MOWING HEIGHT AND VERTICAL MOWING FREQUENCY EFFECTS ON PUTTING GREEN QUALITY

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1991

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by

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A THESIS

Presented to the Faculty of

The Graduate College in the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Horticulture

Under the Supervision of Professors

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August, 1991

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Lowering creeping bentgrass (Agrostis palustris Huds.) green mowing heights to increase putting green speed is a common practice, but can increase the turf's susceptibility to heat and drought stress. Incorporation of cultural practices such as vertical mowing may improve putting green playability. Vertical mowing as a grooming process to improve putting green quality was evaluated in this study. A 'Penncross' creeping bentgrass turf, established in 1988, was subjected to three mowing height treatments (3.2, 4.0, and 4.8 mm) and three vertical mowing frequency treatments (0, 1, and 2 times per month). Sand topdressing was applied every 14 days following vertical mowing treatment applications. Mowing height and vertical mowing frequency effects on distance of ball roll (i.e. putting speed), color, quality, normalized difference vegetation index, root production, and canopy temperature were evaluated in 1989 and 1990. The vegetation index was determined from red and near-infrared spectral band reflectances, using an Exotech Model 100-A spectral radiometer. Vertical mowing had no affect on ball roll, color quality, canopy reflectance, or root production. Canopy temperatures increased upon increasing vertical mowing frequency on one date in each year. Ball roll decreased by 0.2 m in 1989 and 0.4 m in 1990 from 3.2 mm to 4.8 mm mowing height. Canopy temperatures decreased with increasing mowing height.

Putting speed remained fast across mowing heights in 1989 and ranged from medium-fast to fast in 1990. Color, quality, vegetation index, and root production increased with increasing mowing height. Color and quality increased by approximately 0.5 of a rating unit in 1989 and by 1.0 rating unit in 1990. Vegetation index data agreed with color and quality ratings. Root distribution at 76 to 152 mm soil depth on 12 July 1990 and at 152 to 228 mm soil depth on 12 Sept. increased with increasing mowing heights. Fast putting speeds for membership play can be maintained at higher mowing heights if a sound putting green management program is maintained.

To my parents and family,

Who encouraged and supported me

Throughout my college career.

ACKNOWLEDGEMENTS

I wish to thank Dr. R. C. Shearman for his guidance and support throughout my master's program. His willingness to meet and discuss problems during his busiest hours was greatly appreciated. Thanks Bob. I would also like to thank Dr. G. L. Horst for agreeing to act as co-advisor on my committee upon his arrival to the Horticulture department, and Drs. B. L. Blad, T. P. Riordan, and E. A. Walter-Shea for their input and suggestions on the research. I also wish to thank Dr. E. J. Kinbacher for his input during the proposal stage of my research, and Dr. Kent Eskridge for his statistical advise.

The technical help from Cynthia Hayes and Mark Mesarch on spectral radiometry was greatly appreciated. A sincere thank you is extended to Mr. Leonard A. Wit for his practical suggestions in the field, Susan A. De Shazer for her help in preparing this thesis, and Steve Westerholt for his computer help. Thanks also to the graduate students, hourly help, and anyone else who picked up a golf ball and rolled it across the research green.

A very special thank you is extended to the person who was not content to just listen, but to understand and offer solutions to my problems. To the person who forced me to explain and understand my research results. To the person who could always see the bright side of any situation. To the person I could always count on for a smile. To Pamela "JO" Hutchinson... THANKS!

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INTRODUCTION

Many cultural practices are involved in managing creeping bentgrass (Agrostis palustris Huds.) putting greens. Quality putting green surfaces are produced by turfgrass managers through the use of cultural practices that increase putting speed and maintain a high quality turf. Difficulty in choosing a greens management program that will increase putting speed yet produce a healthy turf is a problem faced by golf course superintendents. The many cultural practices involved in the management of greens, compound this problem as some cultural practices such as mowing height, if altered to increase putting speed, may be detrimental to the health of the turfgrass. Research is lacking not only in determining the effects of cultural practices on putting quality, but also in determining their effects on the turf microenvironment and how a turf responds to such changes. Knowing which cultural practices optimize putting green quality and maintain a healthy turf will help the golf course superintendent choose a proper greens management program. Such a program may involve raising the mowing height to improve the physiological condition of the turf and increasing vertical mowing frequency to enhance putting quality. This investigation was conducted to study the interactive effects of mowing height and vertical mowing frequency on putting green quality, root growth, and some microclimatic parameters used to indicate plant stress.

