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NITROGEN FERTILIZATION AND SOIL CULTIVATION UTILIZING HIGH PRESSURE WATER INJECTION

By

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ABSTRACT

NITROGEN FERTILIZATION AND SOIL CULTIVATION UTILIZING HIGH PRESSURE WATER INJECTION

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Water injection cultivation (WIC) was introduced in 1990 as a new method of cultivating turfgrass soils. The Toro HydroJect®, the first WIC unit reaching the market, uses 20 MPa water bursts cultivating at 15 cm depths while causing minimal surface disruption. As with many new technologies, indirect WIC applications and complications merit investigation. Studies were initiated to determine the effectiveness of applying nitrogen fertilizer via WIC and examine the indirect benefits and detriments of WIC technology on putting green and fairway turf. Injecting nitrogen resulted in several beneficial turfgrass responses. *Poa annua* encroachment into an *Agrostis palustris* turf did not differ significantly between turf receiving WIC and hollow tine cultivation after three years of treatments. Frequent WIC of a turf containing a sand topdressing layer overlying a finer-textured soil resulted in mixing of the layers at the interface, but finer-textured soil was not blasted to the turfgrass surface.

To my parents, Harold and Joyce, whose continual love, guidance, and support have made my graduate education possible.

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TABLE OF CONTENTS

List of Tables	vi
Chapter One: Nitrogen Fertilization of Turfgrass Using High Pressure Water Injection	1
Abstract	1
Introduction	3
Literature Review	4
Materials and Methods	5
Results and Discussion	8
Bibliography	34
Chapter Two: Water Injection Cultivation of a Sand Topdressed Putting Green	36
Abstract	36
Introduction	38
Literature Review	39
Materials and Methods	40
Results and Discussion	44
Bibliography	62
Chapter Three: Cultivation Effects on *Poa annua* Encroachment into a Creeping Bentgrass Putting Green	65
Abstract	65
Introduction	67
Literature Review	68
Materials and Methods	69
Results and Discussion	72
Bibliography	89

LIST OF TABLES

Table		Page
1.1.	Effect of nitrogen application method and rate on clipping yields of a *Poa annua* fairway. 1994.	9
1.2.	Effect of nitrogen application method and rate on clipping yields of a *Poa annua* fairway. 1995.	10
1.3.	Effect of nitrogen application method and rate on clipping yields of an *Agrostis palustris* putting green. 1994.	12
1.4.	Effect of nitrogen application method and rate on clipping yields of an *Agrostis palustris* putting green. 1995.	13
1.5.	Effect of nitrogen application method and rate on nitrogen content of a *Poa annua* fairway. 1994 and 1995.	14
1.6.	Effect of nitrogen application method and rate on nitrogen content of an *Agrostis palustris* putting green. 1994 and 1995.	16
1.7.	Effect of nitrogen application method and rate on quality of a *Poa annua* fairway. 1994.	18
1.8.	Effect of nitrogen application method and rate on quality of a *Poa annua* fairway. 1995.	19
1.9.	Effect of nitrogen application method and rate on quality of an *Agrostis palustris* putting green. 1994.	20
1.10.	Effect of nitrogen application method and rate on quality of an *Agrostis palustris* putting green. 1995.	21
1.11.	Effect of nitrogen application method and rate on color of a *Poa annua* fairway. 1994.	23
1.12.	Effect of nitrogen application method and rate on color of a *Poa annua* fairway. 1995.	24
1.13.	Effect of nitrogen application method and rate on color of an *Agrostis palustris* putting green. 1994.	26
1.14.	Effect of nitrogen application method and rate on color of an *Agrostis palustris* putting green. 1995.	27

1.15. Effect of nitrogen application method and rate on wilting. 1994 and 1995. 28

2.1. Effect of cultivation treatment on the mixing of a sand topdressing layer with underlying native soil. Samples collected 9/18/95. 45

2.2. Effect of cultivation treatment on the mixing of a sand topdressing layer with underlying native soil. Samples collected 9/15/96. 46

2.3. Effect of cultivation treatment on quality of a sand topdressed putting green. 49

2.4. Effect of cultivation treatment on moisture stress symptoms of a sand topdressed putting green. 51

2.5. Effect of cultivation treatment on root weight density of a sand topdressed putting green. 1996. 52

2.6. Effect of cultivation treatment on ball roll distance of a sand topdressed putting green. 1994. 53

2.7. Effect of cultivation treatment on ball roll distance of a sand topdressed putting green. 1995. 54

2.8. Effect of cultivation treatment on ball roll distance of a sand topdressed putting green. 1996. 55

2.9. Effect of cultivation treatment on physical soil properties of a sand topdressed putting green. 1995. 57

2.10. Effect of cultivation treatment on physical soil properties of a sand topdressed putting green. 1996. 58

2.11. Effect of water injection cultivation on the mixing of a sand topdressing layer with the underlying native soil. 60

3.1. Effects of cultivation treatment on *Poa annua* encroachment into a creeping bentgrass putting green. 73

3.2 Effects of cultivation on quality of a creeping bentgrass putting green. 1994. 74

3.3. Effects of cultivation on quality of a creeping bentgrass putting green. 1995. 76

3.4. Effects of cultivation on quality of a creeping bentgrass putting green. 1996. 77

3.5. Effect of cultivation on ball roll distance of a creeping bentgrass putting green. 1994. 79

3.6. Effect of cultivation on ball roll distance of a creeping bentgrass putting green. 1995. 80

3.7. Effect of cultivation on ball roll distance of a creeping bentgrass putting green. 1996. 81

3.8. Effect of cultivation treatment on physical soil properties of a creeping bentgrass putting green. 1995. 84

3.9. Effect of cultivation treatment on physical soil properties of a creeping bentgrass putting green. 1996. 85

3.10. Effect of cultivation treatment on earthworm castings and biomass on a creeping bentgrass putting green. 86

CHAPTER ONE

Nitrogen Fertilization of Turfgrass Using High Pressure Water Injection Cultivation.

ABSTRACT

Subsurface placement of nitrogen fertilizers have increased yields in the food and forage industry. Minimal past research has evaluated subsurface placement of nitrogen fertilizers in turfgrass, primarily due to the unavailability of equipment to apply materials subsurfacely without causing considerable surface disruption. The introduction of water injection cultivation in the early 1990's made subsurface placement of soluble materials possible. The HydroJect 3000® uses a 20 MPa blast of water to cultivate turfgrass areas while causing minimal surface disruption. Studies were initiated in 1994 to examine the effects of injecting nitrogen with the HydroJect into an annual bluegrass (*Poa annua* L. *reptans*) fairway and a 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) putting green. Treatments included three rates of urea (fairway study-- 1.2, 2.4, and, 3.6 g N m^{-2} $application^{-1}$; putting green study-- 1.2, 3.4, and 4.8 g N m^{-2} $application^{-1}$) either injected or surface applied and were replicated four times in each study. Nitrogen was applied on five dates during the 1994 growing season at approximately 24 day intervals. Plots injected with urea had significantly higher clipping yields, nitrogen content in leaf tissue, and color ratings than plots receiving surface applications on several evaluation dates. These differences could have been caused by ammonia volatilization from surface applications, even though plots were irrigated shortly after application. This theory was

tested by repeating the studies in 1995 using ammonium nitrate as the nitrogen source. Ammonium nitrate was applied on six dates during the 1995 growing season. Results from the 1995 study were very similar to those recorded the previous year. Therefore, it is likely that factors other than ammonia volatilization increase nitrogen efficiency when applications are made via injection. Although injected plots had darker green color ratings, they exhibited a striping pattern caused by the spacing of the injection nozzles (7.5 cm) that reduced turf quality ratings. Striping lasted for approximately 10 days following application and was less noticeable following succesive applications. During both years, plots injected with nitrogen were less susceptible to wilt stress than those receiving surface applications.

Introduction

Subsurface applications of nitrogen have proven to increase plant nitrogen use efficiency in the food and forage crop industries. More efficient use of nitrogen through better application methods has conserved energy and resources required for nitrogen fertilizer synthesis. Rapid suburban growth and golf course construction has resulted in increased nitrogen fertilizer use in the turfgrass industry during recent decades. More efficient application methods, and the subsequent conservation of nitrogen in the turfgrass industry, would save energy and reduce risk of environmental contamination.

Early agricultural fertilization was accomplished through broadcast applications. Concerns of inefficient fertilizer use from broadcasting, especially nitrogen losses, initiated extensive research efforts to study the effects of subsurface fertilizer placement on plant growth. This research almost exclusively focused on food and forage production with little literature available on subsurface fertilizer placement in turfgrass. The lack of fertilizer placement research in turfgrass is partly the result of insufficient means to place fertilizer below the soil surface in an established turfgrass stand. Equipment used for subsurface placement of fertilizer in food and forage production would result in considerable surface disruption on an established turfgrass stand. The recent development of high pressure water injection as a turfgrass cultivation practice has made subsurface placement of materials a possibility. The Toro HydroJect 3000® uses a 20 MPa blast to inject water 10 to 20 cm below the soil surface while causing minimal surface disruption (Murphy, 1994). Subsurface turfgrass fertilization is made possible by dissolving fertilizer material and pumping it through the HydroJect. Previous research conducted at Michigan State University demonstrated that the injection of dissolved nutrients with the HydroJect was an effective application method (Miller, 1994).

The objective of this research was to determine if the application of nitrogen by injection is an effective means of fertilizing turfgrass. A HydroJect 3000® was used to inject nitrogen into an annual bluegrass (*Poa annua* L. *reptans*) fairway and a 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.)

Literature Review

Past research on subsurface fertilization has focused heavily on food and forage crop production. Mengel et al., in 1982, found that injecting nitrogen carriers below the soil surface with commercial anhydrous knife equipment resulted in significantly higher grain yields for conventional and no-till corn (*Zea mays* L.) compared to surface applications. Nitrogen content of grain and leaves was consistently higher with injected treatments than surface applications. Similar results were obtained by Stecker et al., in 1993, comparing the effects of knifing and broadcasting urea ammonium nitrate on no-till corn. They found corn grain yields increased by 5 to 40% with subsurface nitrogen placement. Nitrogen content of grain and leaves increased significantly when nitrogen was injected. Comparable results have been obtained on no-till corn when nitrogen was injected with pressurized nozzles similar to those used by the HydroJect (Howard and Tyler, 1989). Increased yields, leaf nitrogen concentration, and nitrogen uptake by the plant were obtained by injecting nitrogen rather than surface banding or broadcasting. These results were attributed to a decreased potential for volatilization and/or immobilization in the soil of nitrogen when injected. Subsurface placement of nitrogen improved the production of no-till winter wheat (*Triticum aestivum* L.) (Fowler and Brydon, 1989) and brome grass (*Bromus inermis*, Leyss) (Ogus and Fox, 1970).

Subsurface banding of nitrogen in a tall fescue (*Festuca arundinacea* Schreb) forage crop, a cool season perennial species often utilized as a turfgrass, improved nitrogen uptake, increased forage yields, and increased leaf nitrogen content compared to surface applications (Lamond and Moyer, 1983). Raczkowski and Kissel (1989) obtained similar results and hypothesized that treatment differences resulted from atmospheric losses of nitrogen with the surface application. Both of these studies required non-commercial application equipment to band nitrogen into established sod.

Most literature available on fertilizer placement in turfgrass concerns turfgrass establishment, i.e. fertilizer placement effects on seed germination or sod establishment (Jackson and Burton, 1962; King and Skogley, 1969; King and Beard, 1972, Peacock and Dudeck, 1982). This work has shown minimal differences in turfgrass establishment with regard to fertilizer placement.

When the HydroJect became available as a turfgrass management tool in 1990, research concerning subsurface placement of fertilizer began to focus on established turfgrass systems. Miller (1994) showed that the HydroJect could be utilized to effectively inject P_2O_5 and K_2O. Murphy and Rieke (1992) found that nitrogen injection in the late fall resulted in a more uniform green up the following spring when compared to surface applications, and that nitrogen recovery was 34% greater with injection. Miller and Rieke (1994) discovered that turfgrass injected with nitrogen had significantly higher clipping yields than plots receiving surface applications. Murphy and Zaurov observed, in a 1994 study, that greenhouse turfgrass plots receiving subsurface nitrogen injections demonstrated higher clipping yields, greater root mass, higher nitrogen accumulation in plant tissues, and higher water use rate efficiency than turfgrass receiving surface applications of nitrogen.

Materials and Methods

The nitrogen injection studies were initiated in June 1994, at the Hancock Turfgrass Research Center on the campus of Michigan State University to determine the effects of injecting nitrogen with the HydroJect® on fairway and putting green turfs.

Treatments included three rates of nitrogen, either injected or surface applied. The nitrogen source used for all treatments was urea in 1994 and ammonium nitrate in 1995. No supplemental fertilization was applied. Treatment differences observed in 1994 may have been the result of ammonia volatilization from surface applied urea. Ammonium nitrate was used as the nitrogen source in 1995 to minimize treatment differences possibly resulting from ammonia volatilization (Bandel et al., 1980). Nitrogen injections were made with a HydroJect 3000 provided by the Toro Co. of Minneapolis. A nitrogen solution was pumped from a holding tank to the intake line of the HydroJect and subsequently injected into the soil. Injections were made with 20 MPa blasts that reached average depths of 12 cm. The HydroJect was calibrated for nitrogen injection prior to treatments. Surface applications were made using a CO_2 powered sprayer designed specifically for small plot applications. Approximately 0.5 cm of water was applied to all plots immediately following nitrogen fertilization.

The three nitrogen rates for the fairway study were 1.2, 2.4, and 3.6 g m^{-2} per application. A double rate was used for a late fall application on Nov. 8, 1994. Nitrogen was applied on Jun. 27, Aug. 9, Sep. 1, Sep. 30, and Nov. 8 in 1994; and May 12, Jun. 6, Jun. 30, Jul. 25, Aug. 18 and Sep. 12 in 1995. During each growing season, a total of 7.2, 14.4, and 21.6 g N m^{-2} was applied for the low, medium, and high nitrogen rate treatments. The fairway study was conducted on an 11-year old annual bluegrass turf established on a fine-loamy, mixed, mesic Typic Hapludalf (67.8% sand, 19.1% silt, 13% clay). The experimental area was mowed at 1.25 cm and maintained under typical fairway management practices. Mowing was performed three times per week during the majority of the growing season. Irrigation was applied daily unless the turf received sufficient water from precipitation. Pesticides were applied on a curative basis and no supplemental fertilization was applied during the study.

The three nitrogen rates for the putting green study were 1.2, 3.0, and 4.8 g m^{-2} per application. A double rate was used for a late fall application on Nov. 8, 1994. Nitrogen was applied on Jun. 27, Aug. 9, Sep. 1, Sep. 30, and Nov. 8 in 1994; and May 12, Jun. 6, Jun. 30, Jul. 25, Aug. 18 and Sep. 12 in 1995. During each growing season a total of 7.2, 18.0, and 28.8 g N m^{-2} was applied for the low, medium, and high nitrogen rate treatments. The putting green study was conducted on a three-year old 'Penncross' creeping bentgrass green established on a modified sand (95.1% sand, 0.4% silt, 4.5% clay) meeting USGA specifications. The experimental area was mowed at 0.5 cm and maintained under typical putting green management practices. Mowing was performed five times per week during the majority of the growing season. Irrigation was applied daily unless the turf received sufficient water from precipitation. Pesticides were applied on a curative basis and no supplemental fertilization was applied during the study.

