Strategic management of zoysiagrass in the U.S. transition zone

by

Manoj Chhetri

B.S., Tribhuvan University, 2010
M.S., Oklahoma State University, 2017

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Horticulture & Natural Resources
College of Agriculture

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Abstract

Zoysiagrasses (*Zoysia spp*. Willd.) are widely popular in the U.S. transition zone primarily due to lower input requirements than C_3 species, such as creeping bentgrass (*Agrostis stolonifera* L.), and better cold tolerance than some C_4 species, such as bermudagrass (*Cynodon spp.* L.C. Rich.). 'Meyer' zoysiagrass has long been an industry standard in the transition zone for use in golf course fairways and tees, and home lawns. The new cultivar Innovation™ offers finer leaf texture, improved shoot density, and similar cold tolerance when compared to Meyer. To expand the use of Innovation and other zoysiagrass genotypes that may be released, research on understanding water management, drought tolerance, seedhead management, large patch tolerance, and cold tolerance is needed. As such, the objectives of this dissertation were to: (1) compare Innovation zoysiagrass performance resulting from irrigation applied using the following strategies: i) a routine schedule, ii) reference evapotranspiration (ET)-based, iii) Soil moisture sensor (SMS)-based, and iv) no irrigation; (2) determine the efficacy of ethephon on Innovation zoysiagrass seedhead suppression; (3) identify and validate models that best estimate optimum application time for ethephon to suppress 'Meyer' zoysiagrass seedhead development; (4) evaluate the performance of ten large patch-tolerant zoysiagrass genotypes; and (5) identify new, fine-textured, cold hardy zoysiagrass genotypes. In the irrigation study, the SMS-based irrigation in Manhattan, KS saved 68% and 51% water compared to a routine schedule and ET-based irrigation, respectively. In Dallas, TX the corresponding water savings were 30% and 14%, respectively. The different soil types and the climate likely affected the performance. In Manhattan, KS ethephon applied between 20 August and 18 September were generally effective in Innovation seedhead suppression as >70% suppression was observed on three dates across two seasons. Variation between years was evident, and ethephon application based on calendar dates should be used cautiously. In a separate experiment, a multiple linear regression model, second-degree polynomial, and Gaussian function were fit to Meyer seedhead suppression following ethephon application. The seedhead suppression results were obtained from the field study conducted across four locations in the transition zone. The Gaussian model provided the best fit (adjusted determination coefficient = 0.58, root mean square error = 20.3) among the three identified models and performed best at making predictions within the peak seedhead suppression region upon verification through new independent field observations. The proposed model could be utilized as a prediction tool to effectively time ethephon for effective seedhead suppression in Meyer zoysiagrass in the transition zone. The large patch-tolerant progeny evaluation showed that experimental genotypes, DALZ 1701 and DALZ 1702 had overall better turf performance than Meyer or Innovation zoysiagrass. Another genotype, DALZ 1707 performed better than Meyer, but not as well as Innovation zoysiagrass. In a separate experiment, 20-best performing new zoysiagrass genotypes were selected from a set of 935 progeny that survived the winter from 2018 through 2020. The findings of this dissertation provide insights on innovative and sustainable approaches to zoysiagrass management and would be useful to zoysiagrass managers in the transition zone and beyond.

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Approved by:

Co-Major Professor
Dr. Megan Kennelly

Approved by:

Co-Major Professor
Dr. Jack Fry

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Table of Contents

List of Figures

List of Tables

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Dedication

I dedicate this work to my lovely son, Sohum Chhetri and my wonderful wife, Durga Khadka.

Chapter 1 - Introduction

Zoysiagrass Adaptation

Turfgrasses in the United States have two broad regions of adaptation: north and south. In the northern region, cool-season or C_3 turf species are well-adapted, whereas warm-season or C_4 turfgrasses are best adapted in the southern region (Christians, 2011). The vast area between the north and south is shared by both C_3 and C_4 turf species and is commonly referred to as the transition zone. The transition climate zone is a horizontal region that runs along the lower half of the country from the state of Delaware in the east to California in the west, including the state of Kansas (Dunn & Diesburg, 2004). This region is challenging to manage turfgrass because summers tend to be too hot for C_3 species, while winters are too cold for the survival of some C_4 species.

Warm-season turfgrass is attractive to turf managers in the transition zone because of the lower cost of management, as they require less water and fertilizers inputs than cool-season turfgrasses (Fry et al., 2008). Zoysiagrass (*Zoysia* spp. Willd.), a warm-season turfgrass, is commonly used on home lawns and golf course fairways, tees, and roughs in the transition zone. ‘Meyer’ zoysiagrass (*Zoysia japonica*) forms a dense canopy that provides an excellent playing surface and turf quality for use in golf course fairways and tees. Meyer is recognized for improved cold tolerance that makes this cultivar popular in the U.S. transition zone since its release in 1952 (Grau & Radko, 1951, Fry et al., 2008).

Innovation™ zoysiagrass, an interspecific hybrid crossed between *Z. matrella* ‘Cavalier’ and Anderson 1, an ecotype of *Z. japonica*, is a fine-textured, cold-tolerant zoysiagrass (Chandra et al., 2017). Innovation™ zoysiagrass, patented under the name KSUZ 0802, will be referred to as ‘Innovation’ zoysiagrass throughout this dissertation. It was released in 2015 for use in the transition zone as an alternative to Meyer. Previous multi-location reports demonstrated that

Innovation has superior (finer) leaf texture, turf quality, and resistance to bluegrass billbugs (*Sphenophorus parvulus* Gyllenhal), and similar cold hardiness, spring green up, and fall color retention compared to Meyer at both lawn (3.8 to 6.4 cm) and fairway (1.3 cm) heights of cut (Chandra et al., 2017). Since Innovation is a new cultivar, information on irrigation requirements, drought tolerance, and seedhead production and management are lacking.

Turfgrass Water Requirements

Turfgrass is estimated to cover more than 16 million ha of land, which is about three times the area of any irrigated crop in the continental United States (Milesi et al., 2005), and supplemental irrigation is required to maintain good quality turf (Huang, 2008). Thus, a significant fraction of potable water is used for turfgrass irrigation. The water requirements of C_3 species are higher than those of C_4 species as demonstrated by the higher evapotranspiration (ET) rates of C_3 species across wide locations in both well-watered and water-stressed conditions (Carrow, 1995; Feldhake et al., 1983; Fu et al., 2004; Meyer & Gibeault, 1987; Qian et al., 1996). For instance, under non-limiting soil moisture conditions in Kansas, the daily evapotranspiration (ET) rates of the C_3 species tall fescue [*Schedonorus arundinaceus* Schreb.] (5.7 to 5.9 mm) and Kentucky bluegrass [*Poa pratensis* L.] (5.6 mm) were significantly higher than those of the C_4 species bermudagrass [*Cynodon* spp. L.C. Rich.] (4.0 to 4.1 mm) and zoysiagrass (3.9 to 4.4 mm) (Fu et al, 2004). The use of C_4 rather than C_3 species for turf would be a sustainable water saving alternative.

Irrigation Controllers in Turfgrass

In recent years, smart irrigation controllers, which allow adjustment of irrigation cycles according to weather parameters or soil moisture status, are becoming increasingly popular (Dukes, 2020). Such controllers are equipped with a user interface module to allow run times based on signals received. Two widely popular smart irrigation controllers are those which use ET-based information and those which use soil moisture sensor (SMS)-based information. The former depends on the reference ET (ET_0) data obtained from onsite or a remote weather station, while the latter receives signals from the SMS buried onsite. Results from research stations and residential sites have demonstrated acceptable quality can be maintained with significant water savings over a wide range of soil types and climates using these smart irrigation controllers for both C_3 and C_4 turfgrass species (Blonquist et al., 2006; Chabon et al., 2017; Fazackerley & Lawrence, 2010; Cardenas-Laihacar & Dukes, 2010; Cardenas-Laihacar et al., 2010; Dukes, 2012; Grabow et al., 2013; Haley & Dukes, 2012; Pathan et al., 2007; Serena et al., 2020).

Seedheads in Meyer and Innovation Zoysiagrass

Meyer and Innovation zoysiagrass provide high-quality playing surfaces on fairways and tees; however, they produce seedheads in late spring that impact the playing surface and aesthetics. In both Meyer and Innovation zoysiagrass, seedheads leave a purple cast across fairways and tees on golf courses when they emerge, and after mowing seed stalks that remain leave a white cast to these areas. The disruption of playability and poor aesthetics due to lingering seedheads on playing surfaces are concerning to golf course superintendents and golfers (Kane & Miller, 2003). In addition, the increased mowing requirements due to aggressive seedhead production requires greater fuel, labor, and equipment maintenance costs for golf courses (Brosnan et al., 2012).

Use of Plant Growth Regulators in Seedhead Management

Mowing is a fundamental practice to slow down the inflorescence development in turf; however, there are costs associated with increased mowing requirements and quality post-mowing is not ideal during the seedhead production stage in spring. Therefore, alternative approaches for seedhead management through the use of plant growth regulators (PGRs) are gaining attention.

The use of ethephon (2-Chloroethylphosphonic acid) (Proxy®, Bayer Environmental Science) for seedhead suppression in annual bluegrass (ABG) (*Poa annua*) has been extensively studied, while studies on C_4 turfgrasses are limited. In Tennessee and Indiana, two-sequential spring applications of ethephon on Meyer zoysiagrass suppressed seedheads by 60 to 89% (Brosnan et al., 2012). Recent research on Meyer across three locations in the transition zone demonstrated that a single application of ethephon in autumn provided >90% suppression (Patton et al., 2018). In contrast, a greenhouse study in South Carolina reported that ethephon was ineffective in suppressing seedheads applied to a 'Diamond' zoysiagrass [*Zoysia matrella* (L.) Merr.] in spring or autumn (Ledford, 2019). Anecdotal evidence and other unpublished work support that seedhead suppression results from ethephon are inconsistent as it varies from location to location and year to year (Bigelow & Hardebeck, 2004).

PGR Application Based on Growing Degree-Days

One of the major challenges in the use of ethephon for seedhead suppression is determining the optimum application timing. Researchers have attempted to identify optimum application timing of mefluidide (a widely used PGR) for ABG seedhead suppression using growing degree-days (GDD) (Branham & Danneberger, 1989; Danneberger et al., 1987). The GDDs, a unit that accounts for temperature, more accurately predicts temperature-dependent events such as germination, flowering, and maturity, compared to calendar days (Cross & Zuber, 1972). The GDD-timed application of mefluidide or ethephon for seedhead suppression in C_3 turfgrasses has been successful in several studies (Branham & Danneberger, 1989; Calhoun, 2010; Danneberger et al., 1987; Haguewood et al., 2013; Reicher et al., 2020). Patton et al. (2018) reported that in Meyer zoysiagrass, a spring application of ethephon was found to be ineffective, whereas fall application was effective in a study across three locations. This suggests the application timing influences the efficacy of ethephon in Meyer. No research has been done to determine preferred application timing for ethephon based on GDD or environmental parameters. A study in Georgia reported the relationship between seedhead emergence and environmental conditions in ‘Diamond’ zoysiagrass (McCullough et al., 2017). The peak seedhead production in Diamond zoysiagrass (maintained at 1.3 cm height of cut) was strongly correlated with GDD determined using a 10 ^{0}C base temperature (r = 0.79). In the same experiment, seedhead production in Diamond was also correlated with photoperiod (r = 0.64). Considering the fact that ethephon and mefluidide are most effective in suppressing annual bluegrass seedheads when the timing is based upon GDD, it is plausible to surmise similar models based on environmental factors will be useful on zoysiagrass as well.

