CHAPTER 3

Moisture Depletion on Fairway Turfs Under Three Irrigation Regimes Using Time Domain Reflectometry

Abstract

Improvements in irrigation management by turf managers have focused mainly on irrigation system performance with limited attention paid to the temporal and spatial distribution of soil water following irrigation. The objectives of the study were: i) to evaluate volumetric moisture content dynamics in turf root zones under three irrigation regimes and ii) to adapt time domain reflectometry (TDR) for turf irrigation scheduling. Volumetric soil moisture content was monitored using TDR at 0-5, 5-10, 10-15, and 15-25 cm depths under three irrigation regimes during the summers of 1992, 1993, and 1994. The irrigation treatments were: i) return soil to field capacity (FC); ii) apply 2.5 mm daily (DLY); and iii) apply 25 mm only upon the appearance of wilt stress (STR). Penncross creeping bentgrass (*Agrostis palustris* L. Huds.) and annual bluegrass (*Poa annua* L. var. reptans) were maintained on an Owosso sandy loam soil under fairway conditions. Moisture depletion patterns for both species were measured daily except on rainy days. Applied irrigation differed significantly by irrigation treatment but not during wet periods. Volumetric moisture content by depth ranked 0-5 > 5-10 > 10-15 > 15-25 for the irrigated treatments and for the stress treatment during wet periods. During dry periods, VMC for the stress treatment

ranked 15-25 > 10-15 > 5-10 > 0-5. Volumetric moisture content for the three irrigation treatments ranked FC > DLY > STR during dry periods and DLY > FC > STR for wet periods. Mean volumetric moisture content for the irrigated treatments were above field capacity (0.28 cm^3 cm^{-3}) during wet periods while full recharge of the stress treatment occurred only during heavy rainfall. Under such conditions, there is a potential for leaching of agricultural chemicals into ground water. Time domain reflectometry proved to be a useful tool for turf irrigation scheduling but the question of number of probes and locations on the golf course or other turfs needs to be addressed. Regular monitoring of VMC by TDR could reduce overwatering and minimize potential leaching of agricultural chemicals into ground water.

Introduction

Research on the spatial and temporal dynamics of soil moisture has been impeded by the lack of adequate techniques for soil moisture determination. Soil moisture data could provide useful information on soil hydrological processes, irrigation scheduling and modeling (Ritchie and Amato, 1990; Hanks, 1992). Repeated soil moisture measurements could be used to monitor soil moisture storage and depletion for turf irrigation management. Topp et al (1980) adapted time domain reflectometry (TDR) for determining volumetric moisture content, based on soil dielectric properties, which can be used for irrigation programming. However, the use of TDR in real-time turf irrigation scheduling has been limited to research trials (Carrow, 1991; Saffel, 1994).

Ideally, evapotranspiration (ET) models should be used to schedule irrigation. In practice irrigation scheduling remains a challenge that depends on the experience and convenience of turf managers. In urban areas, ET is site specific (Danielson et al., 1981) and may vary considerably from regional predictions (Feldhake et al., 1983). A soil-based method of irrigation programming is expected to provide better estimates of soil moisture depletion by site than regional ET predictions (Carrow, 1991), thereby improving site-specific irrigation scheduling.

This study evaluated TDR as a tool for repeated and rapid VMC determination for turf irrigation scheduling using two cool-season fairway turfs. The objectives of this study were: i) to evaluate moisture storage in turf root zones using TDR; and ii) to adapt TDR for turf irrigation programming.

Materials and Methods

A three-year study was conducted at the Hancock Turfgrass Research Center at Michigan State University. The soil type was a modified Owosso sandy loam (fine-loamy mixed mesic *Typic Hapludalf*). Volumetric soil moisture content for established annual bluegrass (*Poa annua* L. var. reptans) and Penncross creeping bentgrass (*Agrostis palustris* L. Huds.) turfs was evaluated under three irrigation regimes. The turf was mowed at 16 mm height and maintained according to typical fairway practices recommended for cool-season grasses in Michigan.

The irrigation treatments were: i) return the soil water content to field capacity (FC) on days when TDR readings were taken; ii) apply 2.5 mm of water daily (DLY) (Vargas, 1994); and iii) a rainfed or stress treatment that received no irrigation (STR). Irrigation was applied at 0300 h. All plots received additional irrigation following fertilization to minimize phytotoxicity and during sprinkler evaluations . Time domain reflectometry readings were taken between 0700 and 0900 h for up to 60 days during the summers of 1992, 1993, and 1994.

Irrigation blocks (11 x 11 m) were split in half to form subplots (5.5 x 11 m) randomly seeded to creeping bentgrass or annual bluegrass, established in 1989 (Saffel, 1994). Each plot had a buffer strip about 1.2 m wide. Because there were no significant differences in VMC by species, VMC data for both species were averaged for analysis. A Rainbird pop-up head with 21.5 L min^{-1} average output was installed at each corner of the plot. Plots with the same irrigation treatment were controlled by the same irrigation switch. Irrigation treatments served as whole plots, whereas the turf species and depths of TDR installations served as the split and strip plots, respectively. There were three replications for each treatment.

The TDR setup consisted of the following components: i) a time domain reflectometer (1502C, Tektronix, Redmond, OR) that generates pulses, a sampler that receives the reflected impulse, and an oscilloscope that displays the waveform; ii) a set of antenna or cable wires; and iii) sets of stainless steel wave guides or probes. The cables transmit the pulses from the TDR to the stainless steel probes embedded in the soil (Campbell, 1990).

Stainless steel TDR probes, 200 mm long and 3.2 mm in diameter, were installed as described by Saffel (1994). The center-center separation distance between probe installations was 50 mm. Each subplot (species) had 11 pairs of stainless steel rods installed horizontally at three equidistant locations 2 m from a switch box at the center of each plot (Fig. 3.1). Impedance matching transformers (baluns) were connected to each rotary switch to reduce

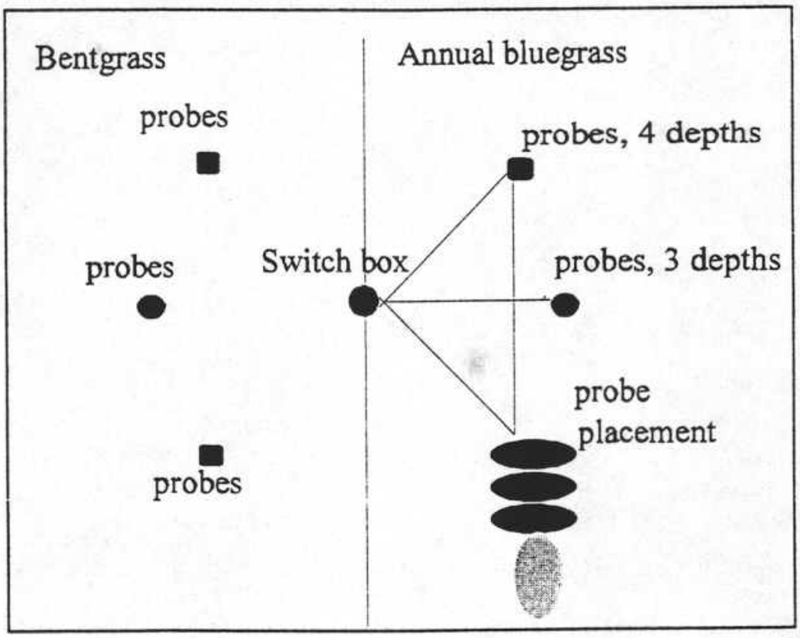

Fig. 3.1 Spatial arrangement of TDR probes per plot for the different depths.

