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Temperature Effects on Warm- and Cool-Season Turfgrass Species and Cultivars

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Temperature effects on warm- and cool-season turfgrass species and cultivars.

By

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Temperature effects on warm- and cool-season turfgrass species and cultivars.

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Research was conducted using the Soil-Plant-Atmosphere-Research (SPAR) units at Mississippi State University, Starkville, MS to investigate temperature effects on warm- and cool-season turfgrasses. Data collected include clipping yield, total root biomass, and relative chlorophyll index (RCI). Cultivars and species in the study included: ‘Latitude 36’, ‘Tifway’, ‘MSB-285’, and ‘TifEagle’ bermudagrass, ‘Meyer’ zoysiagrass, ‘Penn A1/A4’ and ‘Penncross’ creeping bentgrass, ‘Midnight’ Kentucky bluegrass, ‘Fiesta 4’ perennial ryegrass, and ‘Falcon V’ tall fescue. Grasses were grown in the SPAR units at varying day/night temperature regimes. Clipping yield was collected every three days, and regression was used to determine the temperature at which clipping yield equaled zero. Root biomass was collected at the conclusion of the trial, while RCI was taken once weekly. Base temperature for warm-season grasses ranged from 12.5 to 13.2°C. Determined optimum temperatures ranged from 31.8 to 36.1°C for warm-season turfgrasses and 18.8 to 20.6°C for cool-season turfgrasses.

DEDICATION

This thesis is dedicated to all the people that have the same degree as me, and all the future employers that ask, “Why did you get a Master’s degree?”

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

LITERATURE REVIEW

Temperature

Temperature is one of the most important abiotic factors that affect plant growth and development. The efficiency of many physiological functions is influenced directly by temperature (DiPaola and Beard, 1992). Scientists have studied temperature and plant interactions to better comprehend the exact threats and benefits of temperature.

Huang and Gao (2010) examined creeping bentgrass (*Agrostis stolonifera* L.) in response to increasing temperatures. This study was conducted at Kansas State University using three creeping bentgrass cultivars: 'Penncross', 'ISI-AP-89150', and 'SR 1020'. Plants were placed in a growth chamber and sequentially exposed to constant temperatures of 20, 24, 30, 34, and 38°C for 20 days. After 10 and 20 days at each temperature regime, four plants were harvested and measured for various shoot and root parameters. The remaining plants were then exposed to the next temperature treatment, and the process repeated until all temperatures were tested. For all three cultivars, root dry weight decreased to levels below respective 20°C controls after exposure to 30°C and declined further when temperature increased from 34 to 38°C. Researchers concluded that higher temperatures cause an imbalance of photosynthesis and respiration leading to a reduction in carbohydrate availability, thus reducing root growth. Similarly, Reddy et al. (1994) determined that cotton (*Gossypium hirsutum* L.) root dry weight increased with

temperatures up to 22.7°C, and any increases in root growth at temperatures higher than 22.7°C depended on how temperature affected the competition for assimilates between the roots and the shoots.

Forbes et al. (1997) determined the longevity of perennial ryegrass (*Lolium perenne* L.) roots when exposed to changes in temperature. Perennial ryegrass plants were maintained at constant temperatures of 15, 21, or 27°C for 86 days. Roots were observed using a minirhizotron system. Visual reference points marked on the minirhizotron allowed for root growth or desiccation to be observed. Results showed that the longevity of roots decreased with increasing temperatures. Both root length and longevity were greatest at the 15°C treatment. Forbes et al. (1997) hypothesized that root nitrogen uptake is slowed as temperatures increase because nitrate (NO_3^-) concentrations affect root development and nitrogen mineralization to NO_3^- is sensitive to higher temperatures.

Tindall et al. (2008) determined that nutrient uptake in tomatoes (*Lycopersicon esculentum* cv. Burpee 'Big Boy Hybrid') peaked at 26.7°C for all nutrients except boron, iron, and molybdenum which were not affected by temperature. From this same study, Tindall et al. (2008) also determined that the root dry weight of tomatoes was maximized at 25°C.

Clarkson et al. (1986) studied the effect of temperature on the uptake of different nitrogen sources in perennial ryegrass. Perennial ryegrass was grown in a flowing culture solution where the concentrations of NH_4^+, NO_3^-, and K^+ were frequently monitored. Perennial ryegrass plants were exposed to a constant temperature treatment of 3, 7, 9, 11, 13, 17, or 25°C. At temperatures below 9°C, approximately 85% of nitrogen absorbed by

the roots of perennial ryegrass was NH_4^+ as opposed to NO_3^-. However, the amount of total nitrogen in root and shoot tissues had similar concentrations regardless of temperature treatment.

The findings of Clarkson et al. (1986) do not support the statement of Forbes et al. (1997) in that more NO_3^- is absorbed at lower temperatures. These studies on root growth are all comparable in that root size increased up to a certain temperature varying between 15 and 25°C, but temperatures higher than that caused a decrease in root formation. Studies attribute this to either nutrient availability or competition for photosynthates between the roots and shoots at higher temperatures. Therefore, it can be assumed that at higher temperatures the lack of nutrient uptake reduces the production of photosynthates, leading to a reduction in root biomass.

Scientific studies relating temperature to plant growth and development can be dated back to the 18th century (McMaster and Wilhelm, 1997). Réaumur (1735) conducted one of the first documented studies that discovered the relationship between development rate of crops and temperature, thus leading to the concept of heat accumulation models (Bonhomme, 2000; Wang, 1960). Heat accumulation models are widely used to predict timing of pest outbreak, disease outbreak, plant development stages, and weed emergence (Tolleyi and Robinson, 1986; Ryan et al., 2012; Gilmore and Rogers, 1958; Fidanza et al., 1996).

One of the most frequently used heat accumulation models are growing degree days (GDD). Growing degree days are used by agriculturalists to predict when distinct growth stages of plants will occur, such as days until flowering or days until maturity (Miller et al., 2001). Growing degree days are defined by McMaster and Wilhelm (1997)

as the amount of heat energy received by the plant for a given time period. Growing degree days are calculated by averaging the daily maximum and minimum air temperature and then subtracting the base temperature for the plant being grown. Base temperature, as defined by McMaster and Wilhelm (1997), is the temperature at which plant processes do not progress.

In the turfgrass industry, GDD models are predominately used to optimize growth regulator and herbicide application intervals (Kreuser et al, 2011; Brosnan et al., 2010), and to predict seedhead development (Danneberger et al., 1987; McCullough, 2014), weed emergence (Fidanza et al., 1996) and disease outbreak (Ryan et al., 2012). Growing degree day models are gaining in popularity and are slowly becoming the preferred method for product application versus the traditional calendar approach. By using GDD models, timings for these applications can be based more on the needs of the plant as opposed to a calendar based approach.

Fidanza et al. (1996) predicted crabgrass [*Digitaria ischaemum* (Schreb.)Schreb. ex Muhl.] emergence in turfgrass using GDD at the University of Maryland. Crabgrass emergence was monitored weekly by counting seedlings inside a grid measuring 100 cm^2. Accumulated degree days were calculated by subtracting a base temperature of 12°C. Crabgrass first emerged 52, 42, and 78 accumulated degree days in years one, two, and three, respectively. An exponential model predicted the time to 95% of crabgrass emergence was equal to 945 degree days.

At the University of Maryland, Ryan et al. (2012) determined the relationship of GDD and dollar spot symptoms in six creeping bentgrass cultivars (*Agrostis stolonifera* L.). The bentgrass cultivars were divided into two groups: highly susceptible (‘Crenshaw’

and ‘Backspin’) and moderately susceptible (‘Penncross’, ‘Providence’, ‘L-93’, and ‘007’). Dollar spot development was rated visually using a 0 to 100% linear scale where 0 = no blighting and 100% = entire plot infected. A base temperature of 15°C was used to determine accumulated GDD. The onset of dollar spot occurred between 60 and 70 GDD for the highly susceptible cultivars and 105 to 115 GDD for the moderately susceptible cultivars.

Branham and Beasley (2007) determined that the effectiveness of two growth regulators is directly related to air temperature. This study, conducted at the University of Illinois-Urbana, explored the metabolism of trinexapac-ethyl (TE) and paclobutrazol in Kentucky bluegrass (*Poa pratensis* L.) and creeping bentgrass. Both grasses were treated with either paclobutrazol or TE at 0.28 kg a.i. ha^{-1}. Leaf tissue was collected at two, five, eight, 11, and 14 days after TE application, and two, eight, 16, and 23 days after paclobutrazol application. High-performance liquid chromatography was used to determine the amount of plant growth regulator remaining in the leaf tissue. Metabolism studies were conducted in both field and controlled-environment growth chamber conditions to better understand the temperature effects on metabolism. In both studies, the remaining amount of TE and paclobutrazol in the leaf tissue decreased more rapidly as temperature increased. In the growth chamber study, when the temperature was maintained at 18°C, the half-life of TE was 5.3 days and 6.4 days in Kentucky bluegrass and creeping bentgrass, respectively; however, when temperature was maintained at 30°C, the half-life of TE was 3.4 and 3.1 days for Kentucky bluegrass and creeping bentgrass, respectively. Conclusions from this research supported the concept of using

GDD to optimize growth regulator applications, instead of the traditional calendar day approach.

Kreuser and Soldat (2011) conducted two research trials using a GDD model to optimize TE reapplication intervals on an L-93 creeping bentgrass putting green. For experiment one, TE was applied at 0.05 kg ai ha^{-1} every 100, 200, 400, and 800 GDD, every four calendar weeks, and a nontreated control. Cumulative GDD were calculated with a base temperature of 0°C. Cumulative GDD calculations were reset after each application. Clippings were collected five times per week. A rebound phase was observed when TE reapplications occurred at 400, 800 GDD, and four week intervals. The 100 and 200 GDD reapplication intervals resulted in consistent clipping yield suppression without a rebound phase or visible injury. Results from this experiment were used in the design of experiment two, where TE was applied at 0, 0.05, and 0.10 kg ha^{-1} every 200 GDD. Clippings were collected three times per week. The authors noted application rate did not influence the amount or duration of growth suppression. There was no significant difference between the 0.05 and 0.10 kg ai ha^{-1} rates in terms of the magnitude of yield suppression or the duration of yield suppression. Therefore, increasing application rate is not a useful technique in lengthening the yield suppression phase during periods of high temperatures. This research is similar to McCullough et al. (2007) in which TE rates ≤ 0.05 kg ai ha^{-1} applied more frequently resulted in a more consistent clipping yield.

