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**TURFGRASS RESPONSE TO
FERTILIZATION AND CULTIVATION
USING HIGH PRESSURE WATER INJECTION**

presented by

Christopher M Miller

has been accepted towards fulfillment
of the requirements for

M.S. degree in Crop & Soil Science

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**TURFGRASS RESPONSE TO
FERTILIZATION AND CULTIVATION
USING HIGH PRESSURE WATER INJECTION**

By

Christopher Michael Miller

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
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ABSTRACT
**TURFGRASS RESPONSE TO
FERTILIZATION AND CULTIVATION
USING HIGH PRESSURE WATER INJECTION**

By

Christopher Michael Miller

High pressure water injection has been developed as a method of soil cultivation which imparts minimal disruption to a turf surface. Water injection cultivation has beneficial effects on soil physical properties such as lowering bulk density, increasing porosity, and improving water conductivity. Studies were conducted to determine the effectiveness of water injection (WIC) as a method of applying fertilizers and wetting agents, as compared to traditional surface application of these materials. In addition, the effect of WIC on surface hardness was examined. Applications of fertilizers using WIC had no effect on turf quality compared to surface applications. Deeper placement of both P and K in the soil profile was seen from injection compared to surface application. Both injection and surface application of wetting agents were equally effective in preventing formation of localized dry spot on a sand-based putting green, especially at a high rate of application. Water injection cultivation applied as frequently as every two weeks on 2 separate high traffic sites had no effects on turf quality. Surface hardness, measured using the Clegg soil impact tester, decreased immediately following application of WIC. Due to recompaction and settling of the soil from constant traffic, duration of this effect on most occasions did not last longer than a two week period.

To My Parents
Robert and Frances

ACKNOWLEDGMENTS

I would like to thank and extend my deepest gratitude to Dr. P.E. Rieke, chairman of my graduate committee, for giving me invaluable guidance and support throughout my program. His kindness and unending willingness to share his knowledge and valuable time will never be forgotten. I am grateful to Dr. J.M. Vargas and Dr. J.N. Rogers III for participating as members of my graduate committee. I would also like to thank Mark Krick for his valuable friendship, and Jim Murphy and all the other people who have helped me and made my education a rewarding experience.

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CHAPTER ONE

Fertilization of Turfgrass Using High Pressure Water Injection

ABSTRACT

Traditionally, fertilization of turfgrass has been performed using broadcast surface application. However, the advent of high pressure water injection technology as a turfgrass cultivation tool has made subsurface fertilization a possibility. Injection of fertilizer nutrients phosphorus, potassium, and nitrogen was compared to surface applications using soil nutrient tests and evaluation of turf responses. Deeper placement of both P and K in the soil profile was found with injection compared to surface application. Injection application of fertilizers resulted in no improvement or reduction in turfgrass color or quality. Increased clipping yields were seen from injection of urea nitrogen compared to surface application. No difference in clipping yield or in plant tissue content of N or K was observed from injection application of these nutrients. When applied at equal rates, injection of phosphorus reduced phosphorus tissue content compared to surface application, possibly due to reduced root weight densities in the 0 to 7.5 cm soil zone of turf receiving injection application of phosphorus. Injection of nutrients is considered a feasible means of placing nutrients deeper in the profile, especially when deeper roots have reduced nutrient levels at the lower depths.

Fertilization of Turfgrass Using High Pressure Water Injection

Introduction

Fertilization of forages, food crops, and turfgrasses has historically been performed using broadcast applications. In an effort to combat the sometimes inefficient utilization of fertilizer nutrients by crop plants after broadcast application, an alternative method of fertilizer application, placement beneath the surface of the soil, has been studied extensively. Most research in this area is concerned with food crops and forages, with very little literature available on turfgrass management.

Gyles et al. (1985) lists as objectives of fertilizer placement to: 1) result in efficient fertilizer use by the plant, 2) prevent fertilizer salt injury to plants, and 3) provide an economical and convenient operation. Whether these objectives are ultimately achieved is highly dependent on certain general conditions such as soil properties, physical and chemical properties of the fertilizer material, and the extent and location of the plant root system (Mengel et al., 1982).

Nitrogen is often applied to turfgrass as urea because it is relatively inexpensive and is rapidly used by plants. Plant analysis of creeping bentgrass (*Agrostis palustris* Huds.) by Waddington et al. (1972) indicated the highest plant N contents were obtained from applications of urea compared to other N fertilizer sources. Banding urea fertilizer (placing fertilizer in concentrated bands below the seed) has resulted in greater N efficiencies than broadcast applications in corn (*Zea mays* L.) (Maddux et al., 1991), barley (*Hodeum vulgare* L.) (Malhi and Nyborg, 1985), rice (*Oryza sativa* L.) (Wetselaar, 1984), and bermudagrass (*Cynodon dactylon* L.) (Jackson and Burton, 1962). The literature involving subsurface nitrogen fertilization in turfgrass management is less extensive. King and Skogley (1969), found no consistent differences between N placement treatments and surface applications in terms of turfgrass quality or clipping yield of a Kentucky bluegrass

(*Poa pratensis* L.) / red fescue (*Festuca rubra* L.) sod established from seed.

A common problem with broadcast applied phosphorus is the potential for a high percentage of the phosphorus to be tied up or fixed into forms unavailable for immediate plant utilization (Cook and Ellis, 1987). Band placement of P fertilizer for field crops reduces soil-fertilizer contact, resulting in less fixation of the P by the soil (Gyles et al., 1985; Sleight et al., 1984). Banding of phosphorus has been shown to improve yields of corn (Engelstad and Allen, 1971), potatoes (*Solanum tuberosum* L.) (Cook and Ellis, 1987), sugar beets (*Beta vulgaris* L.) (Cook and Ellis, 1987), and oats (*Avena sativa* L.) (Sleight et al., 1984). Apparently, placement produces a concentration of soluble P needed for early growth stimulation (Engelstad and Allen, 1971).

Very little published information is available concerning placement of P fertilizers in turfgrass management. Hipp and Graff (1987) found that placement of P deeper than 3 cm resulted in less than optimum growth on a bermudagrass turf grown on a clay soil, however, depth of placement was found less critical on a sandy soil. The lack of research in this area may be due to the fact that general turfgrass quality has not been dramatically affected by P applications (Christians et al., 1979).

In most finer textured soils, potassium is relatively immobile and does not react with the soil to become unavailable to plants. Therefore, there is no consistent effect of placement on efficient plant utilization of added potassium. Both agricultural crops and turfgrasses have been shown to exhibit no dramatic growth responses from potassium fertilization in soils containing adequate levels of available K⁺ (Gyles et al.; 1985, Beard, 1973). Waddington et al. (1972) found K source or rate to have no effect on clipping yields of creeping bentgrass, although K in clippings was increased with potassium fertilization. Little benefit was shown from band placement of K compared to broadcast application of K in corn (Heckman and Kamprath, 1992) or soybeans (*Glycine max* L.) (Tisdale et al., 1985).

The increased efficiency in the use of fertilizers which can result from placing them

in selected zones of soil shows that the ability of crops to absorb nutrients varies throughout the rooting zone (Newbould et al., 1971). Many plants, such as alfalfa (*Medicago sativa* L.) (Peterson and Smith, 1973), clover (*Trifolium pratense* L.) (Goodman and Collison, 1981), and perennial ryegrass (*Lolium perenne* L.) (Newbould et al., 1971) absorb the majority of their nutrients from the upper areas of the soil profile. According to Garcia et al. (1988), nutrient placement is more important when positional variability of a plant's root system exists, as in row crops such as corn, than when the soil and root system is uniform. Rooting densities within the topsoil under well established forage crops are so great that the distance a nutrient needs to travel to facilitate plant uptake is small except for the most immobile nutrients (Barley, 1970). The dense nature of turfgrass stands suggests that similar rooting densities exist in these situations as well.

The advent of high pressure water injection cultivation technology (Murphy, 1990) has made placement of fertilizers into shallow depths of soil under established turf conditions a possibility. There is very little published information available concerning fertilization using this process. Murphy and Rieke (1992) found late fall injection of N to result in a more uniform green up response the next spring than broadcast applied N on a fairway turf. Nitrogen injection also increased N recovery by 34% over broadcast application in an early March clipping harvest. However, turf response to injection of phosphorus and potassium fertilizers has not been recorded. The objectives of this research were to determine effects of high pressure injection of N, P, and K on turf response and soil tests compared to traditional surface applications.

Materials and Methods

Phosphorus

This study was initiated in August, 1990 at the Michigan State University Robert Hancock Turfgrass Research Center on a nine-year old 'Penncross' creeping bentgrass

(*Agrostis palustris* L.) green grown on a modified loamy sand soil containing 83.5% sand, 10.6% silt, and 5.9% clay. Initial soil tests for phosphorus were medium (35 kg/ha) and low (59 kg/ha) for potassium. Soil pH was 7.3. Thatch thickness was approximately 20 millimeters.

A randomized complete block design was used with 4 replications of 5 treatments. Injection treatments were applied using a prototype high pressure water injection machine (Murphy, 1990) designed by the Toro Co., Minneapolis, MN. Liquid was injected to an average depth of 14 cm at a pressure of 17.3 MPa through 10 injection nozzles (1.2 mm orifice). Three passes with the injection unit were needed to cover a plot area. Nozzles were spaced 76 mm apart and a forward speed of 3.2 km/hour placed the injection holes approximately 75 mm apart. Surface treatments were applied using a CO₂ powered sprayer. Annual treatments were: (i) control - no phosphorus fertilization; (ii) water injection cultivation only - no phosphorus fertilization; (iii) surface application of 5.3 g P / m²; (iv) high pressure injection application of 5.3 g P / m²; and (v) high pressure injection of 10.6 g P / m². Fertilization treatments were split into two separate applications with 1/2 rates applied in early August and late September of each year. Phosphoric acid (H₃PO₄) was used as the phosphorus source.

Nitrogen was applied at 9.8, 14.6, 17.0, and 14.6 g N/m² in 1990 - 1993, respectively. Potassium was applied at 4.0 g / m² in 1990 and 8.1 g N/m² in 1991 - 1993. The green was maintained at a 7.5 mm cutting height. Pesticides were applied as needed to control insects, diseases, and weeds. Supplemental irrigation was provided daily to prevent drought stress.

Soil samples for phosphorus analysis were collected on 2 Nov., 1990; 5 Aug. and 2 Nov., 1991; 8 Aug. and 2 Nov., 1992, and 11 Aug. and 4 Nov., 1993. Approximately 10 subsamples were taken from each plot and divided into sections representing thatch, 0-7.5 cm, 7.5-15.0 cm, and 15.0-22.5 cm depth zones. Subsamples for each depth zone were combined into a representative sample. Each representative sample was then analyzed

for available phosphorus using the Olsen procedure (Olsen et al., 1954).

Five soil cores were taken from each plot on 10 Jun., 5 Aug., and 1 Nov., 1991; 6 Aug. and 4 Nov., 1992; and 12 Jun., 10 Aug., and 31 Oct., 1993 for root weight density determinations. Each 5 cm² by 22.5 cm deep core was divided into 3 sections each 7.5 cm long. Roots were separated from soil with the hydropneumatic elutriation system (Smucker et al., 1982).

Clippings were collected from an area approximately 1.5 m², dried at 60C, and weighed for yield measurements for the growth periods of 2 to 7 Aug., 7 to 19 Aug., 20 Aug. to 2 Sep., 3 to 20 Sep., and 21 Sep. to 10 Oct., 1991; 5 to 10 May, 2 to 7 Jul., 1 to 7 Aug., 9 to 16 Sep., and 2 to 10 Oct., 1992; and 1 to 6 May, 29 Jun. to 6 Jul., 9 to 12 Aug., 11 to 15 Sep., and 1 to 6 Oct., 1993. Turf was not mowed for extended periods of time in order to magnify possible differences in yield measurements that may have been occurring.

Plant tissue analysis of clippings was performed for phosphorus on samples collected 20 Aug. and 10 Oct., 1991; 7 Jul., 7 Aug., and 10 Oct., 1992; and 6 May, 6 Jul., 12 Aug. and 14 Oct., 1993. Clippings were ground through a 40 mesh screen and ashed at 500 C for 5 hours. Ash was then digested for 1 hour in 3N nitric acid and analyzed for phosphorus content.

Turf was rated for color on a scale from 1 to 9 with 1 being brown, 5 acceptable, and 9 dark green. Color ratings began 20 Apr., 1992 and were taken at 3 to 4 week intervals until 27 Oct., 1992. In 1993 ratings were taken from 16 Apr. to 26 Oct.

Turf quality was rated on a scale from 1 to 9 with 1 being dead, 5 acceptable, and 9 excellent. Quality ratings were taken at 3 to 4 week intervals from 8 Jul. to 24 Oct., 1991; 18 May to 27 Oct., 1992, and 16 Apr. to 26 Oct., 1993.

Potassium

This study was initiated in August, 1990 at the Robert Hancock Turfgrass Research

Center, Michigan State University, on an 11-year old annual bluegrass (*Poa annua* L. var. *reptans*) turf growing on a sandy loam soil (fine - loamy, mixed, mesic, Typic Hapludalf). Initial soil tests were high for phosphorus (131 kg / ha) and medium for potassium (131 kg / ha). Soil pH was 7.3.

A randomized complete block design was used with 4 replications of 6 treatments. Injection and surface applications were made as described for the phosphorus study. Liquid was injected to an average depth of 12 cm at the same pressure and hole spacing as the phosphorus study. Thirteen nozzles were used to inject the fertilizer solution and three passes with the unit were required to cover a plot area. Annual treatments were: (i) control - no potassium fertilization; (ii) water injection cultivation only - no potassium fertilization; (iii) surface application of 12.2 g K / m²; (iv) high pressure injection of 12.2 g K / m² ; (v) surface application of 24.4 g K / m² ; and (vi) high pressure injection of 24.4 g K / m². Fertilization treatments were split into 2 separate applications with 1/2 rates applied in mid-July and early September of each year. Potassium chloride (KCl) was used as the potassium source.

Nitrogen was applied at 9.8, 14.6, 19.4, and 19.4 g N/m² in 1990-1993, respectively. Based on soil tests no supplemental phosphorus was applied throughout the study. The turf was maintained at a 12.5 mm cutting height. Pesticides were applied as needed to control insects, diseases, and weeds. Supplemental irrigation was applied daily to prevent drought stress.

Soil samples for potassium analysis were collected 2 Nov., 1990; 23 Oct., 1991, 10 Jul. and 4 Nov., 1992; and 21 Jul. and 12 Oct., 1993. Approximately 10 subsamples were taken from each plot and divided into sections representing 0-7.5 cm, 7.5-15.0 cm, and 15.0-22.5 cm depth zones. Subsamples from each depth zone were combined into a representative sample and analyzed for available potassium using the neutral normal ammonium acetate extraction procedure (Knudsen et al., 1982).

Clippings were collected from an area approximately 1.3 m², dried at 60C, and

weighed for yield measurements for the growth periods of 20 Aug. to 5 Sep., 13 to 27 Sep., and 12 to 22 Oct., 1991; 9 to 15 May, 3 to 8 Jul., 1 to 7 Sep., and 2 to 7 Oct., 1992; and 28 May to 3 Jun., 3 to 8 Jul., 27 Aug. to 4 Sep., and 24 to 29 Sep., 1993.

Plant tissue analysis of clippings was performed for potassium on samples collected 4 Sep. and 22 Oct., 1991; 16 Jul., 7 Sep., and 7 Oct., 1992; and 28 May, 7 Jun., 4 Sep., and 14 Oct., 1993. Clippings were ground through a 40 mesh screen and ashed at 500 C for 5 hours. Ash was then digested for 1 hour in 3N nitric acid and analyzed for potassium content.

Turf was rated for both color and quality as described for the phosphorus study. Ratings were taken at 2 to 4 week intervals from 15 May to 22 Oct., 1992 and from 16 Apr. to 24 Oct., 1992. Turf quality ratings were taken from 31 Jul. to 24 Oct, 1991; 15 May to 22 Oct., 1992; and 16 Apr. to 24 Oct., 1993.

Nitrogen

The study was initiated in 1992 on an 11-year old 'Penncross' creeping bentgrass green grown on a modified loamy sand containing 83.5% sand, 10.6% silt, and 5.9% clay.

A randomized complete block design was used with 4 replications of 8 treatments. Injection treatments were applied using the Hydroject 3000 manufactured by the Toro Co., Minneapolis, MN. Liquid was injected to an average depth of 12 cm at 21 MPa through 1.2 mm orifices. Nozzles on the unit were 76 mm apart and injection holes were spaced 25 mm apart. Surface treatments were applied as described for phosphorus and potassium studies. Treatments were: (i) control - no nitrogen fertilization; (ii) water injection cultivation only - no nitrogen fertilization; (iii) surface application of 2.4 g N/m² for each application date; (iv) surface application of 4.8 g N/m²; (v) injection application of 2.4 g N/m²; (vi) injection application of 4.8 g N/m²; (vii) injection application of 4.8 g N/m² with a late fall treatment; and (viii) surface application of 4.8 g N/m² with a late fall treatment. Treatments (ii) - (vi) were applied 27 Jun., 29 Jul., and 2 Sep., 1992 and 26

May, 2 Jul., 12 Aug., and 16 Sep., 1993. Treatments (vii) and (viii) were applied 27 Jun., 29 Jul., 2 Sep., and 24 Oct., 1992, and 2 Jul., 12 Aug., and 16 Sep., 1993. No supplemental fertilization was applied. The green was maintained at 7.5 mm cutting height. Pesticides were applied as needed to control weeds, insects, and diseases. Supplemental irrigation was provided daily to prevent drought stress.

Clippings were collected from an area approximately 1.3 m², dried at 60C, and weighed for yield measurements for the growth periods of 24 to 31 Jul., 24 to 31 Aug., and 10 to 24 Oct., 1992; and 28 Apr. to 3 May, 29 Jun. to 1 Jul., 2 to 6 Jul., 24 to 29 Jul., 10 to 16 Sep., and 1 to 10 Oct., 1993. On all dates except 6 Jul., 1993, clipping yields were taken one month after treatment. The clipping yields on 6 Jul., 1993 were taken one week after treatment. Plant tissue analysis was performed for total nitrogen on 1 Aug. and 31 Oct., 1992; and 30 Apr., 30 Jun., and 6 Jul. 1993 using the Kheldahl procedure (Schuman et al., 1973).

Turf was rated for both color and quality as described for the phosphorus study. In 1992 both color and quality ratings were taken from 10 Jul. to 20 Oct. at 2 to 4 week intervals. In 1993 ratings for both color and quality were taken from 15 Apr. to 7 Oct.