Clippings were collected by mowing one pass lengthwise on each plot, an area approximately 1.8 m^2, with a walking reel mower at two week intervals. Clippings were harvested on Jul. 14, Jul. 29, Aug. 15, Aug. 29, Sep. 12, and Oct. 7 in 1994; and May 15, May 30, Jun. 12, Jun. 29, Jul. 10, Jul. 24, Aug. 14, Sep. 7, and Oct. 19 in 1995. Clippings were collected following 3 to 5 days of growth. Clippings were dried at 60°C and weighed to determine dry matter yield. Clippings were analyzed for nitrogen content on a monthly basis using micro Kjeldahl techniques: Aug. 15 and Sep. 12, 1994; and May 15, Jun. 26, Aug. 7, Sep. 7, and Oct. 19, 1995.

Turfgrass quality and color ratings were taken approximately every 2 weeks throughout the growing season. Quality ratings were based on turfgrass uniformity, density, and color. Plots were ranked on a scale of 1 to 9, with 1 being dead turf, 6 minimum acceptable quality, and 9 uniform, dense, dark green turf.. A similar scale was used for color ratings with 1 being brown turf, 6 acceptable color, and 9 dark green turf. Quality and color ratings were taken on Jul. 14, Jul. 29, Aug. 15, Aug. 29, Sep. 12, Sep. 26, Oct. 10, Oct. 25, and Nov. 8 in 1994; and Apr. 21, May 8, May 19, Jun. 2, Jun. 16, Jun. 29, Jul. 16, Aug. 9, Aug. 23, and Sep. 17 in 1995.

Wilt ratings were taken when noticeable drying had occurred over the experimental area. Irrigation was turned off to exacerbate moisture stress symptoms during periods of high evapotranspiration. A scale from 1 to 9 was used with 1 being no wilt, 6 moderate wilt, and 9 severe wilt. Due to an unusually wet summer, plots exhibited sufficient wilt for rating only on the fairway study on Sep. 14 in 1994. Wilt ratings were taken on Jul. 12 and Sep. 3 on fairway plots, and Sep. 25 on putting green plots in 1995.

A randomized complete block design was used as the error control design. Treatments were replicated four times. A two-factor analysis of variance was calculated for all data to indicate differences in application methods, differences in nitrogen levels, and levels of interaction between the two factors. Application method means were determined significantly different at probabilities ≤ 0.05. Nitrogen rate means were separated using Fisher's protected least significant difference procedure at the 0.05 level of probability. Differences between application method means and among nitrogen rate means are reported with 95 % confidence intervals for treatment mean differences (Freund and Wilson, 1993). There were no factor interactions when the seasonal data was averaged, so only main effects are reported.

Results and Discussion

Clipping yields

Clipping yield data for the fairway study are summarized in Tables 1.1 and 1.2. On average, plots injected with nitrogen had mean annual clipping yields 1.3 ± 1.9 g m^{-2} greater than plots receiving surface applications in 1994; and 1.7 ± 1.0 g m^{-2} greater than plots receiving surface applications in 1995. Injected plots had significantly greater ($P < 0.05$) clipping yields than surface application on one of six days clippings were collected in 1994 and three of nine dates clippings were collected in 1995. Surface applied plots had significantly greater ($P < 0.05$) yields than injected plots only on Sep. 7, 1995. Plots

Table 1.1. Effect of nitrogen application method and rate on clipping yields of a *Poa annua* fairway. 1994.

	Clipping harvest date						
Fertilization treatment†	14-Jul	29-Jul	15-Aug	29-Aug	12-Sep	7-Oct	Annual mean
				$g\ m^{-2}$			
Application method							
Surface applied	18.3	12.7	18.6	16.8	13.3	11.1	15.1
Injected	15.8	13.5	16.6	19.2	20.5	12.9	16.4
Significance	*	NS	NS	NS	***	NS	NS
Nitrogen rate							
$1.2\ g\ m^{-2}$	15.5	12.0	15.2	16.9	13.4	8.8	13.6
$2.4\ g\ m^{-2}$	15.0	12.2	17.5	17.8	16.9	12.4	15.3
$3.6\ g\ m^{-2}$	20.7	15.1	19.8	19.3	20.4	14.9	18.3
LSD‡	4.8***	NS	NS	NS	4.2***	4.6***	3.2***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

‡ Fisher's protected least significant difference at the indicated level of statistical significance

Table 1.2. Effect of nitrogen application method and rate on clipping yields of a *Poa annua* fairway. 1995.

Fertilization treatment†	Clipping harvest date									
	15-May	30-May	12-Jun	29-Jun	10-Jul	24-Jul	14-Aug	7-Sep	19-Oct	Annual mean
	$g\ m^{-2}$									
Application method										
Surface applied	5.5	20.3	9.1	3.9	6.8	9.5	7.0	15.0	21.7	11.0
Injected	3.9	24.6	10.0	4.7	11.7	13.2	8.0	12.7	25.5	12.7
Significance	NS	*	NS	NS	***	***	NS	**	*	***
Nitrogen rate										
1.2 $g\ m^{-2}$	1.9	20.1	6.7	3.1	4.7	7.3	5.7	11.0	22.1	9.2
2.4 $g\ m^{-2}$	3.8	22.3	9.7	4.5	9.0	12.0	7.8	15.7	23.9	12.1
3.6 $g\ m^{-2}$	8.4	25.0	12.3	5.3	14.0	14.7	9.0	14.7	24.8	14.2
LSD‡	4.7***	NS	2.8***	1.8***	2.6***	2.8***	2.1***	3.6***	NS	1.8***

† Treatments applied on 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

‡ Fisher's protected least significant difference at the indicated level of statistical significance

receiving the high nitrogen rate had mean annual clipping yields 3.0 ± 2.3 g m^{-2} greater than the medium nitrogen rate and 4.7 ± 2.3 g m^{-2} greater than the low nitrogen rate in 1994; 2.1 ± 1.3 g m^{-2} greater than the medium nitrogen rate and 5.0 ± 1.3 g m^{-2} greater than the low nitrogen rate in 1995. There were significant differences in clipping yields ($P < 0.05$) among nitrogen rate treatments on three of six days clippings were collected in 1994 and seven of nine dates clippings were collected in 1995.

Clipping yield data for the putting green study are summarized in Tables 1.3 and 1.4. On average, plots injected with nitrogen had mean annual clipping yields 3.0 ± 0.9 g m^{-2} greater than plots receiving surface applications in 1994; and 3.0 ± 2.1 g m^{-2} greater than plots receiving surface applications in 1995. Injected plots had significantly greater clipping yields ($P \leq 0.05$) than surface application on four of six dates clippings were collected in 1994 and five of nine dates clippings were collected in 1995. Plots receiving the high nitrogen rate had mean annual clipping yields 1.6 ± 1.0 g m^{-2} greater than the medium nitrogen rate and 3.4 ± 1.0 g m^{-2} greater than the low nitrogen rate in 1994; and 3.8 ± 2.6 g m^{-2} greater than the medium nitrogen rate and 13.0 ± 2.6 g m^{-2} greater than the low nitrogen rate in 1995. There were significant differences in clipping yields ($P \leq 0.05$) among nitrogen rate treatments on four of six dates clippings were collected in 1994, and all nine dates clippings were collected in 1995.

Nitrogen content

Nitrogen content data for the fairway study are summarized in Table 1.5. The mean annual nitrogen content in plant tissue for plots injected with nitrogen was 0.6 ± 0.3 g N 100 g^{-1} greater than plots receiving surface applications in 1994; and 0.1 ± 0.2 g N 100 g^{-1} greater than plots receiving surface applications in 1995. Turf injected with nitrogen had significantly higher nitrogen contents ($P \leq 0.05$) in plant tissues on both dates clippings were analyzed in 1994 and only one of five dates that clippings were analyzed in 1995. Turf receiving the high nitrogen rate had mean annual nitrogen contents 0.4 ± 0.4 g N 100 g^{-1} greater than plots receiving the medium nitrogen rate and

Table 1.3. Effect of nitrogen application method and rate on clipping yields of an *Agrostis palustris* putting green. 1994.

	Clipping harvest date						
Fertilization treatment†	14-Jul	29-Jul	15-Aug	29-Aug	12-Sep	7-Oct	Annual mean
	$g\ m^{-2}$						
Application method							
Surface applied	15.3	10.8	10.5	8.0	8.4	7.8	10.1
Injected	16.6	10.9	12.6	11.6	13.7	13.0	13.1
Significance	NS	NS	***	***	***	***	***
Nitrogen rate							
1.2 $g\ m^{-2}$	15.0	11.0	9.9	7.3	8.6	7.4	9.9
3.4 $g\ m^{-2}$	17.0	11.0	11.9	10.0	11.0	9.5	11.7
4.8 $g\ m^{-2}$	16.0	10.5	12.8	12.1	13.8	14.4	13.3
LSD‡	NS	NS	1.7***	1.5***	2.5***	3.9***	1.4***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

‡ Fisher's protected least significant difference at the indicated level of statistical significance

Table 1.4. Effect of nitrogen application method and rate on clipping yields of an *Agrostis palustris* putting green. 1995.

	Clipping harvest date									
Fertilization treatment†	15-May	30-May	12-Jun	29-Jun	10-Jul	24-Jul	14-Aug	7-Sep	19-Oct	Annual mean
	$g\ m^{-2}$									
<u>Application method</u>										
Surface applied	18.4	17.4	17.0	19.0	13.8	11.0	16.2	13.9	11.8	15.4
Injected	27.4	23.8	20.7	26.1	14.1	12.6	13.8	13.8	13.1	18.4
Significance	***	**	**	***	NS	NS	NS	NS	**	***
<u>Nitrogen rate</u>										
1.2 $g\ m^{-2}$	13.8	10.8	9.7	13.5	9.4	7.8	7.7	8.1	7.7	9.8
3.4 $g\ m^{-2}$	24.5	21.8	19.5	21.8	14.5	12.9	16.5	16.0	14.1	18.0
4.8 $g\ m^{-2}$	30.3	29.3	27.3	32.3	17.9	14.7	20.8	17.5	15.5	22.8
LSD‡	9.1***	9.4***	5.2***	5.9***	6.6***	3.8***	6.3***	4.3***	2.2***	3.6***

† Treatments applied on 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

‡ Fisher's protected least significant difference at the indicated level of statistical significance

Table 1.5. Effect of nitrogen application method and rate on nitrogen content of a *Poa annua* fairway. 1994 and 1995.

	1994			1995					
	Clipping harvest date			Clipping harvest date					
Fertilization treatment†	15-Aug	12-Sep	Annual mean	15-May	26-Jun	7-Aug	7-Sep	19-Oct	Annual mean
	g N 100 g^{-1} tissue								
Application method									
Surface applied	1.9	2.4	2.2	2.2	3.2	4.3	2.4	2.7	3.6
Injected	2.6	3.0	2.8	2.3	3.0	4.4	3.0	3.0	3.7
Significance	***	***	***	NS	NS	NS	**	NS	NS
Nitrogen rate									
1.2 g m^{-2}	2.0	2.2	2.1	2.1	3.0	3.8	2.7	2.5	3.4
2.4 g m^{-2}	2.3	2.7	2.5	2.2	3.0	4.1	2.8	3.0	3.6
3.6 g m^{-2}	2.6	3.3	2.9	2.6	3.3	5.1	2.7	3.0	4.0
LSD‡	0.4*	0.7***	0.5***	0.3***	NS	0.7***	NS	0.4*	0.4***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8 in 1994, and 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12 in 1995.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

‡ Fisher's protected least significant difference at the indicated level of statistical significance.

0.8 ± 0.4 g N 100 g^{-1} greater than plots receiving the low nitrogen rate in 1994; and 0.4 ± 0.3 g N 100 g^{-1} greater than plots receiving the medium nitrogen rate and 0.6 ± 0.3 g N 100 g^{-1} greater than plots receiving the low nitrogen rate in 1995. There were significant differences in nitrogen content ($P \leq 0.05$) among nitrogen rate treatments on both days clippings were analyzed in 1994 and three of five dates that clippings were analyzed in 1995.

Nitrogen content data for the putting green study are summarized in Table 1.6. On average, plots injected with nitrogen had tissue nitrogen content 0.5 ± 0.4 g N 100 g^{-1} greater than plots receiving surface applications in 1994; and 0.3 ± 0.2 g N 100 g^{-1} greater than plots receiving surface applications in 1995. Injected plots had significantly higher nitrogen contents ($P \leq 0.05$) in plant tissues on both dates clippings were analyzed in 1994 and two of five dates in 1995. Plots receiving the high nitrogen rate had mean annual nitrogen contents 0.7 ± 0.4 g N 100 g^{-1} greater than plots receiving the medium nitrogen rate and 0.9 ± 0.4 g N 100 g^{-1} greater than plots receiving the low nitrogen rate in 1994; and 0.3 ± 0.2 g N 100 g^{-1} greater than plots receiving the medium nitrogen rate and 0.6 ± 0.2 g N 100 g^{-1} greater than plots receiving the low nitrogen rate. There were significant differences in nitrogen content ($P \leq 0.05$) among nitrogen rate treatments on both dates clippings were analyzed in 1994 and four of five dates in 1995.

Nitrogen content in plant tissues ranged from 1.9 g N 100 g^{-1} on turf from surface applied plots in the fairway study on Aug. 15, 1994 to 5.1 g N 100 g^{-1} on turf from the high nitrogen rate plots in the fairway study on Aug. 7, 1995. This nitrogen content range is similar to ranges reported from previous studies involving nitrogen fertilization of turf. Miller (1994) reported nitrogen contents in plant tissues ranging from 1.6 g N 100 g^{-1} to 4.1 g N 100 g^{-1} in creeping bentgrass clippings receiving from 2.4 g N m^{-2} to 4.8 g N m^{-2}, either injected or surface applied. Munsell and Brown (1939) reported nitrogen contents in plant tissues ranging from 2.0 g N 100 g^{-1} to 4.5 g N 100 g^{-1} in Kentucky bluegrass clippings receiving from 3.4 g N m^{-2} to 6.8 g N m^{-2}.

Table 1.6. Effect of nitrogen application method and rate on nitrogen content of an *Agrostis palustris* putting green. 1994 and 1995.

	1994			1995					
	Clipping harvest date			Clipping harvest date					
Fertilization treatment†	15-Aug	12-Sep	Annual mean	15-May	26-Jun	7-Aug	7-Sep	19-Oct	Annual mean
	g N 100 g^{-1} tissue								
Application method									
Surface applied	2.7	2.7	2.7	2.8	3.9	3.5	2.8	2.7	3.1
Injected	3.1	3.3	3.2	3.1	4.4	3.9	3.2	2.7	3.4
Significance	***	***	***	**	***	NS	*	NS	***
Nitrogen rate									
1.2 g m^{-2}	2.7	2.5	2.6	2.5	3.6	3.8	2.5	2.6	3.0
3.4 g m^{-2}	2.8	2.7	2.8	3.0	4.1	3.5	3.1	2.8	3.3
4.8 g m^{-2}	3.2	3.7	3.4	3.3	4.6	3.8	3.5	2.8	3.6
LSD‡	0.3***	0.6***	0.6***	0.3***	0.5***	NS	0.6***	NS	0.3***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8 in 1994, and 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12 in 1995.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

‡ Fisher's protected least significant difference at the indicated level of statistical significance.