Large Patch in Zoysiagrass

A persistent challenge with zoysiagrass is its susceptibility to large patch disease (Green et al., 1993). Large patch is caused by the fungus *Rhizoctonia solani* Kühn AG 2-2 LP. The disease is most active when zoysiagrass is slowly growing, i.e., before entering dormancy in autumn and after breaking dormancy in spring (Koehler et al., 2017). The cool, wet weather accompanied by poor drainage, restricted airflow, and soil compaction favors large patch disease in zoysiagrass (Obasa et al., 2017). The initial symptoms begin with small, round discolored patches that can expand up to several meters in diameter. The symptoms of large patch are reported to recur at the same location in the following years with an expansion rate of up to one meter annually (Aoyagi et al., 1998; Obasa et al., 2012). Although a few cultural practices have been reported to ameliorate large patch severity (Green et al., 1994; Kennelly et al., 2008; Obasa et al., 2013), most of the zoysiagrass managers rely on routine fungicide applications to manage large patch (Obasa et al., 2017). The cost associated with the use of fungicides in spring and fall to prevent large patch is a concern for zoysiagrass turf managers. The best fungicides for suppressing this disease can cost about \$865 ha^{-1} (Genovesi et al., 2019).

The development of large patch-tolerant zoysiagrass cultivars could be a promising alternative to fungicides. Researchers at Texas A&M AgriLife Research, Dallas, in cooperation with Kansas State University, Manhattan, and Purdue University, West Lafayette have been working to identify and develop large patch-tolerant genotype that can survive the cold winter of the U.S. transition zone (Genovesi & Chandra, 2015; Braun, 2014; Xiang, 2018).

Zoysiagrass Cultivar Selection in The Transition Zone

There are several high quality zoysiagrass cultivars available on the market in the southern U.S. Fine-textured zoysiagrass cultivars, such as 'Zorro', 'Zeon' and 'Trinity' have provided an excellent playing surface for golf course fairways and tees in the southern region (Roberts, 2019). Additionally, in the southeast U.S., ultra-dwarf cultivars, such as 'Diamond' zoysiagrass, can tolerate mowing as low as 2.5 mm. The main reason behind the popularity of finer-textured zoysiagrass in the southeast U.S. is its improved shade tolerance compared to ultra-dwarf bermudagrass. In the transition zone where winters are harsh and bermudagrass often gets damaged from winter kill, cold tolerance of zoysiagrass is highly acclaimed. However, the choice of zoysiagrass cultivars in the transition zone is limited. Thus, development of dense, fine-textured zoysiagrass that can be used on golf course tees and putting greens would open a whole new market in the transition zone.

Objectives

Despite a plethora of research work conducted in the management of zoysiagrass, more research towards improving irrigation strategy, managing seedheads using PGRs, and evaluating large-patch tolerant and cold hardy zoysiagrass genotypes is warranted. As such, the objectives of my research highlighted in subsequent chapters were to: (1) compare Innovation zoysiagrass performance resulting from irrigation applied using the following strategies: i) a routine schedule, ii) reference evapotranspiration (ET)-based, iii) Soil moisture sensor (SMS)-based, and iv) no irrigation; (2) determine the efficacy of ethephon on 'Innovation' zoysiagrass seedhead suppression; (3) identify and validate models that best estimate optimum application time for ethephon to suppress 'Meyer' zoysiagrass seedhead development; (4) evaluate the performance of ten large patch-tolerant zoysiagrass genotypes; and (5) identify new, fine-textured, cold hardy zoysiagrass genotypes.

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Chapter 2 - Water Savings and Performance of Innovation™ Zoysiagrass in Response to Irrigation Strategy

This chapter has been prepared using style guidelines for the journal Crop Science.

Abstract

Water use in turfgrasses have been under scrutiny in recent years. More stringent restrictions on water use for turfgrasses are foreseeable. Irrigation methods that can minimize water use are needed and several prior studies have emphasized use of a "smart" irrigation controller. Innovation™ zoysiagrass is a new warm-season turfgrass for use in golf course fairways/tees and home lawns in the U.S. transition zone. Performance of zoysiagrass has not been evaluated using smart-controller research. Therefore, field experiments were conducted in Manhattan, KS and Dallas, TX. The objectives of this study were to compare the amount of water applied and Innovation performance resulting from irrigation using: 1) routine irrigation (3 cm $week^{-1}$); 2) evapotranspiration (ET)-based irrigation (60% of reference ET); 3) soil moisture sensor (SMS)-based irrigation; and 4) no irrigation, and to evaluate drought tolerance and recovery after drought stress. The experiment was conducted under a rain-out shelter in Kansas from 15 July to 27 Sept. 2019 and 8 June to 19 Oct. 2020. In Texas, the experiment was conducted under open field from 22 June to 9 Sept. 2020. The soil in Kansas was a Chase silty clay loam and in Texas was an Austin silty clay. The SMS-based irrigation method in Kansas reduced water application by 68% and 51%, respectively, compared to routine or ET-based irrigation. In Texas, the corresponding water savings were 30% and 14%, respectively. Visual turf quality of turf receiving SMS-based irrigation remained above the minimal acceptable level throughout the study in Kansas, whereas in Texas, turf quality declined below acceptable level after two weeks. The different soil type and the climate likely affected performance. In Kansas, Innovation zoysiagrass sustained acceptable quality for more than 21 days with no irrigation, and after rewatering nonirrigated turf recovered back to 93% green cover (GC) (from 80%) within one week in 2019 and to 67% GC (from 9%) within two weeks in 2020. Soil moisture sensors are useful for saving irrigation water, and Innovation zoysiagrass demonstrated good drought tolerance and recovery after drought.

Introduction

Turfgrass is estimated to cover more than 16 million ha of land, which is about three times the area of any irrigated crop in the continental United States (Milesi et al., 2005), and supplemental irrigation is required to maintain good quality turf (Huang, 2008). Thus, a significant fraction of potable water is consumed on turfgrass irrigation. Outdoor water use has been reported to contribute up to 67% of total household water use in North America (Deoreo et al., 2016; Haley et al., 2007). Interestingly, Deoreo and Mayer (2012) found that indoor water uses per capita has been declining in recent years mainly due to increased use of water-efficient plumbing fixtures, but the outdoor water uses per person has remained unchanged (if not increased). Studies found that in-ground, timer-based sprinkler systems increased the irrigation amount by up to 47% in home lawns compared to those without in-ground irrigation (Bremer et al., 2012; Mayer et al., 1999). Results from a study conducted across nine cities in North America indicated that 13% of single-family dwellers irrigated their landscape more than the recommended rates for optimal growth (Deoreo et al., 2016). According to a survey, owners of expensive homes and/or newer homeowners in Kansas were more likely to overirrigate their lawns than owners of older homes (Bremer et al., 2015). With increasing urbanization (U.S. Census Bureau, 2016), newer house construction (Milesi et al., 2009), and prolonged drought periods due to climate change (Hatfield, 2017), municipal restrictions on water use are inevitable and therein lies the need for water conservation in landscape irrigation. Reports suggested that the public perceives landscape irrigation as the least important use of water among other reasons for household water use, and this indirectly corroborates the acceptance of restricted water use ordinances on landscapes (Stoutenborough & Vedlitz, 2014). Research, development and use of water-efficient irrigation systems and best management practices, along with selection of species and cultivars requiring less water are, therefore, critical for water conservation.

In the transition zone of United States, both cool-season (C_3) and warm-season (C_4) turfgrasses are adapted for use in home lawns, athletic fields, and golf courses. The water requirements of C_3 species are higher than those of C_4 species as demonstrated by the higher evapotranspiration (ET) rates of C_3 species across wide locations in both well-watered and water-stressed conditions (Carrow, 1995; Feldhake et al., 1983; Fu et al., 2004; Meyer & Gibeault, 1987; Qian et al., 1996). For instance, under non-limiting soil moisture conditions in Kansas, the daily evapotranspiration (ET) rates of the C_3 species tall fescue [*Schedonorus arundinaceus* Schreb.] (5.7 to 5.9 mm) and Kentucky bluegrass [*Poa pratensis* L.] (5.6 mm) were significantly higher than those of the C_4 species bermudagrass [*Cynodon* spp. L.C. Rich.] (4.0 to 4.1 mm) and zoysiagrass [*Zoysia* spp. Willd.] (3.9 to 4.4 mm) (Fu et al, 2004). Grasses with lower ET rates were reported to have more plant water available in the soil profile, and therefore remained green for longer periods during water-limiting conditions (Zhou et al., 2009). Use of C_4 rather than C_3 species for turf, would be a sustainable water saving alternative. There are an estimated 199,662 ha of turfgrass in Kansas, 60% of which are assumed to be irrigated (Milesi et al., 2009). Among the C_4 species, zoysiagrass for use on golf course fairways, tees, and lawns is favored in areas of the transition and northern transition zone like Kansas because of its cold hardiness, shade tolerance, and minimal mowing and nutrition requirements (Hinton et al., 2012; Patton, 2009; Patton & Reicher, 2007; Wherley et al., 2011).

Zoysiagrass is a genetically rich and widely adapted turfgrass as there are at least 11 species cultivated as turfgrass (Anderson, 2000). *Z. japonica* Steud. and *Z. matrella* (L.) Merr. are the two predominant species in the south and transition zone of the United States. Patton et al. (2017)

reported that the *Z. japonica* types perform well at higher mowing heights (13-64 mm), have coarse leaf texture (>2.5 mm), and tolerate low freezing temperatures, while *Z. matrella* types tolerate low mowing heights (6.4 to 51 mm), have finer leaf texture (1.5 to 2.5 mm), and are less tolerant to cold. For example, 'Meyer', a *Z. japonica* cultivar, has good cold tolerance (-11.5 ^{0}C), performs well at lawn and fairway mowing heights, and has a coarser leaf texture than 'Diamond', a *Z. matrella* cultivar, which has a finer leaf texture, performs well at putting green heights, and has poor cold hardiness (-8.4 ^{0}C) (Patton & Reicher, 2007). Innovation™ zoysiagrass, an interspecific hybrid crossed between *Z. matrella* 'Cavalier' and Anderson 1, an ecotype of *Z. japonica*, is a fine-textured, cold-tolerant zoysiagrass (Chandra et al., 2017). Innovation™ zoysiagrass, patented under the name KSUZ 0802, will be referred to as 'Innovation' zoysiagrass throughout this chapter. It has been released recently for use in the transition zone as an alternative to Meyer, which has been an industry standard in the transition zone since its release in 1952 (Grau & Radko, 1951). Previous multi-location reports demonstrated that Innovation has superior (finer) leaf texture, turf quality, and resistance to bluegrass billbugs (*Sphenophorus parvulus* Gyllenhal), and similar cold hardiness, spring green up, and fall color retention compared to Meyer at both lawn (3.8 to 6.4 cm) and fairway (1.3 cm) heights of cut (Chandra et al., 2017). The information on irrigation requirements and drought tolerance of Innovation is limited, however.