the mismatch between TDR connectors and cable wires (Topp et al., 1980; Biran et al., 1981; Spaans and Baker, 1993). The top three probes were installed horizontally and parallel to the soil surface at 2.5, 7.5, and 12.5 cm depths, with three replications. The last pair of probes also was installed parallel to the soil surface but vertically, one at 17.5 cm and the other at 22.5 cm depths. The probes at the 15-25 cm depth were replicated only two times due to the limited number of positions on the rotary switches used to transmit TDR signals from one set of probes to another. This resulted in a statistically unbalanced design.

The spatial arrangement of TDR probes for one plot is shown in Fig. 3.1. The soil volume measured depends on probe configuration and the length of the TDR probes, based on the elliptical sphere of influence of the TDR rods (Topp et al., 1980). The probe placement allows for VMC measurements at four depths (2.5, 7.5, 12.5 cm for the first three probe pairs and 17.5 and 22.5 cm for the last set of probes) with an approximate sphere of influence down to the 25 cm depth. The relative area of soil moisture measurement along the length of the probe pair is shown in the lower-right-hand corner of Fig. 3.1.

The waveform of a voltage pulse propagated through stainless steel probes embedded in the soil and reflected back to the oscilloscope is analyzed to estimate the composite dielectric constant (ϵ) of the soil. The travel time (**t**) along a stainless steel probe of length **L** was used to calculate ϵ and VMC, using an empirically derived polynomial as described by Topp et al. (1980):

$$\mathrm{VMC} = -\,0.053 + 0.0292\epsilon - 0.00055\epsilon^2 + 0.000004393\epsilon^3$$

where $\epsilon = (ct/2L)^2$ and c = the speed of light.

In 1993, gravimetric moisture measurements were converted to VMC by multiplying by the soil bulk density as a basis for comparison to the TDR measurements. Three samples were taken per subplot, using a 3.2 cm diameter probe, and sectioned by depth corresponding to the vertical sphere of influence of the installed TDR probes (0-5, 5-10, 10-15, and 15-25 cm). Because of the destructive nature of gravimetric sampling, samples were taken away from the probes to avoid disturbing the probe installations. This was a potential source of error but was necessary for long term use of TDR installations.

The weighted field capacity of the soil for the 0-25 cm depth (0.28 cm^3cm^{-3}) was determined from TDR measurements two days after a soaking rain and as a reference for estimating irrigation need for the field capacity treatment. Runoff was not measured but may have accounted for some of the moisture loss.

The experimental design was a split-strip plot with three replications. All unbalanced data were analyzed using SAS GLM and SNK mean-separation procedures; otherwise, PROC ANOVA was used (SAS, 1994). The precision of the TDR readings were evaluated using descriptive statistics (means, standard deviations and standard error, variance, and minimum and maximum values).

Results and Discussion

Descriptive statistics for repeated TDR measurements for different probe pairs on two dates are presented in Table 3.1. The mean, mode, and median had the same value, and the standard error and variance were very small for both dates. This confirms that TDR provides reproducible soil moisture measurements in turf ecosystems.

Agreement between gravimetrically determined VMC and TDR measurements (R^2 = 0.99), given anticipated spatial variability, shows that TDR provides reasonable moisture estimates even under turfgrass conditions. However, TDR over predicted VMC at lower moisture contents by up to 2.1 % (Table 3.2). Because TDR and VMC data were not collected from the same location, expected spatial variability could explain some of the differences between methods. The high R^2, despite the expected spatial variability of VMC, suggest that TDR is a dependable tool for soil moisture determination for the shallow rooting depths encountered in cool-season turfs.

Soil moisture content was influenced mostly by precipitation and applied irrigation for the irrigated treatments, moderated by other weather factors. Weather conditions for 1992

Table 3.1. Descriptive statistics for consecutive TDR measurements.

	17 June 1993	23 Aug. 1994
Maximum	0.247	0.245
Minimum	0.234	0.225
Mean	0.241	0.238
Mode	0.241	0.238
Median	0.241	0.238
Std. error	0.0004	0.0004
Variance	0.00001	0.00002
n	43	108

Table 3.2. Comparison of volumetric soil moisture content means across all treatments by the gravimetric method (GMC) and by TDR for different depths.

Depth	TDR	GMC	Difference
(cm)		$cm^3\ cm^{-3}$	
0-5	30.4a†	30.8a	-0.4
5-10	27.9b	26.4b	1.5
10-15	26.7c	24.6c	2.1
15-25	26.0c	23.9c	2.1

†Means within columns followed by the same letter are not significantly different.
n = 66 for 0-5, 5-10, and 10-15 depths, and n = 44 for 15-25 cm depth for TDR and n = 18 for GMC for each depth.

to 1994 are summarized in the appendix. Rainfall amounts and distribution were variable within seasons and among years. In all years, most of the rainfall coincided with the peak of the warm summer months. In 1992 and 1993, heavy rains occurred toward the second half of the season. In 1994, rainfall amounts and frequency masked the effect of higher temperatures and solar radiation on moisture depletion from mid-June to mid-July. The highest single rainfall event of 70 mm occurred on day 166 in 1994. All three years were relatively wet for East Lansing, MI.

Volumetric Moisture Content by Irrigation Treatment

The analysis of variance showed that VMC content was significantly affected by irrigation treatment. However, high amounts of rainfall occasionally masked the differences in VMC among treatments. Volumetric moisture content by depth for the different irrigation treatments for 1992 are presented in Fig. 3.2. Volumetric moisture content for the irrigated treatments fell within 0.25 and 0.35 $cm^3\ cm^{-3}$ for most sampling dates, while VMC for the stress treatment ranged from a low of 0.17 $cm^3\ cm^{-3}$ during a prolonged dry period in 1992 to a maximum of 0.33 $cm^3 cm^{-3}$ at the beginning of the study for the 0-5 cm depth (Fig. 3.2).

Soil moisture depletion ranges were highest for the stress treatment than for the irrigated treatments particularly, the 0-5 cm depth. A critical period for the stress treatment was between sampling day 30 and 40 in 1992 when VMC fell below $cm^3\ cm^{-3}$. The high root density (Chapter 4), the high organic matter content and proximity of the 0-5 cm depth to fluctuating environmental conditions are possible explanations for this. During wet periods VMC by depth ranked 0-5 > 5-10, > 10-15 > 15-25 for all treatments. During dry periods however, the trend was reversed in the stress treatment (15-25 >10-15 > 5-10 > 0-5).

