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TIME DOMAIN REFLECTOMETRY AND TURF IRRIGATION MODELING

By

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ABSTRACT

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Hydrologic models are widely used in crop water management. However, water balance simulations in turf ecosystems are very rare. A three-year study (1992-1994) was conducted at the Hancock Turf Research Center to evaluate the use of Time domain reflectometry (TDR) based turf irrigation scheduling compared to two modified evapotranspiration (ET) models: i) Soil Conservation Service SCHEDULER (SCS-SCHEDULER) and ii) Systems Approach to Land Use Sustainability (SALUS). Both models required weather, soil, and turf-specific input data files with ET and other hydrologic components as output. Volumetric moisture content (VMC) was monitored using horizontally installed TDR probes at 2.5, 7.5, 12.5 and 20 cm depths on established fairway turfs. Irrigation plots (11 x 11 m) were split and randomly seeded to either annual bluegrass (*Poa annua* L. var. reptans) or Penncross creeping bentgrass (*Agrostis palustris* Huds.) grown on an Owosso sandy loam soil (fine Typic mesic Hapludalf). The irrigation treatments were: apply 2.5 cm of water only upon the appearance of stress (STR), apply 2.54 mm daily (DLY), and maintain the soil at field capacity (FC) using TDR. Simulations began on 1 May and ended on 30 September each year. Volumetric moisture content data measured by TDR for up to 60 days each summer were used to validate the SALUS model. SCHEDULER was

used to evaluate available water content and excess water under these three irrigation regimes. Annual bluegrass and creeping bentgrass biomass and inter-species competition, and quality ratings were also measured. Irrigation scheduling based on TDR was more conservative than from weather-based estimates. Because 1992, 1993 and 1994 were wet years, the stress treatment received no irrigation but quality ratings were also lower for the stress treatment. Bentgrass biomass and quality ratings were significantly higher than for annual bluegrass. Differences among irrigation treatments were significant mostly during dry periods. Excess water as predicted by the SCS-SCHEDULER model and drainage as predicted by the SALUS model ranked, DLY > FC > STR for all years. Average VMC for the rooting depth exceeded the 0.28 cm^3 cm^{-3} field capacity level for more than 50% of the time for the irrigated treatments resulting in overwatering for the irrigated treatments. Volumetric moisture content by depth and irrigation treatment as measured by TDR for most sampling dates were within the range of VMC as predicted by the SALUS model.

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CHAPTER 1

Introduction

It is estimated that about 70% of the earth is covered by water, most of which is sea water. In spite of its apparent abundance, water remains the most limiting factor for crop production in the world. There has been a considerable decline in access to quality water due to an increase in population and industrial growth. Recreational and institutional use also contribute toward the contamination of surface and ground waters decreasing potential water resources.

The natural response to water shortages is to explore new sources. Eventually, water may have to be transported longer distances as local sources are depleted or contaminated. Future generations will need to deal more efficiently with the high cost of pumping, purification, conveyance, and redistribution in the allocation of this important, but limited natural resource.

The quest for maximum yield and high-quality crops has resulted in a significant increase in the amount of land under irrigation. Jensen (1974) predicted a threefold increase in irrigated acreage in the U.S. from 1939 to 1980. Increase in irrigation puts a strain on water allocation and distribution, both locally and worldwide. The growing percentage of potable water used for golf course and home lawn irrigation is a strong reason for reevaluating urban irrigation practices and requirements (Feldhake et al., 1983). In California and Texas, 95% and 55%, respectively, of water resources are used for irrigation (Beard, 1973). In Michigan alone, more than 300 million cubic meters of water are used for conventional crop irrigation annually (GEM Report, 1982). Although this accounts for less than 3% of Michigan's water resources, restrictions on water use in Detroit and many cities across the U.S. are examples of the need to reevaluate water allocation efficiencies, particularly in urban areas.

Evaluation of application uniformity is one component in determining irrigation efficiency. Low application efficiencies reported in the literature for hose-move and sprinkler systems used for irrigation of home lawns (Henggeler, 1993) suggest that turf irrigation scheduling techniques must be improved to increase water use efficiencies. Ideally, such improvement should integrate weather based ET as well as soil moisture depletion estimates.

Soil-based irrigation scheduling requires routine determination of soil moisture content. Gravimetric soil moisture determination is time consuming, destructive, and labor intensive, and requires a 24-hour waiting period. Widespread use of the neutron probe in research (Simpson and Meyer, 1987) and to a limited extent in conventional irrigation scheduling, is not amenable to the shallow rooting depths encountered in fine turf management (Snyder et al., 1984). Adaptation of time domain reflectometry (TDR) to volumetric soil moisture determination in the early 1980s, coupled with innovations in computer and electronic technology, provided avenues for automated soil moisture data retrieval (Baker and Allmaras, 1990) which can be used for turf irrigation scheduling and modeling.

Although irrigation practices may not necessarily coincide with the recommendations, modeling provides a means of evaluating such recommendations without the need for ad hoc experimentation. To do this, a working model that has been evaluated under various conditions and at different locations must be used. Such a model must be accurate with the minimum input data requirement (weather data, management records, and soil- and plant-specific data) possible, user friendly, and efficient with respect to computation time (Ritchie, 1991).

In spite of widespread use of simulation models in crop research, the application of models in turfgrass research has been very limited. There is a need to employ hydrologic models to evaluate potential economic and environmental impact of turf irrigation recommendations in rural and urban communities. In this study, an irrigation scheduling and evaluation model (SCS-SCHEDULER) (Shayya and Bralts, 1988) and the new water balance routine of the Systems Approach to Land Use Sustainability model (SALUS) (Ritchie, 1994) were adapted for turf irrigation management and evaluation. Adaptation and evaluation of both models with respect to soil water dynamics under different turf irrigation scenarios was the focus of this study.

CHAPTER 2

Literature Review

Introduction

America's passion for green and well-manicured turf is so compelling that most homeowners and turf managers invest time, effort, and money for the upkeep of their turf. One aspect of turf culture that has come under close environmental scrutiny is turf irrigation. Irrigation improves the aesthetic and functional value of turfgrass (Beard, 1973; Beard and Green, 1994). Unfortunately, irrigation practices employed by turf managers and homeowners may result in overwatering due to lack of adequate methods for assessing turf irrigation needs.

A significant proportion of urban water is used for turf irrigation. Tovey et al. (1969) stated that water was the second largest expense in turf management, after labor cost. This is particularly true when water is obtained from treated municipal sources. Fok and Murabayashi, (1978) estimated that turf irrigation accounted for 33% to 70% of total water use in some large cities in the U.S. In some states, domestic and commercial turf irrigation consumes more water than any other single crop (Hengeller, 1993). Beard (1973) predicted that the amount of water used in turf irrigation would double by the turn of the century. According to these estimates, additional water resources will be needed to meet this growing demand.

Water use regulations for turf irrigation are no longer restricted to arid regions. Aronson et al. (1987a) concluded that turfgrass culture must be directed toward practices that lower turf water requirement as the competition for water increases. Biran et al. (1981) suggested that homeowners and turf managers may have to accept lower quality turf as a means of reducing annual water consumption for turfgrass irrigation. Also, the use of effluent water for turf irrigation is gaining acceptance across the U.S. (Feldhake et al., 1983).

Efficient water management strategies are necessary to sustain the availability of water for turf irrigation (Watson, 1980). The challenge for turf managers and researchers is to strike a delicate balance between water use for the maintenance of quality turf and other competing uses of water in light of scarce water resources and/or environmental concerns.

A considerable amount of time and effort has been given to the evaluation of turfgrass water requirements (Marsh et al., 1980; Kneebone and Pepper, 1982; Johns et al., 1983; Fry et al., 1989; Aronson et al., 1987). These studies range from evaluations of evapotranspiration (ET) rates within and among species to studies on the effects of various cultural practices on water-use rates (Beard, 1982; Beard, 1985). Danielson et al. (1981) reported high correlations between ET and turf quality. That cool-season grasses have higher ET rates than warm-season grasses has been amply documented (Marsh et al., 1980; Biran et al., 1981; Kneebone and Pepper, 1982; Kim and Beard, 1988). Turfgrass ET in urban environments is site-specific and can vary considerably from regional climate predictions (Feldhake et al., 1983). This calls for a concerted effort to search for site-specific turf irrigation scheduling techniques.

Although Fry and Butler (1989) and Beard (1973) reported no significant difference in ET rates between annual bluegrass and creeping bentgrass, Salaiz et al. (1991) observed high variability in water use rates among creeping bentgrass cultivars. Shearman (1986, 1989) evaluated ET rates of cultivars of Kentucky bluegrass and perennial ryegrass. The results showed interspecific as well as intraspecific differences in ET. These findings suggest the potential for selecting and/or improving cultivars with lower ET rates for water conservation purposes.

Several factors influence water use by turf. The amount of supplemental irrigation needed by turf is a function of the area (A) to be irrigated, the evaporative demand (ET), the efficiency of the irrigation system (EF), the degree of shading (S), the soil type (ST), the time of day (T) when the water is applied, and the desired quality (Q) of the turfgrass (Aurasteh, 1983). He expressed the irrigation need (I) mathematically as:

$$I = f\,(A, ET\ EF, S, ST, T, Q)$$

Water uptake by plants can be affected by the physical properties of the soil. Soil compaction affects soil aeration (Carrow, 1980), bulk density (Boufford and Carrow, 1980), and soil strength (Voorhees et al., 1978). In a greenhouse experiment, Agnew and Carrow (1985) studied the effect of long-term compaction and soil water status on Kentucky bluegrass rooting response and water use. They found that compaction increased root mass in the top 5 cm of the soil. Also, the interaction between compaction and water stress significantly increased root porosity, with a corresponding increase in water uptake under low soil oxygen conditions. Soil compaction may thus reduce water uptake, with a significant decline in turf quality and carbohydrate reserves (Carrow, 1980).

Roots and Plant Water Uptake

Roots play a vital role in plant water and nutrient uptake. Letey et al. (1966) cited root permeability and surface area as two important parameters in the quantification of plant water uptake. Although root characteristics are controlled genetically, environmental influences can affect root distribution within the soil profile (Koski, 1983).

Peacock and Dudeck (1984) studied the effects of irrigation intervals on St. Augustine grass (*Stenotaphrum secundatum L.*) rooting. They reported 42% and 37% decreases in root-length density for the first and second years of their study, respectively, with high-frequency irrigation. They observed more than 90% of the roots within the top 30 cm. Doss et al. (1962) observed a decrease in rooting depth of five warm-season forage species with an increase in soil moisture content. Bennett and Doss (1960) explained an observed increase in rooting depth of cool-season forage species under moisture stress as a drought-avoidance mechanism. Rooting patterns for most turfgrasses are likewise affected by the frequency and amount of irrigation (Beard, 1973).

Root distribution within the soil profile is an important parameter in quantifying plant water uptake. A good correlation between root-length density and water uptake makes this measurement a valuable tool for modeling plant water uptake (Ritchie and Amato, 1990; Hanks, 1992). Rooting depth is an indicator of the soil volume explored by the roots in terms of resource capture (Barber, 1984; Arnon, 1992). The root-shoot mass ratio provides an estimate of the partitioning of assimilates in response to environmental conditions. Beard (1973) reported seasonal variations in the partitioning of assimilates to the shoots and roots. Reduced carbohydrate reserves during periods of water or temperature stress may alter assimilate partitioning between roots and shoots (Valoras et al., 1966). Furthermore, water and nutrient uptake, growth rate, and turf quality may be affected by extreme temperatures or water stress (Schmidt & Snyder, 1984).

Water Use and Turf Quality

In turfgrass management, dry matter accumulation and yield are not meaningful measures of response. Aesthetic appeal, turf quality, and stress tolerance of turfgrass are of greater interest to homeowners and turf managers. Limited research has been conducted to quantify, in detail, the relationship between soil water content and turf quality (Fairbone, 1982). Feldhake et al., 1983 showed a linear relation between ET and turfgrass quality. Whereas limited water availability correlates positively with lower turf quality, high moisture content does not necessarily correlate well with high turf quality (Danielson et al., 1981). High moisture content can result in water-logged soils with poor oxygen diffusion rates, which may cause reducing conditions over extended periods with potential reduction in turf quality. Despite the qualitative and subjective nature of turfgrass quality ratings, Aurasteh (1983) suggested that correlations between turf quality ratings and plant-available water could be used to improve turf irrigation scheduling.

Field Capacity and Irrigation Scheduling

Field capacity is a controversial, but useful concept. It is defined as the soil moisture content after gravitational water has drained (Hall and Heaven, 1970). Like the wilting point, field capacity also depends on soil texture (Taylor and Ashcroft, 1972), with moderations from temperature and previous wetting history (Cuenca, 1989). A soil attains field capacity when drainage from that soil, which was previously at or near saturation, has decreased markedly. This is generally assumed to occur 24 to 48 hours after wetting, depending on soil type (Cassel and Nielsen, 1986).

Although field capacity is used as the upper limit of available soil moisture in most crop models, it is important to note that most soils do not drain to a fixed field capacity, nor is this soil characteristic maintained indefinitely (Hanks, 1992). Also, the use of field capacity as the upper limit may be a conservative estimate because some gravitational water may be available for plant growth (Hanks and Hill, 1980; Ritchie and Amato, 1990). In irrigation scheduling, total plant available water is defined as the difference between FC and the permanent wilting point. Plant available water at various moisture contents can be determined as a fraction of total available water. This has practical applications in the determination of irrigation frequency (I_{fr}) based on historic average ET.

$$I_{fr} = \frac{Plant\ available\ water\ (mm)}{Average\ ET\ (mm\ day^{-1})}$$

Irrigation scheduling requires the determination of ET (Cuenca and Amegee, 1987). Conventionally, this determination is based on one of many ET models using climatological data. Some irrigation schedulers often ignore soil moisture content evaluations. However, such measurements provide valuable information on the soil hydrologic processes, such as infiltration, leaching, and evapotranspiration, as well as irrigation scheduling.

Spatial and temporal variations of soil moisture storage require routine monitoring of soil moisture in order to reduce the incidence of water stress to turfgrass. According to Amer et al. (1994), progress in the characterization of soil moisture in space and time depends on the development of cost-effective measurement tools.

Water storage in soils depends on the fraction of the total pore space occupied by water or air and is expressed as a mass or a volume fraction or percentage of the dry soil. Volumetric soil moisture content has practical application as rainfall and irrigation are expressed in terms of equivalent depth of water (D_e) per unit area. A unique advantage of this measurement is that it provides a basis for quantifying equivalent depths for a given amount of rainfall or irrigation (Hanks, 1992).

Until recently, repeated soil moisture determination has been impeded by the lack of rapid, economical, safe, and accurate techniques for VMC determination. For cool-season grasses grown on sand mixes other than U.S. Golf Association (USGA) greens, low-volume, high-frequency irrigation is necessary to compensate for low water retention capacities, in order to maintain high-quality turf. Methods of soil moisture determination include gravimetric (Hanks and Ashcroft, 1980), neutron attenuation (Belcher et al. 1950), electrical resistance (Kirkham and Taylor, 1950; Gardner and Kirkham, 1952), tensiometer (Hagan and Haise, 1967; Hillel, 1980), and TDR (Topp et al. 1980) techniques.

Gravimetric Soil Moisture Determination

The gravimetric method of determining soil moisture content is the standard against which all other methods are compared. It measures the mass of water per unit mass of bulk soil after drying to constant weight at 105°C (Black, 1965). This method requires the collection of several samples and at least a 24-hour drying period. Although the method does not require expensive equipment, it is labor intensive and destructive, and thus it fails to allow for repetitive measurements on the same site. Subsequent determinations are thus subject to spatial variability.

Tensiometers

Tensiometers have been used successfully in irrigation scheduling, with considerable savings in terms of water use. For example, Snyder et al. (1984) reported significant reductions in turf water use with tensiometers. Automated irrigation systems have been designed in which tensiometers are used to activate the irrigation system (Arnon, 1992). These savings, nonetheless, are accompanied by an escalation in costs. Another drawback to using tensiometers is that they require frequent servicing and must be removed from the field during the winter months in cold regions. Today, the use of tensiometers for irrigation scheduling is limited to high-value crops.

Soil moisture potential reflects plant response to water stress better than does volumetric water content (Hagan and Haise, 1967). However, the effective moisture range covered by tensiometers is limited from saturation to about 80 kPa. The water potential is converted to soil moisture content by using the soil moisture characteristic curve. Because this curve is assumed to be unique for each soil type, several curves may be needed for a single field. Although this range may cover about 90% of the available moisture in sandy soils (Arnon, 1992), it encompasses less than 50% of the moisture range for clay soils (Hillel, 1980; Arnon, 1992). At tensions beyond 80 kPa, air penetrates into the ceramic cup and the instrument becomes dysfunctional (Arnon, 1992).

Tensiometers measure a small soil volume and are thus subject to problems associated with spatial variability. Richards and Marsh (1961) proposed installing tensiometers at different depths to monitor soil moisture depletion for the purpose of irrigation scheduling and suggested using several tensiometers to account for spatial variability in soils.

Neutron Probe

The neutron probe consists of a source of fast neutrons, usually a mixture of americium or radium with beryllium, that emits alpha particles, and a slow neutron detector. Once the housing is removed, the neutrons collide with various atomic nuclei in the soil (Belcher et al., 1950). The nuclei of elements with low atomic weight, especially hydrogen, thermalize the alpha particles. Because water is the main source of hydrogen in soils, the number of thermalized neutrons, as recorded on the scaler, is correlated to the volumetric soil moisture content.

Soil moisture determination with the neutron probe is independent of soil salinity under field conditions (Arnon, 1992). Improvements in portability and reductions in electronic and radioactive hazards have increased the use of the neutron probe as a tool for irrigation scheduling (Gear et al., 1977). Application of the neutron probe in turf irrigation was reported by Snyder et al. (1984). The dependence of the spatial resolution on the water content (van Bavel, 1962) and the inaccuracies in predicting near-surface soil moisture content (Snyder et al. 1984) make the neutron probe a less attractive alternative in turf irrigation scheduling. Also, such disadvantages as the high initial and maintenance costs, and potential radioactive hazard, have limited the use of the neutron probe primarily to research (Arnon, 1992).

Electrical Resistance Blocks

Soil moisture measurements with electrical resistance units involve a pair of electrodes embedded in a porous material, usually gypsum, fiberglass, or nylon, buried in the soil. The linear relationship between moisture content and electrical resistance is used to interpolate the moisture content for various electrical resistance measurements. The need to calibrate for each soil type, and the deterioration of gypsum blocks, make measuring soil moisture with electrical resistance blocks highly labor intensive (Cassel, 1984).

The use of soil moisture sensors as tools for irrigation scheduling simplifies the decisions about when to irrigate and how much water to apply. However, gravimetric measurements, electrical resistance and gypsum blocks, and tensiometers in soil moisture studies in laboratory experiments or in field trials have failed to demonstrate the same level of versatility and convenience as time domain reflectometry (TDR) (Topp and Davis, 1985a).

The demonstrated success of TDR technology in soil moisture determination in laboratory (Topp et al., 1980) and in field experiments (Topp and Davis, 1985a & b; Carrow, 1991; Saffel, 1994) shows great promise for potential use in turf irrigation scheduling. Although research on TDR has been primarily limited to laboratory experiments (Heimovaara et al., 1993) this technique can be used to maintain quality turf without compromising environmental quality (Carrow, 1991, Saffel, 1994).

Timing Criteria for Soil-based Irrigation

Irrigation timing is important, regardless of the system of employed. Soil moisture monitoring indicates when the soil moisture content has attained a critical limit beyond which plant growth and quality are affected (Jensen et al., 1971). Management allowable depletion (MAD) is one of the most frequently used timing criteria for soil-moisture-based irrigation scheduling (Stegman, 1985; Cuenca, 1989; Campbell and Campbell, 1982). Doorenbos and Kassam (1979) suggested a 50% allowable depletion, with adjustments of up to 30%, based on evaporative demand, for most crops and soils. Establishing such a threshold provides timing criteria for irrigation scheduling. With low-volume, high frequency irrigation, the allowable depletion approach becomes less critical because irrigation rates and amounts are held within the infiltration rate and storage capacity of the root zone (Stegman, 1950). However, environmental concerns and water shortages are also compelling considerations for more efficient water management strategies.

Using TDR Topp and Davis (1985a) described soil-based irrigation scheduling as a simple network whose major limitation has been soil moisture monitoring and interpretation. The TDR method has been proven effective for soil moisture determination in field crops and to a limited extent in turf soils. The remainder of this discussion focuses on the origin, development, and agricultural applications of TDR.

Time Domain Reflectometry

The process of sending high-frequency electromagnetic signals and analyzing the waveforms through different media is called time domain reflectometry (TDR) (Campbell, 1990). Telephone and electric companies have used TDR extensively for cable testing, to locate cable ends and defects (Dalton, 1992). In the last decade, agricultural applications of TDR have received much attention.

Time domain reflectometry originated from attempts to predict molecular structures from the frequency dependence of the dielectric constants of organic molecules (Fellner-Feldegg, 1969). Studies on the application of TDR for determining dielectric properties of soil were first reported by Davis and Chudobiak (1975). In 1977, Davis et al. reported the electromagnetic detection of soil water content using TDR.

Credit for the development of agricultural applications of TDR has been given to Topp and his co-workers. Topp et al. (1980) proposed an empirical polynomial relationship between volumetric soil moisture content (VMC) and the apparent dielectric constant of soil (ϵ). They assumed that the dielectric constant of soil, for all practical purposes, was insensitive to variations in bulk density, temperature, salinity, and mineral composition (Topp et al., 1980; Baker and Almaras, 1990), eliminating the need for site-specific calibration.

Since its discovery in the early 1980s, agricultural applications of TDR have been extensively evaluated (Topp et al., 1980, 1980; Topp and Davis, 1985a, b & c; Dalton and van Genuchten, 1986; Baker and Allamras, 1990; Wraith and Baker, 1991). These researchers confirmed that TDR determination of soil moisture was not significantly affected by bulk density, temperature, salinity, or mineral composition of the soil. This finding, strengthened the argument for a single empirically derived calibration curve for most soils. Recent research, however, has demonstrated the dependence of the soil dielectric constant on temperature and bulk density (Roth et al. 1990).

Knight (1993) investigated the effect of probe geometry, and Zegelin et al. (1989) studied the effect of transmission line geometries on measurements of VMC by TDR. Roth et al. (1990) resolved the composite dielectric constant of soil into real and imaginary components. Their work also showed that the composite dielectric constant of soil can be resolved into the contributions of the water, soil, and air fractions, while Paterson and Smith (1981) concluded that TDR discriminates between frozen and free water.

An advantages of TDR is the ease of automation for remote VMC data retrieval (Baker and Allmaras, 1990; Heimovaara and Bouten, 1990; Herkelrath and Hamburg, 1986). Hook et al. (1992) used remote diodes to improve soil water determination by TDR, particularly in saline or layered soils. They recovered the effective amplitude of problem waves with significant reduction in background noise through the amplification of highly attenuated waves. Their work showed that reliable VMC measurements could be obtained even at locations of up to 100 m from the TDR unit. For TDR applications involving several pairs of TDR probes, multiplexing has become the method of choice for automated data retrieval (Baker and Allmaras, 1990).

Using an impedance-matching transformer (balun) to reduce the mismatch at the connection between the probes and the transmission lines is a common practice that improves the resolution of the TDR trace (Biran et al., 1981). Bonnell et al. (1991) compared probes with and without baluns. They concluded that the TDR wave resolution for probes with a balun was superior to those without. Hook et al. (1992) used a three-diode probe to obtain better wave resolutions compared to a two-wire probe. Comparing multiple-wire probes to the standard two-wire probes Zegelin et al. (1989) concluded that three-wire probes provided better resolution than two-wire probes but that probes with four or more wires did not further improve TDR resolution.

Application of TDR to Soil Water Determination

The permittivity (dielectric constant) of a medium is a measure of the polarization of the medium when subjected to an electric field (Ledieu et al., 1986). TDR measures the transit time of generated electromagnetic waves along a probe pair embedded in the soil. The velocity of a wave along the probe is determined from the travel time, based on the reflections at the beginning and end of the probes. The propagation velocity of a wave depends on the dielectric constant within the medium of propagation (Topp et al., 1980; Ledieu et al., 1986).

A pulse generator produces a time-step impulse whose reflections are monitored by an oscilloscope. The dissipation of the signal amplitude varies with the bulk soil electrical conductivity (Ledieu et al., 1986). The pulse travel time is proportional to the soil apparent dielectric constant, which is proportional to the soil water content (Topp et al., 1980; Dalton, 1992). At the end of the probe, the electromagnetic wave is reflected back to the TDR unit. The elapsed time from the emission to the reception of the reflected pulse is a function of the probe length and the dielectric constant of the soil.

Soil moisture determination using TDR is thus based on a step-pulse transit time along the length of the TDR probes (Topp et al., 1980). This measurement has been extensively correlated to gravimetrically determined volumetric soil moisture content measurements. The pulse velocity is calculated from the transit time over twice the length of the probe. The volumetric soil moisture content is related to the distance between inflection points.

A critical step in TDR application to VMC determination is the identification of the inflection points. The first inflection point, which is the junction of the probe and the transmission line, is unaffected by the soil water content or salinity (Dalton et al., 1984). The second inflection point, which occurs at the end of the probe, may be very weakly defined in problem waves due to dissipation of the voltage in highly dispersive media (saline soils) or noises in the circuitry (Dalton, 1992).

Tangents at the inflection points are used to determine the distance between reflections. When manually obtained, such measurements are subject to error (Dasberg and Nadler, 1987). Keng and Topp (1983) identified the detection of the inflection point as a major source of error in VMC determination by TDR. Computer algorithms provide better estimates of the inflection points and travel times and, therefore, more precise VMC measurements. However, computer-determined inflection points may not necessarily discriminate between good and problem waves (Keng and Topp, 1983; Yanuka et al., 1988). The derivation of the relationship between soil dielectric constant and volumetric moisture content, as presented by Topp et al. (1980), is as follows. The pulse velocity, **v**, of an electromagnetic wave in a medium of dielectric constant, ϵ, is given by:

$$v = \frac{c}{\sqrt{\epsilon}}$$

where ϵ is apparent soil dielectric constant and **c** is speed of light. The wave velocity back and forth the probe length, **l** is given by:

$$v = 2\,\frac{l}{t}$$

where **t** is transit time which ranges from 2 to 3 ns. Rearranging the above equations results in:

$$\epsilon = \frac{c^2 t^2}{4 l^2}$$

The pulse travel time is proportional to the soil dielectric constant, and the dissipation in the wave amplitude is proportional to the bulk soil electrical conductivity (Bonnell et al., 1991). Volumetric moisture content is estimated from the soil dielectric constant, according to the empirical relationships developed by Topp et al. (1980) and Ledieu et al. (1986). Only the equation of Topp et al. (1980) is presented here:

$$VMC = -0.053 + 0.0292\epsilon - 0.00055\epsilon^2 + 0.0000043\epsilon^3$$

The TDR trace shows the inflections of the pulse as the impedance varies due to mismatch or changes in capacitance around the transmission lines. The signal energy is dissipated as the wave travels along the cable (Zeglin et al., 1992). The magnitude of the loss depends on the type of wire. A twisted-pair wire generally incurs higher losses than coaxial cable (Pierce, 1992, personal communication).

TDR Set-up

A principal component of the TDR is a metallic cable tester, which is employed principally to locate faults in metal cables used in the communications industry (Dalton, 1992). The TDR system consists of a high-speed oscilloscope connected to coaxial cables that are linked to a set of probes embedded in the soil. For automatic data retrieval, the oscilloscope is further connected to a computer or data logger.

Probes usually are made of nonmagnetic materials whose conductivity is greater than that of the medium of interest. In soil studies, stainless steel normally is used (Dalton, 1992). Ramo et al. (1965) proposed the following relationship for approximating probe impedance:

$$Z_o = \left(\frac{120}{\sqrt{\epsilon}}\right) \ln \left(2\frac{s}{d}\right)$$

where Z_o is probe impedance, ϵ is soil dielectric constant, s is probe separation distance in centimeters, and d is probe diameter in centimeters. The wave propagation velocity is affected if the cable or probe impedance does not match the TDR output impedance of 50 Ω. Baluns are thus used to reduce this mismatch (Spaan and Baker, 1993).

Effect of Probe Length Spacing and Diameter

The accuracy of the TDR reading depends, in part, on the probe length, which is a function of the reflection coefficient (ρ), the dielectric constant (ϵ), and the bulk soil electrical conductivity. Dalton et al. (1984) and Dalton and van Genuchten (1986) proposed equations for predicting the maximum probe length (l) for reflection coefficients of at least 10%:

$$l = [\ln (\frac{V_T}{V_R})\sqrt{\epsilon}] \ / \ (120\rho)$$

where V_T and V_R are the amplitudes of the transmitted and reflected waves, respectively, and ρ is the reflection coefficient determined from:

$$\rho = \frac{Z_{o_{(j-1)}} - Z_{o_{(j)}}}{Z_{o_{(j-1)}} + Z_{o_{(j)}}}$$

where $Z_{o(j-1)}$ is the apparent frequency of the first reflection and $Z_{o(j)}$ is the apparent frequency of the next reflection (Dalton, 1992).