In recent years, smart irrigation controllers, which are capable of adjusting irrigation cycles according to weather parameters or soil moisture status, are becoming increasingly popular (Dukes, 2020). Such controllers are equipped with a user interface module to allow run times based on signal received. Two widely popular smart irrigation controllers are those which use ET-based information and those which use soil moisture sensor (SMS)-based information. The former depends on the reference ET (ET_0) data obtained from onsite or remote weather station, while the latter receives signals from the SMSs buried onsite. Results from research stations and residential sites have demonstrated acceptable quality can be maintained with significant water savings over a wide range of soil types and climates using these smart irrigation controllers for both C_3 and C_4 turfgrass species (Blonquist et al., 2006; Chabon et al., 2017; Fazackerley & Lawrence, 2010; Cardenas-Lailhacar & Dukes, 2010; Cardenas-Lailhacar et al., 2010; Dukes, 2012; Grabow et al., 2013; Haley & Dukes, 2012; Pathan et al., 2007; Serena et al., 2020). Water savings from using such smart controllers as compared to irrigation on a time-based routine is largely due to bypassing of irrigation schedules during periods of less water demand. All the previous studies were conducted in open field conditions with no control of natural precipitation and therefore lack of a control treatment that received no water at all. Furthermore, performance of zoysiagrass has not been evaluated using smart-controller research. Therefore, our goal was to investigate the water savings potential of ET-based and SMS-based irrigation methods on Innovation zoysiagrass managed in fine-textured soil. The objectives of this study were to compare the amount of water applied and 'Innovation' performance resulting from irrigation using: 1) a routine schedule (Routine); 2) reference ET-based; 3) SMS-based; and 4) no irrigation and to evaluate drought tolerance and recovery after drought stress.

Materials and Methods

Manhattan Study Site

A two-year field study was conducted from 15 July to 27 Sept. 2019 and 8 June to 19 Oct. 2020 under a fixed, polyethylene-covered (labeled by the company as 90% light transmission; Sunview 6 Mil UV clear, Hummert International, Topeka, KS) rainout shelter at the Rocky Ford Turfgrass Research Center in Manhattan, KS (humid continental climate in the transition zone of

United States; $39^0 13'50''$ N, $96^0 34'46''$ W). The shelter measured 21 m long x 12 m wide x 8 m tall with a ground clearance of 1.5 m on the long sides of the structure and 2.6 m on the 12 m wide ends to promote air circulation. The area was sprigged with Innovation zoysiagrass in June 2017 and had full coverage by the end of the 2017 growing season. The soil type was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) with a pH of 7.3. The edges of the experimental area were at least 1.8 m from the edges of the shelter to avoid rainfall, and the rainout shelter was also equipped with gutters on the long sides to divert rainwater away from the structure. Plots were fertilized before starting the treatment, twice on 3 June and 1 July with urea (46−0−0, Lesco Professional Turf Fertilizer) to provide 98 kg N ha^{-1} $year^{-1}$ in 2019 and once on 26 May to provide 49 kg N ha^{-1} $year^{-1}$ in 2020. The site was mowed with a walk-behind reel mower at 1.6 cm height of cut twice weekly with clippings returned. Dithiopyr (Dimension 2EW, Dow AgroSciences) was applied to prevent crabgrass emergence at 0.28 kg ha^{-1} on 19 April 2019 and 24 April 2020. A mixture of 2,4-D, 2-ethylhexyl ester at 0.43 kg ha^{-1}, mecoprop-p acid at 0.13 kg ha^{-1}, dicamba acid at 0.04 kg ha^{-1}, and carfentrazone-ethyl at 0.01 kg ha^{-1} (Speedzone, pbi/Gordon Corporation) as a post-emergence broadleaf herbicide was applied on 19 April and 20 June 2019, and on 10 May 2020. Flutolanil (ProStar 70 WG, Bayer Environmental Science) was applied on 4 Sept 2019 and 10 Sept. 2020 at 9.8 kg ha^{-1} to prevent large patch infection. Plots were irrigated three times per week before initiating the irrigation treatments to prevent visible drought stress using an in-ground sprinkler system.

The experiment was arranged in a randomized complete block design consisting of four irrigation strategies with three replicates: (i) Routine, (ii) ET-based, (iii) SMS-based, and (iv) Nonirrigated. Plots measured 1.8 m by 3 m. Routine irrigation was applied on Monday, Wednesday, and Friday (MWF) to provide one cm of water each day. Plots receiving ET-based irrigation were watered on MWF at 60% of reference ET (ET_0) since the last irrigation, which was provided by Kansas Mesonet (https://mesonet.k-state.edu/) based upon data collected by a weather station located about 50 m away from the experimental site. Kanas Mesonet uses American Society of Civil Engineers standardized reference ET equation (Walter et al., 2001). SMS-based treatments were applied when average volumetric soil water content within the three replicates averaged 11% in 2019 and 15% in 2020, which were determined to be the point at which visible wilt began to appear during the first dry down of each year. After reaching the threshold levels, 1.5 cm of water was applied each time to bring the soil moisture status to near field capacity. Nonirrigated treatments did not receive irrigation during the dry down period. All plots were hand watered using a fan nozzle and flow meter (Great Plains Industries, Inc., Wichita, KS) attached to a hose with a delivery output of 15 L $min.^{-1}$. In 2019, the irrigation treatment period ran from 15 July to 30 Aug. for 46 days and the recovery period ran from 1 to 27 Sept. for 27 days. In 2020, the irrigation treatment period ran from 8 June to 7 Sept. for 91 days, and recovery period ran from 8 Sept. to 19 Oct. for 41 days. On 9 July 2020, four weeks after initiating the treatment (WAT), the rainout shelter experienced damage due to a thunderstorm, and the entire experimental area received 3.6 cm of rain. The shelter was repaired, and irrigation treatments resumed on 17 July 2020 (8 days after damage). After the completion of irrigation treatments on 30 Aug. 2019 and 7 Sept. 2020, all plots were irrigated three times weekly with in-ground sprinkler system to provide 3 cm of water per week (aka "full irrigation") to evaluate recovery for a period of four weeks in 2019 and six weeks in 2020.

Data were collected weekly to determine visual turf quality (TQ), Normalized Difference Vegetation Index (NDVI), and digital percent green cover (GC) before irrigation was applied. Turf quality was rated on a 1 to 9 scale where 1 = poorest quality; 6= minimally acceptable quality; and

9 = optimum color, uniformity, and density (Morris & Shearman, 1998). Measurement of NDVI was done using a handheld RapidScan CS-45 meter (Holland Scientific Inc., Lincoln, NE) from a height of 76 cm. Digital images were captured using a camera (Nikon D5000) mounted on the top of a light box that provided uniform light to avoid alteration in natural sunlight. Images were subjected to analysis with SigmaScan Pro (version 5.0, SPSS Science Marketing Department) using threshold settings of 48 to 110 for hue and 0 to 100 for saturation to determine GC (Karcher & Richardson, 2005).

A SMS (Model CS655, Campbell Scientific Inc., Logan, UT) was buried at a 10-cm depth in the center of each plot. Each sensor was wired to a CR10X datalogger (Campbell Scientific Inc.) powered with a 20W solar panel (NPA20S-12H, Newpowa) and programmed to obtain data at a 1-min frequency and record the average every hour. The experimental area was irrigated to saturation prior to initiation of irrigation treatments each year and soil moisture data collected 24 hours later was utilized to estimate soil field capacity. Also, the volumetric soil water content at the end of the treatment phase in nonirrigated plots was determined as the permanent wilting point. Data collection for all parameters continued throughout the recovery period.

Dallas Study Site

A separate one-year irrigation experiment on Innovation zoysiagrass was conducted from 22 June through 9 Sept. 2020 at Texas A&M AgriLife Research and Extension Center, Dallas, TX (humid sub-tropical climate in the southern United States; $32^0$59’13’’ N, $96^0$46’3’’ W) in an open-sky environment. The soil at the site was Austin silty clay (fine-silty, carbonatic, thermic Udorthentic Haplustolls) with pH of 7.7, P of 9 mg kg^{-1}, and K of 399 mg kg^{-1}. The study area was established on 29 March 2019 using sod harvested from nearby nursery plots. Immediately after planting, the site received oxadiazon (Ronstar G, Bayer Environmental Science) at 4 kg a.i. ha^{-1} to control weeds and a starter fertilizer (18–24–12, The Andersons, Inc.) at 25 kg N ha^{-1}. The field was verticut on 7 May 2020 using a walk-behind verticutter (Ryan, Johnson Creek, WI) with a single pass in two directions, followed by rolling. The plots were mowed at a 1.3 cm height three times weekly using a reel mower and fertilized with a slow-release fertilizer (25–5–10, Harrell's LLC) at 220 kg N ha^{-1} $year^{-1}$ in three equal split applications on 9 May, 12 June, and 29 July 2020, to meet the recommended amounts for the length of growing season in that location. Additionally, the plots received fertilizer from 5–0–10 with 1% oxadiazon (The Andersons, Inc.) applied at 9.7 kg N ha^{-1} on 29 March 2020 (oxadiazon at 1.9 kg a.i. ha^{-1}). A preventive insecticide, imidacloprid (Mallet 2F T&O, Nufarm Americas, Inc.) at 0.5 kg a.i. ha^{-1} was applied on 19 May 2020. On 29 July, a preventative fungicide mixture cyazofamid at 0.6 kg ha^{-1} and azoxystrobin at 0.3 kg ha^{-1} (Union, pbi/Gordon Corporation) was applied, followed by application of the insecticide bifenthrin (Talstar P, FMC Professional Solutions) at 0.3 kg a.i. ha^{-1} on 7 Aug. 2020 to control grubs (*Phyllophaga* spp.). Plots were well-irrigated to avoid visible drought stress prior to beginning irrigation treatments.

In this experiment, irrigation treatments were carried out in two phases. The first occurred for a period of 30 d from 22 June to 22 July 2020 and the second ran for another 30 d from 10 Aug. to 9 Sept. 2020 after allowing the grass to recover for 18 d between phases. This was done because significant stress occurred on Innovation in nonirrigated treatments, and a recovery period was needed. Each plot measured 3 m by 1.2 m. The treatments were arranged in a randomized complete block design with three replicates. Irrigation treatments were identical to those evaluated in Manhattan, KS: (i) Routine, (ii) ET-based, (iii) SMS-based, and (iv) Nonirrigated. Routine treatments received irrigation on Monday, Wednesday, and Friday (MWF) to provide one cm of water each day. Plots receiving ET-based irrigation were watered on MWF at 60% of ET_0 since the last irrigation. ET_0 data was obtained from the Texas ET Network, Richardson station (https://texaset.tamu.edu/). This station uses the standardized Penman-Monteith method to calculate ET_0. Irrigation schedules were bypassed for routine and ET-based treatments if > 1 cm rainfall occurred in the previous 24 hours. In the first and second phase, plots received 5.7 and 21.4 cm rainfall, respectively. Also, the irrigation amount for ET-based treatments for each application was determined after deducting the rainfall amount accumulated since the last day of irrigation. SMS-based treatments were triggered when average volumetric soil water content reached near 27%, which was determined to be the point at which wilt began to appear during the first dry down. After reaching the threshold level, 1.5 cm of water was applied each time. Nonirrigated treatments did not receive irrigation during either phase. All plots were hand watered using a shower head and flow meter (Great Plains Industries, Inc., Wichita, KS) attached to a hose. During recovery, the plots received one cm of irrigation water every other day from an in-ground sprinkler system.

A SMS (Model CS655, Campbell Scientific Inc.) was buried at a 7.6-cm depth in the center of each plot to continuously monitor the soil moisture status. An onsite rain gauge (Model TE525, Campbell Scientific Inc.) was also installed to record precipitation. All sensors were wired to a CR1000 datalogger (Campbell Scientific Inc.) and data were logged every hour. Data were collected weekly on visual turf quality (TQ), Normalized Difference Vegetation Index (NDVI), and digital percent green cover (GC) before mowing and irrigating the plots. Turfgrass quality and green cover were determined as described for the Manhattan site, while NDVI was measured using a hand-held Crop Circle ACS-430 meter (Holland Scientific Inc., Lincoln, NE).

Data from both locations were analyzed separately due to differences in climate conditions and soil types, and the use of a rainout shelter in Manhattan, but not in Dallas. One-way Analysis of variance (ANOVA) was performed in R (R Core Team, 2020) considering block as a random effect using a lmer function in lme4 package (Bates et al., 2015). When F-test results were significant at $P < 0.05$, treatment means were separated using Tukey's Honest Significance (HSD) test. Spearman's rank correlation test was conducted among TQ, NDVI, and GC in R using a cor function at α=0.05.