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

Results and Discussion

Phosphorus

Phosphorus soil test data is summarized in Figures 1.1-1.4 and data given in Table A in the Appendix. Plots receiving no phosphorus fertilization had the lowest available phosphorus levels in the thatch layer (approximately 20 mm thick) and upper 7.5 cm of soil on all dates. The thatch layer revealed dramatic differences among P fertilization treatments

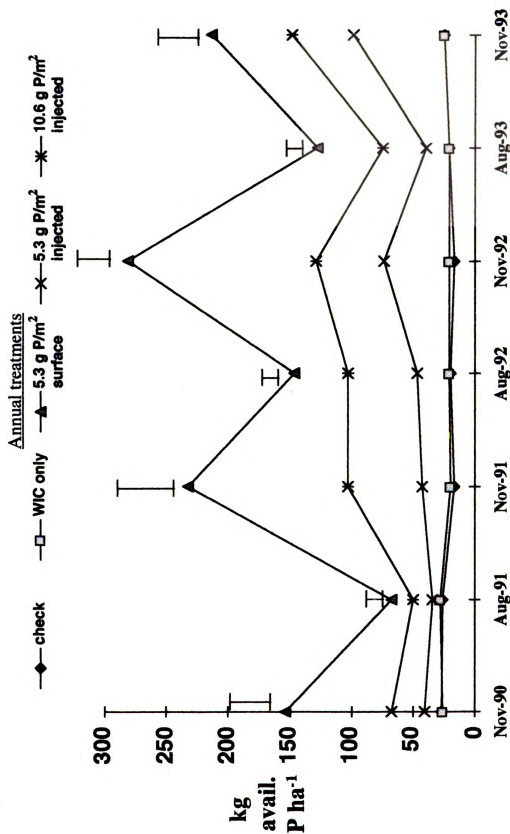


Figure 1.1. Soil phosphorus levels (Olsen) at the thatch layer of a creeping bentgrass green. Treatments were applied at half annual rates on 18 Aug. and 13 Oct., 1990, 20 Aug. and 23 Sep., 1991, 11 Aug. and 2 Oct., 1992, and 12 Aug. and 22 Sep., 1993.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that this is crucial for ensuring transparency and accountability in the organization's operations.

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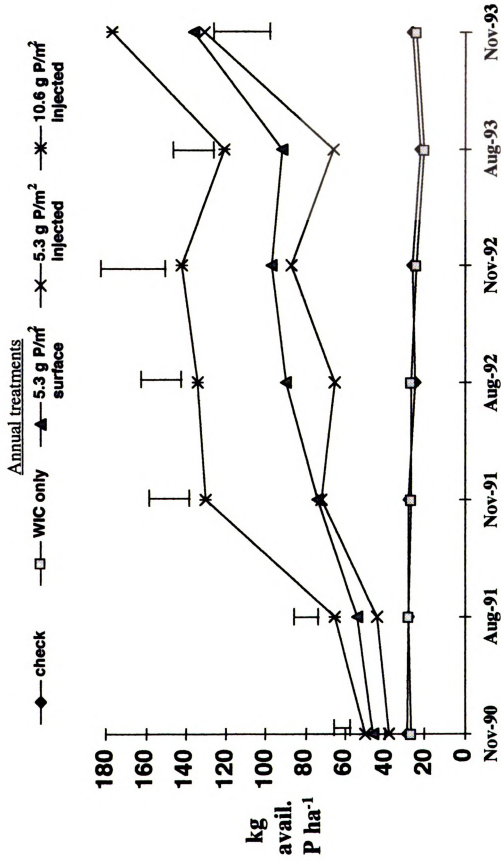


Figure 1.2. Soil phosphorus levels (Olsen) at the 0-7.5 cm soil level of a creeping bentgrass green. Treatments were applied at half annual rates on 18 Aug. and 13 Oct., 1990, 20 Aug. and 23 Sep., 1991, 11 Aug. and 2 Oct., 1992, and 12 Aug. and 22 Sep., 1993.



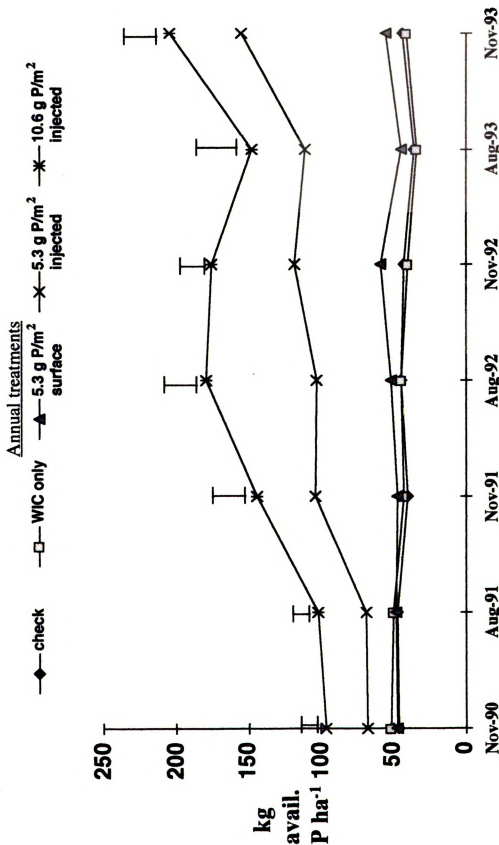


Figure 1.3. Soil phosphorus levels (Olsen) at the 7.5-15.0 cm soil level of a creeping bentgrass green. Treatments were applied at half annual rates on 18 Aug. and 13 Oct., 1990, 20 Aug. and 23 Sep., 1991, 11 Aug. and 2 Oct., 1992, and 12 Aug. and 22 Sep., 1993.

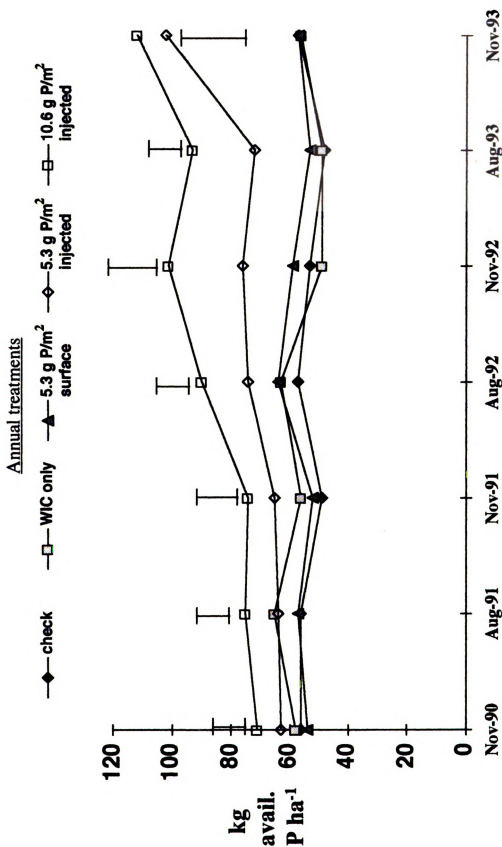


Figure 1.4. Soil phosphorus levels (Olsen) at the 15.0-22.5 cm soil level of a creeping bentgrass green. Treatments were applied at half annual rates on 18 Aug. and 13 Oct., 1990, 20 Aug. and 23 Sep., 1991, 11 Aug. and 2 Oct., 1992, and 12 Aug. and 22 Sep., 1993.

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and the role of the accounting department in ensuring the integrity of the financial statements. It also highlights the need for regular audits and the importance of transparency in financial reporting.

2. The second part of the document focuses on the implementation of internal controls to prevent fraud and ensure the accuracy of financial data. It outlines the key components of a robust internal control system, including segregation of duties, authorization procedures, and regular monitoring and evaluation.

3. The third part of the document addresses the challenges faced by organizations in managing their financial resources effectively. It discusses the importance of budgeting, forecasting, and cost management, and provides practical advice on how to overcome common financial management challenges.

4. The fourth part of the document explores the role of technology in modern accounting and finance. It discusses the benefits of using accounting software and the importance of staying up-to-date with the latest technological advancements in the field.

5. The fifth part of the document concludes by emphasizing the importance of ethical behavior in the accounting profession. It discusses the role of accountants as trusted advisors and the need to adhere to high ethical standards in all financial transactions.

(Figure 1.1). Significantly higher phosphorus levels were found in the thatch layer of the plots receiving surface fertilization (5.3 g P / m^2) compared to both rates of injection fertilization. There was an annual cyclical fluctuation in available phosphorus levels in the thatch layer of plots receiving surface fertilization. Soil P tests in the thatch layer in these plots for the August dates (taken prior to the first fertilization treatment each year) showed an average decrease of $109 \text{ kg available P / ha}^{-1}$ from November soil tests of the previous year (taken after the second fertilization treatment each year). One explanation is that a high amount of phosphorus is being mined from the thatch layer due to clipping removal from these plots between fertilization treatments. Fluctuations of available phosphorus levels in the thatch layer of plots receiving injection fertilization were evident, but not as dramatic.

In the 0-7.5 cm depth zone, plots receiving the high rate of injection fertilization (10.6 g P / m^2) had significantly higher available phosphorus levels than other treatments on all dates except early in the study, Nov., 1990 and Aug., 1991. Comparison between surface and injection fertilization treatments at the low rate of P fertilization (5.3 g P / m^2) revealed equal available P levels on each date except Aug. 1992 and Aug. 1993. Both of these dates were prior to the first semi-annual fertilization treatment. At the end of each season, after fertilization treatments, these differences were no longer present. Reasons for these differences are speculative. Perhaps movement of phosphorus from the thatch layer to this depth zone of the surface fertilized plots may be an explanation. Due to the fact that the phosphorus was injected to an average depth of 14 cm, less phosphorus was present in the thatch layer of plots receiving the low rate of injected phosphorus. Therefore, less, if any, downward movement of phosphorus may have occurred between fertilization treatments in these plots, resulting in lower available P levels. In the surface treated plots, however, available P levels increased with each soil test in plots receiving surface fertilization, with the exception of the Aug. 1993 tests. This suggests in these plots, phosphorus is moving downward out of the thatch layer to the 0-7.5 cm soil depth.

Injection of phosphorus at both rates increased the level of available phosphorus in

the 7.5-15 cm depth zone with each annual application. Comparison of plots receiving surface fertilization with the control and WIC plots consistently revealed equal available P levels. This was true even after the fourth year of treatment. Phosphorus applied to the surface is staying in the thatch layer and the upper 7.5 cm of the soil profile. Clearly, injection fertilization is effective at placing phosphorus past this zone in this loamy sand soil.

In the 15-22.5 cm depth zone, it was seen that after the first year of fertilization treatments, available P levels in plots receiving the high rate of injection were significantly higher than those found in both the check and WIC only plots. After the third year of fertilization treatments, the low rate of injection increased available P levels compared to both the check and WIC only plots. Surface application of phosphorus did not affect available P levels at this soil depth as compared to the control and WIC only plots. It is evident that there was downward movement of phosphorus past the depth of injection at both the high and the low rate of fertilization.

Frequent color differences were seen among control plots and plots receiving phosphorus fertilization (Table 1.1). Purpling of leaf tissue, a common symptom of phosphorus deficiency, often resulted in lower color ratings in control plots. These color differences were more dramatic in late spring and early summer when soil temperatures are traditionally lower. An explanation may be lowered phosphorus availability due to a decrease in microbial breakdown of organic phosphorus sources. As soil temperatures rose, microbial activity increased, making more organic phosphorus available for plant uptake. Therefore, color rating increased, although deficiency symptoms persisted. On several dates, WIC only plots had significantly higher color ratings than control plots. Soil P levels deeper in the soil profile for the check and WIC only plots (see Table A, Appendix) were higher than those found in the surface soil. Treatment of the soil with water injection cultivation may have caused enough movement of soil from deeper in the profile to make more phosphorus available for plant uptake, eliminating the symptoms of

Table 1.1 : Color ratings of a creeping bentgrass green as affected by phosphorus applications. 9=dark green, 5 acceptable, 1=brown turf.

1992	Rating										
	20-Apr	18-May	16-Jun	28-Jun	15-Jul	2-Aug	19-Aug	8-Sep	24-Sep	10-Oct	27-Oct
Annual treatment*											
Control	4.3b [^]	5.6b	5.0b	5.6c	5.6b	5.4d	5.2d	5.2b	5.4c	5.2b	5.2c
WIC Only	4.7b	5.6b	7.1a	7.0b	6.5a	6.0c	6.2bc	6.4ab	6.0bc	5.7ab	5.9b
5.3 g P/m ² surface	5.6a	6.7a	6.4a	7.5ab	6.6a	5.9c	5.7cd	6.0ab	6.5ab	5.6ab	6.1ab
5.3 g P/m ² inject	6.2a	6.4a	7.4a	8.0a	7.0a	6.8ab	7.0a	6.7a	6.7a	5.7ab	6.1ab
10.6 g P/m ² inject	6.2a	6.4a	6.6a	8.0a	7.2a	7.0a	6.7ab	6.7a	6.9a	6.0a	6.7a
1993	Rating										
	16-Apr	14-May	26-May	10-Jun	30-Jun	28-Jul	28-Aug	9-Sep	22-Sep	5-Oct	26-Oct
Annual treatment*											
Control	5.0b	5.1c	5.0c	4.7b	6.2c	7.0b	6.2b	6.5a	6.5b	5.3b	6.0b
WIC Only	5.9a	5.5bc	5.6b	5.2b	7.2b	7.5a	6.7ab	7.0a	7.5a	6.8a	6.5a
5.3 g P/m ² surface	6.0a	6.0ab	6.6a	6.7a	7.5ab	8.0a	6.5ab	7.0a	7.3ab	7.0a	6.8a
5.3 g P/m ² inject	6.0a	6.4a	6.7a	7.0a	8.0a	8.0a	6.8ab	6.8a	7.3ab	6.8a	6.5a
10.6 g P/m ² inject	6.0a	6.2a	7.0a	7.0a	7.8ab	8.0a	7.0a	6.8a	7.5a	7.0a	7.0a

[^] Means within a column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

*Treatment dates (each applied at 1/2 rate): 18 Aug. and 13 Oct. 1990; 20 Aug. and 23 Sep. 1991; 11 Aug. and 2 Oct. 1992; 12 Aug. and 22 Sep. 1993

phosphorus deficiency seen in control plots. These differences did not show up in soil test results, however. No consistent differences in color were found among phosphorus fertilization treatments.

Injection of phosphorus at either rate did not affect clipping yields as compared to other treatments (Table 1.2). Control plots tended to have slightly lower clipping yields than other treatments, although on only one date, 7 Aug., 1992, was the clipping yield in these plots significantly lower than all other treatments. It can be concluded that injection of phosphorus, even at a high rate (10.6 g P / m^2) did not cause a reduction in top growth of a creeping bentgrass stand on this soil.

Root weight densities (RWD) were significantly reduced compared to the control in the 0-7.5 cm depth zone from injection of phosphorus at both rates of phosphorus fertilization in Nov. 1991, Nov. 1992, and Nov. 1993 (Table 1.3). The WIC only treatment did not reduce RWD in this depth zone on any date. This suggests possible root injury from injection of the phosphorus source used (phosphoric acid). Significantly lower RWD's were found in plots receiving injection P fertilization at both the high and low rate compared to plots receiving surface P fertilization in Nov. 1992, Jun. 1993, Aug. 1993, and Nov. 1993. On no dates did surface application of phosphorus significantly decrease RWD compared to control plots.

Percent of total roots in the 0-7.5 cm depth zone of injection fertilized plots decreased in Aug. 1993 and Nov. 1993 compared to surface fertilized plots. However, percent of total roots in the 7.5-15 cm zone increased with injection fertilization compared to surface fertilization in Nov. 1992, Aug. 1993, and Nov. 1993. The water injection cultivation only treatment increased the percent of total roots compared to plots receiving surface fertilization in the 7.5-15 cm zone in Aug. 1993 and Nov. 1993. This may suggest that roots are proliferating in the thatch and upper 7.5 cm of soil in plots receiving surface fertilization, while water injection cultivation, both with and without phosphorus, may be causing a redistribution of a portion of the total root system to deeper in the soil profile.

Table 1.2: Clipping yields of a creeping bentgrass green as affected by phosphorus applications.

Annual treatment*	Dry clipping weight, grams per square meter												
	8/7/91	9/20/91	10/10/91	5/10/92	7/7/92	8/7/92	9/16/92	10/10/92	5/6/93	7/6/93	8/12/93	9/15/93	10/6/93
Control	12.5a^	10.6a	13.3bc	23.3a	13.3a	15.0b	19.9a	27.2a	29.9b	40.2b	11.5a	17.6b	15.5c
W/C Only	13.8a	10.3a	14.8bc	27.6a	16.7a	20.0a	22.7a	28.1a	34.2a	46.5ab	13.4a	20.5ab	18.6bc
5.3 g P/m ² surface	13.7a	11.6a	12.4c	26.7a	16.2a	19.7a	22.0a	26.4a	30.7ab	59.9ab	12.8a	20.5ab	22.5a
5.3 g P/m ² inject	14.8a	12.5a	15.6ab	26.6a	16.8a	19.1a	23.1a	29.5a	30.1b	56.8a	13.8a	20.9ab	18.8bc
10.6 g P/m ² inject	14.3a	11.8a	18.4a	28.9a	18.1a	19.7a	23.3a	29.8a	33.8a	55.4ab	14.4a	21.5a	21.9ab
# days growth	5	18	20	5	5	7	7	8	5	8	3	4	5

[^] Means within a column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

*Treatment dates (each applied at 1/2 rate): 18 Aug. and 13 Oct. 1990, 20 Aug. and 23 Sep. 1991; 11 Aug. and 2 Oct. 1992; 12 Aug. and 22 Sep. 1993.

Table 1.3: Root weight density data from a creeping bentgrass stand.