Quality ratings

Quality rating data for the fairway study are summarized in Tables 1.7 and 1.8. On average, plots injected with nitrogen had a mean annual quality rating of 0.2 ± 0.2 point higher than plots receiving surface applications in 1994; and 0.2 ± 0.3 point higher than plots receiving surface applications in 1995. Injected plots had significantly higher quality ratings ($P \leq 0.05$) on three of nine days ratings were taken in 1994 and five of ten days ratings were taken in 1995. Plots receiving surface applications ranked significantly higher ($P \leq 0.05$) than injected plots only on the Apr. 21, 1995 rating. Plots receiving the high nitrogen rate had mean annual quality ratings 0.4 ± 0.3 point higher than the plots receiving the medium nitrogen rate and 1.0 ± 0.3 point higher than plots receiving the low nitrogen rate in 1994; and 0.9 ± 0.3 point higher than plots receiving the medium nitrogen rate and 2.0 ± 0.3 points higher than plots receiving the low nitrogen rate in 1995. There were significant differences in quality ($P \leq 0.05$) among nitrogen rate treatments seven of nine days ratings were taken in 1994 and on all ten days ratings were taken in 1995.

Quality rating data for the putting green study are summarized in Tables 1.9 and 1.10. On average, plots injected with nitrogen had a mean annual quality rating of 1.0 ± 0.5 point higher than plots receiving surface applications in 1994; and 0.1 ± 0.2 point higher than plots receiving surface applications in 1995. Injected plots rated significantly higher in quality ($P \leq 0.05$) than plots receiving surface applications seven of nine dates ratings were taken in 1994, and only on June 29, 1995. Plots receiving surface application did not rank significantly higher in quality ($P \leq 0.05$) on any dates ratings were taken. Plots receiving the high nitrogen rate had mean annual quality ratings 0.7 ± 0.7 point higher than plots receiving the medium nitrogen rate and 2.0 ± 0.7 points higher than plots receiving the low nitrogen rate in 1994; and 0.5 ± 0.3 point higher than plots receiving the medium nitrogen rate and 2.0 ± 0.3 points higher than plots receiving the low nitrogen rate in 1995. There were significant differences in quality ($P \leq 0.05$) among

Table 1.7. Effect of nitrogen application method and rate on quality of a *Poa annua* fairway. 1994.

	Rating date									
Fertilization treatment†	14-Jul	29-Jul	15-Aug	29-Aug	12-Sep	26-Sep	10-Oct	25-Oct	8-Nov	Annual mean
	rating value‡									
Application method										
Surface applied	6.6	6.5	7.4	6.9	7	6.5	7.2	6.6	6.4	6.8
Injected	6.8	6.5	7.3	7.4	7.6	7.4	7.0	6.6	6.7	7.0
Significance	NS	NS	NS	**	***	***	NS	NS	NS	**
Nitrogen rate										
1.2 g m^{-2}	6.4	6.5	7.0	6.6	6.6	6.8	6.5	5.9	5.6	6.4
2.4 g m^{-2}	6.6	6.5	7.4	7.3	7.3	7.4	7.1	6.6	6.8	7.0
3.6 g m^{-2}	7.1	6.5	7.6	7.5	7.5	7.9	7.6	7.4	7.3	7.4
LSD§	0.4***	NS	NS	0.7***	0.4***	0.7***	0.5***	0.7***	0.7***	0.4***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8.
‡ 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.
*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.
§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 1.8. Effect of nitrogen application method and rate on quality of a *Poa annua* fairway. 1995.

Fertilization treatment†	Rating date										Annual mean
	21-Apr	8-May	19-May	2-Jun	16-Jun	29-Jun	16-Jul	9-Aug	23-Aug	17-Sep	
	rating value‡										
Application method											
Surface applied	6.1	6.0	6.5	4.5	5.2	5.7	5.9	6.2	5.8	5.6	5.7
Injected	5.7	6.0	6.4	4.9	5.6	6.1	6.5	5.8	5.9	6.3	5.9
Significance	**	NS	NS	NS	**	*	***	NS	NS	***	NS
Nitrogen rate											
1.2 g m^{-2}	4.9	4.9	5.4	3.8	4.6	4.9	5.1	4.8	5.2	4.9	4.8
2.4 g m^{-2}	5.9	6.1	6.6	4.7	5.3	5.8	6.3	5.9	5.8	6.3	5.9
3.6 g m^{-2}	6.9	6.9	7.4	5.7	6.4	7.0	7.3	7.2	6.4	6.8	6.8
LSD§	0.6***	0.6***	0.7***	0.8***	0.7***	0.7***	0.6***	1.0***	0.8***	0.9***	0.4***

† Treatments applied on 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12.

‡ 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 1.9. Effect of nitrogen application method and rate on quality of an *Agrostis palustris* putting green. 1994.

Fertilization treatment†	Rating date									Annual mean
	14-Jul	29-Jul	15-Aug	29-Aug	12-Sep	26-Sep	10-Oct	25-Oct	8-Nov	
	rating value‡									
Application method										
Surface applied	6.6	5.2	6.5	4.7	5.9	5.2	5.8	4.7	4.5	5.5
Injected	6.9	2.9	6.9	6.5	6.8	6.8	6.7	5.8	5.8	6.5
Significance	NS	***	NS	***	***	***	**	**	***	***
Nitrogen rate										
1.2 g m^{-2}	6.6	4.9	6.3	4.3	5.3	4.1	4.9	3.9	3.6	4.9
3.4 g m^{-2}	6.6	5.5	6.7	5.8	6.5	6.6	6.5	5.6	5.6	6.2
4.8 g m^{-2}	7.0	6.1	7.2	6.6	7.3	7.4	7.4	6.3	6.4	6.9
LSD§	NS	0.7***	0.7*	1.4***	1.1***	1.5***	1.0***	1.4***	1.4***	0.9***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8.

‡ 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 1.10. Effect of nitrogen application method and rate on quality of an *Agrostis palustris* putting green. 1995.

	Rating date										
Fertilization treatment†	21-Apr	8-May	19-May	2-Jun	16-Jun	29-Jun	16-Jul	9-Aug	23-Aug	17-Sep	Annual mean
	rating value‡										
Application method											
Surface applied	5.8	5.3	6.7	5.2	5.6	5.2	5.7	5.0	5.7	5.8	5.6
Injected	5.7	5.8	6.1	5.6	5.7	5.6	6.0	5.0	5.7	6.2	5.7
Significance	NS	*	NS	*	NS	**	NS	NS	NS	NS	NS
Nitrogen rate											
1.2 g m^{-2}	4.3	4.7	6.4	3.7	4.3	3.9	3.9	4.2	5.1	4.8	4.5
3.4 g m^{-2}	5.9	5.7	6.6	6.1	5.9	5.6	6.4	5.4	6.1	6.4	6.0
4.8 g m^{-2}	7.0	6.3	6.3	6.4	6.8	6.7	7.3	5.5	5.9	6.9	6.5
LSD§	0.8***	0.9***	NS	0.7***	0.8***	0.7***	1.2***	0.9***	0.7***	0.8***	0.4***

† Treatments applied on 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12.

‡ 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

nitrogen rate treatments on seven of nine dates ratings were taken in 1994, and nine of ten days ratings were taken in 1995.

Turf injected with nitrogen exhibited dark green stripes following the nozzle pattern of the HydroJect (7.5 cm wide), which lowered turf quality ratings. The striping appeared most noticeably at lower mowing heights and when the turf was nitrogen starved prior to fertilization. The injection stripes appeared approximately 3 days following treatment and usually faded within a week to 10 days. Striping was less apparant following successive nitrogen applications and faded in a shorter period of time. Turf managers may be able to apply nitrogen at half rates in two opposite directions to avoid dark green stripes in the turf.

Color ratings

Average color rating values were determined for striped turf resulting from nitrogen injection by rating the plots from a distance where the turf appeared as a uniform color. Color rating data for the fairway study are summarized in Tables 1.11 and 1.12. An average color rating value was determined for striped turf resulting from nitrogen injection by rating the plots from a distance where the turf appeared as a single color. On average, plots injected with nitrogen had a mean annual color rating of 0.5 ± 0.2 point higher than plots receiving surface application in 1994; and 0.2 ± 0.2 point higher than plots receiving surface applications in 1995. Injected plots had significantly higher color ratings ($P \leq 0.05$) on four of nine dates ratings were taken in 1994 and five of ten days that ratings were taken in 1995. Plots receiving surface applications ranked significantly higher in color ($P \leq 0.05$) than injected plots on the August 9, 1995 rating. Plots receiving the high nitrogen rate had mean annual color ratings 0.5 ± 0.3 point higher than plots receiving the medium nitrogen rate and 0.9 ± 0.3 point higher than plots receiving the low nitrogen rate in 1994; and 0.8 ± 0.2 point higher than plots receiving the medium nitrogen and 1.6 ± 0.2 points higher than plots receiving the low nitrogen rate in 1995. There were significant differences in color ($P \leq 0.05$) among nitrogen rate treatments

Table 1.11. Effect of nitrogen application method and rate on color of a *Poa annua* fairway. 1994.

Fertilization treatment†	Rating date									Annual mean
	14-Jul	29-Jul	15-Aug	29-Aug	12-Sep	26-Sep	10-Oct	25-Oct	8-Nov	
	rating value‡									
Application method										
Surface applied	6.9	6.5	7.2	6.9	7.1	6.5	7.2	6.6	6.5	6.8
Injected	7.0	6.5	7.4	7.4	8.0	7.5	7.2	6.8	6.9	7.3
Significance	NS	NS	NS	**	***	***	NS	NS	**	***
Nitrogen rate										
1.2 g m^{-2}	6.6	6.5	6.8	6.6	7.0	6.4	6.6	5.9	5.8	6.5
2.4 g m^{-2}	6.9	6.5	7.4	7.3	7.7	6.9	7.2	6.8	6.8	7.1
3.6 g m^{-2}	7.3	6.5	7.8	7.5	7.9	7.7	7.8	7.5	7.4	7.6
LSD§	0.4**	NS	0.7***	0.7***	0.5***	0.5***	0.5***	0.6***	0.6***	0.4***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8.

‡ 9 = dark green, 6 = minimum acceptable color, 1 = brown.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 1.12. Effect of nitrogen application method and rate on color of a *Poa annua* fairway. 1995.

Fertilization treatment†	Rating date										
	21-Apr	8-May	19-May	2-Jun	16-Jun	29-Jun	16-Jul	9-Aug	23-Aug	17-Sep	Annual mean
	rating value‡										
Application method											
Surface applied	5.8	5.9	6.3	4.7	5.3	6.0	6.3	6.4	6.0	6.2	5.9
Injected	5.7	5.9	6.2	5.2	5.8	6.4	6.8	6.0	6.0	6.6	6.1
Significance	NS	NS	NS	**	***	**	***	**	NS	**	NS
Nitrogen rate											
1.2 g m^{-2}	4.7	5.2	5.5	3.9	4.7	5.4	5.8	5.3	5.8	5.6	5.2
2.4 g m^{-2}	5.9	5.9	6.3	5.0	5.4	6.1	6.6	6.2	6.1	6.5	6.0
3.6 g m^{-2}	6.8	6.6	6.9	6.0	6.4	7.1	7.3	7.1	6.3	7.1	6.8
LSD§	0.6***	0.5***	0.4***	0.8***	0.6***	0.5***	0.4***	0.7***	0.4**	0.6***	0.3***

† Treatments applied on 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12.

‡ 9 = dark green, 6 = minimum acceptable color, 1 = brown.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

eight of nine dates ratings were taken in 1994 and on all ten days that ratings were taken in 1995.

Color rating data for the putting green study are summarized in Tables 1.13 and 1.14. On average, plots injected with nitrogen had a mean annual color rating of 1.3 ± 0.5 points higher than plots receiving surface application in 1994; and 0.4 ± 0.3 point higher than plots receiving surface applications in 1995. Injected plots had significantly higher color ratings ($P \leq 0.05$) on all nine dates ratings were taken in 1994 and six of ten days that ratings were taken in 1995. Plots receiving the high nitrogen rate had mean annual color ratings 0.6 ± 0.7 point higher than plots receiving the medium nitrogen rate and 1.2 ± 0.7 points higher than plots receiving the low nitrogen rate in 1994; and 0.6 ± 0.3 point higher than plots receiving the medium nitrogen and 2.0 ± 0.3 points higher than plots receiving the low nitrogen rate in 1995. There were significant differences in color ($P \leq 0.05$) among nitrogen rate treatments seven of nine dates ratings were taken in 1994 and on all ten days that ratings were taken in 1995.

Wilt ratings

Wilt ratings were taken on Sep. 14, 1994, Jul. 12, 1995, and Sep. 3, 1995 on the fairway study and Sep. 25, 1995 on the putting green study when noticeable drying had occurred over the experimental area. Data from these ratings are summarized in Table 1.15. Plots receiving surface applications of nitrogen had significantly more wilt severity ($P \leq 0.05$) than injected plots on all dates that ratings were taken for both studies.

Plots in the fairway study receiving surface applications of nitrogen ranked 2.8 ± 0.7 points higher in wilt severity on Sep. 14, 1994 than plots receiving injected nitrogen. Plots receiving the medium nitrogen rate ranked 1.2 ± 0.9 points lower in wilt severity than plots receiving the high nitrogen rate and 1.0 ± 0.9 point lower in wilt severity than plots receiving the low nitrogen rate. The low and high nitrogen rates were not significantly different in wilt severity ($P \leq 0.05$).

Table 1.13. Effect of nitrogen application method and rate on color of an *Agrostis palustris* putting green. 1994.

Fertilization treatment†	Rating date									
	14-Jul	29-Jul	15-Aug	29-Aug	12-Sep	26-Sep	10-Oct	25-Oct	8-Nov	Annual mean
	rating value‡									
Application method										
Surface applied	6.6	5.3	6.5	4.7	5.9	5.2	6.1	4.7	5.0	5.6
Injected	7.3	6.0	7.7	6.8	7.5	6.9	7.3	6.2	6.3	6.9
Significance	***	***	***	***	***	***	***	***	***	***
Nitrogen rate										
1.2 g m^{-2}	6.8	5.2	6.6	4.4	5.8	4.1	5.6	4.1	4.3	5.2
3.4 g m^{-2}	6.9	5.6	7.1	6.0	6.8	6.6	6.8	5.8	6.0	6.4
4.8 g m^{-2}	7.2	6.0	7.6	6.8	7.6	7.4	7.6	6.4	6.7	7.0
LSD§	NS	0.6***	0.7*	1.3***	1.1***	1.6***	0.9***	1.4***	1.2***	0.8***

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8.

‡ 9 = dark green, 6 = minimum acceptable color, 1 = brown.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 1.14. Effect of nitrogen application method and rate on color of an *Agrostis palustris* putting green. 1995.

Fertilization treatment†	Rating date										
	21-Apr	8-May	19-May	2-Jun	16-Jun	29-Jun	16-Jul	9-Aug	23-Aug	17-Sep	Annual mean
	rating value‡										
<u>Application method</u>											
Surface applied	5.6	6.3	6.2	5.6	5.9	5.8	6.0	5.6	6.2	6.0	5.9
Injected	6.3	6.8	6.3	6.1	6.2	6.4	6.5	6.0	6.3	6.5	6.3
Significance	***	**	NS	**	**	***	NS	NS	NS	**	***
<u>Nitrogen rate</u>											
1.2 g m^{-2}	5.1	5.6	5.2	4.4	4.8	4.9	4.6	4.9	5.4	5.1	5.0
3.4 g m^{-2}	6.1	6.8	6.6	6.3	6.3	6.3	6.7	6.2	6.6	6.5	6.4
4.8 g m^{-2}	6.6	7.4	7.0	6.9	7.0	7.1	7.6	6.3	6.8	7.1	7.0
LSD§	0.7***	0.7***	0.9***	0.7***	0.5***	0.5***	1.1***	0.8***	0.6***	0.6***	0.4***

† Treatments applied on 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12.