Results

Environmental conditions

The silty clay loam soil in Manhattan had an estimated saturation capacity of 45%, field capacity of 37%, and near permanent wilting point of 9%. Likewise, the Austin silty clay soil in Dallas had estimated saturation point, field capacity, and permanent wilting point at 65, 61, and 17%, respectively. These are the approximate estimates based on one cycle of wetting and drying. Chabon et al. (2017) and Serena et al. (2020) used a similar method for estimating the field capacity, although values were not provided. These results reveal the intrinsic differences between the soils at two locations. These two locations differ in the weather conditions as they fall under different USDA cold hardiness climatic zone (8a for Dallas and 6a for Manhattan). The mean air temperatures in Dallas were higher in each month from June through October in 2020 than that in Manhattan (Fig. 2.1). This suggests higher ET demand and water requirements to maintain adequate turf quality in Dallas as compared to Manhattan (Allen et al., 1998; Huang, 2008).

Manhattan Site

Turf canopy performance

Data were analyzed separately by year due to different lengths of treatment periods in 2019 and 2020. Within each year, a significant treatment by measurement date interaction was found, and thus data were analyzed separately by date (Table 2.1). In 2019 and 2020, before starting treatments, all plots had similar TQ, NDVI, and GC (Fig. 2.2 & 2.3). In both years, TQ was above the minimally acceptable level throughout the study period for all three treatments that received irrigation (Fig. 2.2 & 2.3). Earlier research has shown that irrigation scheduled with SMS or deficit ET has maintained acceptable quality across a wide range of turfgrass species, climates, and soil types (Cardenas-Lailhacar & Dukes, 2010; Cardenas-Lailhacar et al., 2010; Chabon et al., 2017; Davis et al., 2009; Serena et al., 2020). However, TQ of Innovation receiving SMS-based irrigation was statistically lower than that receiving ET-based or routine irrigation plots on 5 (ET-based) or 6 (routine) out of 8 dates in 2019, and 7 (ET-based) or 10 (routine) out of 14 measurement dates in 2020.

Lower TQ in tall fescue receiving SMS-based irrigation compared to routine irrigation has also been reported (Chabon et al., 2017; Serena et al, 2020). Innovation in nonirrigated plots exhibited acceptable quality until 21 days after treatment in both years. Hong and Bremer (2021) reported nonirrigated 'Meyer' zoysiagrass maintained acceptable quality until 28 days with no water in the first year and 19 days in the second year in a study conducted under a rainout shelter near this site. The differences between years from long-term drought as observed in that study was not apparent in our study as demonstrated by the similar turf performance metrics at the beginning of the study. It might be partly due to a shorter treatment period in our study in the first year and/or Innovation showing different level of recovery potential than Meyer.

At the end of the irrigation treatments in 2019 (7 WAT), Innovation receiving SMS-based irrigation had 96% GC, which was statistically similar to those of receiving ET-based (99% GC) or routine irrigation (99% GC), but higher than the nonirrigated plots (80% GC) (Fig. 2). NDVI values of plots receiving SMS-based irrigation were lower than those receiving ET-based or routine irrigation, but higher than nonirrigated treatments at 7 WAT.

In 2020 at 4 WAT, a severe storm damaged the rainout shelter and resulted 3.6 cm rainfall across the experiment. This resulted in an increase in TQ for at least a week (Fig. 2.3). The shelter was restored six days later, and when irrigation treatments ended at 13 WAT, TQ of nonirrigated Innovation was rated at 3 (1 to 9 scale; Fig. 2.3). Among 14 measurement dates, NDVI of turf receiving SMS-based irrigation was statistically lower on 7 or 10 dates, respectively, when compared with ET-based or routine irrigation. SMS-based irrigation maintained at least 80% GC throughout the treatment phase, except on the last rating date (13 WAT, 79% GC). Turf receiving routine and ET-based irrigation had GC > 80% throughout the treatment phase, while nonirrigated plots maintained 80% GC until 6 WAT and declined to 9% GC by the end of irrigation treatments.

During the recovery period in 2019, Innovation that was previously not irrigated recovered back to minimally acceptable TQ and 93% GC just one week after rewatering (Fig. 2.2). By the fourth week of recovery, there were no statistical differences among irrigation strategies for all three turf performance metrics. During recovery in 2020, nonirrigated plots recovered to 67% GC (from 9%) within two weeks and 75% GC within six weeks after resuming full irrigation (Fig. 2.3). The slower recovery of nonirrigated plots in the second year might have been due to a longer dry-down period. Overall, Innovation zoysiagrass showed good recovery potential in the Kansas experiment. For comparison, a recent study near our site reported Meyer zoysiagrass maintained 30% GC after 55 d of dry-down and needed 32 d of full irrigation to recover back to 85% GC, although Meyer was mowed at higher height of cut than Innovation in this study (Hong & Bremer, 2021).

Innovation recovery in 2020 among previously irrigated plots showed interesting responses later in autumn. By the end of six weeks after rewatering (on 19 Oct. 2020), routine, ET-based, and SMS-based treatments, respectively had 40, 27, and 27% GC, and all of them were statistically similar, but lower than the nonirrigated plots (75% GC). The treatments that had received irrigation during the period of stress began to enter dormancy earlier than plots that had previously not been irrigated. In Kansas, zoysiagrass typically starts losing green color starting late September. As a reference, Meyer zoysiagrass, which is reported to have similar fall color retention to Innovation zoysiagrass (Chandra et al., 2017) had 49% green color on 8 Oct. 2008 at our site (Okeyo et al., 2011). The retention of fall color in nonirrigated plots for an extended period is likely due to plant vigor resulting from carbohydrate reserves that were not utilized during the irrigation treatment period or differences in leaf characteristics after recovery from drought dormancy. However, although the recovered turf in nonirrigated plots had good green color but the density of the canopy was not ideal.

In 2019 when all observations were combined over treatments (N=144), TQ was strongly correlated with NDVI (r= 0.87, p-value <0.0001), and GC (r=0.88, p-value <0.0001). Likewise, in 2020 for N=216, TQ showed strong correlation with NDVI (r= 0.88, p-value <0.0001), and GC (r=0.89, p-value <0.0001). The good correlation among these three widely used turf performance metrics under varying level of irrigation treatments indicate the credibility of these metrics in a wide range of soil moisture conditions. The strong correlation among TQ, NDVI, and GC is in agreement with several prior studies (Bremer et al., 2011; Hong et al., 2019; Leinauer et al., 2014).

Water savings and soil moisture status

In 2019 and 2020, both ET-based and SMS-based irrigation strategies reduced the total irrigation water used (Table 2.2). Innovation receiving SMS-based irrigation required 72 and 56% less water, respectively, when compared with routine and ET-based irrigation in 2019. Water savings for SMS-based irrigation in 2020 were slightly lower, 63% and 46% compared to routine and ET-based irrigation, respectively. Several studies conducted previously across a range of soil types, climates, and turfgrass species have reported a range of water savings with the use of SMS-based irrigation. A study using SMS-based irrigation on residential or small commercial sites in Colorado required only 73% of irrigation that was estimated based upon net evapotranspiration after accounting for irrigation efficiency (Qualls et al., 2001). In an arid Australian climate, bermudagrass used 25% less water during summer when SMS-based irrigation was used as compared to conventional irrigation that applied 10-mm water every other day (Pathan et al., 2007). Using SMS-based controllers used on home lawns in southwest Florida saved 65% of total water compared to traditional timer-based controllers without any feedback mechanism operated at homeowners' discretion (Haley & Dukes, 2012). In North Carolina, residential irrigation systems with SMS-based controllers saved 42 and 22% water, respectively, when compared with traditional timer-based controllers without feedback mechanism operated at homeowners' discretion and ET-based controllers (Nautiyal et al., 2015). On a sandy loam soil in New Mexico, bermudagrass irrigation scheduled with SMS and 60% ET_0, respectively, required 39 and 29% less water than routine irrigation delivering 40 mm of water per week (Serena et al., 2020). Also, in the same study, tall fescue irrigation scheduled using SMS or 80% ET_0, respectively, saved 44 and 38% water in comparison to routine irrigation that applied 56 mm per week. The greater water savings in our study than most of the above discussed studies could be due to greater water holding capacity of the deep, fine-textured silty clay loam soil at our site. A study conducted at the same site and soil as the current study with tall fescue showed that it required up to 70% less water when using SMS-based irrigation compared to routine irrigation that applied 16 to 23 mm split over three days each week (Chabon et al., 2017). In addition, ET-based irrigation in our study reduced water consumption by 36 and 31% as compared to routine irrigation in the first and second year, respectively. A similar range of water savings potential from ET-based controllers have been reported in numerous prior studies (Davis & Dukes, 2010; Davis et al., 2009; Devitt et al., 2008; McCready et al., 2009; Serena et al., 2020).

Measurement of VWC under Innovation irrigation treatments demonstrated that SMS-based resulted in drier soil due to irrigation applied less frequently than other treatments (Fig. 2.4). In 2019, Innovation receiving SMS-based irrigation received water only four times over a period of 46 d as compared to 20 times by ET-based or routine irrigation treatments. The mean VWC pooled over the treatment period in 2019 for SMS-based plots was 0.19 $m^3\ m^{-3}$, which was statistically lower than ET-based (0.30 $m^3\ m^{-3}$) or routine irrigation (0.36 $m^3\ m^{-3}$), but similar to nonirrigated plots (0.15 $m^3\ m^{-3}$).

In 2020, due to a longer treatment period of 91 d, SMS-based irrigation resulted in Innovation being watered on nine times, while turf receiving ET-based or routine irrigation was watered 35 times in the same period. It is apparent that greater water savings for Innovation receiving SMS-based irrigation resulted because of deeper, less frequent irrigation compared to ET-based and routine irrigation. ET-based irrigation saved water compared to routine irrigation because less water was applied each time. The unusual spike in VWC in 2020 was due to the storm that damaged the shelter and delivered rainfall on all treatments.

In 2020, irrigating Innovation with routine, ET-based, SMS-based, and nonirrigated treatments resulted in an average VWC of 36, 30, 30, 21, and 14%, respectively. These results reveal that under these soil conditions using SMS-based irrigation maintains a lower VWC than the ET-based or routine irrigation, saving a significant amount of irrigation water. However, as discussed above the turf quality, green cover, and NDVI of the SMS-based irrigation plots were statistically inferior to ET-based or routine-based irrigation plots, although maintained above the minimally acceptable level throughout.