Highly conductive soils require shorter probe lengths than soils with low bulk soil electrical conductivity. Short rod lengths induce greater errors than long rods in the identification of inflection points, whereas long rods reduce resolution as voltage decays exponentially along the probe length (Dalton, 1992).

Yanuka et al. (1988) addressed the problems of frequency loss by attenuation. They proposed the following equation for calculating the apparent frequency ($\boldsymbol{Z_a}$):

$$Z_o = \frac{Z_s}{\sqrt{\epsilon}}$$

where $\boldsymbol{Z_s}$ is frequency in the air, $\boldsymbol{Z_a}$ is apparent frequency in the medium of interest, and ϵ is dielectric constant. Whereas probe diameter has no significant influence on the TDR readings, the probe spacing significantly affects soil moisture readings (Knight, 1993). On the basis of spatial resolution of the TDR, a 50 mm spacing has been recommended as the optimal spacing distance for most soil research (Topp et al. 1980; Dalton, 1992).

Spatial Resolution of TDR

The spatial resolution of the TDR is another concern in soil water determination. Theoretical analysis (Topp et al., 1980) and experimental measurements (Dalton et al., 1984; Knight et al., 1993) have suggested that TDR measures an integrated VMC average along the probe length. Baker and Lascano (1989) suggested that the area of influence of TDR ranges from elliptical to rectangular, with no significant variation in sensitivity along the length of the wave guide. The approximate soil volume measured by TDR using the proposed configuring is slightly larger than a cylinder of diameter wider than the probe separation distance.

Using a set of TDR probes with 3.2 mm in diameter, 50 mm spacing distance, and 300 mm long, Baker and Lascano (1989) estimated an effective spatial area of about 1000 mm^2 along the length of the probe. Ledieu et al. (1986) stated that 94% of the electromagnetic energy is restricted to a cylinder with a diameter twice the rod spacing; they also suggested a 50 mm thickness as the maximum effective spacing between probes. Unlike the neutron probe, spatial resolution of TDR is independent of moisture content (Arnon, 1992).

Limited information is available on the spatial and temporal distribution of water in surface soils under different irrigation regimes. Ritchie (1972) developed equations relating soil moisture depletion patterns with time for a bare soil in order to predict water use rates and irrigation needs. Time domain reflectometry provides as high accuracy, precision, and spatial and temporal resolution as the neutron probe, without the need for site-specific calibration or the potential risk of exposure to radiation (Wraith and Baker, 1991).

The spatial resolution of a soil moisture measurement technique depends on the sampling volume. Variation in soil moisture content resulting from infiltration and soil moisture extraction by roots contribute to differences in VMC over short distances (Baker and Lascano, 1989). This variability may be accentuated by cracks, biopores, textural layering, and fingering, as well as preferential routing by roots and water resulting in larger sampling errors (Bouma et al., 1982).

Applications of TDR to Agricultural Research

The empirical relationship between soil water content and soil dielectric properties has been applied successfully in many studies (Patterson and Smith, 1981; Dalton and van Genutchten, 1986; Zeglin et al., 1989; Heimovaara and Bouten, 1990). Topp et al. (1983) used TDR in field infiltration studies to monitor the advancement of a wetting front. Volumetric water content and bulk soil salinity were determined simultaneously by Dalton (1987) and Topp et al. (1988).

Advantages of TDR for Soil Moisture Determination

Major weaknesses of the gravimetric method of volumetric moisture determination are the concurrent determination of bulk density and soil mass water content, and destructive sampling. Errors inherent in standard soil moisture determination methods also raise questions as to the accuracy of these methods, given the spatial and temporal variations in bulk density.

Time domain reflectometry provides excellent spatial resolution (Hook et al., 1992). Roth et al. (1990) showed that the uncertainty in water content for a broad range of soil types did not exceed 0.013 cm^3cm^{-3}. Ledieu et al. (1986) reported an accuracy of within 1% VMC. For all practical purposes, moisture measurements by TDR presents no radioactive risks, are independent of soil type and salinity (Topp et al., 1980); thus require no calibration for most mineral soils. The stainless steel probes used in TDR are not expensive. Also, the ease of automation with multiplexing for remote data retrieval is a distinct advantage of this technique (Baker and Allmaras, 1990; Hook et al., 1992).

As opposed to the neutron probe, TDR has been applied to near-surface measurements of soil water without any loss in accuracy (Topp et al., 1980, 1982, ; Topp and Davis, 1981). In turf management, Carrow (1991) and Saffel (1994) successfully demonstrated the potential use of TDR for measuring soil moisture depletion and irrigation scheduling. Once the TDR probes are installed, the technique is nondestructive and can be used for continuous monitoring of soil moisture content when automated.

A method of soil moisture determination that is fast, accurate, precise, dependable, and affordable is desirable for soil-based irrigation scheduling and irrigation modeling. Research on the use of such technology for the high-frequency, low-volume irrigation in turf management is necessary to evaluate the benefits of turf irrigation modeling and efficient irrigation water management. The objective of the turf manager after all is to provide optimum turf quality and reduce the potential for leaching of agricultural chemicals into ground water.

Disadvantages of TDR for Soil Moisture Determination

Certain exceptions have been encountered in the use of Topp's empirical relationship. In their investigation, Patterson and Smith (1981) and Baker et al. (1982) found that the small difference between the dielectric constant of ice (3.2) and that of soil (2.5-3.5) may cause difficulties in measuring water contents in thawing frozen soils. Topp et al. (1980) and Herkelrath et al. (1991) suggested that high soil organic matter content causes lower dielectric values and lower VMC. Nadler et al. (1991) outlined difficulties encountered in the interpretation of TDR signals in layered soils. These problems indicate the need to explore further the capabilities of TDR for soil moisture determination in unusual soil situations.

Despite the widely reported ease of remote retrieval of data through multiplexing, (Dasberg and Dalton, 1985) extensive field trials using this method have not been successful. This has delayed the use of TDR in real-time irrigation programming. The attenuation of the electromagnetic impulse by long cables, saline soils, and layered soils (Topp et al., 1985a) is a problem that needs to be resolved. The air-gap effect (Anann, 1977; Topp et al., 1988), variation of moisture content along the probe length, variability resulting from contact with succulent roots and/or living organisms such as earthworms (Saffel, 1994), and the calibration recommended for organic samples (Topp et al., 1980; Dalton, 1992) are some limitations of TDR determination of VMC. Keng and Topp (1983) cited the accuracy in inflection-point delineations as a major source of error in VMC determination by TDR. This was true for both manually obtained or computer-derived inflection points.

In spite of the above-mentioned advantages of TDR as a practical tool for soil moisture determination, there is a need to improve the reliability, precision, and accuracy of TDR readings. Such improvements will come about through a better understanding of the theory and limitations of the TDR. Spatial and temporal variations in soil properties may cause variable wave forms without distinct inflection points, resulting in problem reflections that make it difficult to obtain reliable VMC readings. Frequent breakdowns of soldered junctions between stainless steel probes and cable wires require time and effort to repair and may alter the integrity of the waves. New probe designs and construction reduce the chance of breakdown as the junctions of the probes and the cable wires are mounted and molded in an epoxy resin that reduces the chances of breakdown. As with the neutron probe, the prohibitive initial cost of the TDR equipment is a deterrent to its practical use by turf managers.

The general objectives of this study were to evaluate the use of TDR in turf irrigation scheduling, evaluate the competition between annual bluegrass and creeping bentgrass fairway turfs under three irrigation regimes and to evaluate soil moisture retention predictions from two irrigation models to TDR estimates.

Chapter 3 addresses the adaptation of TDR for volumetric soil moisture content determination and irrigation scheduling in fairway turfs. Chapter 4 deals with annual bluegrass-creeping bentgrass competition under three irrigation regimes. Chapter 5 evaluates bihourly moisture depletion patterns during daylight hours. In Chapter 6, the water balance subroutine of the Systems Approach to Land Use Sustainability (SALUS) model was used to evaluate hydrologic components for turfgrass ecosystems during the summers of 1992 through 1994 and in Chapter 7 an irrigation scheduling model (The SCS-SCHEDULER) was used to evaluate seasonal water applications, excess water and excess rainfall and excess irrigation for the three irrigation regimes.

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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

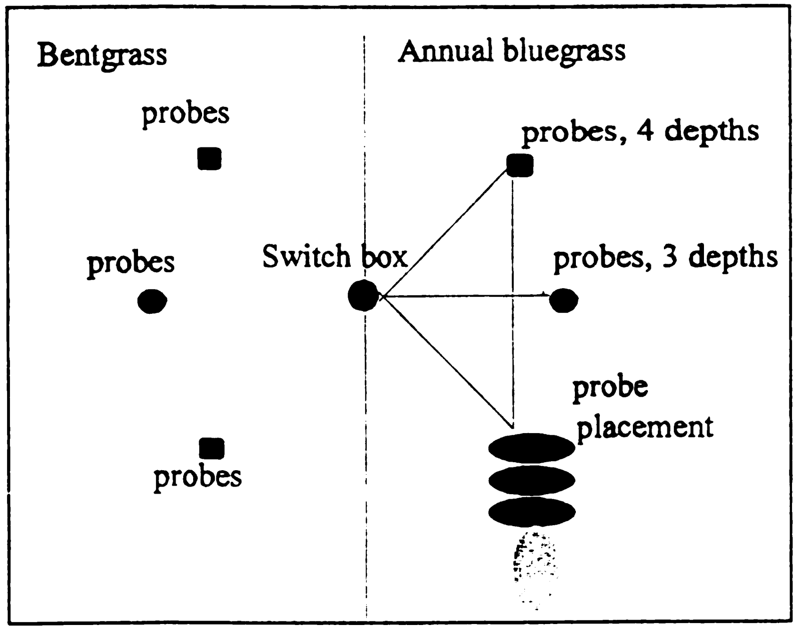

Fig. 3.1 Spatial arrangement of TDR probes per plot for the different depths.

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):

$$VMC = -0.053 + 0.0292\epsilon - 0.00055\epsilon^2 + 0.000004393\epsilon^3$$

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

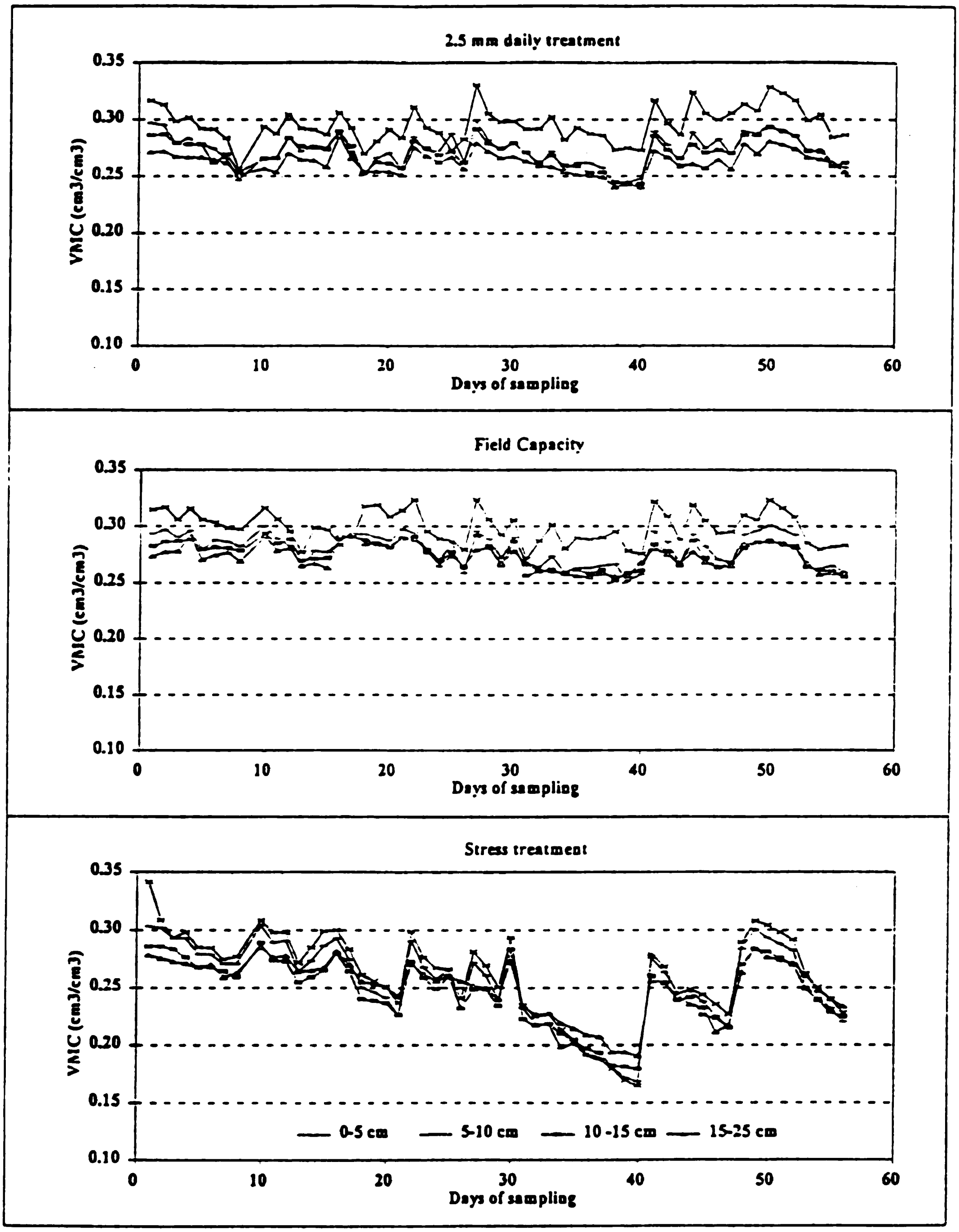

Fig. 3.2. Volumetric moisture content (VMC) means for the different irrigation treatments by depth, 1992.

> 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

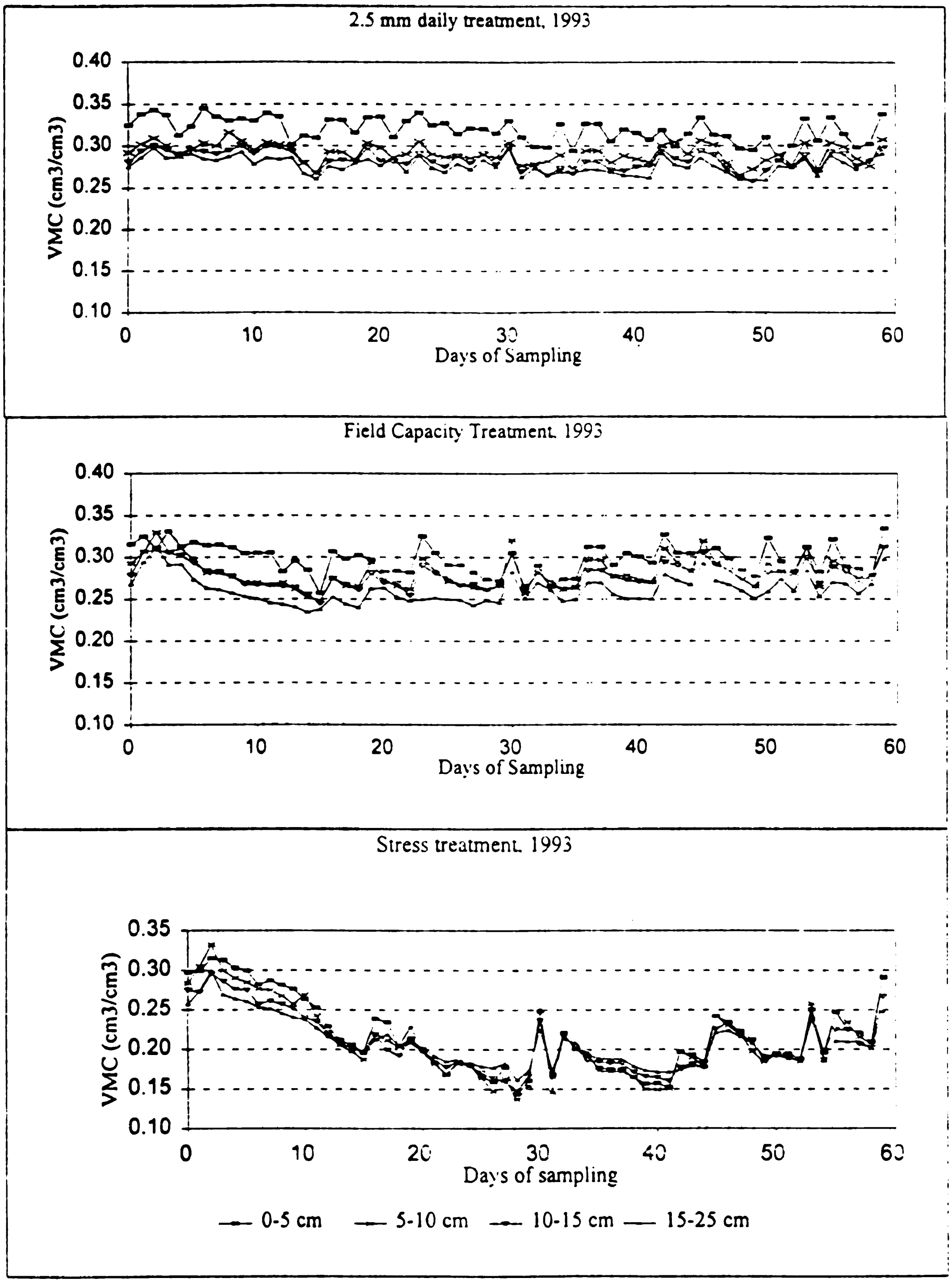

Fig. 3.3. Volumetric moisture content (VMC) for the different irrigation treatments by depth, 1993.

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.

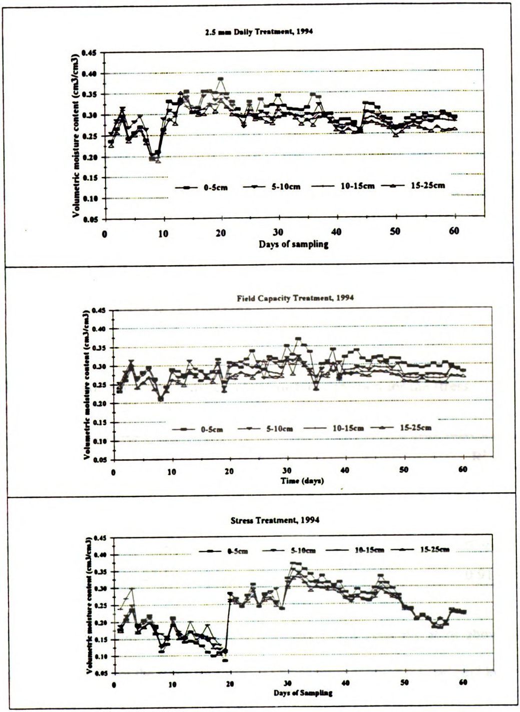

Fig. 3.4. Volumetric moisture content (VMC) means for the different irrigation treatments by depth, 1994.

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	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^3cm^{-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,

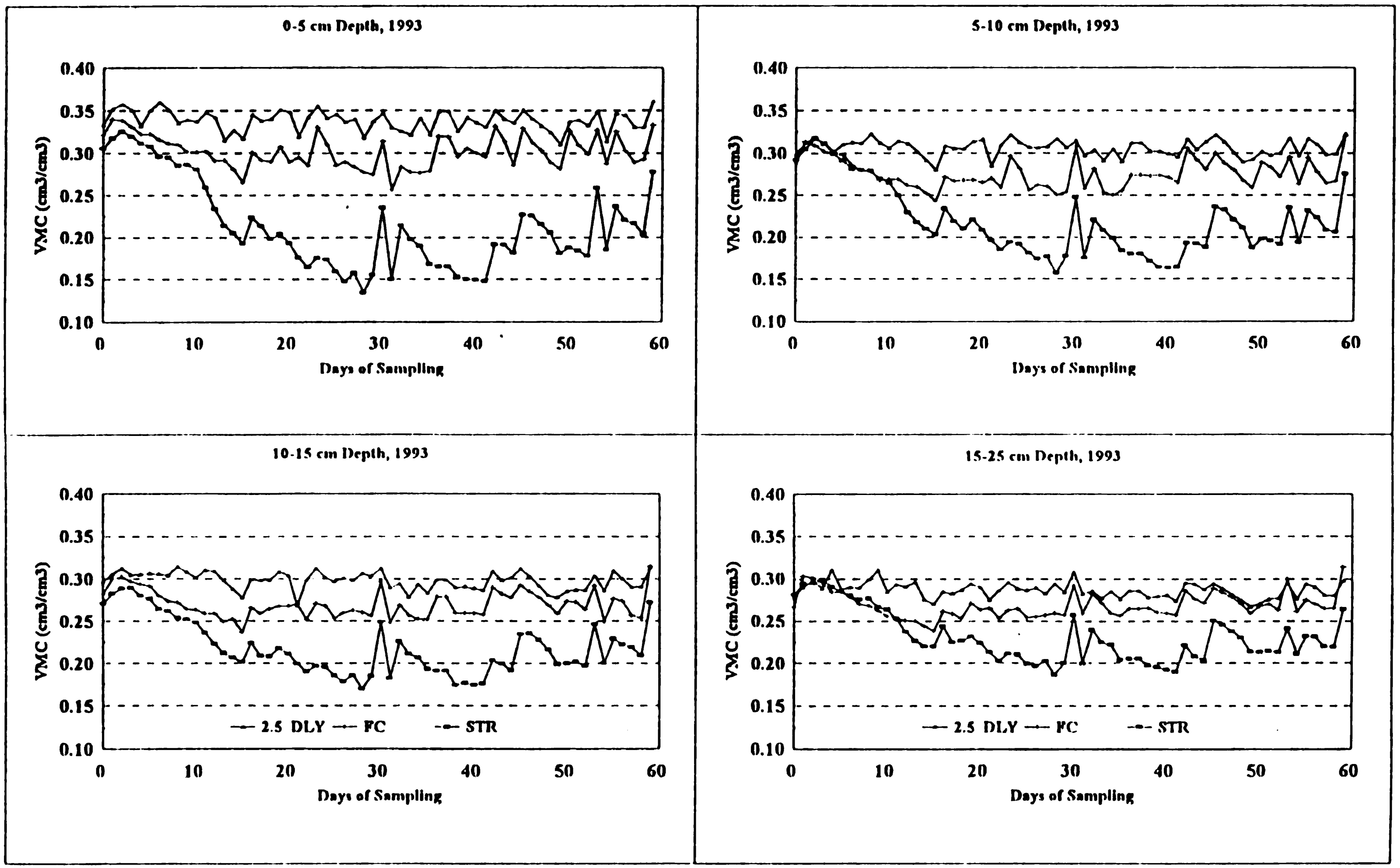

Fig. 3.5. Moisture depletion patterns across species for the different irrigation treatmenrs at four depths, 1993.

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

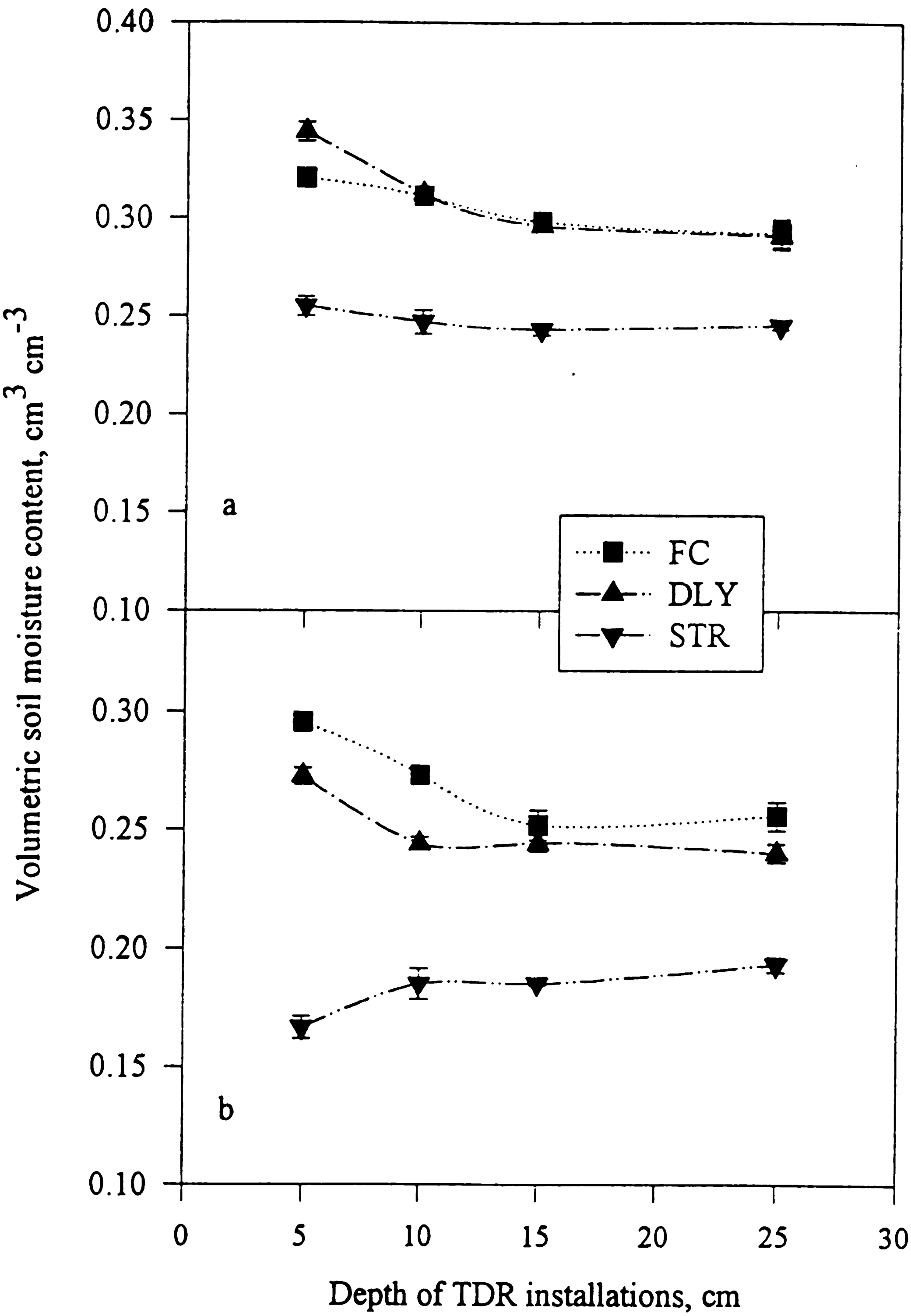

Fig. 3.6. Moisture depletion means across species for the field capaciy, FC; 2.5 mm daily, DLY; and stress, STR treatments for 20 Aug. 1993 (a wet day, **a**) and 25 Aug. 1992 (a dry day, **b**).

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

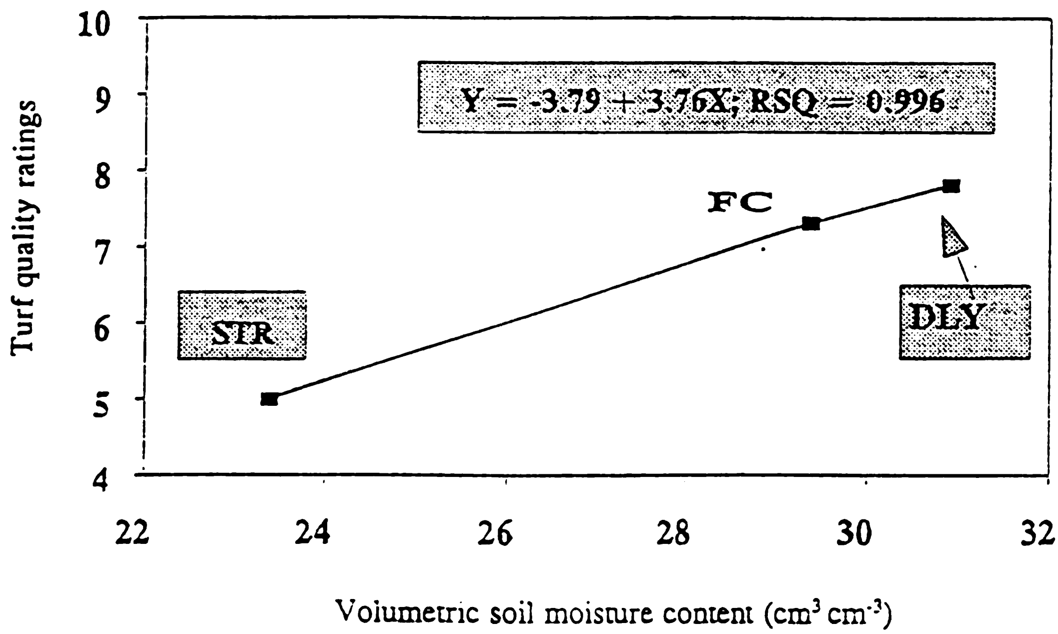

Fig. 3.7. Volumetric moisture content (VMC) means versus turf quality means, 1992.