Time series plots for VMC for 1993 are presented in Fig. 3.3. Moisture content for the irrigated treatments fell between 0.24 and 0.34 $cm^3\ cm^{-3}$ for most sampling days, while VMC for the stress treatment ranged from 0.13 to 0.33 $cm^3\ cm^{-3}$. Again VMC by depth ranked 0-5

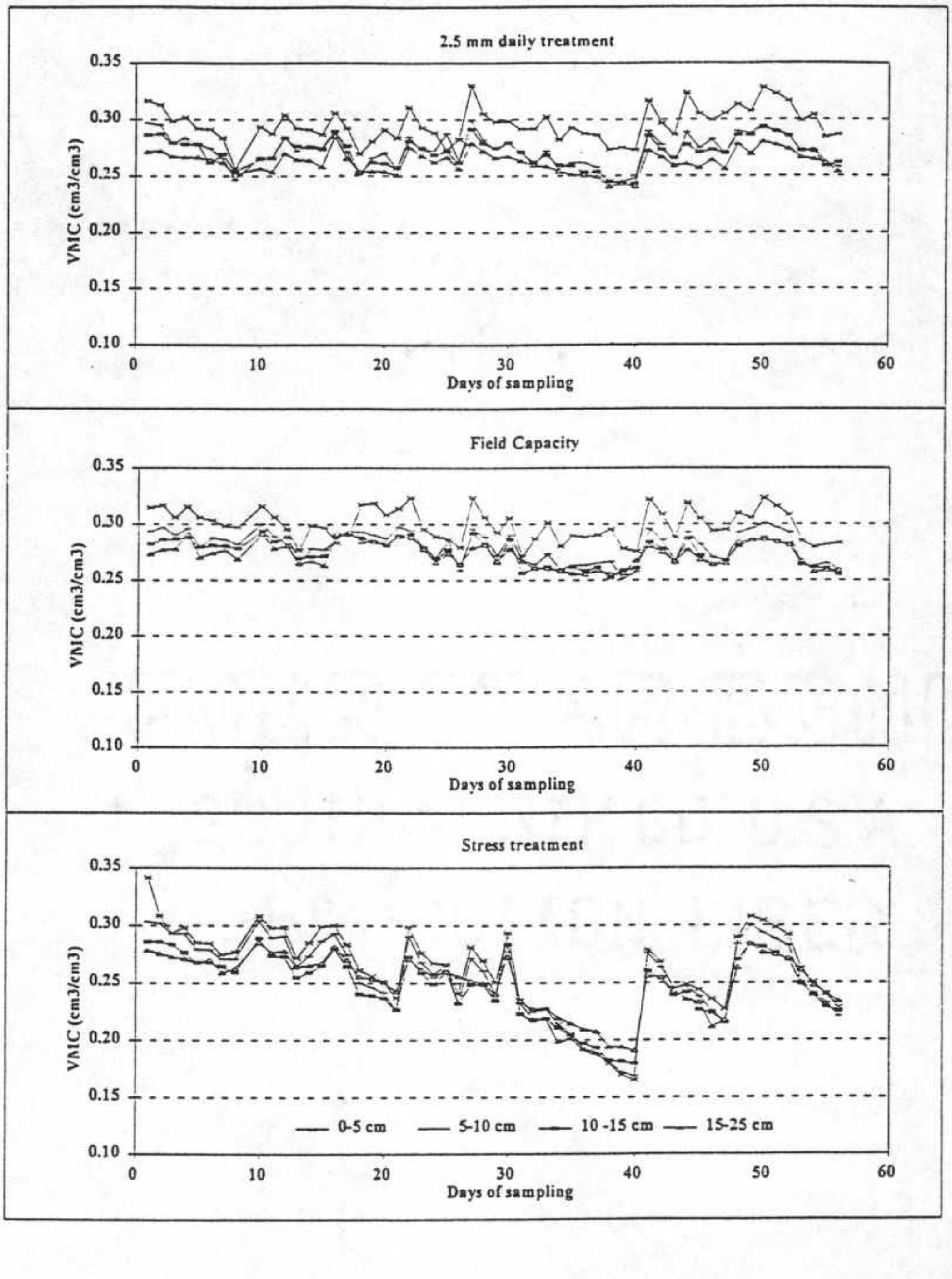

Fig. 3.2. Volumetric moisture content (VMC) means for the different irrigation treatments by depth, 1992.

> 5-10 > 10-15 > 15-25 cm for the irrigated treatments while VMC by depth for the stress treatment ranked 15 -25 > 10-15 > 5-10 > 0-5 cm during dry periods. The 0-5 cm depth for the irrigated treatments had consistently higher VMC than other depths. Volumetric moisture content trends by treatment also followed the same general pattern as in 1992. The 2.5 mm daily and field capacity treatments showed only minor increases in VMC from rainfall for all years. Conversely, the stress treatment showed significant gains in VMC following heavy rains. This indicates that when soils are maintained at or above field capacity, most of the rainfall is lost as drainage or runoff.

Volumetric moisture content trends for 1994 are presented in Fig. 3.4. Early in the season in 1994 moisture readings were out of range due to faulty operation of equipment for Thereafter, VMC levels for the irrigated treatments were above 0.24 cm^3 cm^{-3} as in 1992 and 1993. Increase in VMC on day 40 in 1994 (Fig. 3.4) was highest for the stress treatment while the irrigated treatments showed only marginal gains in VMC for all depths. This indicates that both irrigation treatments failed to efficiently accommodate potential moisture gains from rainfall. On most days, VMC for the bentgrass plots was consistently higher than for the annual bluegrass plots although the differences were not significant. This suggests differential moisture extraction by depth, which may be explained by the differences in root mass density between species.

Volumetric moisture content response to irrigation and rainfall varied significantly by irrigation treatment primarily during dry periods. The field capacity (FC) and 2.5 mm daily (DLY) treatments, respectively, received 234 and 382 mm of irrigation in 1992, 297 and 382 mm in 1993, and 298 and 382 mm in 1994. Applied irrigation ranked DLY > FC > STR for