Dallas site

Turf canopy performance

Data were analyzed by measurement date due to a significant treatment by measurement date interaction (Table 2.1). Innovation receiving all irrigation treatments had similar TQ (average 7.3), NDVI (average 0.80), and GC (average 96%) before the initiation of treatments (Fig. 2.5). During the first (four week) irrigation phase, Innovation receiving with SMS-based or ET-based irrigation maintained minimally acceptable TQ throughout except at 3 WAT. Nonirrigated turf exhibited a decline in TQ below the acceptable level starting at 2 WAT and then declined progressively until the end of the four-week Phase I dry down. At 3 WAT, plots receiving SMS-based irrigation were 34% green, which was statistically lower than turf receiving ET-based (56%) or routine (68%) irrigation treatments, but similar to nonirrigated (17%) turf. Green cover data at 4 WAT were missing due to problems with the digital camera. The first phase of drought was relatively dry as only 6 cm rain occurred over the four weeks; 5 of the 6 cm rain occurred during the first two days of phase 1 (Fig. 2.6). The decline in TQ could be related to choosing the low critical threshold setting of 27 m^3 m^{-3} for SMS-based irrigation. As mentioned above, the estimated field capacity of the soil (61 m^3 m^{-3}) was far above this lower threshold and SMS-based plots never reached near field capacity when irrigated. The poor turf performance under lower thresholds were reported in tall fescue in the first year and was corrected by raising the thresholds in the second year in Kansas (Chabon et al., 2017). In a relatively dry and cold spring season, tall fescue scheduled with SMS had less than acceptable quality in New Mexico (Serena et al., 2020). St. Augustinegrass and bermudagrass had marginally acceptable to unacceptable quality in Florida under low SMS threshold levels and dry weather conditions (Cardenas-Lailhacar et al., 2010; McCready et al., 2009). It is likely that choosing a critical threshold of 27 m^3 m^{-3} and applying 1.5 cm irrigation at the trigger level was not adequate in Dallas as drought conditions prevailed. Also, the higher ET demand during phase 1 was not met sufficiently with the ET-based or routine-based irrigation treatments and TQ, GC, and NDVI were all declining after treatment initiation (Fig. 2.5) Due to the loss of quality in nonirrigated plots during Phase I, all plots were irrigated well after the first four-week period to allow recovery.

Before Phase II irrigation treatments began, Innovation in all plots except nonirrigated recovered to at least 97% green and TQ of 7 (Fig. 2.5). Nonirrigated turf reached 82% green and TQ of 5. During Phase II of the study, all irrigation treatments maintained acceptable quality and were statistically similar to each other throughout the four-week period. Over the four-week period, a total of 10 cm rain was received; precipitation occurred on six separate days on which > 1 cm rain fell (Fig.2.6). Nonetheless, nonirrigated plots did not recover to an acceptable level of TQ during this period (Fig. 2.5). NDVI of plots receiving SMS-based irrigation plots was also statistically similar to those receiving ET-based or routine irrigation on all measurement dates during phase two. At the end of Phase II, all irrigated plots had at least 90% GC and were statistically similar. Cardenas-Lailhacar et al. (2008) have reported that during wet weather conditions in Florida, nonirrigated bermudagrass maintained acceptable quality and was statistically the same as SMS-based irrigated turf or that receiving routine irrigation. When all observations were evaluated (N=120), TQ was strongly correlated with NDVI (r = 0.81, P <0.0001), and GC (r =0 .77, P < 0.0001).

Water savings and soil moisture status

During Phase I, water savings on Innovation receiving SMS-based irrigation plots was 25% and 22% when compared with routine or ET-based irrigated plots, respectively (Table 2.2). However, irrigating using ET-based strategy saved only 4% water compared to routine irrigation during Phase I. Water savings were slightly higher, especially for ET-based irrigation, during Phase II in which Innovation receiving SMS-based irrigation required 35% and 6% less water than plots receiving routine and ET-based irrigation, respectively. In addition, ET-based irrigation saved about 31% water as compared to routine irrigation during the Phase II. The greater water savings from SMS-based irrigation during a period that received more rainfall could be possible because irrigation cycles are bypassed more often when soil moisture doesn't dry to a point where irrigation is triggered (Dukes, 2012). For example, two studies conducted in conducted on the same site demonstrated that greater water savings occurred with SMS-based irrigation during periods when greater rainfall occurred than periods that were drier (Cardenas-Lailhacar et al. 2008; Cardenas-Lailhacar et al. 2010). Water savings reported in earlier studies using ET- and SMS-based irrigation are generally higher than what we reported at the Dallas location herein (Chabon et al., 2017; Haley & Dukes, 2012; Pathan et al., 2007; and Serena et al., 2020) This is most likely due to two reasons. First, irrigation for routine and ET-based treatments did not occur if rainfall occurred in the past 24 h and second, cumulative rainfall was deducted since last irrigation to determine the effective irrigation amount for each application. Coincidentally, in the short testing period, six and five irrigation events were bypassed in Phase I and II, respectively due to rainfall occurring on irrigation day.

The daily averages of VWC revealed that water content in SMS-based plots consistently fell between nonirrigated plots and those receiving ET-based or routine irrigation (Fig 2.6). The mean VWC pooled over time during the Phase I for SMS-based irrigated plots was 0.34 $m^3 m^{-3}$, which was statistically lower than routine irrigation (0.51 $m^3 m^{-3}$), but similar to ET-based (0.45 $m^3 m^{-3}$) or nonirrigated plots (0.34 $m^3 m^{-3}$). This suggests that drought conditions prevailed and both SMS-based and ET-based treatments did not provide enough irrigation to bring soil near to field capacity. During Phase II, SMS-based irrigation resulted in an average soil VWC of 0.41 $m^3 m^{-3}$, which was statistically similar to soil in plots irrigated based upon ET (0.46 $m^3 m^{-3}$) or those receiving routine irrigation (0.51 $m^3 m^{-3}$), but higher than soil under nonirrigated turf (0.37 $m^3 m^{-3}$). It is obvious that precipitation during this period helped to maintain higher soil moisture levels and irrigated treatments performed better than the nonirrigated treatment, which is different than what we found during Phase I.

Conclusion

Using SMS-based or ET-based irrigation was useful for saving irrigation water on Innovation zoysiagrass in a temperate (Manhattan, KS) and sub-tropical (Dallas, TX) climate. These irrigation strategies effectively maintained turf quality and green cover of Innovation maintained at golf course fairway height in Kansas, but not in Texas. A period greater than three weeks would be needed to allow full recovery of nonirrigated turf from drought stress in Texas, under the conditions of this study. Soil at each location likely played a significant role in turf performance. The Chase silty-clay loam soil in Kansas allows for deep root growth and good drought avoidance, which may also have encouraged slightly better performance than observed in Texas on the Austin silty clay soil. Water saved and performance of turf is also closely dependent upon the water content at which irrigation is triggered; these values must be determined with caution. Local weather conditions may also affect the performance of turf irrigated using SMS-based strategies, as noted by the improved performance of Innovation in Texas when greater rainfall occurred. Innovation zoysiagrass also demonstrated good drought tolerance and recovery after drought, particularly in Kansas. Future research on developing methods for fine-tuning the critical thresholds for SMS-based irrigation on a range of soil types would be beneficial to turf managers and researchers. Also, the impact of traffic on the performance of the soil moisture sensors was not assessed and would be useful because traffic can influence turf performance and water availability.

Figure 2.1. Average monthly mean air temperatures during study periods in 2019 and 2020 in Manhattan, KS and Dallas, TX.

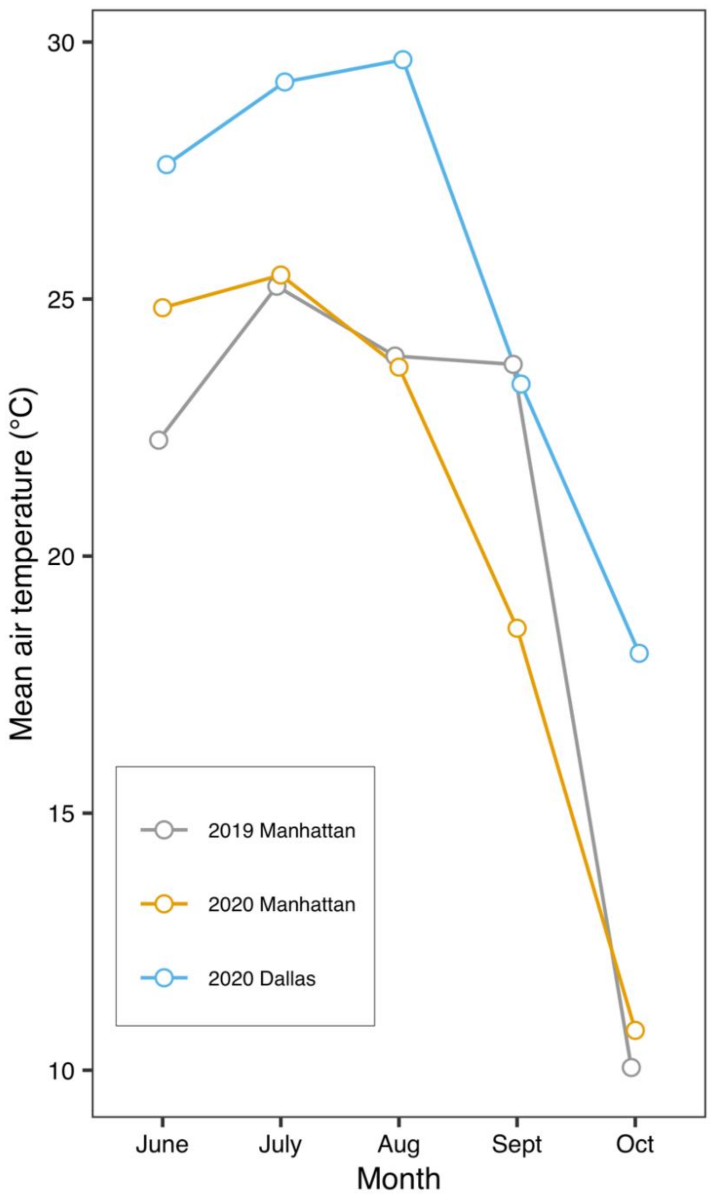

Figure 2.2. Percent green cover (a), normalized difference vegetation index (NDVI) (b), and visual turf quality (c) as affected by four irrigation strategies on Innovation zoysiagrass in Manhattan, KS in 2019. Routine irrigation involved application of 3 cm water per week split over three days each week; evapotranspiration (ET)-based irrigation replaced 60% of reference ET three times a week; soil moisture sensor (SMS)-based irrigation was triggered (1.5 cm water applied) when volumetric soil water content reached 11%; and nonirrigated turf received no water during the treatment phase but was irrigated with other treatments during recovery. Irrigation treatments were applied from 15 June to 30 Aug. 2019; recovery then began by applying 2.5 cm water weekly for four weeks thereafter. Error bars within points represent ±1 SE of the mean. On each measurement date, bars outside the lines represent Tukey's honest significance difference at α = 0.05 and missing bars represent no significance. The vertical red dashed line separates the study into treatment and recovery phases. The horizontal black dashed line is drawn at the minimally acceptable turf quality level (6) on a scale of 1-9. The number on parentheses and square brackets on the x-axis denote weeks after treatments began and recovery, respectively.