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.

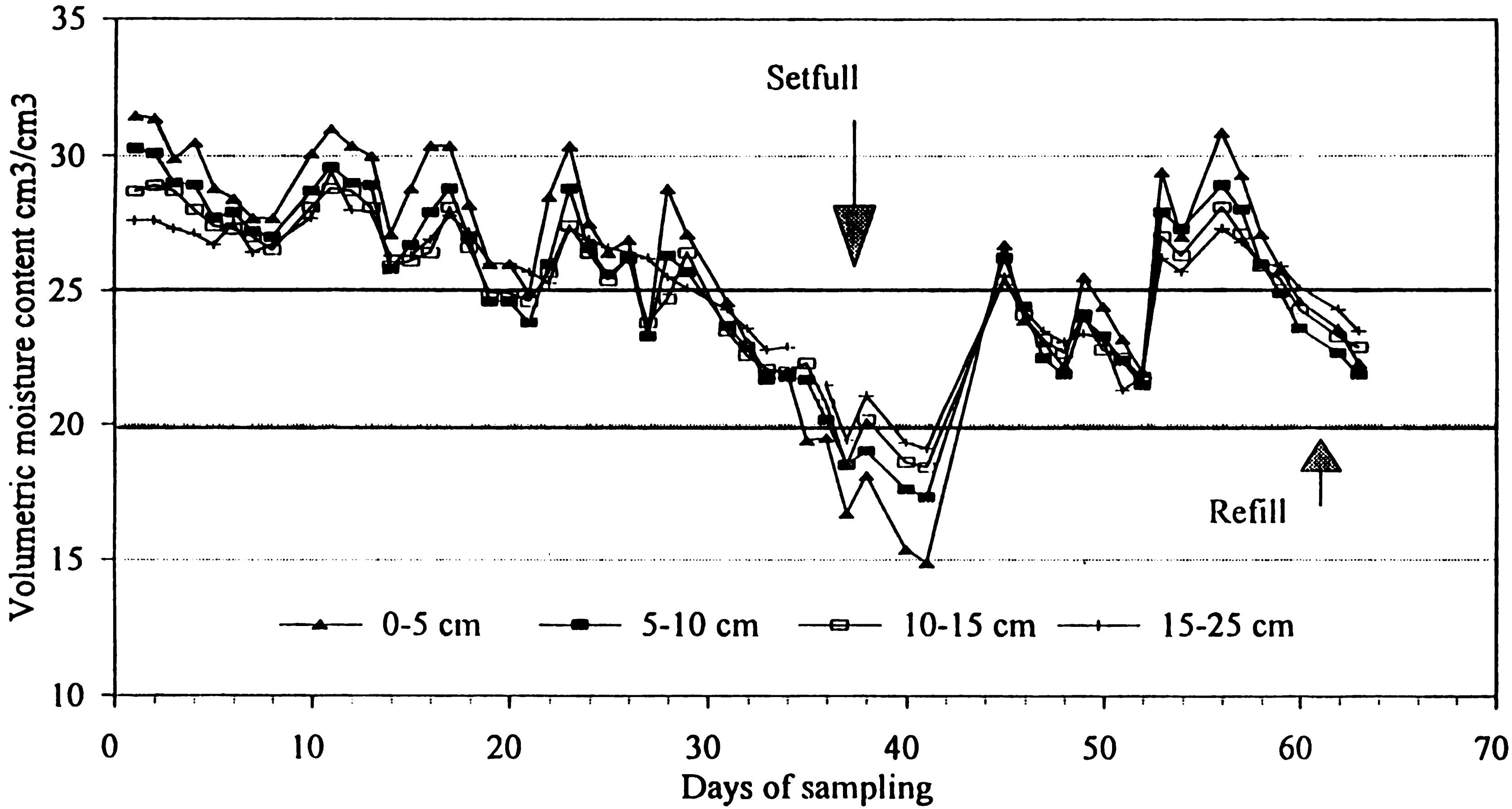

Fig. 3.8. Moisture depletion by depth for the stress treatment during a dry down period in 1992.

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.

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CHAPTER 4

Annual Bluegrass and Creeping Bentgrass Competition Under Variable Irrigation Treatments

Abstract

Interspecific competition between annual bluegrass (*Poa annua* L. var. reptans) and creeping bentgrass (*Agrostis palustris* Huds. L.) has gained much attention over the years as efforts to control annual bluegrass economically have not been very successful. It is widely agreed that annual bluegrass is favored over creeping bentgrass in compacted soils especially when over irrigated. A 3-year study (1992-1994) was conducted at the Hancock Turfgrass Research Center to evaluate the interspecific competition between annual bluegrass and Penncross creeping bentgrass fairway turfs under three irrigation regimes: i) apply 2.5 mm daily irrespective of rainfall; ii) return soil to field capacity based on daily TDR estimated moisture deficits; and iii) apply 25 mm only upon the appearance of wilting stress. Irrigation blocks, established in 1989 with dimensions (11 x 11 m), were split (11 x 5.5 m) and seeded at random as pure stands of annual bluegrass or creeping bentgrass. The turfs were mowed at a height of 16 mm and maintained according to standard practices for cool-season fairway turfs in Michigan. Volumetric soil moisture content (VMC) was measured daily between 700 and 900 h except on rainy days using horizontally installed time domain reflectometry (TDR)

probes at 0-5, 5-10, 10-15, and 15-25 cm depths. The TDR readings averaged over all depths were used to determine irrigation need for the field capacity treatment (FC). Turf biomass, quality ratings and interspecific competition were evaluated. Root mass densities were greatest in the 0-5 cm depth, ranging from 63-73 % of total root mass with an average of 69.7% for 1993 and 1994. The two year average for the percent root mass by depth for the 5-10, 10-15, and 15-25 cm depths were 15.9, 9.5 and 4.4% respectively. Quality ratings for bentgrass were significantly higher than for annual bluegrass. Annual bluegrass/creeping bentgrass species composition was not significantly affected by irrigation treatment. High bentgrass percentages on both annual bluegrass and creeping bentgrass plots was strong evidence of superior bentgrass competition over annual bluegrass under our conditions.

Introduction

Annual bluegrass (*Poa annua* L var. reptans) is a highly competitive species on closely mowed irrigated golf course fairways (Beard et al., 1978). The invasive nature of this weed is favored by: i) the proliferation of persistently viable seeds; ii) strong fibrous roots; iii) lack of a dormancy mechanism and iv) compacted soils (Beard, 1973; Beard et al., 1978; Gaussoin, 1988).

Proper shot control on fairways requires optimum turfgrass uniformity, density, smoothness, and resiliency (Beard, 1982). These factors depend, in part, on soil moisture content. Irrigation of fairway turf should be based on evaporative demand, rooting depth, soil moisture depletion, topography, and traffic intensity (Beard, 1982). Ideally, just enough water should be applied to meet plant requirements. In practice, turf irrigation continues to be a challenge for many turf managers, sometimes resulting in overwatering even as water shortages are reported in some parts of the U.S.

Both annual bluegrass and creeping bentgrass show striking similarities in adapted growing conditions and cultural requirements such as cutting height, mowing frequency, and a wide range of tolerance of fertilization requirements (Beard, 1973; Vargas, 1994). However, different pH, irrigation, and N fertilization requirements are traditionally recommended for each species (Beard, 1982; Vargas, 1994). High N application rates (Engel, 1974), high soil moisture content (Beard, 1982), and soil compaction (Wilson and Latham, 1969) also enhance annual bluegrass encroachment into bentgrass turf.

Various cultural factors influence population dynamics between the desired species and annual bluegrass. Phosphorus fertilization rates (up to 86 Kg ha^{-1}) have been shown to enhance annual bluegrass encroachment into Penncross creeping bentgrass whereas doubling the above P rate produced better bentgrass turf with less annual bluegrass (Goss et al., 1975).

Cultural practices such as clipping removal which removes seedheads can significantly reduce annual bluegrass encroachment into bentgrass plots (Gaussoin et al., 1985) while frequent irrigation generally favors annual bluegrass competition over the desired species (Mahdi and Stoutmeyer, 1953; Younger, 1959; Beard et al., 1978). To the contrary, Saffel (1994) found that irrigation frequency had no significant effect on annual bluegrass/creeping bentgrass population dynamics.

Effective chemical annual bluegrass control has been reported by Gaul and Christians (1988). However, annual bluegrass control remains a permanent feature in turfgrass maintenance programs for many golf courses, with ever-increasing costs. The high cost of annual bluegrass control implies that cultural practices that discourage its competition with desirable species deserve further study. As an alternative, some turf scientists have suggested the use of annual bluegrass as a desired turfgrass species (Vargas, 1994). Development of improved annual bluegrass selections also has been reported (White, 1989).For most turf managers and researchers annual bluegrass control remains a major challenge.

With the growing competition for water amid declining water resources, the study of annual bluegrass competition under variable irrigation deserves renewed attention. This study evaluated the effect of three irrigation regimes on the plant responses and interspecific competition between annual bluegrass and creeping bentgrass under fairway conditions.

Materials and Methods

A 3-year study was conducted at the Hancock Turfgrass Research Center to evaluate interspecific competition between established annual bluegrass and creeping bentgrass under three irrigation regimes. The soil type was a modified Owosso sandy loam (fine-loamy mixed mesic Typic Hapludalf). Irrigation plots were established in 1989 (Saffel, 1994).

The irrigation treatments were: i) apply 2.5 mm daily; ii) apply irrigation daily to return the soil to field capacity, based on moisture depletion as measured by time domain reflectometry (TDR); and iii) apply 25 mm only upon the appearance of wilting stress. Irrigation treatments served as whole plots with dimensions 11 x 11 m. Each plot was split (5.5 x 11 m) and seeded at random to either annual bluegrass or creeping bentgrass. Turfs were mowed three times a week at a cutting height of 16 mm and fertilized with phosphorus and potassium based on soil test with normal N recommendations for cool season fairway turfs in Michigan.

A rotary pop-up Rainbird Maxipaw sprinkler was located at each corner of the plots, with an average flow rate of 21.5 L h^{-1}. The operating pressure of the sprinklers was 276 kPa. The radius of throw was 11 m with head to head coverage. Irrigation was scheduled at 0300 each day to ensure minimum wind effects on application and distribution uniformities.

Time domain reflectometry (TDR) was used to measure volumetric soil moisture content (VMC) at four depths between 0700 and 0900 h except on days when rainfall interrupted data collection. The TDR data were used to schedule irrigation for the field capacity treatment and to provide a basis for comparing soil moisture retention and turfgrass performance under a range of irrigation scenarios practiced in Michigan.

The stainless steel TDR probes, 20 cm in length and 3.2 mm in diameter were installed horizontally, with a 5 cm center-to-center spacing at 2.5, 7.5, and 12.5 cm depths in three replicates. A fourth set of probes was installed with one at 17.5 cm and the other at 22.5 cm, replicated only twice due to the limited number of positions on the rotary switch used to direct the TDR signal from probe to probe. The arrangement of the probes provided moisture content estimates for the 0-5, 5-10, 10-15, and 15-25 cm depth, respectively. The probes were soldered to coaxial cables buried underground and connected to a switch box at the center of each plot.

Composite soil dielectric constant (ϵ) data for each treatment, replicate, depth and species (198 data points per day) as determined by TDR, were converted directly into VMC according to the equation (Topp et al., 1980):

$$VMC = \mathbf{0.053 + 0.0292\epsilon - 0.00055\epsilon^2 + 0.0000043\epsilon^3}.$$

Data collected were stored according to probe number by plot and species for each date.

Root mass was determined using a 1.8 cm diameter probe. Three cores about 40 cm long were taken at random from each split-plot. The thatch layer was cut off and the remainder of each core was separated into subsamples corresponding to the depth increments of the sphere of influence of the probes: 0-5, 5-10, 10-15, and 15-25 cm. The roots were separated from the soil using a hydro-pneumatic elutriator (Smucker et al., 1982). Washed samples were rinsed with 5% alcohol and oven dried at 60°C for 24 h and weighed.

Interspecific competition was determined twice each year (14 July and 16 September 1992, 26 July and 10 September 1993, and 24 May and 29 July 1994) expressed as percent bentgrass on each split-plot. The predominant species at cross hairs of a 1 x 1 m grid on an entire split-plot was used to quantify the population dynamics of annual bluegrass and creeping bentgrass under the study conditions.

Clipping weights were taken three times during the growing season in 1993 and four times in 1994 using a mower with a 0.45 m swath for a 5 m distance. The fresh clippings were oven dried at 60°C for 24 hours and weighed.

Quality ratings were taken three times during the summer of 1993 and 10 times in 1994 for each species by irrigation treatment. Ratings were from 1 to 9, 9 representing ideal turf conditions and 6 as the minimum acceptable turf quality.

The experimental design was a split-strip plot design with three replications. The irrigation treatment served as whole plots. The two turf species were the split, and the strip was the depth. This design allowed for the evaluation of soil moisture retention by depth and by species under the three irrigation regimes and all possible interactions. The data were analyzed using the Statistical Analysis System (SAS) general linear models with the Student Newman Keuls (SNK) mean separation procedure (SAS Institute, Inc., 1994).

Results and Discussion

The analysis of variance showed that irrigation treatment (IRR), turf species (SPE), depth (DEP) and the interactions IRR*SPE and IRR*DEP significantly affected root mass density. Root mass distribution by depth for the different irrigation treatments is presented in Table 4.1. Root mass density in the 0-5 cm depth was significantly higher than in all other depths. The data indicated a range of 63 to 73% of the root mass within the 0-5 cm depth for the three sampling dates. The 5-10 cm depth had about 1.5 times more roots than the 10-15 cm depth and more than three times the root mass density of the 15-25 cm depth averaged across species.

The highest root mass density was recorded in early June, 1994 in the 0-5 cm depth. Samples taken in late July and mid-August for this depth were generally lower with the exception of 27 July 1994 in the stress treatment. This agrees with the conclusion of Koski et al. (1983), who reported reduction in root mass for cool-season grasses from heat and water stress during the hot summer months. The root mass densities for the 0-5 cm depth for STR were higher than for FC on all sampling dates but higher than DLY only on 27 July 1994. Root mass density for STR were highest in the 5-10 cm depth for all sampling dates.

Root mass density averaged across depths for annual bluegrass and creeping bentgrass are presented in Table 4.2. Bentgrass had significantly higher root mass densities than annual bluegrass for all sampling dates for the DLY and FC. For STR root mass density for bentgrass was significantly higher than for annual bluegrass only in 1993. The lack of significant difference between species in 1994, may be explained by heavy rainfall that coincided with the peak of the summer heat

Clipping weights by irrigation treatment are shown in Table 4.3. The irrigated treatments had higher clipping weights than the stress treatment, particularly during dry periods. Even when the differences were not significant, the stress plots had consistently.

Table 4.1. Mean root mass density averaged across species by irrigation treatment, 1993 and 1994.

Irrigation Treatment	Depth	Date		
		18 Aug. 1993	6 June 1994	27 July 1994
			Kg m^{-3}	
DLY	0-5 cm	26.4a†	33.6a	21.9a
	5-10 cm	5.9b	5.7b	5.9b
	10-15 cm	3.8bc	3.5bc	3.6bc
	15-25 cm	1.3d	1.5d	1.1d
FC	0-5 cm	21.2a	28.3a	20.7a
	5-10 cm	4.8b	4.7b	4.3b
	10-15 cm	3.9b	4.6b	4.2b
	15-25 cm	1.5c	1.2c	2.0c
STR	0-5 cm	25.6a	30.2a	29.0a
	5-10 cm	7.1b	7.0b	8.4b
	10-15cm	3.3c	3.3c	2.8c
	15-25 cm	2.0c	2.3c	2.0c

† Means within columns by irrigation treatment followed by the same letter are not significantly different. LSD $\alpha = 0.05$. DLY, FC, and STR and 2.5 mm daily, field capacity, and stress treatments, respectively.

lower clipping weights than did the irrigated treatments. Similar results were reported by Saffel, 1992 suggesting that turfs on the stress plots may not fully recover from moisture stress induced within the growing season. Differences in clipping weight between the 2.5 mm daily and the field capacity treatments were not significant at the 5% probability level. But differences in clipping weight between the FC and DLY were significant at lower probability levels only during dry periods (15 July and 17 Aug. 1993). Differences in clipping weight between species were not significant. This was probably due to the high percentages of bentgrass encroachment on annual bluegrass plots or an inherent similarity in ET for both species as reported by Beard, 1973; and Saffel, 1994.

Table 4.2. Root mass density averaged across depths for annual bluegrass and creeping bentgrass by irrigation treatment, 1993 and 1994.

Irrigation Treatment	Species	Date		
		18 Aug. 1993	6 June 1994	27 July 1994
		Kg m^{-3}		
DLY	Bent	9.1a†	12.7a	11.2a
	Poa	8.7b	9.5b	5.0b
FC	Bent	8.2a	12.7a	10.1a
	Poa	3.9b	6.7b	5.5b
STR	Bent	8.6a	10.6a	10.8a
	Poa	5.8b	10.7a	10.2a

† Means within columns by irrigation treatment followed by the same letter are not significantly different. LSD $\alpha = 0.05$. DLY, FC, and STR are 2.5 mm daily, field capacity, and stress irrigation treatments, respectively.

Quality ratings for the different irrigation treatments and turf species for 1993 and 1994 are presented in Table 4.4. Quality ratings for the daily treatment (DLY) were consistently higher than for the stress treatment (STR). However, differences between DLY and FC were significant only 2 of 7 rating dates. Quality ratings for creeping bentgrass were significantly higher compared to those for annual bluegrass on all rating dates

Table 4.3. Clipping weight means across species by irrigation treatment for 1993 and 1994.

Irrigation Treatment	Date			
	18 July 1993	24 Aug. 1993	18 Sept. 1993	20 June 1994
	$g\ m^{-2}$			
DLY	15.7a†	12.1a	13.0.a	15.7a
FC	12.8a	11.9a	12.1a	12.7b
STR	6.0b	8.2b	7.5b	6.0c

† Means within columns by date followed by the same letter are not significantly different. LSD α = 0.05. DLY, FC, and STR are 2.5 mm daily, field capacity, and stress irrigation treatments, respectively.

Table 4.4. Turfgrass quality ratings by irrigation treatment and species.

	Date						
	6/20/93	7/15/93	8/17/93	9/1/93	9/15/93	6/2/94	8/22/94
Treatment							
DLY	8.2a†	7.8a	7.8a	8.9a	8.8a	8.7a	9.0a
FC	8.0ab	7.3b	7.7a	8.3ab	7.6ab	8.8ab	8.8ab
STR	7.9b	5.0c	6.2b	7.3b	7.3b	8.3b	8.6b
Species							
Bent	8.2a	7.3a	7.6a	8.6a	8.1a	8.4a	8.5a
Poa	7.3b	6.3b	6.8b	7.7b	7.7b	8.3b	7.6b

† Means within columns for each treatment followed by the same letter are not significantly different. LSD α = 0.05. DLY, FC, and STR are 2.5 mm daily, field capacity, and stress irrigation treatments, respectively.

The percent bentgrass in both bentgrass and annual bluegrass plots is given in Table 4.5. The percent bentgrass on annual bluegrass plots ranged from a low of 52% in 1992 on annual bluegrass stress plots to over 81% for the daily irrigation treatment in 1994. High bentgrass counts on both annual bluegrass and creeping bentgrass plots was strong evidence of superior bentgrass competition under our study conditions. The analysis of variance showed that irrigation had no significant effect on annual bluegrass and creeping bentgrass population dynamics under our conditions. This finding is consistent with that of Saffel (1992) but contradicts the popularly held view that higher irrigation favors annual bluegrass competition over bentgrass (Younger, 1959). It must be noted that there was limited traffic on this experimental site compared to that on golf course fairways.

Table 4.5. Percent creeping bentgrass in annual bluegrass and creeping bentgrass plots as affected by irrigation treatment.

Irrigation Treatment	Species	1992		1993		1994	
		7/14	9/16	7/26	9/10	5/24	7/29
		% Composition					
DLY	Bent*	93.0a†	93.1a	97.0a	95.3a	81.4a	91.6a
	Poa	65.3b	64.3b	79.3b	78.5b	73.0b	81.9a
FC	Bent	89.7a	91.0a	96.7a	97.0a	78.2a	87.5a
	Poa	74.7b	76.3b	79.7b	79.3b	70.1b	76.4b
STR	Bent	85.7a	94.0a	95.0a	97.0a	87.9a	89.8a
	Poa	62.0b	52.0b	75.2b	65.3b	70.4b	75.0b

† Means within columns for each treatment followed by the same letter are not significantly different. LSD $\alpha = 0.05$. DLY, FC, and STR are 2.5 mm daily, field capacity, and stress irrigation treatments, respectively. * Plots were established in 1989 as pure stands.
Saffel, 1992.

Conclusions

The analysis of variation showed that irrigation treatment did not significantly affect the percent composition of annual bluegrass and Penncross creeping bentgrass. Consistently high bentgrass percentages in annual bluegrass and bentgrass plots was strong evidence of superior bentgrass competition under our study conditions.

Penncross creeping bentgrass had superior quality than annual bluegrass on most sampling dates. With the exception of 20 June 1994, there was no significant difference in quality ratings between the 2.5 mm daily and the field capacity treatment. Quality ratings for both irrigated treatments were significantly higher than for the stress treatment.

Root mass densities for the creeping bentgrass was significantly higher than for annual bluegrass in both irrigated treatments for all sampling dates. About 63 to 70% of the root mass averaged across species was within the 0-5 cm depth. Although root data was collected for two years, root mass densities for early June were higher than those sampled later in the summer.

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CHAPTER 5

Bihourly Moisture Depletion Patterns in Fairway Turfs

Abstract

Syringing during hot afternoons is a common practice in fine turf management. However, timing criteria for syringing are mostly based on visual observations. Time domain reflectometry (TDR) was used to monitor soil moisture depletion in bihourly time steps at four depths under three irrigation regimes for established annual bluegrass and creeping bentgrass fairway turfs. The objectives were: i) to establish the time of the day when soils moisture depletion is highest under fairway turfs; and ii) compare the summation of bihourly moisture depletion during daylight hours to daily adjusted ET. The irrigation treatments were: i) apply 2.5 mm daily; ii) apply 25 mm upon the appearance of wilting stress; and iii) return the soil to field capacity daily based on soil moisture depletion as measured by TDR. This study was conducted at the Hancock Turfgrass Research Center at Michigan State University to evaluate soil water dynamics in fairway turfs during daylight hours on three different dates with contrasting evaporative demand in 1993 and 1994. Bihourly moisture depletion by species and irrigation treatment were compared to weather based ET. Moisture depletion varied by turf species, soil depth, irrigation treatment and time. Moisture depletion patterns were also dependent on initial moisture content and evaporative demand. The

greatest change in moisture content was from the 0-5 cm depth for the field capacity and 2.5 mm daily irrigation treatments between 0900 and 1300 h confirming that syringing in the early afternoon may reduce moisture and temperature stress. Moisture depletion data as measured by TDR for the irrigation treatments were generally more conservative than the adjusted Penman estimate from a weather station on site. This suggests that potential water savings could be made from soil moisture depletion-based turf irrigation scheduling. However, agreement between moisture depletion and Penman estimates was poor.

Introduction

The competition for water and declining water resources call for more efficient water management strategies in turf as in conventional agriculture. Improved water conservation may delay the search for alternative water sources and reduce possible contamination of surface and ground waters. One method of conserving water is through the development of environmentally sound and efficient irrigation scheduling programs.

Accurate application rates and timing are critical management decisions in turf irrigation management. Several factors must be considered in developing timing criteria for golf course irrigation scheduling. Among these are the prevention of wilting stress and reduction of disease incidence (Vargas, 1994) and leaching of agricultural chemicals into ground water (Augustin and Snyder, 1984). Another factor is interference with play or cultural activities (Beard, 1973).

Few golf courses have automatic weather stations that provide site-specific evapotranspiration (ET) data. Although such technology facilitates the decisions on how much water to apply, it does not provide answers to the question of when to irrigate. Furthermore, it is difficult for turf managers to justify the purchase of such expensive equipment. For the most part, irrigation scheduling on golf courses is based on visual observations of wilting stress, foot printing or as a security measure, light daily applications (Vargas, 1994). Efficient irrigation scheduling remains a major challenge for most turf managers as they strive to maintain a delicate balance between growing quality turf and environmental concerns.

Syringing is commonly used to moderate canopy temperature during hot days. However, studies on the effect of syringing on canopy temperature show variable results. Duff an Beard, (1966) reported a 1 to 2 °C reduction in temperature lasting 2 h following the application of 6.4 mm of irrigation at 1200 h, while Hawes (1965) concluded that application of 3 mm of irrigation between 1130 and 1500 h resulted in canopy temperature reductions between 0.8 to 4 °C for up to 600 s. On the other hand, Dipola (1984) found no significant difference in canopy temperature 1 h after syringing regardless of timing or syringing amounts over a certain range. Ideally, irrigation should be applied prior to the appearance visual signs of stress (Beard, 1982). Soil moisture depletion monitoring could improve timing criteria for turf irrigation (Carrow, 1991) and possibly for syringing on hot days.

Despite good correlation between mini-lysimeters and weather based ET estimates (Feldhake et al., 1984) mini-lysimeters have been criticized for having soil-container interfaces that interrupt upward and lateral water flow and for not being representative of field turf conditions. Weather-based ET estimates fail to account for soil moisture status even when adjustments are made by multiplying the potential ET by a turf or crop coefficient as suggested by Carrow (1991). Comparing various modifications of the Penman equation, Allen (1986) reported 10-25% error compared to large weighing lysimeters.

Although models have been developed that estimate moisture depletion in hourly or shorter time steps (Ritchie, 1990), field methods for soil moisture determination needed to verify such models usually require longer waiting periods and thus fail to serve as effective tools for model validation. For the gravimetric method, at least 24 h are needed to obtain soil moisture data (Hanks, 1992). In addition to destructive sampling, this method is also subject to errors from spatial variability (Hillel, 1980).

While neutron scattering requires considerably shorter waiting periods, the problems of exposure to radiation and the need for routine calibration remain (Hillel, 1980). Also, the neutron probe is not amenable to the shallow rooting depths encountered in turf due to errors from neutrons escaping to the surface (Snyder et al., 1984). Finally, the dependence of the spatial resolution of the neutron probe on the degree of wetness is of concern to some scientists (Arnon, 1992).

Moisture depletion measurements in soils integrate plant, soil and atmospheric interactions into a single measurement. Kirsch (1993) used neutron scattering and gravimetric measurements to locate the zero flux plane and estimate ET with errors of up to 153 %. He acknowledged that techniques such as TDR may yield more reliable ET estimates.

In sand-based soils with low moisture retention, low-volume, high-frequency irrigation is required to supply adequate amounts of water for quality turf maintenance. This implies that methods for rapid and accurate moisture determination are needed to provide adequate and timely supplies of water to the turf, in order to reduce overwatering and the incidence of wilting stress.

In the last decade, time domain reflectometry (TDR) has become an acceptable method for soil moisture determination. This method is accurate, fast, and precise, and does not involve radioactive risks associated with the neutron probe or gamma-attenuation techniques (Topp et al., 1980; Dalton, 1992). Despite the potential benefits of TDR and other soil moisture sensors, their use in real-time turf irrigation scheduling and modeling has not been fully explored.

The literature is replete with articles on the theoretical development and potential agricultural applications of TDR. However, few studies have addressed the use of TDR in real-time irrigation scheduling for field crops (Topp and Davis, 1985) or for turfgrass irrigation (Carrow, 1991; Saffel, 1994). The use of TDR in turf irrigation scheduling may result in more efficient water application rates and timing on greens and fairways and eventually, on home lawns, when the technology becomes affordable.

This study evaluated bihourly moisture depletion patterns in annual bluegrass (*Poa annua* L. var. reptans) or creeping bentgrass (*Agrostis palustris* Huds. L.) fairway turfs under three irrigation regimes. The specific objectives were: i) to monitor moisture depletion patterns of annual bluegrass and Penncross creeping bentgrass fairway turfs under three irrigation regimes and ii) to compare Penman ET to daily moisture depletion.

Materials and Methods

This study was conducted at the Hancock Turfgrass Research Center at East Lansing, MI. The soil type was an Owosso sandy loam (fine-loamy, mixed Typic, Hapludalf) with an average field capacity of 0.28 $cm^3 cm^{-3}$. Bihourly volumetric moisture content was determined by TDR from 0700 to 2100 h on 13 Aug. 1993 and 16 Aug. 1994, and from 0700 to 1900 on 13 Sept. 1994. From long-term weather forecasts, all three dates were expected to be sunny, with high temperatures and high evaporative demand. In 1993, 198 readings were taken bihourly, whereas only 66 readings were taken in 1994 due to some dysfunctional probes.