Annual treatment*	Jun. 1991	Aug. 1991	Nov. 1991	Aug. 1992	Nov. 1992	Jun. 1993	Aug. 1993	Nov. 1993
	Root Weight (g) per 100 cubic cm. - 0-7.5 cm. depth zone							
Control	0.30a [^]	0.48a	1.21a	0.58a	0.92a	1.00ab	0.82b	0.92a
WIC Only	0.35a	0.54a	0.94ab	0.56a	0.88b	1.05ab	0.64b	0.89a
5.3 g P/m ² surface	0.36a	0.56a	0.94ab	0.59a	0.94a	1.09a	1.09a	0.94a
5.3 g P/m ² inject	0.32a	0.56a	0.80b	0.54a	0.70a	0.87b	0.66b	0.70b
10.6 g P/m ² inject	0.32a	0.59a	0.83b	0.50a	0.66c	0.76c	0.73b	0.66b
	% of total roots in 0-7.5 cm depth zone							
Control	84.4a	84.6a	92.2a	86.6ab	88.7a	81.9a	88.2a	87.7ab
WIC Only	85.1a	85.5a	89.6ab	83.6b	85.2ab	79.3ab	83.1b	83.7c
5.3 g P/m ² surface	86.1a	87.9a	90.9ab	86.8a	87.4ab	82.2a	90.8a	89.6a
5.3 g P/m ² inject	83.5a	83.9a	88.5b	84.4ab	83.1c	77.2ab	82.8b	85.2bc
10.6 g P/m ² inject	83.8a	86.7a	89.7ab	86.2ab	84.6bc	73.6b	82.8b	84.1c
	% of total roots in 7.5-15 cm depth zone							
Control	15.6a	11.7a	5.8a	11.9ab	8.7c	13.1a	9.2bc	9.7bc
WIC Only	14.9a	11.5a	8.1a	13.4a	11.9ab	17.3a	12.5ab	12.3ab
5.3 g P/m ² surface	13.9a	9.1a	6.4a	10.3b	9.3bc	12.8a	7.4c	8.5c
5.3 g P/m ² inject	16.5a	12.4a	8.4a	12.5ab	12.9a	17.4a	13.2a	12.4ab
10.6 g P/m ² inject	16.2a	10.9a	7.6a	12.1ab	12.8a	17.7a	14.4a	13.1a
	% of total roots in 15-22.5 cm depth zone							
Control		3.7a	1.9a	1.5a	2.9a	4.9b	2.4bc	2.6a
WIC Only		2.9a	2.3a	2.9a	2.9a	3.4b	4.3a	4.0a
5.3 g P/m ² surface		2.9a	2.6a	2.9a	2.8a	4.9b	1.7c	1.9a
5.3 g P/m ² inject		3.8a	3.1a	3.1a	3.6a	5.4b	3.9ab	2.5a
10.6 g P/m ² inject		2.3a	2.7a	1.7a	2.6a	8.7a	2.8ab	3.0a

[^] Means within a column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

* Treatment dates (each applied at 1/2 rate): 18 Aug. and 13 Oct. 1990; 20 Aug. and 23 Sep. 1991; 11 Aug. and 2 Oct. 1992; 12 Aug. and 22 Sep. 1993.

A high concentration of roots, typically 80 to 90 percent of the total root weight, was found in the 0 to 7.5 cm depth zone. Root weight densities decreased with progression down through the soil profile. Ultimately, a very small percentage of the total root weight, 1.5 to 9 percent, was found in the 15.0 to 22.5 cm depth zone. This may explain the higher available soil phosphorus levels deeper in the soil profile in the control and WIC only plots. Without supplemental phosphorus applications, the dense root system in the surface layer of these plots has extracted a major portion of the available phosphorus. With less roots deeper in the soil, however, less of the available phosphorus has been extracted and higher available phosphorus contents were found.

Plant tissue analysis showed lower phosphorus content in clippings taken from plots receiving no phosphorus fertilization on every date except 6 Jul. and 12 Aug. 1993 (Table 1.4). A consistent difference was found between clippings taken from injection fertilized plots and clippings taken from surface fertilized plots at the low rate of P fertilization (5.3 g P/m²). On every date except 6 Jul. and 12 Aug. 1993, significantly higher phosphorus contents were found in clippings taken from surface fertilized plots. This may be due to the lower root weight densities found in the upper 7.5 cm of soil in the plots receiving injection fertilization. On all dates however, P contents in clippings taken from injected and surface fertilized plots at the low rate are well within the tissue content sufficiency range described by Jones (1980). On every date except 20 Aug. 1991 and 7 Aug. 1992, clippings taken from plots receiving the high rate of injection fertilization had equal phosphorus contents compared to clippings taken from surface fertilized plots.

Potassium

Soil test levels for ammonium acetate extraction of potassium are summarized in Figures 1.5-1.7 and in Table B in the Appendix. In the 0-7.5 cm depth zone, plots receiving no potassium (control and WIC only plots) had significantly lower available potassium levels than plots receiving potassium on all dates. The values found in the

Table 1.4: Phosphorus content of creeping bentgrass clippings.

Annual treatment*	Grams P per kilogram								
	8/20/91	10/10/91	7/7/92	8/7/92	10/10/92	5/6/93	7/6/93	8/12/93	10/14/93
Control	2.8e^A	2.0c	1.9c	2.8d	2.8c	2.4c	3.8ab	5.1a	3.4c
WTC Only	3.3d	2.2c	2.2c	2.9d	2.9c	2.5c	3.6b	4.6a	3.4c
5.3 g P/m2 surface	5.2a	4.1a	4.0a	4.8a	4.6a	4.6a	6.4a	6.2a	6.5a
5.3 g P/m2 inject	4.2c	3.3b	3.5b	4.1c	3.3b	3.9b	6.0ab	6.1a	5.9b
10.6 g P/m2 inject	4.6b	4.0a	3.9a	4.3b	4.0a	4.1ab	5.6ab	6.0a	6.0ab

[^] Means within a column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

*Treatment dates (each applied at 1/2 rate): 18 Aug. and 13 Oct. 1990; 20 Aug. and 23 Sep. 1991; 11 Aug. and 2 Oct. 1992; 12 Aug. and 22 Sep. 1993.

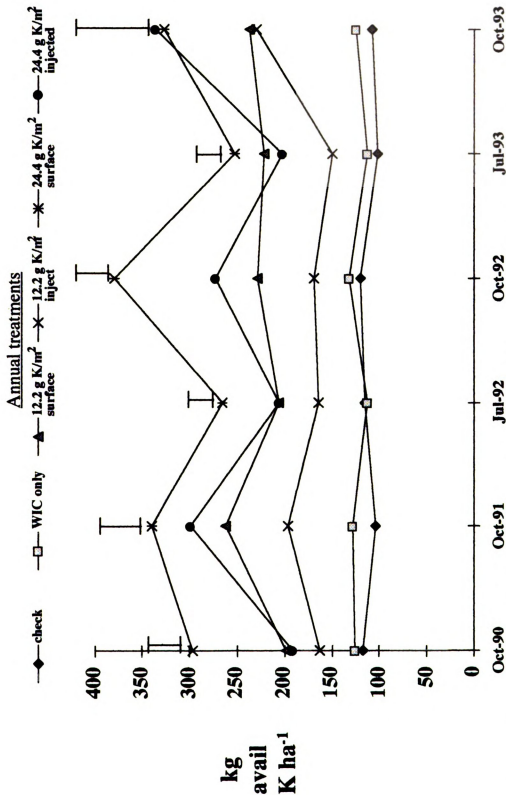


Figure 1.5. Soil potassium levels (Ammonium acetate extractable) at the 0-7.5 cm level of an annual bluegrass turf. Treatments were applied at half annual rates on 9 Aug. and 7 Sep., 1990, 9 Jul. and 6 Sep., 1991, 21 Jul. and 16 Sep., 1992, and 21 Aug. and 18 Sep. 1993.

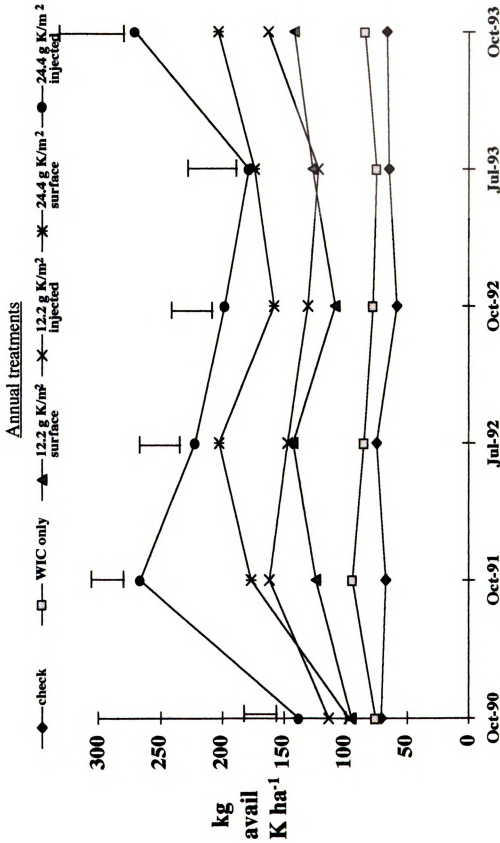


Figure 1.6. Soil potassium levels (Ammonium acetate extractable) at the 7.5-15.0 cm level of an annual bluegrass turf. Treatments were applied at half annual rates on 9 Aug. and 7 Sep., 1990, 9 Jul. and 6 Sep., 1991, 21 Jul. and 16 Sep., 1992, and 21 Aug. and 18 Sep. 1993.

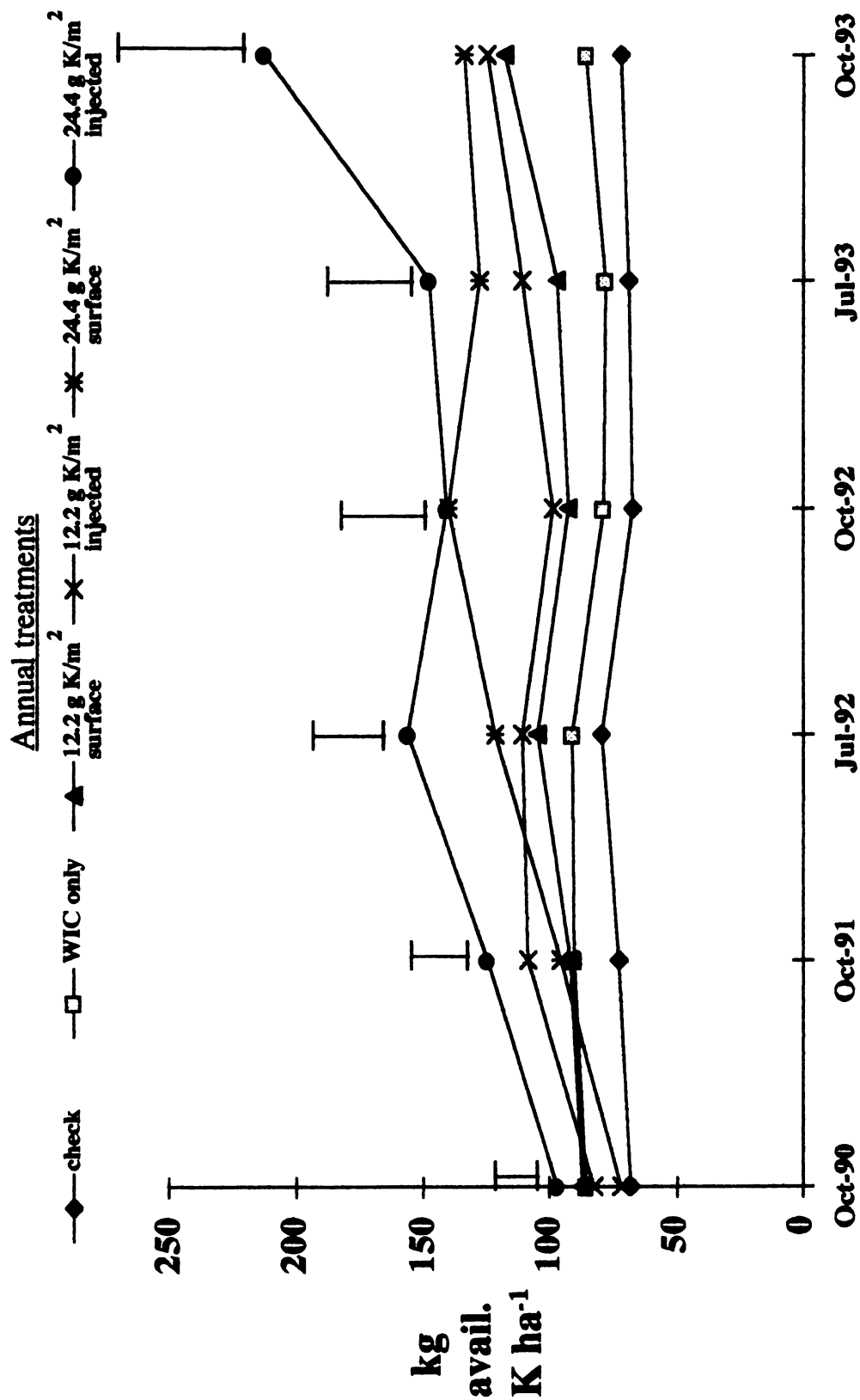


Figure 1.7. Soil potassium levels (Ammonium acetate extractable) at the 15-22.5 cm level of an annual bluegrass turf. Treatments were applied at half annual rates on 9 Aug. and 7 Sep., 1990, 9 Jul. and 6 Sep., 1991, 21 Jul. and 16 Sep., 1992, and 21 Aug. and 18 Sep. 1993.

control and WIC only plots were still well above those considered low in potassium (50-60-70 kg available K / ha) (Turner, 1980). At both the low and high rates of potassium fertilization, plots receiving surface applications showed a trend of having higher available K levels than plots receiving injection fertilization. This could be expected, as potassium applied by injection reached as deep as 12 cm. As with the phosphorus study, there was an annual cycle in the available potassium tests. Since clippings were not removed from these plots, it is assumed the lower potassium tests in summer just before the first application each year was the result of either leaching or minor fixation of potassium by the soil.

In the 7.5-15 cm depth zone (Figure 1.6), there were lower available K levels in the control and WIC only plots. These levels stayed highly similar throughout the study. At the low rate of K fertilization (12.2 g K/m²), injection increased K levels over surface fertilized plots on only one date (Oct. 1991). At the high rate of K fertilization (24.4 g K/m²), however, injection significantly increased K levels compared to surface fertilization in Oct. 1990, Oct. 1991, Oct. 1992, and Oct. 1993. These four soil test dates were all after annual fertilization treatments. Soil tests taken before fertilization treatments in Jul. 1992 and Jul. 1993 do not show these differences. Apparently, potassium applied to the surface has moved downward in the soil profile, especially at the high rate of application.

No consistent differences among treatments were found in the 15-22.5 cm depth zone, except at the high rate of potassium fertilization. Higher K levels were found in plots receiving injection fertilization compared to surface fertilization in Oct. 1990, Oct. 1991, Jul. 1992, and Oct. 1993. Despite these differences, it is still apparent that at both rates, potassium applied using surface and injection methods has moved through the soil profile. In plots which received the low rate of K fertilization, available soil K levels in the 15-22.5 cm depth zone increased an average of 43% after 4 years of treatments. At the high rate, this average increase was 102%.

No differences in color, quality, or clipping yield (data not shown) were found among treatments on any date, regardless of whether the plot received no K, surface K, or

injection K fertilization. Rate of potassium fertilization also had no effect on color, quality, or clipping yield. Sufficient potassium was available for turfgrass growth in this sandy loam soil such that application of additional potassium, regardless of rate or method of application, produced no significant color or growth response.

Plant tissue analysis on 22 Oct. 1991, 7 Oct. 1992, and 4 Sep. 1993 revealed lower potassium contents in clippings taken from plots receiving no potassium fertilization (Table 1.5). Despite having lower potassium contents, the potassium levels in these clippings are within the tissue content sufficiency range described by Jones (1980). No differences in potassium content of clippings were found among treatments which received potassium on any date regardless of method or rate of fertilization.

Nitrogen

The creeping bentgrass green on which this study was performed received no nitrogen fertilization in the year prior to the initiation of the study (1991). Response to nitrogen fertilization in July, 1992 was extremely rapid and dramatic. In 1992, at the high rate of nitrogen fertilization (4.8 g N/m^2), plots receiving injection fertilization exhibited a localized response in the turf immediately surrounding injection holes. This localized response, which gives evidence the nitrogen is not spreading laterally in the soil immediately after application, led to a striped appearance of the turf, which lasted 2 to 3 weeks after application. Response to surface nitrogen applications was a uniform green up. The striped appearance of the turf in the injected plots led to significantly lower color ratings on several dates compared to plots receiving surface application (Table 1.6). At the low rate of nitrogen fertilization however, striping effects from injection of nitrogen were not as dramatic and did not result in lowered color ratings compared to surface application. On all dates in 1992 and 1993, plots receiving no nitrogen fertilization had lower color ratings than all other treatments.

Plots which had received late fall N fertilization in 1992 exhibited early spring green

Table 1.5: Potassium content of annual bluegrass clippings.

Annual treatment*	Grams K per kilogram									
	9/4/91	10/22/91	7/16/92	9/7/92	10/7/92	5/28/92	7/7/93	9/4/93	10/14/93	
Control	21.8b [^]	22.8c	19.8a	20.5a	25.0b	27.7a	28.3a	24.5b	29.6cd	
WTC Only	22.0ab	24.8b	22.4a	20.6a	25.6b	26.5a	30.1a	26.4b	28.7d	
12.2 g K/m ² surface	24.6a	29.9a	21.6a	21.8a	31.5a	27.7a	31.1a	31.1a	30.4bcd	
12.2 g K/m ² inject	24.1ab	28.3a	21.9a	22.4a	30.4a	28.5a	27.9a	31.3a	33.8bc	
24.4 g K/m ² surface	22.6ab	31.0a	21.3a	21.9a	29.9a	26.0a	31.5a	32.4a	36.6a	
24.4 g K/m ² inject	23.2ab	29.4a	20.7a	22.6a	31.8a	27.4a	30.1a	31.5a	30.8bcd	

[^] Means within a column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

*Treatment dates (each applied at 1/2 rate): 9 Aug and 7 Sep 1990; 9 Jul and 6 Sep 1991; 21 Jul and 16 Sep 1992; 21 Aug and 18 Sep 1993.

Table 1.6 : Color ratings of a creeping bentgrass green as affected by nitrogen applications. 9=dark green, 5=acceptable, 1=brown turf.

