5-2023

Methods to Hasten Zoysiagrass Establishment from Sprigs

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Recommended Citation

Carr, Tyler, "Methods to Hasten Zoysiagrass Establishment from Sprigs. " PhD diss., University of Tennessee, 2023.
https://trace.tennessee.edu/utk_graddiss/8089

To the Graduate Council:

I am submitting herewith a dissertation written by Tyler Carr entitled "Methods to Hasten Zoysiagrass Establishment from Sprigs." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Plant, Soil and Environmental Sciences.

John C. Sorochan, Major Professor

We have read this dissertation and recommend its acceptance:

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Accepted for the Council:

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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Methods to Hasten Zoysiagrass Establishment from Sprigs

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Tyler Q. Carr
May 2023

DEDICATION

This dissertation is dedicated to my dog, Brady. While he often expressed discontent that I was writing instead of giving him attention, his unconditional love and support will forever be cherished.

ACKNOWLEDGEMENTS

The completion of this degree would not be possible by myself alone. First, I would like to thank my advisor, Dr. John Sorochan, for allowing this Arkansas kid to pursue a Ph.D. on Rocky Top. His mentorship both professionally and personally has been impactful. I would also like to thank Dr. Jim Brosnan for taking me under his wing to give me experiences in extension that will be valuable for years to come. Additionally, Dr. Brandon Horvath has provided important mentorship and support that was integral to the completion of this degree. Aside from turfgrass science, Dr. Carrie Stephens helped me improve my leadership skills and think about science in a different way. Finally, Dr. Kellie Walters provided valuable plant physiology expertise and was always gracious with her time.

The individuals of The University of Tennessee Turfgrass Team deserve thanks, as they have provided endless support. Specifically, Dr. Kyley Dickson, Taylor Williams, and Rhys Fielder have been great co-workers and friends. I hope to build relationships with more people like them in the future. I would also like to thank the following groups for funding and support: Bladerunner Farms, the Department of Plant Sciences at UT, and UT AgResearch.

My family has always been there to provide emotional support. My mom, dad, and brother have been integral in allowing me to pursue three degrees. Additionally, my grandparents have always been my greatest cheerleaders. I would not be who I am today without these people.

Just as importantly, I would like to thank Tracy Hawk for always being by my side and for providing everlasting love and companionship. Seriously, she deserves an honorary turfgrass degree. My sweet dog of turf, Brady, deserves genuine recognition for being my partner-in-crime and an uplifting spirit.

ABSTRACT

Zoysiagrasses (*Zoysia* spp. Willd.) are commonly used on golf course fairways and tees in addition to residential and commercial lawns due to lower input requirements relative to bermudagrass (*Cynodon* spp.). This has led to increased interest in using zoysiagrass for golf course putting greens; however, zoysiagrass establishment from sprigs is prolonged compared to bermudagrass. A series of experiments were conducted in glasshouses in Knoxville, TN in 2022 to evaluate the effects of environmental conditions and management practices on the establishment of Prizm zoysiagrass from sprigs. To determine the optimal soil temperature for Prizm zoysiagrass establishment, sprigs were exposed to high, medium, and low 5 cm soil temperature treatments, which were imposed via water bath. Over the 49-day study period, the high, medium, and low treatments averaged ~36 °C, ~32 °C, and ~28 °C, respectively. The medium and low treatments averaged 92% turfgrass coverage 49 days after planting (DAP) in run A, which was significantly greater than the high-soil-temperature treatment (70%). In run B, the medium soil temperature achieved 92% turfgrass coverage 44 DAP, which was significantly greater than the low (78%) and high (74%) treatments. Independent of other environmental variables, results from this study imply that an average daily 5 cm soil temperature of approximately 32 °C would likely result in the most rapid establishment of Prizm from sprigs. Another study was conducted to evaluate the effect of irrigation frequency on the establishment of Prizm sprigs. Prizm zoysiagrass was irrigated daily (3 mm) applied via four or 192 events from 06:00 a.m. to 10:00 p.m. In both experimental runs, establishment was unaffected by irrigation frequency and averaged 40% turfgrass coverage after 21.6 and 27.3 days in run A and run B, respectively. Air vapor pressure deficit during the irrigation period averaged 1.05 kPa in run A and 1.57 kPa in run B, respectively, suggesting zoysiagrass sprigs have limited sensitivity to elevated vapor pressure deficit, granted sufficient rootzone moisture is available. These conclusions indicate soil temperature is likely a prominent factor influencing zoysiagrass establishment from sprigs.

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INTRODUCTION

In the United States, managed turfgrass covers the third-most area of any crop, accounting for approximately 20 million ha (Milesi et al., 2005). Of the 20 million ha of managed turfgrass, the 15,121 golf facilities represent over 900,000 ha (Gelernter et al., 2017). While creeping bentgrass (*Agrostis stolonifera* L.) is the predominant turfgrass species on golf course putting greens in the United States, the most widely-used warm-season turfgrass for putting greens in the warm and transitional climatic areas is ultradwarf bermudagrass [(*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* (Burtt Davy)] (Brosnan et al., 2022).

Zoysiagrass (*Zoysia* spp. Willd.) is a warm-season, stoloniferous and rhizomatous, turfgrass that may require fewer inputs than bermudagrass (*Cynodon* spp.). Zoysiagrass has gained recent interest for possible use on golf course putting greens in areas where ultradwarf bermudagrass is used due this potential input reduction. When compared to bermudagrass (*Cynodon* spp.), zoysiagrass has a slower growth rate when used in commercial and residential lawns in addition to golf course fairways and tees (Patton et al., 2017). Busey and Myers (1979) observed daily growth rates of 5% day^{-1} for *Z. japonica* Steud. compared to 9% day^{-1} for common bermudagrass (*C. dactylon*). This reduction in growth rate likely results in reduced mowing inputs.

Zoysiagrasses have enhanced shade tolerance compared to bermudagrass. A fine-textured zoysiagrass cultivar, 'Diamond' [*Zoysia matrella* (L.) Merr.], was released for use on golf course putting greens due to its tolerance to low mowing heights and improved shade tolerance over bermudagrass (Engelke et al., 2002). Yet, maximum ball roll distance for Diamond when maintained at 2.5 mm was 259 cm, which is likely not acceptable for tournament purposes (Radko, 1977; Stiglbauer et al., 2009). More recently, (Carr et al., 2022) evaluated zoysiagrasses ['Lazer' (*Z. matrella* × *Z. minima*), 'M85' (*Z.*

matrella), 'Prizm' (*Z. matrella*), and Trinity (*Z. matrella*)] for putting greens and observed minimum ball roll distance of 300 cm when maintained at 3 mm and received lightweight rolling five times weekly.

While select zoysiagrass cultivars may have comparable ball roll performance relative to ultradwarf bermudagrass, the latter generally has faster establishment from vegetative sprigs compared to zoysiagrass. 'MiniVerde' ultradwarf bermudagrass had faster establishment from sprigs compared to Diamond, achieving 100% turfgrass coverage 7 to 35 days earlier than Diamond (Briscoe et al., 2012). Additionally, Zhang et al. (2021) compared the vegetative establishment of a *Zoysia japonica* (Steud.) cultivar and 'Tifway' hybrid bermudagrass when planted via sprigs during winter dormancy, spring, and summer. The authors reported that bermudagrass reached full coverage within one season, regardless of planting date, whereas only zoysiagrass planted during dormancy reached full coverage by the end of the first growing season. When Prizm zoysiagrass was sprigged at 109 m^3 ha^{-1} throughout spring and summer in Knoxville, TN, in April through June 2020, ≥ 85 days were required to achieve 90% turfgrass coverage; however, plantings in June 2021 achieved 90% turfgrass coverage after ~55 days (Carr et al., 2021).

Ensuring complete establishment within the first growing season is important to ensure putting green playability throughout the subsequent winter and spring months; however, prolonged establishment also extends course closure, which results in decreased revenue while golf course maintenance and expenditures continue. In attempt to accelerate the establishment of zoysiagrass from sprigs, studies have investigated the use of increasing sprigging rate. When establishing Diamond zoysiagrass from sprigs, Stiglbauer et al. (2009) reported 90% turfgrass coverage 42 to 49 days after planting (DAP) when sprigging at 182 m^3 ha^{-1} compared to 70 to 77 DAP at 81 m^3 ha^{-1}. *Z. japonica* has also demonstrated quicker establishment when planted at 60 or 90 m^3 ha^{-1} in spring or summer, achieving 90% turfgrass coverage ~25 to 40 days earlier than sprigging at 30 m^3 ha^{-1} (Zhang et al., 2021). In addition to increasing sprigging rate to hasten establishment, previous research has attempted to increase nitrogen (N) rates during the establishment phase to promote rapid establishment.

While elevated N rates have produced variable results on bermudagrass establishment, the response of zoysiagrasses to increased N has had limited success in accelerating establishment. Carroll et al. (1997) found only a 5 percentage point increase in Meyer zoysiagrass coverage when applying 49 kg ha^{-1} every 4 weeks compared to application only at planting. Richardson and Boyd (2001) sprigged Meyer zoysiagrass at two locations in AR and concluded that applied monthly N rates of 0, 13, 25, 38, or 50 kg ha^{-1} had no practical effect on establishment. In addition, Stiglbauer et al. (2009) established Diamond zoysiagrass under various N rates and sources and reported no establishment rate differences between weekly N applications of 17 and 34 kg ha^{-1}, regardless of N source. Furthermore, Briscoe et al. (2012) found no differences in Diamond establishment among weekly N rates of 12 and 24 kg ha^{-1}. In addition to N fertilization, applying phosphorus during zoysiagrass establishment from sprigs has accelerated establishment relative to areas not treated with phosphorus (Briscoe et al., 2012; Carr et al., 2021). Aside from fertilizer applications, sprigging during the warmest period for a given location may hasten establishment.

Typically, planting warm-season turfgrasses occurs in the late spring or early summer months when soil temperatures are conducive for growth (Johnson & Thompson, 1961). Henry et al. (1988) established ‘El Toro’ (*Z. japonica*) from sprigs or plugs in southern California and observed complete establishment after three to four months when planting in June compared to nine and 11 months when planting occurred in September and the following March, respectively. In Indiana and Kentucky, ‘Zenith’ zoysiagrass (*Z.*

japonica) established fastest when seeded from 1 June to 15 June, whereas seedings occurring after 1 July did not reach 95% coverage in the same growing season (Patton et al., 2004). Similarly, planting ‘Shadow Turf’ (*Z. matrella*) from vegetative plugs in June and July led to faster initial establishment than May plantings; however, planting in May resulted in the greatest turfgrass coverage at the end of the study (Sladek et al., 2011). Previous research has focused on planting sprigs during the summer months which offer variable soil temperatures dependent on geographic location; however, zoysiagrass is used in the subtropical and transition climates in the United States where maximum average soil temperatures are dependent on location and vary from ~27 °C to ~35 °C (GreenCast, 2022). Due to differences in soil temperature, certain geographic locations may provide environments more conducive for rapid zoysiagrass establishment from sprigs. When combined with an appropriate planting date, improved management practices during the establishment phase may promote hastened establishment.

Adequate irrigation is necessary to limit sprig desiccation during establishment because of limited root development, as roots are responsible for water absorption and uptake in plants (Taiz & Zeiger, 2002). Moreover, irrigation is generally recommended to ensure sprigs and surrounding soil remain moist following planting (Beasley et al., 2019; SFMA, 2022). Moist sprigs may be difficult to maintain since increases in temperature, wind, and solar radiation in addition to reductions in relative humidity can decrease available moisture (Huang, 2008). Therefore, frequent irrigation events may be necessary to limit evapotranspiration.

When propagating horticultural cuttings, intermittent mist systems are routinely employed, which involve frequent applications of small water droplets to reduce leaf and air temperature while increasing relative humidity (Hartmann et al., 2011). This reduction in temperature and increase in relative humidity from intermittent mist reduces the vapor pressure deficit (VPD), subsequently reducing leaf transpiration (Hess & Snyder, 1955). Reducing VPD allows propagules to maintain cell turgor in the absence of functional roots and preserve cell competence to form roots (Hartmann et al., 2011). In mature warm-season turfgrasses, a linear relationship exists between increasing VPD and transpiration (Wherley & Sinclair, 2009). Reduced rooting from increasing VPD has been observed in loblolly pine (*Pinus taeda* L.) stem cuttings, which may also be applicable to zoysiagrass sprigs during establishment (LeBude et al., 2005).

To minimize transpiration during cutting propagation, maintaining a low VPD of < 0.5 kPa is generally recommended for most horticultural dicotyledon species (Grange & Loach, 1983). A VPD of 0.5 kPa requires high relative humidity ranging from 75% to 85% with temperatures 17 °C to 26 °C, and may be difficult to achieve in areas with zoysiagrass adaptation since average summer maximum daily temperatures are frequently ≥ 29 °C (Arguez et al., 2010). Additionally, the high irradiance conditions in outdoor environments where sprigs are planted may inhibit establishment of propagules, as leafy pea (*Pisum sativum* L.) cuttings have demonstrated desiccation when exposed to elevated light levels (≥ 350 µmol m^{-2} s^{-1}) for at least 3 hours (Davis & Potter, 1981). It is currently unknown if the application of intermittent mist during the propagation phase of turfgrass from vegetative sprigs will reduce VPD to an extent that establishment is accelerated compared to less frequent irrigation regimes.

Currently, no optimal soil temperature has been reported for vegetative establishment of warm-season turfgrasses. Additionally, there is no research pertaining to the effect of irrigation practices on turfgrass establishment from sprigs. Since zoysiagrass sprigs and horticultural cuttings are both vegetative propagules, irrigating via intermittent mist may result in increased sprig survival and accelerated establishment. Sprigging zoysiagrass at an optimal soil temperature and under ideal irrigation regimes may hasten establishment and reduce economic losses from course closure; therefore, the objectives of this research were to:

1) Determine the effect of soil temperature on Prizm zoysiagrass establishment.
2) Evaluate the effect of irrigation frequency on establishment of Prizm zoysiagrass sprigs.

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CHAPTER I

IMPACT OF SOIL TEMPERATURE ON PRIZM ZOYSIAGRASS ESTABLISHMENT FROM SPRIGS

A version of this chapter was originally published 27 September 2022 by Tyler Q. Carr, John C. Sorochan, James T. Brosnan, and Brandon J. Horvath:

Carr, T. Q., Sorochan, J. C., Brosnan, J. T., & Horvath, B. J. (2022). Impact of soil temperature on Prizm zoysiagrass establishment from sprigs. *Agronomy, 12*(10), 2329. https://doi.org/10.3390/agronomy12102329

The publishing of this article involved an extensive peer-review process that improved the quality of the manuscript. The publishing of this article involved four authors from The University of Tennessee Department of Plant Sciences. All authors made conceptual or technical contributions relative to their area of expertise. My primary contributions to this paper include (i) conceptualization, (ii) experimental design, (iii) investigation, (iv) data analysis, (v) writing.

ABSTRACT

Zoysiagrasses (*Zoysia* spp. Willd.) are commonly used on golf course fairways and tees in addition to residential and commercial lawns due to lower input requirements relative to bermudagrass (*Cynodon* spp.). This has led to increased interest in using zoysiagrass for golf course putting greens; however, zoysiagrass establishment from sprigs is prolonged compared to bermudagrass. Research was conducted in Knoxville, TN to determine the effect of soil temperature on 'Prizm' zoysiagrass establishment from sprigs. The study was conducted over replicate experimental runs in separate glasshouses in 2022. Prizm zoysiagrass was exposed to high, medium, and low 5 cm soil temperature treatments, which were imposed via water bath. Over the 49-day study period, the high, medium, and low treatments averaged ~36 °C, ~32 °C, and ~28 °C, respectively. The medium and low treatments averaged 92% turfgrass coverage 49 days after planting (DAP) in run A, which was significantly greater than the high-soil-temperature treatment (70%). In run B, the medium soil temperature achieved 92% turfgrass coverage 44 DAP, which was significantly greater than the low (78%) and high (74%) treatments. Independent of other environmental variables, results from this study imply that an average daily 5 cm soil temperature of approximately 32 °C would likely result in the most rapid establishment of Prizm zoysiagrass from sprigs.

INTRODUCTION

Zoysiagrass (*Zoysia* spp. Willd.) is a warm-season, perennial turfgrass that is both stoloniferous and rhizomatous. This species is commonly used in the transition and warm climatic regions of the United States and offers lower input requirements relative to bermudagrass (*Cynodon* spp.) (Patton et al., 2017). However, ultradwarf bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* (Burtt Davy)] is the most widely used warm-season turfgrass for putting greens in areas of the United States where zoysiagrass is adapted (Brosnan et al., 2022).

In 1996, ‘Diamond’ zoysiagrass [*Zoysia matrella* (L.) Merr.] was released for putting green use since it tolerated mowing heights common on putting greens and provided improved shade tolerance relative to bermudagrass (Engelke et al., 2002). Nonetheless, Diamond has demonstrated prolonged establishment when planted from vegetative sprigs compared to ultradwarf bermudagrass. Briscoe et al. (2012) evaluated the establishment of ‘MiniVerde’ ultradwarf bermudagrass and Diamond zoysiagrass from sprigs in the transition zone and concluded that MiniVerde achieved 100% coverage 7 to 35 days earlier than Diamond. Additionally, (Zhang et al., 2021) compared the vegetative establishment of a *Zoysia japonica* (Steud.) cultivar and ‘Tifway’ hybrid bermudagrass when planted via sprigs during winter dormancy, spring, and summer. The authors reported that bermudagrass reached full coverage within one season, regardless of planting date, whereas only zoysiagrass planted during dormancy reached full coverage by the end of the first growing season in Arkansas. When ‘Prizm’ zoysiagrass, a recently released *Z. matrella* cultivar (Doguet et al., 2017), was sprigged at 109 m^3 ha^{-1} throughout spring and summer in Knoxville, TN, plantings in April through June 2020 required ≥85 days to achieve 90% turfgrass coverage; however, plantings in June 2021 achieved 90% turfgrass coverage after ~55 days (Carr et al., 2021).

Ensuring complete establishment within the first growing season is important to ensure playability throughout the subsequent winter and spring months; however, prolonged establishment also extends course closure, which results in decreased revenue, while golf course maintenance and expenditures continue. Previous research has demonstrated accelerated zoysiagrass establishment from sprigs when increasing sprigging rate (Stiglbauer et al., 2009; Zhang et al., 2021), but increasing nitrogen fertilization had limited effect in hastening establishment (Briscoe et al., 2012; Carroll et al., 1997; Richardson & Boyd, 2001; Stiglbauer et al., 2009).

Typically, warm-season turfgrasses are planted in the late spring or early summer months when soil temperatures are conducive for growth (Johnson & Thompson, 1961). Henry et al. (1988) established ‘El Toro’ (*Z. japonica*) from sprigs or plugs in southern California and observed complete establishment after 3 to 4 months when planting in June compared to 9 and 11 months when planting occurred in September and the following March, respectively. In Indiana and Kentucky, ‘Zenith’ zoysiagrass (*Z. japonica*) established fastest when seeded from 1 June to 15 June, whereas seedings occurring after 1 July did not reach 95% coverage in the same growing season (Patton et al., 2004). Similarly, planting ‘Shadow Turf’ (*Z. matrella*) from vegetative plugs in June and July led to faster initial establishment than May plantings; nonetheless, planting in May resulted in the greatest turfgrass coverage at the end of the study (Sladek et al., 2011).

Previous research has focused on planting sprigs during the summer months; however, zoysiagrass is well adapted to the subtropical and transition climates in the United States where maximum average soil temperatures are dependent on location and vary from ~27 °C to ~35 °C (GreenCast, 2022). Due to differences in soil temperature, varying geographic locations may provide environments more conducive for rapid zoysiagrass establishment from sprigs.

Currently, no optimal soil temperature has been reported for vegetative establishment of warm-season turfgrasses. Planting zoysiagrass sprigs when soil temperatures are optimal may hasten establishment and reduce economic losses from course closure; therefore, the objective of this research was to determine the effect of soil temperature on Prizm zoysiagrass establishment. It was hypothesized that increasing soil temperature would accelerate establishment of Prizm zoysiagrass sprigs.

MATERIALS AND METHODS

Research Site Management and Treatment Description

This study was conducted in glasshouses at The University of Tennessee (Knoxville, TN, USA) in 2022. Each experimental unit comprised of a 7.6-L bucket (United Solutions, Leominster, MA, USA) with a height of 20 cm and inside diameters at the top and bottom of the bucket of 23 cm and 20 cm, respectively. Each experimental unit was filled with an 80:20 (*v*:*v*) mixture of silica sand meeting United States Golf Association (USGA) particle size specifications and sphagnum peat moss to achieve a uniform bulk density of 1.6 Mg m^{-3} (USGA, 2018). The root zone initially contained 0.8% organic matter.

Two experimental runs were conducted in separate glasshouses during 2022. Under conditions of natural and supplemental light with a 16/8 h day/night photoperiod (PKB, Arize Element L1000 Next-Gen, Current Lighting Solutions, LLC, Cleveland, OH, USA), the average glasshouse temperature in run A was 26.2 °C and 26.6 °C in run B. Over the 49-day study period, plants received an average of 62.4 and 55.0 mol m^{-2} day^{-1} in runs A and B (SQ-500, Apogee Instruments, Inc., Logan, UT, USA).

Individual experimental units were placed in 37.9 L storage totes (Rugged Tote, Centrex, LLC, Findlay, OH, USA) filled with water to create a water bath to maintain consistent soil temperature (Huang et al., 2001; Xu & Huang, 2000) (Figure 1.1). Treatments included a “high”, “medium”, and “low” 5 cm soil temperature by heating each water bath. To achieve the high soil temperature, two 100 W aquarium heaters (SKU: HGH802, Hygger, Shenzhen Mago Co., Ltd., Shenzhen City, Guangdong Province, China) were placed in each water bath, whereas one aquarium heater was placed in water baths used to impose the medium-soil-temperature treatment. The low-soil-temperature treatment was imposed by filling baths with water devoid of an aquarium heater. In one replication within each glasshouse, the 5 cm soil temperature was recorded with an external temperature sensor (Item #3667-20, Spectrum Technologies, Aurora, IL, USA), and was logged at fifteen-minute intervals with a WatchDog 1000 Series Micro Station (Item #3688WD1, Spectrum Technologies, Aurora, IL, USA). Additionally, 5 cm soil temperature was monitored daily in each experimental unit using digital soil thermometers (#6300; Spectrum Technologies Inc., Aurora, IL, USA). The average 5 cm soil temperature for the high, medium, and low treatments were 36.6 °C, 32.1 °C, and 28.6 °C, respectively, in run A and 36.2 °C, 31.9 °C, and 27.9 °C, respectively, in run B (Figure 1.2). Water levels were maintained at the top edge of the water bath during each experimental run.

On 13 April 2022, 30.4 g of Prizm zoysiagrass sprigs were planted in each experimental unit, which equated to a sprigging rate of 181 m^3 ha^{-1} using the conversion of 16.6 kg sprigs m^{-3} (D. Doguet, personal communication, 31 March 2022). A companion study revealed a significant positive correlation (*P* < 0.0001; r = 0.99; GraphPad Prism v. 9.4. GraphPad Software Inc., La Jolla, CA, USA) between increasing sprig material mass and increasing sprig node number. This relationship was used to determine that experimental units in this study were established at approximately 16,146 nodes m^{-2} (Figure S1.1). Sprigs were planted directly on the surface followed by sand topdressing applied to a depth of 3.2 mm. Over the first 14 days after planting, irrigation was delivered 12 times daily, totaling 7 mm d^{-1}. Beginning 14 days after planting through the conclusion of the study, irrigation was applied four times daily, totaling 5 mm d^{-1}. Prior to planting and every two weeks throughout the duration of the experiments, 2.5 g N m^{-2} via complete fertilizer (20-20-20) was applied to each individual experimental unit.

Data Collection and Statistical Analysis

To objectively assess temperature effects on Prizm zoysiagrass establishment, turfgrass coverage was estimated weekly using digital image analysis (Richardson et al., 2001). The images collected by the digital camera (Canon PowerShot G12, Canon Inc., Melville, NY, USA) were rectangular, but the experimental area was round; therefore, a purple frame was placed in the images to exclude non-experimental area from each image. The frame analysis procedure in TurfAnalyzer (Karcher et al., 2017; Karcher & Richardson, 2013) was then used to evaluate only the experimental area within each image for turfgrass coverage. For each experimental run, weekly assessments of turfgrass coverage lasted approximately 30 min in duration.

This study was a one-factor randomized complete block design with six replications of each soil temperature treatment. Turfgrass coverage was subjected to repeated measures analysis of variance (ANOVA) and a means separation technique (LSMEANS) in PROC GLIMMIX (SAS v. 9.4, SAS Institute Inc., Cary, NC, USA). For all data, slicing was performed in PROC GLIMMIX to identify evaluation dates (days after planting (DAP)) when treatment effects were significant. Treatment means for significant effects were separated using Fisher's protected LSD ($\alpha = 0.05$). A significant treatment by experimental run interaction was present; therefore, data for each experimental run will be presented individually.

RESULTS AND DISCUSSION

The soil temperature-by-DAP interaction significantly affected turfgrass coverage in both run A ($P < 0.0001$) and run B ($P = 0.0006$; Table 1.1). In run A, turfgrass coverage was significantly affected by soil temperature on the final three evaluation dates (Table 1.2). No differences occurred among treatments until 35 DAP, when the high-soil-temperature treatment resulted in turfgrass coverage values of 48%, 64%, and 70% at 35, 44, and 49 DAP, respectively, which were significantly lower than both the medium and low-soil-temperature treatments. The medium and low-soil-temperature treatments did not significantly differ in turfgrass coverage on any evaluation date, and the treatments averaged 92% turfgrass coverage 49 DAP compared to 70% for the high-soil-temperature treatment.

In run B, the soil temperature-by-DAP interaction significantly affected turfgrass coverage 28, 35, and 44 DAP (Table 1.2). On all three dates, the medium-soil-temperature treatment resulted in significantly greater turfgrass coverage than both the low and high temperature treatments by ≥12 percentage points. The low- and high-soil-temperature treatments did not differ in turfgrass coverage on any evaluation date within run B. On the final evaluation date (49 DAP), all treatments demonstrated similar turfgrass coverage values.

In both experimental runs, 90% turfgrass coverage was achieved ~44 DAP, which is faster than previously reported for Prizm zoysiagrass establishment. Carr et al. (2021) observed 90% turfgrass coverage ≥55 DAP in a field study when the sprigging rate was 109 m^3 ha^{-1}; however, the sprigging rate was 181 m^3 ha^{-1} in the present study. Previous research on Diamond reported accelerated establishment when increasing sprigging rate, with 182 m^3 ha^{-1} achieving 90% turfgrass coverage 42 to 49 DAP compared to 70 to 77 DAP when utilizing a sprigging rate of 91 m^3 ha^{-1} (Stiglbauer et al., 2009). These results denote that increased sprigging rates may be required to reduce establishment duration.

The optimal soil temperature to hasten establishment varied between experimental runs. In run A, the low- and medium-soil-temperature treatments resulted in the fastest establishment of Prizm zoysiagrass, whereas the medium treatment resulted in faster establishment than all other treatments in run B. Increased establishment via the low-temperature treatment in run A may be attributed to increased water bath temperatures beginning 28 DAP (Figure 1.2). According to continuous soil temperature data in run A, 5 cm soil temperatures averaged 27.7 °C during the first 28 DAP but elevated to 29.8 °C from 29 to 49 DAP. While the average ambient air temperature in each experimental run was similar (26.2 °C and 26.6 °C in run A and run B), run A received greater light quantity (62.4 mol m^{-2} day^{-1}) compared to run B (55.0 mol m^{-2} day^{-1}). The increased thermal energy from increased light quantity in run A likely increased the temperature of the water baths used to impose the low-soil-temperature treatment.

Another factor contributing to the accelerated establishment for the low-soil-temperature treatment in run A may be the increased diurnal soil temperature amplitude (i.e., difference between daytime maximum and nighttime minimum 5 cm soil temperatures). Across the entire experimental run, the average diurnal soil temperature amplitude for the low treatment was 5.5 °C, which was numerically greater than all other treatments in runs A and B (Figure 1.2, Table 1.3). Ivory and Whiteman (1978) observed greater growth rates of tropical pasture grasses when exposed to diurnal temperature amplitude compared to constant temperature. Reduced diurnal temperature amplitude in maize (*Zea mays* L.), another species in the *Poaceae* family, linearly increased night respiration and further provided a linear decrease in plant height, total leaf area, and total biomass accumulation (Sunoj et al., 2016). Additionally, goosegrass [*Eluesine indica* (L.) Gaertn.] has demonstrated increased germination under greater temperature amplitude, where less than 6% germination occurred under constant temperatures of 20 °C, 30 °C, and 35 °C (Nishimoto & McCarty, 1997). The results from the present study imply that further research is needed to determine the effects of diurnal ambient and soil temperature amplitude on establishment and growth of zoysiagrass and other warm- and cool-season turfgrass species.

In run B, the medium-soil-temperature treatment resulted in the greatest turfgrass coverage 28 to 44 DAP (Table 1.2). Soil temperatures averaging approximately 32 °C at a 5 cm depth are limited to the summer months in southeastern United States locations bordering the Gulf Coast and Atlantic Ocean. Soil temperature may be a factor contributing to prolonged establishment, which will become more significant at increasing latitudes. Specifically, 5 cm soil temperatures in Knoxville, TN (35.929° N, 83.949° W) during the summer months rarely average greater than 28 °C (Earthstream Platform, 2022). In geographic areas where soil temperatures do not achieve 32 °C, initiating sprigging at the earliest reasonable date may be necessary to ensure complete establishment within the first growing season. Previous research has identified that zoysiagrass planted during the late part of the dormant season in transitional or subtropical regions can achieve full coverage during the first growing season (Zhang et al., 2021).

A consistent result across both experimental runs was prolonged establishment with the high-soil-temperature treatment. While not measured in the current study, elevated temperature from the high-soil-temperature treatment may have increased vapor pressure deficit (VPD), which has a linear relationship with transpiration in warm-season turfgrasses (Wherley et al., 2009). Increased VPD and transpiration have been shown to reduce rooting percentages of loblolly pine (*Pinus taeda* L.) stem cuttings (LeBude et al., 2005). Elevated VPD while establishing zoysiagrass from vegetative sprigs may require adjustments in irrigation practices to reduce transpiration. Additionally, increased nighttime temperatures associated with the high-soil-temperature treatment likely increased respiration, which has negative impacts on plant growth (Sunoj et al., 2016). These combined factors indicate that 5 cm soil temperatures continuously averaging 36 °C will likely not yield rapid establishment of Prizm zoysiagrass.

CONCLUSIONS

In both experimental runs, 5 cm soil temperatures averaging 32 °C resulted in the most rapid establishment of Prizm zoysiagrass sprigs. Continuous 5 cm soil temperature averaging 36 °C caused prolonged establishment in both experimental runs, potentially due to increased vapor pressure deficit and respiration. Future research should evaluate vegetative zoysiagrass establishment under different average and diurnal soil temperatures to determine if daytime soil temperatures above 36 °C can accelerate establishment if nighttime soil temperatures are reduced. The influence of VPD on the vegetative establishment of zoysiagrass sprigs should also be investigated, as VPD is commonly mitigated when vegetatively propagating horticultural crops.

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APPENDIX 1

Figure 1.1. Experimental area utilized to evaluate ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] establishment from sprigs during 2022 in Knoxville, TN.

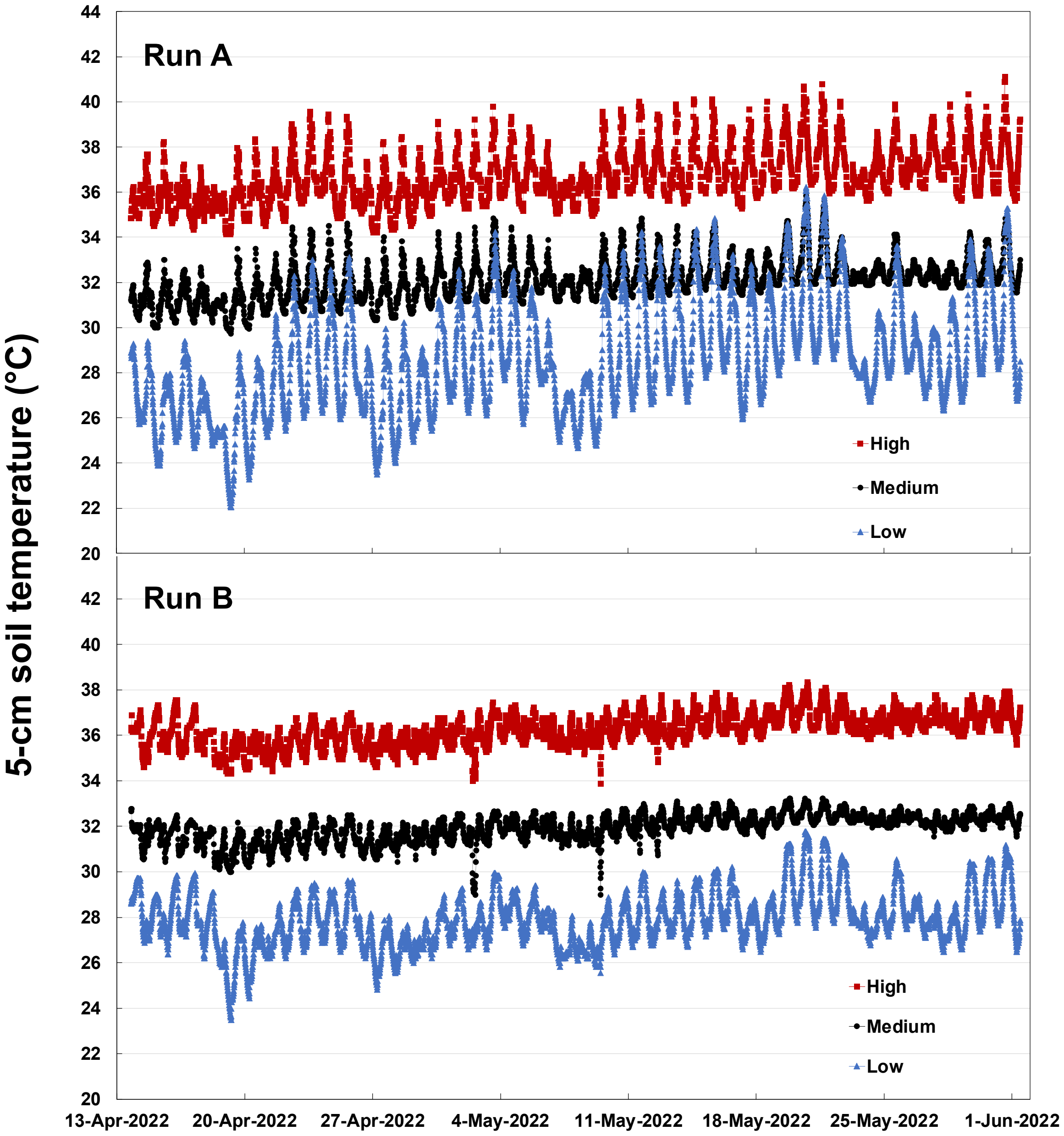

Figure 1.2. Soil temperature at a 5 cm depth collected at 15 min intervals (Item #3667-20, #3688WD1, Spectrum Technologies, Aurora, IL, USA) in the high-, medium-, and low-soil-temperature treatments while establishing ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] from sprigs. Experimental runs were conducted in glasshouses in Knoxville, TN in 2022.

Table 1.1. Analysis of variance testing the main effects and their interactions on turfgrass coverage during experimental run A and B. Bolded *P* values indicate significant higher-order treatment interactions.

Source of Variation	**Run A**	**Run B**
	P > F	
	Turfgrass coverage	
Soil temperature	0.16	0.08
Days after planting (DAP)	<0.0001	<0.0001
DAP × Soil temperature	**<0.0001**	**0.0006**

Table 1.2. Turfgrass coverage of 'Prizm' zoysiagrass [*Zoysia matrella* (L.) Merr.] established in glasshouses in Knoxville, TN. Treatments included high, medium, and low 5 cm soil temperatures, which averaged 36.6 °C, 32.1 °C, and 28.6 °C in run A and 36.2 °C, 31.9 °C, and 27.9 °C in run B. Within evaluation dates, means followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

Soil temperature (°C)	**7 DAP †**	**14 DAP**	**21 DAP**	**28 DAP**	**35 DAP**	**44 DAP**	**49 DAP**
				Turfgrass coverage (%)			
				Run A			
High (36.6)	2	6	12	21	48 b	64 b	70 b
Medium (32.1)	0	3	14	36	68 a	82 a	88 a
Low (28.6)	2	4	9	33	77 a	93 a	96 a
				Run B			
High (36.2)	3	5	11	24 b	55 b	74 b	87
Medium (31.9)	0	4	10	36 a	75 a	92 a	96
Low (27.9)	1	2	4	18 b	53 b	78 b	91

† DAP, days after planting.

Table 1.3. Average daily maximum, minimum, and amplitude 5 cm soil temperature for soil temperature treatments averaging 36.6 °C, 32.1 °C, and 28.6 °C in run A and 36.2 °C, 31.9 °C, and 27.9 °C in run B. Experimental runs were conducted in glasshouses in Knoxville, TN in 2022.

Soil Temperature (°C)	Average Maximum	Average Minimum	Amplitude (Maximum–Minimum)
		Run A	
High (36.6)	38.9	35.3	3.6
Medium (32.1)	33.7	31.2	2.5
Low (28.6)	31.7	26.2	5.5
		Run B	
High (36.2)	37.2	35.4	1.8
Medium (31.9)	32.6	31.2	1.4
Low (27.9)	29.3	26.6	2.7

SUPPLEMENTARY MATERIAL 1

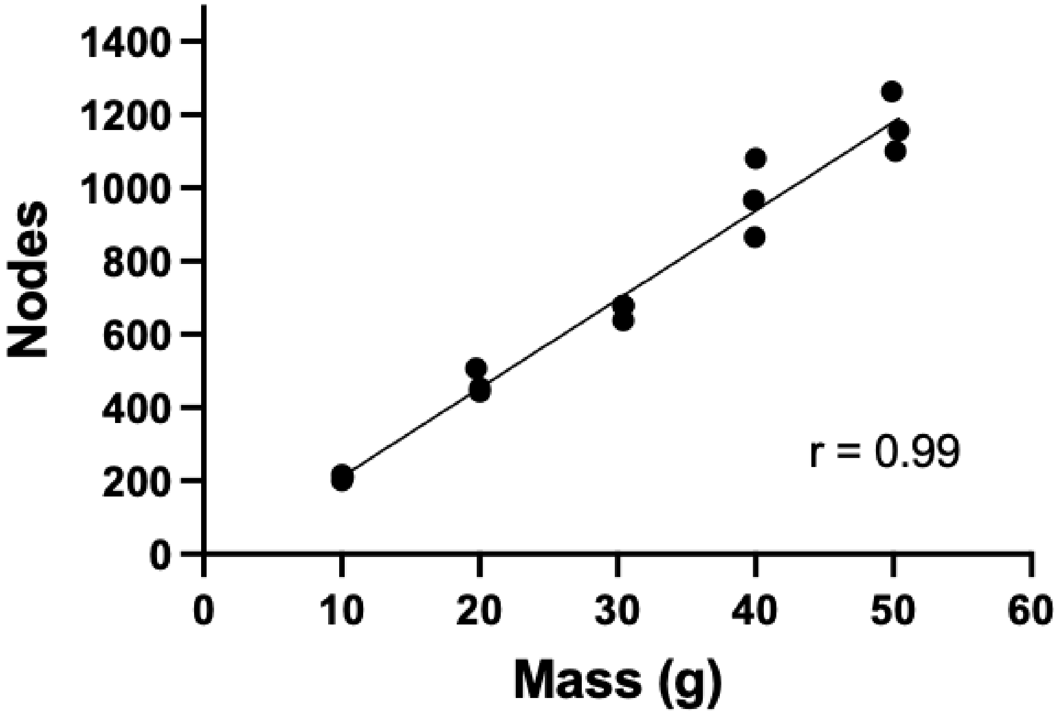

Figure S1.1. Correlation between increasing sprig material mass and increasing sprig node number. The number of ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] nodes were determined for sprigs weighing 10, 20, 30, 40, and 50 g in Knoxville, TN in 2022.

CHAPTER II

IRRIGATION FREQUENCY EFFECTS ON PRIZM ZOYSIAGRASS ESTABLISHMENT FROM SPRIGS

This chapter is based on a manuscript that will be submitted for publication by Tyler Q. Carr, John C. Sorochan, James T. Brosnan, Brandon J. Horvath, Kellie J. Walters, and Carrie A. Stephens:

Carr, T. Q., Sorochan, J. C., Brosnan, J. T., Horvath, B. J., Walters, K. J., & Stephens, C. A. (2023). Irrigation frequency effects on Prizm zoysiagrass establishment from sprigs. *HortScience*.

All authors made conceptual or technical contributions relative to their area of expertise. My primary contributions to this paper include (i) conceptualization, (ii) experimental design, (iii) investigation, (iv) data analysis, (v) writing.

ABSTRACT

Zoysiagrass (*Zoysia* spp. Willd.) is a warm-season, perennial, turfgrass that has a rhizomatous and stoloniferous growth habit. Zoysiagrasses are often used in commercial and residential lawns in addition to golf course fairways and tees due to reduced light, fertilizer, and mowing inputs relative to bermudagrass (*Cynodon* spp.). These reduced inputs have led to increased interest in using zoysiagrass on putting greens. However, zoysiagrass establishment from sprigs is slower than bermudagrass. Research was conducted in a glasshouse in Knoxville, TN to evaluate the effect of irrigation frequency on the establishment of Prizm zoysiagrass sprigs. Two replicate experimental runs were conducted in the same glasshouse in 2022. Prizm zoysiagrass was irrigated daily (3 mm) applied via four or 192 events from 06:00 a.m. to 10:00 p.m. In both experimental runs, Prizm zoysiagrass establishment was unaffected by irrigation frequency and averaged 40% turfgrass coverage after 21.6 and 27.3 days in run A and run B, respectively. Air vapor pressure deficit during the irrigation period averaged 1.05 kPa in run A and 1.57 kPa in run B, respectively, suggesting zoysiagrass sprigs have limited sensitivity to elevated vapor pressure deficit, granted sufficient rootzone moisture is available. Additional research elucidating zoysiagrass sprig physiology during propagation and development is necessary to better define management practices that hasten establishment.

INTRODUCTION

Zoysiagrass (*Zoysia* spp. Willd.) is a rhizomatous and stoloniferous, warm-season (C_4), turfgrass that is native to southeast Asia (Patton et al., 2017). Zoysiagrasses are well adapted to the warm and transition climatic zones in the United States, with primary utility in commercial and residential lawns in addition to golf course fairways and tees (Patton et al., 2017). However, the predominant warm-season turfgrass on golf course putting greens in the United States is ultradwarf bermudagrass [(*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* (Burtt Davy)] (Brosnan et al., 2022).

A fine-textured zoysiagrass cultivar, 'Diamond' [*Zoysia matrella* (L.) Merr.], was released for use on golf course putting greens due to its tolerance to low mowing heights and improved shade tolerance over bermudagrass (Engelke et al., 2002). Yet, maximum ball roll distance for Diamond when maintained at 2.5 mm was 259 cm, which is likely not acceptable for tournament purposes (Radko, 1977; Stiglbauer et al., 2009). More recently, (Carr, Sorochan, & Dickson, 2022) evaluated zoysiagrasses ['Lazer' (*Z. matrella* × *Z. minima*), 'M85' (*Z. matrella*), 'Prizm' (*Z. matrella*), and Trinity (*Z. matrella*)] for putting greens and observed minimum ball roll distance of 300 cm when maintained at 3 mm and received lightweight rolling five times weekly.

While select zoysiagrass cultivars may have comparable ball roll performance relative to ultradwarf bermudagrass, bermudagrass is known to establish faster from vegetative sprigs than zoysiagrass. For example, sprig plantings of 'MiniVerde' ultradwarf bermudagrass achieved 100% turfgrass coverage 7 to 35 d earlier than Diamond (Briscoe et al., 2012). This extended establishment of zoysiagrass prolongs course closure, while expenditures and golf course maintenance continue.

Currently, methods to hasten zoysiagrass establishment are limited. Previous research has attempted to accelerate zoysiagrass establishment from sprigs by increasing nitrogen fertilization rates, often with limited or no effect (Briscoe et al., 2012; Carroll et al., 1997; Richardson & Boyd, 2001; Stiglbauer et al., 2009). Also, applying phosphorus during zoysiagrass establishment from sprigs has hastened establishment relative to areas not treated with phosphorus (Briscoe et al., 2012; Carr et al., 2021). Additional experiments have attempted to determine appropriate planting dates for zoysiagrass sprigs that promote the shortest establishment duration while ensuring complete establishment during the first growing season. Although planting during the warmest summer months correspond with greater establishment rates, plantings in the transition zone should likely occur no later than late spring to achieve complete establishment prior to temperature reductions in the fall and winter (Carr et al., 2021; Zhang et al., 2021). When combined with an appropriate planting date, improved management practices during the establishment phase may promote hastened establishment.

Adequate irrigation is necessary to limit sprig desiccation during establishment because of limited root development, as roots are responsible for water absorption and uptake in plants (Taiz & Zeiger, 2002). Moreover, irrigation is generally recommended to ensure sprigs and surrounding soil remain moist following planting (Beasley et al., 2019; SFMA, 2022). Moist sprigs may be difficult to maintain since increases in temperature, wind, and solar radiation in addition to reductions in relative humidity can decrease available moisture (Huang, 2008). Therefore, frequent irrigation events may be necessary to limit evapotranspiration.

When propagating horticultural cuttings, intermittent mist systems are routinely employed, which involve frequent applications of small water droplets to reduce leaf and air temperature while increasing relative humidity (Hartmann et al., 2011). This reduction in temperature and increase in relative humidity from intermittent mist reduces the vapor pressure deficit (VPD), subsequently reducing leaf transpiration (Hess & Snyder, 1955). Reducing VPD allows propagules to maintain cell turgor in the absence of functional roots and preserve cell competence to form roots (Hartmann et al., 2011). In mature warm-season turfgrasses, a linear relationship exists between increasing VPD and transpiration (Wherley & Sinclair, 2009). Reduced rooting from increasing VPD has been observed in loblolly pine (*Pinus taeda* L.) stem cuttings, which may also be applicable to zoysiagrass sprigs during establishment (LeBude et al., 2005).

To minimize transpiration during cutting propagation, maintaining a low VPD of < 0.5 kPa is generally recommended for most horticultural dicotyledon species (Grange & Loach, 1983). A VPD of 0.5 kPa requires high relative humidity ranging from 75% to 85% with temperatures 17 °C to 26 °C, and may be difficult to achieve in areas with zoysiagrass adaptation since average summer maximum daily temperatures are frequently ≥ 29 °C (Arguez et al., 2010). Additionally, the high irradiance conditions in outdoor environments where sprigs are planted may inhibit establishment of propagules, as leafy pea (*Pisum sativum* L.) cuttings have demonstrated desiccation when exposed to elevated light levels (≥ 350 µmol m^{-2} s^{-1}) for at least 3 hours (Davis & Potter, 1981). It is currently unknown if the application of intermittent mist during the propagation phase of turfgrass from vegetative sprigs will reduce VPD to an extent that establishment is accelerated compared to less frequent irrigation regimes.

While irrigation is a critical component to ensure successful establishment from zoysiagrass sprigs, there is currently no research pertaining to optimal irrigation practices to facilitate sprig establishment. Since zoysiagrass sprigs and horticultural cuttings are both vegetative propagules, irrigating via intermittent mist may result in increased sprig survival and accelerated establishment. Therefore, the objective of this research was to evaluate the effect of irrigation frequency on establishment of Prizm zoysiagrass sprigs. It was hypothesized that increased irrigation frequency would hasten zoysiagrass establishment from sprigs.

MATERIALS AND METHODS

Research Site Management and Treatment Description

The evaluation of irrigation frequency effects on Prizm zoysiagrass establishment was conducted in a glasshouse at The University of Tennessee (Knoxville, TN) in 2022. Each observational unit comprised of a 20.3-cm diameter mum pan (Item #52-3146, Griffin Greenhouse Supplies, Inc., Tewksbury, MA) filled with an 80:20 (v:v) mixture of silica sand meeting United States Golf Association (USGA) particle size specifications and sphagnum peat moss to achieve a uniform bulk density of 1.6 Mg m^{-3} (USGA, 2018). The rootzone initially contained 0.8% organic matter.

Each experimental unit represented an irrigation frequency treatment and consisted of 7 observational units. Irrigation frequency treatments were imposed every 5 minutes for 15 seconds (192x d^{-1}) or every 240 minutes for 12 minutes (4x d^{-1}) from 06:00 a.m. to 10:00 p.m., with each treatment delivering 3 mm of irrigation daily. Visually, rootzone moisture was not limiting over the course of the experiment. To prevent irrigation drift across treatments, irrigation frames measuring 76 cm × 76 cm × 61 cm were constructed using 13-mm schedule 40 polyvinyl chloride (PVC) pipe and 0.08 mm-thick clear plastic sheeting (Item #810476, Project Source 3-mil Plastic Sheeting, Lowe's, Mooresville, NC), with the top and bottom of each irrigation frame remaining uncovered (Figure 2.1, 2.2). A single mini-sprinkler (Item #MELOW-5, Ein Dor Mini-Sprinklers, DripWorks, Willits, CA) was mounted 33 cm above the plant canopy within each irrigation frame. All observational units were placed atop heat mats (iPower Seed Starter Heat Mat, Irwindale, CA) to increase soil temperature above air temperature since Carr, Sorochan, Brosnan, et al. (2022) observed the quickest establishment of Prizm zoysiagrass sprigs when 5 cm soil temperatures averaged ~32 °C.

Two replicate experimental runs were conducted in the same glasshouse during 2022. Run A and run B were initiated on 10 August and 10 September, respectively. Linear regression analysis in a companion study revealed a significant, positive relationship (run A: $P < 0.0001$, $R^2 = 0.96$; run B: $P < 0.0001$, $R^2 = 0.99$; GraphPad Prism v. 9.4., GraphPad Software Inc., La Jolla, CA) between increasing sprig material mass and increasing sprig node number (Figure S2.1, Figure S2.2). Regression equations were used to determine the sprig material mass required to plant in each observational unit using ~16,000 nodes m^{-2}, similar to Carr et al. (2022). The sprig material masses planted in run A and run B were 22.5 g and 25.8 g, respectively. Sand topdressing was applied after planting to a depth of 3.2 mm in each experimental run.

Prior to planting and weekly throughout each experiment, 1.2 g N m^{-2} via complete fertilizer (20.0N-8.8P-16.6K) was applied to each observational unit. Under conditions of natural and supplemental light with a 16/8 hour day/night photoperiod (PKB, Arize Element L1000 Next-Gen, Current Lighting Solutions, LLC, Cleveland, OH), plants received an average of 41.0 and 41.4 mol m^{-2} d^{-1} in runs A and B (SQ-500, Apogee Instruments, Inc., Logan, UT), respectively. Every 4 d, observational units were rotated clockwise to limit effects of light intensity differences within each irrigation frame, which varied from 496 to 756 µmol m^{-2} s^{-1} in the absence of natural light (LI-180, Spectrometer, LI-COR Biosciences, Lincoln, NE). The 5 cm soil temperature for one observational unit within each irrigation frame was recorded with an external temperature sensor (Item #3667-20, Spectrum Technologies, Aurora, IL), and was logged at fifteen-minute intervals with a WatchDog 1000 Series Micro Station (Item #3688WD1, Spectrum Technologies, Aurora, IL). Average 5 cm soil temperature was 31.1 °C in run A and 28.9 °C in run B.

Data Collection and Statistical Analysis

To objectively assess irrigation frequency effects on Prizm zoysiagrass establishment, turfgrass coverage was estimated using digital image analysis 8 days after planting (DAP) and every 4 days thereafter until 50% turfgrass coverage was achieved (Richardson et al., 2001). Images were collected outside the 06:00 a.m. to 10:00 p.m. irrigation window to not affect irrigation treatments. Images collected by the digital camera (Canon PowerShot G12, Canon Inc., Melville, NY) were rectangular, but observational units were round; therefore, a purple frame was placed in the images to exclude non-observational area from each image. The frame analysis procedure in TurfAnalyzer (Karcher et al., 2017; Karcher & Richardson, 2013) was used to estimate turfgrass coverage for only the observational unit within each image.

This study was a one-factor randomized complete block design with three replications of each irrigation treatment. For each experimental run, separate nonlinear regression analyses were performed to estimate the number of days after planting to achieve 40% turfgrass coverage (GraphPad Prism v. 9.4, GraphPad Software Inc., La Jolla, CA). The following sigmoid variable slope model was used to predict the slope for each treatment:

$$\text{turfgrass coverage (\%)} = 100 / \{1+10^{[(\text{Days50} - \text{DAP})\text{Slope}]}\}$$

where DAP was days after planting and Days_{50} and slope were estimated model parameters. Days_{50} was the estimated DAP to achieve 50% turfgrass coverage. The slope parameters defined how rapidly turfgrass coverage changed over time, with increasing slope values corresponding to steeper positive slopes of the sigmoid curve. Days_{50} is a metric used to generate the sigmoid curves; however, all discussion will be based on Days_{40} data because those are most relevant to the study. The threshold was selected since zoysiagrass enters an exponential growth phase once 40% turfgrass coverage is achieved (Carr et al., 2021). The Days_{40} for each treatment was separated using 95% confidence intervals for the predicted values.

At the conclusion of each experimental run, biomass for each sample was determined. Plant material from each sample was washed to remove rootzone material and placed in a forced air dryer at 65°C for 72 hours prior to weighing biomass. Biomass measurements were subjected to one-way analysis of variance (ANOVA) in PROC GLIMMIX (SAS v. 9.4, SAS Institute Inc., Cary, NC).

In the center of each experimental unit (i.e., irrigation frame), air temperature (T) and relative humidity (RH) were recorded every 5 minutes (HOBO MX2301A, Onset Computer Corporation, Bourne, MA). The sensor was enclosed within a solar radiation shield (Part #M-RSA, Onset Computer Corporation, Bourne, MA) to reduce effects of directed or reflected sunlight. The air VPD was calculated from T and RH using the formula $\text{VPD} = (1 - \text{RH}/100) \times 0.611 \times e^{[17.27 \times T/(T+237.3)]}$. Over the 16-hour photoperiod, averages for VPD, temperature, and relative humidity were subjected to repeated measures ANOVA and a means separation technique (LSMEANS) in PROC GLIMMIX (SAS v. 9.4, SAS Institute Inc., Cary, NC). For all data, slicing was performed in PROC GLIMMIX to identify evaluation dates when treatment effects were significant. Treatment means for significant effects were separated using Fisher's protected least significant difference (LSD; $\alpha = 0.05$).

RESULTS

Irrigation Frequency Effects on Establishment

Nonlinear regression analysis indicated that model parameters were significantly different in both run A ($P = 0.02$) and run B ($P = 0.02$); therefore, separate models were developed for each irrigation frequency treatment (Figure 2.3; Table 2.1). The sigmoid models provided a good fit of turfgrass coverage data, with R^2 values ranging from 0.92

to 0.93 in run A and 0.93 to 0.96 in run B. While separate models were created for each irrigation treatment in both experimental runs, Days_{40} values were not significantly different among treatments, averaging 40% turfgrass coverage after 21.6 d in run A and 27.3 d in run B (Figure 2.4).

Irrigation Frequency Effects on Biomass

Biomass samples collected at the conclusion of each experimental run indicated no significant differences in biomass among irrigation frequencies of 192x d^{-1} or 4x d^{-1} (Run A: $P = 0.19$; Run B; $P = 0.23$). The average biomass of all samples was 9.5 g in run A and 10.7 g in run B.

Irrigation Frequency Effects on Environmental Conditions

Vapor Pressure Deficit

An irrigation frequency-by-evaluation date interaction was detected in air VPD data in run A ($P = 0.04$; Table 2.2). On 15 (of 23) evaluation dates, applying irrigation 192x d^{-1} resulted in significantly lower VPD than 4x d^{-1} (Figure 2.5). On those dates, the 192x d^{-1} treatment reduced VPD by an average of 0.33 kPa compared to irrigating 4x d^{-1}. In run B, the evaluation date main effect significantly affected daily average VPD ($P < 0.0001$; Table 2.2). When pooled across the irrigation treatments, VPD averaged 1.57 kPa and ranged from 0.95 kPa to 2.09 kPa (Figure 3.1).

Air Temperature

In run A, main effects of evaluation date ($P < 0.0001$) and irrigation frequency ($P = 0.02$) significantly affected average air temperature (Table 2.2). When pooled across all irrigation treatments, air temperature ranged from 27.7 °C to 29.0 °C (Figure 3.2). Irrigation 4x d^{-1} averaged 28.9 °C when pooled across all evaluation dates, which was significantly greater than 192x d^{-1} (27.5 °C) (Table 3.1).

In run B, the irrigation frequency-by-evaluation date interaction significantly affected air temperature (*P* = 0.002; Table 2.2). On 30 (of 32) evaluation dates, significantly greater air temperature occurred under irrigation 4x d^{-1} (28.1 °C) compared to 192x d^{-1} (26.8 °C) (Figure 2.6).

Relative Humidity

The main effect of evaluation date significantly affected relative humidity in run A (*P* < 0.0001) and run B (*P* < 0.0001) (Table 2.2). In run A, average relative humidity was 72.8% and ranged from 67.4% to 79.1% when pooled across irrigation frequency treatments (Figure 3.3). Relative humidity was lower in run B, averaging 57.8% and ranging from 44.1% to 75.1% (Figure 3.4).

DISCUSSION

Across both experimental runs, irrigation frequency treatments did not significantly affect the establishment of Prizm zoysiagrass. Irrigation applied 192x d^{-1} for 24 to 32 DAP did not accelerate establishment compared to less frequent applications (4x d^{-1}).

While irrigation applied 192x d^{-1} significantly reduced VPD compared to 4x d^{-1} in run A, average daily VPD across both experiential runs was 0.2 kPa to 1.6 kPa greater than the current recommendations for horticultural cutting propagation (0.5 kPa) (Grange & Loach, 1983). VPD in the present study was also routinely greater than the range observed for optimal rooting of loblolly pine stem cuttings (0.60 to 0.85 kPa) (LeBude et al., 2005). Additionally, VPD > 2.0 kPa was reported to be injurious to plants when using dynamic control of mist in propagation (Gates et al., 1998). In the present study, average daily VPD was > 2.0 kPa on 2 dates in run B (23 and 27 September), but the effect of elevated VPD on zoysiagrass establishment is unknown since irrigation frequency did not significantly affect average daily VPD in run B.

Elevated VPD in the present study is a consequence of the increased air temperature and reduced relative humidity compared to environments conducive for cutting propagation. In outdoor turfgrass systems, zoysiagrass sprigging occurs during the summer months to encourage accelerated establishment, which results in VPD greater than levels typical in greenhouse propagation systems (Arguez et al., 2010).

Zoysiagrass sprigs consist of rhizomes and stolons, which differ from cuttings of horticultural plants that are propagated from stems, leaves, or roots. Stolons and rhizomes in turfgrasses are carbohydrate storage organs and contain nodes with meristematic tissues to develop new roots and shoots (Fry & Huang, 2004). Rhizomes of Kentucky bluegrass (*Poa pratensis* L.), a C_3 turfgrass, maintain metabolic activity during drought stress and demonstrate increased concentrations of carbohydrate reserves, which may contribute to improved recuperative potential following rewatering (Chai et al., 2010; Yang et al., 2013). Zoysiagrass sprigs likely enter a similar period of drought stress when harvested and the recuperative potential of rhizomes upon wetting could explain why frequent irrigation of 192x d^{-1} did not provide accelerated establishment relative to 4x d^{-1}. Due to the possible recuperative potential of zoysiagrass rhizomes, frequent irrigation from intermittent mist may not be necessary to ensure meristematic tissue remains viable, resulting in growth of new root and shoot tips from nodes. Similar to Kentucky bluegrass, carbohydrate reserves are likely an important factor when establishing zoysiagrass sprigs.

Furthermore, zoysiagrass, a C_4 species, may have reduced VPD sensitivity compared to C_3 species, including most dicotyledon species commonly propagated under intermittent mist (McNab, 2008). Mature C_4 species can fix CO_2 at rates equal to or greater than C_3 species with decreased stomatal apertures and water loss rates (Taiz & Zeiger, 2002). When comparing mature C_3 and C_4 turfgrass species, C_4 species lacked sensitivity to VPD ranging from 0.79 to 2.99 kPa whereas C_3 species had limitations on transpiration rate at VPD > 1.35 kPa (Wherley & Sinclair, 2009). However, it is unknown if differences in VPD sensitivity among photosynthetic mechanisms at maturity translate to the propagation phase. Therefore, future research should compare stomatal conductance for various monocotyledon and dicotyledon plants undergoing C_3 and C_4 photosynthesis from harvest through adventitious root formation.

Soil temperature likely explains the variation of $Days_{40}$ values among experimental runs. In run A, 40% turfgrass coverage was achieved ~21 DAP, approximately 6 days earlier than in run B. The prolonged $Days_{40}$ in run B may be attributed to reduced average 5 cm soil temperatures in run B (28.9 °C) relative to run A (31.1 °C) since Carr et al. (2022) observed accelerated Prizm zoysiagrass establishment under ~32 °C 5 cm soil temperature compared to ~28 °C. In areas of the transition zone where zoysiagrass is commonly used, which includes latitudes north of 35°, average soil temperatures are rarely ≥ 31 °C during the warmest months (GreenCast, 2022). These lower soil temperatures would lead to slower establishment from sprigs (Carr et al., 2022). Golf courses at these locations are electing to establish putting greens from sod to reduce course closure duration. Because of this, additional research is needed to optimize sod production and post-plant management practices to ensure putting greens are playable within the shortest period.

While soil temperatures in the present study were increased with bottom heat, average air temperature also influences soil temperature. Over a 24-hour daily period, average air temperature was greater in run A (27.8 °C) than run B (26.6 °C), which is due to average minimum temperature reducing from 25.4 °C in run A to 22.5 °C in run B. According to Preece (1993), the optimum air temperature for growing a crop is probably the best for rooting vegetative propagules. Charles V. Piper introduced *Z. matrella* to the United States from the Philippines in 1912 (USDA Bureau of Plant Industry, 1915). The average air temperature in Manila, Philippines is 26.6 °C; however, the average minimum temperature is 24.4 °C, which is greater than experienced in run B in the present study (Climate Data, 2022). It is possible that a minimum air temperature threshold exists for optimal zoysiagrass growth, which warrants further exploration.

Sprigging rate is commonly expressed in volume per unit area (e.g., m^3 ha) (Briscoe et al., 2012; Richardson & Boyd, 2001; Samples & Sorochan, 2007; SFMA, 2022; Stiglbauer et al., 2009; Zhang et al., 2021), which varies depending on sprig moisture and packing density. Since new roots and stems derive from nodes during establishment, sprigs in the present study were planted based on node count at a rate of 16,000 nodes m^{-2}. This concept is similar to calculating seeding rate using seed size, and the sprigging rate in the present study was similar to common seeding rates (Christians et al., 2018). However, pure live seed is considered when planting turfgrass from seed, which corresponds to the amount of live seed in a seed package (Christians et al., 2018). In comparison, the viability of sprig nodes is unknown, likely contributing to sprigging rate variability.

One limitation of this research is that the role of plant hormones such as auxins, gibberellins, cytokinins, ethylene, and abscisic acid on zoysiagrass sprig growth and development was not investigated. While temperature likely modulates establishment rate, evaluating hormone regulation in developing zoysiagrass sprigs would provide better understanding of the underlying cellular mechanisms that contribute to establishment rate. To evaluate this, future research should examine the effects of exogenous hormone application on sprigs during establishment, in addition to the timing of these applications.

CONCLUSIONS

In both experimental runs, Prizm zoysiagrass establishment was unaffected by irrigation frequency, implying that sprig survival and establishment rate is not sensitive to

VPD. However, based on previous research, temperature is a critical factor contributing to establishment rate, as soil and air temperatures were generally greater in run A compared to run B. Currently, the physiological mechanisms of zoysiagrass propagation from sprigs are not well understood. Specifically, future studies evaluating the roles of carbohydrate storage, hormone regulation, and node viability in zoysiagrass sprigs would provide better understanding of zoysiagrass sprig development and help guide management decisions during establishment.

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APPENDIX 2

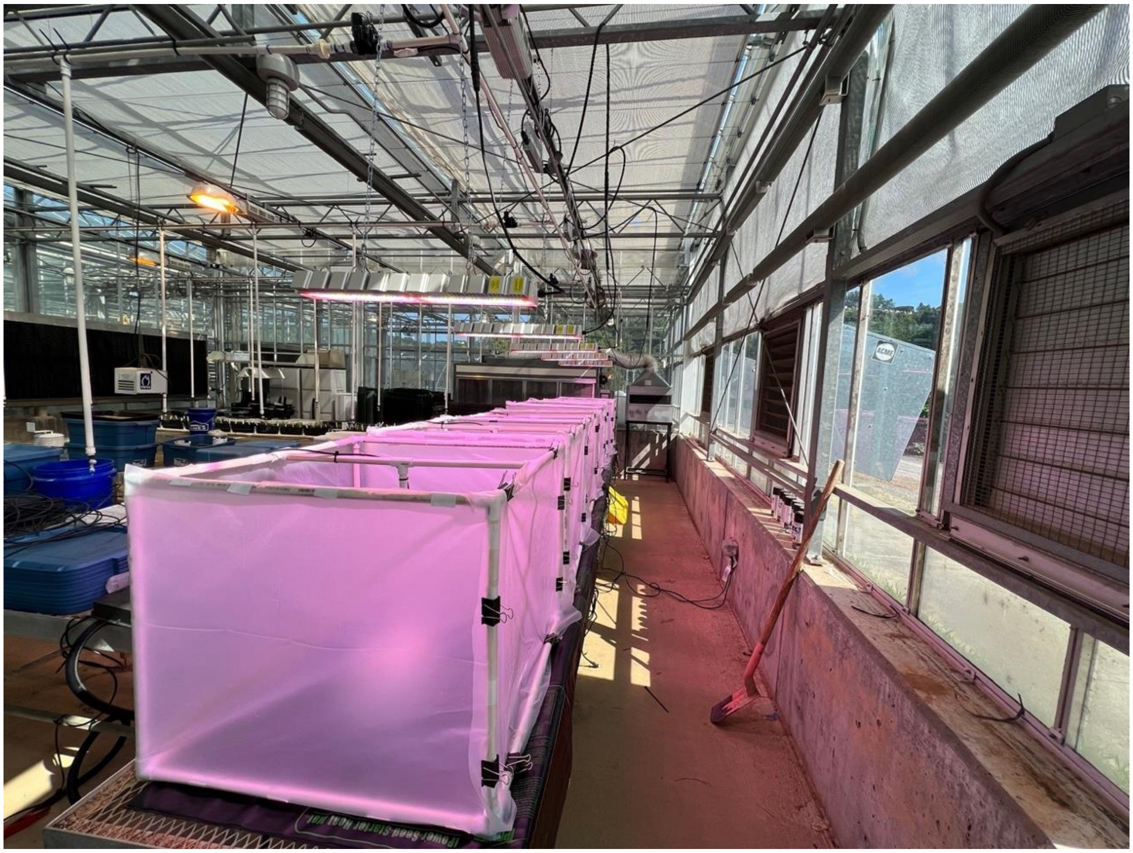

Figure 2.1. The experimental area used to evaluate establishment of ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] sprigs when 3 mm of daily irrigation was applied across either four or 192 events from 06:00 a.m. to 10:00 p.m. in a glasshouse in Knoxville, TN.

Figure 2.2. An experimental unit used to evaluate the establishment of ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] when 3 mm of daily irrigation was applied across either four or 192 events from 06:00 a.m. to 10:00 p.m. in a glasshouse in Knoxville, TN.

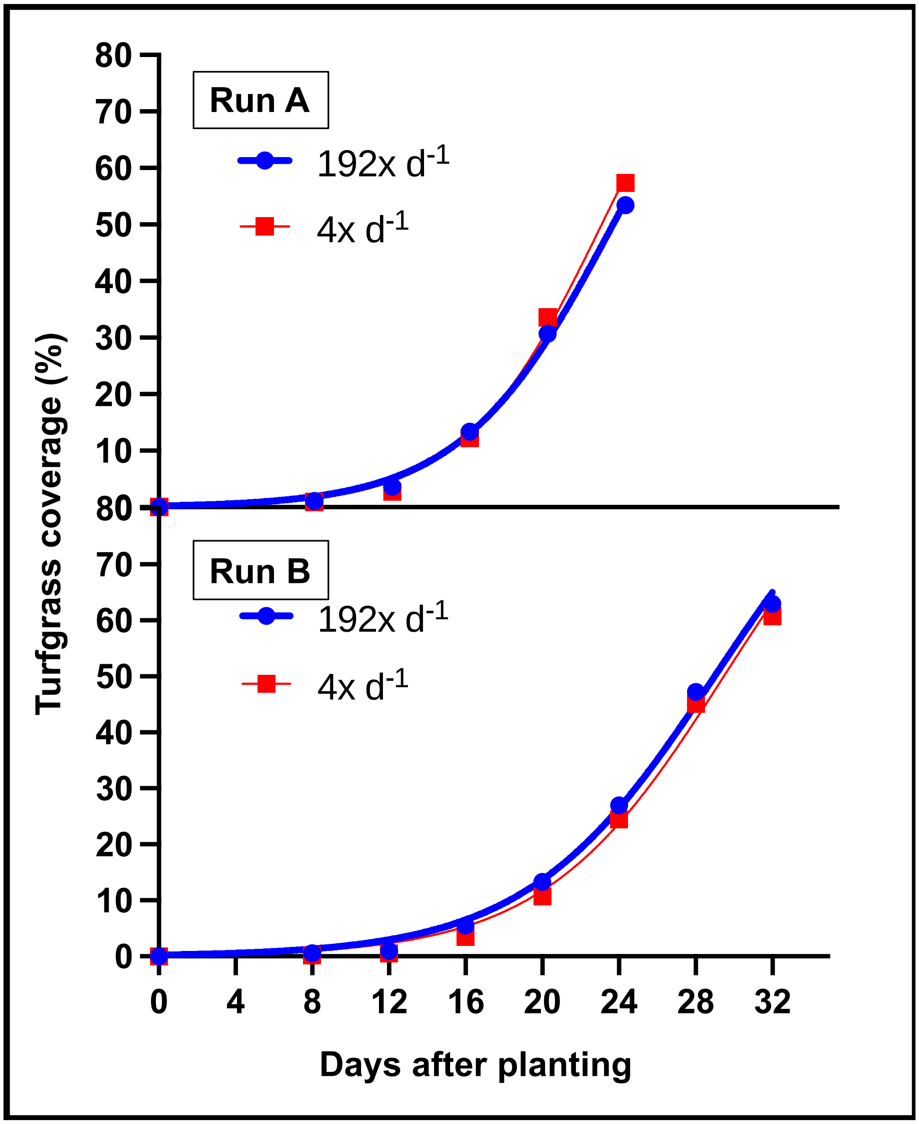

Figure 2.3. Nonlinear regression analysis of ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] coverage during establishment from sprigs over run A and run B in a glasshouse in Knoxville, TN when 3 mm of daily irrigation was applied across either four or 192 events from 06:00 a.m. to 10:00 p.m.

Table 2.1. Statistical parameters for predicting the establishment of ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] in Run A in a glasshouse in Knoxville, TN. Days_{50} is the predicted number of days after planting until turfgrass achieves 50% turfgrass coverage. Larger slope values indicate more rapid increases in turfgrass coverage over time.

Irrigation frequency (events d^{-1})	**Days_{50}[a]**	**SE**	**Slope**	**SE**	**R^2**
	Run A				
192	23.4	0.16	0.112	0.005	0.92
4	22.8	0.14	0.122	0.005	0.93
	Run B				
192	29.0	0.18	0.089	0.003	0.93
4	29.5	0.12	0.093	0.003	0.96

[a] Days_{50} and slope values determine turfgrass coverage (%) according to the formula: $100 / \{1+10^{[(\text{Days50} - \text{DAP})\text{Slope}]}\}$, where DAP = cumulative days after planting.

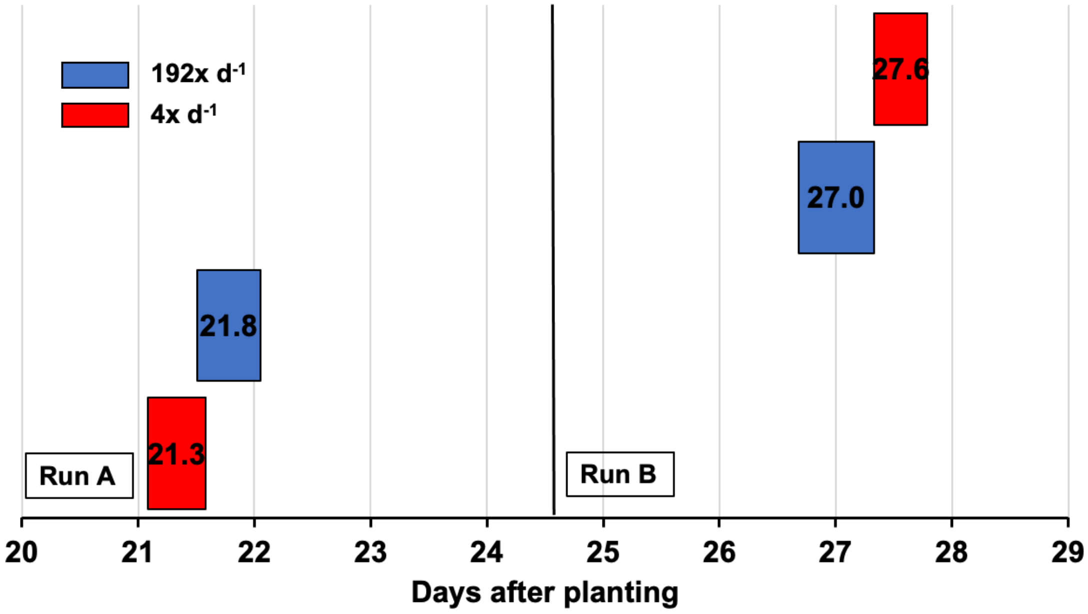

Figure 2.4. Confidence intervals (95%) for ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] to achieve 40% turfgrass coverage during establishment from sprigs over run A and run B in a glasshouse in Knoxville, TN. Daily irrigation of 3 mm was applied across either four or 192 events from 06:00 a.m. to 10:00 p.m. The mean number of days for each irrigation frequency treatment to achieve 40% turfgrass coverage is enclosed within each bar. Within experimental run, treatments with overlapping bars are not significantly different.

Table 2.2. Analysis of variance testing the main effects and their interactions on average daily vapor pressure deficit, temperature, and relative humidity during experimental run A and B.

Source of Variation	**Run A**	**Run B**
	P > F	
	Vapor pressure deficit	
Irrigation frequency	[†]NS	NS
Evaluation date	<0.0001	**<0.0001**
Irrigation frequency × Evaluation date	**0.04**	NS
	Temperature	
Irrigation frequency	**0.02**	NS
Evaluation date	**<0.0001**	<0.0001
Irrigation frequency × Evaluation date	NS	**0.002**
	Relative humidity	
Irrigation frequency	NS	NS
Evaluation date	**<0.0001**	**<0.0001**
Irrigation frequency × Evaluation date	NS	NS

Note. Bolded *P* values indicate significant higher-order treatment interactions and/or main effects.

[†] NS, nonsignificant at the 0.05 probability level

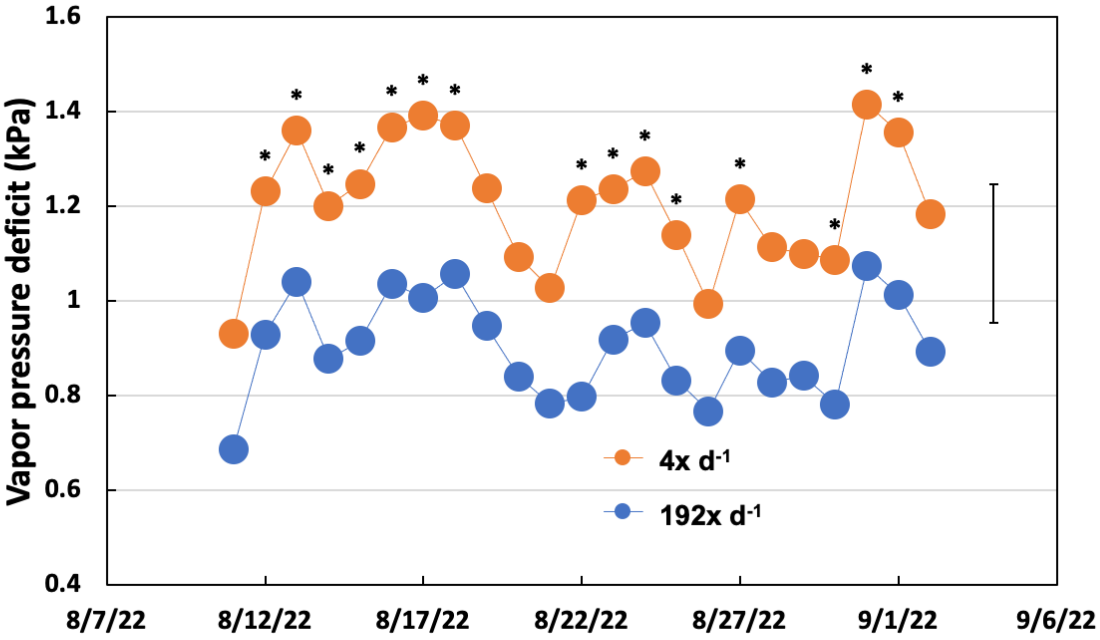

Figure 2.5. Average daily vapor pressure deficit when applying 3 mm of irrigation across either four or 192 events from 06:00 a.m. to 10:00 p.m. over run A in a glasshouse in Knoxville, TN. Error bar indicates least significant difference for comparing means, and asterisks denote dates with significant differences among treatments ($P \leq 0.05$).

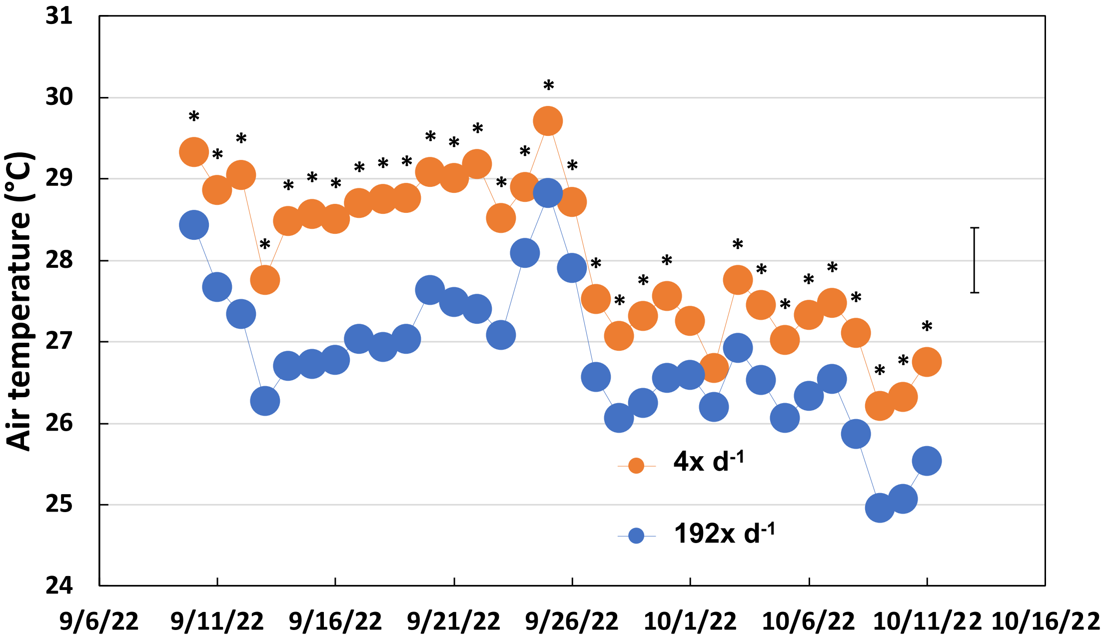

Figure 2.6. Average daily air temperature when applying 3 mm of irrigation across either four or 192 events from 06:00 a.m. to 10:00 p.m. over run B in a glasshouse in Knoxville, TN. Error bar indicates least significant difference for comparing means, and asterisks denote dates with significant differences among treatments (*P* ≤ 0.05).

APPENDIX 3

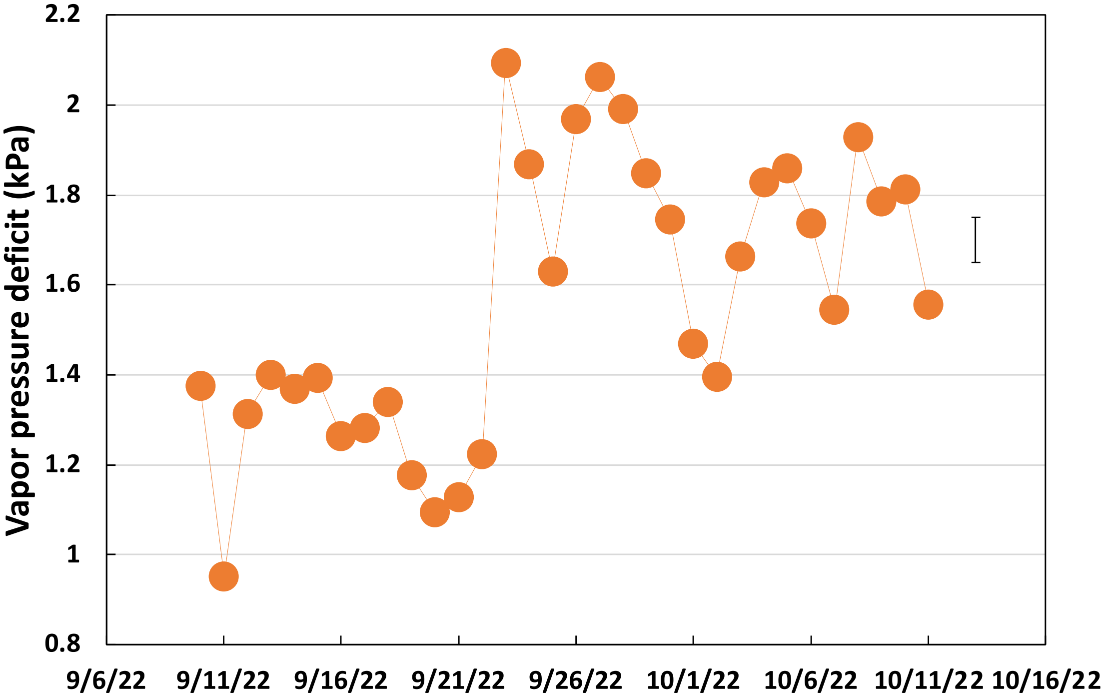

Figure 3.1. Average daily vapor pressure deficit when pooled across 3 mm of irrigation across either four or 192 events from 06:00 a.m. to 10:00 p.m. over run B in a glasshouse in Knoxville, TN. Error bar indicates least significant difference for comparing means (*P* ≤ 0.05).

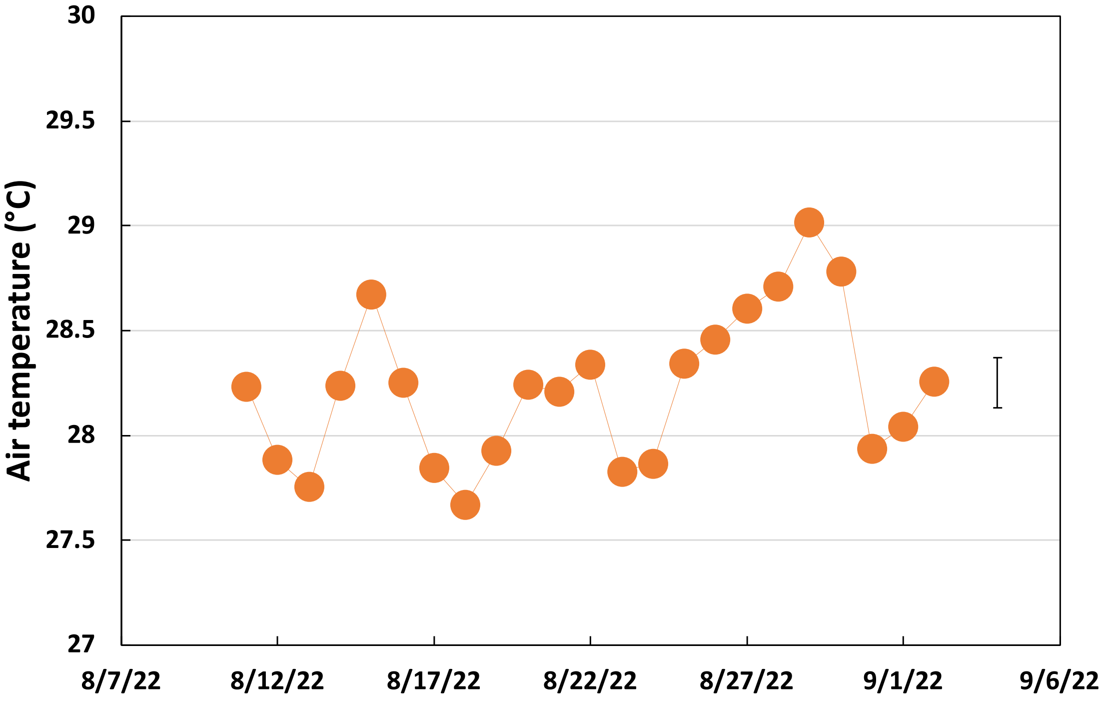

Figure 3.2. Average air temperature when pooled across 3 mm of irrigation across either four or 192 events from 06:00 a.m. to 10:00 p.m. over run A in a glasshouse in Knoxville, TN. Error bar indicates least significant difference for comparing means (*P* ≤ 0.05).

Table 3.1. Average air temperature when applying 3 mm of irrigation across either four or 192 events from 06:00 a.m. to 10:00 p.m. over run A in a glasshouse in Knoxville, TN. Data are pooled across all evaluation dates in run A.

Irrigation frequency (events d^{-1})	**Air temperature (°C)**
4	28.9 a
192	27.5 b
LSD (α = 0.05)	0.9

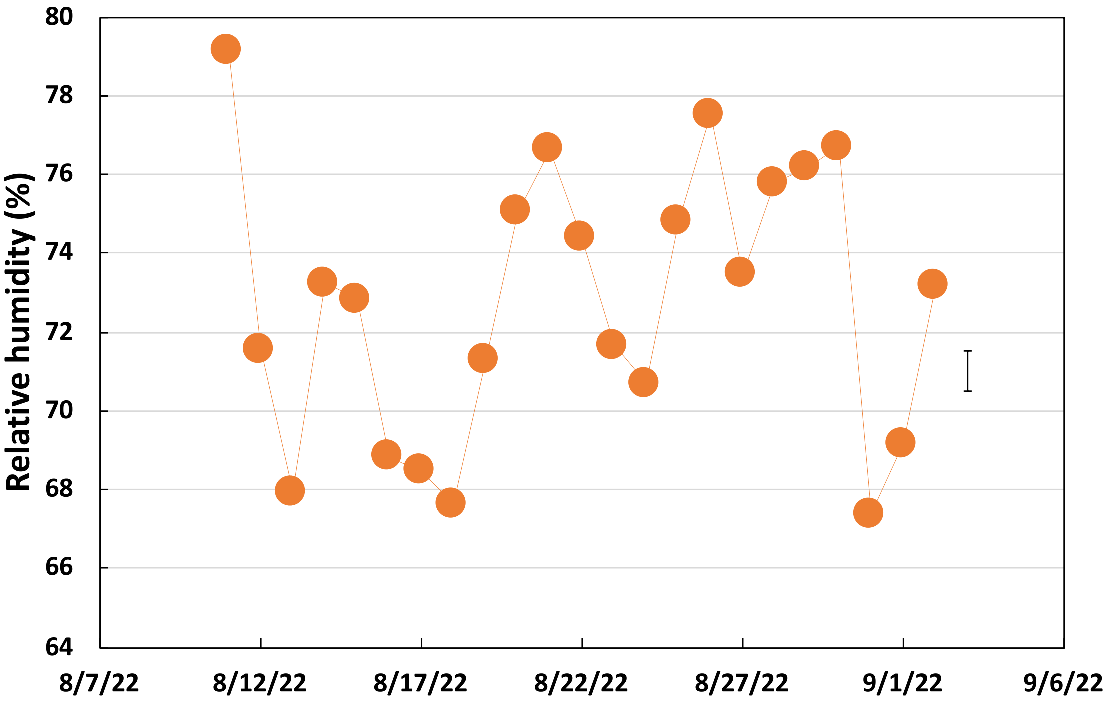

Figure 3.3. Average relative humidity when pooled across 3 mm of irrigation across either four or 192 events from 06:00 a.m. to 10:00 p.m. over run A in a glasshouse in Knoxville, TN. Error bar indicates least significant difference for comparing means ($P \leq 0.05$).

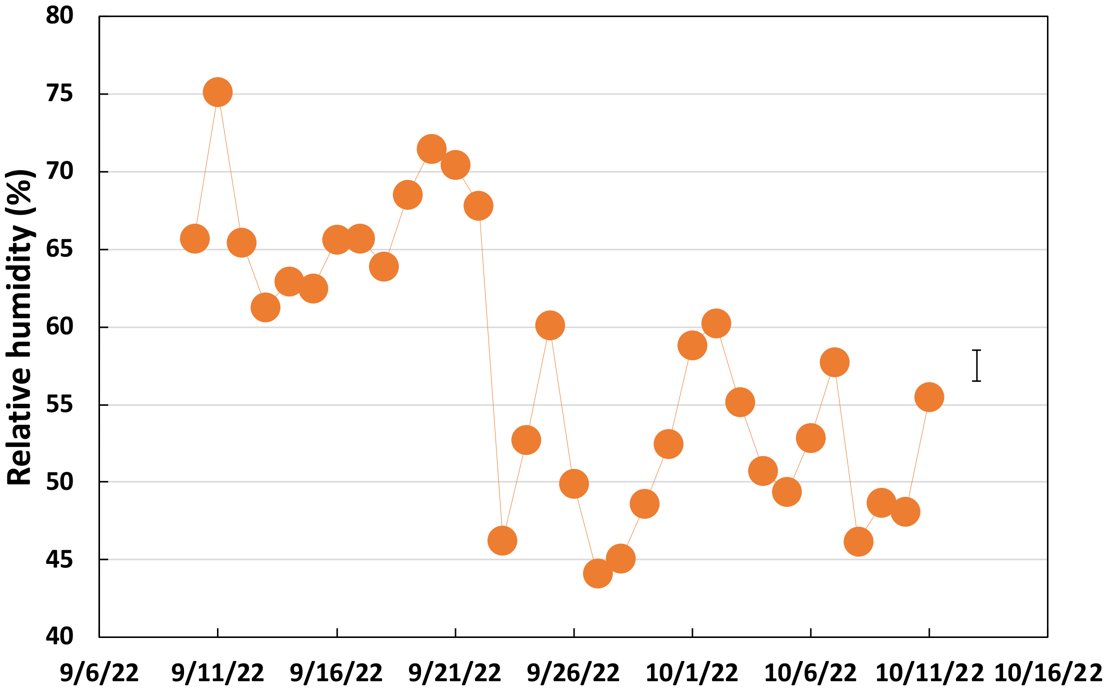

Figure 3.4. Average relative humidity when pooled across 3 mm of irrigation across either four or 192 events from 06:00 a.m. to 10:00 p.m. over run B in a glasshouse in Knoxville, TN. Error bar indicates least significant difference for comparing means (*P* ≤ 0.05).

SUPPLEMENTARY MATERIAL 2

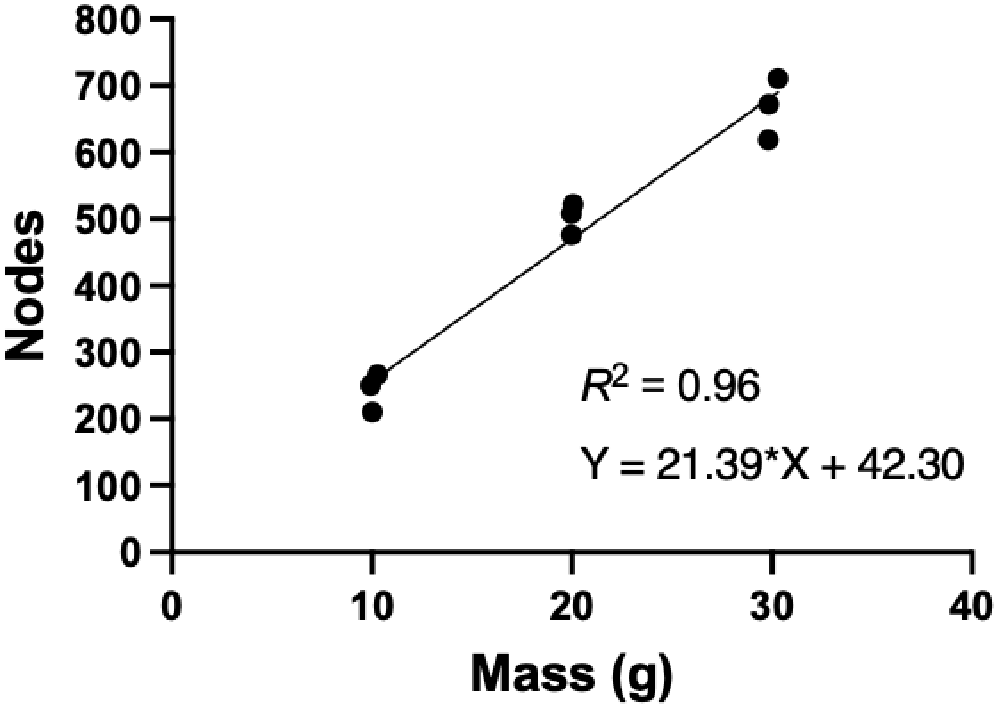

Figure S2.1. Linear regression analysis between increasing sprig material mass and increasing sprig node number in run A. The number of ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] nodes were determined for sprigs weighing 10, 20, and 30 g in Knoxville, TN in 2022.

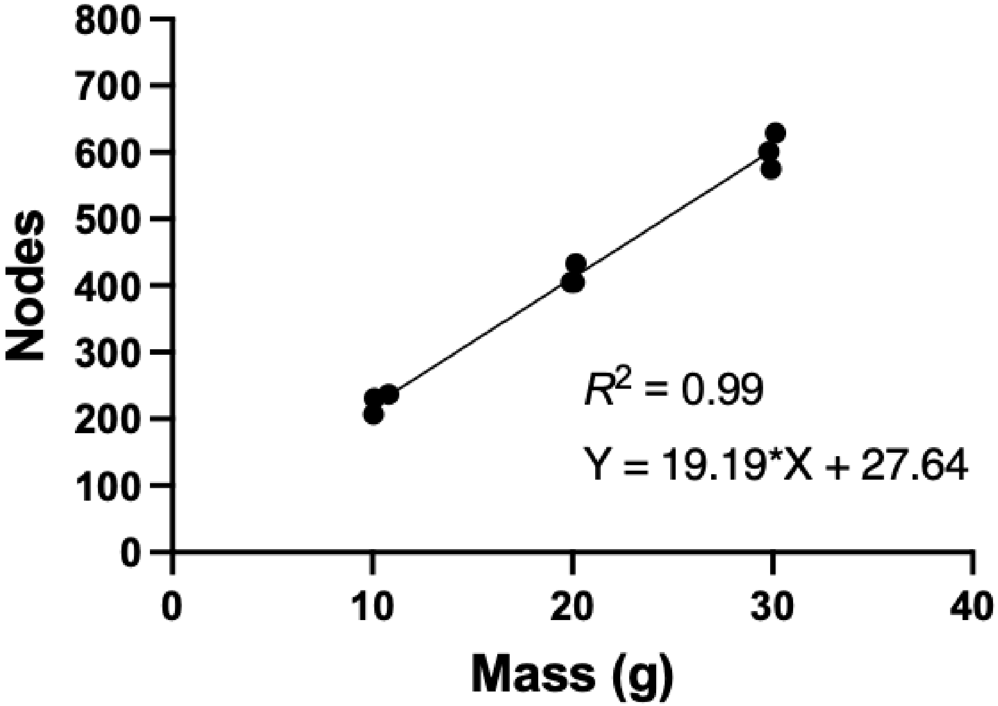

Figure S2.2. Linear regression analysis between increasing sprig material mass and increasing sprig node number in run B. The number of ‘Prizm’ zoysiagrass [*Zoysia matrella* (L.) Merr.] nodes were determined for sprigs weighing 10, 20, and 30 g in Knoxville, TN in 2022.

CONCLUSIONS

In recent years, golf course superintendents have become increasingly interested in the potential to reduce inputs from light, fertilizer, and labor by converting to zoysiagrass putting greens. However, zoysiagrass has consistently demonstrated slower establishment from sprigs than bermudagrass, which is likely a reason for its limited adoption. Findings from glasshouse experiments reveal that soil temperature is likely the factor limiting establishment rate of zoysiagrass sprigs in areas of the transition climatic zone in the United States.

A glasshouse experiment was conducted to evaluate the establishment of Prizm zoysiagrass sprigs under various soil temperature regimes. The findings infer that average 5 cm soil temperatures of 32 °C resulted in accelerated establishment compared to 28 °C or 36 °C. Across the duration of the experiment, limited diurnal variability in soil temperature was observed, which is unlikely to occur in an outdoor growing environment. Therefore, future research should evaluate establishment under varying soil temperatures while also demonstrating diurnal variability similar to field settings.

Frequent irrigation is generally recommended to limit sprig desiccation during establishment and may limit transpirational losses. An additional glasshouse experiment was conducted to determine the effect of irrigation frequency on Prizm zoysiagrass establishment from sprigs and found that establishment did not differ when receiving irrigation 4x d^{-1} or 192x d^{-1}. These results imply that zoysiagrass sprigs likely have limited sensitivity to elevated or variable vapor pressure deficit, which may be due to carbohydrate reserves in stolons and rhizomes. Research outlining energy relations of unrooted zoysiagrass sprigs could help guide management practices during establishment.

When evaluating irrigation frequency effects on establishment, soil temperature also contributed to variable establishment rates, with increasing soil temperature resulting in faster establishment. While these experiments provided an improved understanding of average soil temperature effects on establishment, a minimum soil temperature threshold may exist for optimal establishment.

Due to slower establishment under low temperatures, golf courses located in the transition zone may elect to establish zoysiagrass putting greens from sod instead of sprigs. Sodding will provide a playable putting surface faster than sprigging, but sod is considerably more expensive than sprigs. To best compare sodding and sprigging, a cost analysis should be conducted and include factors such as establishment duration for a given location and revenue lost from course closure over the establishment period (i.e., green fees, food and beverage, etc.). Additionally, future research is needed to outline optimal sod production and post-plant management practices so putting surfaces are playable within the shortest period.

VITA

Tyler Q. Carr was born on 30 March 1995 to Skip and Melissa Carr. Tyler is originally from White Hall, Arkansas and graduated from White Hall High School in 2013 before completing a Bachelor of Science Degree in Horticulture from the University of Arkansas in 2016. Tyler earned a Master of Science in Horticulture from the University of Arkansas in 2019 under the direction of Dr. Doug Karcher. Tyler began the Plant, Soil, and Environmental Sciences Ph.D. program at The University of Tennessee in 2020. At UT, he focused on environmental and management factors affecting zoysiagrass establishment from sprigs, which was directed by Dr. John Sorochan. Tyler is an advocate for graduate students and a proud founding member of the Plant Sciences Graduate Student Association at UT. Tyler is excited to serve current and future turfgrass professionals as Assistant Professor and Turfgrass Extension Specialist at The Ohio State University.