LITERATURE REVIEW

Putting Green Management

Putting greens account for only about two percent of a golf course area, but are involved in approximately 75 percent of golf strokes, consequently, their maintenance is an important part of golf course management (Beard, 1982). Putting greens are managed such that they will provide a dense, smooth, uniform surface, and thus, a true ball roll. Such management involves close, frequent mowing to provide a true ball roll; frequent fertilization to avoid large fluctuations in soil nutrient status and to maintain desired growth; irrigation scheduling to prevent wilting, yet avoiding an environment favorable for disease; pest management to prevent or reduce damage from pests; topdressing to prevent thatch buildup and provide firmness; grooming, verticutting, or brushing to aid in maintaining smoothness; and cultivation such as coring, spiking or slicing to remove soil surface compaction. The most fundamental and yet perhaps the most important of these is mowing, since the height, frequency and direction, all affect ball roll.

Mowing Height

Creeping bentgrass putting greens are maintained at mowing heights of less than 6 mm (Beard, 1973, 1982; Turgeon, 1991). Mowing, a defoliation process, is detrimental to a turfgrass, causing it to undergo several physiological changes. Rooting depth, growth rate, and production are reduced upon mowing and in reductions mowing height (Beard, 1973; Beard and Daniel, 1965; Goss and Law, 1967; Krans and Beard, 1985; Madison, 1962; Youngner and Nudge, 1976). It has also been shown that reductions in mowing height within a species' tolerance range will cause an increase in clipping yield, shoot density, and shoot growth rate (Beard, 1973; Madison, 1960, 1962). These reductions in root growth and increases in topgrowth have been attributed to a higher priority of leaves and shoots over roots for photosynthates (Krans and Beard, 1985; Youngner and Nudge, 1976). In light of these effects on root growth, shoot growth, and photosynthate partitioning, close, frequent mowing can produce a turf susceptible to environmental stresses such as heat and drought. Since creeping bentgrass must be maintained at low mowing heights in order to serve its purpose as a putting green, golf course superintendents are faced with the difficult task of producing a healthy, high quality turf while maintaining respectable putting speed.

Vertical Mowing

Vertical mowing has the potential for increasing putting speed. Vertical mowing or verticutting is a supplementary cultural practice used for grooming, thatch removal, or soil surface cultivation (Beard, 1973, 1982; Turgeon, 1991). Vertically oriented knives mounted to a horizontal shaft provide the cutting action and are adjustable to different depths and density to accomplish the desired objective.

Vertical mowing research has been limited to evaluating the prevention of thatch accumulation (Thompson and Ward, 1965; White and Dickens 1984). Light (i.e. shallow), biweekly vertical mowing was shown to be as effective as severe (i.e. deep) vertical mowing two times per year in controlling thatch on hybrid bermudagrass (Cyndon dactylon (L.) Pers. x C. transvaalensis Burtt-Davy) putting greens (White and Dickens, 1984). Light frequent vertical mowing resulted in less scalping injury than severe vertical mowing. Mazur and Wagner (1987) evaluated severe vertical mowing on overseeded bermudagrass during spring transition and found that vertical mowing treatments reduced cool-season stand density and delayed bermudagrass emergence. Johnson (1986) concluded that severe vertical mowing prior to cool-season overseeding slowed the transition from overseeded cool-season turf to bermudagrass in the spring.

Despite lack of research surrounding light vertical mowing effects on putting green quality, recommendations to use this management practice have been made (Beard, 1973, 1982; Buchanan, 1984; Chalmers, 1984, 1986; O'Brien, 1983; Shoulders, 1983). Light vertical mowing is expected to increase smoothness by controlling grain and eliminating long stolons that may obstruct the path of the ball. Grain refers to the growth of turfgrass leaves and stems horizontally rather than vertically (Beard 1973). In golf green situations where quality is important, vertical mower blades are set to penetrate only the canopy surface, thereby controlling grain. Recent turfgrass industry innovations include greens conditioners or groomers (i.e. verticutting units) that attach and operate in front of reel mowers (Kinzer, 1990).

Putting Speed

Quality components for putting green playability include uniformity, smoothness, firmness, resiliency, close mowing, and absence of grain (Beard, 1982). In a putting situation, resiliency is perhaps not as important as the other quality components since the ball is not striking the ground as it would be on an approach shot. The other five components of putting green playability directly influence trueness and distance of a ball roll following a putting stroke. This distance of ball roll is referred to as putting speed (Beard, 1982). Putting speed is a somewhat misleading term in that velocity (i.e. distance per unit time) is implied, but distance is the actual unit of measure. Putting speed is a widely used and accepted term in describing putting green playability. For purposes of this thesis, ball roll will be used in describing methods and in interpretation of putting speed research results.