Treatment	1992									
	10-Jul	25-Jul	12-Aug	1-Sep	15-Sep	30-Sep	20-Oct	28-Aug	16-Sep	7-Oct
Rating										
Control	4.5c [^]	4.0d	4.2d	4.9c	4.4c	4.7d	4.5c			
WTC only	4.4c	4.0d	4.2d	5.0c	4.4c	4.5d	4.2c			
2.4 g N/m ² surface*	5.6b	6.7c	7.1b	7.1b	7.0b	6.6c	7.0b			
2.4 g N/m ² inject*	6.0ab	6.9c	6.2c	7.2b	6.4b	6.2c	6.5b			
4.8 g N/m ² surface*	5.8ab	7.6b	7.7a	8.0a	8.4a	7.5ab	7.7a			
4.8 g N/m ² inject*	6.0ab	8.2a	7.0b	7.1b	6.7b	6.5c	6.6b			
4.8 g N/m ² surface~	6.8a	7.9ab	8.0a	7.9a	8.0a	7.9a	8.0a			
4.8 g N/m ² inject~	6.4ab	8.1a	6.9b	7.2b	6.7b	6.9bc	6.9b			
Treatment	1993									
	15-Apr	14-May	3-Jun	24-Jun	10-Jul	22-Jul	12-Aug	28-Aug	16-Sep	7-Oct
Rating										
Control	2.9e	4.0c	4.0c	4.0d	4.0c	4.0c	4.3d	4.0c	4.3d	3.3c
WTC only	3.0e	3.8c	4.0c	4.0d	4.0c	4.0c	4.5d	4.3c	4.5d	3.3c
2.4 g N/m ² surface*	4.5d	5.0b	5.8b	5.2c	6.5b	6.8b	6.3c	6.5b	6.0b	4.8b
2.4 g N/m ² inject*	5.2cd	4.9b	6.8a	6.8b	7.0ab	6.5b	6.8b	6.8b	6.3bc	5.0b
4.8 g N/m ² surface*	5.9bc	5.3b	6.5ab	6.0b	7.0ab	7.2ab	7.5ab	8.0a	7.8a	7.3a
4.8 g N/m ² inject*	6.5b	5.5b	7.0a	7.0a	7.5a	8.0a	8.0a	7.8a	8.0a	6.8a
4.8 g N/m ² surface~	7.9a	7.1a	6.4ab	6.0b	7.5a	7.8a	7.5ab	7.8a	7.8a	7.3a
4.8 g N/m ² inject~	8.0a	6.8a	6.4ab	6.0b	7.0ab	7.5a	7.8a	7.8a	7.0b	6.8a

*Dates of nitrogen fertilization: 30 Jun, 31 Jul, 2 Sep 1992, 26 May, 2 Jul, 12 Aug, 16 Sep, 1993.

~Dates of nitrogen fertilization: 30 Jun, 31 Jul, 2 Sep, 24 Oct, 1992 (late fall), 2 Jul, 12 Aug, 16 Sep, 1993.

[^] Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

up in 1993 and showed significantly higher color ratings than all other treatments on 15 Apr. and 14 May. No differences in color were seen between late fall injection and surface fertilization treatments on these two dates, however. In 1993, localized response to injection of nitrogen was less apparent compared to 1992, and striping of turf was minimal. No consistent differences in color were seen between injection and surface fertilized plots at either rate of N fertilization. Perhaps there was enough residual nitrogen in the soil from the 1992 applications to mask the localized response seen after injection.

Significantly lower clipping yields were found in plots receiving no nitrogen fertilization on all dates (Table 1.7). At both the low and high rates of N fertilization, higher clipping yields were found on several dates in plots receiving nitrogen injection compared to plots receiving surface fertilization. Although nitrogen applied to the surface was watered in immediately following application, a small degree of volatilization may still have occurred. Injection of nitrogen may decrease these volatilization losses, resulting in increased clipping yields. Plots which received late fall N fertilization treatments in 1992 had significantly higher clipping yields than other treatments in an early spring harvest 3 May 1993. On this date a comparison of the two late fall treatments showed significantly higher clipping yields in plots which had received nitrogen injection fertilization compared to surface application.

Total nitrogen content in clippings for both 1992 and 1993 is summarized in Table 1.8. Inconsistent results were seen among the 5 dates. On 2 dates (1 Aug., 1992 and 30 Jun., 1993), no differences in nitrogen were seen among treatments. Three dates (31 Oct., 1992, 30 Apr. and 6 Jul., 1993) revealed differences among treatments, however. Lower nitrogen content was generally found in clippings from the control and WIC only plots. On no dates did method of application affect N content in the clippings. This was true at both the high and low rates of nitrogen fertilization.

In summary, high pressure water injection is an effective method of applying

Table 1.7: Clipping yields from a creeping bentgrass green as affected by nitrogen applications.

Treatment	Dry clipping weight, grams per square meter									
	7/31/92	8/31/92	10/24/92	5/3/93	7/1/93	7/6/93	7/29/93	9/16/93	10/10/93	
Control	2.0d [^]	1.2g	1.2f	2.7f	1.8cd	1.2e	1.1d	1.5c	1.3c	
W/C only	1.6d	0.9g	0.9f	2.9f	0.8d	1.6e	1.4d	2.2c	1.4c	
2.4 g N/m ² surface*	3.2c	2.9f	4.9e	5.7e	1.9cd	6.7d	3.4c	3.8b	3.7b	
2.4 g N/m ² inject*	4.2b	3.2e	6.7d	7.8d	3.6b	8.5cd	6.2b	5.0ab	5.3ab	
4.8 g N/m ² surface*	3.1c	3.9d	8.6c	7.4d	3.2b	6.2d	4.7bc	4.0b	5.2ab	
4.8 g N/m ² inject*	6.6a	6.1c	11.1a	9.8c	6.1a	17.1a	7.7a	4.5ab	5.6ab	
4.8 g N/m ² surface~	4.3b	6.5b	10.4b	11.7b	3.5b	9.4bc	6.2b	5.6a	6.1a	
4.8 g N/m ² inject~	7.1a	6.7a	11.4a	13.4a	3.7b	10.7b	7.9a	4.7ab	6.3a	
# days growth	7	7	14	6	2	5	5	6	10	

*Dates of nitrogen fertilization: 30 Jun, 31 Jul, 2 Sep 1992, 26 May, 2 Jul, 12 Aug, 16 Sep, 1993.

~Dates of nitrogen fertilization: 30 Jun, 31 Jul, 2 Sep, 24 Oct (late fall), 1992, 2 Jul, 12 Aug, 16 Sep, 1993.

^ Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

Table 1.8: Total nitrogen content in clippings from a creeping bentgrass green.

Treatment	% total nitrogen content				
Control	2.1a^	2.1bc	2.3d	2.5a	3.0bc
W/C only	2.3a	1.6c	2.4d	2.9a	2.9c
2.4 g N/m2 surface*	2.4a	2.1bc	2.4d	2.7a	3.7a
2.4 g N/m2 inject*	2.5a	2.5ab	2.7cd	3.0a	3.5ab
4.8 g N/m2 surface*	2.2a	2.5ab	2.7cd	2.8a	3.6ab
4.8 g N/m2 inject*	2.7a	3.3a	3.0bc	3.1a	4.1a
4.8 g N/m2 surface~	2.5a	2.8ab	3.6a	2.7a	3.9a
4.8 g N/m2 inject~	2.7a	2.6ab	3.3ab	2.8a	4.0a

*Dates of nitrogen fertilization: 30 Jun, 31 Jul, 2 Sep 1992, 26 May, 2 Jul, 12 Aug, 16 Sep, 1993.

~Dates of nitrogen fertilization: 30 Jun, 31 Jul, 2 Sep, 24 Oct, 1992 (late fall), 2 Jul, 12 Aug, 16 Sep, 1993.

^ Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

fertilizers to turfgrass, especially P and K. When compared to surface application of fertilizers, water injection fertilization was equally sufficient in maintaining turf quality, growth, and plant tissue nutrient content. Water injection placed nutrients deeper in the soil profile, especially phosphorus, which is less susceptible to leaching than nitrogen or potassium in most soils. Surface applications of phosphorus tended to be held in the thatch and the upper 7 cm of the soil profile even at the relatively high rates applied in this study.

Injection of potassium initially increased levels of K deeper in the soil profile. However, potassium applied on the surface moved downward in the profile past the surface 7.5 cm. Injection of nitrogen increased clipping yields, which gave evidence that greater nitrogen efficiency may result when applied using water injection. In addition to receiving fertilization from water injection, the turf stand may be benefiting from improvement in soil physical properties such as decreased bulk density, and increased porosity and water conductivity (Murphy, 1990). This observation needs further investigation.

In the creeping bentgrass green in the phosphorus study, 80-90% of the creeping bentgrass root mass resided in the surface 7.5 cm of the soil profile. This brings up the important aspect of the ideal depth of fertilizer placement in similar situations. Injection of nutrients past this zone of concentrated roots may be an inefficient use of fertilizer. Although roots are present below this zone that are capable of nutrient uptake, they exist in limited concentration. Therefore, much of the fertilizer placed in this zone may not be taken up by the plant, and in the case of nitrogen and potassium, could be lost through leaching. This is an important issue which deserves attention in the future.

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CHAPTER TWO

High Pressure Injection of Wetting Agents in Sand-Based Greens

ABSTRACT

The phenomenon of localized dry spot (LDS) is a problem frequently found on sand-based greens. The application of wetting agents in these situations is a common practice used to aid in the control of LDS. Applications of wetting agents using traditional surface treatment were compared to those using high pressure water injection based on soil moisture tests and evaluation of turf response. HydroWet was effective in preventing formation of localized dry spot, especially when applied at a high rate (5.1 ml/m²). Both injection and surface applications of HydroWet were equally effective in terms of maintaining turf quality and gravimetric soil moisture contents. When a less effective wetting agent was applied, lower water drop infiltration times in soil 1.25 cm below the thatch layer were found in soil cores receiving injection application of wetting agents. The longest water drop infiltration times were found in the thatch layer and were on average 10 times greater than those found in soil 1.25 cm below the thatch layer.

High Pressure Injection of Wetting Agents In Sand-Based Greens

Introduction

The phenomenon of localized dry spot (LDS), sometimes referred to as dry patch, has been well documented. Cases have been reported in pasture soils in Australia (Bond, 1969), bushlands in California (Holzhey, 1969), burned over areas of forest soils (Osborn et al, 1964), and citrus orchards in Florida (Wander, 1949). However, the most frequent occurrences have been in turfgrass areas (York and Baldwin, 1992). Localized dry spots are almost always found on areas with coarse-textured sandy soils, although not exclusively (Bond, 1969).

Localized dry spot is a term which is commonly used to describe the occurrence of an irregular area of turfgrass which shows signs typical of drought stress (Karnok and Tucker, 1989). With the increased use of sand-based putting greens and sand topdressing programs, LDS has become a major problem for golf course managers. Circumstantial evidence points to soil fungi as causal agents of localized dry spots (York and Baldwin, 1992). Another suggested source of LDS is the production of a water repellent coating by microorganisms during organic matter decay (Wilkinson and Miller, 1978). This material was thought to be an organic acid (fulvic acid), which when dry, becomes extremely hydrophobic. Use of an electron microscope has shown sand from LDS or hydrophobic areas to have a covering or coating over much of the particle. Inspection of sand taken from healthy or non-hydrophobic areas revealed clean, relatively smooth surfaces (Bond and Harris, 1964). No firm link, however, has been provided which can unquestionably connect the presence of microbes with the production of water repellent molecules (York and Baldwin, 1992).

Using a water drop infiltration time test on soil samples taken from LDS-afflicted areas, Letey (1969) indicated that the area of maximum hydrophobicity (non-wettability)

occurs just below the thatch-soil interface. Deeper in the soil there is less effect (Henry and Paul, 1978). Soil found in the root zone beneath localized dry spot afflicted areas is often extremely dry (Baldwin, 1990). Once the turf begins to exhibit symptoms of LDS the problem is usually difficult to correct (York and Baldwin, 1992). Therefore, prevention, by keeping the soil profile moist, is viewed as the most effective defense against formation of LDS (Wilkinson and Miller, 1978).

This is not always possible, however, and dry spots do still develop. In the 1950's, soap and detergent solutions were sometimes used to aid the percolation of water into LDS affected areas. These chemicals were not designed for this purpose, however, and had many undesirable side effects such as severe phytotoxicity and adverse effects on soil structure (Baldwin, 1989). Since then, commercial products specifically designed for use on turfgrass have been developed. These products, commonly called surfactants (surface active agents) or wetting agents are now commonly used to assist in alleviating the severity of the symptoms expressed in areas of turf affected by LDS (York and Baldwin, 1992).

High pressure water injection was developed to give turf managers a cultivation tool that could be used frequently, while imparting minimal disturbance to the turf surface (Murphy, 1990). This technology, referred to as water injection cultivation (WIC), also offers the potential to place materials such as wetting agents deeper in the soil profile. Wetting agents have been reported to improve soil percolation, infiltration, and drainage, help wetting of LDS affected areas, reduce evapotranspiration rates, minimize dew formation, decrease disease incidence, and reduce thatch buildup (Petrovic, 1985). Very little published information is available concerning application of wetting agents using high pressure water injection. In work done by Murphy and Rieke (1992), injection of wetting agent following a rainfall event resulted in an increase in gravimetric soil moisture content of 132% compared to plots receiving no wetting agent. The majority of research on the application of wetting agents, however, has been done with their application to the surface

of turf areas. The objective of this research was to compare high pressure injection of wetting agents to conventional surface application by observing turf and soil responses.

Materials and Methods

A study was initiated in Aug. 1992 at the Michigan State University Robert Hancock Turfgrass Research Center on an 11-year old Penncross creeping bentgrass (*Agrostis palustris* Huds.) green grown on a modified loamy sand soil containing 83.5% sand, 10.6% silt, and 5.9% clay.

A completely randomized design was used with 4 replications of 10 treatments. Water injection treatments were applied using the Hydroject 3000^m, manufactured by the Toro Co., Minneapolis, MN. Liquid was injected to an average depth of 120 mm at 21 MPa through 1.2 mm orifices. Nozzles on the unit were 76 mm apart and injection holes were spaced 75 mm apart. Surface treatments were applied using a CO₂ powered sprayer. Two wetting agents were applied in this study: HydroWet from the Kalo Co., and Hydrozone from WMC Products Inc. Treatments were (i) control; (ii) water injection cultivation only - no wetting agent application; (iii) Hydrozone, injected at a rate of 1.3 ml/m²; (iv) Hydrozone, injected at a rate of 5.1 ml/m²; (v) Hydrozone, surface applied at a rate of 1.3 ml/m²; (vi) Hydrozone, surface applied at a rate of 5.1 ml/m²; (vii) HydroWet, injected at a rate of 1.3 ml/m²; (viii) HydroWet, injected at a rate of 5.1 ml/m²; (ix) HydroWet, surface applied at a rate of 1.3 ml/m²; and (x) HydroWet, surface applied at a rate of 5.1 ml/m². Application dates were 18 Aug., 1992; and 16 Jun. and 27 Jul., 1993. The plot area was irrigated following treatment application to assist wetting agents into the soil profile.

Nitrogen was applied at 9.8 and 14.6 g N/m² in 1992 and 1993, respectively. Potassium was applied at 8.1 g K/m² in both 1992 and 1993. Phosphorus was applied at 5.3 g P/m² in both 1992 and 1993. Pesticides were applied as needed to control insects,

diseases, and weeds. Supplemental irrigation was not applied in order to augment development of LDS.

Soil samples were collected for gravimetric moisture analysis on 26 Aug., 16 Sep., and 28 Oct., 1992, and 23 Jun., 21 Jul., 26 Jul., 12 Aug., 24 Aug., 4 Sep., and 24 Sep., 1993. Five subsamples were taken from the top 7.5 cm of each plot and combined into a representative sample. Samples were taken from random locations within a plot. Each representative sample was weighed, dried at 105 C for 24 hours, and weighed again for gravimetric moisture analysis.

Turf was rated for quality on a scale of 1 to 9 with 1 = brown, 5 = minimum acceptable, and 9 = excellent. Turf quality ratings were taken on 26 Aug., 15 Sep., 8 Oct., 1992, and 16 Jun., 30 Jun., 10 Jul., 21 Jul., 7 Aug., 28 Aug., 10 Sep., 24 Sep., and 7 Oct., 1993. Five soil cores were selected from the driest area in each plot based on visual observations on 24 Aug., 1993. These cores were then air dried, and analyzed for water drop infiltration time (Letey, 1969) at thatch, 1 cm, and 7 cm depths.

All tests were subjected to analysis of variance and means were separated using Fisher's protected LSD procedure at the 0.05 level of probability.

Results and Discussion

Turf quality ratings are summarized in Table 2.1. Analysis of 1992 data revealed high quality ratings and no consistent differences among treatments. A small amount of phytotoxicity was seen in plots receiving the high rate of HydroWet on 26 Aug., resulting in lower quality ratings than other treatments. These differences disappeared by the next ratings taken, 15 Sep. No formation of localized dry spots occurred, most likely due to frequent rainfall received in the months of August, September, and October.

Initial quality ratings in 1993 showed no differences among treatments, with extremely high quality found in all plots. As warmer weather progressed, a decrease in rainfall may have precipitated localized dry spot formation. By 21 Jul., differences among

Table 2.1 : Quality ratings of a creeping bentgrass green as affected by wetting agent applications. 9=excellent, 5=acceptable, 1=dead turf.