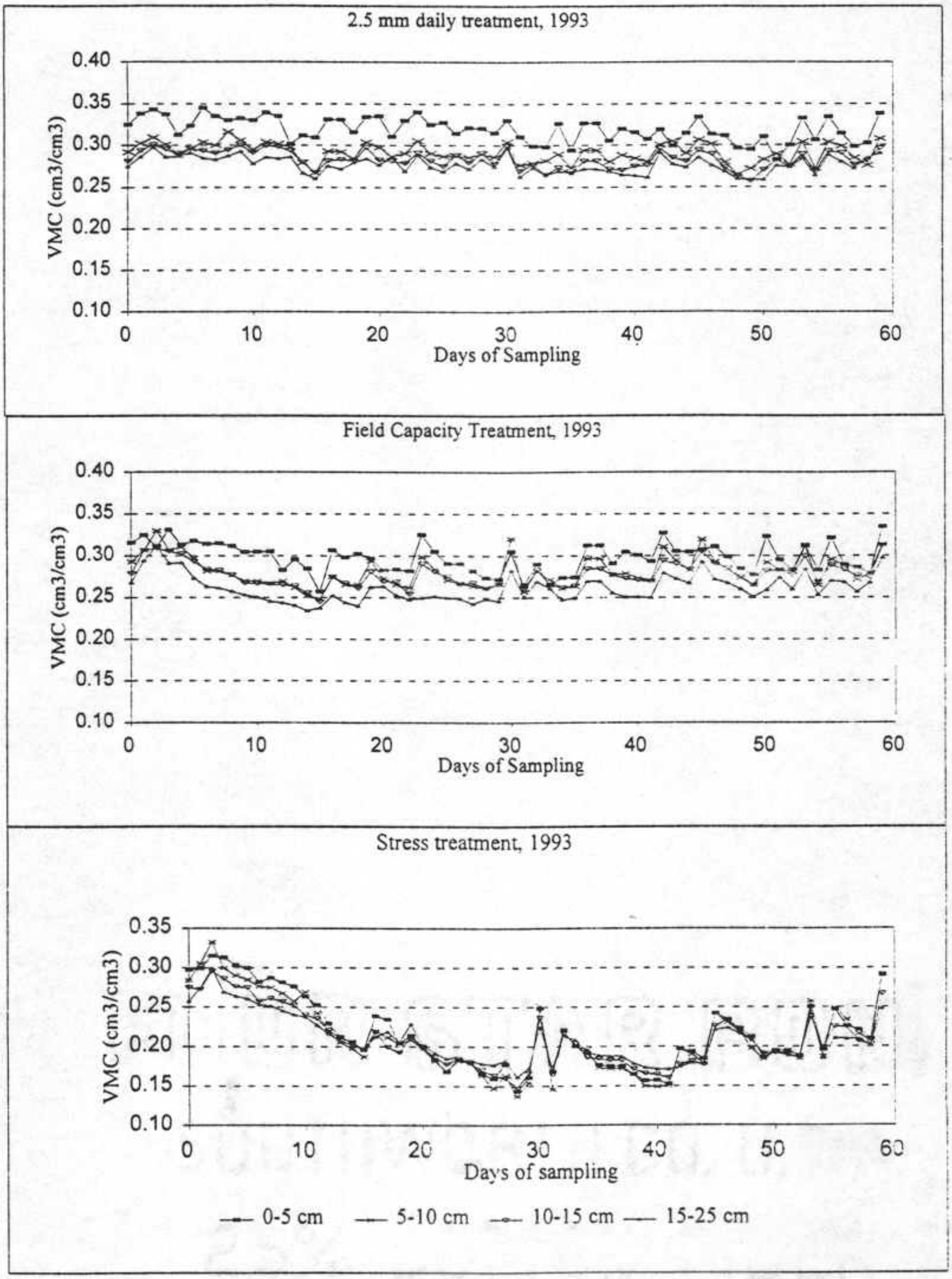

Fig. 3.3. Volumetric moisture content (VMC) for the different irrigation treatments by depth, 1993.

all years. The stress treatment received no irrigation for all years as 1992, 1993, and 1994 were very wet years. The stress treatment showed the highest moisture depletion for all depths, as expected. Because no irrigation was applied to the stress treatment, water deficit accumulated until it rained.

Volumetric Moisture Content by Depth

The analysis of variance showed that soil moisture content was significantly different by soil depth. Because of the large amount of data involved, only data from 1993 were used for the discussion that follows. Time series plots (Fig. 3.5) show the effect of irrigation treatment on VMC by depth for the three irrigation treatments. The 0-5 cm depth had the highest VMC for all irrigated treatments throughout the study. This implies that with light and frequent irrigation, more water resides in the 0-5 cm depth. The delineation between the 0-5 cm depth and the other depths was most consistent in the 2.5 mm daily treatment. In this treatment, the rankings for the three other depths were 5-10 > 10-15 > 15-25. On several dates, there were significant differences in VMC among sampling depths and irrigation treatment.

Volumetric moisture content for the irrigation treatments for a typical wet day in 1993 and for a dry day in 1992 are presented in Fig. 3.6a and Fig. 3.6b. Moisture content decreased with depth for the irrigated treatments. Generally, differences between irrigation treatments were more apparent during dry periods than in wet periods. For the stress treatment, VMC followed the same pattern as in the irrigated treatments during very wet periods. During dry periods VMC trends by depth ranked 15-25, > 10-15 > 5-10 > 0-5 cm.