The United States Golf Association (USGA) developed a device (i.e. stimpmeter) to measure putting green speed, and made it available to golf course superintendents in 1978 (Hoos, 1982). The Stimpmeter is a one meter long aluminum bar with a v-shaped groove on one surface and a ball-release notch 76 cm from the slanted end (Beard, 1982; Hoos, 1982). Step by step procedures for Stimpmeter use have been outlined to avoid measurement inaccuracies (Beard, 1982; Hoos, 1982). Procedures for measuring speed on sloped putting greens has recently been investigated (Brede, 1990). The USGA developed reference charts relating Stimpmeter measurements to putting speed (Table 1; Hoos, 1982). Use of the Stimpmeter has caused considerable discussion and controversy concerning its role in golf course management (Albaugh, 1983; Buchanan, 1984; Chalmers, 1984; Hankley, 1984; Hoos, 1982; Mitchell, 1983; Owens, 1984; Thomas, 1983; Zontek, 1983). The controversy surrounds unfair comparisons and too much emphasis on putting speed. Recommendations now include identifying a desired putting speed (Buchanan, 1984; Mitchell, 1983; Zontek, 1983).

Table 1. Reference chart relating Stimpmeter measurements to speeds for membership and tournament play.

Relative green speed	Stimpmeter Measurement			
	Membership Play (m)	Membership Play (ft.)	Tournament Play (m)	Tournament Play (ft.)
Fast	2.6	8.5	3.2	10.5
Medium-Fast	2.3	7.5	2.9	9.5
Medium	2.0	6.5	2.6	8.5
Medium-Slow	1.7	5.5	2.3	7.5
Slow	1.4	4.5	2.0	6.5

From: Hoos, D.D. 1982. The green section's Stimpmeter: Most think friend-some think enemy. USGA Green Section Rec. July/Aug. 1982. pp. 9-10.

Research information currently available concerning management effects on putting speed is limited. Stahnke and Beard (1981) reported dew removal, footprinting, and double mowing increased putting speed, while coring plus topdressing increased putting speed over mowing plus coring alone.

Spectral Radiometry

Small, hand-held radiometers have been developed in response to increasing interest in remote sensing during the late 1970s and early 1980s (Celis-Ceusters, 1980; Jackson et al., 1980; Rosenberg et al., 1983). These instruments measure target-reflected radiation (radiance) in narrow wavebands corresponding to wavelength intervals of the electromagnetic spectrum (Jackson et al., 1980; Rosenberg et al., 1983). The Exotech model 100-A radiometer (Exotech, Inc.) measures radiance in the four wavebands corresponding to bands 4-7 on multispectral scanners (MSS) (Celis-Ceusters, 1980; Jackson et al., 1980). Bands 4-7 correspond to 0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.1 μm, respectively.

Evaluation of radiance from these wavebands can tell us something about the quantity as well as the quality of vegetation present during a measurement. Leamer et al. (1978) used reflectance over the wavelength interval of 0.45 to 2.5 μm to track seasonal changes of wheat reflectance. The waveband between 0.63 and 0.69 μm is known as the chlorophyll absorption band and is characterized by maximum soil and minimal plant radiance (Jackson et al., 1980). Taking the ratios of instrument voltages, radiances, or reflectances from two bands yields vegetation indices which can be used to estimate leaf area, green biomass and percent cover (Jackson et al., 1980). In order to obtain meaningful vegetation indices, ratios should be calculated such that radiance from one band decreases with increasing green vegetation, and radiance from the other band increases with increasing green vegetation (Jackson et al., 1980). One such index utilizes a ratio of a band within the RED portion of the visible spectrum to a near-infrared (NIR) band, and is highly sensitive to vegetation (Jackson et al., 1980). The normalized difference is a vegetation index utilizing a ratio of the difference between values for the RED and NIR bands to the sum of the values for the two bands: (NIR-RED)/(NIR+RED) (Jackson et al., 1980; Lo, 1986). The normalized difference vegetation index, making use of MSS bands 7 and 5, has been used to delineate winter wheat stand densities for reseeding decisions (Aase and Siddoway, 1980). Indices of determination ranging from 0.88 to 0.937 were observed for this normalized difference vs. leaf dry matter.

Microclimatic Responses

Soil Temperatures

Sand modified greens have relatively high soil temperature extremes at the surface, due to the nature of coarse textured soils. These sand modified greens, because of their rapid drainage, high macroporosity, and the low conductivity of air, exhibit poor downward transmission of heat. This is important since a large percentage of creeping bentgrass roots are found near the soil surface (Beard, 1973).