1992*	Treatment	26-Aug	15-Sep	8-Oct	Rating						
		Rating									
1992*	Control	8.5a^	8.0ab	8.0a							
	WIC only	8.3ab	8.0ab	7.8a							
	Real Kleen 4 oz/M injected	8.0abc	7.8ab	8.0a							
	Real Kleen 16 oz/M injected	8.0abc	7.8ab	8.0a							
	Real Kleen 4 oz/M surface	7.8abc	7.8ab	7.5a							
	Real Kleen 16 oz/M surface	7.8abc	7.3b	7.8a							
	HydroWet 4 oz/M injected	7.5bc	8.5a	8.0a							
	HydroWet 16 oz/M injected	7.8abc	7.8ab	7.3a							
	HydroWet 4 oz/M surface	8.3ab	8.3a	7.5a							
HydroWet 16 oz/M surface	7.3c	8.0ab	7.5a								
1993~	Treatment	16-Jun	30-Jun	10-Jul	21-Jul	7-Aug	28-Aug	10-Sep	24-Sep	7-Oct	
		Rating									
	Control	9.0a	8.5a	6.8b	5.5bc	5.5b	5.3c	6.8ab	7.3ab	7.0a	
	WIC only	9.0a	9.0a	7.3ab	6.5abc	6.3ab	5.5bc	7.0ab	7.5a	6.3ab	
	Hydrozone 1.3 ml/m2 injected	8.5a	7.8a	7.3ab	6.3abc	5.8b	6.0bc	7.3a	7.3ab	7.0a	
	Hydrozone 5.1 ml/m2 injected	8.8a	8.5a	7.8a	7.3ab	6.8ab	5.8bc	6.3ab	6.5b	6.5ab	
	Hydrozone 1.3 ml/m2 surface	8.8a	8.3a	6.8b	5.0c	5.0b	4.8c	5.5b	6.8ab	6.0b	
	Hydrozone 5.1 ml/m2 surface	9.0a	8.3a	7.3ab	6.0abc	6.0ab	5.3c	6.3ab	7.0ab	6.5ab	
	HydroWet 1.3 ml/m2 injected	8.5a	8.8a	7.8a	7.5ab	7.3a	8.0a	7.0ab	7.3ab	6.8ab	
	HydroWet 5.1 ml/m2 injected	8.8a	8.3a	7.5ab	7.5ab	7.8a	7.8ab	7.3a	7.5a	6.3ab	
	HydroWet 1.3 ml/m2 surface	9.0a	8.3a	7.5ab	7.0abc	6.5ab	7.8ab	7.5a	7.3ab	6.8ab	
	HydroWet 5.1 ml/m2 surface	8.8a	8.0a	8.0a	8.0a	7.5a	7.8ab	6.5ab	7.3ab	6.0b	

* Date of wetting agent application: 18 Aug 1992

~ Dates of wetting agent application: 16 Jun, 29 Jul 1993

^ Means within the same column followed by the same letter are not significantly different at $P=0.05$ according to Fisher's PLSD test.

treatments were evident. Extreme variability, however, resulted in limited statistical significance. The most severe dry spot formation was found in control plots, or those receiving water injection cultivation (WIC) only, and surface or injection application of the low rate of Hydrozone (1.3 ml/m^2). Moderate development of LDS occurred on several dates in plots receiving the injected or surface application of the high rate of Hydrozone (5.1 ml/m^2) as well as in plots receiving the injected or surface application of the low rate of HydroWet (1.3 ml/m^2). Little or no LDS formation occurred in plots receiving surface or injected applications of the high rate of HydroWet. There was no difference in quality ratings between surface and injection treatments. Frequent rainfall in September and October caused a reduction in the severity and amount of LDS. Consistent differences in quality among treatments during these two months were not evident.

Gravimetric soil moisture data are given in Table 2.2. As with quality ratings, analysis of 1992 data revealed no differences among treatments.

Initial soil moisture data in 1993 on 23 Jun. showed no differences among treatments. Based on visual observations of the plot area, localized dry spot formation did develop but extreme variability made detection of a definitive trend in soil moisture results difficult. The highest soil moisture contents in 1993 were found in plots receiving the high rate of HydroWet. No consistent differences between methods of application of HydroWet were apparent, however. The success of these treatments at maintaining a steady level of soil moisture explains the lack of localized dry spot formation in these plots. Plots injected with the high rate of Hydrozone had higher soil moisture contents than plots receiving the high rate surface application on only two dates (21 and 26 Jul.). Injection of the high rate of Hydrozone improved soil moisture over the check on 3 dates. On no dates was this seen with the high rate of surface application of Hydrozone. This suggests injection of certain wetting agents is more effective at maintaining soil moisture than surface applications.

Water drop infiltration times from soil cores taken 24 Aug. 1993 are given in Table 2.3. As with quality and soil moisture data, variability was high. Uniformity in plots

Table 2.2 : Gravimetric soil moisture of a modified loamy sand soil as affected by wetting agent applications.

Treatment	1992*				1993~							
	26-Aug	16-Sep	28-Oct		23-Jun	21-Jul	26-Jul	12-Aug	24-Aug	4-Sep	24-Sep	
	% Soil Moisture											
Control	13.1a [^]	12.6a	14.9a		17.8a	7.2cd	11.3c	11.0bc	9.2a	12.4c	15.8ab	
WIC only	13.1a	12.8a	14.2a		17.5a	7.5cd	12.5bc	12.3bc	10.7a	14.0bc	18.2ab	
Hydrozone 1.3 ml/m2 injected	14.6a	12.3a	14.7a		17.0a	7.0cd	13.5bc	14.1ab	12.6a	13.3bc	16.9ab	
Hydrozone 5.1 ml/m2 injected	14.6a	14.4a	15.3a		17.0a	13.0a	18.0a	16.6ab	13.5a	17.9ab	18.0ab	
Hydrozone 1.3 ml/m2 surface	13.6a	12.8a	14.3a		17.2a	6.0d	12.0c	10.6c	10.5a	13.8bc	15.7b	
Hydrozone 5.1 ml/m2 surface	11.7a	12.5a	13.8a		17.3a	7.5cd	10.3c	11.2bc	9.7a	13.2bc	16.4ab	
HydroWet 1.3 ml/m2 injected	13.7a	13.5a	15.2a		18.8a	8.3cd	15.3abc	16.1ab	14.2a	18.3ab	18.3ab	
HydroWet 5.1 ml/m2 injected	12.9a	13.3a	15.3a		16.8a	12.3ab	18.0ab	17.9a	14.9a	19.6a	19.5a	
HydroWet 1.3 ml/m2 surface	13.1a	12.7a	14.9a		17.8a	6.8cd	12.0c	12.6bc	11.9a	15.5abc	17.5ab	
HydroWet 5.1 ml/m2 surface	12.7a	12.5a	14.6a		17.7a	10.3abc	19.5a	18.1a	15.4a	17.9ab	17.7ab	
Treatment	% Soil Moisture											

* Date of wetting agent application: 18 Aug. 1992

~ Dates of wetting agent application: 16 Jun., 29 Jul. 1993

^ Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

Table 2.3: Water drop infiltration times, in seconds, from soil cores taken from a modified loamy sand putting green, 24 Aug., 1993.

Treatment*	Thatch	Seconds	
		1.25 cm	7.5 cm
Control	3143a [^]	426ab	3.0a
WIC only	3214a	222bc	2.9a
Hydrozone 1.3 ml/m2 injected	2672ab	169c	3.0a
Hydrozone 5.1 ml/m2 injected	1856bc	140c	2.1ab
Hydrozone 1.3 ml/m2 surface	3074a	659a	2.9a
Hydrozone 5.1 ml/m2 surface	3178a	362b	2.8ab
HydroWet 1.3 ml/m2 injected	1366c	34c	1.6b
HydroWet 5.1 ml/m2 injected	906cd	79c	1.6b
HydroWet 1.3 ml/m2 surface	1048cd	221bc	2.4ab
HydroWet 5.1 ml/m2 surface	224d	83c	2.0ab
Average	2068	201	2.4

* Dates of wetting agent application: 16 Jun., 29 Jul. 1993

[^] Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

treated with effective wetting agent treatments was good, therefore, there was no apparent localized dry spot in some plots. Soil taken from plots treated with HydroWet tended to have the lowest water drop infiltration times in both the thatch layer and 1.25 cm below the thatch layer. Infiltration times in soil taken from plots receiving injection of Hydrozone at the high rate had significantly lower infiltration times than soil taken from plots receiving surface application of the high rate of Hydrozone in both the thatch layer and 1.25 cm below the thatch layer. The same results were found for the low rate of Hydrozone, however only in the zone 1.25 cm below the thatch layer. Surface applications of low rates of wetting agents may not be penetrating past the thatch layer, limiting water infiltration into the soil. Injection of wetting agents can be an effective method of distributing the wetting agents through the surface hydrophobic layer, improving the wettability of soil and reducing susceptibility to localized dry spot.

Results of this study are difficult to interpret due to the variability and nature of localized dry spot formation. It can be stated that the application of wetting agents, especially HydroWet applied at a high rate, is an effective means of preventing localized dry spot formation on sand based putting greens. Both injection and surface applications of wetting agents were equally effective in terms of maintaining turf quality by preventing LDS. Injection and surface applications of a high rate of HydroWet were equally effective at maintaining a higher level of soil moisture than the control. Injection of the high rate of Hydrozone, however, was more effective than surface application at maintaining a higher level of soil moisture than the control on several dates. Injection of high rates of certain wetting agents may be more effective at maintaining soil moisture than their surface application. Higher water drop infiltration times in soil immediately below the thatch layer in soil taken from plots receiving the low rate of surface applied Hydrozone suggest that low rates of wetting agents may not penetrate past the thatch layer, limiting water infiltration into the soil.

Injection of wetting agents is an effective method of distributing the wetting agents through the surface hydrophobic layer, improving the wettability of soil and reducing susceptibility to localized dry spot. It is important to note, however, that deep placement of wetting agents may be an inefficient use of these materials. With the water injection unit used in this study, wetting agents were injected to an average depth of 12 cm. This could be placing much of the wetting agent past the zone where it is most needed, which is just below the thatch-soil interface (Letey, 1969). The study of injection of wetting agents to shallower depths deserves further attention.

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CHAPTER THREE

Water Injection Cultivation Effects on Surface Hardness and Turfgrass Quality

ABSTRACT

Wear and compaction caused by concentrated traffic and equipment ultimately affect turfgrass growth, quality, and vigor. Water injection cultivation can help alleviate adverse effects of traffic stress by lowering bulk density and improving porosity and hydraulic conductivity of the soil. A cultivation program using frequent applications of water injection cultivation was employed on two high traffic sites to determine effects on turfgrass quality and surface hardness. Water injection cultivation applied as frequently as every 2 weeks had no effect on turf quality. Ball roll on a putting green increased an average of 22% after application of water injection cultivation. Surface hardness readings, as given by the Clegg soil impact tester, decreased immediately following application of water injection cultivation. Duration of this effect on most occasions lasted less than two weeks due to recompaction of soil from constant traffic.

Water Injection Cultivation Effects On Surface Hardness and Turf Quality

Introduction

As the use of areas such as athletic fields and golf courses increases, so does the need to address the detrimental effects of wear and compaction caused by concentrated foot traffic and equipment. Ultimately, compaction affects turfgrass growth, quality, and vigor. Shoot densities of perennial ryegrass (*Lolium perenne* L.) and Kentucky bluegrass (*Poa pratensis* L.) decrease under compaction stress (O'Neil and Carrow, 1982; O'Neil and Carrow, 1983). Clipping yields and root growth also suffer under compaction stress (Sills and Carrow, 1982; Carrow, 1980). Physical resistance to root penetration in compacted soils restricts most rooting patterns to the surface soil where they are more exposed to environmental stresses. Eventually, the compromised root system leads to reduced quality or a limited ability to recover from stress (Sills and Carrow, 1982).

Impact absorption affects both playability and safety of an athletic field (Rogers and Waddington, 1986). A wide range of surface conditions in recreational turfs are caused by factors such as soil texture and structure, construction methods, grass conditions, maintenance practices, and use levels. Variation in surface characteristics can lead to different effects on player performance in all sports and on the behavior of balls in sports such as golf, soccer, and baseball (Rogers and Waddington 1990a).

The Clegg soil impact tester (CIT) has been developed as a quick measure of impact absorption, or hardness, of a turfgrass surface (Clegg, 1976). Developed in western Australia for testing dirt road surfaces by Baden Clegg, the CIT consists of a weight (4.5 kg missile) attached to a piezoelectric accelerometer, a device which measures how fast an object speeds up or slows down (Rogers and Waddington, 1990a). Upon impact with a surface, the accelerometer sends a signal (voltages or charges generated in disks or crystals in the accelerometer) corresponding to negative acceleration or g (acceleration due to gravity). The energy created during the fall is partly absorbed by the surface or is returned

to the missile. A higher amount of energy returned to the missile corresponds to a faster deceleration and a higher voltage signal from the accelerometer.

Soil and plant conditions can be rated. However, the importance of these agronomic factors is more clearly recognized when they are related to a quantitative measurement of impact characteristics (Rogers and Waddington, 1990a). When the soil is compacted, the surface absorbs less impact energy and peak deceleration values increase (Rogers and Waddington, 1990b; Holmes and Bell, 1987).

Aeration of compacted turf sites using hollow tine cultivation (HTC) has been shown to have a positive effect on lowering peak deceleration values (Rogers et al., 1989). Athletic fields which had received aeration treatments in the past were reported to have lower bulk densities and lower impact values.

In an effort to alleviate soil compaction on high use turf sites, cultivation is often employed by turf managers. One frequently used method of cultivation is core cultivation, or hollow tine cultivation, which involves the removal of soil cores from established turf to alleviate problems caused by soil surface compaction, layering, and thatch accumulation. This can be very stressful on turf, is a time-consuming process, and is traditionally performed on golf courses in the spring or fall when weather stress and traffic are lower (Bishop, 1990).

High pressure water injection cultivation was introduced by the Toro Company, Minneapolis, MN, as a method to cultivate turf while minimizing playing surface disturbance (Murphy, 1990). This cultivation tool is called the Hydroject 3000^m. In contrast to hollow tine cultivation, water injection offers the potential for routine cultivation during periods of high site usage and environmental stresses (Vavrek, 1992).

Water injection, shown to have many beneficial effects on soil physical properties, is a cultivation technique employed by some golf course superintendents. Water injection cultivation increases large macropores compared to untreated turf, and is equal or superior to hollow tine cultivation in improving bulk density, porosity, and saturated hydraulic

conductivity (Murphy, 1990). There is no effect of WIC on clipping yield, rooting, and stand density, while turf treated with hollow tine cultivation exhibits lower clipping yields, in addition to a rooting and stand density decrease .

The effects of both WIC and HTC dissipate over time, especially on high traffic sites. Following cultivation, the soil gradually settles back into place and continued traffic recompacts the soil (Murphy and Rieke, 1990). This demonstrates the need for a regular cultivation program on turf in these situations. Little research has been performed in regard to a regular cultivation program using WIC on high traffic sites. Murphy and Rieke (1992) showed WIC to lower peak deceleration values (g_{max}) with the Clegg soil impact tester by up to 23% on a practice putting green immediately following treatment. They pointed out however, that the response lasted less than 2 weeks in duration. The objectives of this research were to conduct a frequent, regular water injection cultivation program on high traffic sites and determine the effect this program has on turf quality and impact absorption values (g_{max}).

Materials and Methods

The study was conducted at two different sites on the campus of Michigan State University. The first site was a practice putting green at the Forest Akers East golf course. The site consisted of a mixed stand of several creeping bentgrasses (*Agrostis palustris* Huds.) and annual bluegrass (*Poa annua* L. var. *reptans*) grown on a loamy sand soil containing 79.3% sand, 13.0% silt, and 7.7% clay with 4.5% organic matter. The green was maintained at a height of 4 mm. Topdressing was applied 2 times in 1992 and 3 times in 1993. Nitrogen was applied at 24.5 g N/m² in both 1992 and 1993. The study was initiated Jun., 1992.

Cultivation treatments at the Forest Akers site consisted of : (i) control; (ii) monthly application of high pressure water injection; and (iii) water injection cultivation applied every two weeks. Treatments were arranged in a randomized complete block design with

four replications. Treatments in 1992 were applied from 29 Jun. to 24 Aug. and in 1993, from 10 Jun. to 24 Sep. Treatment (ii) was applied 3 times in 1992 and 4 times in 1993. Treatment (iii) was applied 5 times in 1992 and 8 times in 1993. Water injection treatments were applied using the Hydroject 3000^m. Plot size was approximately 4.5 by 1.5 meters. Water was injected to an average depth of 110 mm at 21 MPa through 1.2 mm orifices. Nozzles on the unit were 76 mm apart and injection holes were spaced 75 mm apart. Average spacing of the injection holes was approximately 75 by 75 mm on all dates treatments were performed.

Turfgrass quality was evaluated on a scale from 1 to 9 with 1 being brown, 5 minimum acceptable, and 9 excellent. Monthly ratings were taken in both 1992 and 1993 from mid- May to mid-September.

Surface hardness was evaluated using the Clegg soil impact tester (Clegg, 1976). A 2.25 kg hammer, or missile, was dropped from a height of 60 cm (Rogers and Waddington, 1990a). Five measurements at different locations within the plot were taken on each plot on each date. Readings were recorded as peak deceleration (gmax) of the missile. At the time of taking the surface hardness measurements, 3 soil plugs approximately 12 cm³ each were taken from each plot and combined into a representative sample for each replication to determine gravimetric moisture content of the soil. On dates cultivation treatments were applied, soil moisture samples were taken both before and after treatment. In 1992 surface hardness readings taken on 14 separate dates which began 8 Jul. were taken at three to four day intervals until 24 Aug. In 1993 surface hardness readings taken on 26 different dates were taken at three to eight day intervals from 10 Jun. to 24 Sep.

Stimpmeter readings were taken using a USGA stimpmeter (Radko, 1980), and were evaluated before and after each cultivation treatment in 1993. On each plot, 3 readings in both lengthwise directions were taken for a total of 6 readings per plot. Stimpmeter readings were taken on five separate dates in 1993.

The second site was Beal Horticultural Gardens, a public garden which receives intensive foot traffic and is located near the library. This site was divided into two sections, the first being a native sandy loam soil containing 60.6% sand, 21.3% silt, and 18.1% clay with 4.0% organic matter. The second was a modified soil consisting of approximately 10 cm of a loamy sand soil overlying approximately 30 cm of coarse sand. This surface soil was originally the native soil described above, but in the process of soil modification the texture was changed to a loamy sand containing 79.9% sand, 11.0% silt, and 9.1% clay with 3.2% organic matter. Both sections consisted of a mix of Kentucky bluegrass, perennial ryegrass, and annual bluegrass, with small amounts of bermudagrass (*Cynodon dactylon* L.) and creeping bentgrass. The turf was maintained at a height of 62 mm. Adequate fertilization and irrigation were applied to prevent stress. The study was initiated 29 Jun., 1992.

Cultivation treatments at the Beal Horticultural gardens site consisted of: (i) control ; (ii) one pass of the water injection unit over a plot area; (iii) two passes of the water injection unit over a plot area. Treatments (i)-(iii) were performed on the same plots in both 1992 and 1993. A fourth treatment initiated in 1993 was hollow tine cultivation. Treatments (ii) and (iii) were applied using the Hydroject 3000^m. Water injection treatments in 1992 were applied 3 times at 2 to 3 week intervals from 29 Jun. to 23 Aug., and 7 times in 1993 at 2 to 4 week intervals from 10 Jun. to 15 Sep. Plot size was approximately 3 by 1.5 meters. Hole spacing was approximately 75 by 75 mm. Hollow tine treatments were performed 2 times in 1993 using a Jacobsen (Jacobsen division of Textron, Inc., Racine, WI) greens aerator with 9.4 mm diameter tines on 10 Jun. and 15 Sep., 1993. Tines aerated to an average depth of 50 mm. Hole spacing was approximately 50 by 70 mm and soil cores were left on the surface of plot areas on both dates. Treatments on both sections at Beal Gardens were arranged in a completely randomized design with 2 replications per treatment.