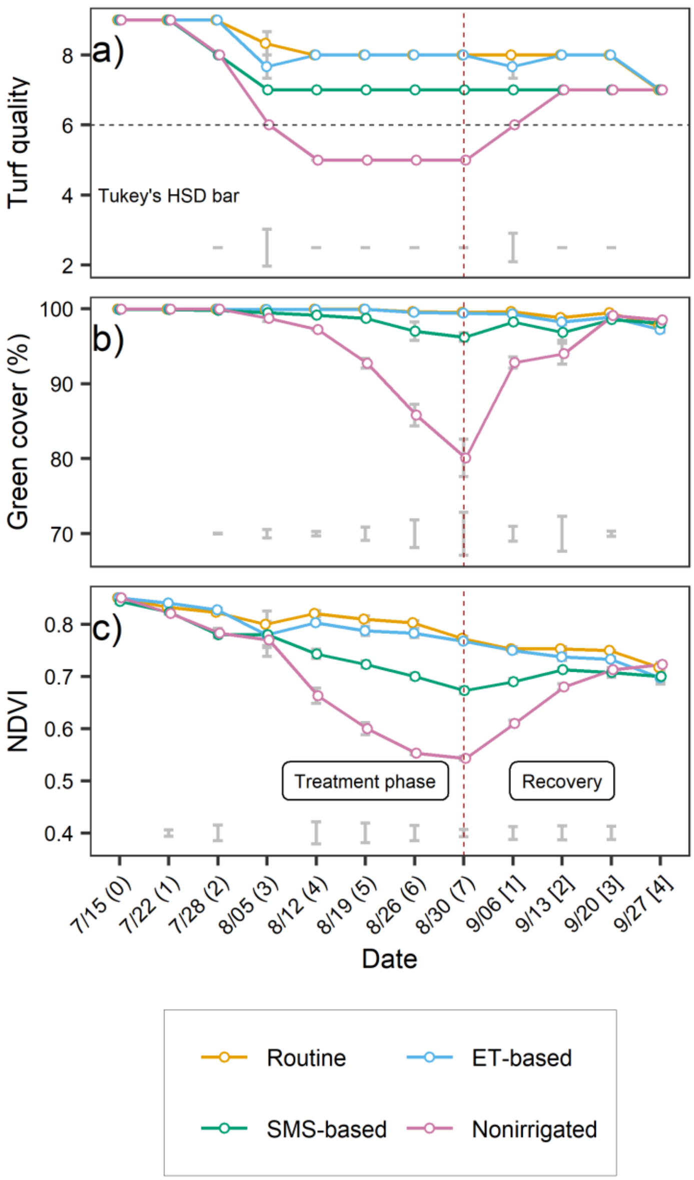

Figure 2.3. Percent green cover (a), normalized difference vegetation index (NDVI) (b), and visual turf quality (c) as affected by four irrigation strategies on Innovation zoysiagrass in Manhattan, KS in 2020. Routine irrigation involved application of 3 cm water per week split over three days each week; evapotranspiration (ET)-based irrigation replaced 60% of reference ET three times a week; soil moisture sensor (SMS)-based irrigation was triggered (1.5 cm water applied) when volumetric soil water content reached 15%; and nonirrigated turf received no water during the treatment phase but was irrigated with other treatments during recovery. Irrigation treatments were applied from 8 June to 6 Sept. 2020; recovery then began by applying 2.5 cm water weekly for six weeks thereafter. Error bars within points represent ±1 SE of the mean. On each measurement date, bars outside the lines represent Tukey's honest significance difference at $\alpha = 0.05$ and missing bars represent no significance. The vertical red dashed line separates the study into treatment and recovery phases. The horizontal black dashed line is drawn at minimally acceptable turf quality rated on a scale of 1-9. The number on parentheses and square brackets on x-axis denote weeks after treatment and recovery, respectively.

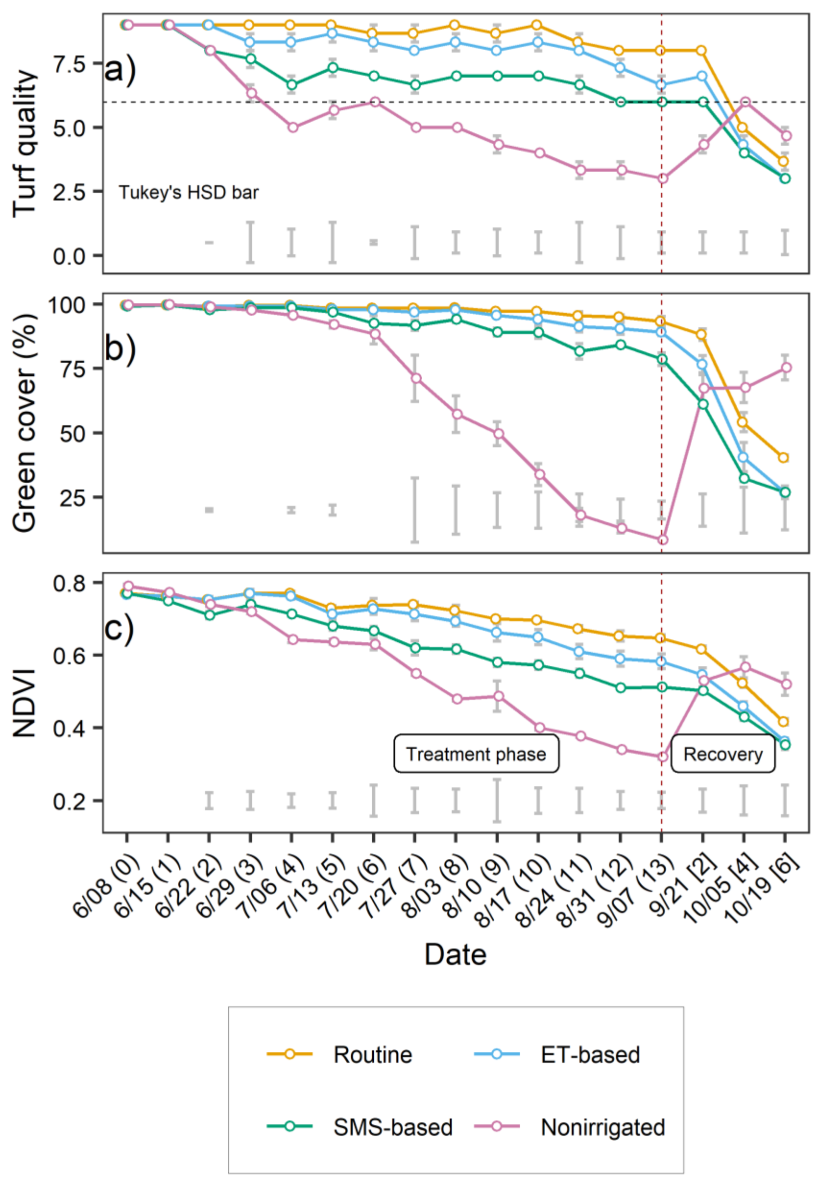

Figure 2.4. Daily averages of volumetric soil water content (m^3 m^{-3}) under Innovation zoysiagrass as affected by irrigation strategy in Manhattan, KS in 2019 (a), and 2020 (b). The vertical red dashed line separates the study into treatment and recovery phases. Irrigation treatments were applied from 15 June to 30 Aug. 2019; recovery began on 31 August by applying 2.5 cm water weekly for four weeks. In 2020, the treatment phase ran from 8 June through 6 Sept. 2020, and recovery phase then ran for six weeks with water application as in 2019.

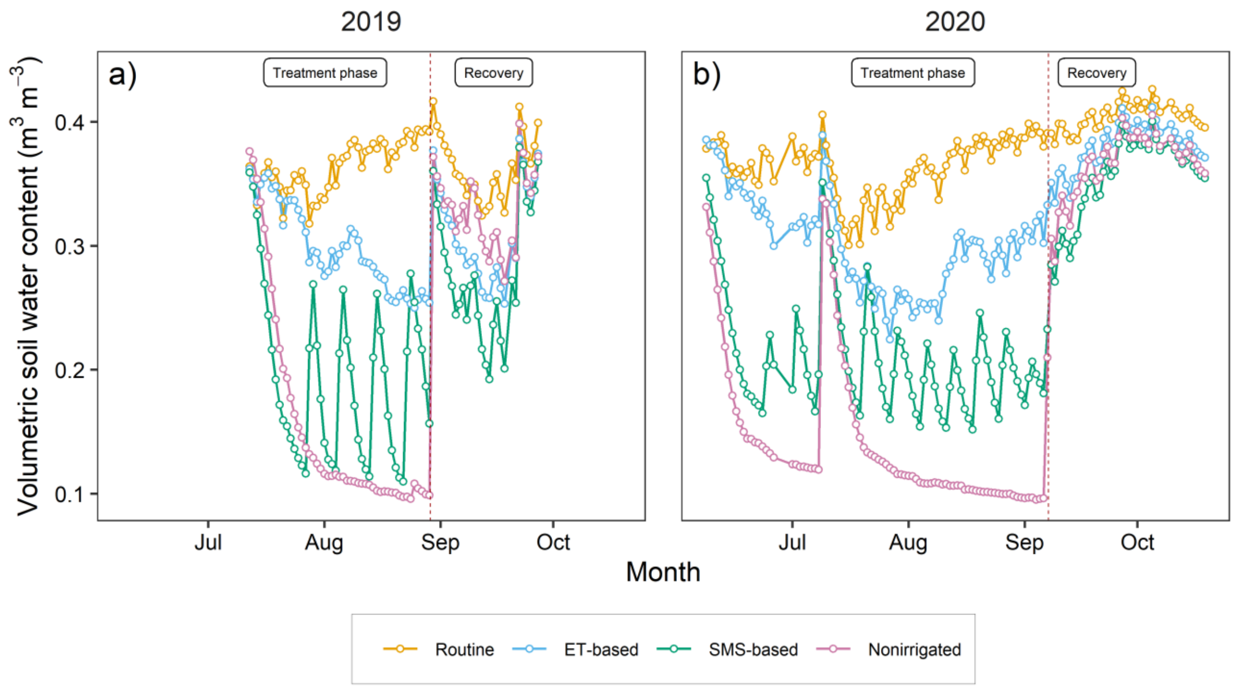

Figure 2.5. Percent green cover (a), normalized difference vegetation index (NDVI) (b), and visual turf quality (c) as affected by four irrigation strategies on Innovation zoysiagrass in Dallas, TX in 2020. Routine irrigation involved application of 3 cm water per week split over three days; evapotranspiration (ET)-based irrigation replaced 60% of reference ET three times a week; soil moisture sensor (SMS)-based irrigation was triggered (1.5 cm water applied) when volumetric soil water content reached 27%; and nonirrigated turf received no irrigation. The first treatment phase ran from 22 June through 22 July; the second treatment phase began from 10 Aug. until 9 Sept., and all plots were well-watered with one cm water every other day between phases to allow recovery. The horizontal black dashed line is drawn at a minimally acceptable turf quality (6) rated on a scale of 1-9. Error bars within points represent ±1 SE of the mean. On each measurement date, bars outside the lines represent Tukey's honest significance difference at α = 0.05 and missing bars represent no significance. The number on parentheses on x-axis denote weeks after beginning of Phase I and II treatments, respectively.

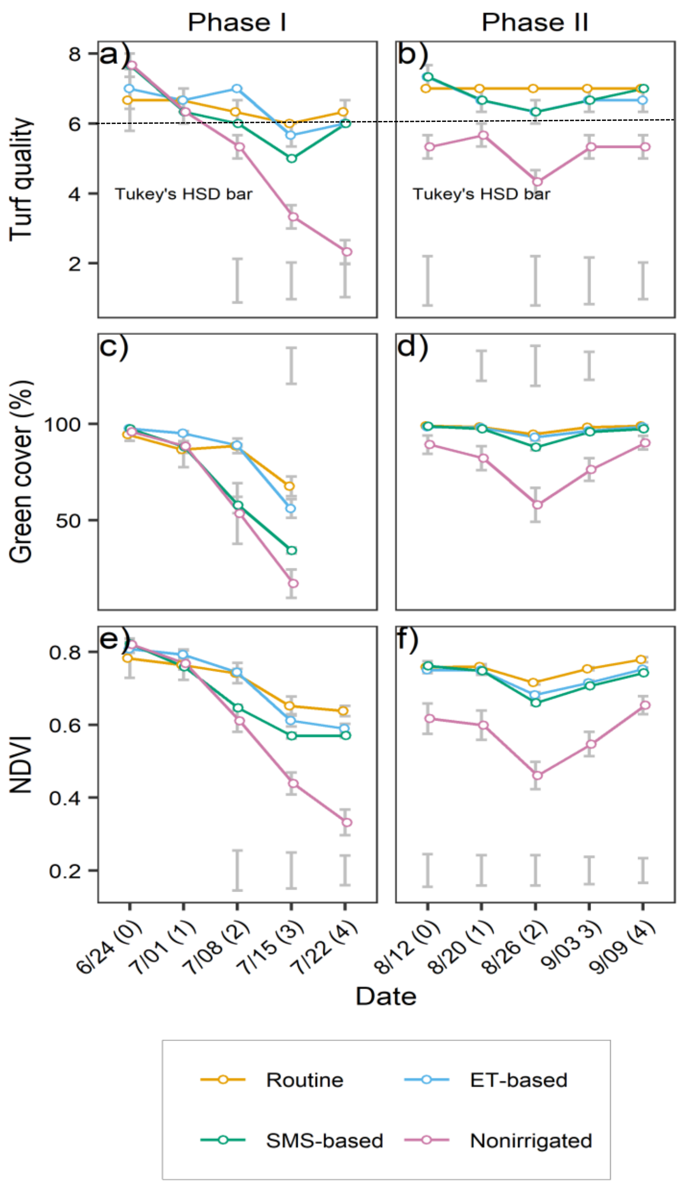

Figure 2.6. Daily averages of volumetric soil water content (m^3 m^{-3}) as affected by four irrigation strategies on Innovation zoysiagrass in Dallas, TX in 2020. Additional vertical bars on the secondary y-axis represent amount of rainfall (cm) during the study period. The vertical red dashed lines divide the study period into two phases of irrigation treatment and a recovery period in between. The first treatment phase ran from 22 June through 22 July; the second treatment phase ran from 10 Aug. until 9 Sept., and all plots were well-watered between the 1st and 2nd phases to encourage recovery with application of 1 cm water every other day.