‡ 9 = dark green, 6 = minimum acceptable color, 1 = brown.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 1.15. Effect of nitrogen application method and rate on wilting. 1994 and 1995.

	1994	1995			
	Fairway study			Putting green study	
Fertilization treatment†	14-Sep	12-Jul	3-Sep	Fertilization treatment†	25-Sep
	rating value‡				
Application method				Application method	
Surface applied	5.5	6.2	5.3	Surface applied	2.7
Injected	2.7	2.5	3.5	Injected	1.8
Significance	***	***	***	Significance	**
Nitrogen rate				Nitrogen rate	
1.2 g m^{-2}	4.3	4.5	3.2	1.2 g m^{-2}	2.1
2.4 g m^{-2}	3.3	4.2	4.0	3.4 g m^{-2}	1.9
3.6 g m^{-2}	4.5	4.4	6.0	4.8 g m^{-2}	2.9
LSD§	0.9**	NS	1.4***	LSD	NS
Interaction means					
Surface 1.2 g m^{-2}		5.6	3.5		
Surface 2.4 g m^{-2}		6.3	4.7		
Surface 3.6 g m^{-2}		6.8	7.7		
Injected 1.2 g m^{-2}		3.4	2.9		
Injected 2.4 g m^{-2}		2.1	3.4		
Injected 3.6 g m^{-2}		2.0	4.4		
LSD		1.35*	1.93***		

† Treatments applied on 6/27, 8/9, 9/1, 9/30, and 11/8 in 1994, and 5/12, 6/6, 6/30, 7/25, 8/18, and 9/12 in 1995.

‡ 9 = severe wilt, 6 = moderate wilt, 1 = no wilt.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Plots in the fairway study receiving surface applications of nitrogen ranked 3.7 ± 0.9 points higher in wilt severity on Jul. 12, 1995 than plots receiving injected nitrogen. There were no significant differences in wilt severity among nitrogen rate treatments. There was evidence of an interaction in wilt severity ($P = 0.08$) between method of application and nitrogen rate. Plots receiving surface applications of nitrogen increased in wilt severity with increasing nitrogen rate. Injected plots did not exhibit this trend.

Plots in the fairway study receiving surface applications of nitrogen ranked 1.8 ± 0.8 points higher in wilt severity than plots receiving injected nitrogen on Sep. 3, 1995. Plots receiving the high rate of nitrogen ranked 2.0 ± 1.0 points higher in wilt severity than plots receiving the medium rate of nitrogen and 2.8 ± 1.0 points higher in wilt severity than plots receiving the low nitrogen rate. There was a significant interaction in wilt severity ($P \leq 0.05$) between method of application and nitrogen rate. Plots receiving surface applications of nitrogen increased greatly in wilt severity with increasing nitrogen rate. Injected plots did not exhibit this trend.

Putting green plots receiving surface applications of nitrogen ranked 0.9 ± 0.9 point higher in wilt severity than plots injected with nitrogen on Sep. 25, 1995. There were no significant differences in wilt severity among nitrogen rate treatments, nor was there any evidence of interaction between application method and nitrogen rate on the putting green study.

Differences in wilt severity between nitrogen application treatments may be the result of a deeper active root system for turf that is injected with nitrogen, although roots were not measured in this study. Fox et. al, (1953) found that deeper rooting of Kentucky bluegrass occurred in a silt loam soil when a favorable supply of nutrients was present at all depths in the profile. Deep placement of nitrogen in a coarse textured soil has resulted in more extensive root proliferation and enhanced sub-soil water utilization by wheat (Sharma and Chaundry, 1984).

Increases in moisture stress symptoms with increasing rates of surface applied nitrogen has been reported in several studies. Rieke and McElroy (1986) reported more wilting on creeping bentgrass putting green turf on plots receiving high nitrogen rates during summer months. Watschke and Waddington (1975) reported that 'Merion' Kentucky bluegrass wilted quicker and recovered slower as nitrogen rates were increased. Turf growing in nitrogen fertile soils tends to develop shoots at the expense of roots, which decreases the ability to extract moisture from lower soil depths. Increased leaf canopy is also associated with turf receiving high nitrogen rates. Turf transpiration rates increase with increasing leaf canopy on a per area basis. Consequently, turf receiving high amounts of nitrogen depletes soil moisture and exhibits moisture stress symptoms more rapidly than unfertilized turf. Significant nitrogen rate x application method interactions on the fairway study were the result of nitrogen rate not affecting moisture stress symptoms on turf injected with nitrogen. This turf may not exhibit increased moisture stress typically associated with high nitrogen rates because of more effective water uptake from lower soil depths. Enhanced water uptake by turf injected with nitrogen was likely the result of a more active root system at lower depths in the soil profile. Root system enhancement was probably caused by higher nitrogen concentrations at lower soil depths (Fox et. al, 1953; Sharma and Chaundry, 1984) and/or increased macropores at lower soil depths from the cultivation action of the injection equipment (Murphy and Rieke, 1994).

Summary

On the majority of dates turf was evaluated, the nitrogen injection treatment significantly increased clipping yields and quality ratings in the putting green study, significantly decreased moisture stress symptoms in the fairway study, and significantly increased plant tissue nitrogen content and turf color ratings in both studies during the 1994 growing season when compared to surface applications. These results suggest that turf used injected urea more efficiently than surface applied urea. The increased efficiency with injected urea could have been the result of decreased atmospheric losses of nitrogen due to ammonia volatilization. Bowman and Paul (1990) found that 11.6 % of urea applied to the thatch and surface soil of a Kentucky bluegrass turf was lost to ammonia volatilization. Significant ammonia volatilization is possible, even when 2.5 cm of irrigation is applied to the turf immediately following nitrogen application (Raczkowski and Kissel, 1989). Ammonium nitrate, which is much less susceptible to volatilization, was used as the nitrogen source in 1995 to verify if treatment differences in 1994 resulted solely from ammonia volatilization of urea. In 1995, the nitrogen injection treatment significant increased the plant tissue nitrogen content and color ratings in the putting green study, and significantly increased clipping yields and decreased moisture stress symptoms in both studies.

Factors other than ammonia volatilization are probably involved in increasing nitrogen use efficiency of turfgrass injected with nitrogen compared to surface application. There were no check plots (surface applied nitrogen plus water injection cultivation) in these studies to separate the effects of nitrogen placement and water injection cultivation. Positive turfgrass responses resulting from subsurface nitrogen injection may be partially attributed to changes in soil physical properties resulting from water injection cultivation. An increase in macropore space from nitrogen applied by water injection cultivation may reduce denitrification losses compared to turf receiving surface applied nitrogen. Mancino et. al, (1988) reported increasing denitrification losses from a 'Baron' Kentucky bluegrass turf as air filled pores decreased.

Immobilization by soil microbes and/or localized denitrification may decrease as a result of placing nitrogen below the soil surface, but it is not conclusive from these studies. Another possible explanation of treatment differences is that turf used surface applied nitrogen in a quick burst of growth shortly following application and became nitrogen starved for a longer period of time prior to subsequent application compared to turf injected with nitrogen. Bowman, et al. (1990) found that all of the nitrogen that was surface applied to a Kentucky bluegrass turf was depleted from the soil within 48 hours. Rapid depletion of nitrogen was attributed to rapid absorption by turf with high root length densities. Surface applied nitrogen is absorbed rapidly when turf has high root length density, representing both a large absorbing surface and a very small mean distance between roots. The uptake of injected nitrogen may be somewhat slower since the nitrogen is localized in pockets not accessible to the entire turf root system and where root length densities are lower than those immediately beneath the surface. Measurements of nitrogen uptake with respect to time following applications were not evaluated in this study.

Nutrient application using water injection cultivation equipment will benefit compacted turfgrass areas, especially putting greens, by improving soil physical properties. High pressure water injection cultivation has been shown to improve bulk density, porosity, and saturated hydraulic conductivity (Murphy and Rieke, 1994). Furthermore, subsurface injection of nitrogen may allow turfgrass managers to use less expensive nitrogen sources while gaining several benefits typically associated with more expensive slow release nitrogen sources. Turfgrass injected with nitrogen seemed to have a longer response period, remaining darker in color than surface applications prior to subsequent nitrogen applications. The turfgrass manager could apply nitrogen less frequently when implementing subsurface injections. Nitrogen use efficiency should increase since excess uptake is likely reduced with subsurface nutrient placement. The potential for foliar burn normally associated with soluble nitrogen sources, which is intensified by very dense turf on putting greens, would be virtually eliminated by subsurface nutrient placement.

Subsurface nitrogen applications would be most effective on high maintenance turf areas such as golf course putting greens. Striping from the nozzle pattern could be reduced by alternating injection directions each application, injecting in two directions per application at a larger nozzle spacing, or using injection nozzles with a more dispersed spray pattern. These results indicate that turfgrass mangers could reduce total nitrogen inputs and irrigation requirements through subsurface injections of nitrogen. These properties of subsurface nitrogen application may prove to be extremely benefical as increased environmental awareness and water use restrictions will require managers to maintain quality turf with fewer inputs.

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CHAPTER TWO

Water Injection Cultivation of a Sand Topdressed Putting Green

ABSTRACT

Sand topdressing, an application of a thin layer of sand to the turfgrass surface, is a popular putting green management practice. Following several years frequent sand topdressing, many golf course putting greens have a sand layer of 5 cm, or greater, overlying a finer textured soil. Some turfgrass managers have voiced concerns of blasting finer-textured soil to the surface, possibly sealing surface pores, when water injection cultivation (WIC) is exercised on these types of putting greens. A study was initiated in August, 1994, to examine the effects of WIC and Hollow tine cultivation (HTC) treatments on the mixing of a sand topdressing layer with the underlying native soil. Treatments included three frequencies of WIC (weekly, biweekly, and monthly), HTC twice per year, and a control. 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) sod was laid on a 5 cm layer of sand, overlying a loam soil, to represent a putting green with a significant accumulation of topdressing sand. There were no differences in soil mixing among cultivation treatments in September 1995. In September 1996 WIC weekly plots had more sand and less clay in the underlying soil than HTC and control plots. WIC weekly plots also had less sand in the topdressing layer. There was no evidence of soil mixing beyond 2.5 cm above or below the topdressing sand-native soil interface. These mixing characteristics are likely to benefit water percolation and root

penetration at the topdressing sand-native soil interface. Control plots exhibited significantly more moisture stress symptoms than cultivated plots during periods of high evapotranspiration. Although there were no differences in root mass densities among the treatments, turf receiving cultivation treatments appeared to have more active roots within the soil profile based on visual observation. The rolling action of the WIC equipment resulted in a 6 to 10 percent increase in ball roll distance on the day of treatment.

Introduction

Sand topdressing is the application of a thin layer of sand to the surface of a turfgrass area. This cultural practice has been utilized on putting greens since the early days of turfgrass management at St. Andrews Golf Course in Scotland (Zontek, 1976). Benefits from frequent sand topdressing of putting green turf include increased surface uniformity and smoothness, modification of surface soil, improved turfgrass color, tighter and finer textured turf, and dilution of the thatch layer (Beard, 1973). These benefits have made sand topdressing a popular putting green cultural practice utilized by many turfgrass managers. After several years of regular topdressing, a sand layer builds to a point where it becomes the primary medium for root growth.

Golf course putting greens are subjected to high levels of traffic, which may cause several problems. Soil compaction resulting from intense traffic negatively impacts turfgrass health by decreasing oxygen diffusion, water infiltration and percolation rates. Compaction has also been reported to decrease turfgrass shoot and root growth rates, nitrogen use per unit area, and visual quality (Sills and Carrow, 1982). Hollow tine cultivation (HTC) is often used in the spring and fall to relieve soil problems resulting from compaction. Traditional core cultivation is normally avoided during the mid-season because of disruption of the putting green surfaces interferes with play. These mid-season months, however, are when traffic is at a maximum and so is the need for cultivation. High pressure water injection cultivation (WIC) has gained popularity in recent years as a method of cultivating putting greens while causing minimal surface disruption, which makes it an ideal tool for mid-season cultivation. The Toro HydroJect 3000® blasts a 20 MPa jet of water 10 to 20 cm below the soil surface (Murphy and Rieke, 1994). There is some concern whether using high pressure water injection to cultivate putting greens with a significant sand topdressing layer blasts underlying native soil to the surface of the putting green. If so, finer-textured soil blasted to the putting green surface could possibly seal surface pores, negatively impacting soil physical properties. Soil fines settling in surface macropores would likely decrease air-filled porosity and increase the tortuosity of the surface soil. Oxygen diffusion and water infiltration rates decrease with a decrease in air-filled porosity and an increase in tortuosity (Hillel, 1982).

The objective of this study was to determine the effects of WIC and HTC on a putting green that contains a significant sand layer overlying a native, finer-textured soil. Cultivation treatments, which were initiated during the summer of 1994, included three frequencies of WIC, HTC twice per year, and a control.

Literature review

Research regarding the mixing of soil layers as affected by cultivation has been extremely limited. Previous research concerning putting green cultivation has almost exclusively focused on physical properties of the bulk soil. Past sand topdressing research has primarily regarded effects on thatch, microbial populations, and turfgrass quality.

Conventional hollow tine cultivation is often practiced to improve infiltration rates. Cultivation of a Kentucky bluegrass turf (*Poa pratensis* L.) growing on compacted soil decreased runoff (Alderfer, 1954). Conversely, core cultivation has been attributed to a decrease in infiltration, probably resulting from the creation of a compaction pan just beneath the cultivation depth (Murphy et. al, 1993). Verti-Drain units with hollow tines have reportedly loosened soil to depths of up to 20 cm to prevent compaction pan development (Murphy and Rieke, 1989). Vertical mowing and hollow tine cultivation treatments were both reported effective in reducing thatch (Murray and Juska, 1977). Biweekly hollow tine cultivation of 'Tifdwarf' bermudagrass (*Cynadon dactylon* L. Pers.

x *Cynadon transvaalensis* Burtt-Davy) reduced thatch weight, and to a lesser extent, thatch thickness (Smith, 1979). High pressure water injection cultivation increased macropores relative to untreated soil and was as effective as hollow tine cultivation at improving bulk density, porosity, and saturated hydraulic conductivity (Murphy and Rieke, 1994).

Sand topdressing primarily functions to provide a firm, uniform putting surface while diluting the thatch. Biweekly sand topdressing of a 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) putting green provided a true, firm surface while providing adequate thatch to cushion and lessen ball marks and reduce ball bounce (Murphy, 1983). An autumn sand topdressing application improved spring recovery of a 'Penncross' creeping bentgrass putting green (Christians et al., 1985). Sand topdressing of a heavily thatched creeping bentgrass green reduced the organic content of the thatch and improved visual quality during summer months (Fermanian et al., 1985). In that study, however, topdressed turf had greater incidences of diseases and annual bluegrass (*Poa annua* L.) infestation. Four sand topdressings per year applied to three different bermudagrass cultivars decreased the thatch thickness, but increased the combined thickness of the thatch and mat layer (White and Dickens, 1984). Similarly, sand topdressing increased mat and root weights of a zoysiagrass turf (*Zoysia japonica* Steud.) (Dunn, et al., 1995). Sand topdressing was demonstrated to have no effects on microbial populations of 'Penneagle' creeping bentgrass putting greens (Robbeloth et al., 1987).