Turfgrass quality was evaluated on a scale from 1 to 9 with 1 being brown, 5 acceptable, and 9 excellent. Ratings in 1992 were taken on 15 Jul., 6 Aug., and 23 Aug. Monthly ratings in 1993 began in mid-May and were taken until mid-September.

Surface hardness was evaluated using the Clegg soil impact tester and soil moisture was determined as described above. In 1992, surface hardness readings were taken on 12 different dates beginning 15 Jul. and were taken at 3 to 5 day intervals until 23 Aug. In 1993, surface hardness readings were taken on 27 different dates at 3 to 11 day intervals from 10 Jun. to 24 Sep.

Hole depths were measured following water injection cultivation treatments on 29 Jun., 15 Jul., 6 Aug., and 23 Aug., 1992, and 10 Jun., 24 Jun., 23 Jul., 31 Aug., and 15 Sep., 1993. Depth was measured by placing a 2 mm diameter steel rod to the bottom of each injection hole. Six measurements were taken from each plot on each date measurements were taken.

All data were subjected to analysis of variance and means were separated using Fisher's protected LSD procedure at the 0.05 level of probability.

Results and Discussion

Forest Akers Site

Turf quality ratings for 1992 and 1993 are summarized in Tables 3.1 and 3.2, respectively. Quality of turf at this site was generally acceptable, despite high traffic. No effects were seen from water injection cultivation in terms of quality improvement or degradation, as on only one date were there significant differences among treatments. Ratings from 12 May, 1993 revealed slightly higher quality ratings in plots receiving the WIC 2x monthly treatment. It should be noted that traffic patterns were inconsistent at this site due to frequent changings of golf cup sites within the plot area. These alternating traffic patterns may have produced variability within a treatment block, making statistical differences among treatments less apparent.

Table 3.1 : Turfgrass quality ratings of a creeping bentgrass / annual bluegrass putting green. Forest Akers East Golf Course. 1992. 9 = Excellent, 5 = acceptable, 1 = brown.

Treatment	Date				
	24 Jun	8 Jul	6 Aug	23 Aug	8 Sep
check	6.1 a [^]	6.2 a	6.5 a	6.6 a	6.6 a
HJ 1x monthly	6.0 a	6.5 a	7.0 a	6.7 a	6.2 a
HJ 2x monthly	6.2 a	6.5 a	6.5 a	7.2 a	6.9 a

[^]Numbers followed by the same letter are not significantly different at the 0.05 level of probability using Fisher's PLSD test.

Table 3.2 : Turfgrass quality ratings of a creeping bentgrass / annual bluegrass putting green. Forest Akers East Golf Course. 1993. 9 = Excellent, 5 = acceptable, 1 = brown.

Treatment	Date				
	12 May	10 Jun	8 Jul	12 Aug	15 Sep
check	5.3 b [^]	6.5 a	6.3 a	5.5 a	5.5 a
HJ 1x monthly	5.8 ab	6.8 a	6.0 a	5.8 a	5.8 a
HJ 2x monthly	6.0 a	6.8 a	6.5 a	6.0 a	5.5 a

[^]Numbers followed by the same letter are not significantly different at the 0.05 level of probability using Fisher's PLSD test.

Clegg surface hardness readings are given in Tables 3.3 and 3.4 for 1992 and 1993, respectively. A consistent pattern was seen in both years. Surface hardness tended to increase with decreasing soil moisture. This is consistent with data from Rogers and Waddington (1990b). Surface hardness readings taken immediately following treatment, on 9 of 10 dates in 1992 and 1993, revealed significantly lower g_{max} values in plots which had received water injection cultivation as compared to control plots. Surface hardness readings taken immediately following treatment with water injection cultivation were an average of 14.5% lower than those taken immediately preceding treatment. This shows water injection lowered surface hardness values.

It may be argued that this could have been a result of increased soil moisture from water injection. Field calibration of the Hydroject at the particular hole spacing used showed an average injection of 17.5 liters per square meter. The addition of this water to the water already present in the soil may have affected soil moisture. As a result, soil hardness values may have been affected. Soil moisture for each individual plot was not measured directly in this study, as only an average soil moisture content for each replication was taken (three 12 cm³ soil plugs from each plot combined into a representative sample). Average soil moisture values did in fact increase after WIC treatments on 8 of 9 dates in 1992 and 1993. These increases ranged from 0.2 to 0.8%, averaging 0.4%. Therefore, soil moisture content is likely increased by water injection and the lowered surface hardness values seen are possibly a combination of this and loosening of soil from the penetrating action of the water injection jets. However, since lowered surface hardness values from water injection frequently lasted several days, the majority of the effect is most likely due to loosening of soil. Differences in soil moisture would most likely not last and would reach equilibrium in a short period of time. The trend of lowered surface hardness after treatment can be easily seen in Figures 3.1 (1992) and 3.2 (1993). On only one date (22 Jul., 1992) were significant differences in surface hardness found among treatments immediately

Table 3.3. Surface Hardness Readings (Clegg - 2.25 kg hammer). Forest Akers East Golf Course practice green. Loamy Sand Soil.1992.

Treatment	Date																
	8-Jul*	8-Jul~	13-Jul	16-Jul	20-Jul	22-Jul*	22-Jul~	26-Jul	31-Jul	3-Aug	6-Aug*	6-Aug~	10-Aug	14-Aug	18-Aug	21-Aug	
	Surface hardness, gmax																
Control	73a^	74a	78a	81a	84a	88a	88a	84a	85a	82a	78a	78a	79a	81b	86a	86a	
Hydroject 1x month	76a	75a	77a	81a	85a	74b	91a	81ab	84ab	80a	80a	77a	77a	85a	85a	87a	
Hydroject 2x month	71a	57b	66b	71b	79b	69b	84b	78b	81b	79a	78a	67b	70b	76c	81b	86a	
GSMC(%)	25.7	25.9	24.2	24.1	22.9	21.6	21.6	22.1	21.6	20.7	20.7	20.9	21.7	21.5	20.8	20.1	19.6

*Readings taken preceding Hydroject treatment.

~ Readings taken following Hydroject treatment.

^ Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

Table 3.4. Surface Hardness Readings (Clegg - 2.25 kg hammer). Forest Akers East Golf Course practice green. Loamy Sand Soil. 1993.

Treatment	Date															
	10-Jun*	10-Jun~	14-Jun	18-Jun	21-Jun	24-Jun*	24-Jun~	28-Jun	1-Jul	6-Jul	8-Jul*	8-Jul~	12-Jul	23-Jul*	23-Jul~	26-Jul
	Surface hardness, gmax															
Control	66a^	61a	65b	70b	64a	79a	79a	80a	79a	74a	67a	67a	70a	82a	82a	65b
Hydroject 1x month	67a	58b	69a	71ab	65a	80a	80a	81a	80a	73a	69a	59b	68a	85a	85a	70a
Hydroject 2x month	67a	63a	70a	75a	65a	82a	69b	75b	80a	73a	68a	58b	67a	86a	70b	65b
GSMC(%)	22.1	22.5	23.1	23.1	26.7	22.7	22.9	21.9	22.1	24.5	26.9	26.9	24.1	21.7	22.3	25.1

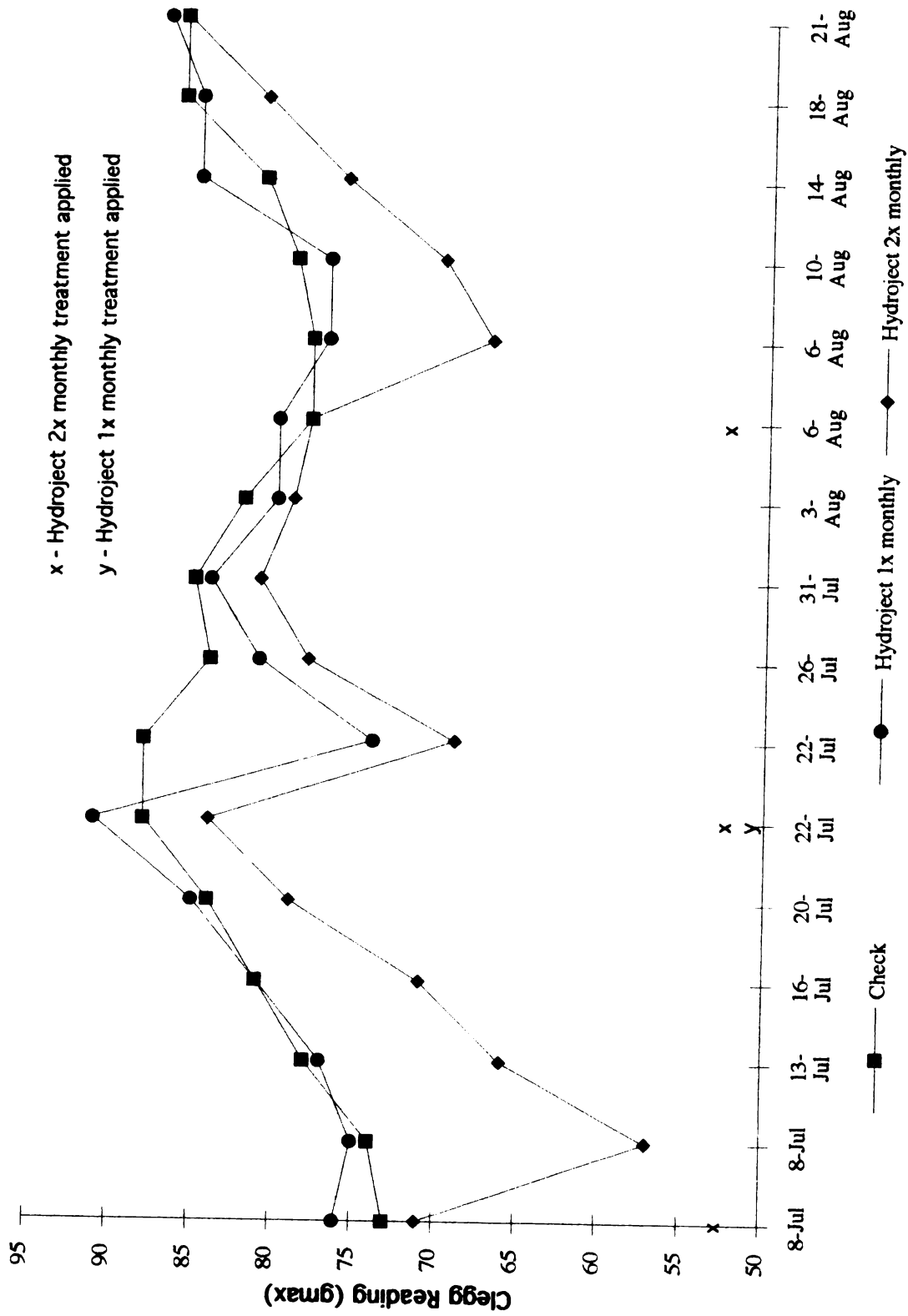
57

Treatment	30-Jul	3-Aug	5-Aug	5-Aug*	12-Aug	16-Aug	23-Aug	26-Aug*	26-Aug~	30-Aug	2-Sep	7-Sep	15-Sep*	15-Sep~	17-Sep	21-Sep
	Surface hardness, gmax															
Control	82ab	79a	73a	73a	77a	70a	74ab	72a	72a	69a	73b	78a	75a	75a	78a	72a
Hydroject 1x month	83a	80a	74a	64b	77a	71a	72b	70a	70a	69a	76a	82a	74a	67b	73b	72a
Hydroject 2x month	79b	77a	74a	60c	76a	70a	77a	71a	62b	65b	73b	79a	72a	67b	72b	70a
GSMC(%)	23.1	23.7	24.1	24.5	23.1	22.1	24.3	23.7	24.1	22.2	24.2	23.7	24.9	25.2	24.1	24.7

*Readings taken preceding Hydroject treatment.

~Readings taken following Hydroject treatment.

[^] Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test



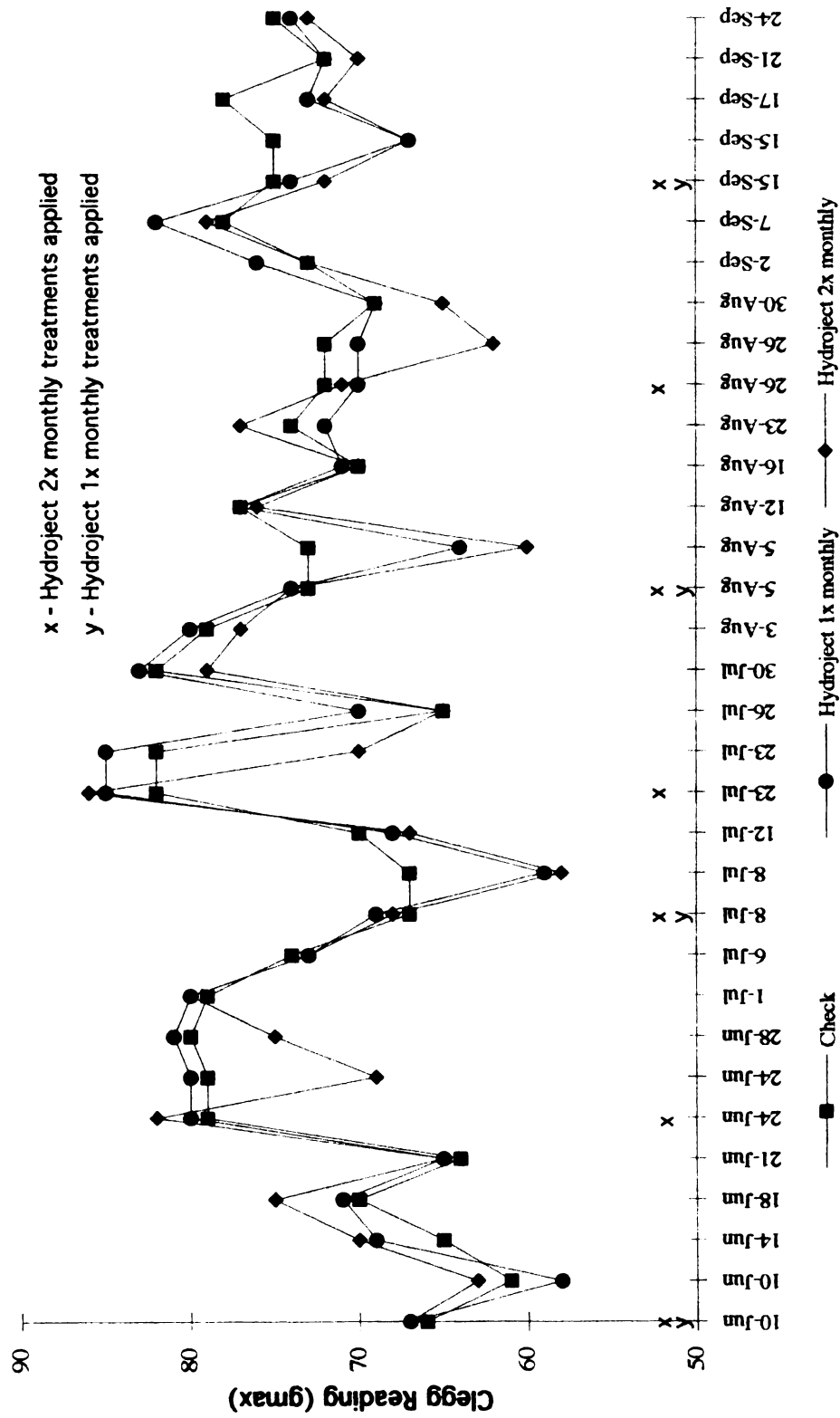


Figure 3.2. Surface Hardness Readings (Clegg). Forest Akers East Golf Course practice green. 1993.

preceding treatment, showing lowered surface hardness due to water injection cultivation dissipated after several days.

Stimpmeter readings taken prior to and following water injection cultivation treatments in 1993 are given in Table 3.5. As with surface hardness, treatment with water injection cultivation produced a significant effect on stimpmeter readings. On all dates, stimpmeter readings taken immediately following treatment revealed significantly higher values in plots which had received water injection cultivation as compared to control plots. On no dates were differences among treatments evident prior to treatment. This increase in stimpmeter readings is likely caused by a rolling or smoothing effect from the Hydroject machine passing over the plot area. Duration of this effect was not tested in this study, but it did not last the 2 to 3 week interval between treatments.

Beal Gardens Site

Turf quality ratings for both native and modified soils are summarized in Tables 3.6 (1992) and 3.7 (1993). As at the Forest Akers site, the turf received a high amount of traffic. Quality ratings taken on turf grown on the native soil were generally 1 to 2 rating points higher than those taken on turf grown on the modified soil. On no dates on either soil, however, were differences in quality among treatments apparent.

Data for depth of water injection channels following treatment is given in Tables 3.8 and 3.9 for 1992 and 1993, respectively. Injection channels in the native soil were an average of 4.5 cm longer than those seen in the modified soil. On all dates in both soils, injection channels in plots receiving 2 passes of water injection cultivation were significantly longer than those in plots receiving only one pass of water injection cultivation. Apparently, the initial pass provided enough of a loosening effect on the soil, such that water injection jets in the second pass over the plot area penetrated the soil to a deeper depth. Two passes of water injection produced an average channel length increase of 5.0 centimeters in the native soil and 5.1 centimeters in the modified soil. This increased

Table 3.5. Stimpmeter readings before and after water injection treatment. Forest Akers East Golf Course practice green. 1993.

	<u>Stimpmeter reading, meters</u>		
	<u>before</u>	<u>after</u>	<u>% increase</u>
<i><u>July 8</u></i>			
Check	2.13 a [^]	2.16 b	1.4
HJ 1x monthly*	2.07 a	2.53 a	22.2
HJ 2x monthly*	2.04 a	2.55 a	25.0
<i><u>July 23</u></i>			
Check	2.30 a	2.25 b	-
HJ 1x monthly	2.28 a	2.29 b	-
HJ 2x monthly*	2.31 a	2.77 a	19.9
<i><u>August 5</u></i>			
Check	2.50 a	2.60 b	4.0
HJ 1x monthly*	2.54 a	2.93 a	15.3
HJ 2x monthly*	2.60 a	2.90 a	11.5
<i><u>August 26</u></i>			
Check	2.22 a	2.22 b	-
HJ 1x monthly	2.25 a	2.25 b	-
HJ 2x monthly*	2.20 a	2.74 a	24.5
<i><u>September 15</u></i>			
Check	2.07 a	2.07 b	-
HJ 1x monthly*	2.05 a	2.59 a	26.3
HJ 2x monthly*	2.04 a	2.68 a	31.3

* Water injection cultivation treatment performed

[^] Numbers followed by the same letter are not significantly different at the 0.05 level of probability using Fisher's PLSD test.