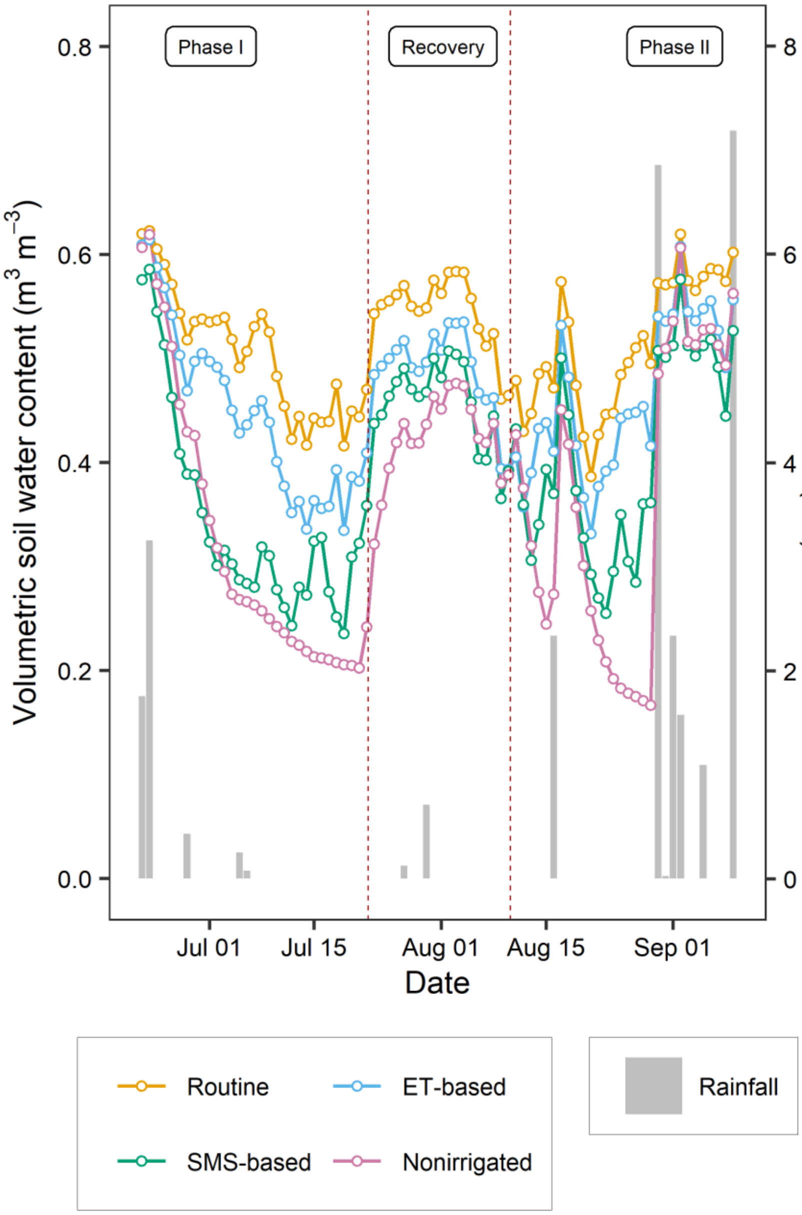

Table 2.1. Analysis of variance for the effects of irrigation strategy, measurement date, and their interaction on visual turf quality (TQ), normalized difference vegetation index (NDVI), and percent green cover (GC) of Innovation zoysiagrass in Manhattan, KS and Dallas, TX.

		During treatment†				During recovery			
Study site	Source	df	TQ‡	NDVI	GC	df	TQ	NDVI	GC
		2019							
Manhattan	Treatment (T)	3	<0.0001§	<0.0001	<0.0001	3	<0.0001	0.0006	0.0042
	Date (D)	7	<0.0001	<0.0001	<0.0001	3	<0.0001	<0.0001	<0.0001
	T x D	21	<0.0001	<0.0001	<0.0001	9	<0.0001	<0.0001	<0.0001
		2020							
	Treatment (T)	3	<0.0001	<0.0001	<0.0001	3	0.0014	0.0063	0.0008
	Date (D)	14	<0.0001	<0.0001	<0.0001	2	<0.0001	<0.0001	<0.0001
	T x D	42	<0.0001	<0.0001	<0.0001	6	<0.0001	<0.0001	<0.0001
		2019							
Dallas	Treatment (T)	3	0.0097	0.0174	0.0103	3	0.0047	0.0008	0.0082
	Date (D)	4	<0.0001	<0.0001	<0.0001	4	<0.0001	<0.0001	<0.0001
	T x D	12	<0.0001	<0.0001	<0.0001	12	0.0047	<0.0001	<0.0001

†A two-year study was conducted in Manhattan, KS. Irrigation treatments were applied from 15 July to 30 Aug 2019; all plots received 2.5 cm water weekly beginning on 31 Aug, and this continued for four weeks to evaluate recovery. In 2020, the treatment phase ran from 8 June through 6 Sept.; irrigation was then applied as in 2019, and recovery was evaluated for six weeks thereafter. In Dallas, TX the first treatment phase ran from 22 June through 22 July; second treatment phase began from 10 Aug. until 9 Sept., and all plots were well-watered with 1 cm water every other day in between during recovery.

‡Turf quality was rated on a scale of 1 to 9 in which 1 represented brown turf; 6 was a minimally acceptable quality; and 9 represented green, dense, and uniform turf. Normalized difference vegetation index was determined using RapidScan CS-45 meter. Percent green cover was estimated from digital images using SigmaScan Pro software.

§*P*-values from linear mixed-model analysis at $P = 0.05$.

Table 2.2. Total water applied and water savings using different irrigation treatments on Innovation zoysiagrass in Manhattan, KS in 2019 and 2020 and Dallas, TX in 2020.

Treatment†	Total water applied		Water savings	
	Manhattan‡		Manhattan‡	
	2019	2020	2019	2020
	———cm———		———%———	
Routine	20.4	35.4	0.0	0.0
ET-based	13.1	24.3	35.8	31.4
SMS-based	5.7	13.1	72.0	63.0
Nonirrigated	0.0	0.0	100.0	100.0
	Dallas§		Dallas§	
	1st phase	2nd phase	1st phase	2nd phase
	———cm———		———%———	
Routine	10.1	7.1	0.0	0.0
ET-based	9.7	4.9	3.9	30.9
SMS-based	7.6	4.6	24.7	35.2
Nonirrigated	0.0	0.0	100.0	100.0

†Routine irrigation involved application of 3 cm water per week split over three days each week; Evapotranspiration (ET)-based irrigation replaced 60% of reference ET three times a week; soil moisture sensor (SMS)-based irrigation (1.5 cm) was triggered applied when volumetric soil water content reached 11% (2019) or 15% (2020) in Manhattan, and 27% in Dallas; nonirrigated turf received no irrigation.

Percent reduction in water use compared to routine treatment.

‡A two-year study was conducted in Manhattan, KS. Irrigation treatments were applied from 15 June to 30 Aug 2019. In 2020, the treatment phase ran from 8 June through 6 Sept. The experiment was conducted under a polyethylene covered rainout shelter.

§In Dallas, TX the first treatment phase ran from 22 June through 22 July; second treatment phase ran from 10 Aug until 9 Sept. The experiment was conducted in an open-sky environment.

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Chapter 3 - Ethephon Application for Seedhead Suppression of Innovation™ Zoysiagrass

This chapter has been prepared using style guidelines for the journal Crop, Forage, & Turfgrass Management.

Abstract

Innovation™ zoysiagrass provides a high-quality playing surface for use on golf course fairways and tees. However, seedheads produced in late spring create nuisance on the playing surface. The use of the plant growth regulator ethephon to suppress seedheads on golf courses has gained increasing attention primarily due to ease of operation and quality enhancement. The efficacy of ethephon on Innovation has not yet been evaluated, however. Therefore, a two-year field experiment was conducted during the 2019–2021 growing season in Manhattan, KS to evaluate the performance of ethephon (Proxy®) on seedhead suppression of Innovation zoysiagrass. Treatments evaluated Proxy® applied in a single autumn application at 5 fl. oz./1,000 ft^2 on multiple dates between August and November. Seedhead suppression compared to nontreated control plots was determined by counting seedheads in a 20 by 20-inch area in each plot. Seedhead suppression ranged from 5% (application on 29 October) to 85% (applied on 3 September). Dates between August 20 and September 18 were generally effective in suppression as >70% suppression was observed on three dates across two seasons. Variations between the years were evident, and application based on calendar dates should be used cautiously. Applications made between 20 and 28 August had effective suppression, but commercially unacceptable discoloration was observed until four weeks post application. Application timing affected turf quality in late spring as plots with fewer seedheads had better quality post-mowing. However, no influence was found on green up during early spring. Ethephon is an effective PGR for Innovation seedhead suppression.

Introduction

The sport of golf requires smooth, uniform playing surfaces and high-quality turf. Zoysiagrass (*Zoysia* spp. Willd.) provides high-quality turf and playing surfaces for use on golf course fairways and tees throughout the transition zone of the U.S. (Lyman et al., 2007). The superior cold tolerance and low maintenance requirement of zoysiagrass make it attractive for use in the transition zone (Patton et al., 2017). Innovation™ zoysiagrass (*Zoysia matrella* 'Cavalier' x *Z. japonica* 'Anderson 1') is a new (released in 2015) zoysiagrass cultivar with higher density and finer texture compared to 'Meyer' zoysiagrass (*Z. japonica*), but has equivalent cold tolerance (Chandra et al., 2017; Patton et al., 2017). Innovation™ zoysiagrass, patented under the name KSUZ 0802, will be referred to as 'Innovation' zoysiagrass throughout this chapter. Innovation provides high-quality playing surfaces on fairways and tees; however, it produces seedheads in late spring that impact the playing surface and aesthetics. In Innovation zoysiagrass, seedheads leave a purple cast across fairways and tees on golf courses when they emerge, and after mowing seed stalks that remain leave a white cast to these areas. The disruption of playability and poor aesthetics due to lingering seedheads on playing surfaces are concerning to golf course superintendents and golfers (Kane & Miller, 2003). In addition, the increased mowing requirements due to aggressive seedhead production requires greater fuel, labor, and equipment maintenance costs for golf courses (Brosnan et al., 2012).