Pairs of TDR stainless steel rods 3.2 mm in diameter and 200 mm long, with 50 mm center-to-center spacing, were installed at 2.5, 7.5, and 12.5 cm from the soil surface in three replicates (Topp et al., 1980; Saffel, 1994). A fourth set of probes of similar configuration was also installed, with one rod at 17.5 cm and the other at 22.5 cm in only two replicates due to restrictions on the number of positions on the rotary switch used to move between sets of probes. These probe pairs measured VMC in the 0-5, 5-10, 10-15, and 15-25 cm depths respectively.

Three irrigation treatments were evaluated on Penncross creeping bentgrass or annual bluegrass turfs. The irrigation treatments were: i) apply 2.5 mm daily (Vargas, 1994); ii) return the soil to field capacity (0.28 $cm^3\ cm^{-3}$) daily based on TDR readings; and iii) apply 25 mm only upon the appearance of wilting stress. Irrigation treatments served as whole plots with dimensions 11 x 11 m in three replicates. Each irrigation plot was split in half (11 x 5.5 m) and planted at random to pure stands of either annual bluegrass (*Poa annua* L. var. reptans) and Penncross creeping bentgrass (*Agrostis palustris* L. Huds.) established in 1989 (Saffel, 1994). Both species were maintained according to standard management practices for cool-season fairway turfs in Michigan with a cutting height of 16 mm.

Evapotranspiration data for each date were recorded from a Rainbird automatic weather station at the site 2 m above the ground. Soil moisture depletion (mm) for each depth was calculated from the equation of Arya et al. (1975):

$$(VMC_{n+1} - VMC_n) * \text{depth of soil layer (mm)}$$

where n is initial VMC reading and n+1 represents successive VMC readings.

The experimental layout was a 3*2*4 factorial split-strip design with three replicates. Time domain reflectometry installations at four depths served as the strip. Bihourly VMC data were analyzed using repeated-measures analysis of the general linear model and Student Neuman-Keuls (SNK) mean separation procedures (SAS Institute, Inc., 1994).

Results and Discussion

Solar radiation, minimum and maximum temperatures values for the three study dates are given in Fig. 5.1. Temperatures from 0600 to 1700 h were similar for 13 Aug. 1993 and 16 Aug. 1994. However, minimum and maximum temperatures on 13 Sept. 1994 started about seven degrees lower than on the other days. Temperatures increased rapidly from 0700 to 1100 h, with similar slopes on all dates. After 1100 h, the rate of increase declined and temperatures remained fairly constant until 1900 when maximum temperature peaked again for all dates, although this was more pronounced on 13 Aug. 1993. Solar radiation trends were about the same on all days, except that changes between 1600 and 1700 h were more drastic on 13 Sept. 1994 (Fig. 5.1). This date also had shorter daylight hours.

Bihourly relative humidity and wind velocity for study dates are presented in Fig. 5.2. Relative humidity ranged from 85% (between 0600 and 0900 h) to a low of 60% at 1600 h on 13 Aug. 1993 and 16 Aug. 1994 but rose back to 85% and 75%, respectively. Relative humidity on 13 Sept. 1994 was significantly lower than on other dates, with a maximum of less than 60% early in the morning to a low of 25% at 1800 h.

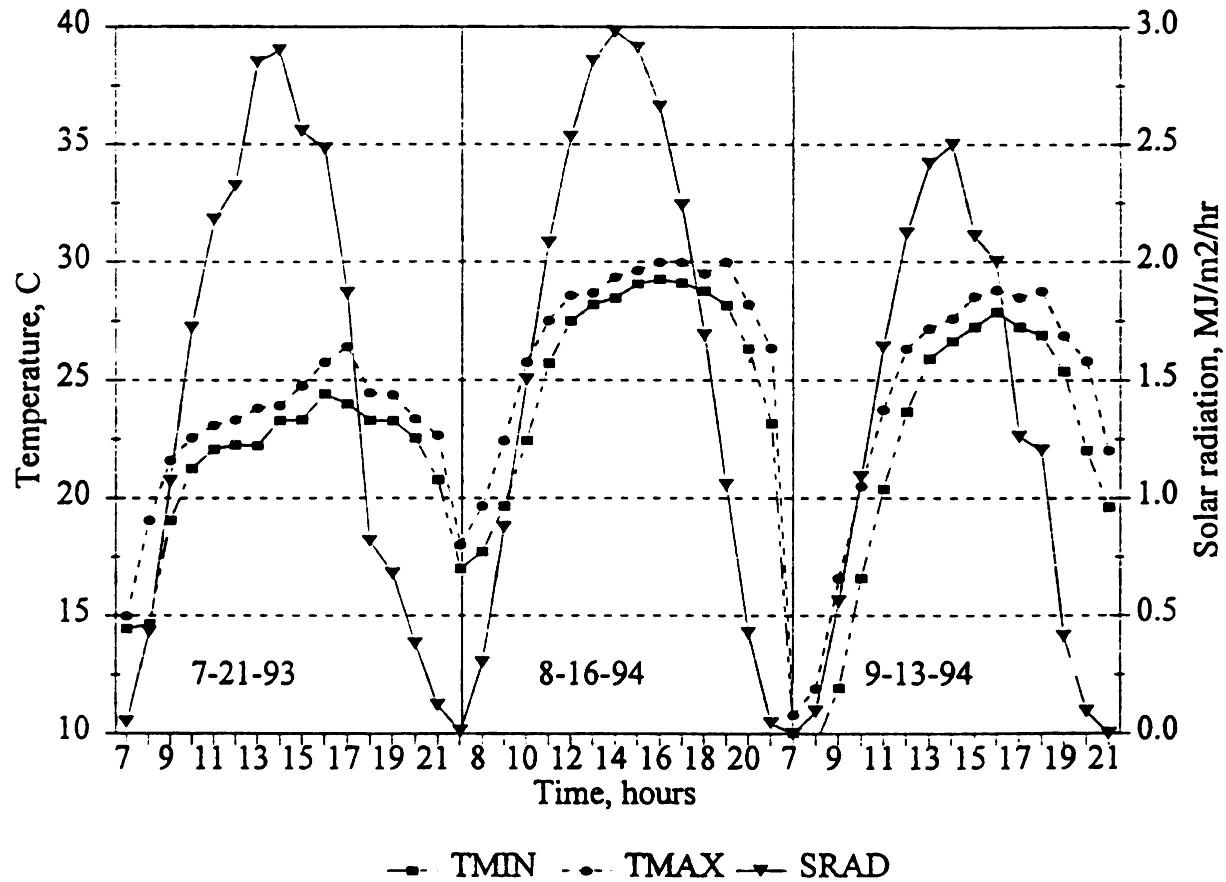

Fig. 5.1. Bihourly minimum temperature (TMIN), maximum temperature (TMAX) and solar radiation (SRAD), for 13 August 1993, 16 August 1994 and 13 September 1994.

Wind velocities for both dates in August were comparable and were much higher than those on 16 Sept. 1994. Turfgrass leaves were wet early in the morning either from dew, guttation or irrigation. By 1100, most of the moisture had either infiltrated into the soil or evaporated as solar radiation and temperature increased.

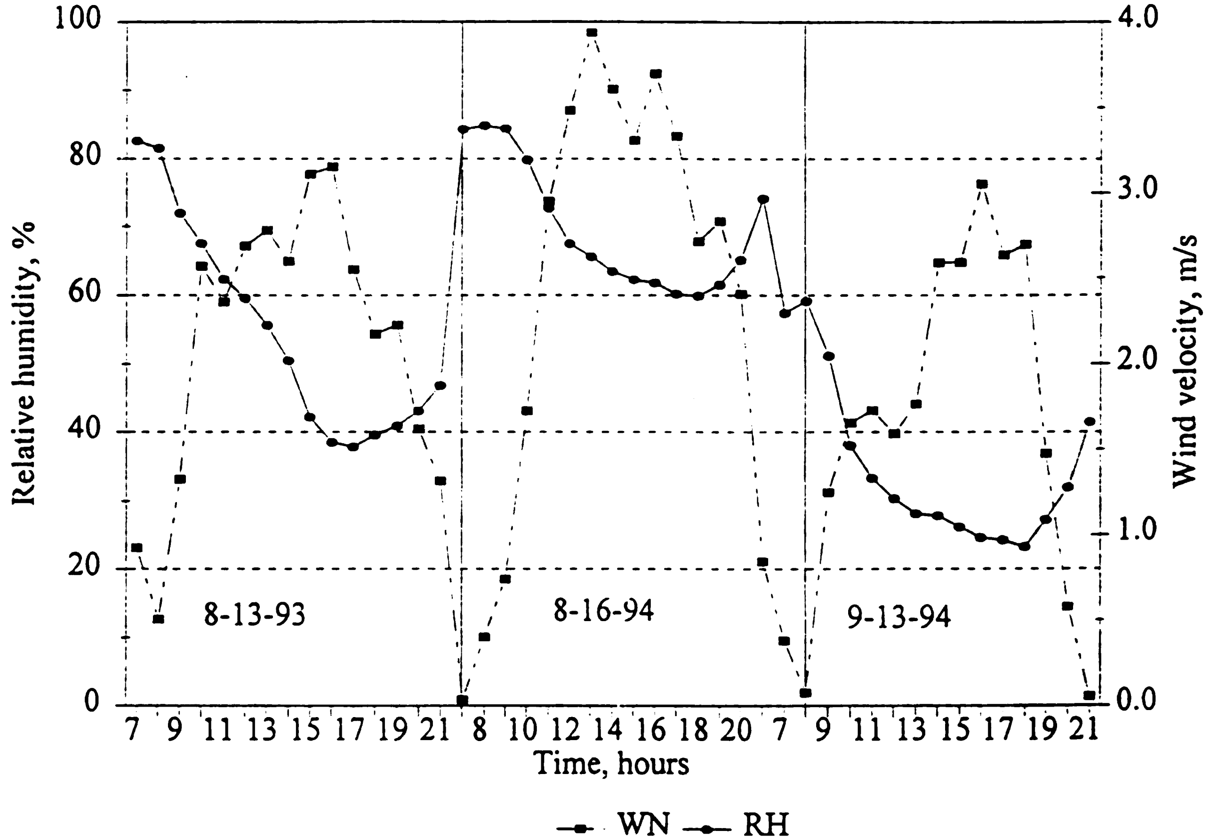

Fig. 5.2. Bihourly relative humidity (RH) and wind velocity (WV) for 13 August 1993, 16 August 1994 and 13 September 1994

The analysis of variance (Table 5.1) showed that irrigation treatment (TRT) and the TRT*DEP (sampling depth) interaction significantly affected VMC for all sampling dates while species (SPE) and sampling depth (DEP) were significant only on the first two dates. The effect of species on VMC was significant on 13 Aug. 1993 and 16 Aug. 1994, but not at all intervals on 13 Sept. 1994. The significance of the TRT*DEP interaction was due to inherent moisture-retention capacities for the various soil depths as shown earlier (Fig.3.6).

Table 5.1. Analysis of variance for the test of hypotheses for between- (among-) subject effects for bihourly volumetric moisture content.

Source	13 Aug. 1993		16 Aug. 1994		13 Sept. 1994	
	df	*MS*	*df*	*MS*	*df*	*MS*
REP	2	0.003	2	0.001	2	0.0003
TRT	2	2.013***	2	0.029***	2	0.584***
REP*TRT	4	0.003	4	0.003*	4	0.007
SPE	1	0.046***	1	0.005*	1	0.004
TRT*SPE	2	0.013*	2	0.001	2	0.011
REP*SPE*(TRT)	6	0.004	6	0.003	6	0.002
DEP	3	0.015**	3	0.022***	3	0.004
TRT*DEP	6	0.043***	6	0.003*	6	0.016**
SPE*DEP	3	0.001	3	0.001	3	0.001
TRT*SPE*DEP	6	0.002	6	0.002	6	0.002
Error	162	0.003	30	0.001	30	0.003

*,**,***Significant at the P = .05, .01, and .001 levels, respectively.
REP, DEP and SPE are replicate, depth and species respectively.

The repeated measures procedure (SAS Institute Inc., 1994) was used to analyze the data since multiple observations were taken per experimental unit at different times. The analysis of variance for repeated measures showed a time dependent variation of VMC during the course of the day as expected (Table 5.2). Variations in solar radiation, temperature, relative humidity and wind speed with time resulted in variable moisture redistribution within the soil profile for each sampling date. The TIME*DEP and TIME*TRT interactions were significant ($p > 0.01$) on all sampling dates.

Table 5.2. Repeated-measures analysis of variance for the test of hypotheses for VMC among subject effects.

Source	13 Aug. 1993		16 Aug. 1994		13 Sept. 1994	
	df	*MS*	*df*	*MS*	*df*	*MS*
TIME	7	0.0030*	7	0.0019***	7	0.0009***
TIME*REP	14	0.0001	14	0.0017	14	0.0001**
TIME*TRT	14	0.0001	14	0.0002	14	0.0001
TIME*REP*TRT	28	0.0001	28	0.0002	24	0.0001
TIME*SPE	7	0.0001	7	0.0001	7	0.0001
TIME*TRT*SPE	14	0.0002*	14	0.0003	14	0.0001
TIME*REP*SPE*(TRT)	42	0.0001	42	0.0002	42	0.0001
TIME*DEP	21	0.0003***	21	0.0004**	21	0.0001**
TIME*TRT*DEP	42	0.002*	42	0.003*	42	0.0001*
TIME*SPE*DEP	21	0.0039	21	0.0001	21	0.0000
TIME*TRT*SPE*DEP	42	0.0043	42	0.0002	42	0.0000
Error (TIME)	1134	0.0135	210	0.0002	180	0.0000

*,**,***Significant at the P = .05, .01, and .001 levels, respectively.
REP, DEP and SPE are replicate, depth and species respectively.

Bihourly volumetric moisture content (VMC) changes, however, were not greater than the measurement error for TDR and thus fail to provide conclusive evidence of soil water movement. Except for the stress treatment on 16 Aug. 1994, all maximum VMC values for the irrigation treatments were recorded at 0900 h for each date. All minimum VMC values were recorded at 2100 h on 13 Aug. 1993. On 16 Aug. 1994 and 13 Sept.

1994, minimum VMC values were recorded either at 1700 or at 1900 h for all treatments. There was no significant difference between the 2.5 mm daily and the field capacity treatments, both of which were significantly higher than the stress treatment.

Initial VMC by depth for 13 Aug. 1993 (Fig. 5.3) and 16 Aug. 1994 (Fig. 5.4) ranked 0-5 > 5-10 > 10-15 > 15-25 cm depths. Graphs for moisture depletion with time for the 5-10 and 10-15 cm depths for field capacity treatment on 13 Aug. 1993 (Fig. 5.3) were about the same and followed the same moisture depletion pattern throughout the period of data collection. However, variations in VMC trends occurred with time for most other depths and treatments on both dates. For example, both annual bluegrass and creeping bentgrass showed a decrease in VMC for the 0-5 cm depth from 1700 to 1900 h, with a corresponding increase in VMC for the 15-25 cm depth for the stress treatment.

Moisture depletion from the 2.5 mm daily treatment on 13 Aug. 1993 showed contrasting trends between species and among depths (Fig. 5.3). At 0700 h, VMC by depth was in the order 0-5 > 5-10 > 10-15>15-25 cm, as expected since water wets the surface during irrigation. By 0900 h, the 0-5 and 5-10 cm depth for the bluegrass species had the same VMC. The greatest moisture depletion in the bluegrass plots was evident between 0700 and 0900 h for the 0-5 cm depth. While the high root density for this depth may explain greater water depletion there was no logical explanation for the timing since temperature and solar radiation were still increasing. Similar depletion for the bentgrass species was between 0900 and 1300 h (Fig. 5.3) suggesting a difference in timing between annual bluegrass and creeping bentgrass response to changes in environmental conditions.

Generally, the 0-5 cm depth for the irrigated treatments had significantly higher moisture content than all other depths. This may have been due to higher organic matter

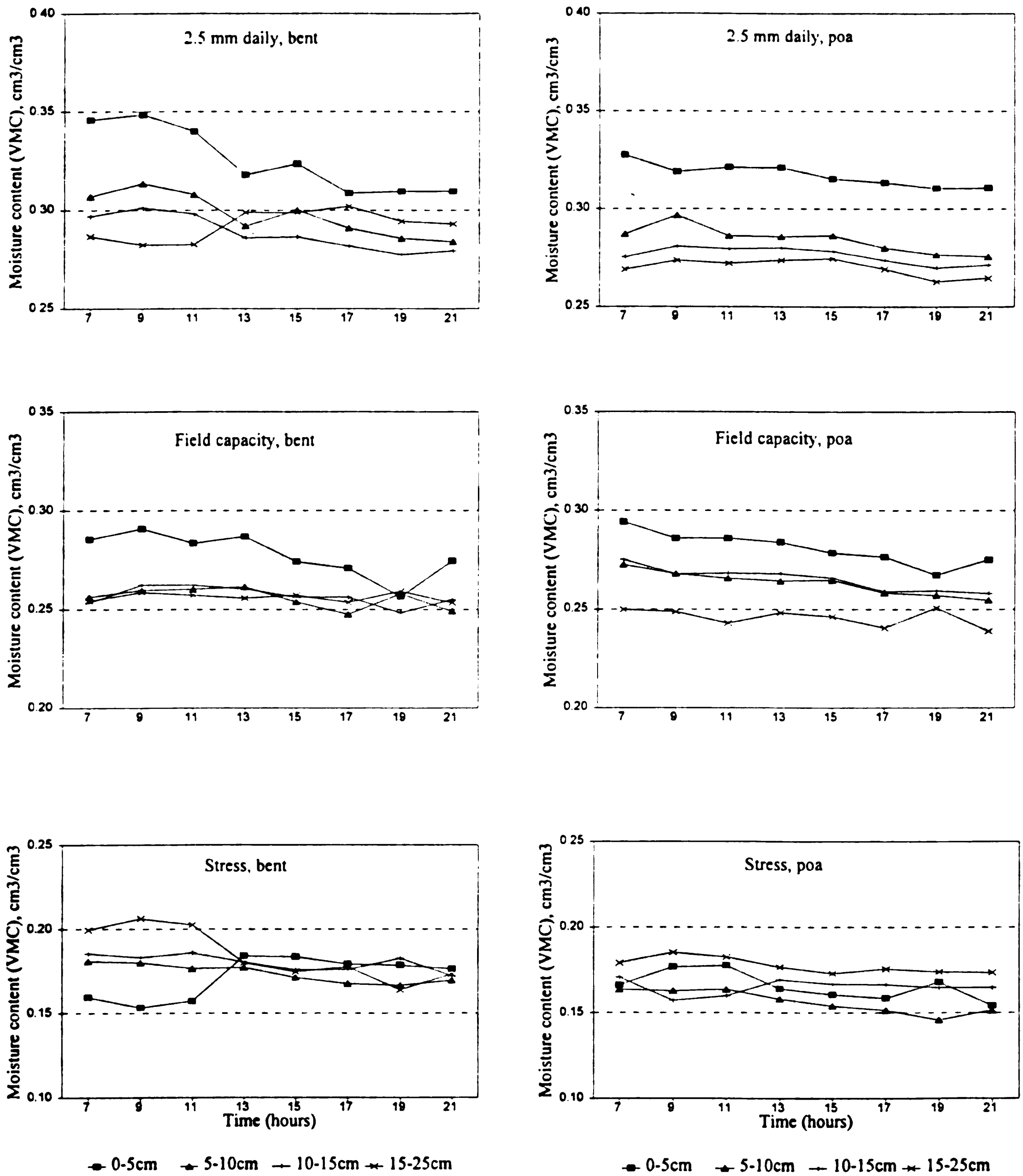

Fig. 5.3. Bihourly moisture depletion patterns for annual bluegrass and Penncross creeping bentgrass by irrigation treatment 13 August 1993.

content or it may indicate that TDR detects water in root tissues (about 70% of the root mass was in the 0-5 cm depth). Moisture depletion from the irrigated treatments was higher than from the stress treatment because VMC was lower for the stress treatment. The 15-25 cm depth for the stress treatment had the highest VMC levels until 1300 h. Whereas this trend persisted for the bluegrass species, VMC for the bentgrass species (0-5 cm depth) increased rapidly between 1100 and 1300 h.

Symmetrical moisture depletion and accretion patterns between depths suggest preferential as well as differential moisture uptake and redistribution by species for the different depths. The 15-25 cm depth for the bentgrass species showed the greatest increase in soil moisture content for both species on 13 Aug. 1993 in the stress treatment (Fig. 5.3). Moisture depletion for the bentgrass species showed similar patterns for all depths except the 15-25 cm depth (Fig. 5.3). Between 1300 and 1500 h, VMC for the 0-5 and 5-10 cm depths increased slightly. This increase may have been due to hydraulic lifting of water by the roots, coinciding with partial closing of the stomata (Jensen and Taylor, 1971). From 1700 h to the end of the day most depths showed only a minor depletion in moisture as solar radiation and temperature had dropped substantially.

On 13 Aug. 1993, volumetric moisture content means across treatments and depths for the bentgrass species were significantly higher than for the annual bluegrass for all sampling time intervals (Fig. 5.3) but not on the other two dates. All treatments showed an increase in VMC from 0700 to 0900 h except the stress treatment on 16 Aug. 1994 and the field capacity and stress treatments on 13 Sept. 1994. Since no irrigation was applied during this time course experiment significant increases in VMC suggest net water movement from one depth to another.

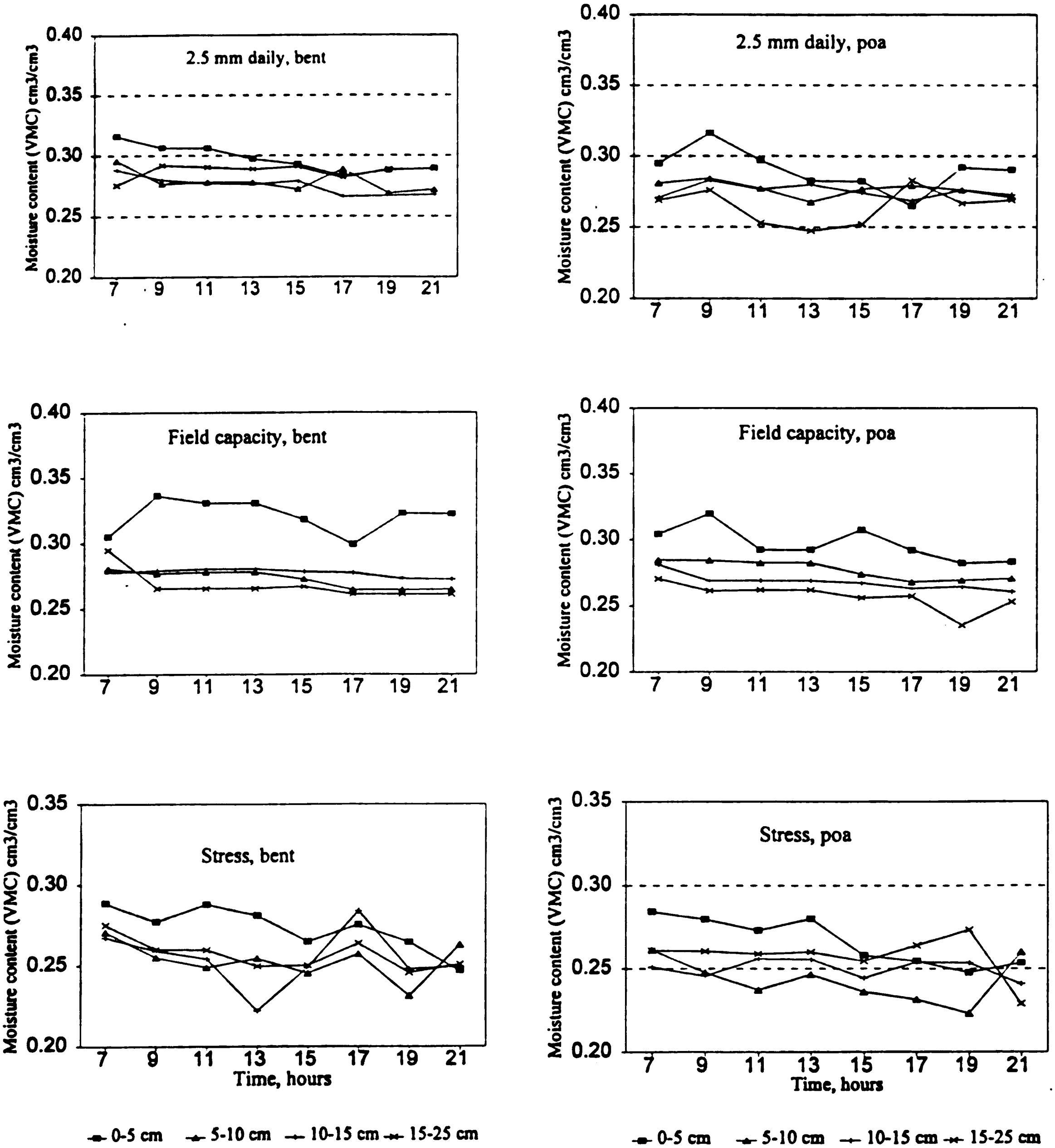

Fig. 5.4. Bihourly moisture depletion patterns for annual bluegrass and Penncross creeping bentgrass by irrigation treatment, 16 August 1994.

The mechanisms governing upward flow observed in this study were not investigated but deserve further study. Upward flow of water may be due to hydraulic lift by roots (Murphy et al. 1994), capillary rise (Hillel, 1980) or vapor diffusion if there is a high temperature gradient. Beard (1973) stated that dew may contribute as much as 0.3 to 0.4 mm a night under favorable conditions. While dew formation or guttation may explain the increase in VMC in the late afternoons, it is difficult to discard their contribution to increases in VMC during early morning hours. For the most part, changes in VMC were again within the margin of error of TDR.

Although moisture changes in soil varied by depth, species, and irrigation treatment, there was no clear-cut trend for moisture depletion by irrigation treatment, species, or depth. Symmetry between moisture accretion and depletion patterns between the 0-5 and 5-10 cm depths for annual bluegrass in the stress treatment suggests a net flux of water from one depth to another over certainn time intervals (Fig. 5.3). For the bentgrass species, the less pronounced symmetry between the 0-5 and the 15-25 cm depths from 0700 and 1300 h may be the effect of deeper roots used in water uptake causing a net flux of water from the 15-25 cm depth to the 0-5 cm depth. Between 1700 and 2100 h, VMC was fairly constant for both species. The greatest moisture depletion was from the 0-5 cm depth of the daily treatment between 0900 to 1300 h for the bluegrass species on August 16, 1994. Moisture content for the 0-5 cm depth for the bentgrass species decreased steadily till 1700 h. (Fig. 5.4).

Moisture depletion patterns for the 2.5 mm daily treatment on 16 Aug. 1994 were characterized by many interactions among depths (Fig. 5.4). The increase in VMC observed in the bluegrass species for the 2.5 mm daily treatment for all depths from 0700 to 0900 h was seen only in the 15-25 cm depth for the bentgrass species.

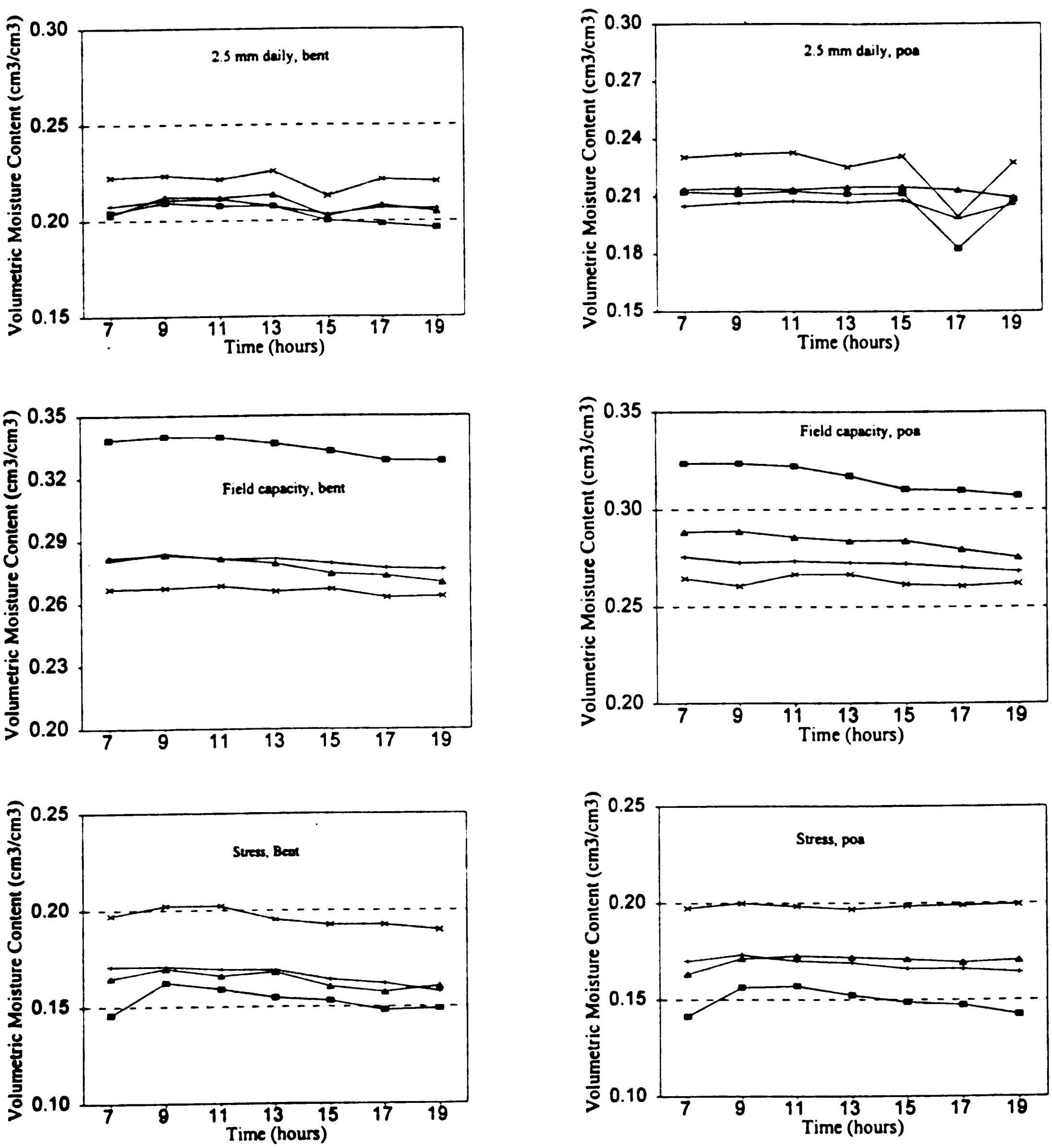

Fig. 5.5. Bihourly moisture depletion patterns for annual bluegrass Penncross creeping bentgrass by irrigation treatment 13 Septemberr 1994.