Materials and Methods

The sand topdressing study was conducted at the Hancock Turfgrass Research Center on the Michigan State University campus. Creeping bentgrass putting green sod, growing on a fine-loamy, mixed, mesic, Typic Hapludalf, was removed on 17 May, 1994. Approximately five centimeters of topdressing sand (96% sand, 3% silt, and 1% clay) was placed over the native soil to simulate a long term topdressing program. The putting green was sodded on 27 May with 'Penncross' creeping bentgrass, provided by Hugget Sod Farm, Marlette, MI, which was harvested from a sand soil similar to the sand used in this study. The experimental area was mowed at 0.5 cm and maintained under typical putting green management practices. Mowing was performed five times per week during the majority of the growing season. Irrigation was applied daily unless the turf received sufficient water from precipitation. Pesticides were applied on a curative basis. Cultivation treatments were initiated when the sod had rooted down well, approximately 11 weeks following establsihment. Treatments included three frequencies of water injection cultivation (WIC) (weekly, biweekly, and monthly), HTC in the spring and fall, and a control. Water injection cultivation was accomplished with a HydroJect 3000® provided by the Toro Company, Minneapolis, MN. The HydroJect was operated at the closest nozzle spacing, approximately 7.5 cm by 2.5 cm. Hollow tine cultivations were achieved with a Ryan Greensaire provided by the Ransomes America Corporation, Lincoln, NE. Hollow tines were 1.0 cm in diameter and operated at a 7.5 cm by 5.0 cm spacing. Cores were brushed in following cultivation and the remaining thatch was removed.

Water injection cultivation treatments were initiated 16 Aug., 1994, and continued until 29 Sep., 1994. The first HTC treatment was applied 13 Oct., 1994. Treatments were applied from 15 May to 15 Oct. in 1995 and 17 May to 4 Oct. in 1996. Hollow tine cultivation treatments were applied on the first and last treatment dates of both 1995 and 1996. A light sand topdressing (approximately 0.0032 m^3 sand m^{-2}) was applied approximately every three weeks throughout the study.

Turfgrass quality ratings were taken monthly throughout the growing season. Quality ratings were based on turfgrass uniformity, density, and color. Plots were ranked on a scale from 1 to 9 with 1 being dead turf, 6 minimum acceptable quality, and 9 uniform, dense, dark green turf. Quality ratings were taken on 7 Sep. and 10 Oct. in

1994, 11 May, 13 Jun., 1 Aug., and 7 Sep. in 1995, and 17 May, 24 Jun., 29 Jul., 30 Aug., 27 Sep., and 25 Oct. in 1996.

Wilt ratings were taken when noticeable drying occurred over the experimental area on 8 Jul., 1996. The plots were dried down to exacerbate moisture stress symptoms and two additional wilt ratings were taken on 9 Aug. and 17 Aug. in 1996. Ratings values were based on a scale of 1 to 9 with 1 being no wilt, 6 moderate wilt, and 9 severe wilt.

Golf ball roll measurements were taken weekly, on days of treatment in 1994 and early 1995. Readings were taken on all plots prior to treatment, and immediately after for only those plots receiving treatment. Golf ball roll was evaluated using a USGA Stimpmeter (Radko, 1980). Three golf balls were rolled in two opposite directions to obtain an average roll distance for each plot. Golf ball roll measurements were taken on 24 Aug., 31 Aug., 7 Sep., and 19 Sep. in 1994; 2 Jun., 12 Jun., and 19 Jun. in 1995; and 21 May, 28 May, 9 Jul., and 1 Aug. in 1996.

Soil samples were taken 18 Sep., 1995, at 2.5 cm intervals, to a depth of 12.5 cm for particle size analyses. Some of these samples included the sand topdressing-native soil interface, which increased the variability of the data. Sampling directly at the interface was avoided in 1996 to decrease variability. Since the interface was easily detectable, samples were collected at 0 to 2.5 cm and 2.5 to 5.0 cm, both above and below the topdressing-native soil interface. Soil samples were collected on 15 Sep. in 1996. Particle size analyses were performed by the pipette method (Day, 1965). Soil textures differing from control plot textures were assumed to be the result of cultivation treatment.

Undisturbed soil cores were taken in October of 1995 and 1996 to determine saturated hydraulic conductivity, bulk density and pore size distribution. Soil cores were extracted by pounding 7.5 cm by 7.5 cm aluminum cylinders into the soil, lifting the cores containing turf and soil, and cutting of the thatch and verdure (Blake, 1963). Soil cores were refrigerated at 4° C immediately upon excavation until laboratory analysis.

Saturated hydraulic conductivites were evaluated using the constant-head method described by Klute (1963). Pore sized distributions were evaluated by breaking down pore space into macropores and micropores. Macropores were determined by draining saturated soil cores with a positive pressure of 0.4 MPa using the pressure chamber method (Vomocil, 1963).

The soil profile in this study was constructed to simulate a golf course putting green that has been on a light, frequent topdressing program for several years. The putting green used in this study lacked the gradual accumulation of root mass and organic matter that would normally occur with a light, frequent topdressing program. Fortunately, Rutgers University had a research putting green with a significant sand topdressing layer, accumulated over several years of light frequent applications, overlying a finer textured soil. A two year cultivation study was conducted by Dr. James Murphy on this putting green in 1994 and 1995 with water injection cultivation treatments. Treatments on this study included WIC weekly, WIC triweekly, and a control. Treatments were replicated four times. The WIC weekly treatment had been applied 25 times and the WIC triweekly treatment had been applied 9 times prior to the collection of soil samples. Soil samples were collected Jun. 28, 1996 from the Rutgers study with the cooperation of Dr. Murphy and brought to Michigan State University for particle size analysis. Soil textures in WIC plots statistically different from control plot textures were assumed to be the result of cultivation treatment. These results were used to help verify results obtained from the model sand topdressed putting green.

A randomized complete block design was used as the experimental model with three treatments replications for the Michigan State Study. A randomized complete block design with four replications was used as the experimental model for the Rutgers study. A one factor analysis of variance was calculated for all data to indicate treatment differences. Treatment means were determined significantly different at probabilities $\leq$ 0.05. and separated using Fisher's protected least significant difference procedure

(Freund and Wilson, 1993). Results are reported by constructing 95 % confidence intervals for differences between treatment means.

Results and Discussion

Particle size analysis

Particle size analysis data for soil samples taken on 18 Sep., 1995 are summarized in Table 2.1. There were no significant differences in percent sand or clay among any cultivation treatments at any depth in 1995. The 1995 soil samples were taken after a 1.5-year total of 7 WIC weekly treatments, 15 WIC biweekly treatments, 9 WIC monthly treatments, and 3 HTC treatments were applied.

Particle size analysis data for soil samples taken on 15 Sep., 1996 are summarized in Table 2.2. These samples were taken after a 2.5-year total of 48 WIC weekly treatments, 27 WIC triweekly treatments, 15 WIC monthly treatments, and 5 HTC treatments. There were no significant differences in percent clay or sand among any cultivation treatments at 2.5 to 5.0 cm above, and below, the sand-native soil interface.

There were no significant differences in percent clay among cultivation treatments in the 0 to 2.5 cm layer above the sand-native soil interface. However, there were significant differences ($P \leq 0.05$) in percent clay at the 0 to 2.5 cm layer below the interface and in sand content at the 0 to 2.5 cm layer both above and below the interface. Significant differences in clay content on only one side of the sand-native soil interface was probably the result of slight error in measurement causing a relatively large experimental error and no significant treatment effects above the interface.

Water injection cultivation weekly samples contained 2.4 ± 0.7 percent less clay and 7.1 ± 0.5 percent more sand than check samples at the 0 to 2.5 cm layer below the sand-native soil interface. Water injection cultivation weekly samples contained 6.1 ± 0.5, 5.3 ± 0.5, and 3.5 ± 0.5 percent more sand, respectively, than HTC, WIC monthly,

Table 2.1. Effect of cultivation treatment on the mixing of a sand topdressing layer with underlying native soil. Samples collected 9/18/95.

Treatment†	Sampling Depth (cm)									
	0.0 - 2.5	2.5 - 5.0	5.0 - 7.5	7.5 - 10.0	10.0 - 12.5	0.0 - 2.5	2.5 - 5.0	5.0 - 7.5	7.5 - 10.0	10.0 - 12.5
	g clay 100 g^{-1} soil					g sand 100 g^{-1} soil				
Check	1.3	1.0	10.2	9.1	9.0	95.0	97.3	64.9	60.6	57.9
WIC weekly (27)‡	1.4	1.9	8.2	9.4	10.3	93.8	89.1	66.6	59.3	57.1
WIC biweekly (15)	1.6	2.2	9.4	9.6	9.0	94.3	90.0	61.3	58.9	57.2
WIC monthly (9)	1.1	1.8	9.6	10.0	9.3	94.7	90.4	61.4	58.9	56.7
HTC spring and fall (3)	1.3	1.0	8.9	10.2	10.6	94.5	94.9	62.4	58.3	57
LSD§	NS	NS	NS	1.1*	NS	NS	NS	NS	NS	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 2.2. Effect of cultivation treatment on the mixing of a sand topdressing layer with underlying native soil. Samples collected 9/15/96.

Treatment†	Sampling distance from layer interface (cm)							
	Above		Below		Above		Below	
	2.5 - 5.0	0.0 - 2.5	0.0 - 2.5	2.5 - 5.0	2.5 - 5.0	0.0 - 2.5	0.0 - 2.5	2.5 - 5.0
	g clay 100 g^{-1} soil				g sand 100 g^{-1} soil			
Check	2.1	0.7	9.2	9.1	92.9	96.0	57.3	57.2
WIC weekly (48)‡	1.8	1.3	6.8	7.8	92.0	91.2	64.4	59.8
WIC biweekly (27)	1.7	1.4	8.4	8.4	93.6	93.4	60.9	58.9
WIC monthly (15)	1.2	1.3	7.5	7.7	93.6	95.2	59.1	61.2
HTC spring and fall (5)	2.0	1.2	8.8	9.3	93.4	96.3	58.3	58.6
LSD§	NS	NS	1.7**	NS	NS	3.3***	2.9***	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

and WIC biweekly samples at the 0 to 2.5 cm layer below the sand-native soil interface. Water injection cultivation biweekly samples contained 3.6 ± 0.5 and 2.6 ± 0.5 percent more sand, respectively, than check and HTC samples 0 to 2.5 cm below the sand-native soil interface.

Check samples and HTC samples were not significantly different ($P \leq 0.05$) in sand content at the 0 to 2.5 cm layer above the sand-native soil interface. Hollow tine cultivation samples contained 5.1 ± 1.0 and 2.9 ± 1.0 percent more sand, respectively, than WIC weekly and WIC biweekly samples at the 0 to 2.5 cm layer above the sand-native soil interface. Check samples contained 4.8 ± 1.0 and 2.6 ± 1.0 percent more sand, respectively, than WIC weekly and WIC biweekly samples at the 0 to 2.5 cm layer above the sand-native soil interface. WIC monthly samples contained 4.0 ± 1.0 percent more sand than WIC weekly samples 0 to 2.5 cm above the sand-native soil interface.

These data suggest that significant mixing of the sand topdressing layer and underlying native soil occurs after several treatments. Although soil textures among cultivation were statistically different, their actual differences were small and need to be watched over a long period of time. All detectable soil layer mixing took place within 2.5 cm of the sand topdressing-native soil interface. A larger percentage of topdressing sand moved into the underlying soil than clay moved into the topdressing layer. These layer mixing characteristics are considered beneficial in the soil immediately above and below the interface. Abrupt soil texture changes impede water percolation (Hillel, 1982) and root penetration. Casimaty et. al (1993) found that transplanting washed sod increased rooting and infiltration compared to transplanting sod containing soil different in texture from the soil on site. Layer mixing by cultivation should alleviate detriments associated with soil layering. There was no evidence of clay accumulating at the soil surface with any cultivation treatment. Cultivation did not appear to play a role in sealing surface pores of the sand topdressing layer with finer textured underlying soil in this study. Turfgrass managers may find WIC beneficial when used in conjunction with the initiation of a light, frequent sand topdressing program. Water injection cultivation treatments could cause mixing at the interface of a sand topdressed green by incorporating topdressing sand into the underlying soil and vice versa as long as soil layers are compatible.

Quality ratings

Quality rating data for all rating dates are summarized in Table 2.3. Water injection cultivation treatments decreased quality at the beginning of the study, probably by damaging the root system of the recently laid sod. All WIC treatments ranked significantly lower than the HTC and check treatments on 7 Sep., 1994, approximately three weeks after treatments were initiated (≈ 3 mos. after sod was laid).

Turf quality ratings were lowest in 1995 due to an unusually stressful summer. Hollow tine cultivated plots had significantly low quality on 11 May (≈ 5 mos. after treatment) and 13 Jun. (29 days after first 1995 treatment) resulting from aerification holes reducing turf uniformity. The weekly and biweekly WIC treatments had significantly low quality on 1 Aug., 1995. Frequent WIC probably damaged an already weak root system that was under stress because of weather extremes. Quality ratings were still significantly low for the WIC weekly treatment on 7 September.

Quality ratings were initially low in 1996, resulting from a harsh summer the previous year and a cold spring in 1996, but increased with improving weather conditions. Frequent WIC treatments did not significantly ($P \leq 0.05$) lower turf quality when weather conditions were more optimal 1996. The HTC treatment had significantly low quality on 24 Jun. (38 days after treatment) and 25 Oct. (16 days after treatment), resulting from aerification holes reducing turf uniformity. Check plots had significantly low quality on 30 Aug. and 27 Sep. resulting from moisture stress symptoms when the experimental area was dried down.

Table 2.3. Effect of cultivation treatment on quality of a sand topdressed putting green.

	Rating date											
	1994		1995				1996					
Treatments†	7-Sep	10-Oct	11-May	13-Jun	1-Aug	7-Sep	17-May	24-Jun	29-Jul	30-Aug	27-Sep	25-Oct
	rating value‡											
Check	6.8	6.0	6.2	6.2	5.3	6.0	4.2	7.2	6.8	5.2	5.0	6.2
WIC weekly	4.7	6.5	6.2	6.3	4.2	5.0	4.0	7.5	6.5	6.7	7.0	6.9
WIC biweekly	5.5	6.7	6.7	6.0	4.5	5.8	4.0	7.2	6.2	6.8	6.2	7.2
WIC monthly	6.0	7.2	5.5	6.3	4.7	6.5	4.0	7.2	6.5	6.3	5.8	7.2
HTC	7.2	7.3	4.8	5.0	5.5	6.5	4.0	7.0	7.3	7.2	6.5	4.8
LSD§	1.2***	0.7**	1.5**	0.9***	1.0**	1.0**	NS	0.3*	0.9**	1.7***	1.2**	1.0***

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Wilt ratings

Wilt rating data taken in 1995 are summarized in Table 2.4. The check treatment had significantly increased moisture stress symptoms ($P \leq 0.05$) than all cultivation treatments on the 8 Jul. and 17 Aug. rating dates. Check plots had significantly increased moisture stress symptoms than the WIC weekly, WIC monthly, and HTC treatments on the 9 Aug. rating date. There were no significant differences in moisture stress symptoms among turfs that received some type of cultivation treatment on all three dates that plots were rated.

Soil samples were excavated from 2.5 to 7.5 cm and 7.5 to 15 cm in September, 1995 to evaluate a possible correlation between root mass density and moisture stress symptoms. During sampling, a greater abundance of white roots, particularly in the aerification channels, were apparent at lower soil depths in plots receiving frequent WIC treatments and HTC treatment. However, there were no significant differences in root mass density at either sampling depth ($P \leq 0.05$) among the treatments upon analysis (Table 2.5). There was probably a greater mass of active roots at lower soil depths, but root mass analysis could not distinguish between living and dead roots. Turf under moisture stress probably had increased root turnover and therefore a combined root mass density of living and dead roots not significantly different from non moisture stressed turf. Cultivation treatments probably increased porosity and oxygen levels at greater soil depths, encouraging root initiation (Hillel, 1982; Taiz and Zieger, 1991). These deep root systems would be capable of extracting moisture at greater depths than more shallow active roots of non cultivated turf.

Stimpmeter evaluations

Stimpmeter data are summarized for 1994, 1995, and 1996, respectively, in Tables 2.6, 2.7, and 2.8. There were no differences in ball roll distance among the treatments prior to application on any dates that plots were evaluated. Ball roll distance was significantly low for the HTC treatment on Aug. 31, 1994. Treatment applications

Table 2.4. Effect of cultivation treatment on moisture stress symptoms of a sand topdressed putting green. 1996.

	Rating date		
Treatments†	8-Jul	9-Aug	17-Aug
	rating value‡		
Check	4.8	5.5	5.8
WIC weekly	1.2	1.8	2.2
WIC biweekly	2.0	3.5	3.0
WIC monthly	1.5	3.2	3.5
HTC	1.2	1.7	2.5
LSD§	2.6***	2.2**	2.6**

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ 9 = severe wilt, 6 = moderate wilt, and 1 = no wilt.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 2.5. Effect of cultivation treatment on root weight density of a sand topdressed putting green. 1996.

	Sample depth (cm)	
Treatments†	0 - 7.5	7.5 - 15
	$g\ cm^{-3}$	
Check	7.2	1.4
WIC wekly (48)‡	4.3	1.1
WIC biweekly (27)	5.9	1.5
WIC monthly (15)	6.4	1.1
HTC spring and fall (5)	5.6	1.0
LSD§	NS	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

§ Fisher's least significant difference test at $P \leq 0.05$.

Table 2.6. Effect of cultivation treatment on ball roll distance of a sand topdressed putting green. 1994.

	Stimpmeter reading date											
	8/24/94			8/31/94			9/7/94			9/19/94		
Treatments†	before	after	increase‡	before	after	increase‡	before	after	% increase‡	before	after	% increase‡
	cm			cm			cm			cm		
Check	216	216	-	232	232	-	240	240	-	245	245	-
WIC weekly	206	223	8.3	218	226	3.7	237	239	0.8	233	241	3.4
WIC biweekly	208	208	-	223	244	9.4	242	242	-	237	256	8.0
WIC monthly	210	210	-	224	224	-	240	240	-	236	248	5.1
HTC	205	205	-	216	216	-	233	233	-	234	234	-
LSD§	NS	NS		NS	20***		NS	NS		NS	NS	

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments with no value under "% increase" were not applied on the corresponding stimpmeter date.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 2.7. Effect of cultivation treatment on ball roll distance of a sand topdressed putting green. 1995.

	Stimpmeter reading date								
	6/2/95			6/12/95			6/19/95		
Treatments†	before	after	increase‡	before	after	increase‡	before	after	increase‡
	cm			cm			cm		
Check	187	187	-	203	203	-	203	203	-
WIC weekly	181	194	7.2	207	229	10.6	187	201	7.5
WIC biweekly	180	180	-	197	227	15.2	193	193	-
WIC monthly	178	178	-	207	207	-	198	198	-
HTC	175	175	-	200	200	-	188	188	-
LSD§	NS	NS		NS	17***		NS	NS	

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments with no value under "% increase" were not applied on the corresponding stimpmeter date.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

Table 2.8. Effect of cultivation treatment on ball roll distance of a sand topdressed putting green. 1996.

	Stimpmeter reading date											
	5/21/96			5/28/96			7/9/96			8/1/96		
Treatments†	before	after	increase‡	before	after	increase‡	before	after	% increase‡	before	after	increase‡
	cm	cm		cm	cm		cm	cm		cm	cm	
Check	169	169	-	203	203	-	207	207	-	200	200	-
WIC weekly	173	188	8.7	202	220	8.9	221	236	6.8	202	230	13.9
WIC biweekly	168	178	6.0	200	200	-	235	235	-	206	216	4.9
WIC monthly	170	182	7.1	192	192	-	214	214	-	208	208	-
HTC	165	165	-	199	199	-	207	207	-	200	200	-
LSD§	NS	18**		NS	18**		NS	NS		NS	24**	

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments with no value under "% increase" were not applied on the corresponding stimpmeter date.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

§ Fisher's protected least significant difference at the indicated level of statistical significance.

resulted in significantly increased ball roll distances for WIC treated plots on 12 Jun. in 1995, and 28 May and 1 Aug. in 1996. The HydroJect 3000® has two rollers surrounding the injection nozzles that function similar to traditional putting green rollers. This rolling action increased ball roll distances on plots receiving WIC treatment, probably by decreasing surface irregularities (Beard, 1997). Ball roll increases following WIC treatment averaged 6 percent in 1994, 10 percent in 1995, and 8 percent in 1996. These increases in ball roll distance are similar to those observed in studies evaluating traditional greens rollers (Beard, 1997). Similar ball roll data was reported by Miller (1994) where WIC treatment resulted in an immediately increase in ball roll distance that averaged 22 percent.

Soil physical properties

Saturated hydraulic conductivity, porosity, and bulk density data are summarized in Tables 2.9 and 2.10. There were no significant differences among cultivation treatments for any soil property in 1995 and 1996. Saturated hydraulic conductivity and porosity data were somewhat lower in 1996 than in 1995. A decrease in saturated hydraulic conductivity could have been caused by an increase in root mass and organic matter in macropore space. Lodge and Baker (1993) reported significant decreases in infiltration rates of sand based root-zones probably due to the sealing off of the surface pores with organic material. A decline in porosity could have resulted from settling of the sand topdressing layer, compaction from mowers and foot traffic, or possibly a combination of both.

These results were somewhat surprising, and not typical for cultivation treatments. Hollow tine cultivation and WIC treatments typically increase hydraulic conductivity and porosity, and lower bulk density. Murphy and Rieke (1994) reported that WIC was equal or superior to HTC in reducing soil bulk density, and increasing porosity and saturated hydraulic conductivity. In another study, Murphy et. al (1993)

Table 2.9. Effect of cultivation treatment on physical soil properties of a sand topdressed putting green. Soil cores harvested October 1995.

	Physical analyses			
Treatments†	Ksat	Air porosity‡	Total porosity	Bulk density
	— $cm\ hr^{-1}$ —	—— $m^3\ 100m^{-3}$ ——		— $Mg\ m^{-3}$ —
Check	20	24.4	41.2	1.64
WIC weekly (27)§	20	23.1	40.1	1.64
WIC biweekly (15)	30	22.3	40.1	1.64
WIC monthly (9)	14	25.4	41.2	1.63
HTC spring and fall (3)	20	21.9	40.3	1.63
LSD¶	NS	NS	NS	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Water drained between 0 and -0.04 MPa moisture potential.

§ Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

¶ Fisher's least significant difference test at $P \leq 0.05$.

Table 2.10. Effect of cultivation treatment on physical soil properties of a sand topdressed putting green. Soil cores harvested October 1996.

	Physical analyses			
Treatments†	Ksat	Air porosity‡	Total porosity	Bulk density
	— $cm\ hr^{-1}$ —	—— $m^3\ 100m^{-3}$	——	— $Mg\ m^{-3}$ —
Check	17	18.4	38.2	1.65
WIC weekly (48)§	13	15.5	39.5	1.63
WIC biweekly (27)	17	18.2	38.7	1.62
WIC monthly (15)	16	17.8	38.0	1.63
HTC spring and fall (5)	11	19.0	39.4	1.63
LSD¶	NS	NS	NS	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Water drained between 0 and -0.04 MPa moisture potential.

§ Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

¶ Fisher's least significant difference test at $P \leq 0.05$.

reported a 3 percent decrease in bulk density with and 62 % increase in saturated hydraulic conductivity with HTC.

Variability among treatments was high within the 5 soil cores extracted per plot. This may have been the result of earthworm activity. Several earthworms surfaced from check treatment soil cores following saturation. Earthworm burrowing may have increased porosity and saturated hydraulic conductivity in check soil cores to a level not significantly different from cultivation treatment soil cores.

Particle size analysis (Rutgers University samples)

Particle size analysis data from the Rutgers University cultivation study are summarized in Table 2.11. Check samples had 2.7 ± 0.2 and 0.6 ± 0.2 percent more sand in the topdressing layer, respectively, than WIC weekly and WIC triweekly samples. Water injection cultivation triweekly samples had 2.1 ± 0.2 percent more sand in the topdressing layer than WIC weekly samples. Water injection cultivation weekly samples had 1.2 ± 0.4 percent more clay in the topdressing layer than check samples. Check samples had 4.1 ± 1.6 and 2.8 ± 1.6 percent less sand, respectively, than WIC triweekly and WIC weekly samples in the underlying native soil. There were no significant differences among treatments in clay content in the underlying soil. This data correlates fairly well with the data obtained from the constructed model sand topdressed putting green.

Summary

Mixing of a sand topdressing layer and a finer-textured underlying soil became significant after several WIC treatments. Water injection cultivation treatments had a greater effect on the mixing of soil layers than the HTC treatment. Soil layer mixing was not evident at distances greater than 2.5 cm from the sand topdressing-native soil interface. These data were obtained from a model putting green constructed to represent several years of sand topdressing and correlates well to data obtained from a Rutgers University putting green study that had a significant sand layer from years of light,

Table 2.11. Effect of water injection cultivation on the mixing of a sand topdressing layer with the underlying native soil.†

Treatment‡	Sampling distance from layer interface			
	0.0 - 2.0 cm above	0.0 - 2.0 cm below	0.0 - 2.0 cm above	0.0 - 2.0 cm below
	—— g clay 100 g^{-1} soil ——		—— g sand 100 g^{-1} soil ——	
Check	0.5	10.1	98.0	53.2
WIC triweekly (9)§	1.1	10.0	97.4	57.4
WIC weekly (25)	1.7	9.9	95.3	56.0
LSD¶	0.9**	NS	0.8***	3.0*

† Treatments applied at Rutgers University turfgrass research facilities in 1994 and 1995.

‡ WIC - Water Injection Cultivation

§ Numbers in parentheses represent the amount of treatments applied before soil samples were collected.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

¶ Fisher's protected least significant difference at the indicated level of statistical significance.

frequent topdressing. Turfgrass managers initiating a topdressing program may benefit by supplementing it with WIC treatments. Light, frequent sand topdressing in tandem with regular WIC treatments may provide a smooth uniform playing surface while preventing the development of a zone with an abrupt change in soil texture that would occur without cultivaition.

Frequent WIC treatments during periods of summer stress, and on young sod, reduced turf quality. Stressed turf seemed to respond negatively to weekly and biweekly WIC, possibly from damage to an already weakened root system. Turfgrass managers should consider weather conditions and perhaps reduce WIC intensity when turfgrass vigor is sub-optimal. For mature greens, one should evaluate carefully the effect of high frequency of WIC to ensure there is not excessive injury to roots.

Plots receiving no form of cultivation had increased moisture stress symptoms during periods of high evapotranspiration. This likely resulted from increased amounts of active roots deeper in the soil profile for turf that received cultivation treatments. Greater root mass densities could not be quantified by laboratory analysis. Root mass density analysis did not distinguish between living and dead roots.

HydroJect treatments results in a 6 to 10 % increase in ball roll distance immediately following treatment application. These increases are caused by the smoothing action of the two rollers located on either side of the injection nozzles on the HydroJect. Similar increases in ball roll distances have been reported in previous HydroJect research as well as research evaluating traditional greens rollers.

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CHAPTER THREE

Cultivation Effects on *Poa annua* Encroachment into a Creeping Bentgrass Putting Green.

ABSTRACT

Core cultivation of putting greens is often practiced during the spring and/or fall, coinciding with optimal conditions for *Poa annua* L. *reptans* germination. Soil disturbance from hollow tine cultivation (HTC) provides space and light, enhancing the potential for germination of *Poa annua*. High pressure water injection cultivation (WIC) is a relatively new technique developed to cultivate turf areas while causing minimal surface disruption. This study was conducted to compare the effects of different frequencies of HTC and WIC, and combinations of HTC and WIC on *Poa annua* encroachment into a creeping bentgrass (*Agrostis palustris* Huds.) putting green growing on a loamy sand soil (modified fine-loamy, mixed, mesic, Typic Hapludalf). The experiment consisted of eight treatments: WIC weekly; WIC biweekly; WIC monthly; HTC spring and fall; HTC spring, summer, and fall; HTC spring and fall and WIC biweekly; and HTC spring and fall at a narrow tine spacing in combination with WIC biweekly; and a control. A HydroJect 3000® was used to apply WIC treatments. *Poa annua* populations were counted in the spring and fall of 1994, 1995, and 1996. Turfgrass quality, ball roll distance, soil physical properties, and earthworm populations were also evaluated periodically. *Poa annua* populations were not affected by cultivation

treatments throughout the study. Populations decreased slightly with all treatments during 1994 and 1995. A compaction treatment was initiated in 1996, which resulted in slight increases in populations for all cultivation treatments. Surface disruptions in plots receiving HTC treatments significantly decreased turfgrass quality for up to 21 days following treatment. Ball roll distances on plots receiving WIC treatment increased 6 to 10 % immediately following treatment because of the rolling action the HydroJect. Earthworm castings on the turfgrass surface were significantly decreased with weekly WIC application. Spring and fall HTC treatments had significantly greater earthworm biomass than the control treatment in the surface 30 cm of the soil.

Introduction

Poa annua L. *reptans* is a fine textured, cool-season turfgrass of high shoot density that is well adapted to mowing heights under 1.25 cm. Although *Poa annua* can provide a quality turf if properly maintained, it is never intentionally included in seed mixtures and is generally considered a weed. Encroaching *Poa annua*, easily identified by its lighter yellow-green color and prolific seed head formation, decreases the visual and functional quality a creeping bentgrass (*Agrostis palustris* Huds.) putting green. *Poa annua* is extremely prone to disease in hot, humid weather, which becomes apparent on infested putting greens and fairways during mid-summer months (Beard, 1973).

Turfgrass researchers have been investigating controls for *Poa annua* since 1917 when it was noted that dense growing creeping bentgrasses were less susceptible to weed infestation (Robinson, 1952). The demand by golfers for luxurious turf and all-season good play resulted in increases in irrigation and closer mowing heights in the early 1960's (Schery, 1968). These changing cultural practices gave *Poa annua* an ecological boost to compete with fine fescue (*Festuca* spp.) and creeping bentgrass. Arsenate containing herbicides were somewhat effective at reducing *Poa annua* populations (Kerr, 1968; Twombly, 1952), but these chemicals were taken off the market in the early 1970's. Since then, turfgrass managers have been battling *Poa annua* infestations with limited success. Putting green re-construction that includes soil sterilization has been the most effective *Poa annua* control in recent years, but it is extremely costly and *Poa annua* plants typically reappear within 3 to 5 years.

Putting green core cultivation, a cultural practice to relieve soil compaction, is often utilized during cool periods of the growing season to limit both turfgrass stress and disruption of play. These cooler periods are when germination of *Poa annua* is most favorable (Cockerham and Whitworth, 1967). It has been recognized that soil disturbance from core cultivation may enhance *Poa annua* germination and increase infestation severity (Schmidt and Shoulders, 1972; Bengeyfield, 1969; Youngner, 1968; Beard, 1973). Water injection cultivation (WIC) was introduced in 1990 as an effective means of cultivation while causing minimal surface disruptions (Murphy and Rieke, 1994). The use of WIC on creeping bentgrass putting greens may reduce *Poa annua* infestations compared to traditional core cultivators during periods of favorable *Poa annua* germination.

The objective of this research was to determine the effects of cultivation method and frequency on *Poa annua* infestation of a creeping bentgrass putting green. Treatments included three frequencies of WIC, two frequencies of hollow tine cultivation (HTC), two combination treatments, and a control.

Literature Review

Poa annua research dates back to 1917, when Hartman and Damon found that dense growing Rhode Island creeping bentgrass was resistant to invasion by weeds (Robinson, 1952). Since then, a wealth of studies have followed investigating factors that encourage, or discourage, *Poa annua* infestations.

Evans (1932) advised that maintaining sheep on a golf course may increase *Poa annua* incidence through colonization of sheep scalds. Cockerham and Whitworth (1967) discovered that 16 °C was the optimal germination temperature for *Poa annua* seeds at several different seed aging intervals. Koch (1968) discovered that *Poa annua* germinated over a wide range of temperatures and there were hardly any limiting temperatures (except frost) for germination under natural conditions.

Roberts (1986) demonstrated that *Poa annua* is often a major contributor to seed banks of arable, as well as grassland soil. In that study, *Poa annua* germination from a weed seed bank was consistently high throughout each of four years and highest following soil disturbance. In a similar study, Roberts and Ricketts (1979) found that *Poa annua* was one of the most frequent weed seed species found in a wide range of agricultural soils.

Two studies conducted in the mid 1980's investigated the effects of turfgrass cultivation on pre-emergent herbicide efficacy and subsequent annual grass infestation. Branham and Rieke (1986) found that neither cultivation method nor cultivation timing had an effect on pre-emergent herbicide efficacy, and subseqent crabgrass invasion, on a *Poa annua* var. *reptans* fairway. Similarly, Johnson (1987) found that core cultivation timing had no effect on crabgrass invasion of a bermudagrass (*Cynodon dactylon* L. Pers.) turf.

Schmidt and Shoulders (1972) discovered that turf receiving early summer cultivations and twice-cultivated turf contained significantly higher amounts of *Poa annua* than control plots. It was concluded that cultivation in late May to early June provided an excellent seedbed, which coincided with the natural seeding of *Poa annua*. Delaying cultivations until *Poa annua* seed production ceased reduced infestation.

Materials and Methods

This study was initiated in June, 1994 at the Hancock Turfgrass Research Center at Michigan State University on a 4-year old 'Penncross' creeping bentgrass green growing on a modified loamy sand soil (modified fine-loamy, mixed, mesic, Typic Hapludalf). The experimental area was mowed at 0.5 cm and maintained under typical putting green management practices. Plots were 4.6 m in length and 0.8 m wide. The experiment consisted of the following eight treatments: Water injection cultivation (WIC) weekly; WIC biweekly; WIC monthly; HTC spring and fall (HTCSF); HTC spring summer and fall (HTCSSF); HTC spring and fall and WIC biweekly (HTCSFW); and HTC spring and fall at a narrow tine spacing and WIC biweekly (HTCSF*W); and a control. Water injection cultivation was accomplished with a HydroJect 3000® provided by the Toro Company, Minneapolis, MN. The HydroJect was operated at the closest nozzle spacing, approximately 7.5 cm by 2.5 cm. Hollow tine cultivations were achieved with a Jacobsen Aero-King® provided by Jacobsen Company, Racine, WI. Hollow tines were 1.0 cm in diameter and operated at a 7.5 cm by 5.0 cm for treatments with normal spacings and 5.0 cm by 2.5 cm for treatments narrow spacings. Cores were brushed in following cultivation and the remaining thatch was removed.

Water injection cultivation treatments were initiated 7 Jun., 1994, and continued until 27 Sep., 1994. Spring and fall HTC treatments were applied 9 Jun. and 13 Oct. in 1994. The summer HTC treatment was applied on 30 Aug. on appropriate plots. Treatments were applied from 22 May to 3 Oct. in 1995 and 23 May to 10 Oct. in 1996. Hollow tine cultivation treatments were applied on the first and last treatment dates of 1995 and 1996. Summer HTC teatments were applied on 28 Aug., 1995 and 7 Aug., 1996 on appropriate plots.

Poa annua counts were made using a counting grid to calculate population percentages for each plot. Plant species were identified at each of 162 grid crosshairs per count and two counts were made per plot. Counts were made in Jun. and Oct. in 1994, and May and Oct. in both 1995 and 1996. Decreases in *Poa annua* populations during 1994 and 1995 prompted compaction treatments with a vibration roller in 1996 to encourage *Poa annua* encroachment. Compaction treatments were made three times per week from Jun. through Sep. with a Ryan Rollaire® (Ransomes America Corporation, Lincoln, NE) applying approximately 50 kPa static pressure.

Turfgrass quality ratings were taken monthly throughout the growing seasons. Quality ratings were based on turfgrass uniformity, density, and color. Plots were ranked on a scale from 1 to 9 with 1 being dead turf, 6 minimum acceptable quality, and 9 uniform, dense, dark green turf. Quality ratings were taken on 11 Jul., 20 Jul., 7 Sep. and

11 Oct. in 1994; 11 May, 14 Jun., 1 Aug., and 7 Sep. in 1995; and 23 May, 20 Jun., 25 Jul., 22 Aug., 25 Sep., and 23 Oct. in 1996.

Golf ball roll measurements were taken periodically, on days of treatment. Readings were taken on all plots prior to treatment, and immediately after for only those plots receiving treatment. Golf ball roll was evaluated using a USGA Stimpmeter (Radko, 1980). Three golf balls were rolled in two opposite directions to obtain an average roll distance for each plot. Golf ball roll measurements were taken on 11 Jul., 30 Aug., 8 Sep., and 20 Sep. in 1994; 25 May, 1 Jun., 8 Jun., and 15 Jun., and 22 Jun. in 1995; and 30 May, 14 Jun., and 21 Aug. in 1996.

Undisturbed soil cores were taken in October of 1995 and 1996 to determine saturated hydraulic conductivity, bulk density and pore size distribution. Soil cores were extracted by pounding 7.5 cm by 7.5 cm aluminum cylinders into the soil, lifting the cores containing turf and soil, and cutting off the thatch and verdure (Blake, 1965). Soil cores were refrigerated at 4° C immediately upon excavation until laboratory analysis. Saturated hydraulic conductivites were evaluated using the constant-head method described by Klute (1965). Pore size distributions were evaluated by breaking down pore space into macropores and micropores. Macropores were determined by draining saturated soil cores with a positive pressure of 0.4 MPa using the pressure chamber method (Vomocil, 1965).

Earthworm castings were counted on a few dates when a significant amount of castings were noticeable on the experimental area. Casting counts were made on 1 Oct., 1994, 6 Sep., 1995, and 17 Sep., 1996. Differences in castings numbers among the treatments prompted earthworm biomass evaluations to find whether casting numbers correlated with actual earthworm populations. Due to time constraints only the WIC weekly, HTCSF, and control plots were sampled. Two soil samples with volumes of 25 cm by 25 cm in area by 30 cm deep were excavated per plot. The samples were sifted for adult worms and then washed and screened for cocoons.

A complete randomized design was used as the experimental model with four treatments replications. A one-way analysis of variance was calculated for all data to indicate treatment differences. Treatment means were determined significantly different at probabilities ≤ 0.05 and separated using Fisher's protected least significant difference procedure (Freund and Wilson, 1993).

Results and Discussion

Poa annua counts

Poa annua encroachment data are summarized in Table 3.1. There were no significant differences in percentage of *Poa annua* ($P \leq 0.05$) among any treatments at the beginning of the study. Nor were were there any significant differences in percentage *Poa annua* or total increase in *Poa annua* on any dates that counts were made. Turf plots averaged 1.8 % on Jun, 1994 and increased to 2.6 % and 5.2 %, respectively, on the Oct., 1994 and May, 1995 counting dates. Total increases in *Poa annua* percentages fell to 2.2 % on the Oct, 1995 counting date and 0.7 % on the May, 1996 counting date. These results suggest that when turf is healthy and growing well at the time of cultivation, *Poa annua* may not infest.

The experimental area received moderate, to little, traffic in 1994 and 1995. This may explain why *Poa annua* plants were not significantly competitive in encroaching into the creeping bentgrass. A vibrating compaction treatment (51 kPa static pressure) was applied to the experimental area three times per week and irrigation rates were increased in 1996. The Oct., 1996 counts revealed a 2.5 % increase in *Poa annua* since the May, 1996 counting date.

Quality ratings

Quality rating data taken in 1994 are summarized in Table 3.2. The WIC weekly and HTCSF*W treatments ranked significantly low in quality on the 11 Jul. rating date.

Table 3.1. Effects of cultivation treatment on *Poa annua* encroachment in an creeping bentgrass putting green.

Treatments†	Counting date										
	Jun-94	Oct-94	% increase††	May-95	% increase	Oct-95	% increase	May-96	% increase	Oct-96	% increase
	% *Poa annua*										
Check	1.8	2.2	0.4	4.8	3.0	1.8	0.0	0.9	-0.9	2.7	0.9
WIC weekly	1.4	1.6	0.2	4.6	3.2	1.9	0.5	0.5	-0.9	3.8	2.4
WIC biweekly	1.7	2.5	0.8	4.5	2.8	2.3	0.6	0.5	-1.2	2.9	1.2
WIC monthly	2.8	4.0	1.2	7.0	4.2	2.5	-0.3	0.8	-2.0	3.8	1.0
HTCSFW‡	1.4	2.3	0.9	5.6	4.2	2.1	0.7	1.1	-0.3	2.9	1.5
HTCSF‡	1.7	3.0	1.3	5.3	3.6	2.0	0.3	0.5	-1.2	3.1	1.4
HTCSSF§	2.0	3.3	1.3	4.8	2.8	2.8	0.8	0.8	-1.2	3.2	1.2
HTCSF*W‡¶	1.5	1.7	0.2	5.3	3.8	2.1	0.6	0.7	-0.8	3.1	1.6
LSD#	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments applied in spring and fall.

§ Treatments applied spring, summer, and fall.

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at ($P \leq 0.05$).

†† Percent increase from initial counting date.

Table 3.2. Effects of cultivation on quality of a creeping bentgrass putting green. 1994.

Treatments†	Rating date			
	11-Jul	20-Jul	7-Sep	11-Oct
	rating value††			
Check	6.5	7.4	7.1	6.1
WIC weekly	5.8	7.0	7.3	5.9
WIC biweekly	6.5	7.1	7.4	6.3
WIC monthly	6.4	6.9	7.3	6.1
HTCSFW‡	6.3	6.6	7.5	6.1
HTCSF‡	6.8	6.9	7.5	6.1
HTCSSF§	7.0	6.9	5.5	5.8
HTCSF*W‡¶	5.4	6.1	7.3	6.3
LSD#	1.1***	NS	0.5***	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments applied in spring and fall (6/9 and 10/13).

§ Treatments applied spring, summer, and fall (6/9, 8/30, and 10/13).

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at the indicated level of significance.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

†† 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.

The HTCSF*W plots ranked significantly lower in quality than all other treatments. Core cultivation holes were still apparent on HTCSF*W plots 32 days after treatment. Hence, there was a decreased rate of turf recovery from hollow tine cultivation with closer tine spacing. The WIC weekly treatment ranked significantly lower in quality than HTCSF and HTCSSF treatments. Weekly WIC may have damaged some turfgrass roots, stressing the turf and lowering quality. Plots receiving HTCSSF treatments ranked significantly lower in quality than all other treatments on the 7 Sep. rating date. The summer hollow tine cultivation treatment was applied eight days prior to rating. Core cultivation holes were still obvious, lowering turf uniformity and overall quality.

The 1995 quality rating data are summarized in Table 3.3. There were significant differences among cultivation treatments on all four rating dates. The HTCSF*W treatment ranked significantly lower than all other treatments on the 11 May rating date, due to slow turf recovery from the narrow tine spacing. Turf quality was significantly low for the HTCSF*W plots, even a little more than six months after treatment. All plots receiving hollow tine cultivation ranked significantly lower in quality than the other treatments on the 14 Jun. rating date. Core cultivation holes were still apparent 23 days after treatment. The WIC weekly treatment ranked significantly lower than other treatments on the 1 Aug. rating date. This was during a period of hot, humid weather conditions and the turf was under substantial stress. Frequent WIC may have damaged root systems of turf already weakened by high soil temperatures. Turf is slow to recover from any injury during periods of high evapotranspiration. Effective cultivation practices will cause some injury to turfgrass roots while modifying the soil. The HTCSSF treatment ranked significantly lower than all other treatments on the 7 Sep. rating date because of hollow tine cultivation treatment applied 10 days earlier. Cultivation holes were very obvious, lowering turfgrass uniformity and overall quality.

Quality rating data for 1996 are summarized in Table 3.4. There were significant differences in turfgrass quality among cultivation on five of six dates that ratings were

Table 3.3. Effects of cultivation on quality of a creeping bentgrass putting green. 1995.

Treatments†	Rating date			
	11-May	14-Jun	1-Aug	7-Sep
	rating value††			
Check	6.0	6.1	5.4	6.3
WIC weekly	6.1	6.4	4.9	7.0
WIC biweekly	6.1	6.3	5.5	6.6
WIC monthly	6.1	6.3	5.9	6.1
HTCSFW‡	5.6	5.3	5.3	7.1
HTCSF‡	6.0	5.4	6.0	6.0
HTCSSF§	6.6	5.4	6.0	4.8
HTCSF*W‡¶	4.2	3.8	6.1	6.3
LSD#	0.9***	1.1***	0.5**	1.0**

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments applied in spring and fall (5/22 and 10/3).

§ Treatments applied spring, summer, and fall (5/22, 8/28, and 10/3).

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at the indicated level of significance.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

†† 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.

Table 3.4. Effects of cultivation on quality of a creeping bentgrass putting green. 1996.

	Rating date					
Treatments†	23-May	20-Jun	25-Jul	22-Aug	25-Sep	23-Oct
	rating value††					
Check	6.3	7.4	7.3	7.3	7.3	7.1
WIC weekly	6.5	7.3	7.0	6.9	7.1	7.3
WIC biweekly	6.5	7.4	6.9	6.9	7.3	6.8
WIC monthly	6.4	7.0	7.3	7.1	7.1	7.0
HTCSFW‡	6.4	7.4	7.4	7.0	7.3	4.4
HTCSF‡	6.6	6.9	7.1	7.0	7.4	5.0
HTCSSF§	6.6	6.9	7.0	5.1	6.6	4.4
HTCSF*W‡¶	5.0	6.5	7.1	6.5	6.8	3.0
LSD#	0.8***	0.6***	NS	0.7***	0.4**	0.8***

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments applied in spring and fall (5/23 and 10/10).

§ Treatments applied spring, summer, and fall (5/23, 8/7, and 10/10).

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at the indicated level of significance.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

†† 9 = optimal quality, 6 = minimum acceptable quality, 1 = dead turf.

taken. Plots receiving HTCSF*W had significantly lower quality than all other treatments on the 23 May rating date. This was the result of slow recovering turf associated with narrow tine spacing. Although the 11 May rating was taken six months after the last hollow tine cultivation treatment, HTCSF*W plots were still exhibiting detrimental affects from the treatment. The 5.0 by 2.5 cm tine spacing had decreased turf density, along with the previously mentioned decreased uniformity. The HTCSF*W treatment ranked significantly lower than the WIC weekly, WIC biweekly, HTCSFW, and check treatments on the 20 Jun. rating date (28 days after hollow tine cultivation treatments). The HTCSSF treatment ranked significantly lower than all other treatments, except the HTCSF*W treatment, on the 22 Aug. These differences occurred because of visible core cultivation holes left from HTCSSF treatments 15 days earlier. Plots receiving HTCSF*W treatment still ranked significantly lower in quality than several treatments on the 25 Sep. rating date, 49 days after treatment. All treatments with a hollow tine cultivation ranked significantly lower than other treatments on the 23 Oct. rating date, again because of visible core cultivation holes 13 days after treatment.

Stimpmeter evaluations

Stimpmeter data are summarized for 1994, 1995, and 1996 in Tables 3.5, 3.6, and 3.7, respectively. Prior to treatment application, there were significant differences ($P \leq 0.05$) in ball roll distance among cultivation treatments on nine of twelve days ball roll was evaluated.

There were no significant differences in ball roll distances among the treatments, prior to application, on the first two evaluation dates in 1994. The HTCSSF plots had significantly low ball roll distances on 8 Sep. because of surface disruption caused by the summer hollow tine cultivatIons applied 9 days earlier. These plots still had significantly lower ball roll distances than several other treatments on the 20 Sep. evaluation date, 21 days after hollow tine cultivations. Plots receiving water injection cultivation had significantly higher ball roll distances than other treatments, immediately following

Table 3.5. Effect of cultivation treatment on ball roll distance of a creeping bentgrass putting green. 1994.

	Stimpmeter reading date											
	11-Jul			30-Aug			8-Sep			20-Sep		
Treatments†	before	after	% increase††	before	after	% increase††	before	after	% increase††	before	after	% increase††
	cm			cm			cm			cm		
Check	201	201	-	199	199	-	212	212	-	187	187	-
WIC weekly	202	221	9%	196	231	18%	214	240	12%	200	209	5%
WIC biweekly	205	223	9%	198	198	-	215	239	11%	197	204	4%
WIC monthly	195	195	-	194	194	-	207	236	14%	188	188	-
HTCSFW‡	202	230	14%	203	203	-	220	241	10%	191	205	7%
HTCSF‡	191	191	-	192	192	-	208	208	-	194	194	-
HTCSSF§	192	192	-	193	193	-	186	186	-	180	180	-
HTCSF*W‡¶	194	215	11%	194	194	-	203	231	14%	190	204	7%
LSD#	NS	18***		NS	21***		22***	20***		12**	16***	

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments applied in spring and fall (6/9 and 10/13).

§ Treatments applied spring, summer, and fall (6/9, 8/30, and 10/13).

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at the indicated level of significance.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

†† Treatments with no value under "% increase" were not applied on the corresponding stimpmeter date.

Table 3.6. Effect of cultivation treatment on ball roll distance of a creeping bentgrass putting green. 1995.

	Stimpmeter reading date														
	25-May			1-Jun			8-Jun			15-Jun			22-Jun		
Treatments†	before	after	% increase††	before	after	% increase††	before	after	% increase††	before	after	% increase††	before	after	% increase††
	cm			cm			cm			cm			cm		
Check	180	180	-	204	204	-	218	218	-	213	213	-	206	206	-
WIC weekly	176	198	13%	198	214	8%	222	230	4%	217	227	5%	210	224	7%
WIC biweekly	185	185	-	207	219	6%	223	223	-	206	214	4%	209	209	-
WIC monthly	181	181	-	204	204	-	211	211	-	195	209	7%	196	196	-
HTCSFW‡	168	168	-	197	209	-	219	219	-	209	223	7%	207	207	-
HTCSF‡	164	164	-	190	190	-	210	210	-	202	202	-	198	198	-
HTCSSF§	172	172	-	192	192	-	222	222	-	205	205	-	200	200	-
HTCSF*W‡¶	177	177	-	206	219	6%	250	250	-	235	251	7%	219	219	-
LSD#	13***	15***		11**	21***		14***	16***		23***	25***		14***	17***	

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments applied in spring and fall (5/22 and 10/3).

§ Treatments applied spring, summer, and fall (5/22, 8/28, and 10/3).

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at the indicated level of significance.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

†† Treatments with no value under "% increase" were not applied on the corresponding stimpmeter date.

Table 3.7. Effect of cultivation treatment on ball roll distance of a creeping bentgrass putting green. 1996.

	Stimpmeter reading date								
	30-May			14-Jun			21-Aug		
Treatments†	before	after	% increase††	before	after	% increase††	before	after	% increase††
	cm			cm			cm		
Check	174	174	-	217	217	-	225	225	-
WIC weekly	188	198	5%	223	228	2%	224	239	7%
WIC biweekly	186	186	-	229	229	-	219	235	7%
WIC monthly	182	182	-	216	216	-	223	239	7%
HTCSFW‡	183	183	-	220	220	-	223	238	7%
HTCSF‡	171	171	-	215	215	-	225	225	-
HTCSSF§	168	168	-	220	220	-	209	209	-
HTCSF*W‡¶	189	189	-	233	233	-	236	246	4%
LSD#	13***	13***		NS	NS		10***	15***	

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

‡ Treatments applied in spring and fall (5/23 and 10/10).

§ Treatments applied spring, summer, and fall (5/23, 8/7, and 10/10).
¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).
# Fisher's least significant difference test at the indicated level of significance.
*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.
†† Treatments with no value under "% increase" were not applied on the corresponding stimpmeter date.

application, on all evaluation dates in 1994. On average, water injection cultivation increased ball roll distance 10 % following treatment. The HydroJect 3000® has two rollers surrounding the injection nozzles that function similar to traditional putting green rollers. This rolling action increased ball roll distances on plots receiving WIC treatment, probably by decreasing surface irregularities (Beard, 1997). Similar ball roll data was reported by Miller (1994) where WIC treatment resulted in an immediately increase in ball roll distance that averaged 22 percent.

There were significant differences in ball roll distances among the treatments, prior to treatment application, on all five evaluation dates in 1995. Plots that received hollow tine cultivations had significantly low ball roll distances on 25 May because of surface disruption caused by treatments 3 days earlier. Plots receiving hollow tine cultivation treatment and no water injection cultivation treatment had significantly lower ball roll distances than the other treatments on 1 Jun. These plots probably had lower ball roll distances because the HydroJect rollers smoothed the surface disruptions caused by hollow tine cultivation in plots with combination cultivation treatments. The HTCSF*W treatment had significantly higher ball roll distances than several other treatments on 8 Jun., 15 Jun., and 22 Jun. Several hollow tine cultivation treatments with narrow spacings caused the turf to thin, based on visual observations, which supported longer ball roll distances. Plots receiving water injection cultivation had significantly high ball roll distances, immediately following application, on all dates except 15 Jun. in 1995. On average, water injection cultivation increased ball roll distance 7 % following treatment.

On two of three evaluation dates in 1996, there were significant differences in ball roll distances among treatments prior to treatment. The HTCSF*W treatment had significantly high ball roll distances on 30 May (7 days after hollow tine cultivation) and 21 Aug. Once again, increased ball roll distances were probably the result of thinning turf caused by hollow tine cultivation with narrow tine spacing. The HTCSSF treatment had significantly lower ball roll distances than all other treatments on 21 Aug. Decreased ball roll distances for the HTCSSF treatment was the result of surface disruptions caused by summer hollow tine cultivation 14 days earlier. Plots receiving water injection cultivation had significantly higher ball roll distances than all other treatments, immediately following application, on 30 May and 21 Aug. in 1995. On average, water injection cultivation increased ball roll distance 6 % following treatment.

Soil physical properties

Saturated hydraulic conductivity, porosity, and bulk density data are summarized in Tables 3.8 and 3.9. There were no significant differences among cultivation treatments for any soil property in 1995 and 1996. These results were somewhat surprising, and not typical for cultivation treatments. Hollow tine cultivation and WIC typically increase hydraulic conductivity and porosity, and lower bulk density. Murphy and Rieke (1994) reported that WIC was equal or superior to HTC in reducing soil bulk density, and increasing porosity and saturated hydraulic conductivity. In another study, Murphy et al. (1993) reported a 3 % decrease in bulk density and 62 % increase in saturated hydraulic conductivity with HTC. Earthworm channels and occasional pieces of gravel were observed in several samples and probably significantly increased the variability to a level where differences among treatment means were undetectable.

Saturated hydraulic conductivity decreased substantially in 1996 ($\approx$ 600 %). This was probably the result of compression of macropore space by the rolling treatment in 1996. The soil was not compacted from the rolling treatment, as bulk density did not increase in 1996. However, macropore space decreased significantly in 1996 ($\approx$ 80 %). There was probably an increase in tortuosity as the macropore space decreased, resulting in the decrease in saturated hydraulic conductivity.

Earthworm populations

Earthworm casting and biomass data are summarized in Table 3.10. There were significant differences in cast numbers among treatments on all three dates casts were counted. All treatments having a water injection cultivation component had significantly

Table 3.8. Effect of cultivation treatment on physical soil properties of a creeping bentgrass putting green. 1995.

Treatments†	Physical analyses			
	Ksat	Air porosity††	Total porosity	Bulk density
	— $cm\ hr^{-1}$ —	—— $m^3\ 100m^{-3}$ ——		— $Mg\ m^{-3}$ —
Check	45	17.2	37.9	1.64
WIC weekly (37)†††	23	15.9	37.3	1.64
WIC biweekly (19)	32	17.7	39.1	1.61
WIC monthly (10)	23	17.7	38.5	1.62
HTCSF‡ (4) W (19)	26	17.0	39.3	1.62
HTCSF‡ (4)	22	19.5	38.1	1.64
HTCSSF§ (6)	36	18.9	38.5	1.62
HTCSF*‡¶ (4) W (19)	25	20.4	39.0	1.62
LSD#	NS	NS	NS	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

†† Water drained between 0 and -0.04 MPa moisture potential.

††† Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

‡ Treatments applied in spring and fall.

§ Treatments applied spring, summer, and fall.

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at ($P \leq 0.05$).

Table 3.9. Effect of cultivation treatment on physical soil properties of a creeping bentgrass putting green. 1996.

Treatments†	Physical analyses			
	Ksat	Air porosity††	Total porosity	Bulk density
	— $cm\ hr^{-1}$ —	—— $m^3\ 100m^{-3}$	——	— $Mg\ m^{-3}$ —
Check	3.9	10.9	38.4	1.61
WIC weekly (58)†††	7.6	8.7	39.3	1.60
WIC biweekly (30)	4.5	9.6	38.8	1.61
WIC monthly (15)	6.3	10.7	40.6	1.57
HTC‡ (6) W (30)	3.5	9.4	40.2	1.60
HTCSFW‡ (6)	4.3	11.5	38.3	1.61
HTCSSF§ (9)	4.0	10.5	38.7	1.62
HTCSF*‡¶ (6) W (30)	4.4	9.4	37.2	1.65
LSD#	NS	NS	NS	NS

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

†† Water drained between 0 and -0.04 MPa moisture potential.

††† Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

‡ Treatments applied in spring and fall.

§ Treatments applied spring, summer, and fall.

¶ HTC treatment applied at closest hole spacing (5.0 cm by 2.5 cm).

Fisher's least significant difference test at ($P \leq 0.05$).

Table 3.10. Effect of cultivation treatment on earthworm castings and populations on a creeping bentgrass putting green

Treatments†	Counting dates 1-Oct-94	6-Sep-95	17-Sep-96	3-Oct-96
	cast m^{-2}			mg biomass cm^{-3} soil
Check	10	15	11	0.09
WIC weekly	5	7	5	0.03
WIC biweekly	6	8	8	-
WIC monthly	6	14	9	-
HTCSFW‡	5	14	12	-
HTCSF‡	9	21	21	0.23
HTCSSF§	12	19	15	-
HTCSF*W‡¶	8	16	12	-
LSD#	3.1***	9.1**	5.8***	0.15**

† WIC - Water Injection Cultivation, HTC - Hollow Tine Cultivation.

†† Numbers in parenthesis represent the amount of treatments applied before soil samples were collected.

‡ Treatments applied in spring and fall.

§ Treatments applied spring, summer, and fall.

Fisher's least significant difference test at the indicated level of significance.

*, **, *** Significant at the 0.10, 0.05, and 0.01 level of probability respectively.

fewer earthworm casts than the check and hollow tine cultivation only treatments, with the exception of the HTCSF*W treatment on 1 Oct., 1994. The WIC weekly treatment had significantly fewer castings than the HTCSFW, HTCSF, and HTCSF*W treatments on 6 Sep., 1995. The WIC weekly treatment had significantly fewer castings than all treatments with an HTC component on 17 Sep., 1996. Also on this date, WIC biweekly and WIC monthly treatments had significantly less castings than treatments with only an HTC component.

There was significantly more earthworm biomass in HTCSF plots than WIC weekly or check plots (Table 3.10). Although there was 200 % less biomass in the WIC weekly treatment than check treatment, variability was substantially high, reducing statistical significance. These data suggest that earthworm casting numbers correlate reasonably well with actual earthworm populations. Water injection cultivation decreased earthworm populations in this study compared to treatments with a hollow tine cultivation component. This may have been achieved by physical harm to the organisms with the high pressure water streams, changes in the soil environment not conducive to earthworm habitat, or a combination of both.

Summary

Cultivation method and frequency did not affect the *Poa annua* populations in this study. A lack of traffic on the experimental area probably favored creeping bentgrass growth during 1994 and 1995, resulting in no increase in *Poa annua* populations.

Turfgrass quality was reduced following hollow tine cultivations and turf receiving cultivations with a narrow tine spacing was slower to recover. A hollow tine spacing of 5.0 cm by 2.0 cm had a thinning effect on the turf after 3 treatment applications. Weekly WIC reduced turf quality during periods of environmental stress. Turfgrass managers should be aware of stressful conditions when using WIC and avoid high frequency use when turfgrass vigor is sub-optimal.

Surface disruption from hollow tine cultivations reduced ball roll distances for up to 21 days following treatment. Narrow tine spacing reduced turf density, based on visual observations, after 3 applications, which probably increased ball roll distances. Water injection cultivations resulted in a 6 to 10 % increase in ball roll distance immediately following treatment application. These increases were caused by the smoothing action of two rollers located on either side of the injection nozzles on the HydroJect. Similar increases in ball roll distances have been reported in previous HydroJect research as well as research evaluating traditional greens rollers.

Hollow tine cultivation increased and WIC decreased earthworm casting activity when compared to check plots. Soil excavation and analysis revealed that earthworm populations were significantly higher where hollow tine cultivation treatments had been applied. Turfgrass managers may benefit from regular WIC by eliminating the need for pesticide control of earthworm activity on putting greens, especially during a period of increasing environmental awareness.

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