There is considerable research concerning soil temperature effects on turfgrass physiology. Beard and Daniel (1965) showed significant reductions in creeping bentgrass root growth rate and total root production when soil temperatures were raised from 26.7 to 32.2 ^{o}C, under both cut and uncut conditions. Root growth rate was unchanged from 15.6 to 26.7 °C, but total root production was reduced at temperatures above 15.6 °C. Field evaluations by these two researchers found soil temperature at 152 mm depth highly correlated to root growth and a good indicator of seasonal variations in rooting (Beard and Daniel, 1966). Continuing work in this area showed soil temperature at the 152 mm depth to be a key factor influencing nitrogen compounds in creeping bentgrass leaf tissues (Beard and Daniel, 1967). Total amide content extracted from leaf tissues decreased during peak mid-summer temperatures, while total nitrogen content was positively correlated to average daily temperatures exceeding 18 °C. Work with Kentucky bluegrass revealed reduced root growth at 27 °C compared to 18 °C soil temperatures (Youngner and Nudge, 1976). More recently, seasonal rooting characteristics of five cool-season turfgrasses were evaluated at Columbus, Ohio (Koski, 1983). Active root length values for creeping bentgrass were highest in the spring, with the largest peak in early June and a smaller peak of activity in mid-October through November (Koski, 1983). Reduced root activity from July through mid-October was accompanied by a period of high shoot activity.

Thermocouples, constructed of copper constantan wires are used for temperature measurements in micrometeorology. Thermocouples generally measure temperatures with accuracies of 0.1 to 0.25 °C (Rosenberg et al., 1983). The resolution of temperature differences can be increased if thermocouples are wired differentially, while parallel wiring will give an average temperature for all points sampled. Three methods of installing thermocouples for soil temperature measurements in a Kentucky bluegrass sod have been studied (Welterlen and Watschke, 1981). One method involved placing the thermocouples horizontally in the soil, causing considerable site damage due to the removal of sod plugs and is recommended only for long term temperature measurements. The other two methods involved placing the thermocouples vertically in the ground and attaching them to wooden dowel rods, causing little, if any damage to the turfgrass canopy. Soil temperatures measured with all three methods measured showed no significant differences.

Canopy Temperatures

Leaf temperatures have been studied as indicators of crop water stress (Jackson, 1982). However, interpretation of canopy temperatures is difficult due to many environmental and plant factors combining to determine canopy temperature (Idso, 1982). Mathematical models which take into account several environmental factors have been used to develop plant water stress indices. Jackson (1982) reviewed several indices developed over the years. One such index makes use of the stress degree day (SDD), defined as the temperature difference (ΔT) between canopy (Tc) and air (Ta), plotted as a function of time, to track water stress. Accumulated SDD's have been shown to be linearly related to transpirational water use (Jackson, 1982). A positive SDD indicates plant stress and negative values indicate non-stressed plants. Evidence has shown, however, that the SDD is not appropriate for all environmental conditions as canopy temperatures in humid climates are generally near to or higher than air temperatures with a small range of ΔT, whereas canopy temperatures in arid regions may be 10 °C or more below the air temperature with ΔT ranges of approximately 15 °C. Idso et al. (1981) normalized the SDD to vapor pressure deficit (VPD), to develop a crop water stress index (CWSI). Calculations of the CWSI requires the estimate of lower, nonwater stressed baselines determined as ΔT for a crop transpiring at the maximum potential rate, regressed against VPD, and an upper, water stressed baseline determined as ΔT for a nontranspiring crop, as a function of VPD. Recent work in this area has resulted in the development of CWSI scheduling programs for Kentucky bluegrass and determinations of turfgrass baselines using empirical and energy balance methods (Horst, 1989; Throssell et al., 1987)

A second index reviewed by Jackson (1982) makes use of midday canopy temperature variations brought on by variable soil moisture levels as a result of drying conditions. Field plots reaching a certain degree of soil moisture variability above that for a fully irrigated field plot are said to be under water stress and in need of irrigation. The major drawback of such an index is that it may be influenced by the degree of soil variability. A third index compensates for environmental effects such as air temperature and vapor pressure deficit by using the difference in canopy temperature between a stressed plot and a well-watered plot as a reference. This index, referred to as the temperature stress day (TSD), could be used successfully as an irrigation-scheduling tool, but requires a well-watered reference plot to be in close proximity to the field being studied.

MATERIALS AND METHODS

Mowing height by vertical mowing (VM) frequency treatment effects were evaluated on a 'Penncross' creeping bentgrass green established in 1986, at the John Seaton Anderson Turfgrass Research Facility located near Mead. The study was initiated in June 1989 and continued through October 1990. Treatment plot sizes were 13.4 m^2 (3.7 by 3.7 m) with 0.6 m borders between mowing height treatments. Sand topdressing at 800 cm^3 m^{-2} was applied biweekly. Aerification was not applied to the study site due to potential interference with thermocouple wires located 25 mm beneath the canopy surface. Fertilization was applied to the test area at 20 g N, 10 g P, and 20 g K m^{-2} per season. Liquid urea (46N-0-0) was the source of N and potassium (0-0-41.5K) were applied 16 times at 1.25 g N and 1.25 g K m^{-2} per application, every 15 days from 2 April to 15 November. Phosphorus was (0-19.8P-0) was applied at 2.5 g P m^{-2} in April, May, September, and October. Subdue 2E (Metalaxyl) and Aliette (Fosetyl Al) fungicides were used to control pythium blight (Pythium aphanidermatum and Pythium graminicola) and brown patch (Rhizoctonia solani). Dursban 2E (Chlorpyrifos) was applied to control sod webworm (Crambus spp.). Pesticides were applied on a curative basis. Daily irrigation was based on a three day replacement of 80% potential evapotranspiration (ET) accumulated over the previous three days.