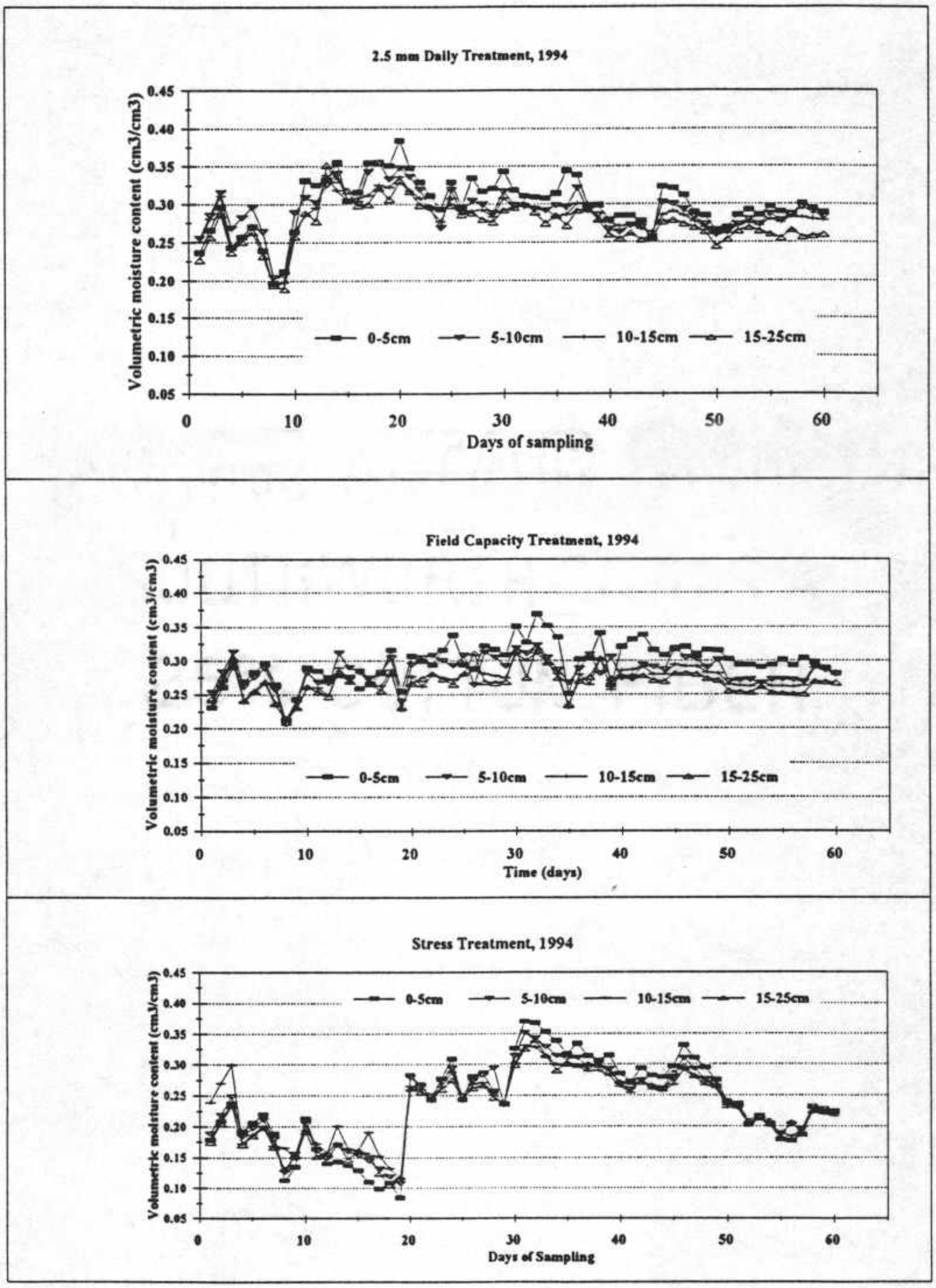

Fig. 3.4. Volumetric moisture content (VMC) means for the different irrigation treatments by depth, 1994.

However, during wet periods, a reversal of the VMC sequence for the different depths was observed (0-5 > 5-10 > 10-15 > 15-25) as for the irrigated treatments. Reversals in soil moisture content for the different depths in the stress treatment occurred in all years when VMC fell below the 0.20 and 0.25 $cm^3\ cm^{-3}$ range for the stress treatment as shown earlier (Figs. 3.2, 3.3, and 3.4).

Upward water flux may contribute moisture to the 15-25 cm depth and subsequently to that of other depths. The mechanisms operational under these conditions are not fully understood and deserve further investigation. It has been suggested that hydraulic lift by roots (Richards and Cardwell, 1987) and capillary rise during periods of high evaporative demand may contribute water to the rootzone

Table 3.3. Regression equation coefficients for moisture depletion for the stress treatment during a dry-down cycle in 1992.

Depth	**a**	**b**	**c**	$\mathbf{R^2}$
0-5 cm	31.3	0.44	0.03	0.87
5-10 cm	30.2	0.38	0.02	0.87
10-15 cm	30.8	0.36	0.02	0.96
15-25 cm	27.5	0.06	0.01	0.91

Mean VMC by depth for the irrigated treatments were generally at or above field capacity for most days. For the stress treatment, VMC dropped as low 0.13 $cm^3\ cm^{-3}$ in 1992, 0.14 $cm^3 cm^{-3}$ 1993 and less than 0.10 $cm^3\ cm^{-3}$ in 1994 during peaks of dry down cycles. Most water balance models estimate plant water uptake from root length density. Higher root mass density from bentgrass plots (Murphy et al., 1994; Saffel, 1994) suggests higher water uptake,

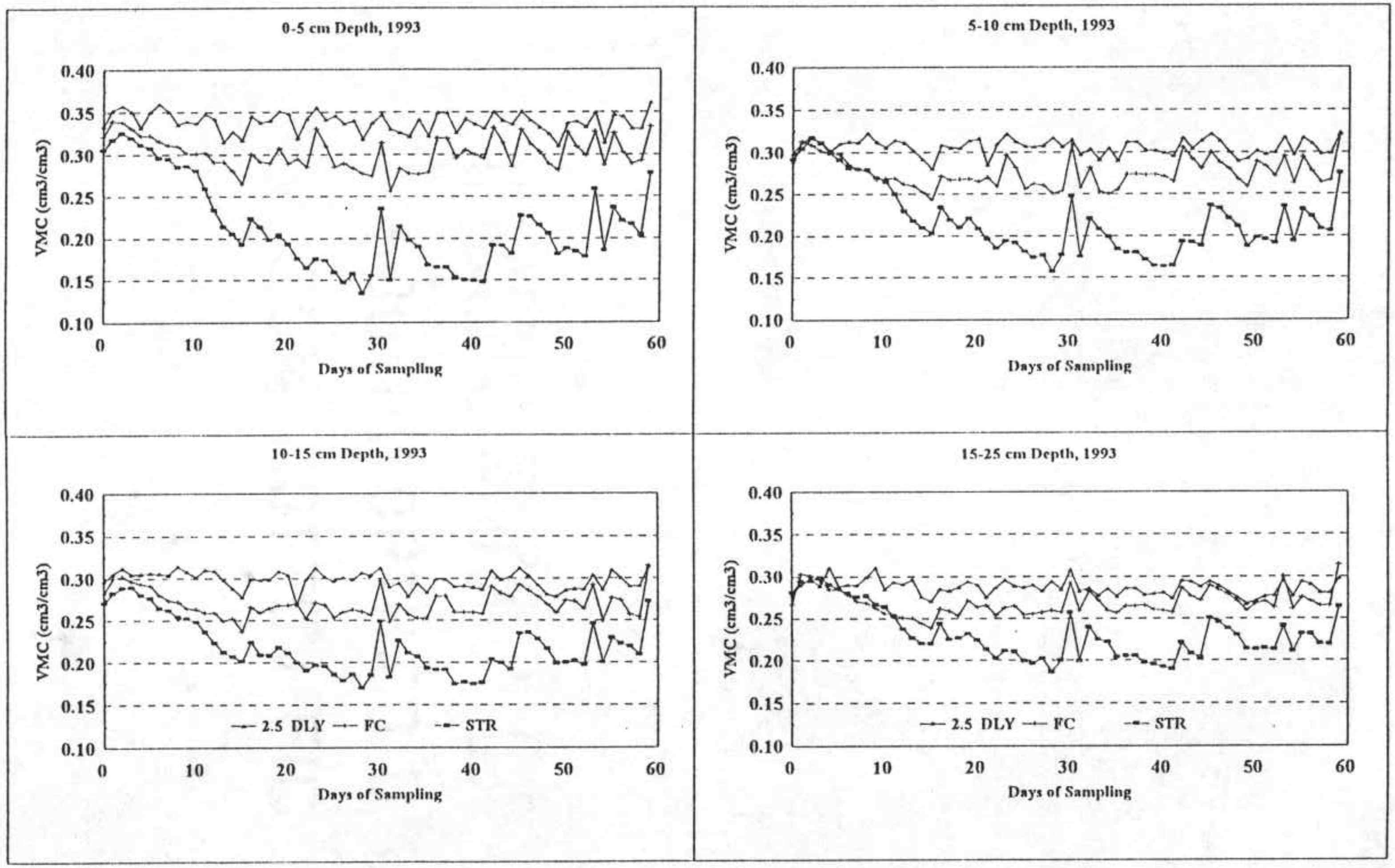

Fig. 3.5. Moisture depletion patterns across species for the different irrigation treatmenrs at four depths, 1993.

assuming equally functional roots. Differences in VMC by depth between species occurred on a few dates in all years. However, VMC means across all depths were not significantly different by species as reported by Saffel, 1994. In earlier studies, Beard (1973), Fry and Butler (1989) reported no significant difference in ET between annual bluegrass and creeping bentgrass.