At the University of Tennessee, Brosnan et al. (2010) investigated herbicide applications based on GDD in order to control dallisgrass (*Paspalum dilatatum* Poir.) in a stand of tall fescue. Postemergence herbicide was applied at either <160 GDD or >500 GDD accumulated from 1 January. The authors determined that postemergence herbicide

application was more effective when applied <160 GDD versus >500 GDD. A base temperature of 10°C was selected to calculate GDD accumulation. The <160 GDD application was made on 7 April; however, if a base temperature of 12°C had been used the application would have been delayed, and the effectiveness of the herbicide would have more closely mimicked the >500 GDD.

A critical factor in using any heat model is the determination of an accurate base temperature (Arnold, 1959). If a base temperature used in the calculation of GDD is off by 2°C, then the total accumulated GDD can vary by as much as two calendar weeks (Unruh, 1996). Base temperature can vary between species and growth stages (Wang, 1960). Multiple studies on determining base temperature for seed germination prove that different temperature requirements are needed for seed germination of different species (Jordan and Haferkamp, 1989; Gajanayake et al., 2011).

In turfgrass, only one study has been conducted to specifically determine base temperature. Unruh (1996) determined the base temperature of various warm-season turfgrasses. Species and cultivars used in the study included ‘Midiron’ and ‘Arizona Common’ bermudagrass, ‘Kansas Common’ and ‘Texoka’ buffalograss, ‘Meyer’ zoysiagrass, ‘Raleigh’ and ‘Floratam’ St. Augustinegrass, and ‘Common’ centipedegrass. Turfgrasses were placed in growth chambers set at varying temperatures and received 400 μmol m^{-2} s^{-1} of light per day. Turfgrasses remained in the chambers until two leaves had fully expanded at each temperature. Growth rates were modeled to determine the temperature when growth rate equaled zero. Base temperatures for the grasses tested ranged from 1.2 to 12.3°C. Common centipedegrass had the highest base temperature, while Raleigh St. Augustinegrass had the lowest base temperature. Since warm-season

species generally have a high light requirement (Baldwin et al., 2009), the low levels of light may have caused additional stress that influenced turfgrass growth in response to temperature. In order to determine a true response to temperature, all other aspects of plant development (i.e. light, nutrients, water, etc.) would have to be optimum. Due to increasing research efforts regarding GDD modeling in turfgrass and the lack of information for warm- and cool-season turfgrass species specific base temperatures, research is warranted to investigate base temperatures. The Soil-Plant-Atmosphere-Research facility at Mississippi State University is ideal for this research due to the ability to control an abundance of environmental aspects.

Soil-Plant-Atmosphere-Research Facility

The Soil-Plant-Atmosphere-Research (SPAR) facility is located at the Rodney R. Foil Plant Science Research Center, Starkville, MS, Mississippi State University (33° 28' 10" N, 88° 43' 58" W). Reddy et al. (2001) described the operation details and control algorithms of the SPAR units. Briefly, the SPAR facility is composed of ten naturally-lit chambers on a 20 × 30 m concrete pad. Each unit is composed of a Plexiglas® [Poly(methyl methacrylate)] chamber measuring 2.5 m high and a steel soil bin measuring 1.0 m deep × 2.0 m long × 0.5 m wide. A hinged door located on the bottom of the aerial portion of the chamber allows access to the above ground portion of the plants. The Plexiglas® measures 1.27 cm thick and transmits approximately 95% photosynthetically active radiation. A fan connected to the air-handling unit blows air into the Plexiglas® chamber about halfway between the bottom and the top of the unit. The air circulates just above the plant canopy simulating natural air flow before it returns to the air-handling unit. The air-handling unit contains a pressure pump to direct air to the

laboratory room for analysis by a dedicated carbon dioxide (CO_2) analyzer (Model, LI 6200, LI-COR Biosciences, Lincoln, NE). Each SPAR unit contains two 5 kilowatt heating elements on either side of the unit for high temperature control, and all units are connected to a 50 ton cooling unit for low temperature control.

Temperature in the SPAR units can be controlled to ± 0.5°C of the treatment set points over a daytime range between 18 to 40°C and a nighttime range of 12 to 32°C. A thermocouple monitors and records air temperature in the unit. Ninety-six observations of air temperature are recorded every 24 hours to find the average daily temperature in each unit. A gold mirror hygrometer (Model Dew-10, General Eastern Instruments, Woburn, MA) is located just inside the return airline to monitor dew point temperature. Dew point temperatures are recorded every 10 seconds and then averaged over 900 second periods. Cooling coils located in the air-handling unit of each SPAR chamber are able to condense excess water vapor in order to regulate relative humidity. Carbon dioxide is also monitored and adjusted every 10 seconds to be maintained within 10μL L^{-1} of desired level. Chamber air temperature, CO_2, and soil watering, as well as continuous monitoring of environmental and plant gas exchange variables, is controlled by a dedicated computer system. The control capabilities of the SPAR units allow for a wide range of studies on various plant responses to temperature, CO_2, drought, nutrient deficiency, UV-B light, and climate change (Wijewardana et al., 2015; Brand et al., 2016; Wijewardana et al., 2016; Reddy et al., 1997).

Grasses

Warm-Season

Warm-season is the common term to describe turfgrasses that are characterized by the C_4 photosynthetic pathway. This characteristic gives warm-season grasses advantage in hot, dry climates; however, the many disadvantages of warm-season grasses provide objectives for plant breeders. Such breeding objectives include: shade tolerance, cold tolerance, and fine leaf texture (Hanna et al., 2002).

Tifway hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy) was released in 1960 by Dr. Glenn Burton at the Georgia Coastal Plain Experiment Station (Burton, 1966). Tifway is one of the most widely used bermudagrasses for golf courses, athletic fields, and home lawns, and it is consistently used as an industry standard in the National Turfgrass Evaluation Trials (Beard, 2002; www.ntep.org). TifEagle ultradwarf hybrid bermudagrass was released by the Georgia Coastal Plains Experiment Station in 1997, and is extensively used on putting greens due to its short, dense growth habit (Hanna, 1999). Latitude 36 hybrid bermudagrass is a cultivar released by Oklahoma State University that is considered to have superior cold tolerance relative to other bermudagrasses (Richardson, 2014). MSB-285 hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] is an experimental bermudagrass cultivar from the Mississippi State University breeding program. This cultivar was a top performer in the 2013 National Turfgrass Evaluation Program/USGA warm-season putting green test (www.ntep.org). Liu et al. (2014) stated that MSB-285 has outstanding density, quality, and winter color retention.

Meyer zoysiagrass (*Zoysia japonica* Steud.) was jointly released in 1951 by the Crops Research Division, Agricultural Research Service, and the United States Golf Association Green Section (Hanson, 1966). Meyer has good low temperature tolerance relative to other warm-season grasses making it a popular choice for golf courses and home lawns in the transition zone (Dunn, 1999).

Cool-Season

Contradictory to warm-season species, cool-season grasses are characterized by the C3 photosynthetic pathway. Cool-season turfgrasses are generally much more tolerant to cold weather than warm-season turfgrasses; however, cool-season grasses are much less efficient in hot climates. Thus, common breeding objectives of cool-season grasses include: heat tolerance, disease tolerance, and canopy density (Bonos and Huff, 2002).

Midnight Kentucky bluegrass (*Poa pratensis* L.) was released by Turf Seed, Inc. in 1981 (Meyer et al., 1984). Midnight is often used as a standard entry in the NTEP National Kentucky Bluegrass Test (www.ntep.org). Midnight Kentucky bluegrass shows improved drought and heat tolerance relative to other Kentucky bluegrasses (Richardson et al., 2008; Perdomo et al., 1996).

Creeping bentgrass (*Agrostis stolonifera* L.) is a species used worldwide on golf course fairways and greens. Creeping bentgrass is noted for its low, dense growth habit, its relatively good recuperative ability, and its adaptation to both temperate and transition zone climates (Fagerness, 2000). Penncross was released in 1958 and has since become one of the most widely used standards for creeping bentgrass (Hein, 1958; www.ntep.org). Both Penn A1 and Penn A4 cultivars exhibit improved heat tolerance and canopy density (Toubakaris and McCarty, 2000).

Fiesta perennial ryegrass was released in 1982 (Funk et al., 1982). Several genetically related cultivars have since been marketed for improved quality under the name Fiesta (Pepin et al., 1989). Fiesta 4 was used as a commercially available standard in the 2010 NTEP National Perennial Ryegrass Test (www.ntep.org).

Falcon tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.] was released in 1981 (Funk et al. 1981). Similar to the Fiesta ryegrass mentioned above, newer, genetically related cultivars have since been released also donning the name Falcon. Both Falcon IV and Falcon V are used in the NTEP National Tall Fescue Test (www.ntep.org).

Proposed Research

Temperature has been proven to cause a response in turfgrass growth and development. Numerous studies have shown that both physiological processes and anatomical development are affected by temperature; therefore, uses of GDD are becoming more popular in the turfgrass industry. To this point, base temperatures used to calculate GDD have been arbitrarily assigned based on a general range of temperatures known to cause a decline in turfgrass growth. A wrong base temperature will change the amount of accumulated GDD leading to mistimed product applications and predictions. Due to limited research on base temperatures in turfgrass and temperature effects on multiple species, research is warranted to determine an exact base temperature and how a broad range of temperatures effect various turfgrass growth and development.