Initial moisture contents for the 0-5 cm depth for the field capacity treatment for both species were about the same at 0700 h and increased until 0900, but decreased between 0900 and 1100 h (Fig. 5.4). Although the largest decrease in VMC for the 15-25 cm depth occurred between 0700 and 0900 for bentgrass, the major decrease at this depth for the bluegrass species was between 1700 and 1900. As temperature and solar radiation had dropped significantly this decrease could either be due to rapid uptake of water following the opening of the stomata or due to TDR error as the computer battery was running low.

The stress treatment showed the most variation in VMC on 16 Aug. 1994. Initial VMC for the 0-5 cm depth for both species was about the same at 0700 h. For both species, there was no increase in moisture content in this treatment between 0700 and 0900 h on this date. However, VMC for the bluegrass species decreased until 1100 h, but the decrease in bentgrass species lasted until 0900 h. Symmetrical moisture depletion patterns were more obvious in the bluegrass species than in the bentgrass species. The deeper rooting depth of bentgrass compared to annual bluegrass may have contributed to more uniform water uptake along the soil profile. The largest increase in VMC was observed in the bentgrass species at 1700 h for all depths; only the 10-15 and 15-25 cm depths showed a corresponding increase between 1500 and 1900 h.

On 13 Sept. 1994, the 2.5 mm daily treatment showed similar moisture distribution patterns with respect to initial moisture content by depth at 0700 and 1300 h (Fig. 5.5). Whereas maximum depletion for the bluegrass species occurred at 1700 h, maximum depletion for the bentgrass species occurred at 1500 h. The large decrease in VMC observed toward the end of the day may have been due to TDR error.

On 13 Sept. 1994, cloudy skies and shorter day length accounted for low evaporative demand. The 15-25 cm depth had the lowest VMC, whereas the 0-5 cm depth had the highest VMC levels for both species in this treatment. However, by the end of the day, moisture levels for the 5-10, 10-15, and 15-25 cm depths were about the same (Fig. 5.5). This suggests differential moisture extraction patterns by depth for both species. Different rooting habits for annual bluegrass and creeping bentgrass during the heat of the summer (Koski, 1983; Murphy et al., 1994) may be a possible explanation for this. Also, Saffel (1994) suggested differential water uptake by depth for annual bluegrass.

Table 5.3. Comparison of soil moisture depletion (mm) across species by irrigation treatment and daily adjusted ET from a weather station at the Hancock Turf Research Center, Michigan State University.

	Irrigation Treatment			
Date	DLY	FC	STR	ET (adjusted)
	mm			
13 Aug. 1993	3.0 (46)	3.0 (46)	2.0 (64)	5.6
16 Aug. 1994	3.5 (29)	3.8 (22)	3.3 (32)	4.9
13 Sept. 1994	3.3 (32)	2.8 (42)	2.3 (52)	4.8

† Values in parentheses reflect potential percent water savings for each irrigation treatment by date compared to the adjusted ET from a Rainbird weather station on site

On 13 Sept. 1994, all four depths for the annual bluegrass species in the 2.5 mm daily treatment had different initial moisture content (Fig. 5.5). Initial VMC for the bentgrass species showed only two distinct moisture levels. Only minor depletions were observed for the bentgrass species. This is probably due to the high soil moisture content in this treatment on this date. For the bentgrass species, the 5-10 and 10-15 cm depths had identical moisture depletion patterns throughout the day, increasing only from 0700 to 0900 h. Moisture depletion occurred mostly in early afternoon. Differences in moisture depletion patterns between species may be attributed to preferential moisture uptake by species and/or differential rooting patterns by depth (Saffel, 1994). This suggests that moisture depletion in response to evaporative demand is moderated by turf species and hence the need for site/cop-specific turf coefficients.

On 13 Sept. 1994, VMC differences by depth for the bentgrass species were not as great as those for the bluegrass species. For both species, moisture content for the 0-5 and 5-10 cm depths increased from 0700 to 0900 h. The 15-25 cm depth showed very little variation in the bluegrass plots, whereas all other depths showed a gradual decrease in VMC through the course of the study.

Initial water content for the bentgrass species was higher than for the bluegrass species in the 2.5 mm daily treatment. Changes in VMC for the bluegrass species observed in the 2.5 mm daily and field capacity treatments were lowest between 1100 and 1300 h (Fig. 5.5). In particular, the 2.5 mm daily treatment showed only minimal gains or losses in soil moisture content for the depths of interest over this interval, even though this coincided with peak values for solar radiation, minimum relative humidity and high temperatures, conditions that favor high evaporative demand. Possible explanations for these observations are: i) the stomata closed to the extent that plant water uptake was about the same as the evapotranspiration thus maintaining a steady VMC, and ii) the shallow root system of annual bluegrass may not be as efficient in water uptake as that of creeping bentgrass.

There was no distinct pattern to the data with respect to irrigation treatment or species. This suggest that the different species show variable response to different levels of evaporative demand. This variation may be based on amount of available water, root distribution within the profile, and time of the day. While bentgrass species have been shown to have higher and deeper root mass than annual bluegrass (Murphy et al., 1994; Saffel, 1994). It must be cautioned that higher root mass may not necessarily imply higher water and nutrient uptake efficiency.

Moisture depletion as measured by TDR ranked FC > DLY > STR for all sampling dates because dates selected for bihourly moisture depletion studies coincided with dry periods. Although the Penman ET recorded on August 13, 1993 was highest, the moisture depletion data were highest on August 16, 1994 for all treatments. This illustrates the discrepancies in comparisons between ET and soil moisture depletion and underscores the complex nature of the interactions between plant species and soil under different evaporative demand. It also illustrates the need for conjunctive use of weather based ET and soil moisture depletion measurements in irrigation scheduling.

Moisture depletion data shown on (Table 5.3) were more conservative than the adjusted ET from the modified Penman equation for all dates and treatments probably due to upward water movement. The percent difference between soil moisture depletion and weather based ET (shown in parenthesis in Table 5.3) indicate potential water savings of up to 46 % for the irrigated treatments from soil moisture depletion based irrigation scheduling compared to the adjusted Penman ET. These results show less variation than those of Kirsch (1993) and confirm his prediction that instruments with better resolution like TDR could improve assessment of plant water use.

Conclusions

The above results show that TDR could be used as a tool for soil moisture monitoring and irrigation scheduling even in turf ecosystems. However, bihourly VMC changes were within the margin of error of TDR measurements and thus fail to provide conclusive information on moisture depletion patterns.

Evidence of upward flow at different times under different conditions, even under the shallow rooting depths for turf species suggest that water drained below the root zone may again become available to the plant following moisture redistribution. Moisture depletion measurements such as these reflect actual VMC changes in response to variable irrigation treatments, plant species and evaporative demand.

Time domain reflectometry estimates of moisture depletion were more conservative than weather based ET estimates even after adjustments have been made. Water savings of up to 46 % could be achieved from moisture depletion based irrigation scheduling compared to weather based estimates. Despite widespread efforts to equate moisture depletion to ET, it should be noted that weather based ET estimates fail to account for upward flow of water to replenish water extracted from the root zone. This may explain in part the difference between ET and TDR estimates. When it becomes affordable, widespread use of this soil moisture sensor could reduce overwatering and the potential for leaching of agricultural chemicals into ground water.

Moisture depletion patterns were highly variable between annual bluegrass and creeping bentgrass during the course of the day although daily means of VMC by species show no significant differences. Bihourly moisture patterns show three major trends: they upward water movement, water from guttation or infiltration of dew during morning hours.

Moisture depletion from transpiration or soil evaporation in response to evaporative demand also contributed to observed differences. Stomatal regulation during hot periods may account for reduced water loss by turf leaves as turfgrass strive to maintain osmotic balance in the tissues under conditions of high evaporative demand. Generally, the greatest moisture depletion occurred between 0900 and 1300 h suggesting that syringing after this period may be optimum timing to minimize heat and moisture stress. Periods that show no moisture change may reflect steady states between moisture loss and gains.

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CHAPTER 6

Adaptation of a New Water Balance Model for Turfgrass Under Variable Irrigation Regimes

Abstract

The water balance routine of the System Approach to Land Use Sustainability (SALUS) model was modified to simulate water balance in fairway turfs under three irrigation regimes at the Hancock Turf Research Center at Michigan State University. The irrigation treatments were: i) apply 2.5 mm daily; ii) maintain soil at field capacity; and iii) apply 2.5 mm only upon the appearance of wilting stress. Model components included subroutines for estimating infiltration, drainage, soil evaporation, transpiration, evapotranspiration, and soil volumetric moisture content (VMC) from soil, plant, and weather input files. Model modifications included the assumption of a fixed leaf area index and root length density through the growing season. Field measurements of VMC by depth were obtained for up to 60 days each year using time domain reflectometry (TDR) during the summers of 1992 through 1994. Evapotranspiration estimates were within the expected ranges for the site. The TDR measurements fell within the range of simulated VMC values. However, agreement between model simulations and field observations ranged from $0.12 < R^2 > 0.29$ for the irrigated treatments. The best agreement between observed and simulated VMC was with the stress

treatment for all depths ($0.39 < R^2 > 0.47$) suggesting that poor application uniformity may account for some of the variability. More turf-specific data would be needed to improve agreement between field VMC observations and model output.

Introduction

Turfgrasses continually are subjected to biochemical and physical adjustments in response to changing environmental conditions or managerial inputs. These changes result either from natural inputs such as rainfall, solar radiation, wind speed, temperature, and relative humidity or from managerial inputs such as traffic, irrigation, fertilizers, pesticides, mowing, and other cultural practices. For example, turfgrasses grown on sandy soils can lose most of the available soil water over a very short period.

Available water content (AWC) is widely used as the basis for scheduling irrigation, yet inexpensive, rapid, accurate, repetitive, and noninvasive methods of soil moisture determination are still lacking. Accurate VMC measurements are needed to improve irrigation scheduling for quality turf maintenance without compromising environmental quality.

Improvements in water balance models and computer simulation techniques can be used to improve water management strategies in urban agriculture. The need for predictive models such as the System Approach to Sustainable Land Use (SALUS) for soil water balance studies (Ritchie, 1991) stems from the lack of fast, safe, accurate, and affordable methods for determining volumetric moisture content (VMC). Such models are invaluable in estimating soil moisture status within the root zone for irrigation scheduling and for reducing the leaching of agricultural chemicals into ground water.

The SALUS model integrates soil, plant, and climatological inputs using either physically based or empirically derived relationships between system components to calculate the desired outputs. This study focuses mainly on water inputs, storage, and outputs as influenced by environmental conditions, plant factors, and managerial inputs, conveniently described by the hydrologic balance equation (Ritchie, 1981):

$$VMC_t = VMC_{t-1} + P_t + I_t - R_t - D_t - ET_t$$

where VMC_t is the volumetric moisture content at time t, $\mathbf{P_t}$ is precipitation, $\mathbf{I_t}$ is irrigation, $\mathbf{R_t}$ is runoff, $\mathbf{D_t}$ is drainage, and $\mathbf{ET_t}$ is evapotranspiration for a given time interval.

Operational estimates of the range of AWC are based on laboratory determination of soil water content. Ritchie and Amato (1990) summarized some of the criticisms of this approach: i) drainage water may be available to plants; ii) 1500 kPa may not represent the lowest potential of moisture extraction by plants; iii) moisture extraction is highly dependent on root density; and iv) the effects of spatial and temporal variability of soil moisture are largely ignored.

The water balance models of Richardson and Ritchie (1973) and Skaggs (1978) were among the earliest dynamic water balance models. Innovations in computer technology have increased the number of user-friendly models. Despite widespread applications of water balance models in crop studies, their use in the study of turfgrass ecosystems has been limited. Ritchie et al. (1991) cited the lack of accommodation for spatial and temporal variability in the factors used to predict plant performance as a deficiency in the usefulness of such models for agrotechnology transfer.

Time domain reflectometry provides the convenience of rapid and accurate moisture determination in space and time (Topp and Davis, 1980; Dalton, 1992). Carrow (1991) and Saffel (1994) demonstrated the successful use of TDR for VMC determination within turfgrass root zones. This could provide a database for the verification of water balance models in turfgrass ecosystems.

The objectives of this study were: i) to simulate the water balance components of a turfgrass ecosystem, using the new water balance subroutine of the SALUS model; ii) to compare volumetric moisture content under different irrigation regimes; and iii) to compare modeled volumetric soil moisture content to TDR data measured in the field.

Materials and Methods

This study was conducted at the Hancock Turfgrass Research Center at Michigan State University. Three irrigation treatments provided contrasting moisture inputs for established annual bluegrass (*Poa annua*, L. var. reptans) and Penncross creeping bentgrass (*Agrostis palustris* Huds. L.) fairway turfs mowed three times a week at a cutting height of 16 mm. Irrigation treatments were: i) return the soil to field capacity (FC); ii) apply 2.5 mm daily (DLY) (Vargas, 1994); and iii) apply 25 mm only upon the appearance of wilting stress (STR). There were three replications for each treatment. A fourth irrigation management scenario, the effects of applying 2.5 mm every other day (EOD), also was simulated. There were no corresponding field observations for this treatment.

Irrigation plots had a slope of about 1.5%, with dimensions 11 m x 11 m. Each plot was split (11 x 5.5) and randomly seeded to annual bluegrass or creeping bentgrass. Four pop-up Rainbird irrigation heads were located at each corner of the plots, with average flow rate of

21.5 L per minute. Irrigation clocks were set to apply water at 0300 h under the assumption that low wind velocities at that time would be less likely to reduce application uniformity.

Table 6.1. Soil physical properties for SALUS model.

Depth (cm)	LL	DUL	SAT	INISW	RWCON	KSMAC	KSMTX
	$cm^3\ cm^{-3}$					$cm\ day^{-1}$	
2.0	0.12	0.33	0.38	0.33	0.25	40.0	3.1
5.0	0.11	0.29	0.32	0.29	0.25	53.0	3.0
8.0	0.11	0.28	0.32	0.28	0.25	55.0	2.9
11.0	0.10	0.27	0.32	0.27	0.25	57.5	2.8
14.0	0.10	0.27	0.32	0.27	0.15	75.5	2.5
17.0	0.10	0.27	0.32	0.27	0.12	74.1	2.3
20.0	0.10	0.27	0.32	0.27	0.11	80.0	2.0
23.0	0.10	0.27	0.32	0.27	0.11	80.0	1.8

LL is drained lower limit, DUL is drained upper limit, SAT is moisture content at saturation, INISW is initial soil moisture content, RWCON is root constant, KSMAC is saturated macropore hydraulic conductivity, and KSMTX is matrix hydraulic conductivity.

Field volumetric soil moisture was determined by time domain reflectometry (TDR). Pairs of stainless steel probes, 3.2 mm in diameter and 20 cm long, were placed horizontally at 2.5, 7.5, and 12.5 cm for the first three pairs of sensors and at 17.5 and 22.5 cm for the fourth pair of sensors. These represent depths of 0-5, 5-10,10-15 and 15-25 cm. The depths did not correspond to the soil-depth increments in the SALUS model as shown in Table 6.1. Weighted VMC averages from the water balance simulations were calculated to correspond to the field installations and were used in validating the model.

The soil type was a modified Owosso sandy loam (Fine mixed mesic Typic Hapludalf). Initial soil hydraulic properties were taken from taxonomic properties of an Owosso sandy loam, as described in the Ingham County Soil Survey. Weighted means of the volumetric soil moisture content by depth from the model were calculated to yield VMC values that correspond to the depth increments of the TDR installations. The soil file included the wilting point or drained lower limit (LL), the drained upper limit (DUL) or field capacity, moisture content at saturation (SAT), and the macropore (KSMAC) and soil matrix (KSMTX) hydraulic conductivities for the different soil depths, as shown in Table 6.1. The drained upper limit (DUL, 0.28 $cm^3 cm^{-3}$) was determined from TDR field observations 48 h following a soaking rain. Hall and Heaven (1970) used similar procedure to estimate field capacity, in-situ, in early spring using a neutron probe. This value agreed with the gravimetrically determined value of 0.281 cm^3 cm^{-3} (Saffel, 1994).

Model Description

Functional models like SALUS have modest input requirements, minimum computational time, making them more user-friendly. The model contains subroutines for estimating infiltration, drainage, upward-flow, moisture redistribution, potential soil evaporation, transpiration and evapotranspiration, and root water uptake. The model requires a weather file, a soil file, and a plant data file. A detailed outline of the input files was provided by Ritchie and Baer (1994, personal communication).

Infiltration amounts were assumed equivalent to irrigation and/or rainfall assuming negligible runoff. The model assumes that drainage occurs only when soil moisture content in a given depth exceeds the DUL. Daily drainage amounts were estimated from the equation (Ritchie, 1981):

$$drainage = SWON\ (VMC_I - DUL_I) * DLAYR_I \qquad ($$

where **SWON** is a unitless drainage coefficient that varies between 0 and 1; $\mathbf{VMC_I}$ and $\mathbf{DUL_I}$ are daily volumetric moisture content and the drained upper limit, respectively; and $\mathbf{DLAYR_I}$ is depth of the soil layer.

Potential evapotranspiration was calculated according to the equation of (Ritchie, 1994 personal communications). This equation differs from the Penman equation in that it does not include a wind function or vapor pressure deficit term. An advantage of the SALUS model is that it partitions evapotranspiration ($\mathbf{E_o}$) into soil evaporation ($\mathbf{E_s}$) and transpiration ($\mathbf{E_p}$) on the basis of the leaf area index. Potential soil evaporation ($\mathbf{E_s}$) was estimated from potential evapotranspiration as a function of the leaf area index (LAI) according to the equation (Ritchie, 1972):

$$E_s = E_p^{-(0.4\ LAI)} \qquad ($$

Upward water flow was calculated using Richards (1931) equation. The new water balance model was written in FORTRAN. Modifications in the FORTRAN code were made by J. L. Ritchie (personal communication).

Model Inputs

Weather data from a Rainbird weather station 2 m high and 30 m from the plots were used in soil-water-balance simulations. Weather data sets for these simulations included daily solar radiation (MJ m^{-2} day^{-1}), maximum and minimum temperatures (°C), and rainfall (mm). For the irrigated treatments, irrigation amounts were added to rainfall. These data were used to estimate infiltration, drainage, soil evaporation and turf transpiration. Data files were set in arrays specified for the SALUS model (Ritchie, Personal communication).

Plant Properties

Plant variables used for simulations were LAI and root length density (RLD) for the four depth increments. An effective root length density of 5 cm cm^{-1} was assumed for the 0-5 cm depth. Root length density for the 5-10, 10-15, and 15-25 cm depths were calculated based on the percent root mass distribution by depth (1.1 cm cm^{-1}, 0.55 cm cm^{-1} and 0.45 cm cm^{-1} respectively). These percentages were derived from average root mass ratios for four depths from three sampling dates presented in Chapter 4. These estimates fell within the range of values observed by Murphy et al. (1994) in minirhizotron studies.

Leaf area index is needed in practically all ET models (Ritchie and Amato, 1990). Instruments for accurate leaf area determination for closely mowed turf are not yet practical. Leaf area indices for fairway turfs are not easy to measure because of the small leaf area for closely mowed turfs and the folding habits of some species such as annual bluegrass. For a fairway turf mowed three times a week at a cutting height of 16 mm, a constant LAI of 3.5 was assumed (Ritchie personal communications)

Model Modifications

Simulations began on May 1 each year and ended on September 30 (152 days annually). The model was modified by; i) setting a fixed leaf area index, and ii) allowing for user defined root length density. This provides greater flexibility in simulation options. Output files were also modified to generate only data relevant for the water balance study. Descriptive statistics was used to analyze the output data. Volumetric moisture content as measured by TDR were compared to simulated VMC by regression analysis.

The SALUS model assumes homogeneity of each soil depth. Water movement from irrigation or rainfall into lower depths occurs only after the previous depth is saturated. The model also uses a two-domain saturated hydraulic conductivity: matrix and macropore hydraulic conductivities.

Results and Discussion

Weather for the 1992, 1993 and 1994 seasons are presented in the appendix. In 1992, rainfall was spread more evenly than in 1993 or 1994. In 1993, most of the rainfall occurred in the latter half of the season. In 1994, heavy and frequent rains occurred between days 163 and 235, coinciding with the peak of hot summer conditions.

Model output of interest include infiltration, drainage, VMC, and ET components. Infiltration amounts generated by the model were the sum of rainfall and/or irrigation for the different treatments. The 2.5 mm daily treatment had the highest total water input as irrigation was applied daily regardless of rainfall. As a result, cumulative seasonal infiltration was also highest in the 2.5 mm daily treatment for all years. The water input per application tended to be highest for the FC which had lower irrigation frequency than the DLY treatment but had higher amounts of applied water per irrigation event. The stress treatment had the lowest mean seasonal infiltration, as expected.

Mean seasonal infiltration ranked DLY > FC > EOD > STR (Table 6.2). Seasonal water application for the FC, EOD and STR treatments were 0.80, 0.75 and 0.50 of the amounts for the DLY treatment in 1992. Similar results were observed for other years (1993; 0.89, 0.76, 0.51 and 1994; 0.91, 0.73, and 0.53 respectively for the FC, EOD and STR). This suggest that during wet years application of 2.5 mm daily supplies more water than is required to maintain the soil at field capacity. Futhermore, maintaining soil moisture levels at field capacity fails to accommodate potential moisture gains from rainfall, hence increasing water losses.

Cumulative infiltration by irrigation treatment for 1992 is given in Fig. 6.2a. The data for all years are shown in Table 6.2. Cumulative infiltration of more than 700 mm for the DLY treatment was nearly double that for STR (357 mm) in 1992 but only 1.3 times compared to FC and EOD. Cumulative infiltration ranked DLY > FC > EOD > STR for all years.

Daily drainage for 1992 are presented in Fig. 6.1. Seasonal values for all years and treatments are presented in Table 6.3. Drainage from the stress treatment was minimal compared to the irrigated treatments. Overall daily and seasonal drainage by irrigation treatment also ranked DLY > FC > EOD >STR. Variation in drainage losses was also dependent on rainfall amounts and distribution. For a water balance model in which the depth of interest is only 25 cm, drainage losses are expected to be high due to low storage capacity of the shallow soil depth under consideration.

This was particularly true when 2.5 mm of irrigation is applied daily or when the soil is returned to field capacity daily in years with above average rainfall. Drainage in this modelwas estimated below the 100 cm depth hence the low drainage values reported in Table 6.3 Daily application of 2.5 mm of irrigation resulted in 1.4 times more drainage losses than

Table 6.2. Seasonal water application by irrigation treatment and by year based on 152 day season.

Year	Irrigation Treatment			
	2.5 mm Daily	2.5 mm Alternate Days	Field Capacity	Stress
	mm			
1992				
Mean	4.7 ± 5.2	3.5 ± 5.6	3.8 ± 6.5	2.3 ± 5.5
Total	717.4	536.1	573.6	357
1993				
Mean	4.8 ± 5.0	3.7 ± 5.4	4.3 ± 6.7	2.5 ± 5.4
Sum	740.9	563.9	658.7	384.3
1994				
Mean	5 ± 5.9	3.7 ± 6.7	4.4 ± 6.0	2.6 ± 6.3
Sum	757.9	556.2	689.3	404.2

EOD, 1.2 to 1.3 more drainage loses than FC and more than 2 times more drainage compared to STR.

Cumulative drainage for the different treatments for 1992 are presented in Fig. 6.2b. Drainage amounts were low because drainage was estimated below the 1 m depth, four times deeper than the sphere of influence of TDR installations. Estimates for the 25 cm depth are expected to be much higher suggesting poor resource capture by shallow rooted cool season turfs. Maintaining the soil at or near field capacity does not allow maximum utilization of rainfall.However, there was evidence of upward capillary presented in Chapter 5.

Table 6.3. Seasonal drainage by irrigation treatment and by year based on 152 day season as predicted by SALUS.

Year	Irrigation Treatment			
	2.5 mm Daily	2.5 mm Alternate Days	Field Capacity	Stress
	mm			
1992				
Mean	0.4 ± 0.3	0.3 ± 0.3	0.3 ± 0.5	0.2 ± 0.3
Range	2.8	2.7	3.5	2.6
Total	64.9	47.0	50.9	29.3
1993				
Mean	0.4 ± 0.3	0.3 ± 0.3	0.4 ± 0.6	0.2 ± 0.3
Range	2.3	2.1	3.5	1.8
Sum	67.4	49.3	58.3	31.6
1994				
Mean	0.5 ± 0.4	0.3 ± 0.3	0.4 ± 0.5	0.2 ± 0.3
Range	2.6	2.5	3.4	2.3
Total	68.5	49.2	57.8	33.4

Daily soil evaporation, (E_s) and plant transpiration (E_t) for 1992 are presented in Fig. 6.3a. Daily E_s soil as predicted by the SALUS model ranged from 0.02 to 1.4 mm but seasonal E_s means ranged from 0.8 to 1.0 mm for all years as presented in Table 6.4. It is worth noting that E_s was strictly a function of the leaf area index. Based on an assumed fixed leaf area index of 3.5, assumed in the calculation of E_s the more or less constant value is expected. This implies that soil evaporation is independent of soil moisture conditions, once

Table 6.4. Seasonal soil evaporation by irrigation treatment and by year based on 152 day season as predicted by SALUS.

Year	Irrigation Treatment			
	2.5 mm Daily	2.5 mm Alternate Days	Field Capacity	Stress
	mm			
1992				
Mean	0.9 ± 0.3	0.9 ± 0.3	0.9 ±0.3	0.8 ± 0.3
Range	1.3	1.3	1.9	1.3
Sum	129.4	129.3	126.4	126.4
1993				
Mean	0.8 ± 0.3	0.8 ± 0.3	0.9 ± 0.5	0.8 ± 0.3
Range	1.4	1.3	2	1.3
Total	125.2	125.2	141	123.3
1994				
Mean	0.9 ±0.3	0.8 ±0.4	1 ± 0.3	0.9 ± 0.3
Range	1.3	1.8	1.6	1.3
Sum	136.7	120.3	156.6	132.4

again emphasizing the need for soil moisture-based irrigation scheduling. Further research would be needed to obtain accurate seasonal variation of LAI for closely mowed turf. This may improve predicted values of the different hydrologic components.

Cumulative seasonal values for soil evaporation, plant transpiration and potential evapotranspiration (E_p) are presented in figure 6.3b. The highest and lowest transpiration and soil evaporation values were recorded between day of the year (DOY) 140 and 160. Overall, soil evaporation contributed up to 20% of daily potential ET. It must be noted that the

Table 6.5. Seasonal transpiration by irrigation treatment and by year based on 152 day season as predicted by SALUS.

Year	Irrigation Treatment			
	2.5 mm Daily	2.5 mm Alternate Days	Field Capacity	Stress
	mm			
1992				
Mean	3.4 ± 1.3	3.3 ± 1.2	3.5 ± 1.2	3.3 ± 1.3
Range	5.1	5.1	7.3	5.3
Total	511.2	509.5	531	514.2
1993				
Mean	3.2 ± 1.3	3.2 ± 1.3	3.6 ± 2.0	3.3 ± 1.6
Range	6	5.4	9	5.7
Total	494.1	494.4	554.4	495.9
1994				
Mean	3.6 ± 1.3	3.1 ± 1.6	4.1 ± 1.2	3.6 ± 1.3
Range	5.4	7.7	6.1	5.5
Total	540.2	474.3	617.9	544.3

quantification of E_t was based on an assumed rather than measured leaf area index (LAI) given the difficulties involved in measuring LAI for closely mowed turfs.