Table 3.6 Turfgrass Quality Ratings Beal Gardens. 1992. 9=Excellent, 5=acceptable, 1=brown turf.

<u>Native Soil</u>	<u>Date</u>		
Treatment	15 Jul	6 Aug	23 Aug
Check	6.2 a [^]	6.2 a	6.0 a
HJ 1x pass	6.7 a	6.2 a	6.2 a
HJ 2x pass	6.5 a	6.0 a	6.2 a
 <u>Modified Soil</u>			
Treatment			
Check	4.0 a	4.5 a	4.0 a
HJ 1x pass	4.0 a	4.5 a	4.0 a
HJ 2x pass	4.0 a	4.5 a	4.0 a

[^] Numbers followed by the same letter are not significantly different at the 0.05 level of probability using Fisher's PLSD test.

Table 3.7. Turfgrass Quality Ratings Beal Gardens. 1993. 9=excellent, 5=acceptable, 1=brown turf.

<u>Native Soil</u>	<u>Date</u>				
<u>Treatment</u>	<u>15 May</u>	<u>10 Jun</u>	<u>12 Jul</u>	<u>12 Aug</u>	<u>9 Sep</u>
Check	5.5 a^	6.0 a	6.5 a	6.5 a	6.0 a
HJ 1x pass	5.5 a	6.0 a	6.5 a	7.0 a	6.5 a
HJ 2x pass	5.0 a	6.0 a	6.5 a	6.5 a	6.5 a
HTC	*	6.0 a	6.0 a	6.5 a	6.0 a
 <u>Modified Soil</u>					
<u>Treatment</u>					
Check	4.0 a	5.0 a	5.5 a	4.5 a	4.5 a
HJ 1x pass	4.5 a	5.0 a	6.0 a	5.5 a	4.5 a
HJ 2x pass	5.0 a	5.0 a	6.0 a	5.5 a	5.0 a
HTC	*	5.0 a	5.5 a	5.0 a	4.5 a

* Hollow tine treatment initiated 10 Jun., 1993

^ Numbers followed by the same letter are not significantly different at the 0.05 level of probability using Fisher's PLSD test.

Table 3.8 Depth of injection holes following Hydroject treatment. Beal Gardens. 1992.

Native Soil		<u>Hole depth, centimeters</u>			
Treatment	29 Jun	15 Jul	6 Aug	23 Aug	
HJ 1x pass	10.5 [^]	14.3	13.0	12.0	
HJ 2x pass	14.5	20.3	17.3	18.0	
Significance	*	*	*	*	
Modified Soil					
Treatment					
HJ 1x pass	7.8	9.5	7.5	7.5	
HJ 2x pass	11.5	16.8	12.0	12.5	
Significance	*	*	*	*	

[^] Significance was tested at the 0.05 level of probability using Fisher's PLSD test.

Table 3.9. Depth of injection holes following Hydroject treatment. Beal Gardens. 1993.

Native Soil	Hole depth, centimeters				
	10 Jun	24 Jun	23 Jul	31 Aug	15 Sep
Treatment					
HJ 1x pass	10.3 [^]	12.0	12.5	11.0	10.3
HJ 2x pass	14.0	17.0	16.5	15.5	17.5
Significance	*	*	*	*	*
Modified Soil					
Treatment					
HJ 1x pass	8.5	8.5	8.8	8.0	8.8
HJ 2x pass	12.5	13.5	12.0	13.0	17.5
Significance	*	*	*	*	*

[^] Significance was tested at the 0.05 level of probability using Fisher's PLSD test.

channel depth with two passes of water injection cultivation is important, as on some highly compacted sites, one pass of water injection cultivation may not be providing adequate compaction relief due to lack of sufficient penetration of water injection jets into the soil. Several passes of water injection on these sites may ultimately be necessary to reach a desired depth. The effect this practice may have on soil structure is not known, however, and was not investigated in this study. There was, however, no apparent loss in turf quality after 18 passes in two years for the 2x pass treatment.

Clegg surface hardness readings for the native soil are given in Tables 3.10 (1992) and 3.11 (1993). Data is summarized in Figures 3.3 and 3.4 for 1992 and 1993, respectively. Unlike data obtained at the Forest Akers site, results were inconsistent. Surface hardness readings taken on plots immediately following treatment with 1 pass of water injection cultivation were an average of only 7.1% lower than those taken immediately preceding treatment. On three dates, out of a total of eight measurements (24 Jun., 8 Jul., and 5 Aug., 1993), little or no difference was seen between readings taken prior to and readings taken following treatment with one pass of water injection. Soil moisture was increased following WIC cultivation on 5 of 8 dates in 1992 and 1993, with increases ranging from 0.1 to 0.6% averaging 0.35% . On dates where differences in soil hardness were seen between readings taken before and readings taken after treatment, this increased soil moisture may be playing a role in the lowering of surface hardness values. However, soil moisture in this soil was fairly high, with an average of 31.7% soil moisture in 1992 and 1993. Due to this high soil moisture, surface hardness readings may have been lowered to the point where treatment with water injection cultivation produced little effect on surface hardness.

Overall, Clegg readings were fairly consistent with the exception of the period from 30 Jul. to 12 Aug. A power outage caused damage to the irrigation system and no supplemental irrigation was applied. Soil moisture values decreased, and surface hardness values rose to higher than normal levels. Except for this two week period, surface

Table 3.10. Surface Hardness Readings (Clegg - 2.25 kg hammer). Beal Gardens. Sandy Loam Soil.1992.

Treatment	15-Jul~	19-Jul	23-Jul	27-Jul	2-Aug	6-Aug*	6-Aug~	9-Aug	12-Aug	15-Aug	18-Aug	21-Aug	23-Aug
	Surface hardness, gmax												
Control	57a^	66a	67a	71a	72a	81a	80a	79a	80a	75a	76a	73a	76a
W/C 1 pass	46b	57b	62b	65b	70a	75b	64b	70b	71b	69b	73b	74a	71a
W/C 2 passes	43b	59b	60b	67b	69a	77b	66b	70b	71b	68b	72b	71a	80a
GSMC(%)	35.7	31.5	30.1	30.1	29.5	28.5	28.8	27.6	27.5	27.1	28.5	28.4	25.4

*Readings taken preceding Hydroject treatment

~Readings taken following Hydroject treatment

^Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test

Table 3.11. Surface Hardness Readings (Clegg - 2.25 kg hammer). Beal Gardens. Sandy Loam Soil.1993.

Treatment	10-Jun*	14-Jun	18-Jun	21-Jun	24-Jun*	28-Jun	1-Jul	6-Jul	8-Jul*	8-Jul~	12-Jul	23-Jul*	23-Jul~	26-Jul
	Surface hardness, gmax													
Control	54a^	55a	60a	62a	52a	64a	66ab	51a	61a	61a	54a	57a	57a	57a
W/C 1 pass	55a	49b	54b	62a	48b	65a	68a	48a	62a	62a	53a	54a	50bc	54a
W/C 2 passes	57a	47bc	53b	59a	50ab	60a	67ab	47a	62a	58a	52a	54a	46c	50b
HTC"	56a	44c	51b	55b	45c	61a	61b	47a	61a	61a	50a	54a	53ab	55a
GSMC(%)	35.8	35.8	36.1	34.7	38.8	32.1	32.2	30.1	31.8	38.4	34.1	34.3	34.6	36.9

68

Treatment	30-Jul	3-Aug	5-Aug*	5-Aug~	12-Aug	16-Aug	23-Aug	26-Aug	31-Aug*	31-Aug~	2-Sep	9-Sep	15-Sep*	15-Sep~	17-Sep	21-Sep
	Surface hardness, gmax															
Control	78a	89a	99a	100a	65a	68a	60a	69a	62a	63a	62a	67a	58a	58a	58a	58a
W/C 1 pass	74ab	81b	95a	93a	62ab	67ab	60a	66ab	62a	56b	59a	62b	56a	51b	52b	54ab
W/C 2 passes	69b	79b	87a	81b	60b	65ab	60a	63b	59a	52c	54b	59b	54a	50bc	51b	51b
HTC "	72b	81b	89a	90ab	61b	63b	60a	65ab	60a	61a	62a	62b	57a	47c	48b	50b
GSMC(%)	26.6	24.5	20.5	21.1	32.9	30.6	30.3	33.5	31.6	32.2	33.2	32.5	34.3	34.3	37.1	37.1

*Readings taken preceding Hydroject treatment

~Readings taken following Hydroject treatment

" HTC treatments applied 10 Jun. and 15 Sep.

^Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test

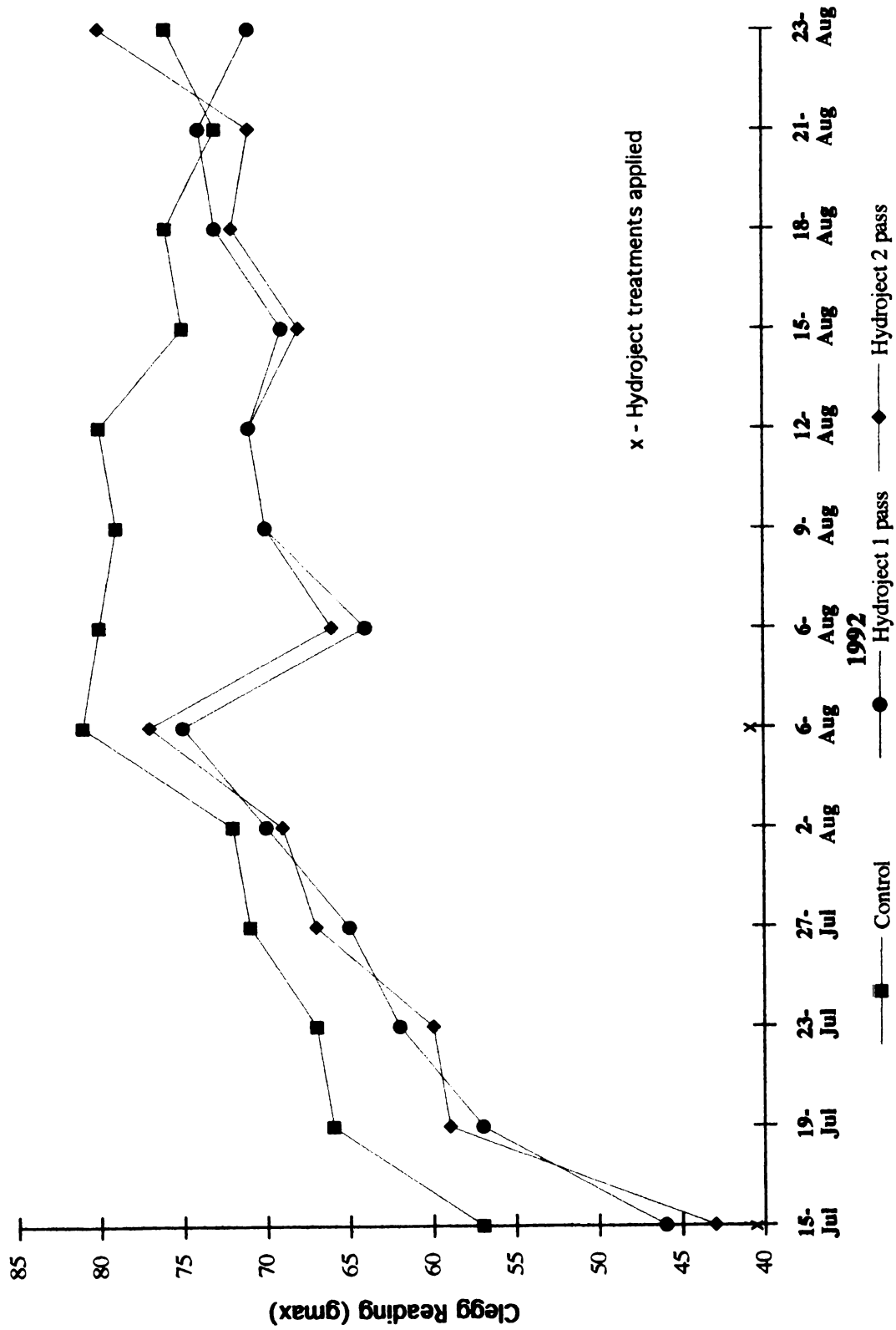


Figure 3.3. Surface Hardness Readings. (Clegg). Sandy Loam Soil. Beal Gardens. 1992

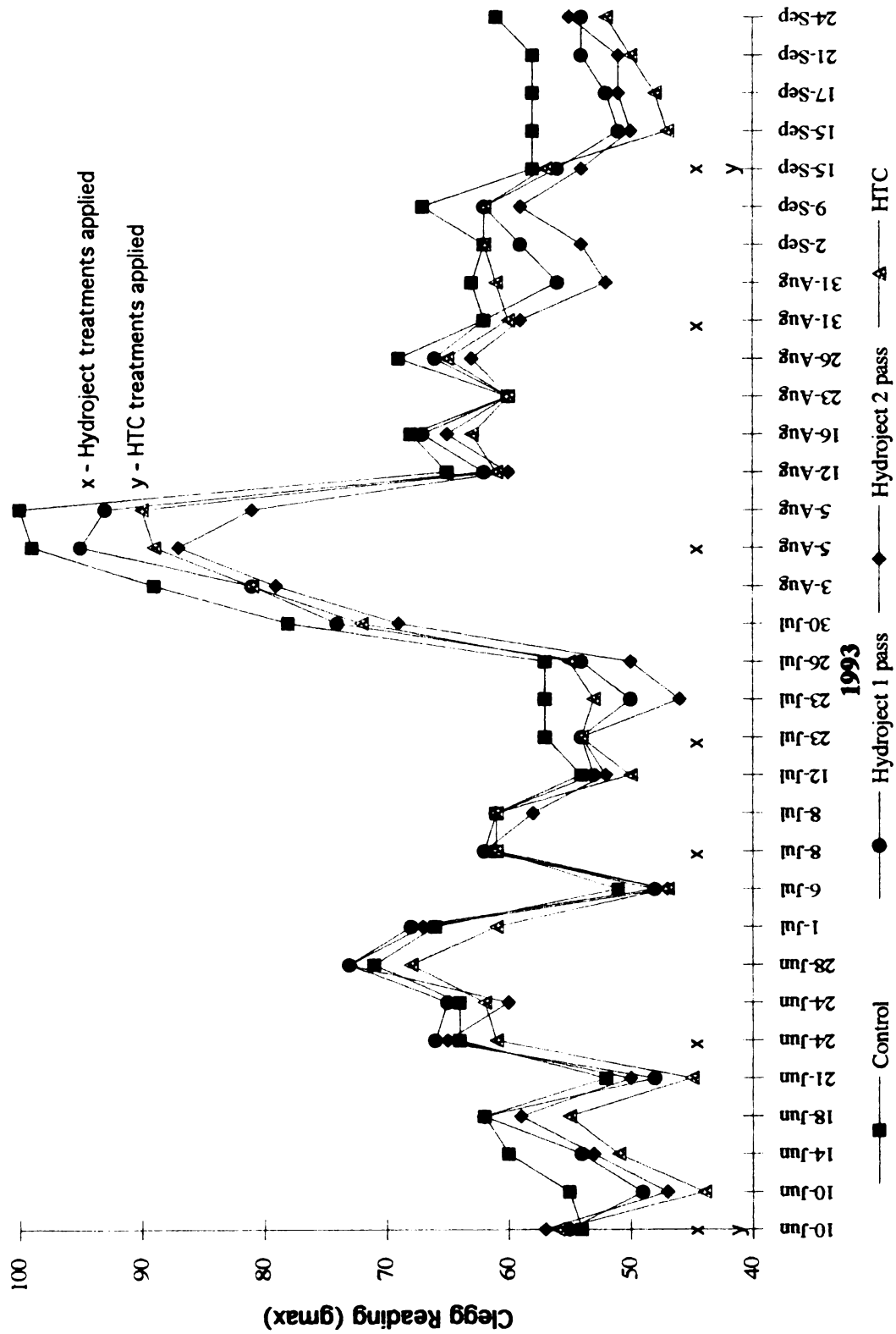


Figure 3.4. Surface Hardness Readings. (Clegg). Sandy Loam Soil. Beal Gardens. 1993.

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hardness readings were generally lower and soil moisture values were generally higher than those found at the Forest Akers site, perhaps due to more frequent irrigation. This also may have been due to differences in soil texture, as the Forest Akers soil contained more sand and may have been more subject to compaction.

Surface hardness readings taken following hollow tine cultivation were an average of 19.5% lower than those taken immediately preceding treatment. Lowered surface hardness due to both forms of cultivation dissipated over time, however, as was seen at the Forest Akers site. Analysis of surface hardness immediately preceding treatment showed that on only one date (6 Aug., 1992) were significantly lower surface hardness readings found in plots receiving water injection cultivation compared to control plots. Immediately following treatment with hollow tine cultivation on 10 Jun., 1993, lower surface hardness readings were seen compared to control plots. By 24 Jun., 1993, differences in surface hardness between these two treatments were no longer evident.

Clegg surface hardness readings for the modified soil are given in Tables 3.12 (1992) and 3.13 (1993). Data is summarized in Figures 3.5 and 3.6 for 1992 and 1993, respectively. Surface hardness readings taken immediately following treatment with 1 pass of water injection cultivation were an average of 20% lower than surface hardness readings taken immediately preceding treatment and those taken immediately following treatment with 2 passes of water injection cultivation were an average of 19.1% lower. These were averages of 1992 and 1993 data combined. Surface hardness readings were generally higher and soil moisture values were generally lower (22.8% average in modified vs. 31.7% average in native) than those found in the native soil. In the process of soil modification, some of the underlying sand was apparently mixed with the native soil and soil texture was changed to a loamy sand. This explains the lower soil moisture readings seen, as well as the higher average surface hardness readings. As with both the Forest Akers and Beal Gardens native soil site, soil moisture was frequently increased following treatment with water injection cultivation (7 of 8 dates in 1992 and 1993). These increases

Table 3.12. Surface Hardness Readings (Clegg - 2.25 kg hammer). Beal Gardens. Loamy Sand Soil.1992.