References

Baldwin, C.M., H. Liu, L.B. McCarty, H. Luo, C.E. Wells, and J.E. Toler. 2009. Impacts of altered light spectral quality on warm season turfgrass growth under greenhouse conditions. Crop Sci. 49(4):1444-1453.

Bonhomme, R. 2000. Bases and limits to using 'degree.day' units. Euro. J. of Agron. 13:1-10.

Bonos, S.A. and D.R. Huff. 2002. Cool-season grasses: biology and breeding. p. 591-660. In J.C. Stier et al. (ed.) Turfgrass: Biology, Use, and Management. Agron. Monogr. 56. ASA, CSSA, and SSSA, Madison, WI.

Brand, D., C. Wijewardana, W. Gao, and K.R. Reddy. 2016. Interactive effects on carbon dioxide, low temperature, and ultraviolet-B radiation on cotton seedling root and shoot morphology and growth. Front. Earth Sci. 10(4):607-620.

Branham, B., and J. Beasley. 2007. PGRs: metabolism and plant responses. Golf Course Manage. July 75(7): p. 95-99.

Burton, G.W. 1966. Tifway (Tifton 419) Bermudagrass. Crop Sci. 6:93-94.

Clarkson, D.T., M.J. Hopper, and L.H.P. Jones. 1986. The effect of root temperature on the uptake of nitrogen and the relative size of the root system in Lolium perenne. I. Solutions containing both NH_4^+ and NO_3^-. Plant, Cell and Environ. 9:535-545.

DiPaola, J.M. and J.B. Beard. 1992. Physiological effects of temperature stress. p. 231-267. In D.V. Waddington et al. (ed.) Turfgrass. Agron. Monogr. 32. ASA, CSSA, and SSSA, Madison, WI.

Dunn, J.H., S.S. Bughara, M.R. Warmund, and B.F. Fresenburg. 1999. Low temperature tolerance of zoysiagrasses. HortScience 34(1):96-99.

Fagerness, M.J., F.H. Yelverton, J.I. Isgrigg III, and R.J. Cooper. 2000. Plant growth regulators and mowing height affect ball roll and quality of creeping bentgrass putting greens. HortScience. 35(4):755-759.

Fidanza, M.A., P.H. Dernoeden, and M. Zhang. 1996. Degree-Days for predicting smooth crabgrass emergence in cool-season turfgrass. Crop Sci. 36:990-996.

Forbes, P.J., K.E. Black, and J.E. Hooker. 1997. Temperature-induced alteration to root longevity in *Lolium perenne*. Plant and Soil 190:87-90.

Funk, C.R., C.J. Petersen, W.K. Wiley, M.C. Pick, and D. King. 1982. Registration of Fiesta perennial ryegrass [cultivar]. Crop Sci.

Funk, C.R., W.K. Dickson, W.A. Meyer, and R.J. Petersen. 1981. Registration of Falcon tall fescue (reg. no. 19). Crop Sci 21(4):632.

Gajanayake, B., B.W. Trader, K.R. Reddy, and R.L. Harkess. 2011. Thermotolerance classification of ornamental pepper cultivars using seed germination traits. Seed Tech. 33(2):134-146.

Gilmore Jr., E.C., and J.S. Rogers. 1958. Heat units as a method of measuring maturity in corn. Agron J. 50(10):611-615.

Hanna, W.W., and J.E. Elsner. 1999. Registration of 'TifEagle' bermudagrass. Crop Sci. 39:1258.

Hanna, W., P. Raymer, and B. Schwartz. 2002. Warm-season grasses: biology and breeding. p. 543-590. In J.C. Stier et al. (ed.) Turfgrass: Biology, Use, and Management. Agron. Monogr. 56. ASA, CSSA, and SSSA, Madison, WI.

Hanson, A.A. 1966. Meyer zoysia (Reg. No. 12). Crop Sci. 6(1):99.

Huang, B. and H. Gao. 2010. Growth and carbohydrate metabolism of creeping bentgrass cultivars in response to increasing temperatures. Crop Sci. 40:1115-1120

Jordan, G.L., and M.R. Haferkamp. 1989. Temperature responses and calculated heat units for germination of several range grasses and shrubs. J. of Range Manag. 42(1):41-45.

Kreuser, W.C. and D.J. Soldat. 2011. A growing degree day model to schedule Trinexapac-ethyl applications on *Agrostis stolonifera* golf putting greens. Crop Sci. 51:2228-2236.

Liu, W. 2014. Development and evaluation of hybrid bermudagrass varieties with cold hardiness for golf course putting greens. M.S. Thesis. Oklahoma State University, 2014.

McCullough, P.E., H. Liu, L.B. McCarty, and J.E. Toler. 2007. Trinexapac-ethyl application regimens influence growth, quality, and performance of bermudagrass and creeping bentgrass putting greens. Crop Sci. 47:2138-2144.

McMaster, G.S., and W.W. Wilhelm. 1997. Growing degree-days: one equation, two interpretations. Ag and For. Meteo. 87:291 – 300.

Meyer, W.A., B.L. Rose, J.M. Johnson-Cicalese, and C.R. Funk. 1984. Registration of Midnight Kentucky bluegrass. Crop Sci. 24(4):822-823.

Miller, P., W. Lanier, and S. Brandt, 2001. Using growing degree days to predict plant stages. Ag/Extension Communications Coordinator, Communications Services, Montana State University-Bozeman, Bozeman, MO.

Pepin, G.W., W.K. Wiley, D.E. King, C.J. Petersen, and C.R. Funk. 1989. Registration of 'Fiesta II' perennial ryegrass. Crop Sci. 29(5):1328.

Perdomo, P., J.A. Murphy,and G.A. Berkowitz. 1996. Physiological changes associated with performance of Kentucky bluegrass cultivars during summer stress. HortSci. 31(7):1182-1186.

Réaumur, R.A. 1735. Observations du thermométre faites pendant l'année MDCCXXXV compares à celles qui ont été faites sous la ligne à l'Isle-de-France, à Alger et en quelques-unes de nos Isles de l'Amérique. Mémoires de l'Académie Royale des Sciences, 545-576.

Reddy, K.R., H.F. Hodges, J.J. Read, J.M. McKinion, J.T. Baker, L. Tarpley, and V.R. Reddy. 2001. Soil-Plant-Atmosphere-Research (SPAR) facility: a tool for plant research and modeling. Biotronics 30:27-50.

Reddy, K.R., H.F. Hodges, J.M. McKinion. 1997. A comparison of scenarios for the effect of global climate change on cotton growth and yield. Australian J. of Plant Physio. 24(6):707-713.

Reddy, V.R., K.R. Reddy, M.C. Acock, and A. Trent. 1994. Carbon dioxide enrichment and temperature effects on root growth in cotton. Biotronics 23:47-57.

Richardson, M.D., D.E. Karcher, K. Hignight, and D. Rush. 2008. Drought tolerance and rooting capacity of Kentucky bluegrass cultivars. Crop Sci. 48(6):2429-2436.

Richardson, M.D., J.T. Brosnan, and D.E. Karcher. 2014. Turfgrass winterkill observations from the transition zone. Applied Turfgrass Science 11(1).

Ryan, P.R., P.H. Dernoeden, and A.P. Grybauskas. 2012. Seasonal development of dollar spot epidemics in six creeping bentgrass cultivars in Maryland. HortSci. 47:422-426.

Tindall, J.A., H.A. Mills, and D.E. Radcliffe. 2008. The effect of root zone temperature on nutrient uptake of tomato. Journal of Plant Nutrition 13(8):939-956.

Tolleyi, M.P., and W.H. Robinson. 1986. Seasonal abundance and degree-day prediction of sod webworm (Lepidoptera: Pyralidae) adult emergence in Virginia. J. of Economic Entomol. 79(2):400-404.

Toubakaris, M., and L.B. McCarty. 2000. Heat stress separates old and new bentgrasses. Golf Course Manage. 68(7):49-53.

Unruh, J.B., R.E. Gaussoin, and S.C. Wiest. 1996. Basal growth of temperatures and growth rate constants of warm-season turfgrass species. Crop Sci. 36:997-999.

Wang, J.Y. 1960. A critique of the heat unit approach to plant response studies. Ecology 41(4):785-790.

Wijewardana, C., M. Hock, B. Henry, and K.R. Reddy. 2015. Screening corn hybrids for cold tolerance using morphological traits for early-season seeding. Crop Sci. 55:851-867.

Wijewardana, C., W.B. Henry, W. Gao, and K.R. Reddy. 2016. Interactive effects on CO2, drought, and ultraviolet-B radiation on maize growth and development. Journal of Photochem. and Photobiol. B: Biology 160:198-209.

Wu, Y., D.L. Martin, C.M. Taliaferro, J.A. Anderson, and J.Q. Moss. 2014. Latitude 36 turf bermudagrass. U.S. Patent PP24,271.

CHAPTER II

DETERMINING BASE TEMPERATURE OF WARM- AND COOL-SEASON TURFGRASS SPECIES AND CULTIVARS

Introduction

Temperature is one of the most influential components of plant growth and development. Réaumur (1735) conducted one of the first documented studies regarding temperature and plant interactions (Bonhomme, 2000). Since then, extensive research has been conducted to determine the exact effects that temperature induces both physiologically and anatomically in plants. Temperature has a significant impact on root growth. Root size typically increases as temperatures approach an optimum temperature and then decline as temperatures rise above that optimum temperature (Huang and Gao, 2010; Reddy et al., 1994; Forbes et al., 1997). The optimum temperature for root growth is often found to be lower than the general optimum range for canopy growth (DiPaola and Beard, 1992).

Heat accumulation models are used throughout agriculture to predict and plan a multitude of agronomic practices and occurrences. Currently, growing degree days (GDD) are perhaps the most commonly used method of calculating heat accumulation. McMaster and Wilhelm (1997) defined GDD as a way to describe the amount of heat energy received by a crop over a given time period. Growing degree days are used extensively in agriculture to predict when distinct plant growth stages will occur, such as

days until flowering or days until maturity (Miller et al. 2001). In the turfgrass industry, GDD models are predominately used to optimize growth regulator and herbicide application intervals (Kreuser et al, 2011; Brosnan et al., 2010), and to predict seedhead development (Danneberger et al., 1987; McCullough, 2014), weed emergence (Fidanza et al., 1996), and disease outbreak (Ryan et al., 2012).

The components of the GDD model include average daily air temperature, as well as a base temperature. Base temperature, as defined by McMaster and Wilhelm (1997), is the temperature in which plant processes do not progress. However, base temperature can vary between species and growth stage (Wang, 1960). In previous research on GDD modeling, selection of a base temperature has varied. Brosnan et al. (2010) used a base temperature of 10°C when scheduling herbicide applications in tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.]. McCullough (2014) also used a base temperature of 10°C when predicting seedhead formation in zoysiagrass (*Zoysia japonica* Stued.), seashore paspalum (*Paspalum vaginatum* Sw.), and bermudagrass (*Cynodon* spp.). Alternatively, Kreuser and Soldat (2011) used a base temperature of 0°C when scheduling growth regulator reapplication intervals on creeping bentgrass. According to Unruh et al. (1996), if a base temperature varies by 2°C, the total accumulated GDDs can vary two calendar weeks.

To the authors' knowledge, Unruh et al. (1996) conducted the only study that has determined base temperature for warm-season turfgrass species. Species and cultivars used in the study included 'Midiron' and 'Arizona Common' bermudagrass, 'Kansas Common' and 'Texoka' buffalograss (*Buchloe dactyloides* Nutt.), 'Meyer' zoysiagrass, 'Raleigh' and 'Floratam' St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze),

and ‘Common’ centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.). The authors reported that base temperatures ranged from 1.2°C to 12.3°C across species. This study was conducted in a growth chamber with a maximum light output of 400 μmol m^{-2} s^{-1}. The average light levels in the Southeastern United States can reach 2300 μmol m^{-2} s^{-1}. Since warm-season species generally have a high light requirement (Baldwin et al., 2009), the low light levels may have caused additional stress that influenced turfgrass growth in response to temperature. Ideally, in order to determine an exact response to temperature, turfgrasses would be grown in an optimal growing environment. Also, only warm-season turfgrass species were investigated. Due to increasing research efforts regarding GDD modeling in turfgrass and the lack of information for warm- and cool-season turfgrass species specific base temperatures, research is warranted to investigate base temperatures. Therefore, the primary objective of this research was to determine the base and optimum temperatures of warm- and cool-season turfgrass species. The secondary objective was to investigate temperature effects on relative chlorophyll index and total root biomass.

Materials and Methods

Research was conducted from 24 April to 15 May 2016 utilizing the Soil-Plant-Atmosphere-Research (SPAR) units located at the Rodney R. Foil Plant Science Research Center in Starkville, Mississippi (33° 28’ 10” N, 88° 43’ 58” W), Mississippi State University. The SPAR facility is composed of ten naturally-lit chambers on a 20 × 30 m concrete pad. Each unit is composed of a Plexiglas® [Poly(methyl methacrylate)] chamber measuring 2.5 m high and a steel soil bin measuring 1.0 m deep × 2.0 m long × 0.5 m wide. A hinged door located on the bottom of the aerial portion of the chamber

allows access to the above ground portion of the plants. The Plexiglas® measures 1.27 cm thick and transmits approximately 95% photosynthetically active radiation. A fan connected to the air-handling unit blows air into the Plexiglas® compartment about halfway between the bottom and the top of the unit. The air circulates just above the plant canopy simulating natural air flow before it returns to the air-handling unit. The air-handling unit contains a pressure pump to direct air to the laboratory room for analysis by a dedicated CO_2 analyzer (Model, LI 6200, LI-COR Biosciences, Lincoln, NE). Each SPAR unit contains two 5 kilowatt heating elements on either side of the unit for high temperature control, and all units are connected to a 50 ton cooling unit for low temperature control.

Temperature in the SPAR units can be controlled to ± 0.5°C of the treatment set points. A thermocouple monitors and records air temperature in the unit. Ninety-six observations of air temperature are recorded every 24 hours to find the average daily temperature in each unit. A gold mirror hygrometer (Model Dew-10, General Eastern Instruments, Woburn, MA) is located just inside the return airline to monitor dew point temperature. Dew point temperatures are recorded every 10 seconds and then averaged over 900 second periods. Cooling coils located in the air-handling unit of each SPAR chamber are able to condense excess water vapor in order to regulate relative humidity. Carbon dioxide is also monitored and adjusted every 10 seconds to be maintained within 10μmol mol^{-1} of desired level. Chamber air temperature, carbon dioxide, and soil watering, as well as continuous monitoring of environmental and plant gas exchange variables, are controlled by a dedicated computer system. Reddy et al. (2001) described the operation details and control algorithms of the SPAR chambers.

Cool-season grasses included ‘Penn A1/A4’ and ‘Penncross’ creeping bentgrass (*Agrostis stolonifera* L.), ‘Midnight’ Kentucky bluegrass (*Poa pratensis* L.), ‘Fiesta 4’ perennial ryegrass (*Lolium perenne* L.), and ‘Falcon V’ tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort.). Penn A1/A4 and Penncross creeping bentgrass samples were taken as plugs from putting greens located at the Country Club of Birmingham, Birmingham, AL and Musgrove Mill Golf Club, Clinton, SC, respectively. Midnight Kentucky bluegrass and Falcon V tall fescue samples were taken as plugs from research farms located at the University of Arkansas, Fayetteville, AR and Mississippi State University, Starkville, MS. Fiesta 4 perennial ryegrass was grown from seed planted at a rate of 391 kg ha^{-1}.

Warm-season grasses included ‘MSB-285’ (experimental cultivar), ‘Latitude 36’ (Yu, 2014), ‘TifEagle’ (Hanna and Elsner, 1999), and ‘Tifway’ (Burton, 1966) hybrid bermudagrasses (*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy) and ‘Meyer’ (Hanson, 1966) zoysiagrass (*Zoysia japonica* Steud.). All warm-season grasses were taken as plugs from Mississippi State University Rodney R. Foil Plant Science Research Center, near Starkville, MS.

All grass samples were placed in 15.2 cm diameter pots and grown in a greenhouse for approximately two months before moving into lysimeters. Upon moving into lysimeters, the roots were removed, and the plug was cut to fit into the lysimeter. Samples were then grown in PVC [poly(vinyl chloride)] lysimeters measuring 10 cm in diameter and 41 cm deep, allowing for a grass plug with an area of 78.5 cm^2. Grass samples were grown in a 3:1 sand to native topsoil mix. This soil mixture is classified as a sandy loam (87% sand, 2% clay, and 11% silt) with 500 g of gravel at the bottom of

each lysimeter. Each lysimeter had a hole drilled in the bottom to allow for drainage. Five units were designated for the cool-season grasses and five were designated for the warm-season grasses. In each SPAR unit, 30 lysimeters (six replications of each turfgrass) were arranged in a completely randomized design in three rows with ten lysimeters in each row. Prior to initiating temperature treatments, grasses were maintained at a day/night temperature regime of 26/18°C for the cool-season grasses and 30/22°C for the warm-season grasses for two to allow for acclimation. After the initiation of temperature treatments, each of the ten SPAR units was maintained at a different 12 h day/night temperature regime. Day/night temperature regimes for the cool-season units were 18/10, 22/14, 26/18, 30/22, and 34/26°C. Day/night temperature regimes for the warm-season units were 20/12, 25/17, 30/22, 35/27, and 40/32°C (Table 2.1). Penn A1/A4, Penncross, and TifEagle were maintained at 1.27 cm, Latitude 36, MSB-285, and Tifway were maintained at 1.9 cm, Midnight, and Fiesta 4 were maintained at 2.5 cm, and Falcon V and Meyer were maintained at 3.8 cm. Irrigation was provided three times per day at 07:00, 12:00, and 17:00 h using a half-strength Hoagland's nutrient solution (Hewitt, 1952) through an automated and computer-controlled drip irrigation system. Use of Hoagland's nutrient solution is standard for projects conducted in the SPAR units and allowed for nutrient levels to be maintained at optimum without additional monitoring. All SPAR units were maintained at a CO_2 level of 400 μmol mol^{-1} by a dedicated infrared model LI-6252 (LI-COR Biosciences, Lincoln, NE) gas analyzer. No additional pesticide or fertilizer applications were necessary.

Data Collection

Clipping yield (g m^{-2}) was collected every three days using scissors and a PVC guard cut to desired height. The collected clippings were dried in a forced air oven (Blue M, Blue Island, IL) at 75 °C for at least 48 hours and then weighed.

Relative chlorophyll index (RCI) (0-999) was recorded using a FieldScout CM 1000 (Spectrum Technologies Inc., Aurora, IL) chlorophyll meter once per week two days after clippings were collected for the duration of the experiment. The CM 1000 chlorophyll meter wave bands are red-edge (700 nm) and near infrared (840 nm), and receptors include four photodiodes, two for ambient light and two for reflected light from the sample. Relative chlorophyll index was related to the model: Index = [(S840/A840)/(S700/A700)]*1000 where S = sensor and A = ambient light (Wait, 2017). One reading per lysimeter was taken by centering the device on the middle of each lysimeter one meter from the top of the lysimeter.

At the conclusion of the trial, the root systems in each lysimeter were separated from the thatch layer and washed by emptying the lysimeters onto wire soil sieves and lightly spraying with a water hose. The washed roots of each plant were collected, oven-dried for at least 48 hours at 75°C, and then weighed (g m^{-2}).

Data Analysis

Lysimeters were placed in a completely randomized design with six replications of each grass allowing for 30 lysimeters within each unit. Clipping yield, RCI, and total root biomass was subjected to least squares regression using SigmaPlot (Version 11.0; Systat Software, Inc., San Jose, CA). Base temperature was determined for each grass by extrapolating the quadratic regression line to the x-axis intercept to predict the

temperature at which clipping yield equaled zero. Optimum temperature was determined by predicting the apex of the quadratic regression line. Significance tests of RCI and total root biomass were performed using the GLM procedure in Statistical Analysis System (Version 9.4; SAS Institute Inc., Cary, NC) at a significance level of 0.05. Poor turf quality of the Meyer zoysiagrass samples altered the results of the project; therefore, no results will be reported or discussed.

Results and Discussion

Warm-Season Base and Optimum Temperatures

Base temperatures for each bermudagrass did not vary due to overlapping 95% confidence intervals. Base temperatures for Latitude 36, MSB-285, Tifway, and TifEagle were 13.2, 12.5, 12.7, and 12.6 °C, respectively (Figure 2.1). These base temperatures were consistent with temperatures reported by Youngner (1959) to cause decline in growth of bermudagrasses. Additionally, Lyons (1973) reported that chilling injury to tropical and subtropical plants occur at temperatures below 12°C. It is reasonable to conclude that, in order to avoid injury, bermudagrass ceases growth and induces dormancy before temperatures reach these low temperatures. Base temperatures from this trial were similar to Unruh et al. (1996) as base temperatures across bermudagrass cultivars did not significantly differ; however, the base temperatures determined by Unruh et al. (1996) were 7-10°C lower than the base temperatures determined in this trial. It can be hypothesized that these differences can be explained by the low light levels in the growth chambers when compared to the natural light of the SPAR units.

Using base temperatures reported in this research to calculate GDD can more accurately represent total accumulated GDD, leading to better timed product applications

and occurrence predictions. For example, if GDD accumulation started on 1 March, 2016 in Starkville, MS, >300 accumulated GDD would occur on 22 April, 2016 calculated with a base temperature of 10°C. However, if a base temperature of 13°C was used in calculating base temperature, >300 GDD would occur on 10 May, 2016 (Figure A.1). In this example, if a growth regulator or herbicide application is scheduled for 300 GDD, using the wrong base temperature can mistime the application by 18 calendar days.

Optimum temperatures for Latitude 36, Tifway, and TifEagle were 36.1, 32.1, and 31.8 °C, respectively. For MSB-285, the SPAR units did not maintain a temperature high enough to cause a reduction in clipping yield. As a result of this, the optimum temperature for MSB-285 was well above the normal range of optimum temperatures given for bermudagrass and is not reported. It can be hypothesized that the excess amount of top growth from MSB-285, regardless of temperature, is attributed to its increased amount of shoot density and upright growth habit (Liu, 2014). However, Latitude 36, Tifway, and TifEagle were within the optimum range for C_4 photosynthesis of 30 to 40°C (Dudeck and Peacock, 1992). Future research is warranted to use these determined optimum temperatures in modeling growth potential for each grass.

Cool-Season Base and Optimum Temperatures

The SPAR units did not maintain a low enough temperature to cause a consistent decline in top growth from Penn A1/A4, Penncross, Midnight, Fiesta 4, and Falcon V, and because of this, the R-squared values from the graphs were poor. R-squared values represent the amount correlation between clipping yield and temperature treatment. Since there was not an acceptable correlation between clipping yield and base temperature, base

temperatures for Penn A1/A4, Penncross, Midnight, Fiesta 4 and Falcon V cannot be reported confidently.

The determined optimum temperatures for Penn A1/A4, Penncross, Midnight, Fiesta 4, and Falcon V are 18.8, 20.1, 19.0, 19.4, and 20.6°C, respectively. The optimum temperatures are reported, unlike the base temperatures, because optimum temperatures fell on the regression line; thus, the regression line did not have to be extrapolated to determine an optimum temperature (Figure 2.2). These optimum temperatures match the range reported by Baker and Jung (1986), who determined the ideal temperature range for top growth of cool-season grasses is between 18.3 and 21.6°C. Similar to warm-season grasses, future research is needed to utilize these optimum temperatures in growth potential models.

Relative Chlorophyll Index

TifEagle was the only bermudagrass cultivar that showed no interaction between temperature and RCI. Because of this, an optimum temperature of RCI for TifEagle could not be determined. Optimum temperature for RCI in Tifway and MSB-285 are 25.8 and 30.1°C, respectively (Figure 2.3). Due to an unexplainable low response in RCI for Latitude 36 at the 30/22°C temperature treatment, the optimum temperature for RCI of Latitude 36 cannot be presented confidently; however, the response of temperature and RCI was similar to that of Tifway. The optimum temperatures for RCI in Tifway and MSB-285 are lower than the optimum temperatures for top growth of those cultivars. It can be hypothesized that at temperatures below optimum for shoot growth, the grasses

are still producing chlorophyll at a similar rate; however, the grasses are not producing as much leaf tissue so the chlorophyll content is more concentrated.

There was no significant change in RCI of cool-season grasses due to temperature. Because there is no change in RCI due to temperature, the regression analysis lines are relatively flat and an optimum chlorophyll temperature cannot be predicted (Figure 2.4). It can be assumed that this response is similar to the response in the clipping yield of the cool-season species in that the SPAR units did not maintain a temperature cold enough to cause a reduction in RCI in the cool-season grasses.

Total Root Biomass

For all bermudagrass cultivars, the total root biomass declined as temperatures increased (Figure 2.5). By using the slope of the linear regression line, the rate of decline in root growth was able to be determined. Total root biomass of Latitude 36, Tifway, MSB-285, and TifEagle declined by 4.1, 4.2, 2.4, and 1.7 g m^{-2} for every 1°C increase in temperature, respectively.

For cool-season grasses, similar result were shown as total root biomass declined as temperatures increased (Figure 2.6). Total root biomass for Penn A1/A4, Penncross, Midnight, Fiesta 4, and Falcon V declined by 6.1, 2.7, 3.3, 3.6, 7.0 g m^{-2} for every 1°C increase in temperature.

For all cool- and warm-season grasses, there was more root biomass at the lowest temperature treatment when compared to the highest temperature treatment. Similar results have been discussed by Reddy et al. (1994), Huang and Gao (2010), and Forbes (1997) in that temperatures favoring shoot growth leads to a decline in root production.

Reddy et al. (1994) determined the optimum temperature for root growth in cotton (*Gossypium hirsutum* L.) was 22.7°C, and at temperature above 22.7°C, root growth depended on how temperature affected the competition for assimilates between the root and shoot. Huang and Gao (2010) determined that root dry weight of creeping bentgrass decreased when exposed to higher temperatures and concluded that higher temperatures cause an imbalance of photosynthesis and respiration causing a reduction in carbohydrate availability, thus leading to a reduction in root mass. It can be hypothesized that the same type of interaction occurred in our study which caused the reduction of root growth at higher temperatures.

Conclusion

By using the base temperatures of bermudagrass and perennial ryegrass determined in this trial, an accurate calculation of GDD can be made. With the ability to more accurately calculate accumulated GDD, turfgrass managers will be able to better determine when to apply growth regulators and herbicides, and predict when weed emergence and disease outbreak will occur. Scientists will also be able adequately research various GDD models for easier and more efficient use in the turfgrass industry. Because the base temperature of creeping bentgrass, Kentucky bluegrass, perennial ryegrass, tall fescue, and zoysiagrass were unable to be determined, future research is needed to determine base temperatures of these species along with other species used in the turfgrass industry. Additional turfgrass research using the SPAR units may also investigate the effects of other environmental factors individually or including temperature. Future research can also investigate nutrient uptake and carbohydrate

storage in turfgrass roots as a response to temperature to better explain the results discussed in this study.

Table 2.1 The set day/night temperature treatments (°C) and the measured day, night, and average temperatures (°C) for each SPAR unit

	Day/night temperature treatments	Measured Temperature		
		Day	Night	Average
Cool-season	18/10	18.1 ± .07[†]	10.8 ± .04	15.0 ± .05
	22/14	21.9 ± .06	14.4 ± .03	18.7 ± .04
	26/18	25.4 ± .06	17.9 ± .04	22.2 ± .05
	30/22	29.4 ± .06	21.8 ± .04	26.1 ± .04
	34/26	32.8 ± .06	25.3 ± .05	29.6 ± .04
Warm-season	20/12	20.1 ± .06	12.6 ± .03	16.9 ± .04
	25/17	24.8 ± .07	17.2 ± .04	21.5 ± .05
	30/22	29.2 ± .08	21.6 ± .04	25.9 ± .06
	35/27	33.5 ± .12	26.0 ± .05	30.3 ± .07
	40/32	38.1 ± .12	30.6 ± .13	34.9 ± .12

[†] Mean ± standard error of maintained temperature during the experimental period.

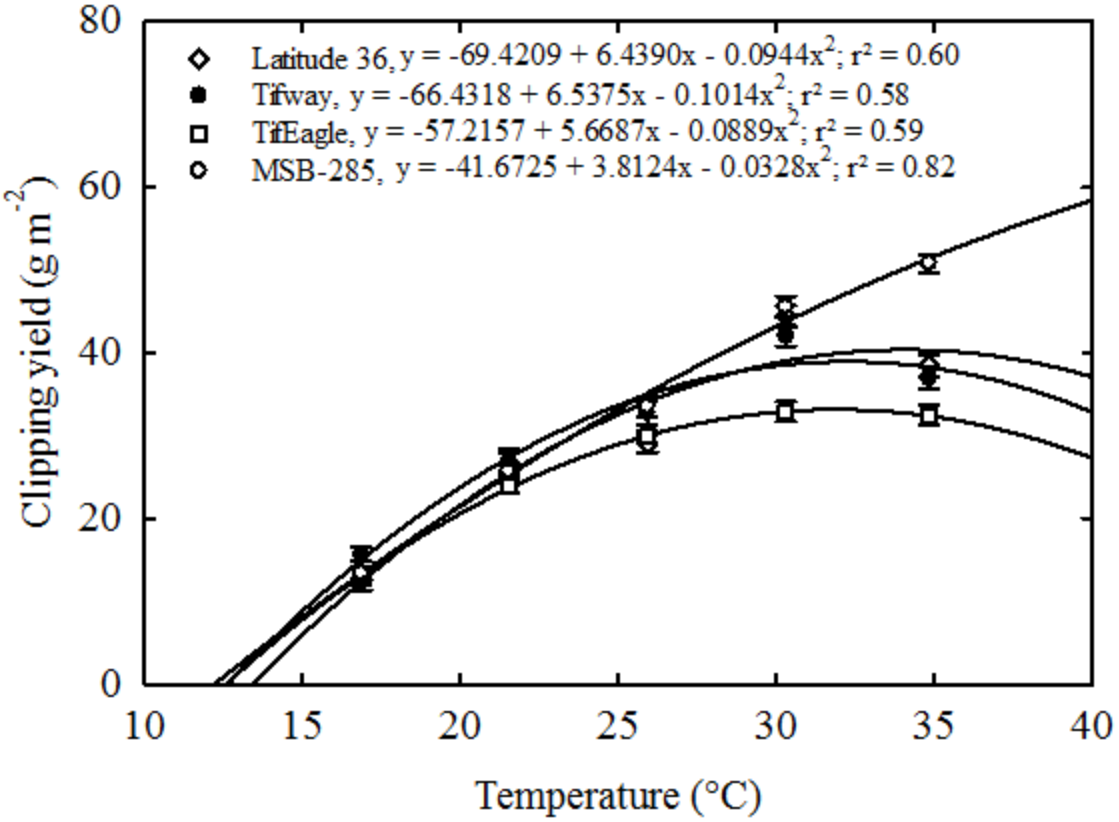

Figure 2.4 Quadratic least squares regression line relating clipping yield (g m^{-2}; y-axis) of warm-season turfgrass to temperature (x-axis).

Each point represents a mean of 36 clipping collections for each temperature treatment.

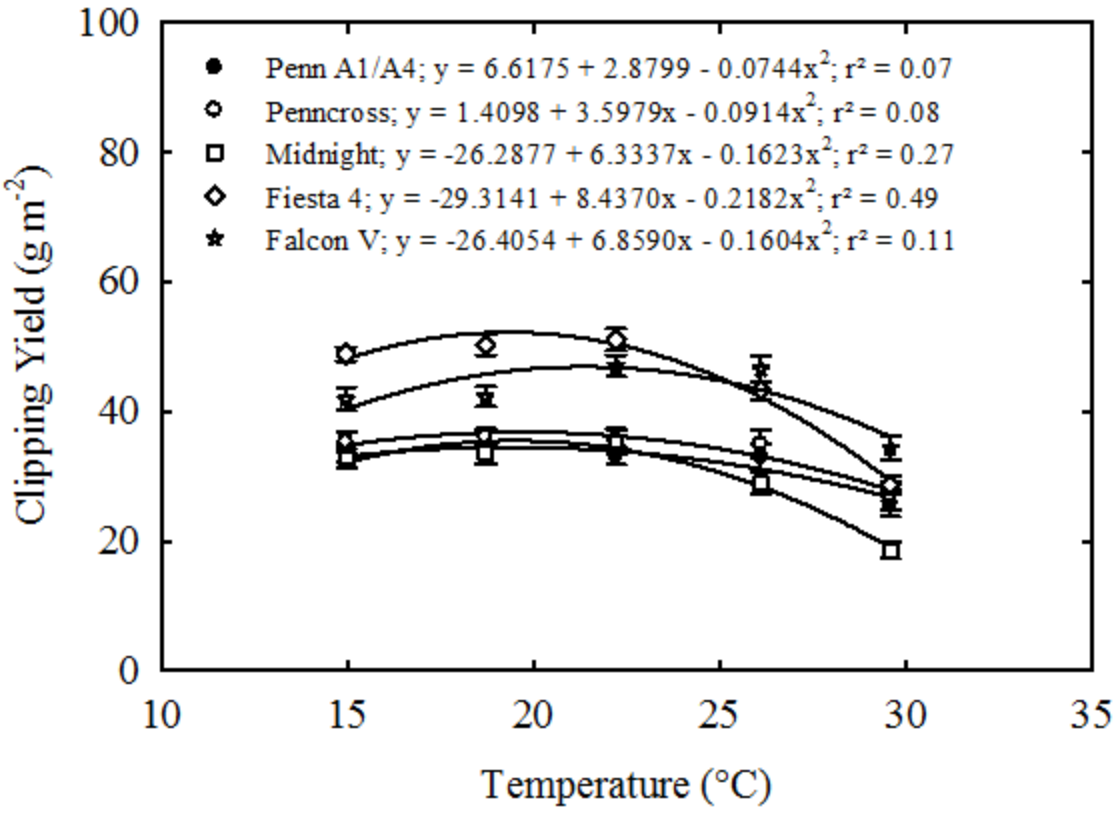

Figure 2.5 Quadratic least squares regression line relating clipping yield (g m^{-2}; y-axis) of cool-season turfgrass to temperature (x-axis).

Each point represents a mean of 36 clipping collections for each temperature treatment.

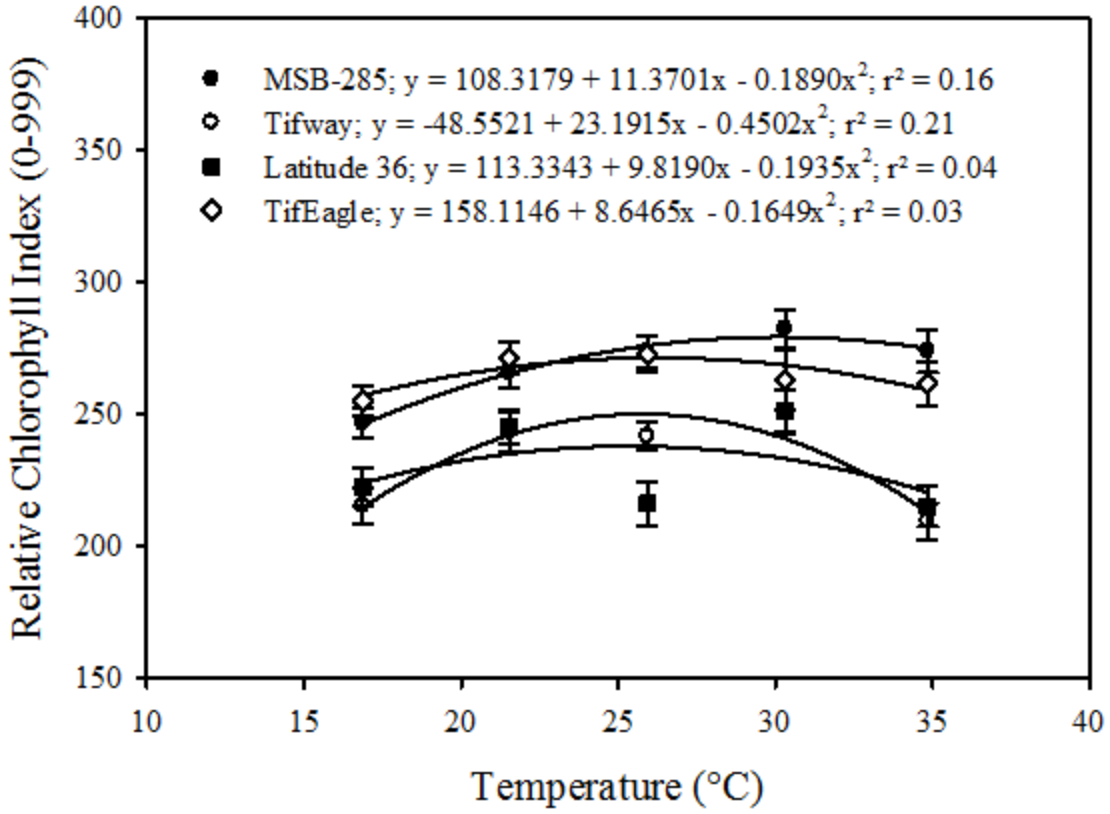

Figure 2.6 Quadratic least squares regression line relating relative chlorophyll index (0-999; y-axis) of warm-season turfgrass to temperature (x-axis).

Each point represents a mean of 18 RCI collections for each temperature treatment.

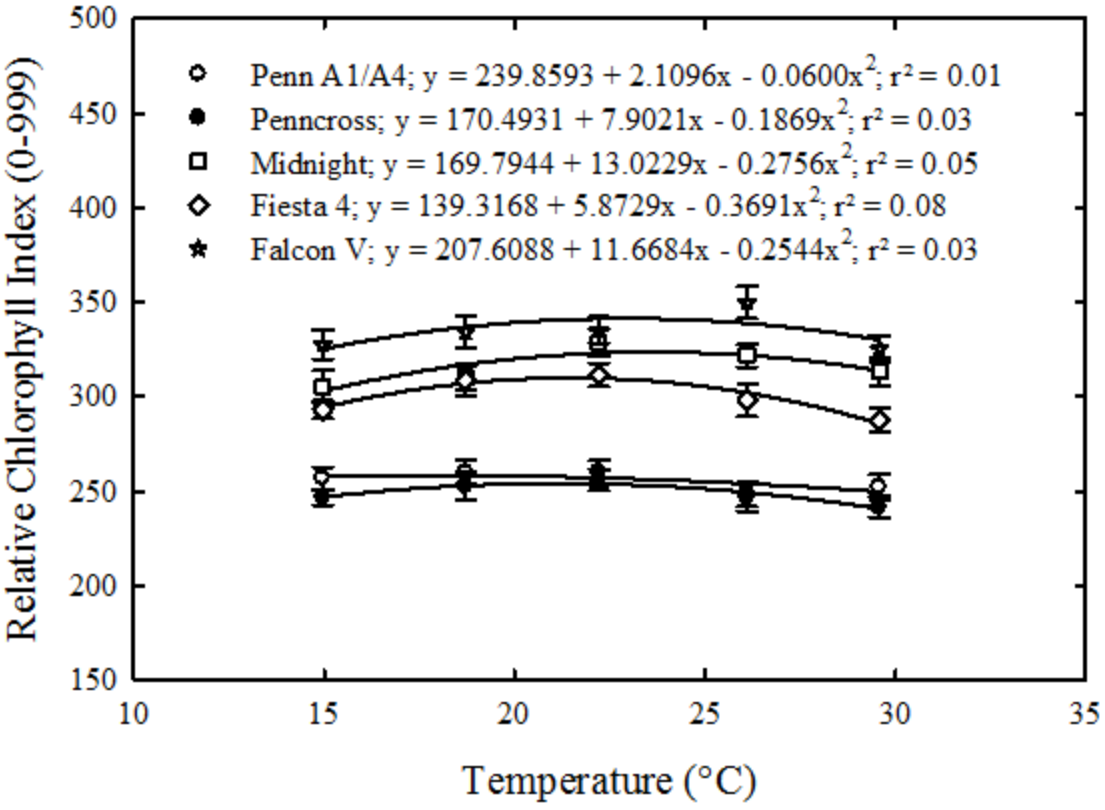

Figure 2.8 Quadratic least squares regression line relating relative chlorophyll index (0-999; y-axis) of cool-season turfgrass to temperature (x-axis).

Each point represents a mean of 18 RCI collections for each temperature treatment.

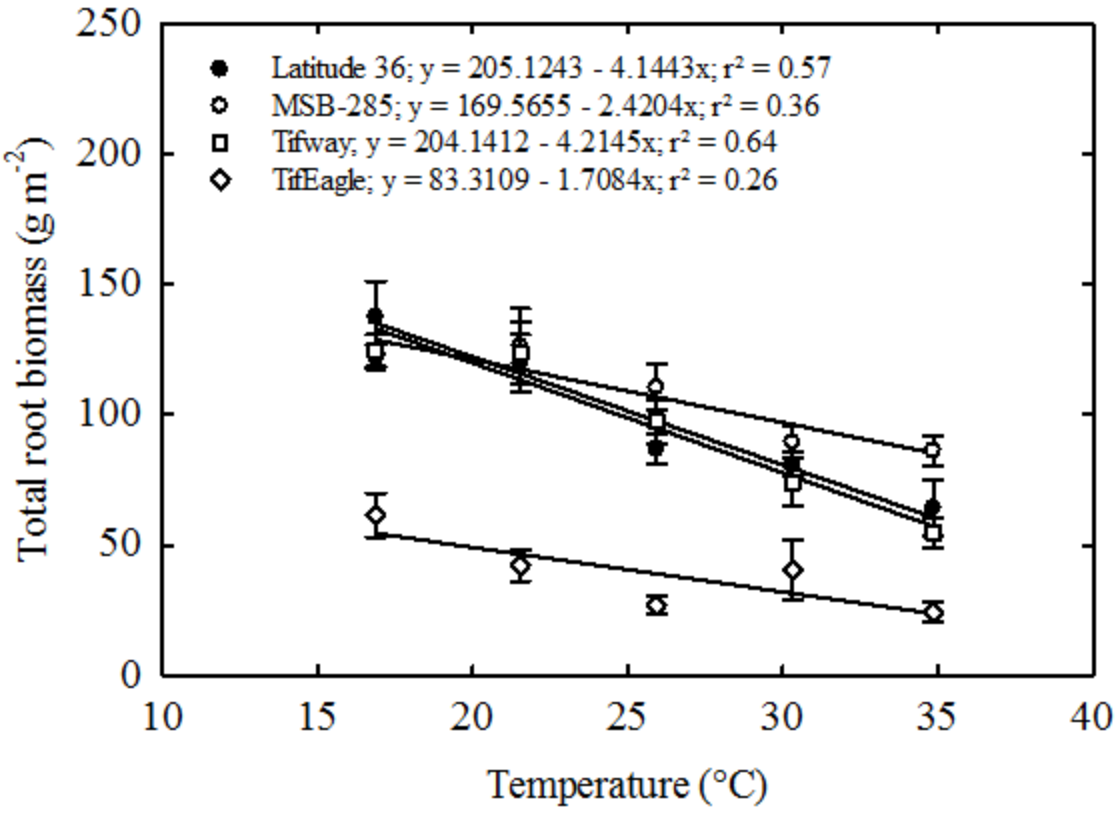

Figure 2.10 Linear least squares regression line relating total root biomass (g m^{-2}; y-axis) of warm-season turfgrass to temperature (x-axis).

Each point represents a mean of 6 root masses collected for each temperature treatment.

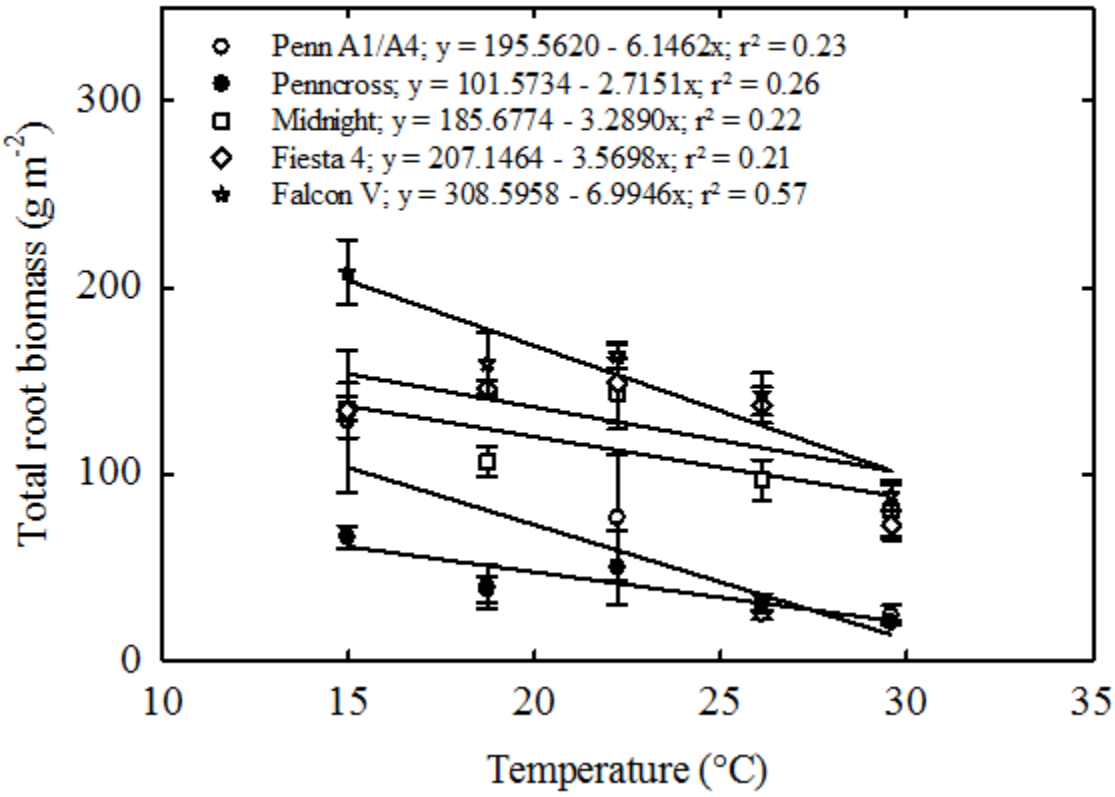

Figure 2.11 Linear least squares regression line relating Total Root Biomass (g m^{-2}; y-axis) of cool-season turfgrass to temperature (x-axis).

Each point represents a mean of 6 root masses collected for each temperature treatment.

References

Baker, B.S. and G.A. Jung. 1968. Effect of environmental conditions on the growth of four perennial grasses. I. Response to controlled temperature. Agron. J. 60(2):155-158.

Baldwin, C.M., H. Liu, L.B. McCarty, H. Luo, C.E. Wells, and J.E. Toler. 2009. Impacts of altered light spectral quality on warm season turfgrass growth under greenhouse conditions. Crop Sci. 49(4):1444-1453.

Beard, J.B. 2002. Turf management for golf courses. Ann Arbor Press, Chelsea, MI.

Bonhomme, R. 2000. Bases and limits to using 'degree.day' units. Euro. J. of Agron. 13:1-10.

Brosnan, J.T., G. K. Breeden, and M.T. Elmore. 2010. Early and late postemergence control of Dallisgrass in tall fescue. Online. Applied Turfgrass Science. DOI 10.1094/ATS-2010-0312-02-RS.

Brown, E.M. 1939. Some effects of temperature on the growth and chemical composition of certain pasture grasses. Mo. Agr. Exp. Sta. Res. Bull. 299.

Burton, G.W. 1966. Tifway (Tifton 419) Bermudagrass. Crop Sci. 6:93-94.

Carroll, J.C. 1943. Effects of drought, temperature, and nitrogen on turf grasses. Plant physiol. 18:19-36.

Danneberger, T.K., B.E. Branham, and J.M. Vargas Jr. 1987. Mefluide applications for annual bluegrass seedhead suppression based on a growing degree-day accumulation. Agron. J. 79:69-71.

DiPaola, J.M. and J.B. Beard. 1992. Physiological effects of temperature stress. p. 231-267. In D.V. Waddington et al. (ed.) Turfgrass. Agron. Monogr. 32. ASA, CSSA, and SSSA, Madison, WI.

Dudeck, A.E. and C.H. Peacock. Shade and turfgrass culture. p. 269-284. In D.V. Waddington et al. (ed.) Turfgrass. Agron. Monogr. 32. ASA, CSSA, and SSSA, Madison, WI.

Ebdon, J.S., R.A. Gagne, and R.C. Manley. 2002. Comparative cold tolerance in diverse turf quality genotypes of perennial ryegrass. HortScience 37(5):826-830.

Forbes, P.J., K.E. Black, and J.E. Hooker. 1997. Temperature-induced alteration to root longevity in *Lolium perenne*. Plant and Soil 190:87-90.

Gitelson, A. A., Y. Gritz, and M. N. Merzlyak. 2003. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. J. plant phys. 160:271 – 282.

Gusta, L.V., J.D. Butler, C. Rajashekar, and M.J. Burke. 1980. Freezing resistance of perennial turfgrasses. HortScience 15(4):494-496.

Hanna, W.W., and J.E. Elsner. 1999. Registration of 'TifEagle' bermudagrass. Crop Sci. 39:1258.

Hanson, A.A. 1966. Meyer zoysia (Reg. No. 12). Crop Sci. 6(1):99.

Hewitt E.J. 1952. Sand and water culture: methods used in the study of plant nutrition. Technical Communication No. 22, Commonwealth bureau of horticulture and plantation, East Malling, Maidstone. Kent Publishers, Commonwealth agricultural bureau farmham royal, Bucks, England, 187 – 190.

Huang, B. and H. Gao. 2010. Growth and carbohydrate metabolism of creeping bentgrass cultivars in response to increasing temperatures. Crop Sci. 40:1115-1120

Kreuser, W.C. and D.J. Soldat. 2011. A growing degree day model to schedule Trinexapac-ethyl applications on *Agrostis stolonifera* golf putting greens. Crop Sci. 51:2228-2236.

Liu, W. 2014. Development and evaluation of hybrid bermudagrass varieties with cold hardiness for golf course putting greens. M.S. Thesis. Oklahoma State University.

Lyons, J.M. 1973. Chilling injury in plants. Ann. Rev. of Plant Physio. 24:445-466.

Mangiafico, S. S., and K. Guillard. 2007. Cool-season turfgrass color and growth calibrated to leaf nitrogen. Crop Sci. 47:1217 – 1224.

McCarty, L.B. and G. Miller. 2002. Managing bermudagrass turf. Ann Arbor Press, Chelsea, MI.

McCullough, P. 2014. Management practices and prediction models for controlling seedheads on warm-season turfgrasses. USGA TERO. 13:8-9.

McMaster, G.S., and W.W. Wilhelm. 1997. Growing degree-days: one equation, two interpretations. Ag and For. Meteo. 87:291 – 300.

Miller, P., Lanier, W. and Brandt, S., 2001. Using growing degree days to predict plant stages. Ag/Extension Communications Coordinator, Communications Services, Montana State University-Bozeman, Bozeman, MO.

Reddy, K.R., H.F. Hodges, J.J. Read, J.M. McKinion, J.T. Baker, L. Tarpley, and V.R. Reddy. 2001. Soil-Plant-Atmosphere-Research (SPAR) facility: a tool for plant research and modeling. Biotronics 30:27-50.

Reddy, V.R., K.R. Reddy, M.C. Acock, and A. Trent. 1994. Carbon dioxide enrichment and temperature effects on root growth in cotton. Biotronics 23:47-57.

Russelle, M.P., W.W. Wilhelm, R.A. Olson, and J.F. Power. 1984. Growth analysis based on degree days. Crop Sci. 24:28 – 32.

Ryan, P.R., P.H. Dernoeden, and A.P. Grybauskas. 2012. Seasonal development of dollar spot epidemics in six creeping bentgrass cultivars in Maryland. HortScience 47:422-426.

Unruh, J.B., R.E. Gaussoin, and S.C. Wiest. 1996. Basal growth of temperatures and growth rate constants of warm-season turfgrass species. Crop Sci. 36:997-999.

Wait, S.B., B.R. Stewart, C.M. Baldwin, M. Tamaso-Peterson, and J.D. McCurdy. 2017. Water-use characteristics of warm-season putting green cultivars and management practices associated with new putting green genetics. MS Thesis. Mississippi State University.

Wang, J.Y. 1960. A critique of the heat unit approach to plant response studies. Ecology 41(4):785-790.

Wu, Y., D.L. Martin, C.M. Taliaferro, J.A. Anderson, and J.Q. Moss. 2014. Latitude 36 turf bermudagrass. U.S. Patent PP24,271.

Youngner, V.B. 1959. Growth of U-3 bermudagrass under various day and night temperatures and light intensities. Agron. J. 51:557-559.

APPENDIX A

SUPPLEMENTARY MATERIAL

Table A.1 Weather data in Starkville, MS, from 1 March to 10 May 2016 showing accumulated growing degree days calculated with a base temperature of 10°C and 13°C.

Calendar Date	Max Temp	Min Temp	Max Temp	Min Temp	GDD_{10}	Accum GDD_{10}	GDD_{13}	Accum GDD_{13}
	--------°F--------		-------°C--------					
3/1/2016	69	46	20.6	7.8	4.2	4.2	1.2	1.2
3/2/2016	56	37	13.3	2.8	0.0	4.2	0.0	1.2
3/3/2016	48	40	8.9	4.4	0.0	4.2	0.0	1.2
3/4/2016	56	40	13.3	4.4	0.0	4.2	0.0	1.2
3/5/2016	69	36	20.6	2.2	1.4	5.6	0.0	1.2
3/6/2016	69	38	20.6	3.3	1.9	7.5	0.0	1.2
3/7/2016	75	43	23.9	6.1	5.0	12.5	2.0	3.2
3/8/2016	76	50	24.4	10.0	7.2	19.7	4.2	7.4
3/9/2016	78	61	25.6	16.1	10.8	30.6	7.8	15.2
3/10/2016	77	64	25.0	17.8	11.4	41.9	8.4	23.6
3/11/2016	67	63	19.4	17.2	8.3	50.3	5.3	28.9
				…				
4/21/2016	79	60	26.1	15.6	10.8	298.9	7.8	168.1
†4/22/2016	79	58	26.1	14.4	10.3	309.2	7.3	175.3
4/23/2016	79	54	26.1	12.2	9.2	318.3	6.2	181.5
4/24/2016	81	52	27.2	11.1	9.2	327.5	6.2	187.7
4/25/2016	82	58	27.8	14.4	11.1	338.6	8.1	195.8
4/26/2016	83	64	28.3	17.8	13.1	351.7	10.1	205.8
4/27/2016	77	64	25.0	17.8	11.4	363.1	8.4	214.2
				…				
5/2/2016	77	63	25.0	17.2	11.1	420.8	8.1	257.0
5/3/2016	71	55	21.7	12.8	7.2	428.1	4.2	261.2
5/4/2016	76	51	24.4	10.6	7.5	435.6	4.5	265.7
5/5/2016	72	50	22.2	10.0	6.1	441.7	3.1	268.8
5/6/2016	74	47	23.3	8.3	5.8	447.5	2.8	271.7
5/7/2016	82	50	27.8	10.0	8.9	456.4	5.9	277.6
5/8/2016	83	56	28.3	13.3	10.8	467.2	7.8	285.4
5/9/2016	73	64	22.8	17.8	10.3	477.5	7.3	292.7
5/10/2016	85	66	29.4	18.9	14.2	491.7	11.2	303.8

†Highlighted rows show the date of >300 accumulated GDD from 1 March 2016 using a base temperature of 10°C compared to using a base temperature of 13°C.

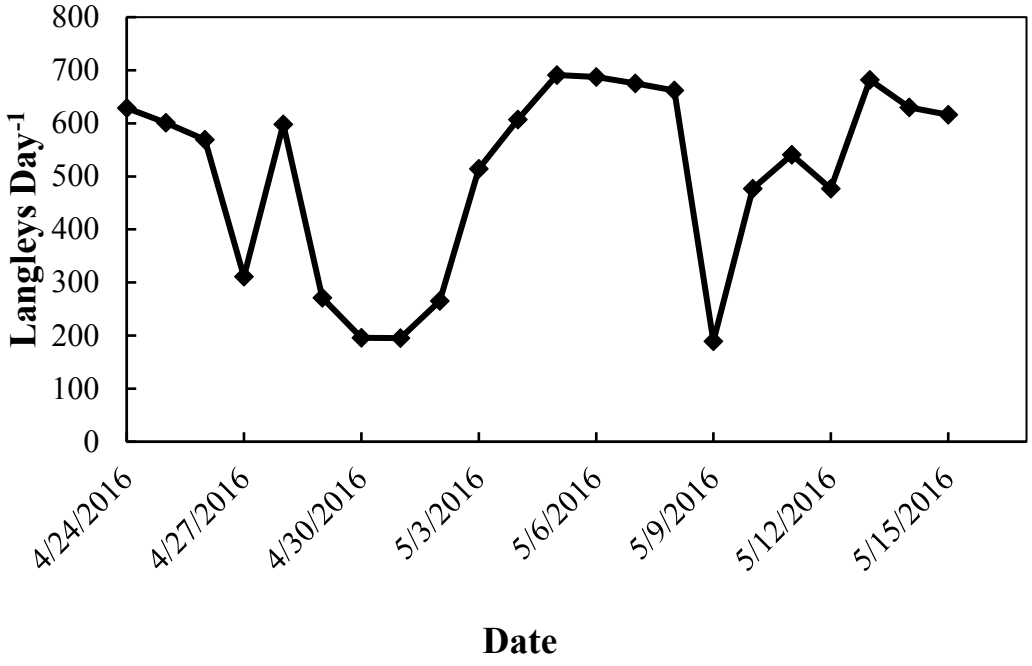

Figure A.1 The amount of solar radiation (Langleys day^{-1}) received in Starkville, MS from 24 April to 15 May 2016.

Dates labeled on the x-axis are the dates of clipping collection.

Figure A.2 Harvesting clippings using scissors and a PVC guard cut to a desired height and the collection of relative chlorophyll index data using the CM 1000 handheld reflectance meter.

Figure A.3 Harvesting roots at the conclusion of the temperature trial.

Figure A.4 Overview of the SPAR facility on the Rodney R. Foil Plant Science Research Center located near Starkville, MS.

Figure A.5 Overview of the acquisition panel and the computer control system in the SPAR control room located in the Environmental Plant Physiology Laboratory at the Rodney R. Foil Plant Science Research Center near Starkville, MS.