Mowing height and VM frequency treatments were replicated three times in a split-block design. Mowing height treatments were 3.2, 4.0, and 4.8 mm. Turfs were mowed five to six times per week and mowing direction was changed daily. Vertical mowing frequency treatments were 0, 1, and 2 times per month. Vertical mower knife spacing was 13 mm, and depth was set so that knives entered the canopy surface only.

Data Collection and Analysis

Ball Roll

A USGA Stimpmeter was used to measure distance of ball roll, giving an indication of putting speed (Hoos, 1982). Two stimpmeter measurements were taken in each of four directions (Figure 1). The eight measurements were averaged to obtain a ball roll distance for each treatment. Measurements were taken on seven consecutive days following VM treatments in 1989, and immediately following VM, four, and eight days following in 1990. Measurements were made only on relatively calm days, following mowing treatments when the turf had sufficient time to dry.

Turfgrass Color and Quality Ratings

Ratings were taken every two weeks in 1989. General observations of the research area during 1989 indicated daily changes in color and quality; therefore, ratings were taken 0, 2, 4, 6, and 8 days after VM in 1990 to gain a better understanding of these daily changes in color and quality. Turfgrass color ratings were based on a one to nine scale with 1 = straw brown, 6 = light green, and 9 = dark green. Turfgrass quality ratings were based on a one to nine scale with 1 =

Figure 1. Ball roll measurement using USGA stimpmeter.

poorest, 6 = acceptable, and 9 = best putting green quality. Uniformity, density, texture, growth habit, smoothness, and color were taken into account in making turfgrass quality ratings.

Turfgrass Canopy Reflectance

An Exotech Model 100-A (Exotech, Inc.) spectral radiometer was used to measure canopy reflected radiation in MSS bands five and seven corresponding to red (0.6 to 0.7 μm) and near-infrared (NIR, 0.8 to 1.1 μm) radiation, respectively. A standard $BaSO_4$ reflectance plate was used to estimate incoming radiation (radiance). Target reflectance factors, calculated as (panel reflectance) x (target radiance) ÷ (panel radiance), were used to calculate a normalized difference vegetation index (NIR-RED/NIR+RED) as an indication of vegetation greenness (Jackson et al., 1980). Four measurements per plot were taken over a 30 minute period, beginning 15 minutes before solar noon, on clear days. In 1989, measurements were taken on 20 July and 23 August, with the radiometer held at approximately 1.5 m above and perpendicular to the canopy surface. In 1990, a stand was constructed and used to hold the radiometer at a constant height of 2 m (Figure 2).

Root Distribution

Six soil core samples per plot were obtained three times in 1989 and 1990, using a soil sampling tube, 305 mm in length and 20 mm in diameter. Each core