Several studies have been conducted on understanding the physiology of inflorescence development on annual bluegrass (ABG) (*Poa annua* L.), a widely cultivated C_3 turfgrass species and the most cosmopolitan weed on creeping bentgrass (*Agrostis stolonifera* L.) fairways and greens. From the standpoint of plant physiology, the inflorescence is produced at the expense of vegetative growth (Ong & Marshall, 1975). The allocation of carbohydrate reserves to the inflorescence during floral initiation on ABG is reported to compromise reserves in shoots, rhizomes, and roots; thus, decline in plant vigor is common (Cooper et al. 1988; Ong & Marshall 1975; Askew, 2017). In turf used on golf courses, unlike other crops, reproductive growth is unwanted, while vegetative growth is desirable to produce better shoot density, uniformity, recuperative ability, and stress tolerance. Mowing is a fundamental practice to slow down the inflorescence development in turf and enhance turf quality (density, uniformity, and smoothness) by restricting the vertical growth. However, mowing heights can be lowered only to a certain limit, and there are costs associated with increased mowing requirements. Also, the mowing quality is poor due to tough, fibrous, and stemmy zoysiagrass seedheads. Therefore, alternative approaches for seedhead management are needed.

Plant growth regulators (PGRs) are widely used on golf courses to benefit turf in several ways, including shoot growth inhibition, shoot density promotion, color enhancement, seedhead suppression, and increased tolerance to abiotic stresses (Beam & Askew, 2007; Hussein et al., 2012; McCann & Huang, 2007; McCarty et al., 2004; McCullough et al., 2005a; McCullough et al., 2005b; McCullough et al., 2005c; Qian & Engelke, 1999). The performance of PGRs in seedhead suppression has been studied extensively in ABG, while studies evaluating their effects on C_4 turfgrasses are limited. The PGR mefluidide [N-(2,4-dimethyl-5-{[(trifluoromethyl)-sulfonyl] amino} phenyl) acetamide] was previously used to suppress seedheads in ABG but inconsistent performance and unacceptable phytotoxicity were a problem (Haguewood et al., 2013; Askew, 2016). Furthermore, mefluidide (Embark, PBI/Gordon) was recently phased out from the turf market and is no longer manufactured (Reicher et al., 2020). Another PGR, ethephon (2-Chloroethylphosphonic acid) (Proxy®, Bayer Environmental Science), is gaining attention for use in suppressing seedheads in a wide range of turfgrasses, including C_4 turf species. Unfortunately, the Proxy® label does not have information on zoysiagrass seedhead suppression included. Nevertheless, a few studies reported effective seedhead suppression on Meyer zoysiagrass with minimal injury. A greenhouse study in Georgia reported that following the ethephon application, ‘Zenith’ zoysiagrass (*Zoysia japonica* Steud.) sustained an acceptable level of injury (9 to 20%), whereas bermudagrass [*Cyndon dactylon* (L.) Pers., Princess 77] or seashore paspalum (*Paspalum vaginatum* L., Sea Isle 1) suffered unacceptable injury (21 to 44%) across multiple mowing heights and application rates (Sidhu et al., 2014). Ethephon was applied at half, equal, and two times the current label rate (3.4 lb. a.i. $acre^{-1}$) in that study. A recent field study on Meyer zoysiagrass (*Zoysia japonica* Steud.) reported minimal and commercially acceptable injury (< 10%) following the ethephon application applied at 3.4 lb. a.i. $acre^{-1}$ studied across three locations in the transition zone (Patton et al., 2018).

A few studies conducted on zoysiagrass seedhead suppression by ethephon have reported promising results. In Tennessee and Indiana, two-sequential spring applications of ethephon on Meyer zoysiagrass suppressed seedheads by 60 to 89% (Brosnan et al., 2012). Recent research on Meyer across three locations in the transition zone demonstrated that a single application of ethephon in autumn provided greater seedhead suppression than single application or two-sequential applications in spring (Patton et al., 2018). The early autumn (23 to 29 Sept.) ethephon applications had greater efficacy in seedhead suppression than late autumn (14 to 31 Oct.) applications in the same study. In contrast, a greenhouse study in South Carolina reported that ethephon was ineffective in suppressing seedheads applied to a ‘Diamond’ zoysiagrass [*Zoysia matrella* (L.) Merr.] in spring or autumn (Ledford, 2019). Since Innovation is a new cultivar of zoysiagrass with great potential for use in the golf course fairways and tees in the transition zone, effective management of seedheads through ethephon use would be helpful. Contrary to other cultivars of zoysiagrass, particularly those adapted in the Southern US, which produces seedheads both in fall and spring, so far in its use Innovation is known to produce seedheads only during late spring, similar to Meyer. As such, we hypothesize that ethephon would suppress seedheads on Innovation similarly as in Meyer when applied in autumn. Therefore, the objectives of this study were to: 1) determine the efficacy of ethephon on Innovation zoysiagrass seedhead suppression; 2) determine the optimum application window; and 3) evaluate phytotoxicity after ethephon application.

Materials and Methods

The experiment was conducted at Rocky Ford Turfgrass Research Center in Manhattan, KS (39^{0}13’50’’ N, 96^{0}34’46’’ W) over two growing seasons from August 2019 to May 2020 and August 2020 to May 2021. The study area was established with sprigs of Innovation zoysiagrass (*Zoysia matrella* ‘Cavalier’ x *Z. japonica* ‘Anderson 1’) in June 2017 and had full coverage by the end of growing season in 2017. The soil type was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) with a pH of 7.3. The site was mowed at 0.625 inches up to three times a week with a walk-behind reel mower and clippings were returned. Nitrogen was applied with urea (46−0−0, Lesco Professional Turf Fertilizer) to provide 1 lb. N per 1000 ft^2 on 3 June and 1 July in 2019, and on 26 May and 2 July in 2020. The area was sufficiently irrigated to prevent visible wilting. Dithiopyr (Dimension 2EW, Dow AgroSciences) was applied to prevent crabgrass emergence at 1 lb. a.i. acre^{-1} on 19 April 2019 and 24 April 2020. A mixture of 2,4-D, 2-ethylhexyl ester at 0.38 lb. a.i. acre^{-1}, mecoprop-p acid at 0.12 lb. a.i. acre^{-1}, dicamba acid at 0.035 lb. a.i. acre^{-1}, and carfentrazone-ethyl at 0.0089 lb. a.i. acre^{-1} (Speedzone, pbi/Gordon Corporation) was applied on 19 April and 20 June 2019, and on 10 May 2020 to kill broadleaf weeds. Flutolanil

(ProStar 70 WG, Bayer Environmental Science) was applied on 4 Sept. 2019 and 10 Sept. 2020 at 8.6 lb. a.i. acre^{-1} to prevent large patch.

The experiment was arranged in a randomized complete block design with four replicates. Treatments began in August 2019 and data were collected in the following spring in May 2020. After completion of the first experiment, plots were re-randomized, and the study was repeated in the same site from August 2020 to May 2021. Each plot measured 4 by 4 ft. Treatments consisted of eleven application timings of ethephon (Proxy® 2L, Bayer Environmental Science) applied from late August through early November, and a nontreated control (Table 3.1). In experiment two, one additional application timing was added. Each plot received the treatment once and the treatments were continued even after the first frost as grasses entered winter dormancy. Proxy® was applied at 5 fl. oz. per 1000 ft^2 with a CO_2-pressurized sprayer equipped with a TP8006EVS flat-fan nozzles (TeeJet Technologies, Glendale Heights, IL) calibrated to deliver 2 gallons per 1000 ft^2 at 40 psi. Irrigation and mowing were withheld for at least two days after ethephon treatment application throughout the study period.

Once formation of seedheads was visible in the zoysiagrass canopy, mowing was ceased until the peak inflorescence stage, which was determined through counting and visual inspection. A 20 by 20-inch template was randomly placed in each experimental plot and visible seedheads were counted. The peak inflorescence stage was identified visually as 31 May 2020 and 8 June 2021. Based upon seedhead no. percent seedhead suppression (PSS) was calculated as:

$$\text{Seedhead suppression (PSS, \%)} = \left(1 - \frac{\#\ \text{seedheads in treated plot}}{\#\ \text{seedheads in control plot}}\right) \times 100$$

Also, the suppression results were estimated visually on a scale of 0-100% compared to nontreated control plots just before beginning the seedheads counts. The plots with seedheads coverage visually similar to control plots were rated as 0% visual seedhead suppression (VSS) and the plots with no visible seedheads on the canopy were rated as 100% VSS.

Phytotoxicity from ethephon application was measured as change in turf color determined visually on a scale of 1-9 in which 9 = dark green leaf with no discoloration, 6= commercially acceptable discoloration with minimal browning, and 1= completely bleached white leaf. Turf color was rated weekly starting one week after the first treatment until first frost occurred. Also, spring green-up was rated visually on a scale of 1-9 in which 1= brown turf and 9 = fully green turf on 8 April, 21 April, and 5 May 2020 for experiment one, and on 15, 23, and 30 April; and 7 May 2021 for experiment two. Once all the seedhead counts were completed, plots were mowed and were rated for mowing quality on 2 and 8 June 2020 for experiment one, and on 9 and 15 June 2021 for experiment two. Mowing quality was rated visually on a scale of 1-9 in which 9= green canopy with no white cast and 1= canopy with abundance of white cast.

All data were subjected to one-way analysis of variance (ANOVA) using a lmer function on a lme4 package in R (R Core Team, 2020) considering block as a random effect. When F-test results were significant at $P < 0.05$, treatment means were separated using Tukey's Honest Significance (HSD) test. Pearson's correlation test was conducted between PSS and VSS in R using a cor function at $\alpha = 0.05$. The application timing dates were different on experiment 1 and 2 and thus data were analyzed and presented separately for each experiment.

Seedhead Suppression

Ethephon application timing affected PSS in both Expt. 1 (P <0.0001, 10 df) and 2 (P <0.0001, 11 df). Percent seedhead suppression ranged from 15 to 82% in Expt. 1 and 5 to 85% in Expt. 2 (Table 3.1). In Expt. 1, ethephon applied on 4 Sept. resulted in greatest PSS (82%) and that applied on 1 Nov. caused the least PSS (15%). Ethephon between 4 Sept. and 23 Oct. had at least

50% PSS. Ethephon applied between 4 Sept. and 3 Oct. had at least 62% PSS and the results were statistically not different among timings.

In Expt. 2, ethephon applied on 3 Sept. resulted in 85% PSS, and that applied on 29 Oct. had 5% PSS. Applications of ethephon made between 20 August and 8 Oct. had at least 50% PSS, except for applications on 10 Sept. and 1 Oct. (Table 3.1). At least 68% suppression was observed on 5 of 12 ethephon application dates and two dates had suppression < 12%. The results reflected the large variation in the efficacy of ethephon on Innovation zoysiagrass. Patton et al. (2018) reported that on Meyer zoysiagrass, ethephon applied in early fall (23 to 29 Sept.) had 5% seedhead coverage and late fall (14 to 31 Oct.) application had 40% coverage on average over three locations. The seedhead emergence on 'Diamond' zoysiagrass [*Zoysia matrella* (L.) Merr.] in the southeast US was found to be correlated to growing degree days, photoperiod, and calendar date (McCullough et al., 2017). The application of other PGRs, such as mefluidide for effective seedhead suppression is based upon growing degree days (Calhoun, 2010). Considering the fact that metabolism of ethephon is related to air temperature (Lougheed & Franklin, 1972; Walters & Lopez, 2018), the efficacy of ethephon could be more consistent when applied based on growing degree days during fall.

Seedhead suppression alone can be misleading if the seedhead counts are ignored. For example, 70% suppression compared to the nontreated control seems impressive, but the seedhead levels in the plot could be aesthetically unacceptable. Therefore, seedhead counts and percent seedhead suppression are both important to report. