The treatments consisted of (i) no cultivation (check), (ii) hollow tine cultivation (HTC), and (iii) high pressure water injection cultivation (WIC). HTC was performed with a TORO greens aerator equipped with 13 mm hollow tines. WIC was applied using 19.3 to 22.1 MPa line pressure through thirteen injection nozzles (orifice of 1.2 mm i.d.) spaced 76 mm apart. Soil brought to the surface with both cultivation methods was removed with a flat shovel followed by brushing.

Three minirhizotron tubes of 91 cm length and 51 mm i.d. were installed in each plot on 26 and 27 April, 1986 at an angle of 30 degrees from the soil surface. Minirhizotron tube entry ports were mounted subsurface to facilitate normal turf maintenance and compacting operations and faced north to minimize exposure to thermal radiation. Video recording of roots was performed on several dates in 1988 and 1989 using the system described by Ferguson and Smucker (1989). Cultivation holes created during treatment application were no closer than 160 mm to the soil exit point of the minirhizotron tubes. The number of active roots in each viewing frame was counted. The root counts were summed over four frames for a total number of roots observed at 24 mm depth intervals. Active roots were considered to be those roots white in color and having sharp edges. As roots aged they became darker in color and began to lose definition as the edges became blurred. Roots of dark color and having blurred edges were considered inactive and not counted. Root counts became very high and difficult to accurately count in 1988 along the first 48 mm (eight frames) of the minirhizotrons. By 1989, the viewing area along the surface 48 mm of the minirhizotrons was often totally covered with roots. Because of the inability to obtain accurate root counts information will not be reported for the first 48 mm of depth along the minirhizotrons.

Nitrogen was applied at 98, 146, 317, and 171 kg ha^{-1} in 1986, 1987, 1988, and 1989, respectively. Nitrogen rates were high in 1988 because of the longer than normal growing season experienced that year. Fertility applications were made on 29 Apr., 20 May, 4 June, 26 June, 19 July, 12 Aug., 1988, and 9 May, 14 June, 31 July, 23 Aug., 22 Sept., 1989. Potassium and phosphorus were applied according to soil test recommendations. Pesticides were applied as necessary to control insects and diseases. Irrigation was used to maintain soil moisture potential below -30 kPa, except for drydown periods used to evaluate moisture loss as affected by treatment.

Clippings were collected and weighed for the growth periods of 15 to 19 Aug., 23 to 26 Aug., 26 to 31 Aug., and 26 Sept. to 1 Oct., 1988, and 22 to 27 May, 6 to 11 July, 3 to 9 Aug., 30 Aug. to 4 Sept., 4 to 21 Sept., and 4 to 29 Oct., 1989.

Water extraction was estimated by tensiometry (Gaussoin et al., 1990) from 6 to 9 Aug., 1989. Two tensiometers were installed in each plot for the 10 to 50 mm and 90 to 140 mm soil depth zones. Time-domain reflectometry (Topp and Davis, 1985) was utilized as a measure of water extraction during 6 to 9 Aug. and 18 to 21 Sept., 1989. Two pairs of waveguides were installed in each plot for the 0 to 100 and 0 to 200 mm depth zone. Water use from the 100 to 200 mm depth zone was determined by subtraction.

Sampling for root, thatch/mat, and shoot tissue weights was performed November 1988, and July and November, 1989. The term thatch/mat will be used to describe the approximately 15 mm thick layer of organic matter between the soil surface and the green shoot tissue. This layer included organic material which was unmixed (thatch) and well-mixed (mat) with soil. Soil cores 102 mm in dia. and 200 mm in depth were excavated. Soil was sectioned into 0 to 50, 50 to 100, and 100 to 200 mm intervals. Soil and roots were separated by the hydropneumatic elutriation method (Smucker et al., 1982). Thatch and shoot tissue were sectioned from the soil cores and frozen until washing with the elutriation system could be performed. All samples were dried overnight at 60° C and weighed.

Soil core sampling was achieved using 76 i.d. by 76 mm high cores. Samples were taken at the 0 to 76 and 76 to 152 mm soil depth zones for bulk density, soil porosity, and saturated hydraulic conductivity determinations in November, 1988 and 1989. Only 0 to 76 mm samples were excavated in August 1989.

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. Data for cultivation effects on soil density, aeration porosity, total porosity, and saturated hydraulic conductivity are presented in Table 2.1. After 3 treatments (November 1988), HTC and WIC lowered soil bulk density, and increased aeration porosity and total soil porosity in the 0 to 76 mm soil zone. Aeration

Table 2.1. Soil (0 to 76 mm) bulk density, total porosity, aeration porosity (0 to -6 kPa moisture potential), and saturated water conductivity (K Sat) responses to hollow tine (HTC) and water injection (WIC) cultivation of a loamy sand soil.

	Bulk Density	Total Porosity	Aeration Porosity	K Sat
November 1988 (5 weeks after treatment)				
	$Mg\ m^{-3}$	— $m^3\ 100\ m^{-3}$	–	$mm\ hr^{-1}$
Check	1.83	29.3	7.3	21
HTC	1.78	31.4	9.2	23
WIC	1.77	32.2	9.6	46
LSD (0.05)	0.03	0.79	2.0	NS
August 1989 (46 weeks after treatment)				
Check	1.84	29.6	3.8	ND
HTC	1.80	30.9	4.8	ND
WIC	1.81	30.8	4.7	ND
LSD (0.05)	0.026	0.8	0.8	
November 1989 (7 weeks after treatment)				
Check	1.83	29.6	7.4	10
HTC	1.77	32.2	9.0	21
WIC	1.75	32.3	9.0	29
LSD (0.05)	0.05	1.3	NS	11

ND denotes not determined.
NS denotes not significant.

porosity was measured as the amount of water drained between 0 and -6 kPa moisture potential. WIC was more effective in increasing total porosity of the soil compared to HTC. Data taken prior to treatment in 1989 (August 1989) showed that the improved soil conditions measured in the previous year (November 1988) were beginning to diminish (Table 2.1). Others have observed short-lived soil responses to cultivation treatment (Roberts, 1975; Lee, 1989). Two additional cultivation treatments in 1989 resulted in density and porosity values similar to those observed in 1988.

Although aeration porosity was increased, saturated hydraulic conductivity was not significantly affected by cultivation in 1988. The nonsignificant effect of cultivation was due to considerable variability, particularly with WIC soil. While excavating the soil samples, WIC channels were observed to be variable in depth of penetration with some channels extending beyond the 76 mm depth. This inconsistency of depth was thought to account for the lack of significance in 1988 conductivity data. By November 1989, conductivity was significantly improved with WIC compared to check plots ($P<0.05$). Conductivity was increased with HTC compared to the check at the 0.10 level of probability.

In the 76 to 152 mm soil zone, total soil porosity was found to increase after 3 WIC treatments compared to the check and HTC plots in November 1988 (Table 2.2). Most likely, this response was a result of the slightly greater depth of penetration (soil channels created) with WIC compared to HTC. Channels were typically 50 to 70 mm deep with HTC and 80 to 100 mm with WIC. However, an increase in total porosity was not observed in November 1989. No other soil responses were detected

Table 2.2. Soil (76 to 152 mm) bulk density, total porosity, aeration porosity (0 to -6 kPa moisture potential), and saturated water conductivity (K Sat) responses to hollow tine (HTC) and water injection (WIC) cultivation of a loamy sand soil.

	Bulk Density	Total Porosity	Aeration Porosity	K Sat
November 1988 (5 weeks after treatment)				
	$Mg\ m^{-3}$	— $m^3\ 100\ m^{-3}$	—	$mm\ hr^{-1}$
Check	1.85	27.3	9.0	8
HTC	1.84	27.6	9.5	9
WIC	1.83	28.4	10.1	10
LSD (0.05)	NS	0.67	NS	NS
November 1989 (7 weeks after treatment)				
Check	1.84	28.1	8.7	15
HTC	1.86	27.7	8.1	10
WIC	1.84	28.0	8.8	17
LSD (0.05)	NS	NS	NS	NS

NS denotes not significant.

in the 76 to 152 mm soil zone in 1988 and 1989.

Table 2.3 presents soil porosity distribution for the 0 to 76 mm soil depth zone as determined by the water drained between various water potential ranges. Moisture release data was used to evaluate porosity distributions for each cultivation treatment. Each ten-fold increment in moisture potential was considered an endpoint for a particular pore size range. For this discussion 0 to -1 kPa represents the very large macropores, -1 to -10 kPa represents the medium-sized macropores, -10 to -100 kPa represents intermediate sized pores (mesopores), and -100 kPa to oven-dry (OD) represents the very fine pores (micropores).

Cultivation resulted in an increased quantity of the very large macropores (0 to -1 kPa) in the 0 to 76 mm soil zone, with both HTC and WIC being of similar effectiveness in November 1988 and 1989. The 0 to -1 kPa porosity levels measured in August 1989 showed that both HTC and WIC treated plots had lost some porosity within this range and WIC was no longer significantly greater than the check soil. This data substantiated the previously mentioned loss in treatment effect during the non-treatment period of October 1988 to August 1989 (Table 2.1).

Neither HTC nor WIC changed the volume of mesopores or micropores. Murphy (1986) found that hollow and solid tine cultivation decreased the -1 to -10 kPa macropore region and increased the amount of micropores in the 0 to 76 mm depth zone. This was concluded to be a compactive effect on the soil which reduced soil water conductivity. During the course of this study, neither HTC nor WIC resulted in any soil response which would indicate the development of severely compacted zones or layers.

Table 2.3. The influence of hollow tine (HTC) and water injection (WIC) cultivation on soil porosity drained between several moisture potentials in the 0 to 76 mm zone.

	Water Potential Range (-kPa)			
	0 to 1	1 to 10	10 to 100	100 to OD*
November 1988 (5 weeks after treatment)				
	m^3 100 m^{-3}			
Check	2.0	7.4	5.1	14.8
HTC	4.1	7.0	5.3	15.0
WIC	3.8	8.2	5.3	14.9
LSD (0.05)	0.4	NS	NS	NS
August 1989 (46 weeks after treatment)				
Check	1.9	7.4	4.5	15.8
HTC	2.8	6.9	4.7	16.5
WIC	2.4	7.5	4.9	16.0
LSD (0.05)	0.6	NS	NS	NS
November 1989 (7 weeks after treatment)				
Check	1.9	7.1	5.3	15.4
HTC	3.6	6.8	5.7	16.1
WIC	3.4	7.2	6.0	15.7
LSD (0.05)	0.6	NS	NS	NS

*, OD = Oven dry 105° C.
NS denotes not significant.

Soil porosity data for the 76 to 152 mm zone showed WIC increased total soil porosity in November 1988 (Table 2.2). This increase in soil porosity occurred primarily in the very large macropore region, 0 to -1 kPa (Table 2.4). The porosity response to WIC at this soil depth demonstrated the benefit of deeper penetration, improving soil conditions below that achieved with HTC. No treatment responses were detected in this soil zone for the 1989 sampling.

The lack of response to WIC at the 76 to 152 mm depth zone in 1989 was thought to be due to soil variation. During soil core sampling in 1989, a large number of stones were observed at the 76 to 152 mm zone in many of the plots. Only a few plots in 1988 were observed to have such a soil condition. The greater occurrence of stones may have limited water injection penetration and/or increased variability in the soil parameters measured.

Figure 2.1 shows soil strength values recorded on 25 July following 9 July cultivation treatment in 1988. HTC reduced soil strength at the 30 mm depth compared to the noncultivated plots. Between 40 and 60 mm both HTC and WIC provided similar reductions in soil strength compared to the noncultivated plots. From 70 to 100 mm, only the WIC treatment resulted in a significant reduction in soil strength compared to the check plots. Thus, WIC provided a significant loosening of this compacted loamy sand to the 100 mm soil depth while HTC influence was limited to the 60 mm depth. Penetration resistance data also demonstrated WIC was not as disruptive (less loosening) in the soil surface 30 mm compared to HTC. Carrow (1988) reported that HTC was the most effective of five cultivation treatments in lowering penetration resistance.

Table 2.4. The influence of hollow tine (HTC) and water injection (WIC) cultivation on soil porosity drained between several moisture potentials in the 76 to 152 mm zone.

	Water Potential Range (-kPa)			
	0 to 1	1 to 10	10 to 100	100 to OD*
November 1988 (5 weeks after treatment)				
	m^3 100 m^{-3}			
Check	1.7	8.8	3.7	13.1
HTC	1.8	9.2	3.7	12.9
WIC	2.0	9.7	3.7	13.0
LSD (0.05)	0.2	NS	NS	NS
November 1989 (7 weeks after treatment)				
Check	1.9	7.8	3.6	14.8
HTC	1.8	7.2	3.5	15.2
WIC	1.9	8.0	3.8	14.3
LSD (0.05)	NS	NS	NS	NS

*, OD = Oven dry 105° C.
NS denotes not significant.

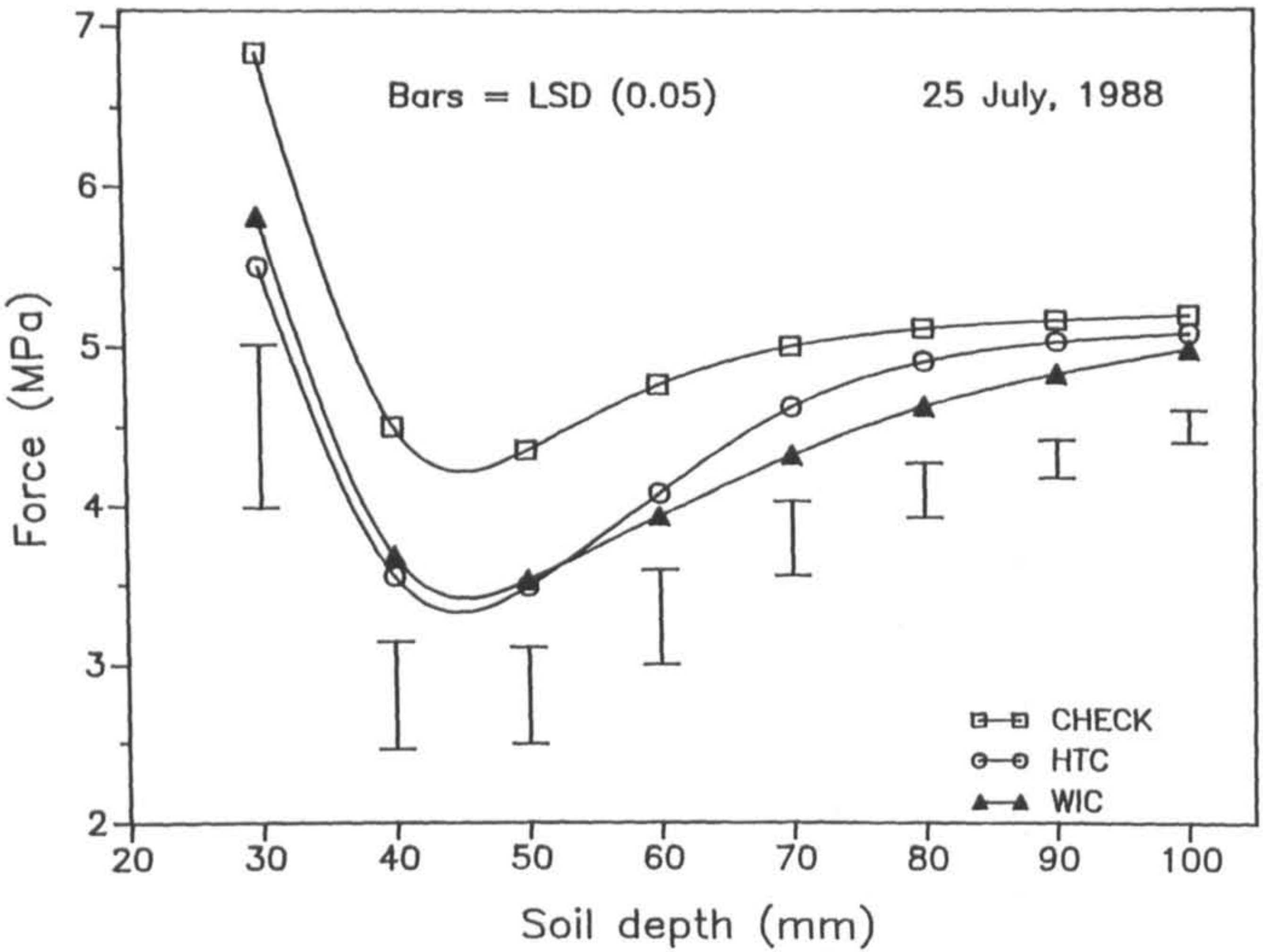

Figure 2.1. Influence of cultivation (HTC = hollow tine, WIC = water injection) on penetration resistance of a loamy sand soil sampled 25 July, 1988.

Plant Responses. Clipping yield data on 26 August demonstrated that WIC and HTC increased shoot growth immediately following treatment compared to check plots in 1988 (Table 2.5). HTC and WIC increased growth 16% and 42%, respectively compared to the check. This difference in yield between HTC and WIC was attributed to the removal of crown tissue with HTC. Penetration resistance data (Figure 2.1) showed HTC resulted in more surface loosening (disruption) compared to WIC. Most likely, greater disruption with HTC also imposed more mechanical injury stress to the turf than WIC. Yield data on 31 August showed that only WIC had significantly greater clipping yield compared to the check plots. Shoot growth enhancement with both HTC and WIC declined with time and became equivalent to the check plots prior to the 3 October treatment date in 1988.

Clipping yields on 27 May, 1989 showed growth on WIC plots was greater than the check plots during early spring growth. During a period of high growth rate in July no treatment differences were observed. On 9 August both HTC and WIC increased growth compared to the check. Compaction stress may have become great enough during this time to limit growth and cause a response in cultivated plots. Alderfer (1954) reported that cultivation of a heavily compacted Kentucky bluegrass turf did not increase growth. Roberts (1975) found cultivation of a Kentucky bluegrass turf reduced clipping yield. Sampling dates in September and October, 1989 showed no growth responses to cultivation (Table 2.5). This lack of response to cultivation treatment may be a result of the slow growth rates observed during this period.

Table 2.5. The influence of hollow tine (HTC) and water injection (WIC) cultivation on clipping yield of a compacted creeping bentgrass green mowed at 6 mm.

	1988 Clipping Yields			
	8/19	8/26	8/31	10/1
	$g\ m^{-2}\ day^{-1}$			
Check	2.8	1.9	1.9	1.2
HTC	2.7	2.2	2.3	1.3
WIC	2.8	2.7	2.6	1.2
LSD (0.05)	NS	0.2	0.4	NS

	1989 Clipping Yields					
	5/27	7/11	8/9	9/4	9/21	10/29
	$g\ m^{-2}\ day^{-1}$					
Check	1.6[Z]	3.6	2.2	1.7	0.6	0.2
HTC	1.8	3.7	2.5	1.7	0.7	0.2
WIC	1.9	3.7	2.5	1.8	0.6	0.2
LSD (0.05)	0.26	NS	0.2	NS	NS	NS

Z, Only 4 replications were available for 5/27 sampling.
NS denotes not significant.
Treated 9 July, 19 Aug., and 3 Oct., 1988 and 14 Aug. and 2 Oct., 1989.
Nitrogen applied 29 Apr., 20 May, 4 June, 26 June, 19 July, and 12 Aug., 1988, and 9 May, 14 June, 31 July, 23 Aug., and 22 Sept., 1989.

Table 2.6 shows the effect of cultivation treatment on visual quality in 1988 and 1989. WIC increased creeping bentgrass quality on these compacted plots by late August while HTC did not improve quality until late September in 1988. WIC had better quality in November compared to both HTC and check plots, and HTC plots were of better quality than check plots. It is important to note that two treatment applications (9 July and 19 August) were required before any improvement in quality could be observed in this study. Thus soil cultivation does not necessarily have an immediate impact on quality in a turfgrass system.

Quality ratings in 1989 showed that WIC plots had the best ratings throughout the season with three of the five dates being significantly better than the check. HTC received a better rating compared to the check on only one date; WIC was better than HTC on two dates.

Table 2.7 gives the shoot, thatch/mat, and total root weights measured in 1988 and 1989. Neither HTC nor WIC treatment had an effect on shoot tissue weight in November of 1988 and 1989. However, shoot tissue weight was found to be greater in cultivated plots compared to check plots in July 1989. This increase in shoot tissue was greater in WIC plots than HTC plots. Shoot tissue may have increased with cultivation only in July 1989 in response to reduced compaction stress during a period when other stresses, such as temperature and moisture, may be additive to the compaction stress.

Thatch/mat data supported the conclusion of crown tissue removal and injury. HTC resulted in lowering the amount of thatch compared to noncultivated and WIC plots. The 17% decrease in thatch/mat weight observed in November 1988 with HTC corresponded well with the

Table 2.6. The influence of hollow tine (HTC) and water injection (WIC) cultivation on visual quality of a compacted creeping bentgrass green mowed at 6 mm.

	1988 Quality Ratings				
	7/20	8/28	9/11	9/30	11/8
	(9=ideal and 6=acceptable)				
Check	8.2	7.1	7.5	7.0	5.0
HTC	8.0	6.9	7.2	7.5	5.5
WIC	8.6	7.9	7.8	7.6	6.1
L.S.D.(0.05)	NS	0.76	NS	0.35	0.46

	1989 Quality Ratings				
	5/27	7/10	8/3	10/7	11/1
	(9=ideal and 6=acceptable)				
Check	6.0	7.6	7.2	6.0	5.8
HTC	7.4	6.8	6.9	7.0	6.0
WIC	8.0	8.2	8.1	7.0	7.1
LSD (0.05)	NS	NS	0.8	0.6	0.5

NS denotes not significant.
Treated 9 July, 19 Aug., and 3 Oct., 1988 and 14 Aug. and 2 Oct., 1989.
Nitrogen applied 29 Apr., 20 May, 4 June, 26 June, 19 July, and 12 Aug., 1988, and 9 May, 14 June, 31 July, 23 Aug., and 22 Sept., 1989.

Table 2.7. The influence of hollow tine (HTC) and water injection (WIC) cultivation on the shoot tissue, thatch/mat, and total root weights of a compacted creeping bentgrass green.

	Shoot Tissue	Thatch/ Mat	Total Root Weight
November 1988 (4 weeks after treatment)			
		$kg\ m^{-2}$	
Check	0.246	1.25	0.534
HTC	0.223	1.04	0.466
WIC	0.205	1.31	0.518
LSD (0.05)	NS	0.18	0.065
July 1989 (40 weeks after treatment)			
Check	0.196	0.70	0.469
HTC	0.216	0.76	0.397
WIC	0.230	0.65	0.431
LSD (0.05)	0.013	NS	0.046
November 1989 (6 weeks after treatment)			
Check	0.232	1.47	0.633
HTC	0.211	1.06	0.477
WIC	0.223	1.28	0.600
LSD (0.05)	NS	0.16	0.065

NS denotes not significant.

calculated 13% area affected by three HTC treatments with 13 mm dia. tines (4.6% per treatment). Smith (1979) partially attributed the reduction in thatch organic matter to the physical removal via cultivation. No treatment differences in thatch/mat weight were observed in July 1989. Thatch/mat weights in July 1989 dropped compared to the November 1988 weights suggesting that the washing technique used for the July 1989 samples differed in some way. Thatch/mat weights in November 1989 again showed that HTC reduced this material compared to the check plots. Surprisingly, WIC also showed significantly lower thatch/mat weight compared to the check. Apparently, WIC inhibited the accumulation of organic material in the thatch/mat zone.

Total root weight (TRW) was reduced with HTC compared to the check on all three sampling dates (Table 2.7). HTC lowered TRW compared to WIC by November 1989. The reduction in rooting following HTC was limited to the 0 to 50 mm depth zone for the November 1988 and July 1989 sampling dates (Table 2.8). However, after a total of five HTC treatments, root weight density (RWD) was significantly decreased in both the 0 to 50 and 50 to 100 mm depth zones compared to the check and WIC plots. WIC resulted in significantly lower RWD compared to the check on only one date (July 1989) at 0 to 50 mm. There is likely some injury to roots which occurs with any effective cultivation method including WIC. These data demonstrated that HTC resulted in considerably more damage to the surface root system than WIC.

Root weight data indicated that large increases in surface root development during the fall did not occur following summer and fall cultivation. Large increases in surface rooting due to cultivation may

Table 2.8. The influence of cultivation on root weight densities of a creeping bentgrass green.

	Root Weight Density Zone (mm)		
	0 to 50	50 to 100	100 to 200
November 1988 (4 weeks after treatment)			
		$kg\ m^{-3}$	
Check	7.95	1.95	0.39
Hollow Tine	7.02	1.73	0.29
Water Injection	7.76	1.84	0.38
LSD (0.05)	0.91	NS	NS
July 1989 (40 weeks after treatment)			
Check	6.99	1.87	0.26
Hollow Tine	5.63	1.71	0.29
Water Injection	6.29	1.82	0.26
LSD (0.05)	0.67	NS	NS
November 1989 (6 weeks after treatment)			
Check	10.30	1.80	0.28
Hollow Tine	7.63	1.46	0.23
Water Injection	9.54	1.86	0.30
LSD (0.05)	1.40	0.29	NS

NS denotes not significant.

result in the spring when the initiation rate of new roots is greatest. Koski (1983) found the greatest length of active creeping bentgrass roots occurred during March through June.

Minirhizotron root observations (MRO) made on 15 Nov., 1988 (Figure 2.2), and 9 Aug. (Figure 2.3) and 29 Oct., 1989 (Figure 2.5) corroborated the root weight data and are representative of MRO videotaped on other dates during this study. MRO demonstrated that HTC reduced root numbers in the upper 100 to 150 mm of the soil profile. WIC did not result in a consistent lowering of root numbers within this zone.

Root numbers below the depth (200 mm) evaluated by the soil sampling method showed that WIC increased root numbers below 260 mm in November 1988 (Figure 2.2), from 144 to 384 mm in August 1989 (Figure 2.4), and from 220 to 408 mm in October 1989 (Figure 2.5) compared to the check. HTC did not result in such a response until August 1989, and any increase was of a smaller magnitude compared to WIC. Carrow (1988) has observed increased rooting below 200 mm after cultivation of a compacted bermudagrass turf.

Examination of the root turnover along minirhizotrons yields root growth information concerning where roots are appearing and disappearing within the soil profile (Ferguson and Smucker, 1989). Root turnover between 18 July and 30 Sept., 1988 demonstrated that both HTC and WIC resulted in a loss or a smaller increase in root numbers in the upper 168 mm of the profile compared to the check (Figure 2.6). However, WIC resulted in a large increase in rooting at the 264 to 360 mm depth zone. The third HTC treatment in 1988 resulted in a loss of roots between 30 September and 15 November at numerous depths

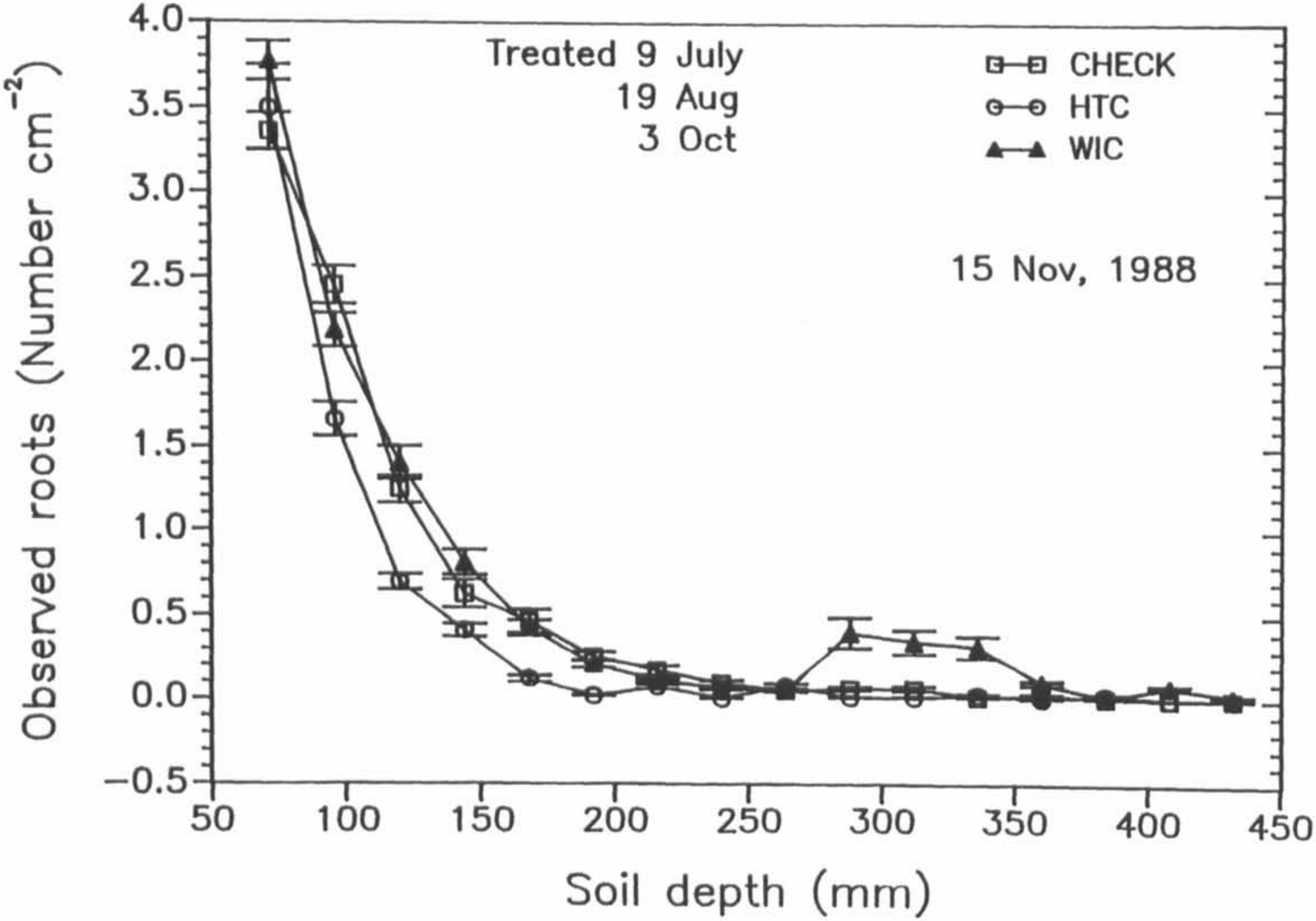

Figure 2.2. Influence of cultivation (HTC = hollow tine, WIC = water injection) on minirhizotron root observations taken 15 November, 1988.

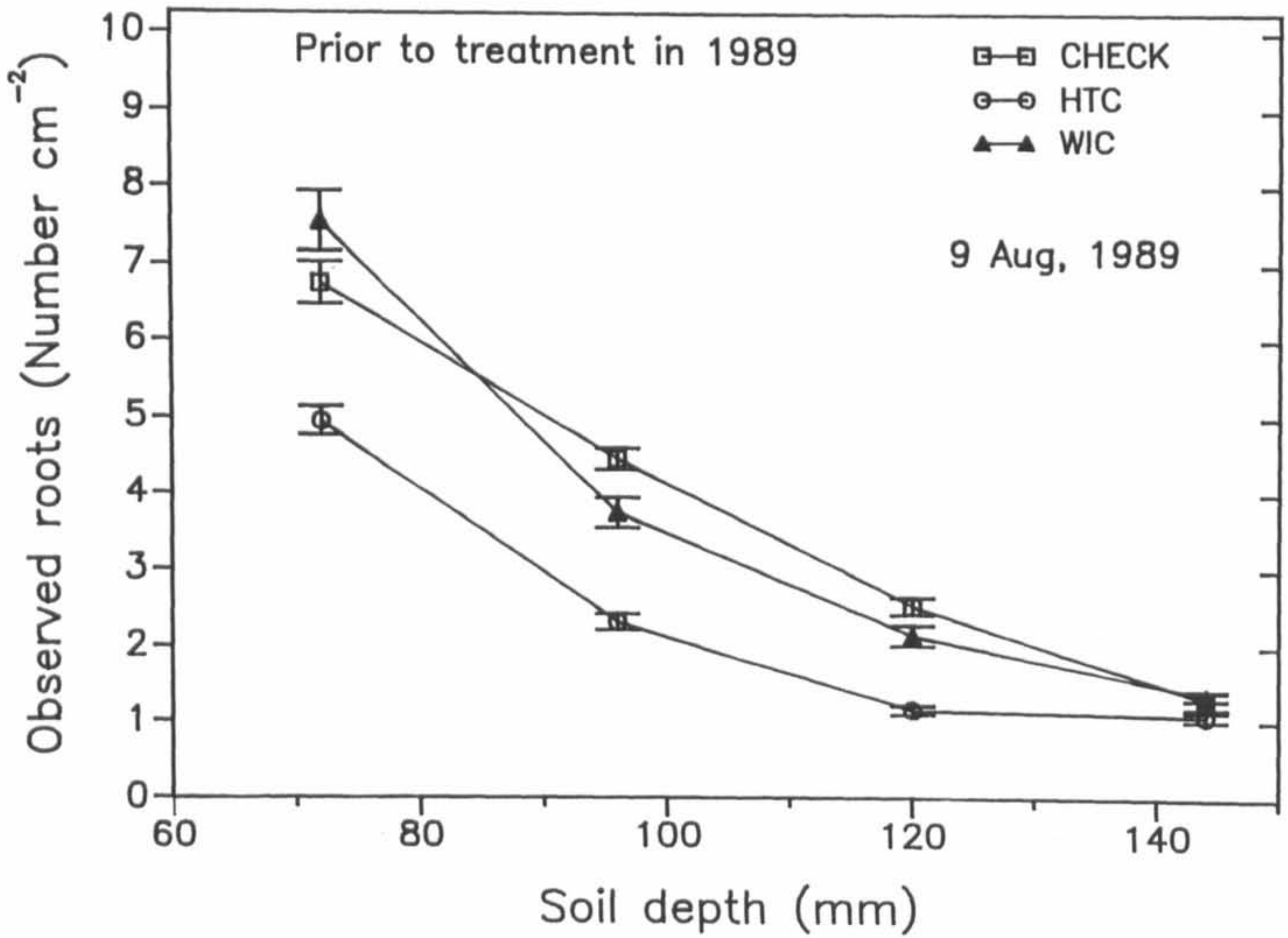

Figure 2.3. Influence of cultivation (HTC = hollow tine, WIC = water injection) on minirhizotron root observations at the 48 to 144 mm depth taken 9 August, 1989.

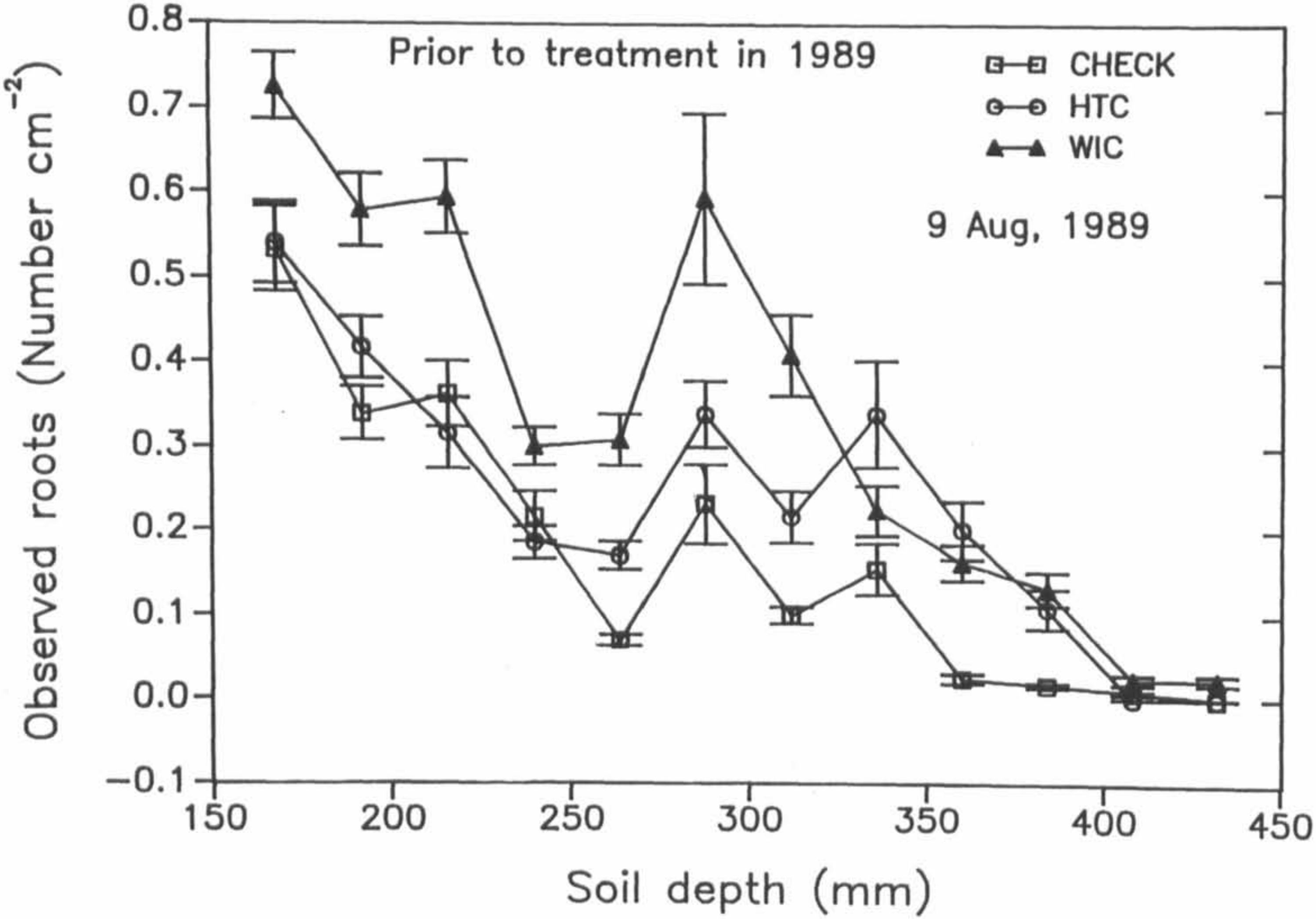

Figure 2.4. Influence of cultivation (HTC = hollow tine, WIC = water injection) on minirhizotron root observations at the 144 to 432 mm depth taken 9 August, 1989.

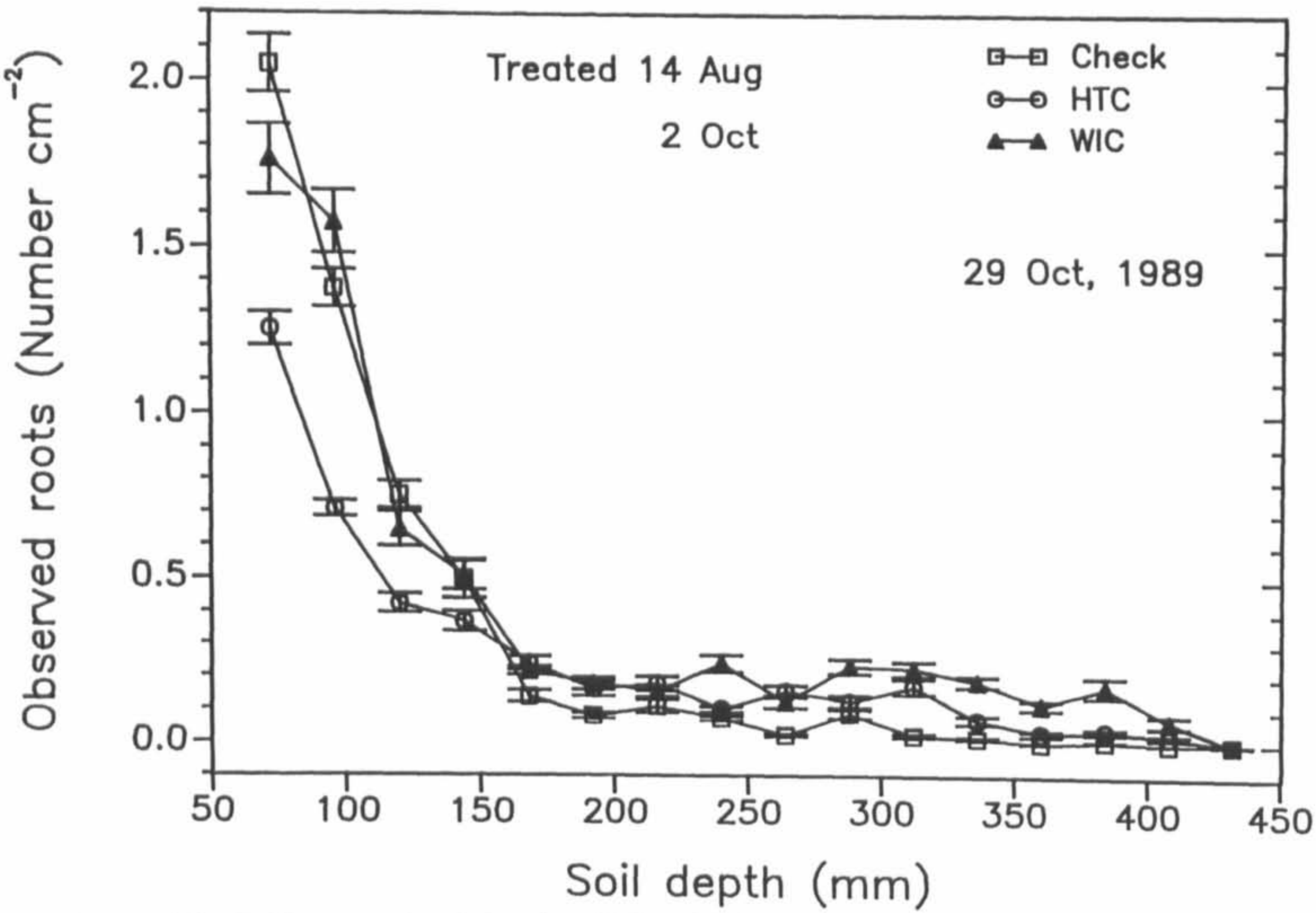

Figure 2.5. Influence of cultivation (HTC = hollow tine, WIC = water injection) on minirhizotron root observations taken 29 October, 1989.

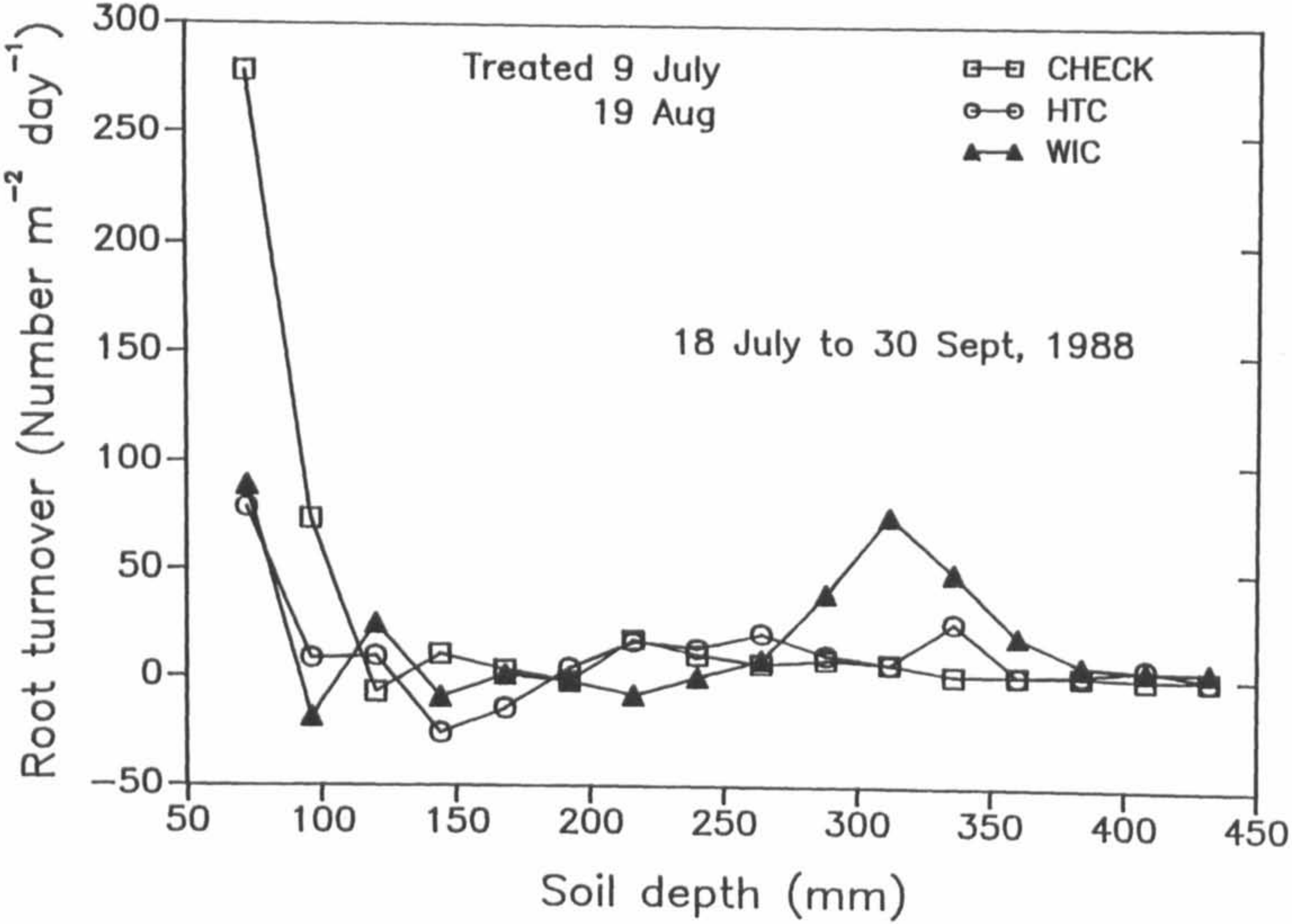

Figure 2.6. Influence of cultivation (HTC = hollow tine, WIC = water injection) on daily root turnover along minirhizotrons between 18 July and 30 September, 1988.

(Figure 2.7). WIC produced a gain in rooting at many depths above 288 mm for this observation period. WIC plots lost roots between 288 and 384 mm reflecting the greater number of roots present in this zone earlier in the season.

HTC plots lost roots from 19 Sept. to 29 Oct., 1989 in the upper 144 mm while WIC plots tended to gain roots in this zone (Figure 2.8). During this period, root turnover data below 144 mm tended to be erratic, but did show that WIC resulted in a gain of roots at many depths while HTC produced a loss of roots. As a result of the larger number of deep roots present in WIC plots, the percent of roots lost in HTC was much greater than that observed in WIC plots (Table 2.9).

Estimated Water Use. Water extraction data as estimated in 1989 by tensiometry and time domain reflectometry (TDR) is presented in Table 2.10. Water use estimated by tensiometry suggested that WIC plots used less water from the surface 76 mm in August compared to the noncultivated checks. Water use at the 76 to 152 mm depth did not differ among treatments. Water use estimated by the TDR method did not support the tensiometry data in August 1989. Water use estimated by the TDR method in September demonstrated that WIC plots lost less water compared to the checks during this measurement period. Carrow (1988) reported greater water extraction between 200 and 600 mm following cultivation treatment of a compacted bermudagrass turf. Rooting of the bermudagrass turf was also increased within this depth zone. Although no data was taken below 200 mm in this study, the lower water use observed in the surface 100 mm suggests that an increase in water utilization deeper in the soil profile may have occurred.

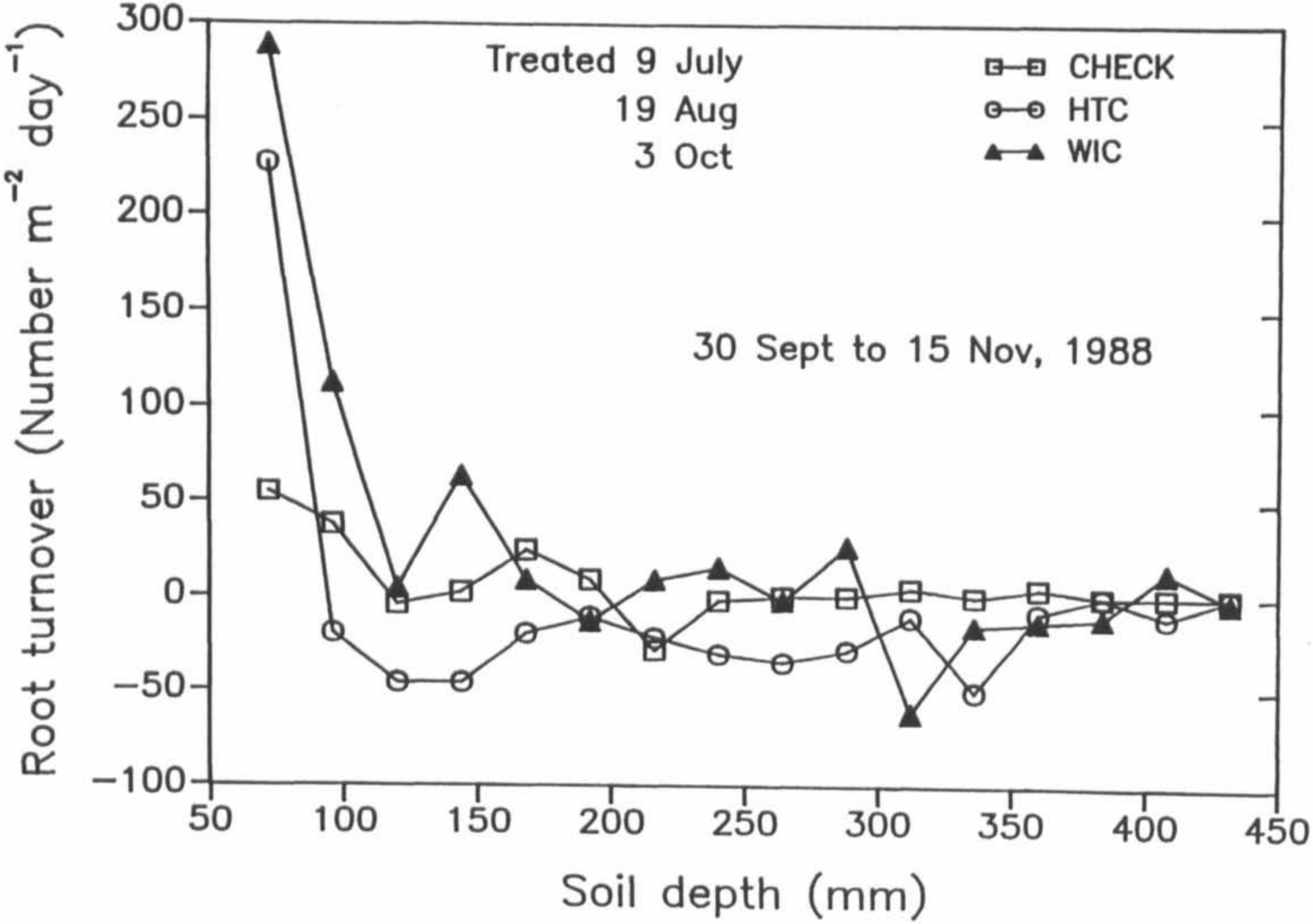

Figure 2.7. Influence of cultivation (HTC = hollow tine, WIC = water injection) on daily root turnover along minirhizotrons between 30 September and 15 November, 1988.

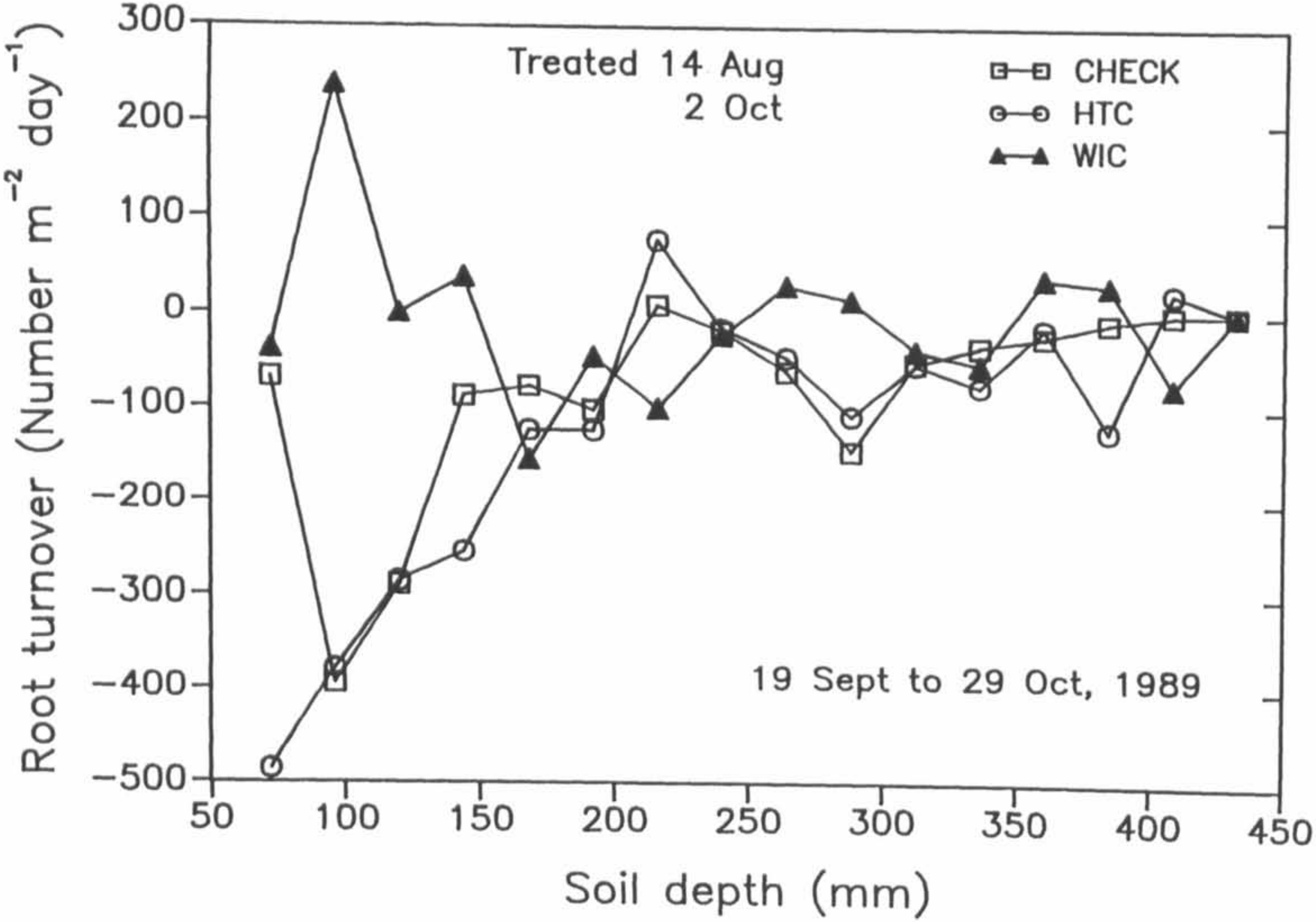

Figure 2.8. Influence of cultivation (HTC = hollow tine, WIC = water injection) on daily root turnover along minirhizotrons between 19 September and 29 October, 1989.

Table 2.9. The influence of cultivation on daily percent root turnover between 19 September and 29 October, 1989.

Depth	Check	Hollow Tine	Water Injection
mm		% day^{-1}	
72	-0.08	-0.70	-0.05
96	-0.56	-0.87	-0.45
120	-0.70	-1.00	0.00
144	-0.38	-1.02	0.20
168	-0.90	-0.85	-1.04
192	-1.40	-1.08	-0.52
216	0.24	1.92	-0.98
240	-0.51	-0.33	-0.22
264	-1.84	-0.58	0.83
288	-1.56	-1.17	0.18
312	-1.77	-0.60	-0.37
336	-1.77	-1.32	-0.56
408	0.00	-0.77	-1.32
432	0.00	0.00	0.00
Total	-15.13	-9.97	-1.59
Average	-0.95	-0.62	-0.10

Table 2.10. The influence of cultivation on water extraction as estimated by tensiometry and time-domain reflectometry (TDR) in 1989.

	Tensiometry	TDR	
	8/6 to 8/9	8/6 to 8/9	9/18 to 9/21
Depth Zone	0 to 152 mm	0 to 200 mm	
	mm H_2O		
Check	12.7	13.3	7.9
HTC	11.3	14.9	5.7
WIC	11.0	14.8	4.9
LSD (0.05)	NS(1.5)	NS	NS(2.7)
Depth Zone	0 to 76 mm	0 to 100 mm	
Check	8.6	5.4	2.2
HTC	7.7	5.4	1.7
WIC	7.0	5.2	0.8
LSD (0.05)	NS(1.4)	NS	1.0
Depth Zone	76 to 152 mm	100 to 200 mm	
Check	4.1	7.8	5.7
HTC	3.6	9.4	4.0
WIC	4.0	9.5	4.1
LSD (0.05)	NS	NS	NS

NS denotes not significant.
Values in parentheses are the LSD at the 5.0% probability level but did not meet Fisher's protected LSD requirement.

Minirhizotron observations showed an increase in rooting below 200 mm on WIC plots which lends support to the idea of deeper soil water extraction (Figures 2.1, 2.3, & 2.4).

One reason for the discrepancy in TDR during August was unfamiliarity with the operation of the TDR which may have resulted in considerable operator error. Comparison of the tensiometry and TDR data showed that the TDR method estimated greater water extraction in the deeper portions of the profile relative to the surface profile. Water extraction by the tensiometer method showed the opposite. Total water use was similar for the two methods suggesting that the shorter probes (100 mm) used in the TDR method may have yielded inaccurate data. It should be noted that comparison of the two methods is confounded by the different depth zones for each type of measurement.

SUMMARY

Analysis of soil physical properties demonstrated that water injection cultivation (WIC) was equal or superior to hollow tine cultivation (HTC) in improving bulk density, total soil porosity, aeration porosity, and saturated hydraulic conductivity in the 0 to 76 mm depth zone. Total soil porosity was increased slightly in 1988 at the 76 to 152 mm zone with WIC compared to HTC and check plots. Increased soil porosity resulted from the very large pores created by cultivation, i.e., coring holes and injection channels. Saturated hydraulic conductivity was increased with WIC compared to the check. HTC did not have a significant effect on conductivity in the two years of treatment. HTC was more effective in loosening the surface 30 mm of soil compared to WIC. However, below the 60 mm depth only WIC provided a significant loosening of the soil down to the 100 mm depth.

WIC stimulated creeping bentgrass shoot growth of a compacted putting green over that achieved after conventional HTC. An immediate shoot growth increase following WIC would allow for faster recovery of putting greens from compaction stress relative to HTC treatment. Mechanical injury to turf and roots and loss of crown tissue following HTC would place an additional stress on the turf, which may slow the recovery time of the turf to improved soil conditions. WIC had no measurable effect on thatch/mat weight after three treatments while HTC decreased thatch/mat weight after one season. WIC did not reduce thatch/mat levels in a single growing season. The impact on long term thatch accumulation with continued WIC remains a question, even though a reduction in thatch/mat weight was evident after five treatments over two seasons.

HTC reduced total root weight compared to the check and WIC plots. Root damage and removal during cultivation was the reason for this response to HTC. Minirhizotron root observations (MRO) supported the conclusion of reduced rooting following HTC and to a limited extent following WIC. Reduced injury to the root system should enable the turf to respond more quickly to the improved soil conditions following cultivation. Minimizing the amount of mechanical injury stress incurred by the turf during cultivation should be important when considering cultivation during and prior to periods when environmental stresses are high (e.g., treatment of isolated dry spot in putting greens). MRO below the soil zone sampled for root weight revealed increased rooting for both HTC and WIC plots compared to the check.

This deep rooting response was greater in WIC plots than HTC plots. Increased rooting below 200 mm may help explain the decreased water extraction at the 0 to 100 mm zone in WIC plots. The presence of deep roots may have distributed water consumption over a larger soil volume (depth), thus minimizing surface water consumption.

The data demonstrated WIC produced soil responses similar to HTC. However, WIC appeared to alter soil properties deeper in the soil profile while reducing the amount of surface disturbance. HTC resulted in considerable disruption of the turf surface which damaged and removed plant tissue. WIC should be a very beneficial cultivation method during periods of high demand for recreational use and environmental stresses.

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