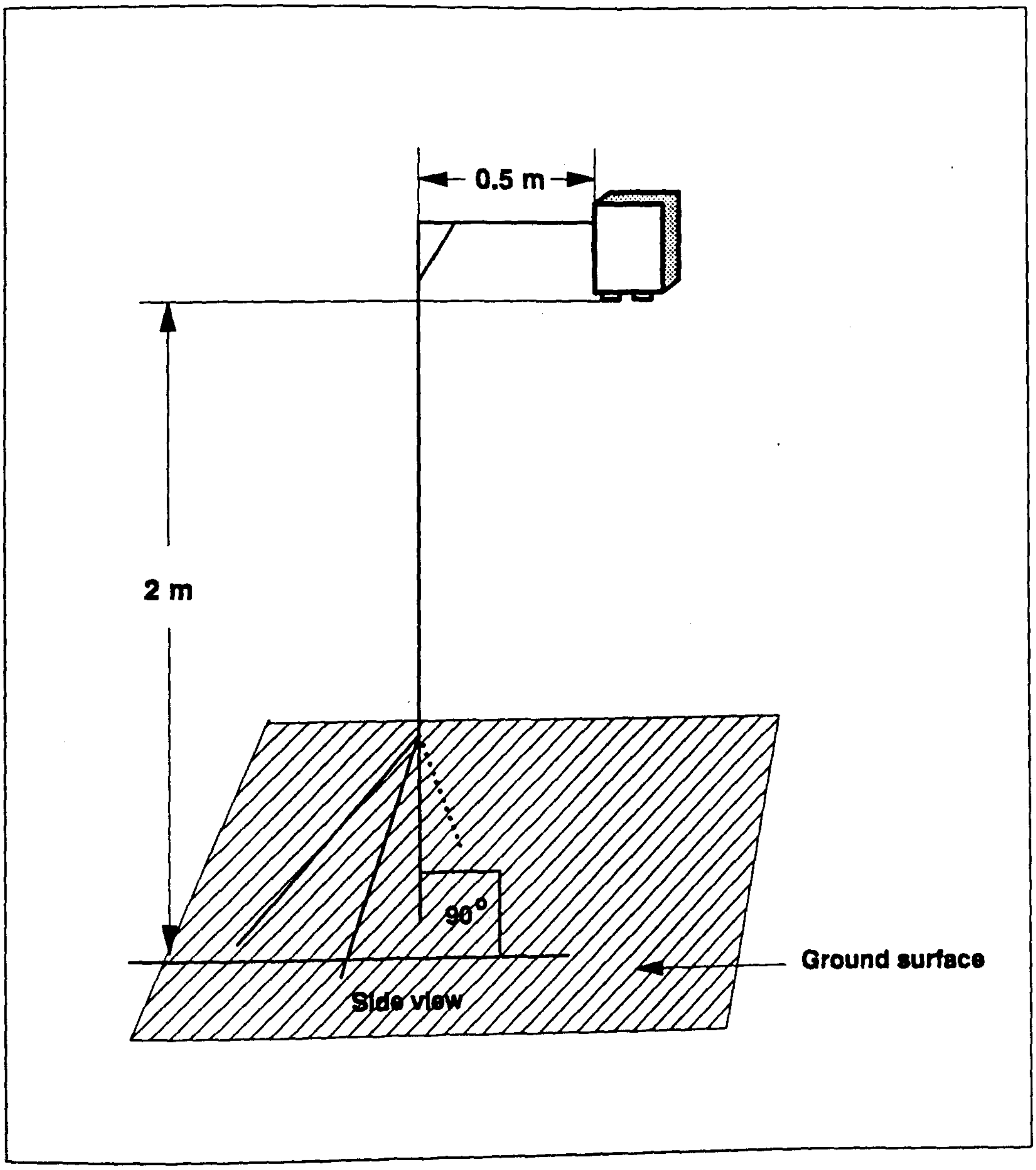

Figure 2. Relative dimensions for stand used to hold radiometer at a height of 2 m, perpendicular to the target surface.

was divided into three 102 mm sections in 1989 and four 76 mm sections in 1990. The six samples per depth were combined. Samples were hand washed to remove all soil, dried at 70°C for 72 h, weighed, and reported as root density in mg dry weight cm^{-3} per 102 or 76 mm section.

Soil Temperatures

Three copper-constantan thermocouples wired in parallel were placed 25 mm below the soil surface in each treatment plot, by removing a turfgrass plug 76 mm in diameter. Hourly soil temperatures throughout the day were recorded as an average of the three thermocouples daily in 1989 and 1990 on an 84-channel datalogger (Campbell Scientific, Logan, Utah; Model CR7).

Canopy Temperatures

A hand-held infrared thermometer (Telatemp Corp., Fullerton, CA, Model #AG42) was used to measure canopy temperature. The thermometer was held approximately one meter from the canopy surface, at a 45° angle to the target, with the operator facing south. In 1989, measurements were taken at 1300 h for seven days following VM. To better optimize periods of peak atmospheric stress conditions in 1990, measurements were taken approximately two hours after solar noon, 0, 2, 4, 6 and 8 days after VM. Four measurements per plot were taken such that measurement one was completed for all plots, followed by measurement two, etc. Relative humidity and air temperature were measured in addition to canopy temperature on 8 Aug, 3, 5, and 9 Sept. 1990, following acquisition of a Vaisala temperature and relative humidity probe (Easy Logger, Model ES-120). An empirical crop water stress index was calculated on these dates to help in interpretation of canopy temperatures.

Data Analysis

Since enough measurements were taken in each year to justify a yearly average, ball roll and visual rating data were averaged for each year and tested for year by mowing height or VM frequency interaction. If interactions were significant (PR > F = 0.05), then years were analyzed separately and data subjected to analysis of variance using General Linear Model procedures and the Statistical Analysis System (SAS Institute, 1985). If a mowing height by vertical mowing frequency interaction was not significant at $P = 0.05$, linear and quadratic regression analyses were conducted for main effects and significant ($P = 0.05$) models generated. Both model r^2 and r^2 determined from main effect means, were presented, since the r^2 from main effect means is representative of the figure, but not of the variance associated with the analysis. When linear and quadratic analyses were not significant at $P = 0.05$, main effect means were separated using Duncan's Multiple Range Test (DMRT) at $P = 0.05$. Vegetation index means were analyzed for each year separately, since measurements in 1989 were fewer and concentrated towards the end of the summer, while in 1990, measurements were taken throughout the growing season. Daily Tc measurements were analyzed separately since many factors are involved in determining Tc and a yearly average could be misleading.

Root distribution data from the first sampling date in each year were subjected to analysis of variance. Data from second and third sampling dates in each year were subjected to analysis of covariance, using the first sampling date in each year as the covariate (Steel and Torie, 1980).

Separation of ball roll and visual rating data were separated by year and day to determine daily changes following VM treatment application. Linear and quadratic trends over time were analyzed.

RESULTS AND DISCUSSION

Ball Roll

A year by treatment interaction was observed for ball roll, therefore years were analyzed separately. Vertical mowing frequency treatments had no effect on ball roll. This was somewhat surprising since a smoothing of the putting surface was anticipated with VM. Lack of grain due to human and vehicular traffic may explain why vertical mowing had no effects on ball roll. The VM frequencies studied may not have caused any dramatic changes in the turfgrass surface. Ball roll differed among mowing height treatments in 1989 and in 1990. Ball roll decreased linearly as mowing height increased (Figure 3). Ball roll was reduced by 6% and 13% in 1989 and 1990, when mowing height was increased from 3.2 to 4.8 mm. Based on USGA membership standards, putting speeds rated fast in 1989 and medium-fast in 1990 at the 4.8 mm mowing height. Light frequent sand topdressing and a sound management program, were sufficient in producing high quality putting green conditions in both years.

Ball roll data were analyzed over time to determine if daily changes could be observed after vertical mowing treatment applications. Mowing height by sampling day and vertical mowing frequency by sampling day interactions were observed for ball roll in 1989. Since treatment effects on ball roll already have been discussed and since trends were similar over sampling days, data were averaged over sampling days for each year. No significant linear or quadratic trends were observed for ball roll over sampling day in 1989 (Figure 4). Daily changes in ball roll, despite following no significant linear trends, agreed quite well with early work by Madison (1960) which showed that the growth curve of creeping bentgrass after mowing has two components; a four-day component resulting from cut leaf elongation, and a second component resulting from new leaf production. Ball roll in 1989 decreases from zero to four days after vertical mowing as a result of increased vegetative resistance to roll as both growth components allow the turfgrass to grow out of the sand topdressing applied immediately after vertical mowing. Increases in ball roll after day five indicate a stabilizing and firming of the surface as the turf has grown out of the sand topdressing. In 1990, measurements were taken to help decrease the work load and still allow for regression over time. Ball roll decreased linearly as sampling day after vertical mowing treatment increased. The larger sampling day interval in 1990 by-passed the increase in ball roll observed in 1989 after day four.

Turfgrass Color and Quality Ratings

A year by mowing height interaction was observed for turfgrass color and quality ratings, therefore years were analyzed separately. Vertical mowing frequency did not influence color or quality ratings in either year. As with the ball roll data, anticipated smoothness with vertical mowing was expected to improve turf quality. Color and quality ratings were affected by mowing height in both years. In 1989, color increased by 0.6 of a rating unit for each mm increase in mowing height, while quality increased by 0.4 of a rating unit for each mm increase in mowing height (Figure 5a). In 1990, color and quality increased by 1.0 rating unit for each mm increase in mowing height (Figure 5b). Increased rating values at the higher mowing heights were assumed to be the result of more photosynthetic leaf tissue present at the higher mowing heights.

Color and quality ratings in 1990 also were analyzed over time to determine if daily changes could be seen after VM application. Color and quality ratings increased linearly over time (Figure 6). This agrees with the ball roll data as turfgrass growth out of the sand topdressing reduced ball roll and increased color and quality.

Turfgrass Canopy Reflectance

Normalized difference vegetation index values were averaged across all dates within years and each year analyzed separately. Vertical mowing frequency had no effect on the vegetation index in either year. This agrees with the ball roll and visual rating data. Vegetation index values increased linearly with increasing mowing height (Figure 7). The larger slope in 1990 supports 1990 color and quality data. Larger mowing height differences in 1990 than in 1989 may have been due to maturing treatment effects on the turfgrass. Analysis of the vegetation index for each measurement day, revealed similar results as with ball roll and visual ratings with the index increasing with increasing mowing height. A significant mowing height by vertical mowing frequency interaction was observed on 8 August 1990 (Figure 8). At the 4.0 mm mowing height, the vegetation index increased from the 0 to 1 X month^{-1} VM frequency then decreased from the 1 to 2 X month^{-1}, while at 3.2 and 4.8 mm, the index decreased slightly with increasing vertical mowing frequency. Since this interaction was the only one observed in both years, its biological significance is questionable. Presence of fairy ring (Marasmius oreades) on parts of the research green in 1990 may have caused high index values, due to the dark green circles produced by the pathogen.

Root Distribution

No mowing height by vertical mowing frequency interaction was observed for root distribution in 1989 or 1990. Neither mowing height nor vertical mowing frequency significantly affected root distribution at all three sampling dates in 1989. Root distribution in 1990 was not affected by vertical mowing frequency. Mowing height affected root production at the 76 to 152 mm depth on the 12 July 1990 sampling (Figure 9), and at the 152 to 228 mm depth on the 12 September 1990 sampling (Figure 10). Increased root production with increasing mowing height is attributed to increased leaf area and hence, increased photosynthesis and photosynthate supply (Krans and Beard, 1985).

Root distribution data also were averaged across treatments and analyzed over sampling dates to observe seasonal growth trends. Root production at the uppermost sampling depth (0 to 102 mm in 1989, and 0 to 76 mm in 1990) changed over time (Figures 11 and 12). Seasonal rooting patterns of creeping bentgrass show peaks of growth in spring and fall (Koski, 1983). Quadratic relationships were used to explain data presented here, since the three sampling dates bracket the summer heat stress declination portion of the seasonal growth curve. Although two opposite quadratic relationships were observed for root growth at the uppermost sampling dates in both years, the data agree with the results reported in the other study (Koski, 1983). In 1989, sampling dates fell within the two peaks of root growth activity and the second sampling date fell within the midsummer stress period (Figure 11). In 1990, sampling dates were approximately one month earlier than in 1989. The first sampling date was at the start of spring root growth activity. The second fell at the decline of maximum spring growth activity, and the third at the start of maximum root growth in the fall (Figure 12). Root production at the other sampling depths did not change over time in either year.

Soil Temperature

To aid in interpretation of rooting data, soil temperatures were averaged over all treatment combinations on each day and plotted against days, giving an average daily soil temperature curve for each year (Figure 13). In 1989 first and third root sampling dates are associated with low average soil temperatures while the second is associated with higher soil temperatures (Figure 13a), hence the upwardly-concave characteristic of seasonal root growth at the uppermost depth in 1989 (Figure 11). In 1990, a downward-concave characteristic seasonal root growth curve for the uppermost depth (Figure 12), is explained by soil temperatures at the first two sampling dates being relatively lower than temperatures at the third sampling date.

Canopy Temperatures

Vertical mowing frequency treatments affected canopy temperature (Tc) on only one date in 1989 and 1990. Canopy temperatures were highest at the 2 X month^{-1} frequency on 16 June 1989 (Figure 14a). Similar results were observed for Tc on 18 May 1990 (Figure 14b). Slight grooves in the canopy surface created by vertical mowing may allow more incoming radiation into the canopy and decrease the amount of transpirational leaf surface, causing increases in Tc. These measurement dates follow the initial vertical mowing treatment applications for each year. This indicates that vertical mowing may have a more dramatic effect on the turf when first applied than subsequent applications, as the turf becomes acclimated to the treatments.

Mowing height treatments affected Tc on three dates in both years. A quadratic response on 14 June 1989 indicates a peak Tc occurring at a mowing height between 3.2 and 4.0 mm (Figure 15). A linear response was observed on 16 June 1989 (Figure 16). Canopy temperature decreased linearly as mowing height increased. Shearman and Beard (1973) showed that increasing the mowing height of creeping bentgrass increased its water use rate. With this in mind, higher cut turfs will have lower canopy temperatures due to increased evaporative cooling of the canopy. On 11 June 1990, Tc again changed quadratically (Figure 17) as it did on 14 June 1989 (Figure 16). Surprising responses were observed on 28 June 1989 (Figure 18) and 25 June 1990 (Figure 19). Canopy temperatures were actually higher at the higher mowing heights on both dates. High relative humidities on those dates may have slowed evapotranspiration rates causing the higher-cut, darker colored turfs to absorb more heat. Disruption of the laminar boundary layer by small wind gusts also may have caused measurement errors.

An attempt was made at deriving empirical CWSI values for creeping bentgrass by plotting the upper and lower 25% of ΔT values measured on 3, 5, and 9 September 1990 against VPD (Figure 20). Linear regression models for the baselines were not significant, but were utilized nonetheless for comparison of CWSI with Tc analysis. On 9 September 1990 Tc and CWSI decreased with increasing mowing height by similar linear models (Figure 21). Crop water stress index values indicated differences among mowing heights, lending support to the usefulness of such an index in delineating turfgrass water stress.