Mean seasonal transpiration values for all years and treatments are shown in Table 6.5. Mean transpiration values among irrigation treatments were fairly constant in 1992 and 1993, but not in 1994. The highest mean seasonal transpiration values from the simulations were for the field capacity treatment, whereas those from the 2.5 mm daily and the stress treatment

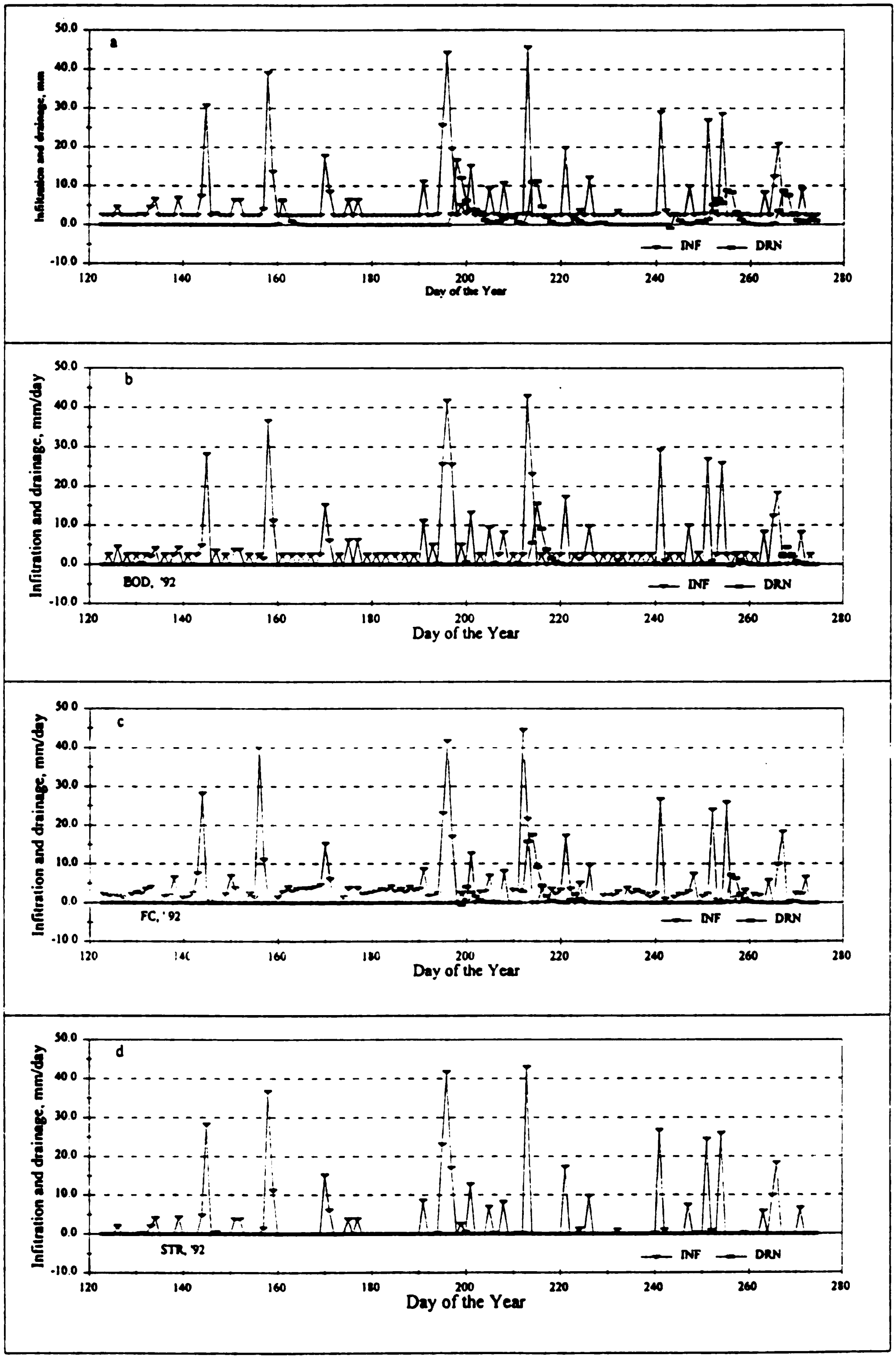

Fig. 6.1 Seasonal infiltration and drainage for the 2.5 mm daily (DLY); 2.5 mm every other day (EOD); Field capacity (FC); and Stress treatments (STR) for 1992.

were about the same.

Transpiration estimates were based on weather data at the site. Mean transpiration rates were about the same, regardless of irrigation treatment, for all years. Because the stress plots received no irrigation, one would expect less moisture depletion from this treatment and hence lower transpiration values. This provides a good argument for conjunctive use of soil moisture monitoring and conventional ET methods for irrigation scheduling.

Cumulative transpiration was similar for all irrigation treatments for 1992 (Fig. 6.3c). The lack of separation of the different treatments in the cumulative transpiration plots from year to year is evidence that irrigation treatments did not significantly affect transpiration in this model. This is again obvious because unlike rainfall, the effect of irrigation on ET is not accounted for in weather data used in ET calculations.

Volumetric moisture content was the most important variable in this study because TDR observations in the field could be compared to simulated VMC. Simulation outputs for VMC for the different depths for the 2.5 mm daily treatment and TDR measurements are presented in Fig. 6.4. Both measured and simulated VMC ranked 0-5 > 5-10 $\geq$ 10-15 > 15-25 cm depths with values ranging from 0.24 cm^3 cm^{-3} for the 15-25 cm depth to a high of 0.33 cm^3 cm^{-3} for the 0-5 cm depth. Although the 5-10 cm depth was consistently higher in VMC than the 10-15 cm depth, the differences were not always significant. Measured VMC values were often lower than simulated values with increasing depth.

Measured and simulated VMC response to rainfall and irrigation for the field capacity treatment are presented in Fig. 6.5 The field capacity treatment showed higher variability than the 2.5 mm daily treatment in all years. Both the predicted and measured VMC show

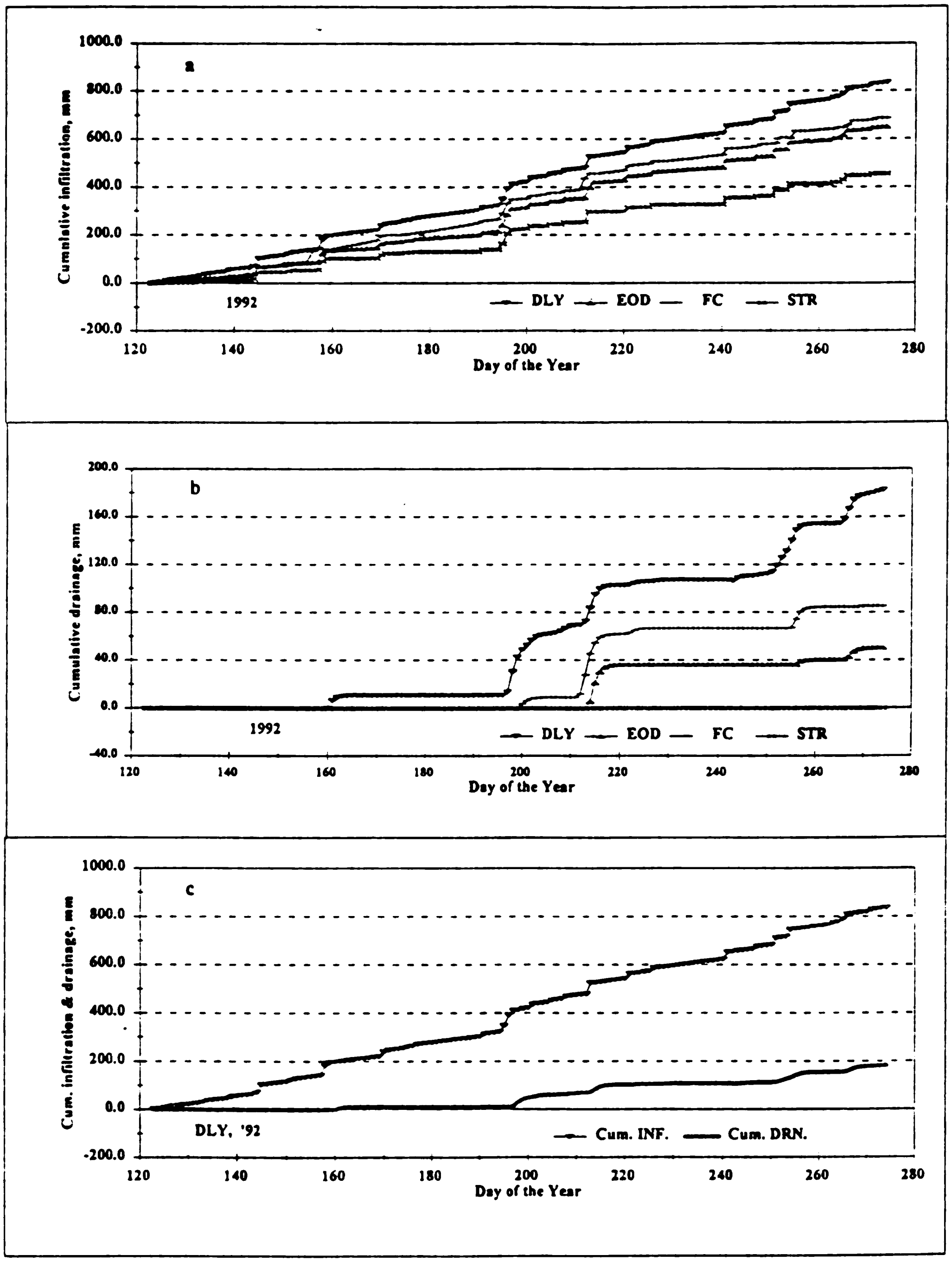

Fig. 6.2. Cumulative infiltration (a), and cumulative drainage (b) for the daily (DLY), 2.5 mm every other day (EOD), field capacity (FC), and stress (STR) treatments and cumulative infiltration and drainage (c) for the daily treatment , 1992.

a very narrow range over time. Volumetric moisture content, by depth, followed the pattern observed in the 2.5 mm daily treatment. Maximum VMC values during rainy periods for the 0-5 cm depth seemed to coincide for both irrigated treatments. The field capacity treatment showed greater moisture depletions for the 15-25 cm depth than did the 2.5 mm daily treatment.

The stress treatment (Fig. 6.6) showed the highest variation in VMC for all years. There was better agreement between simulated VMC and field observations for the stress than other treatments in both years, $0.39 < R^2 < 47$ compared to $0.12 < R^2 < 0.29$ for the irrigated treatments. For the irrigated treatments, VMC for the 0-5 cm depth was comparably high during wet periods. Ritchie and Amato (1990) stated that organic matter content increases the drained upper limit by 23% for each percentage increase in organic matter content. Accumulation of organic matter at the surface may thus explain higher VMC values observed in the 0-5 cm depth. However, during extended dry periods, the 0-5 cm depth for the stress treatment was also the driest depth. The highly dynamic nature of this depth, as exemplified in the stress treatment, was due to its proximity to the changing environmental conditions, high root density, and organic matter content.

Three prevalent philosophies that have been used in validation of models are: i) comparison of measured versus modeled values; ii) expert opinion, and iii) use of an existing model (Manetsch and Park, 1993). This new water balance model is being developed and verified for various field crops. Field observations of VMC as measured by TDR under fairway turfs for 1992 were compared to model predictions. Field measurements using TDR fell with the range of the SALUS model VMC for all treatments and for all years. However, R^2 values (up to 0.29 for the irrigated treatments and 0.47 for the stress indicate that much

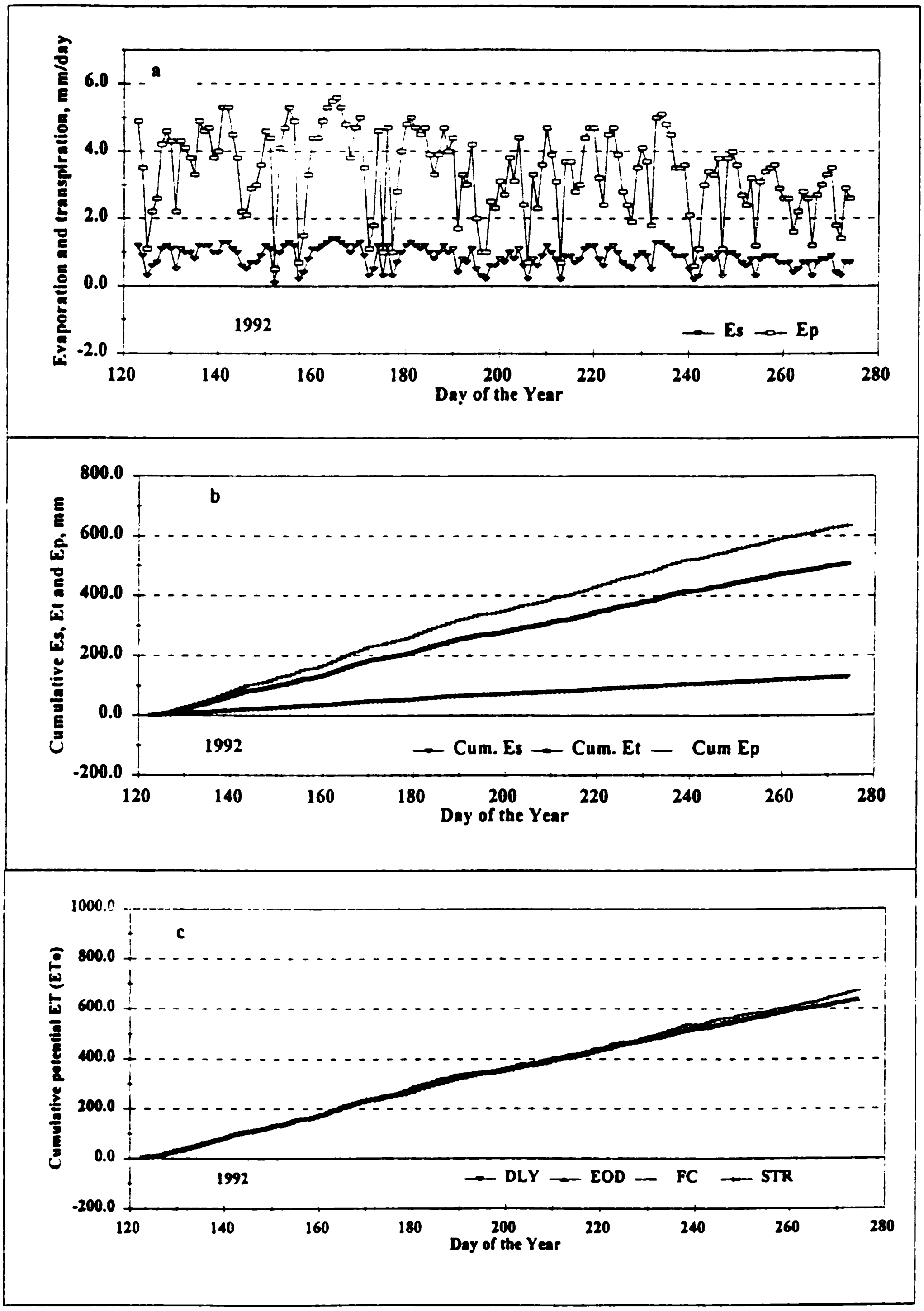

Fig.6.3. Daily soil evaporation (Es) and transpiration (Es) (a); cumulative soil evaporation (Cum Es), transpiration (Cum. Et), and evapotranspiration (Cum. Ep) (b); and cumulative potential evapotranspiration (ET_o) for the daily (DLY) 2.5 mm every other day (EOD), field capacity (FC) and stress (STR) treatments (c), 1992.

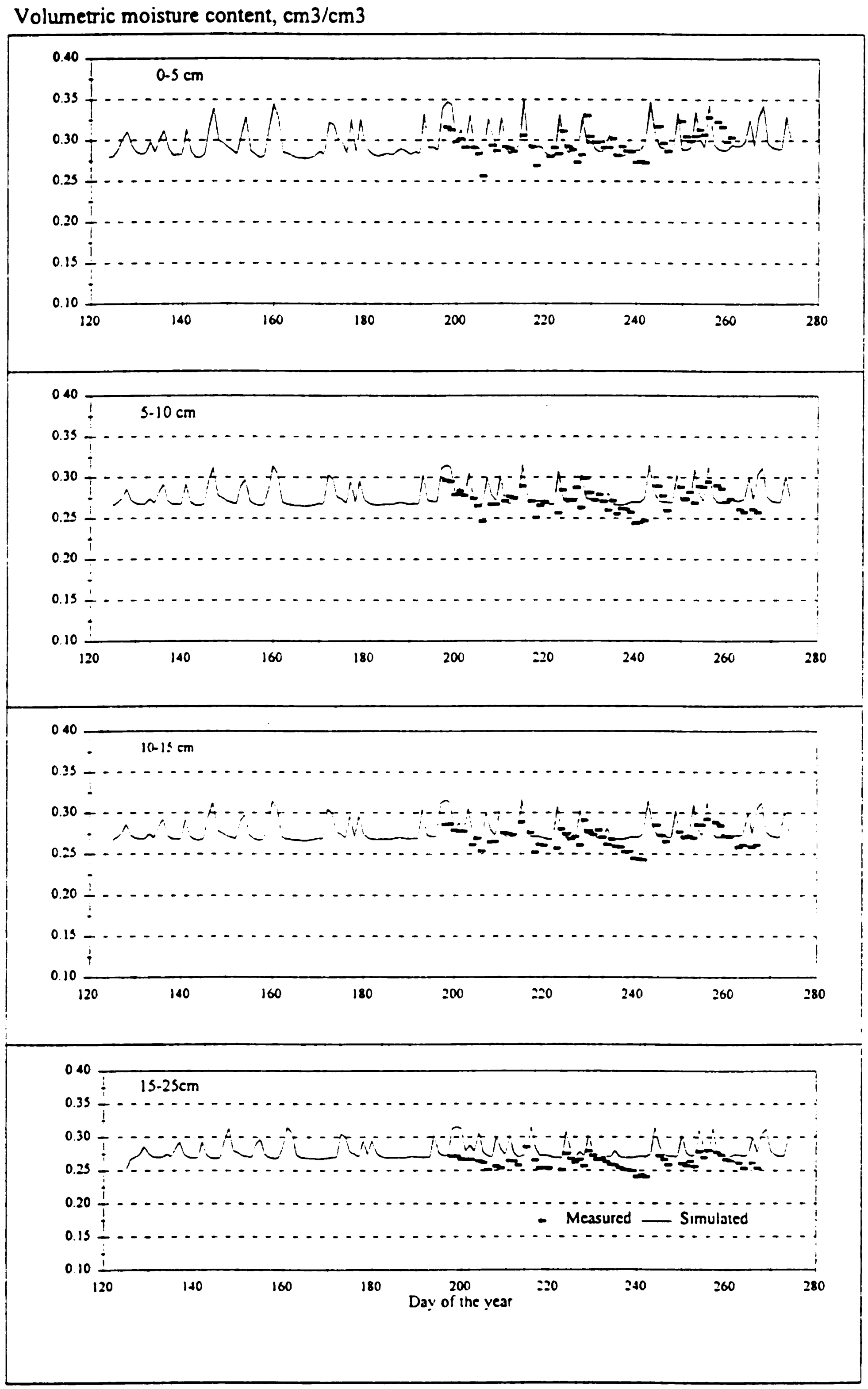

Fig. 6.4. Measured and simulated volumetric moisture content by depth for 2.5 mm daily treatment (DLY), 1992.

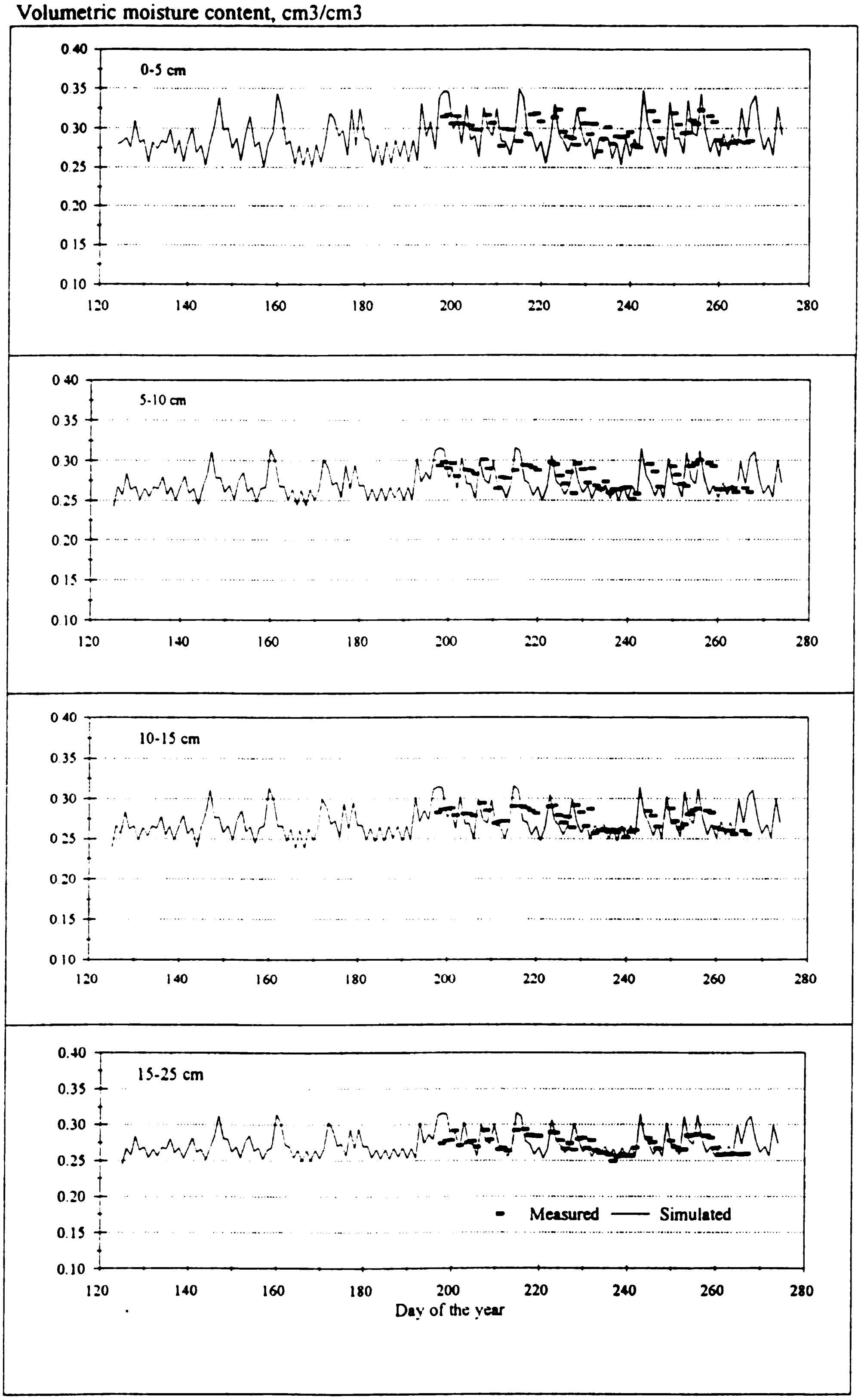

Fig. 6.5. Measured and simulated volumetric moisture content by depth for the field capacity treatment (FC), 1992.

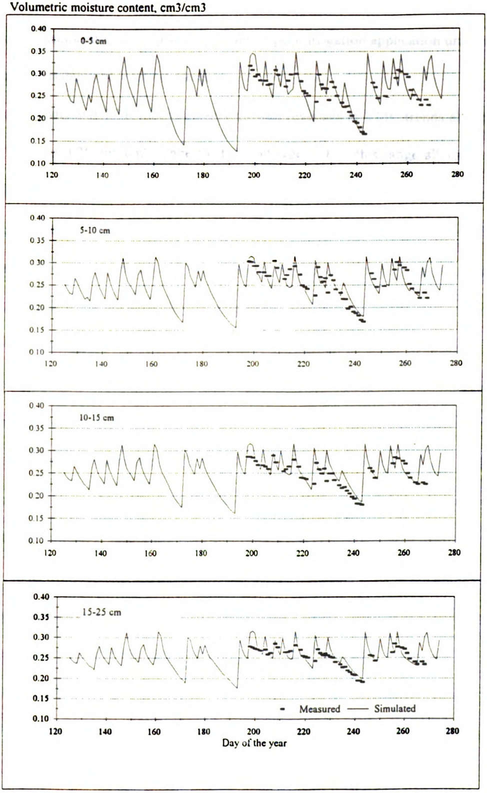

Fig. 6.6. Measured and simulated volumetric moisture content by depth for the stress (STR) treatment, 1992.

of the variation in soil moisture content is not explained by the model. This low correlation for the irrigated treatments could explained in terms of poor irrigation application uniformity, and the spatial variability of VMC in the field.

Simulated VMC and TDR measurements showed reversals in VMC trends above and below the 0.20 to 0.25 $cm^3\ cm^{-3}$ range for this soil type. Over this range all soil depths showed only minor differences in VMC for the stress treatment and it is reasonable to assume that there is no net moisture flux among depths in spite of evapotranspiration losses. From an environmental standpoint, this could be an ideal level to maintain soil moisture content if soil moisture based irrigation scheduling is employed. Two advantages of this are: i) the above moisture level guarantees at least the minimum acceptable turf quality rating (6); ii) potential water savings could result from lower irrigation rates, with greater accommodation for water inputs from rainfall.

Simulated versus the measured VMC for 1992 are presented in Figs. 6.4, 6.5, and 6.6. Volumetric moisture content for the irrigation treatments at four different depths were compared to the simulated values for 1992 and 1993. For the 5-10, 10-15, and 15-25 cm depths, the model overpredicted soil moisture levels for all treatments in turfgrass ecosystems.

The assumption of constant soil hydraulic properties for both years, when soil hydraulic properties are indeed dynamic may also account for differences between the model and field data. In addition, poor irrigation application efficiency may contribute to the observed differences. Model predictions of volumetric moisture content were based on the instantaneous VMC following rainfall or irrigation. The time lag between irrigation application (0300 h) and TDR measurements (0700 to 0900 h) may explain some of the variability between predicted VMC and TDR readings.

Conclusions

The modified water balance routine of the SALUS model provided reasonable estimates of hydrologic components for turf ecosystems. Time domain reflectometry data fell within the range of simulated VMC. The best agreement was with the 0-5 cm depths and the stress treatment. The highest R^2 values between simulated and TDR VMC were for the stress treatment and the 0-5 cm depths for all years. Model estimates for the 0-5 cm depth provided the best approximation of field conditions for all treatments in all years. Although simulated VMC were within the range of TDR measurements, R^2 values were low. More turf specific data would be needed to improve correlations between field observations and simulation output.

Mean seasonal infiltration and drainage ranked DLY > FC > EOD > STR. The low drainage amounts may not imply less leaching from the 25 cm depth as drainage was calculated below the 100 m depth as for field crops. Daily soil evaporation contributed about 20% of total ET based on assumed leaf area index of 3.5. Transpiration values were within the expected range for East Lansing MI. Contrary to expectation, seasonal cumulative transpiration was not different for the various irrigation.

The stress treatment showed the greatest variation in VMC for all years. While changes in VMC for the irrigated treatments were over a very narrow margin, volumetric moisture content by depth ranked 0-5 > 5-10 >10-15 >15-25 cm at all times for the irrigated treatments. This trend was also true for the stress treatment during wet periods but during dry periods, the trend was reversed (15 -25 > 10-15 > 5-10 > 0-5 cm). These reversals were evident in both the simulated and measured VMC. For a model based on limited weather input the SALUS model provides accurate ET estimates and VMC estimates by depth for a turfgrass ecosystem. Once all the data is arranged, it takes less than 5 seconds to execute. This is a high level of efficiency with respect to computation time.

Because the model was initially designed for crops the model structure did not allow for adjustments in the soil data input by depth. Future modifications in programming may hopefully resolve this weakness. With technological advancement more accurate leaf area indices for closely mowed turf will improve the partitioning of soil evaporation and transpiration. Overall this model could serve as a management tool for improving turf irrigation management.