Regression Equations for Moisture Depletion During a Dry-Down Period

Ritchie (1972) reported a linear relationship for moisture depletion from a bare soil plotted against the square root of time. Regression equations fitted to moisture depletion data from the stress treatment during a 1992 drydown period could be used to predict when the soil moisture content will attain an established threshold for irrigation. The general equation for each depth was of the form:

$$\mathbf{Y = a - bX + cX^2}$$

where **Y** is the VMC, **X** is time in days, **a** is the y-intercept, and **b** and **c** are **X** coefficients for the exponential dry-down prediction equation, as shown in Table 3.3. Because the intercept and coefficients of the dry-down curve may vary over time depending on evaporative demand and rainfall, regular moisture readings are necessary for this method.

Seasonal VMC means and turf quality ratings for the different irrigation treatments for 1992 showed a linear relationship as presented in Fig. 3.7. Danielson et al. 1981; Aurasteh, 1983, also reported linear turf quality response to applied irrigation over certain moisture ranges. From Fig. 3.7 it is evident that to maintain a turf quality rating of 7or higher, soil moisture content must be greater than 0.27 cm^3 cm^{-3}. To maintain the turf at the minimum

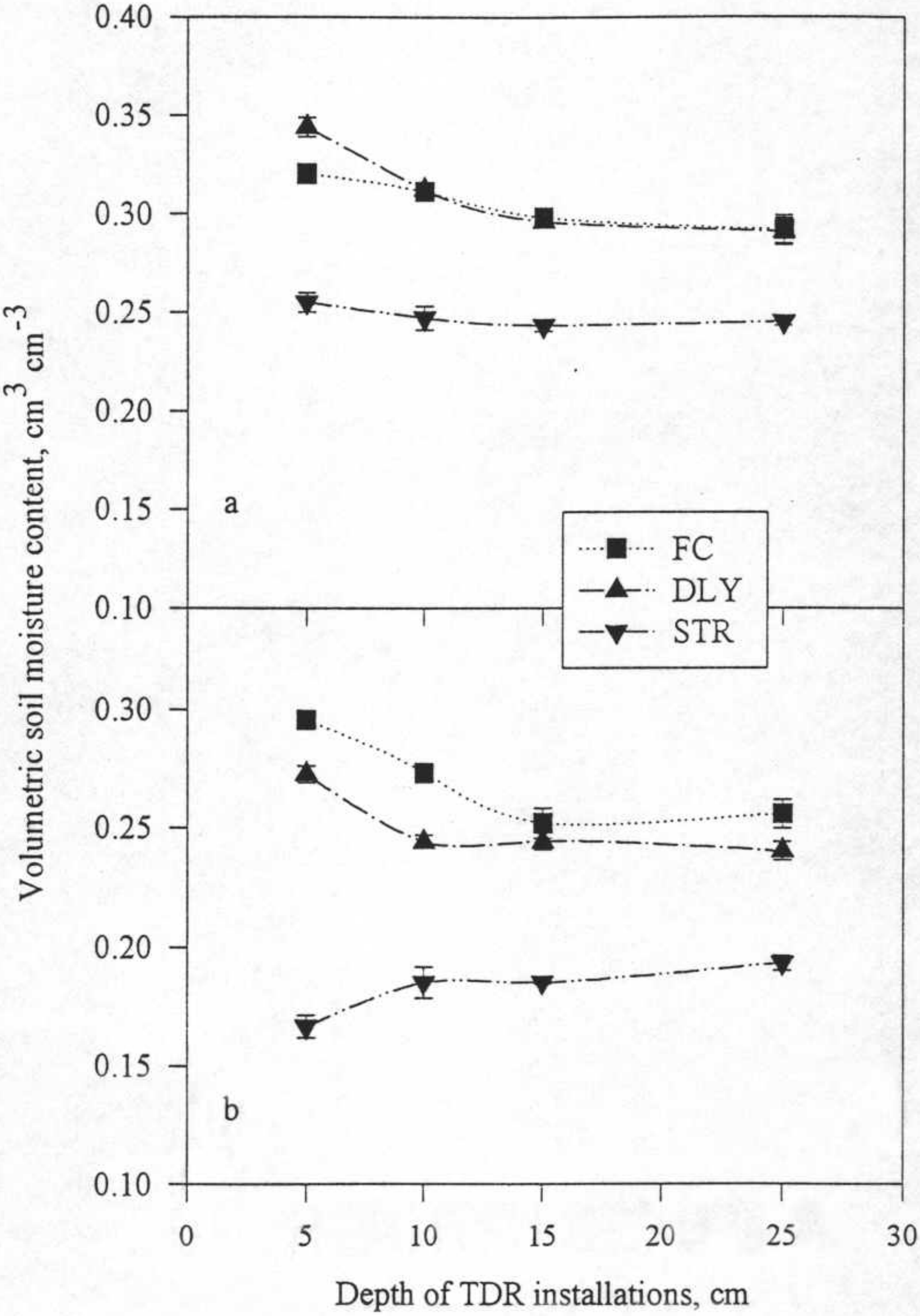

Fig. 3.6. Moisture depletion means across species for the field capaciy, FC; 2.5 mm daily, DLY; and stress, STR treatments for 20 Aug. 1993 (a wet day, **a**) and 25 Aug. 1992 (a dry day, **b**).

acceptable quality rating of 6, volumetric moisture content should be maintained at about 0.26 cm^3 cm^{-3}. This implies that if water conservation is the goal then lower quality turf must be acceptable. Using a soil moisture sensor to predict when soil VMC attains a pre-established critical level will lead to more efficiently irrigation scheduling with acceptable reductions in turf quality. When moisture sensors become affordable repeated moisture measurements may help conserve water and reduce drainage losses from irrigation in urban areas as well as on golf courses.

Moisture Depletion and Irrigation Scheduling

Soil moisture sensors have been used for turf irrigation scheduling with significant water savings (Augustin and Snyder, 1984). Volumetric soil moisture content trends by depth for the TDR study were the same for all treatments during wet periods, i.e., 0-5 > 5-10 10-15 > 15-25 cm. During drydown periods the stress treatment showed unique soil moisture depletion trends by depth (Fig. 3.8) that could be used for irrigation scheduling. A transient state (0.20 to 0.25 cm^3 cm^{-3}) was evident in the stress treatment during each prolonged drydown period, where all soil depths had about the same soil moisture content implying that there was very little net movement of moisture between soil depths of interest over this moisture range. This could be an ideal level at which soil moisture should be maintained to minimize drainage losses without subjecting the turfs to moisture stress. For example if the 0.25 cm^3 cm^{-3} moisture level is assigned as the setfull and the 0.20 cm^3 cm^{-3} the refill point as suggested by Topp and Davis, 1985, then irrigation is applied each time VMC is depleted to the 0.20 cm^3 cm^{-3} level and stopped when VMC attains the 0.25 cm^3 cm^{-3} level. The lower limit selected in this illustration is 0.03 to 0.05 cm^3 cm^{-3} above the moisture

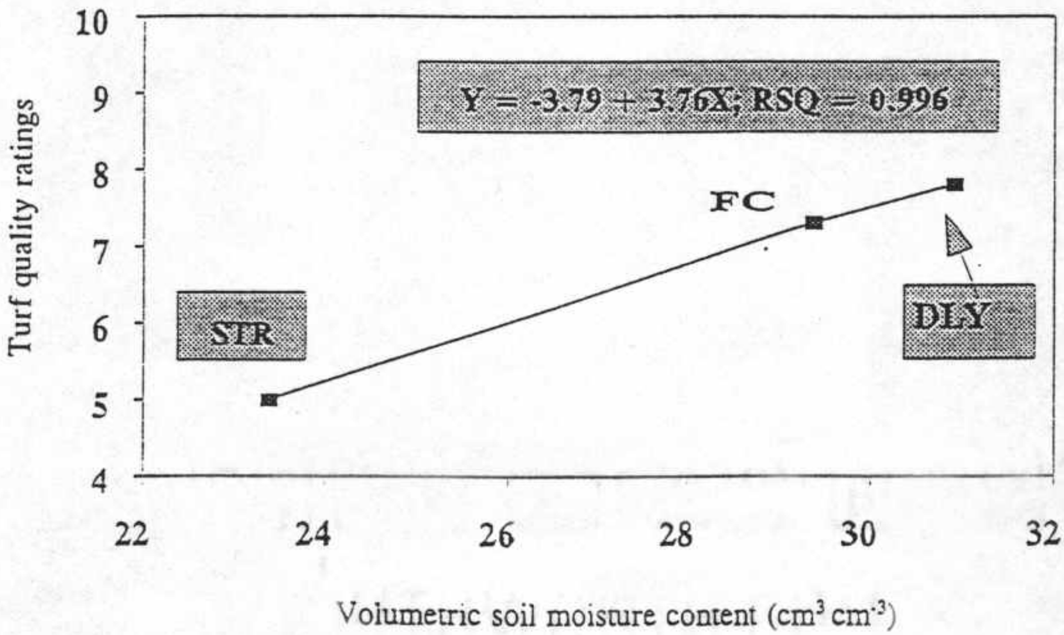

Fig. 3.7. Volumetric moisture content (VMC) means versus turf quality means, 1992.

levels at which Saffel (1994) reported visual signs of wilt stress, and 0.03 $cm^3\ cm^{-3}$ below the drained upper limit of 0.28 $cm^3\ cm^{-3}$. Further moisture depletion below the above range, however, led to differential moisture retention by depth but the observed trends were again reversed with adequate rainfall (Figs.3.3, 3.4, 3.5 and 3.8). When moisture levels fell below the 0.20 $cm^3\ cm^{-3}$ limit the 0-5 cm depth had the lowest VMC followed sequentially by the 5-10, 10-15, and 15-25 cm depths. The observed VMC trend is the opposite of that observed during wet periods and coincides with root mass distribution patterns by depth.

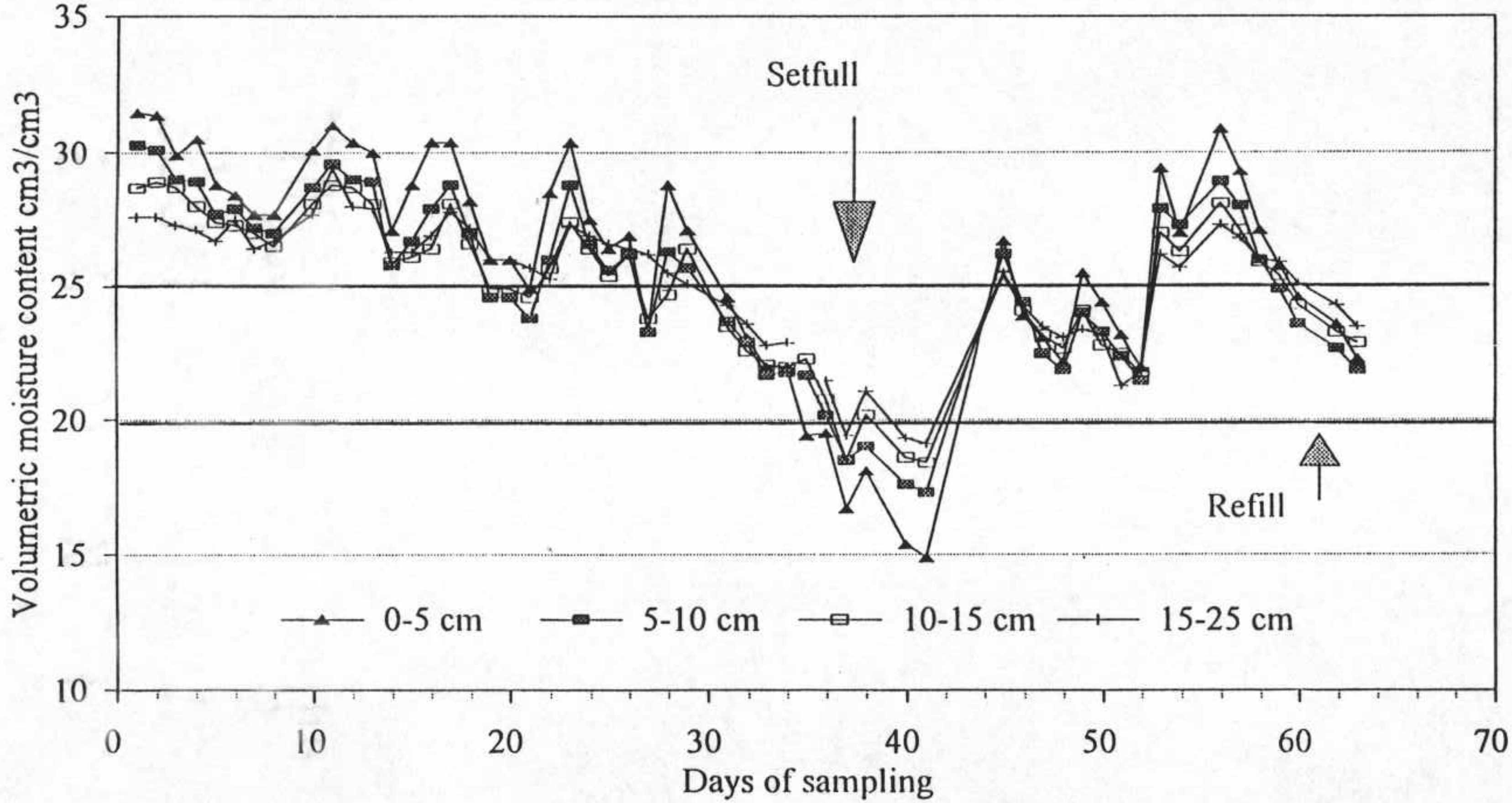

Fig. 3.8. Moisture depletion by depth for the stress treatment during a dry down period in 1992.