Treatment	15-Jul~	19-Jul	23-Jul	27-Jul	2-Aug	6-Aug*	6-Aug~	9-Aug	12-Aug	15-Aug	18-Aug	21-Aug	23-Aug
	Surface hardness, gmax												
Control	87a^	93a	92a	100a	111a	117a	112a	101a	107a	104a	114a	118a	122a
WIC 1 pass	65b	83b	85b	99a	105b	107a	84b	86b	86b	85b	86b	103b	108b
WIC 2 passes	56b	83b	82b	90b	97b	97b	78b	85b	83b	85b	82b	89c	92c
GSMC(%)	23.4	23.1	23.1	22.9	21.6	22.1	22.9	20.7	20.8	21.1	21.7	21.5	20.8

*Readings taken preceding Hydroject treatment

~Readings taken following Hydroject treatment

^Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test

Table 3.13. Surface Hardness Readings (Clegg - 2.25 kg hammer). Beal Gardens. Loamy Sand Soil.1993.

Treatment	10-Jun*	10-Jun~	14-Jun	18-Jun	21-Jun	24-Jun*	24-Jun~	28-Jun	1-Jul	6-Jul	8-Jul*	8-Jul~	12-Jul	23-Jul*	23-Jul~	26-Jul
	Surface hardness, gmax															
Control	83a^	81a	98a	94a	79a	88a	89a	114a	98a	91a	116a	115a	91a	94a	95a	85a
Hydroject 1 pass	81a	62b	82b	79b	74a	90a	69bc	93b	91ab	80b	103ab	77c	77ab	88ab	71b	75b
Hydroject 2 passes	81a	62b	75b	74bc	71ab	78ab	62c	85b	78b	68c	84c	61c	66b	74c	60c	65b
HTC "	78a	55b	65c	69c	64b	75b	76b	85b	79b	78bc	97bc	97b	72b	81bc	81b	72b
GSMC(%)	24.7	25.1	25.1	24.3	24.7	26.1	26.5	22.7	23.1	25.6	24.1	24.2	24.5	22.7	23.2	22.9
Treatment	30-Jul	3-Aug	5-Aug	5-Aug~	12-Aug	16-Aug	23-Aug	26-Aug	31-Aug*	31-Aug~	2-Sep	9-Sep	15-Sep*	15-Sep~	17-Sep	21-Sep
	Surface hardness, gmax															
Control	101a	125a	92a	92a	90a	104a	90a	96a	85a	86a	91a	90a	84a	88a	89a	91a
Hydroject 1 pass	89b	110b	88a	72bc	82a	84b	77b	83b	80b	73b	77b	83ab	83ab	66b	70b	78b
Hydroject 2 passes	79b	102b	79a	61c	70b	78b	79ab	80b	72b	68b	72b	75b	77ab	66b	67b	70bc
HTC "	87b	111ab	85a	86ab	86a	96a	87ab	88ab	87a	86a	87a	83a	76b	49c	54c	64c
GSMC(%)	22.2	20.7	18.7	19.3	21.9	22.7	24.1	23.3	22.9	22.9	22.9	23.1	22.8	23.2	23.3	24.1

*Readings taken preceding Hydroject treatment

~Readings taken following Hydroject treatment

" HTC treatments applied 10 Jun. and 15 Sep.

^ Means within the same column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test

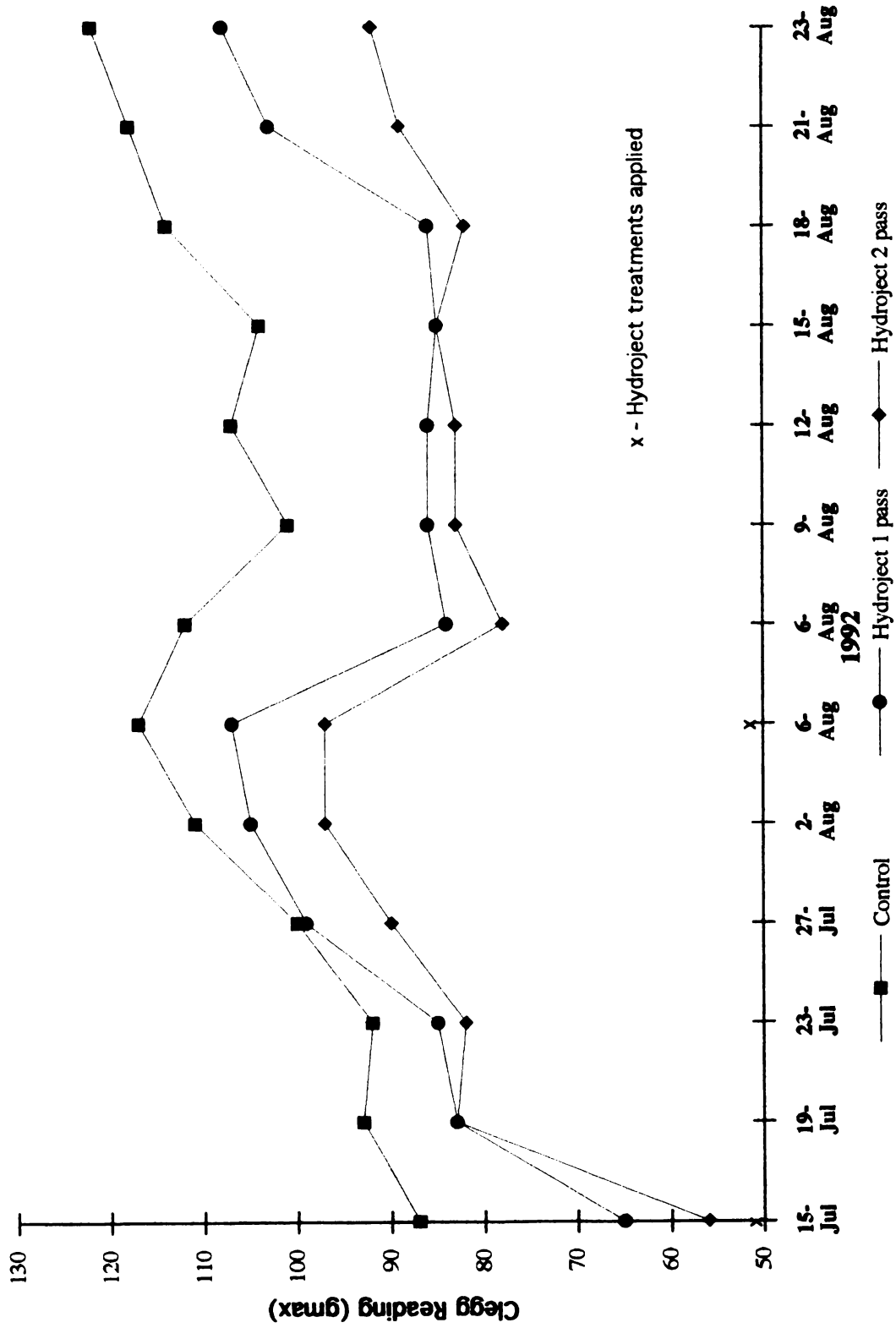


Figure 3.5. Surface Hardness Readings. (Clegg). Loamy Sand Soil. Beal Gardens. 1992.

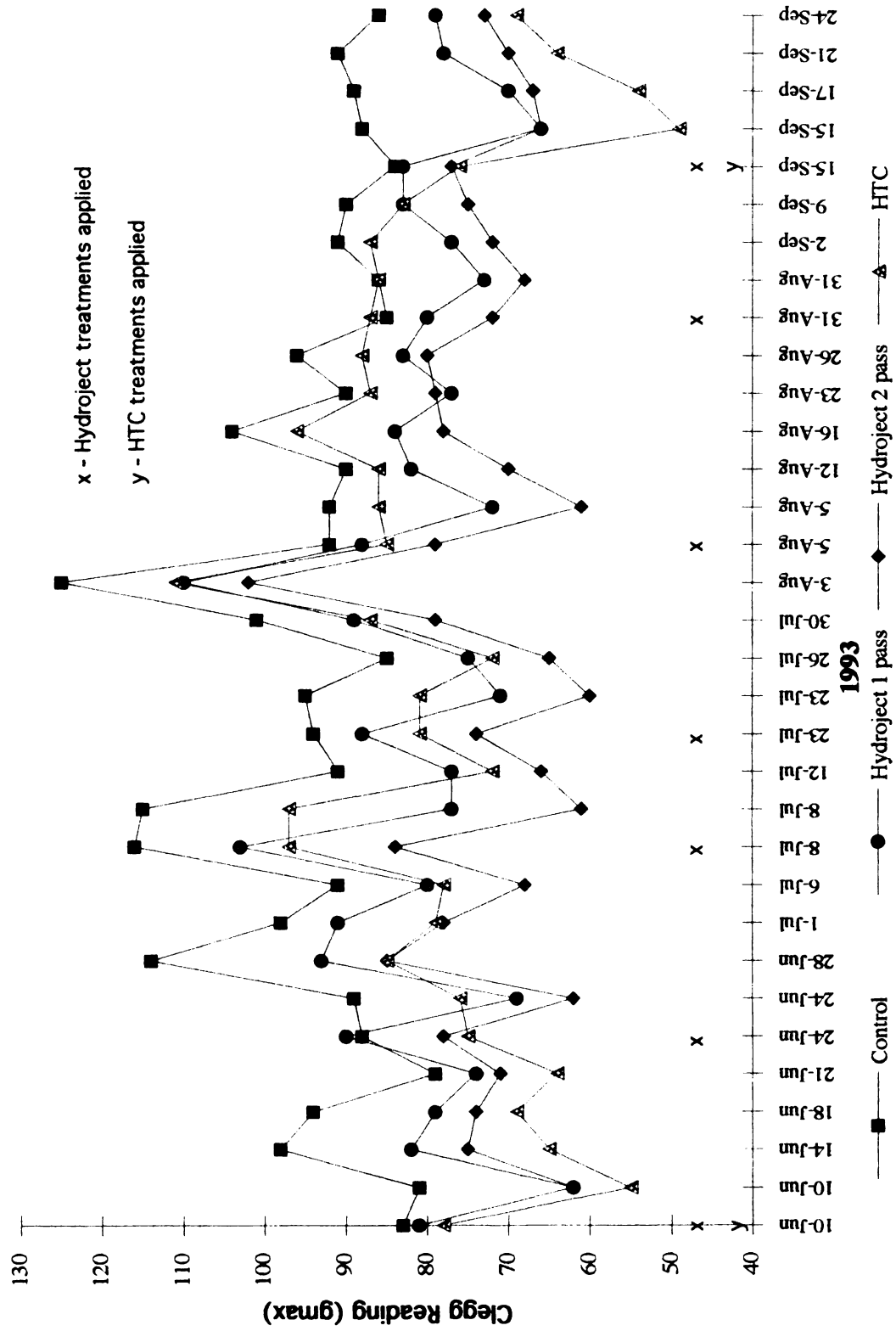


Figure 3.6. Surface Hardness Readings. (Clegg). Loamy Sand Soil. Beal Gardens. 1993.

ranged from 0.1 to 0.8%, averaging 0.4%. Again, it can be stated that this increase in soil moisture may be from WIC treatment, and may be partly responsible for the lowered surface hardness values following treatment. However, since lowered surface hardness values from water injection frequently lasted several days, the majority of the effect is most likely due to loosening of soil from the penetrating action of the water jets.

Surface hardness readings taken following hollow tine cultivation were an average of 32.5% lower than those taken immediately preceding treatment. Lowered surface hardness due to both forms of cultivation did dissipate over time, as was seen at the Forest Akers site and on the native soil. On this modified soil, however, the dissipation time was generally longer, especially with hollow tine cultivation. Immediately following treatment with hollow tine cultivation on 10 Jun., 1993 (Table 3.13), lower surface hardness values were seen compared to control plots. This difference between these two treatments persisted until 3 Aug., a period of almost 2 months.

Analysis of surface hardness readings immediately preceding treatment showed that on several dates, significantly lower surface hardness readings were found in plots receiving water injection cultivation compared to control plots. These differences were more frequently found between the control and the 2 pass water injection cultivation treatment, and were seen on 4 dates (6 Aug., 1992, 8 Jul., 23 Jul., 31 Aug., 1993). Between the control and water injection cultivation 1 pass treatments, these differences were seen on only one date (31 Aug., 1993). This gives evidence that 2 passes of water injection over a surface prolongs the effect this cultivation technique has on lowering surface hardness for this soil.

In summary, results of these studies show a frequent cultivation program on high traffic sites using high pressure water injection has no detrimental effects on turf quality. Quality ratings of control turf were equal to those of turf receiving water injection cultivation throughout the study. Water injection cultivation consistently lowered Clegg

surface hardness readings. Among the three sites, soil moisture was seen to increase following treatment with WIC on 80% of treatment dates. This may be evidence that the lowered surface hardness values seen following treatment are due to a combination of increased soil moisture and loosening of soil from the penetration action of the water injection jets. Soil moisture readings in this study were averages taken across all plots for each replication. However, based on the rate of water application (17 liters/m²) at the hole spacing used in this study, the calculated increase in soil moisture for each plot area was small. These increases ranged from 0.5% on the Forest Akers soil to 1.0% with 2 passes over the plot area on the Beal Gardens modified soil. It is difficult to say how much of the phenomenon of lowered surface hardness from water injection cultivation is due to increased soil moisture and how much is due to loosening of the soil.

Hollow tine cultivation also lowered surface hardness readings. The effect that these cultivation techniques had on lowering surface hardness, however, dissipated over time, although the duration of this effect was variable among the three soils. Relief of compaction resulted in lowered surface hardness, but this relief was limited in duration due to rapid recompacting of the soil. Differences in surface hardness between control plots and plots receiving water injection cultivation which were seen immediately following treatment on most occasions did not last the 2 week time period between water injection treatments. Surface hardness is only one parameter, however, and other meaningful tests such as bulk density, porosity, and hydraulic conductivity were not measured in this study. Regular cultivation is needed on high traffic sites. Water injection is a method of cultivation that can be frequently applied on high traffic sites, especially highly compacted portions of an athletic field or golf green. Water injection cultivation provides short term relief of compaction, while imparting minimal stress to the turf plant and playing surface. The ability to lower surface hardness with WIC could be an important tool for athletic turf managers in need of a way to decrease surface hardness without adding water to a field or core cultivating.

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APPENDIX

Table A : Available soil phosphorus (Olsen) levels at the thatch, 0 to 7.5, 7.5-15.0, and 15.0-22.5 cm soil levels, 1990-1993.

Depth	Annual treatment*	kg available P per hectare							
		Nov. 1990	Aug. 1991	Nov. 1991	Aug. 1992	Nov. 1992	Aug. 1993	Nov. 1993	
Thatch	Control	27c [^]	26c	17c	20d	17d	21d	25d	
	WIC Only	26c	28c	20c	21d	21d	21d	25d	
	5.3 g P/m ² surface	155a	68a	233a	146a	281a	128a	214a	
	5.3 g P/m ² inject	41bc	34c	43c	47c	74c	40c	99c	
	10.6 g P/m ² inject	68b	50b	103b	103b	129b	75b	149b	
0-7.5 cm	Control	29c	28c	28c	25d	26c	22d	26c	
	WIC Only	27c	28c	27c	27d	24c	20d	24c	
	5.3 g P/m ² surface	46ab	54ab	74b	90b	97b	92b	136b	
	5.3 g P/m ² inject	38bc	44b	72b	65c	87b	66c	131b	
	10.6 g P/m ² inject	50a	65a	130a	134a	142a	121a	177a	
7.5-15.0 cm	Control	46c	47c	40c	45c	43cd	36c	44c	
	WIC Only	52c	50c	43c	45c	40d	34c	41c	
	5.3 g P/m ² surface	47c	48c	47c	52c	59c	45c	55c	
	5.3 g P/m ² inject	68b	69b	104b	103b	118b	111b	155b	
	10.6 g P/m ² inject	97a	102a	144a	179a	176a	148a	205a	
15.0-22.5 cm	Control	56b	56b	49c	57c	53c	48c	57b	
	WIC Only	58ab	65ab	56bc	63bc	49c	49c	56b	
	5.3 g P/m ² surface	54b	57b	52bc	64bc	59bc	53c	57b	
	5.3 g P/m ² inject	63ab	64ab	65ab	74b	76b	72b	102a	
	10.6 g P/m ² inject	71a	75a	74a	90a	101a	93a	112a	

[^] Means within a column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

* Treatment dates (each applied at 1/2 rate): 18 Aug. and 13 Oct. 1990; 20 Aug. and 23 Sep. 1991; 11 Aug. and 2 Oct. 1992; 12 Aug. and 22 Sep. 1993.

Table B : Ammonium acetate extractable potassium at the 0 to 7.5, 7.5 to 15.0, and 15.0 to 22.5 cm soil levels, 1990-1993.

Depth	Annual treatment*	Oct. 1990	Oct. 1991	Jul. 1992	Oct. 1992	Jul. 1993	Oct. 1993
		kg available K/hectare					
0 - 7.5 cm	Control	117d ^a	104d	115d	119e	101d	108c
	WIC Only	125d	128d	112d	131de	112d	124c
	12.2 g K/m ² surface	198b	262b	206b	228c	221ab	237b
	12.2 g K/m ² inject	163bc	196c	164c	168d	149c	230b
	24.4 g K/m ² surface	297a	340a	266a	379a	252a	327a
	24.4 g K/m ² inject	191b	299ab	206b	273b	202b	336a
7.5 - 15 cm	Control	71d	68d	75c	58e	65c	67d
	WIC Only	76cd	94d	85c	78de	75c	84d
	12.2 g K/m ² surface	95bcd	124c	142b	108cd	127b	141c
	12.2 g K/m ² inject	114ab	162b	147b	130bc	122b	163bc
	24.4 g K/m ² surface	97bc	177b	202a	158b	174a	203b
	24.4 g K/m ² inject	138a	266a	222a	198a	178a	271a
15 - 22.5 cm	Control	68c	73c	80d	67b	69d	72d
	WIC Only	86ab	90bc	91cd	79b	78cd	86cd
	12.2 g K/m ² surface	87ab	92bc	105bcd	93b	97bcd	118bc
	12.2 g K/m ² inject	83abc	109ab	111bc	99b	111bc	125bc
	24.4 g K/m ² surface	72bc	96bc	122b	140a	128ab	134b
	24.4 g K/m ² inject	97a	125a	156a	141a	148a	213a

^a Means within a column followed by the same letter are not significantly different at P=0.05 according to Fisher's PLSD test.

*Treatment dates (each applied at 1/2 rate): 9 Aug and 7 Sep 1990, 9 Jul and 6 Sep 1991, 21 Jul and 16 Sep 1992, 21 Aug and 18 Sep 1993.