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CHAPTER 7

An Evaluation of Turfgrass Irrigation Scheduling Using the Soil Conservation Service (SCS) SCHEDULER Model

Abstract

Modeling has become an important tool in crop research. The use of models in turfgrass studies, however, has been very limited. A three-year study (1992-1994) was conducted at the Hancock Turfgrass Research Center to simulate evapotranspiration, available water and drainage losses (excess water) from turfgrass plots under three irrigation regimes using the Soil Conservation Service (SCS)-SCHEDULER model (Shayya and Bralts 1994). Irrigation treatments were: i) apply 25 mm upon the appearance of wilt stress (STR), ii) apply 2.5 mm daily (DLY), and iii) maintain soil at field capacity daily (FC) based on time domain reflectometry (TDR) measurement. Predicted daily potential evapotranspiration (ET_p) values during 152 day season over a three year period ranged from 0.5 to 7.6 mm. Predicted turf ET (ET_t) for the stress treatment was lower than the actual ET for all years, suggesting that soil moisture levels for the stress treatment did not meet the optimum amounts and frequency needed for optimum turf growth. The ranking for amounts of applied irrigation by treatment was DLY > FC > STR during wet periods and FC > DLY > STR during dry periods. In all years seasonal cumulative rainfall exceeded the cumulative potential ET, but poor rainfall distribution necessitated supplemental irrigation. Poor rainfall

distribution resulted in inefficient use of rainfall water, with a high potential for drainage losses. Excess rainfall and irrigation ranked DLY > FC > STR. During wet periods, the excess water from DLY treatment was higher than from the field capacity and stress treatments. Simulated available water content did not agree well with field measurements. These disparities suggest that further modifications are necessary to improve the agreement between field observations and model output. Additional site-specific seasonal rooting depth data may be necessary to improve model AWC and TDR observations. Since, the SCS-SCHEDULER model does not account for upward water flow, predicted daily moisture depletion values were much larger than normal.

Introduction

Considerable water savings can be achieved in turf management through efficient irrigation scheduling based on soil moisture depletion measurements (Augustin et al., 1984; Snyder et al., 1984; Carrow, 1991). Economical irrigation requires the determination of actual evapotranspiration. The multiplicity of ET models and the lack of agreement among methods (Penman, 1948; Jensen and Haise, 1963; Doorenbos and Pruitt, 1977; Wright, 1981) makes it difficult to choose anyone model. Operational estimates for most ET models are based on the assumptions of Penman (1948) or some modification of them. The basic assumptions of Penman's definition of potential ET (ET_p) do not match the conditions encountered in turf culture. Thus, adjustments are necessary to accommodate variations in climate and model specifications.

Two important considerations in crop ET calculation are; crop coefficients needed to estimate actual ET; and plant height that influences the aerodynamic component or wind function of the Penman model. The cutting heights recommended for turf maintenance range from less than 4 mm on greens to more than 80 mm on some low maintenance turfs. This cutting height range is well below the specifications of Doorenbos and Pruitt (1977) or Jensen and Haise (1963). The lack of agreement among ET models by location, even after adjustments have been made to obtain realistic ET values, suggests a higher level of empiricism into an otherwise physical model. Crop coefficients are used to adjust ET_p to actual turf ET (ET_t). Mini-lysimeters are used to estimate actual or turf ET (ET_t) and hence the turf coefficient (K_t) (Carrow, 1991) from the ratio:

$$Et_t \ / \ ET_p = K_t$$

Turfgrasses show a wide degree of genetic diversity and adaptive radiation reflected in the variability in water use rates. Evapotranspiration rates have been shown to vary by species (Tovey et al., 1969; Biran et al., 1981; Kneebone and Pepper, 1982; Kim and Beard, 1988) and even by cultivar (Biran et al., 1981; Shearman, 1986; Kopec et al., 1988). Johns et al. (1983) developed a method of classifying turfgrass ET that assigns the following ratings: low for ET values less than 4 to 4.9 mm per day, medium for ET values from 5 to 7.5, and high for ET values above 8 mm.

Ideally just enough water should be applied to wet the rooting zone. Suggested recommendations for turf irrigation include: application of water to replace daily ET or some fraction thereof; irrigation using timers to apply fixed amount of water on regular basis for example 2.5 mm daily or 2.5 mm every other day (Vargas, 1994); or irrigation upon the appearance of wilting stress. Although some recommendations are successful in maintaining turf quality, there has been no quantitative evaluation with respect to total water use or excess water for each of the above irrigation scenarios.

An initial step in the development of moisture-depletion-based irrigation scheduling is the establishment of the "setful" point or field capacity (also called the drained upper limit, DUL) and the refill point based on the management allowable depletion (MAD) (Campbell and Campbell, 1982), where MAD ranges from 30-50% of available soil water (AW) . The basic assumption is that when the soil moisture is between (DUL) and MAD, moisture stress is less likely to occur. Below the MAD, turf growth and quality could be adversely affected.

Conventional methods for soil moisture determination include the gravimetric method, resistance blocks, neutron and gamma attenuation techniques. These methods are time consuming, labor intensive, involve radioactive sources or destructive soil sampling. Spatial variability from changing sampling sites during successive measurements also introduces errors into these soil moisture-evaluation methods. Despite good accuracy (Simpson and Meyer, 1987), the neutron probe is not amenable to the shallow depths encountered in cool-season turf management (Augustin and Snyder, 1983). However, there is still a need to develop affordable and dependable soil moisture sensors for evaluating turf irrigation requirements in addition to ET estimates.

In recent years, time domain reflectometry (TDR) has been widely applied in determining soil moisture and salinity (Topp et al., 1980). Time domain reflectometry uses the relationship between the composite soil dielectric constant and volumetric moisture content (VMC) proposed by Topp et al. (1980). Compared with other methods of determining VMC, TDR is adaptable for automation and multiplexing (Wraith and Baker, 1991), and remote retrieval of soil moisture data on a continual basis by a single TDR (Baker and Allmaras, 1990). Good agreement between simulated values and TDR estimates is necessary to establish confidence in the modified model for turf irrigation scheduling. One such model, the Soil Conservation Service (SCS)-SCHEDULER (version 3) was developed by Shayya and Bralts (1994) at Michigan State University. A previous version of this model has been described as one of the most accurate irrigation scheduling and evaluation software for field crops (Allan, 1991).

The SCS-SCHEDULER model uses the FAO-modified Penman equation to calculate potential ET (ET_p), actual ET (ET_a), and cumulative ET. Moisture depletion within the rooting zone is calculated using the following method (Hillel, 1980):

rainfall + irrigation - (change in soil moisture content + drainage + runoff) = ET

Estimates of excess rainfall and irrigation are important for improving irrigation application rates and reducing the frequency of drainage losses. Good agreement between model output and field data would indicate that the model may serve as a management tool (Ritchie, 1991) for irrigation managers. The SCS-SCHEDULER has a short-term forecasting routine based on historic or actual data that predicts irrigation scheduling for up to 60 days, for a given location. It also. Like other models, it allows for ad hoc experimentation without the labor, delays, and costs associated with field experimentation (Ritchie, 1991).

Although considerable turf irrigation research has been reported in the literature (Danielson et al., 1981; Aronson et al., 1987), the data are not reported in a form that can easily be incorporated into models. With increased use of computers in turf irrigation programming and research, modeling will no longer be restricted to researchers and consultants. Innovations in technology may eventually reduce the cost of soil moisture sensors. Conjunctive use of soil moisture sensors such as TDR with computers models will bring turf irrigation management another step into the computer age.

Model Description

The SCS-SCHEDULER (Shayya and Bralts, 1994) is an irrigation scheduling and evaluation package. This model provides a viable option for interactive crop irrigation scheduling and evaluation for periods of up to 60 days. The input requirements include local crop, soil, and weather data. The model computes the water balance within the rooting zone or depth of interest and suggests irrigation scheduling for optimum crop management. Evapotranspiration, rainfall, irrigation, and deep percolation are used to calculate excess water (excess rain + irrigation). The model quantifies various irrigation scheduling scenarios and their effects on plant-available water.

The objectives of this study were to: i) adapt the SCS-SCHEDULER model for use in turf irrigation; and ii) compare ET, soil moisture depletion and excess water under three turf irrigation regimes.

Materials and Methods

Three irrigation treatments were applied on an annual bluegrass (*Poa annua* var. reptans L.) and a Penncross creeping bentgrass (*Agrostis palustris* Huds. L.) fairway turfs established in 1989 at the Hancock Turfgrass Research Center at Michigan State University (Saffel, 1994). The soil type was a modified Owosso sandy loam (fine-loamy mixed mesic Typic Hapludalf). The turfs were mowed three times a week at a cutting height of 16 mm and were maintained according to standard practices for cool-season fairway turfs in Michigan. Because there were no significant differences in water use by species, the data were pooled across species.

The irrigation treatments in this study represented a range of prevalent irrigation practices in Michigan: i) apply 25 mm only upon the appearance of wilt stress; ii) apply 2.5 mm daily (Vargas, 1994); and iii) return the soil to field capacity based on TDR-measured moisture depletion.

Weather data for the summers of 1992, 1993, and 1994 were down-loaded from a Rainbird Maxipaw TM station located at the site. The weather data were converted into arrays compatible for use in the SCS-SCHEDULER by a routine in Quick Basic written for this study by Walid Shayya, visiting Professor and V. F Bralts Professor of Agricultural Engineering at MSU. This model uses the FAO-modified Penman equation (Penman, 1948) to calculate ET. The calculated ET serves as the basis for estimating soil moisture depletion, and excess irrigation and rainfall, and scheduling irrigation for various field crops.

Irrigation treatments served as whole plots (11 m by 11 m) with split plots (5.5 x 11 m) seeded randomly to either annual bluegrass or creeping bentgrass. Pop-up irrigation heads were located at each corner of the plot. Irrigation was applied at 0300 h and TDR readings were taken between 0700 and 0900 h. The application and distribution uniformities were greater than 85% (Saffel, 1994). However, lower values were obtained during windy conditions early in the morning.

The model inputs included crop, weather, and soil data files. Seasonal turf coefficients, rooting depth, and management allowable depletion (MAD) used for the SCS-SCHEDULER simulations are presented in Table 7.1. The values were selected from the literature (Feldhake et al., 1983; Aronson et al., 1987; Kim and Beard, 1988), where available, or estimated from established values for field crops in the SCS-SCHEDULER data base.

7.1. Seasonal crop coefficients, rooting depth, and management allowable depletion used for the SCHEDULER simulations.

Growing Season	Rooting Depth	Crop Coefficient	Minimum Available Water Before Irrigation
(%)	cm	K_t†	%
0	15.2	0.45	50
10	20.3	0.50	50
20	21.6	0.60	50
30	12.7	0.70	50
40	16.5	0.75	50
50	14.0	0.75	50
60	15.2	0.75	50
70	17.8	0.70	50
80	17.8	0.60	50
90	16.5	0.50	50
100	15.2	0.40	50

† Initial K_t values were obtained from Kneebone and Pepper, (1982). The rooting depth variation with time was adapted from Koski (1983).

Data used to develop the crop curve (turf curve), root zone expansion curve used in the simulations were adapted from the rooting-depth patterns of cool-season grasses in response to temperature stress during the warm summer months (Koski, 1983). Turf coefficients (K_t) ranging 0.50 to 0.85 have been reported in the literature (Kneebone and Pepper, 1982). However, the moisture depletion rates using the above values were so high that simulated AWC was much lower than values obtained by TDR or gravimetric methods. The K_t values were lowered progressively until there was agreement between simulated AWC and field measurements. The coefficients presented in Table 7.1 were reduced sequentially to obtain the best fit to the field data.

Table 7.2. Farm (turf)-specific input data for SCS-SCHEDULER simulations.

Plant type		Turf
Starting date		May 1
Ending date		October 1
Duration of simulation		152
Degree days or % season		% season
Management allowable depletion (MAD)		50%
Available water content by depth		100%
Allowable excess water above field capacity		105%
Available water-holding capacity by depth	0-5 cm	$0.155\ cm^3cm^{-3}$†
	5-10 cm	$0.145\ cm^3cm^{-3}$
	10-15 cm	$0.135\ cm^3cm^{-3}$
	15-25 cm	$0.125\ cm^3cm^{-3}$

†The available water-holding capacity of each soil depth was assumed to be half of the volumetric soil moisture content, expressed as equivalent depths. The weighted volumetric moisture content for all depths is $0.28\ cm^3\ cm^{-3}$.

Simulations began on May 1 (DOY 122 for 1992, and DOY 121 for 1993 and 1994) of each year and ended on October 1, resulting in 152 days of simulation each year. The default MAD value of 50% of soil-available water content was used for all simulations (Table 7.1). This value, commonly used in most irrigation models, indicates that irrigation is suggested when half the available water content is depleted (Campbell and Campbell, 1982). Below

50% available water left in the soil, the plants expend higher amounts of energy per unit of water uptake, hence the model calculates an adjusted ET (ET_a). Also, the default allowable excess water (105%) of field capacity was utilized for all simulations. Above this value, the water is lost either through drainage or as runoff and labeled excess water. Excess water amounts and frequency estimates were based on the amount and frequency with which soil moisture content exceeded the allowable excess water in the rooting depth (Table 7.2).

The plot used in this study had a slope of approximately 1.5%, so runoff would be limited unless the rainfall intensity was high. In this model, water lost by percolation or runoff was considered excess water.

Results and Discussion

Seasonal rainfall, temperatures and means are presented in Table 7.3. Rainfall maxima and means increased from 1992 through 1994. For example rainfall in 1992 and 1993 were 0.75 and 0.87 times that for 1994. Mean maximum and minimum temperatures showed less variation compared to rainfall. The range within minimum temperatures and maximum temperatures were strikingly similar for all years.

The lowest and highest potential evapotranspiration (ET_p) values for 1992 were 0.5 mm on May 31 and 6.8 mm on June 15, respectively. In 1993, a minimum ET_P of 0.5 mm was recorded on September 3, whereas a maximum of 7.4 mm occurred on both 16 and 17 July. Potential ET ranged from a minimum of 1.0 mm on 1 May, 1994, to a maximum of 7.6 mm on 22 June is not understood. Potential evapotranspiration is a weather-dependent variable estimated strictly from atmospheric variables. Predicted cumulative ET_p, and ET_t for all treatments (Table 7.4) ranked 1993 > 1994 >1992. The order for ET_a was 1993 > 1994 > 1992.

Table 7.3. Seasonal rainfall totals, daily seasonal means and maximum rainfall events; seasonal lowest, highest and mean maximum temperatures; seasonal lowest, highest and mean minimum temperatures for 1992, 1993, and 1994.

Weather Factor	Year		
	1992	1993	1994
		mm	
Rainfall			
Maximum	38.9	52.6	70.0
Mean & SD	2.7 ± 6.6	3.2 ± 8.1	3.7 ± 10.1
Total	421	493	565
Max. Temperature		°C	
Maximum	34.4	33.9	38.0
Minimum	9.4	10.0	10.4
Mean & SD	23.1 ± 4.6	24.0 ± 5.2	24.8 ± 5.7
Range	25.0	23.9	27.6
Min. Temperature		°C	
Minimum	-1.7	0.6	-0.1
Maximum	20.6	23.9	22.1
Mean & SD	9.8 ± 5.7	11.9 ± 5.4	11.6 ± 5.7
Range	22.2	23.3	22.2

Adjusted ET (ET_a) values for the stress treatment were substantially lower in 1992 than for the irrigated treatments but not in 1993 and 1994. This indicates that the stress treatment supplied less than adequate amounts of water to turfs in 1992 which had the lower rainfall (Table 7.4). The ET_t values were remarkably consistent within years for all treatments. With the exception of the stress treatment in 1994, ET_t was consistent for all irrigation treatments for each year. Variation in evapotranspiration from year to year may thus be attributed more to weather factors other than temperature since year to year variations in temperature were not statistically significant.

A weakness of ET models is that they fail to include the soil water status or soil water dynamics. This underscores the importance of incorporating soil moisture data into efficient irrigation scheduling practices. Rainfall and irrigation amounts and simulated available water content (AWC) for 1992, 1993 and 1994 are presented in Figs. 7.1, 7.2 and 7.3, respectively. The figures show the variation in AWC with time in relation to the drained upper limit (DUL) and the management allowable depletion (MAD).

Rainfall and irrigation amounts and available water content for the 2.5 mm daily, field capacity, and stress treatments for 1992 are presented in Fig. 7.1. Rainfall amounts and frequencies were highly variable from year to year. The variability of rainfall amounts and frequencies, as evident in the available water graphs for the field capacity and stress treatments, dictated the irrigation requirement. Available water content for the irrigated treatments was above the MAD for the entire season. This indicates that both irrigated treatments supplied adequate or more than adequate amounts of water for plant needs.

The field capacity treatment deviated slightly from the 0.28 cm^3 cm^{-3} average field capacity value during days with successively high ET. There were four distinct dry-down periods when AWC for the stress treatment fell below the MAD limit in 1992 (around day 140, 163, 170 to 180 and 235 in 1992). Quality ratings for the stress treatment were

Table 7.4. Seasonal cumulative potential (ET_p), turf (ET_t), and adjusted seasonal ET (ET_a), by year and irrigation treatment as predicted by the SCHEDULER model.

Irrigation Treatment		Year		
		1992	1993	1994
	ET_p	526	716	696
Field Capacity	ET_t	328	452	436
	ET_a	324	448	436
	ET_p	520	716	696
2.5 mm Daily	ET_t	326	457	439
	ET_a	324	452	439
	ET_o	526	714	696
Stress	ET_t	328	456	429
	ET_a	269	334	418

significantly lower than for the irrigated treatments (see Chapter 4). With the increase in rainfall amounts and frequency in the second half of the season, the AWC for STR stayed between the MAD and the drained upper limit (DUL) most of the time. Occasionally, the water content exceeded the 105% AWC limit, with the excess water lost as drainage or as runoff. The available water content for the 2.5 mm daily treatment in 1992 (Fig. 7.1) shows that VMC was at or above field capacity from July 10 to the end of the 1992 season. Compared to the stress treatment, the 2.5 mm daily treatment had two distinct dry-down periods at about days 160 to 170 and 180 to 195 but AWC fell never fell below MAD.

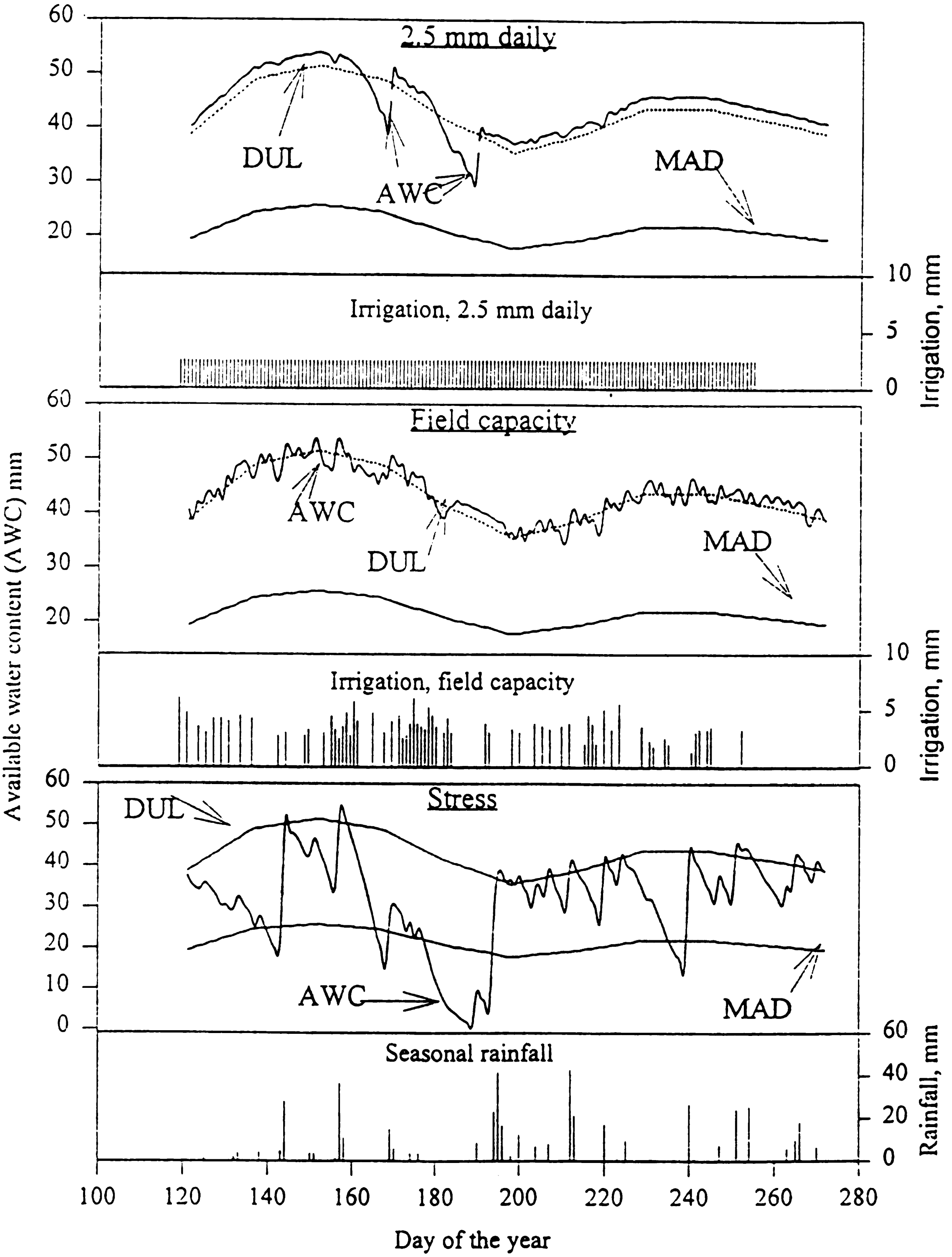

Figure 7.1. Available water content (AWC), irrigation and rainfall for the 2.5 mm daily, field capacity and stress treatments in relation to the drained upper limit (DUL) and management allowable depletion (MAD), 1992.

The field capacity treatment maintained the soil moisture level at about field capacity more consistently than DLY and received less seasonal irrigation. The amounts of water applied per irrigation for the field capacity treatment were greater than for the 2.5 mm daily treatment but irrigation was applied less frequently. This indicates that DLY supplied more water than FC and hence more than adequate water for turf growth.

In 1993 (Figure 7.2), the 2.5 mm daily treatment supplied more than adequate water for turf growth early in the season and toward the end of the season. Mid-season application of 2.5 mm daily was lower than the evaporative demand. In no instance, however, was the AWC below the MAD for this treatment. The deviation of the AWC from the DUL for the field capacity treatment was less than for the 2.5 mm daily treatment. The field capacity treatment maintained AWC at or near field capacity, as expected. There were several days in 1993 when the AWC was below the MAD for the stress treatment. When AWC is less than the MAD, there is a potential for plants to be subjected to moisture stress, particularly on days with high ET. Actual turf evapotranspiration (ET_a) is adjusted accordingly to reflect the potential for moisture stress. Poor rainfall distribution thus causes a need for supplemental irrigation to maintain quality turf as stated by Aronson et al., (1987) even when seasonal rainfall exceeded cumulative turf ET.

The figures showing rainfall, irrigation, and available water content for 1994 are presented in Fig. 7.3. The 1994 season began with a dry period from day 130 to 163. The heaviest rainfall (70 mm) for the entire study occurred on day 163. Rainfall was more evenly spread from day 163 through the rest of the season. Soil water content for both irrigated treatments oscillated about the DUL line depending on rainfall or irrigation. Soil water content for the stress treatment was below the DUL line between day 140 to 162, 207 to 217, and 245 to 258.

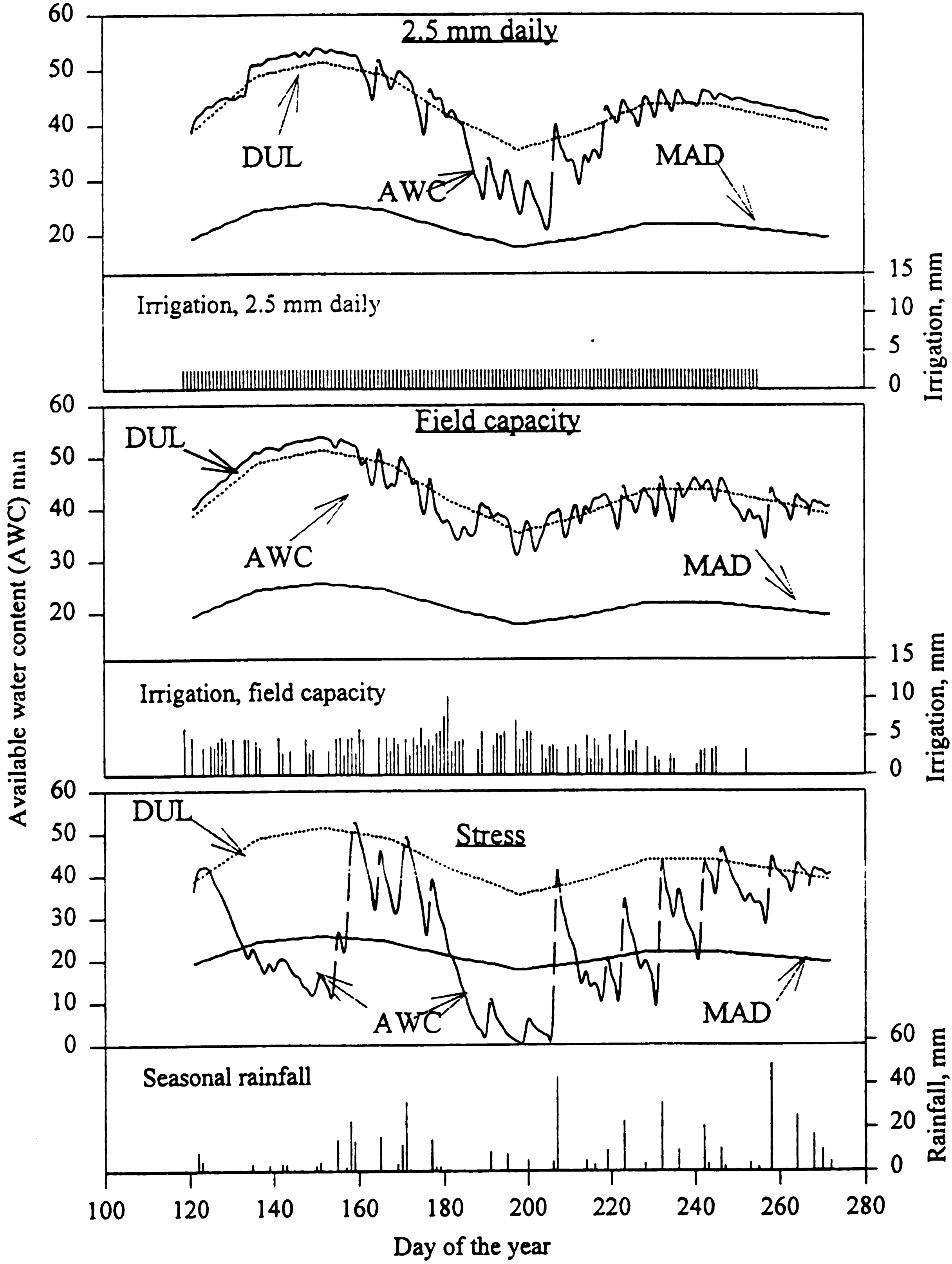

Figure 7.2. Available water content (AWC), irrigation and rainfall for the 2.5 mm daily, field capacity and stress treatments in relation to the drained upper limit (DUL) and management allowable depletion (MAD), 1993.

For the last third of the season, AWC by irrigation treatment ranked DLY > FC > STR for all years due to frequent rainfall (Figs. 7.1 through 7.3). In a dry year, one would expect the trend to be FC > DLY > STR. In terms of irrigation scheduling, the results showed that during wet periods, the field capacity and 2.5 mm daily treatments both supplied more than adequate water for quality turf maintenance. Turf quality ratings for both species for the stress treatment were significantly lower than for the irrigated treatments (Chapter 4).

Excess water by year for three irrigation treatments are given in Table 7.5. Excess water lost as drainage or runoff reduces water use efficiency, having environmental and economic implications. Excess water resulted from applied irrigation and/or rainfall when AWC is near or above the field capacity. Excess water trends were highly variable from year to year between irrigated and stress treatments due to variation in rainfall. Rainfall accounted for all the excess water from the stress and most of the excess water from the field capacity treatments. The amount of water applied per application for the field capacity treatment varied from day to day, as expected. By contrast, the 2.5 mm daily treatment was obviously constant. As expected, the least amount of excess water was from the stress treatment for all years. Although considerable water savings were evident from the stress treatment, this treatment subjects turfgrass to cycles of stress, with potential reduction in turf quality.

Because excess water lost from the stress treatment was due to rainfall, the amounts were much lower than for the irrigated treatments (Table 7.5). Excess water from irrigation for DLY ranged from 29 to 47, times that for FC, while the combined excess from rainfall and irrigation ranged from 1.2 to 1.3 times that for FC. For the stress treatment excess water from rainfall ranged from 0.1 in 1992 to a peak of 0.34 times that of FC in 1993. The excess rainfall amounts ranked DLY > FC > STR. This indicates a rather low efficiency with respect to water-resource capture for shallow-rooted, cool-season turfs. However, some of

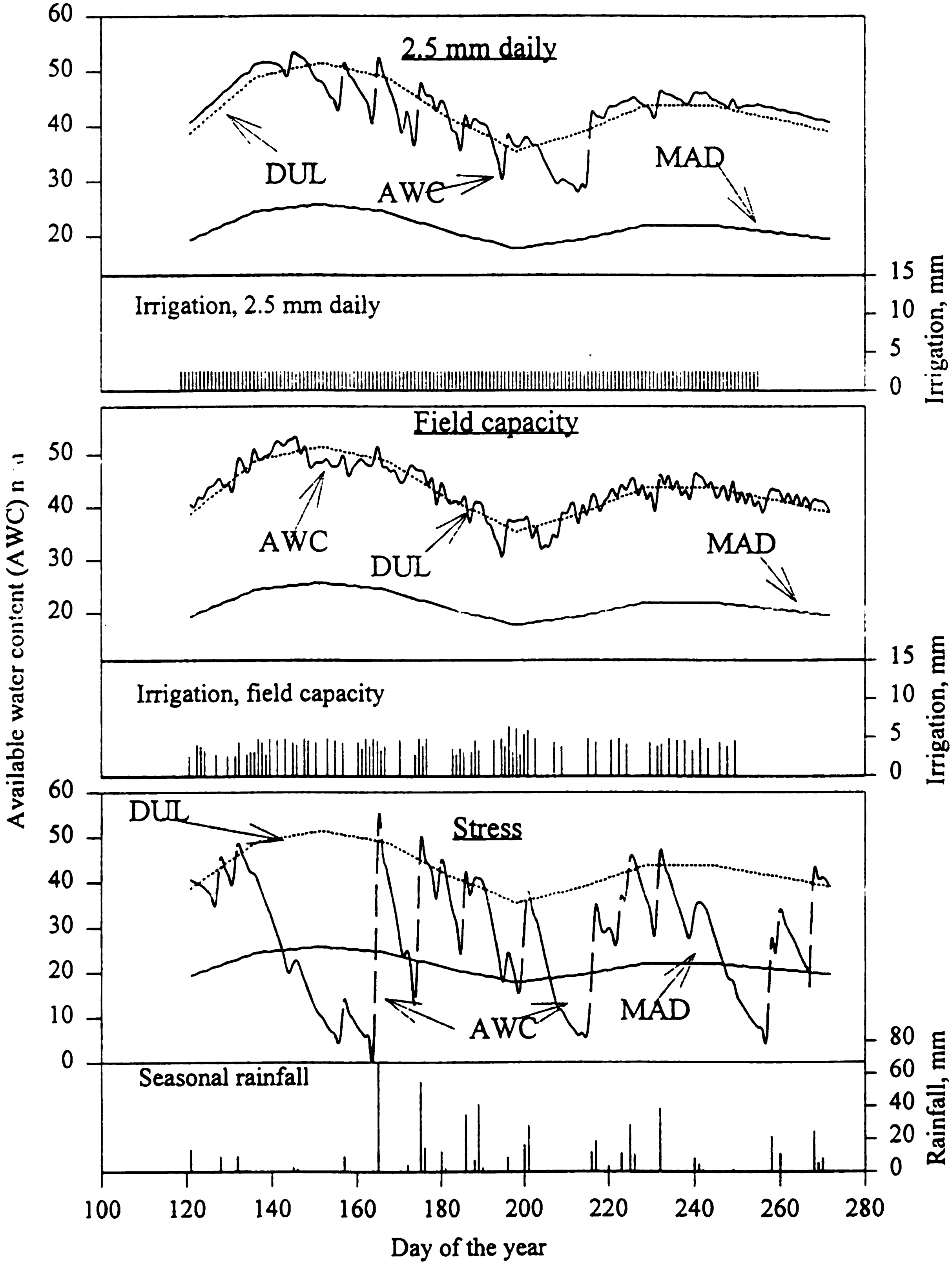

Figure 7.3. Available water content (AWC), irrigation and rainfall for the 2.5 mm daily, field capacity and stress treatments in relation to the drained upper limit (DUL) and management allowable depletion (MAD), 1994.

the excess water could reenter the root zone through upward water flow. Irrigation to field capacity or irrigation during wet periods are thus not efficient water management strategies.

The frequencies of excess rainfall and irrigation by treatment are presented in Table 7.6. The frequency of excess irrigation as predicted by the SCHEDULER model showed greater variation than that of excess rainfall for all years. The 2.5 mm daily treatment had the highest frequency of excess water applied for all three years. A maximum combined excess frequency of 104 occurred in the 2.5 mm daily treatment in 1992, whereas the minimum combined excess frequency (26) occurred in the field capacity treatment in 1994. The stress irrigation treatment had fewer excess events, as expected. The excess frequency of rainfall for all treatments was consistent from year to year for the irrigation treatments.

The number of days with excess rainfall was not very different between the 2.5 mm daily and the field capacity treatments (Table 7.6). However, the number of days with excess irrigation was drastically different. The 2.5 mm daily treatment had excess water loss from irrigation. This suggests that for wet years, the application of adequate amounts of water to replenish the soil to field capacity would result in water savings over daily application of 2.5 mm. Still losses from rainfall remained high because the soil was maintained at about field capacity. During dry years, however, the 2.5 mm daily treatment subjected the turfs to moisture stress (Saffel, 1994).

A major objective of turf irrigation scheduling is to supply adequate water for quality turf growth without compromising environmental quality. Both irrigation and rainfall play a vital role in the amounts of excess water (drainage losses) and the potential leaching of nutrients and other agricultural chemicals. Table 7.7 shows the means and ranges of excess water amounts by irrigation treatment for the different years. The highest excess water event of about 64 mm of water occurred on June 14, 1994, after 70 mm of rainfall. Up to 91% of

Table 7.5. Seasonal excess rainfall and irrigation, by year and by irrigation treatment as predicted by the SCS SCHEDULER model.

Excess Rain and Irrigation	Year	Irrigation Treatment		
		Field Capacity	2.5 mm Daily	Stress
		mm		
Rainfall	1992	363	386	28
Irrigation		2.6	123	0
Total excess		395	509	28
Rainfall		318	292	108
Irrigation	1993	1.8	86	0
Total excess		320	378	108
Rainfall		419	396	135
Irrigation	1994	3.1	90	0
Total excess		419	486	135

the rainfall was not stored in the root zone for both irrigated treatments. A minimum leaching amount of 0.3 mm was recorded for the stress and field capacity treatments in all years but only in 1992 and 1993 for the field capacity treatment. A distinct advantage of the SCS-SCHEDULER is that it partitions rainfall and irrigation amounts into the fraction stored in the soil depth of interest, the amount lost by evapotranspiration, and the excess water loss by runoff and percolation. Although leaching is not estimated by the model, the solubility of various agricultural chemicals, in the excess water, could provide useful estimates of the leaching potential of various chemicals of interest.

Table 7.6. Frequency of excess rainfall and irrigation, by irrigation treatment as predicted by the SCS-SCHEDULER model.

Year	Type	Irrigation Treatment		
		Field Capacity	2.55 mm Daily	Stress
1992	Rainfall	26	27	13
	Irrigation	0	77	0
	Combined	26	104	13
1993	Rainfall	27	22	11
	Irrigation	1	46	0
	Combined	28	68	11
1994	Rainfall	26	24	12
	Irrigation	0	55	0
	Combined	26	79	12

The high frequencies of excess water from the 2.5 mm daily and field capacity treatments suggest that irrigation scheduling should utilize a more conservative approach than returning the soil to field capacity daily, or applying 2.5 mm daily and when possible should include soil moisture monitoring as a feed back system.

Table 7.7. Means and ranges of excess water amounts by irrigation treatment as predicted by the SCS-SCHEDULER model.

Year	Excess	Irrigation Treatment		
		Field Capacity	2.5 mm Daily	Stress
		mm		
	Maximum	39.1	44.2	31.9
1992	Minimum	0.3	0.3	0.3
	Mean	2.6	3.3	1.2
	Maximum	41.4	50.3	34.8
1993	Minimum	0.3	0.3	0.3
	Mean	1.5	2.5	0.7
	Maximum	64.0	60.2	34.4
1994	Minimum	0.8	0.3	3.0
	Mean	2.7	3.2	0.9

Conclusions

Evapotranspiration estimates from the model were within the ranges of ET for the location. The available water content measured by TDR did not agree with simulated values. This may be due to faulty assumptions in adapting the model for turfgrass. More research would be needed to improve agreement between model prediction and field data.

Moisture depletion estimates from the SCS-SCHEDULER account for seasonal variations in rooting depth. This is important because rooting patterns of cool-season grasses are affected by root senescence during periods of high temperatures and other weather conditions in response to differential partitioning of assimilates.The model provides information on water use that would otherwise be unavailable or require time to calculate. Most important, it provides a method for site-specific irrigation scheduling and evaluation.

Benefits from simulations in terms of time, money, and labor savings have been documented (Hanks and Hill, 1980; Ritchie, 1991). Good simulation models serve as a useful basis for irrigation management and decision making. A method of irrigation scheduling that is accurate, site- and crop-specific, rapid, and dependable can be used to rapidly build a data base for model validation purposes. At this time the data base for turf modeling is not as extensive as in conventional agriculture. Model development calls for an extensive data base with quantitative information on the development of turfgrasses.

Although much research has been done in turf, the results are not reported in a form that can be readily applied in simulations. Information on parameters such as leaf area index, root length density, leaf extension rate and turf coefficients for different locations are not readily available. The collection of such data requires several years of research. To compensate for these shortcomings, assumptions are made which quite often oversimplify various processes and at the same time introduce errors in the analysis. In this study, a crop irrigation simulation model (the SCS SCHEDULER) was adapted for use in turfgrass research. Conventionally, rooting depths for row crops exceed those for cool season turfs. Turf coefficients for row crops are different from those encountered in fine turf management. These may lead to higher drainage amounts and higher than normal moisture depletion rates under turf ecosystems than with other crops. Hopefully, this study will generate interest in further development of turf specific models that could serve as useful tools for research and decision making in turf irrigation.

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APPENDICES

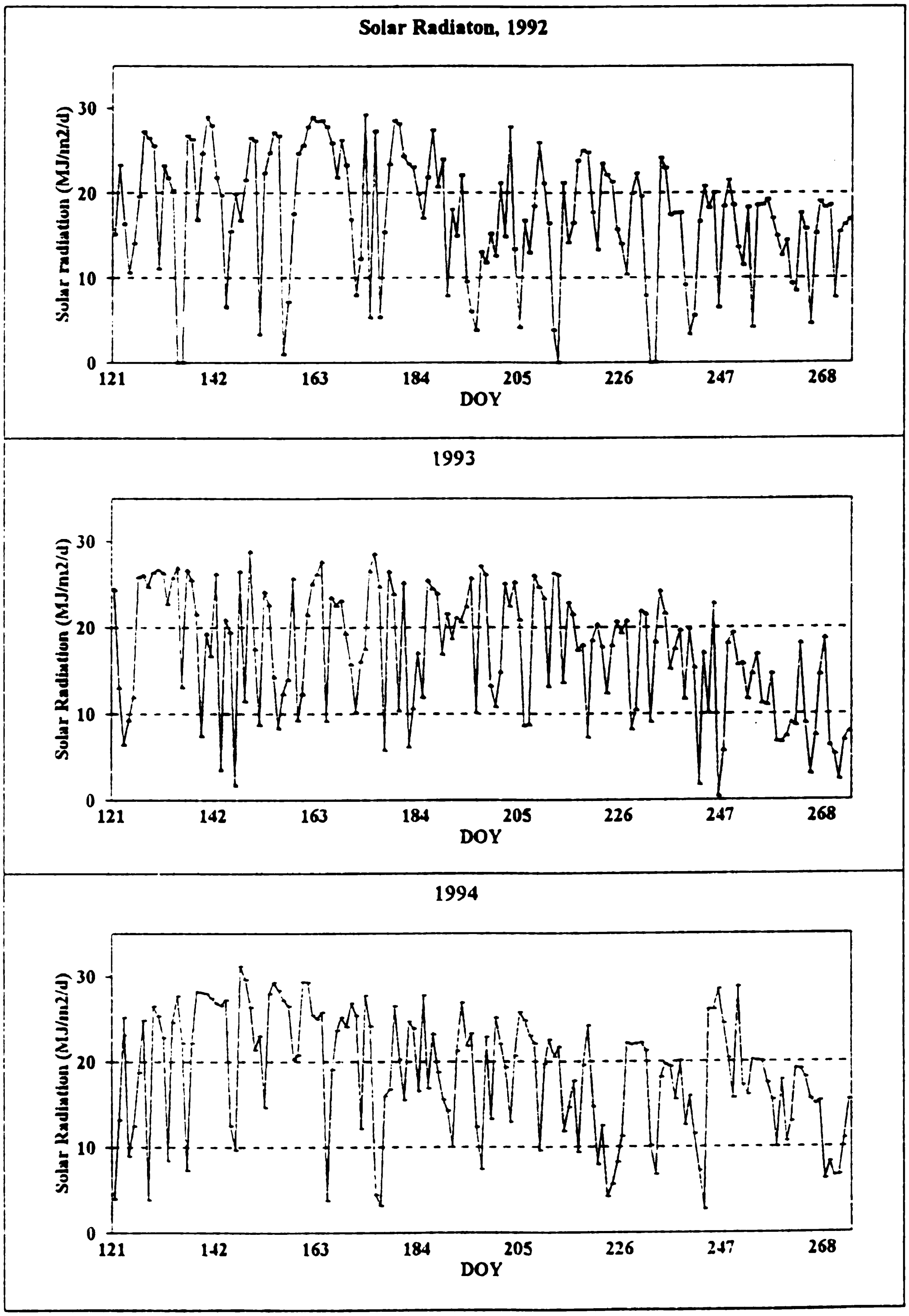

Fig. A1. Seasonal solar radiation at the Hancock Turf Research Center, East Lansing, MI for 1992, 1993 and 1994.

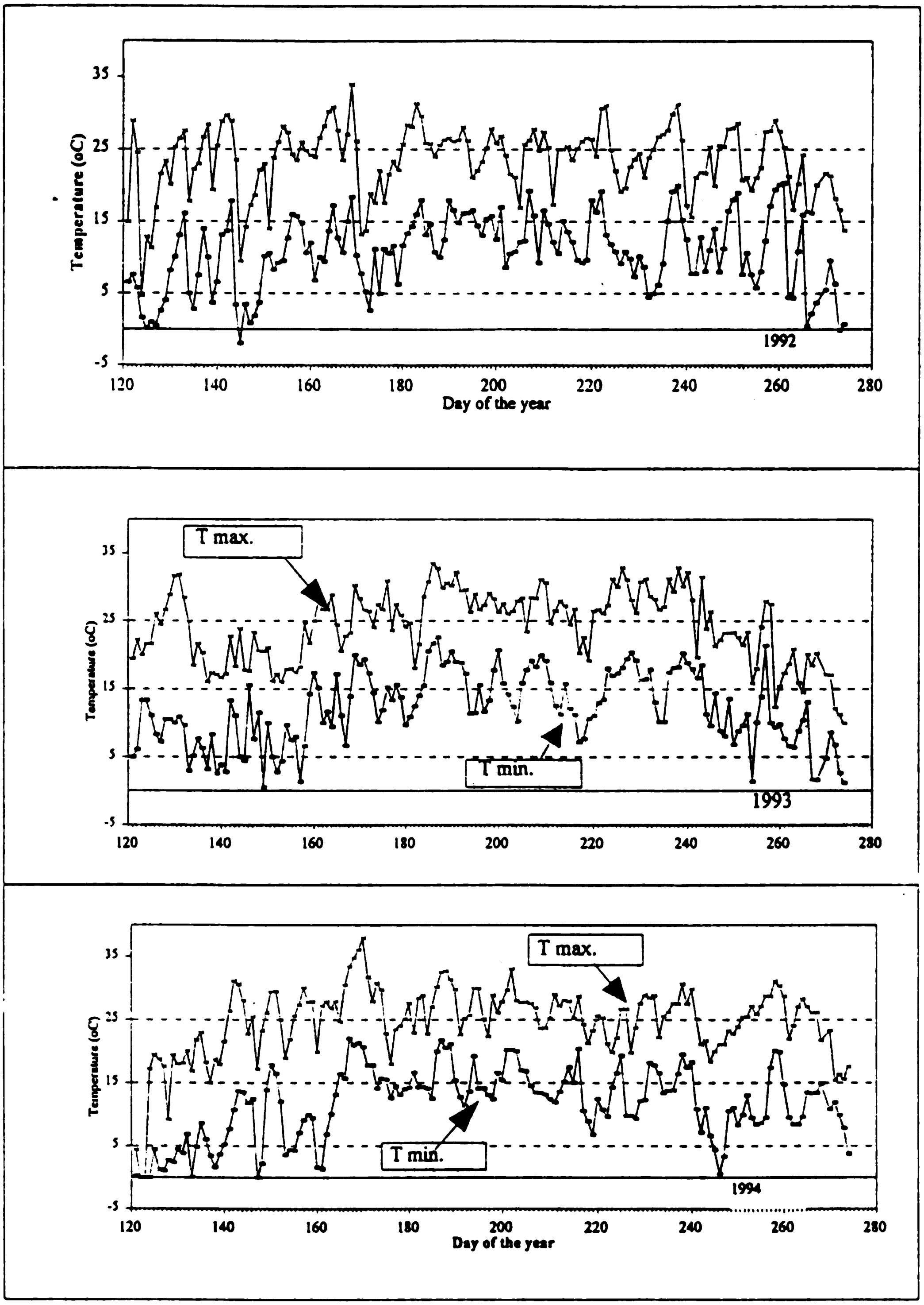

Fig. A2. Seasonal maximum and minimum temperatures at the Hancock Turf Research Center, East Lansing, MI for 1992, 1993 and 1994.

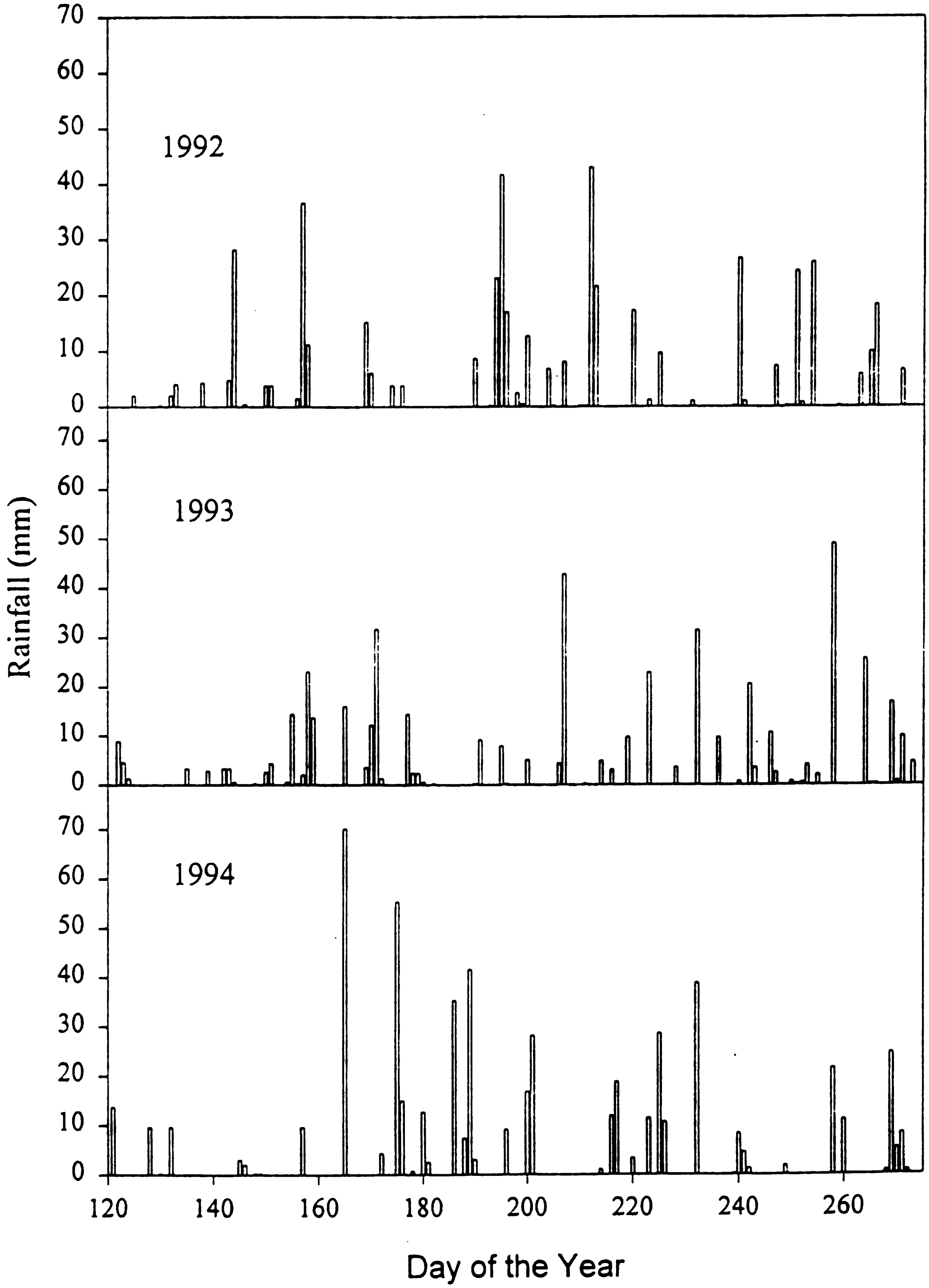

Fig. A3. Seasonal rainfall at the Hancock Turf Research Center, East Lansing, MI for 1992, 1993 and 1994.

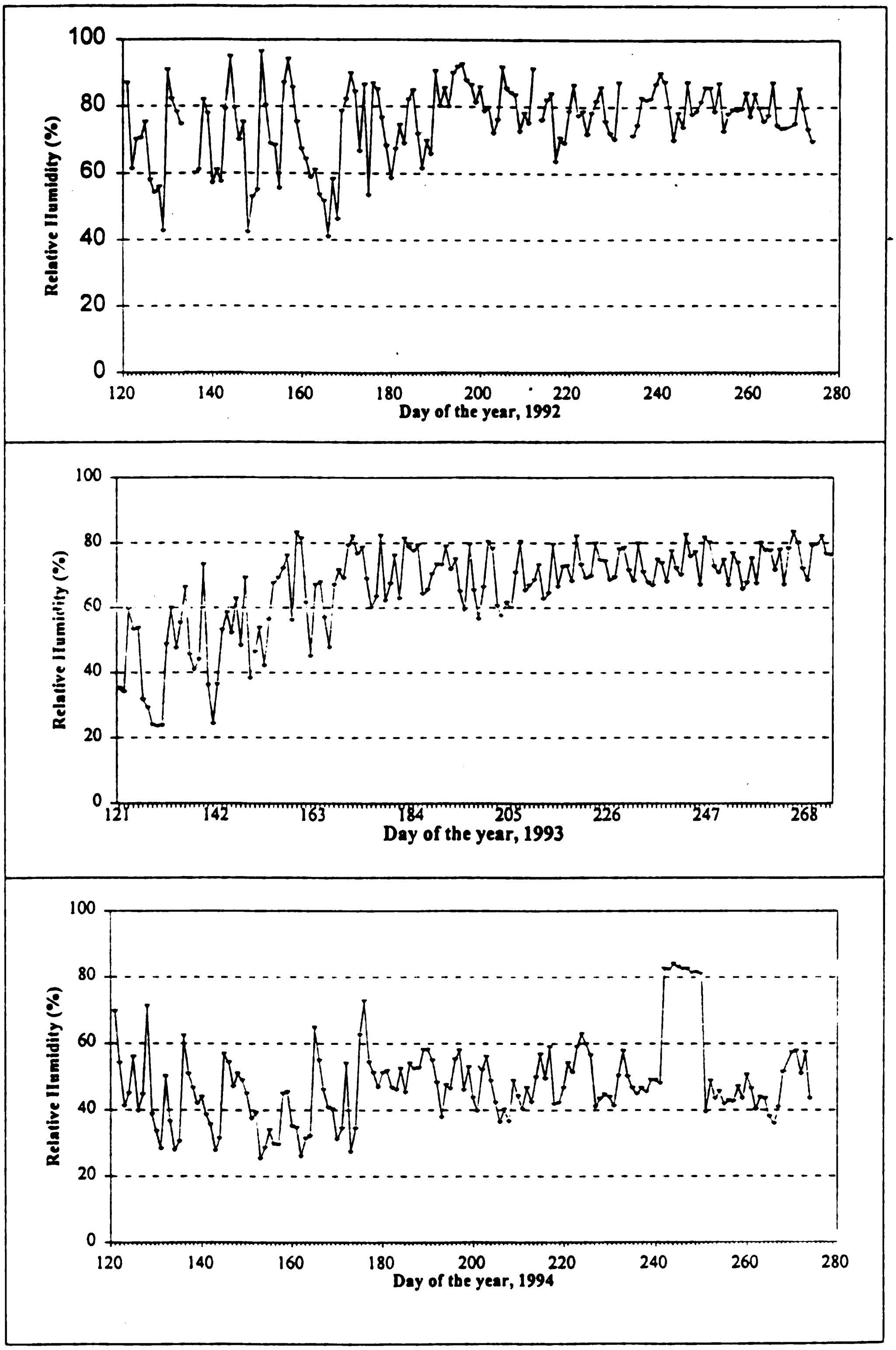

Fig. A4. Seasonal relative humidity at the Hancock Turf Research Center, East Lansing, MI for 1992, 1993 and 1994.

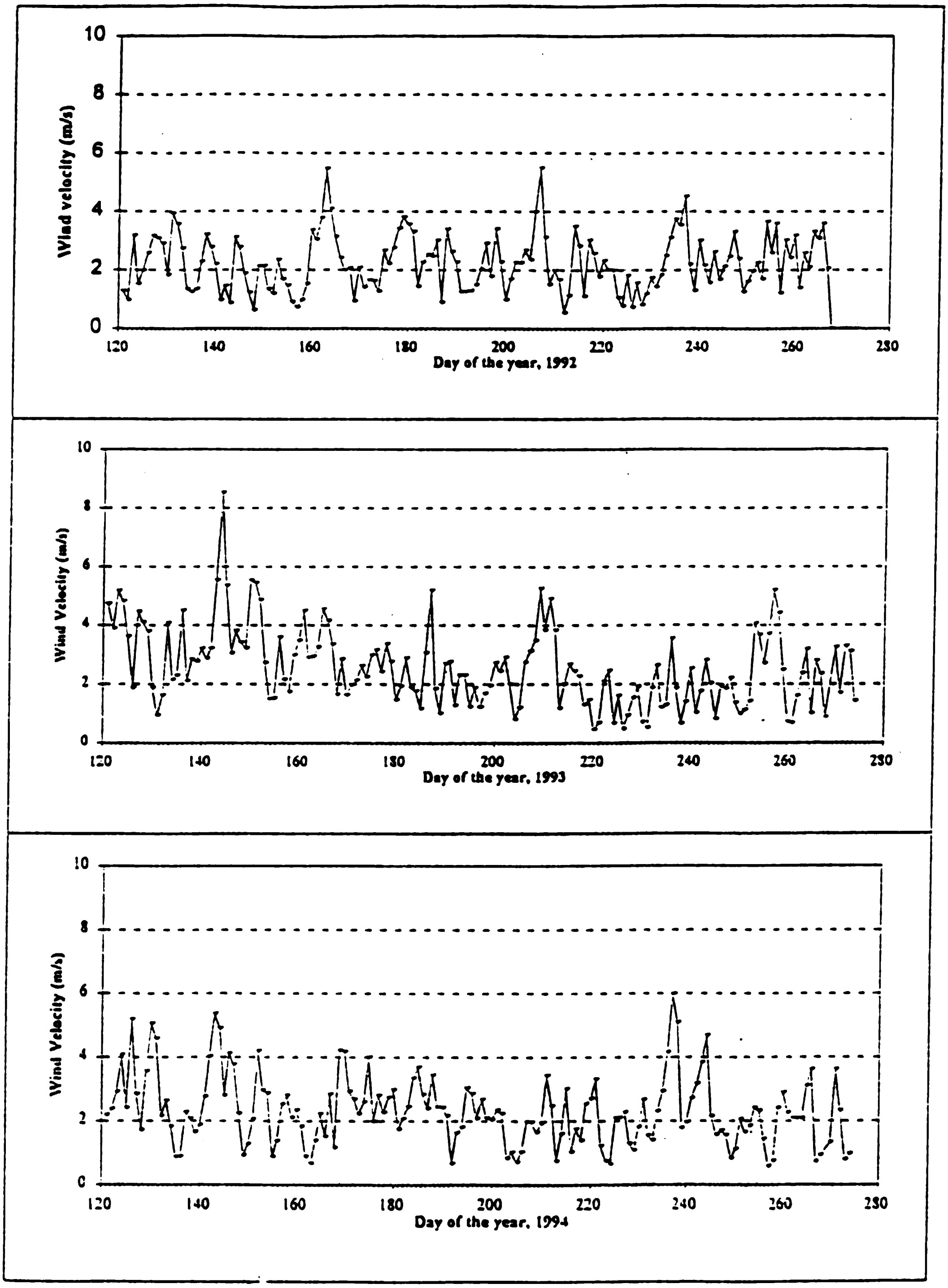

Fig. A5. Seasonal wind velocity at the Hancock Turf Research Center, East Lansing, MI for 1992, 1993 and 1994.