Two important decision faced by turf managers are: i) when to irrigate, and ii) how much to irrigate. Using a soil moisture sensor such as TDR simplifies the decision on how much and when to irrigate by establishing two critical limits - the "setful" and "refill" points (Campbell and Campbell, 1982; Topp and Davis , 1985). The refill point indicates when to start irrigation and the setfull point indicates when to stop. The establishment of these points will depend on the quality of turf desired as well as other management considerations.

A relationship between VMC versus turf quality for a given soil type, turf species and location may facilitate the selection of the setfull and refill points by selecting appropriate VMC limits in relation to turf quality. Repeated VMC measurement provide information as to when the established limit is attained for efficient irrigation used to schedule turf irrigation based on established soil moisture limits.

Conclusions

The above discussion confirms that TDR measurements in turf soils show a high degree of precision (standard error < 0.001) and accuracy ($R^2 = 0.99$). Repeated monitoring of VMC by TDR in turf root zones as a basis for irrigation planning can help reduce overwatering and the potential for ground water contamination in turf ecosystems.

Volumetric soil moisture content trends for the irrigated treatments show average moisture content levels at or above field capacity most of the time. Moisture depletion from both irrigated treatments were over a narrow range while VMC ranges for STR were particularly, for the 0-5 cm depth. The high VMC for the irrigated treatments in this study suggest that irrigation scheduling in wet years should not be based on field capacity (100% ET) or 2.5 mm daily as such recommendations fail to accommodate potential moisture gains from rainfall. Conjunctive use of ET and soil moisture depletion data could improve turf irrigation management and minimize drainage losses. Such a schedule would account for contributions from upward water flow, particularly when the water table is shallow.

The ranking of soil moisture retention by irrigation treatment during wet periods was DLY > FC > STR, but during dry periods the ranking was FC > DLY > STR. Soil moisture depletion by depth was similar for both species but differed by irrigation treatment depending on rainfall amounts and frequency. Moisture retention by depth was in the order 0-5 > 5-10 > 10-15 > 15-25 cm for the irrigated treatments. For the stress treatment the trend was the same as for the irrigated treatments during wet periods, but a complete reversal of the above trend (15-25 > 10-15 > 5-10 > 0-5) was evident during peak dry periods. Although the 0-25 cm depth is usually considered as one depth in conventional cropping, the partitioning of this depth is important in understanding soil moisture dynamics in shallow-rooted turf. Regression equations developed from dry down cycle showed that short term irrigation forecasting is possible from repeated VMC measurements.

A method of scheduling irrigation that is accurate, site specific, rapid, dependable, and affordable is most desirable for the turf industry. Time domain reflectometry accurately measures a known spatial volume. The possibility of automation and accuracy at shallow depths are advantages of TDR compared to the neutron probe that may benefit the turf industry. In addition to saving time and labor, widespread adaptation of TDR in irrigation programming will result in more efficient use of limited water resources and reduce drainage losses and the potential for ground water contamination in turf ecosystems. However, the high initial cost of TDR is prohibitive at this time. Secondly, the question of placement and number of probes to be used for specific sites need to be addressed.

Literature Cited

Augustin, B.J., and G.H. Snyder. 1984. Moisture sensor-controlled irrigation for maintaining Bermudagrass turf. Agron. J. 76:848-850.

Aurasteh, M.R. 1983. A model for estimating lawn grass water requirement considering deficit irrigation shading and application efficiency. Ph.D. Diss. Utah State Univ., Logan.

Beard, J.B. 1973. Turfgrass Science and Culture. Prentice-Hall, Englewood Cliffs, NJ.

Biran, I., B. Brando, I. Bushkin-Harav, and E. Rawitz. 1981. Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil moisture. Agron. J. 75:85-90.

Campbell, G.S., and M.D. Campbell. 1982. Irrigation scheduling using soil moisture measurements: theory and practice. p. 25-42. *In* D. Hillel (ed.) Advances in irrigation, Vol. 1. Academic Press, New York.

Campbell, G.S. 1990. Dielectric properties and influence of conductivity in soils at 1 to 50 megahertz. Soil Sci. Soc. Am. 54:332-341.

Carrow, R.N. 1991. Turfgrass water use, drought resistance and rooting patterns in the Southeast. Technical Completion Report. ERC. 01-91. USDI/USGS.

Danielson, R.E., C.M. Feldhake, and W.E. Hart. 1981. Urban lawn irrigation and management practices for water savings with minimum effect on lawn quality. Water resources Res. Inst., Fort Collins, CO.

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

Fry, J.D., and J.D. Butler. 1989. Annual bluegrass and creeping bentgrass evapotranspiration rates. Hortscience. 24:269-271.

Hanks R.J. 1992. Applied soil physics: Soil water and temperature applications. Springer-Verlag. New York.

Murphy, J.A., M.G. Hendricks, P.E. Rieke, A.J.M. Smucker, and B.E. Branham. 1994. turfgrass root systems evaluated using minirhizotron and video recording method. Agron. J. 86:247-250.

Richards, J.H. and M.M. Caldwell. 1987. Hydraulic lift: substantial nocturnal water transport between soil layers by Artemisia tridentata roots Oecologia 73:486-489.

Ritchie, J.T. 1972. A model for predicting evapotranspiration from a row crop with incomplete cover. Water Resour. Res. 8:1204-1213.

Ritchie, J.T., and M. Amato. 1990. Field evaluation of plant extractable soil water for irrigation scheduling. Acta Horticulturae 278:595-615.

Safell, M.T. 1994. Time domain reflectometry for turf irrigation programming. MS thesis, Mich. State Univ., East Lansing.

SAS Institute. 1994. SAS user's guide: Statistics. SAS Inst., Cary, NC.

Spaans, E.J.A., and J.M. Baker. 1993. Simple baluns in parallel probes for time domain reflectometry. Soil Sci. Soc. Am. J. 57:668-673.

Tektronix. 1987. Tektronix metallic TDR's for cable testing. Tektronix, Redmond, OR.

Topp, G.C., and J.L. Davis. 1985c. Time-domain reflectometry (TDR) and its application to irrigation scheduling. p. 107-127. *In* D. Hillel (ed.) Advances in irrigation. Academic Press, New York.

Topp, G.D., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res. 16:574-582.

Vargas, J.M., Jr. 1994. Management of turfgrass diseases. Lewis Publishers, Ann Arbor, MI.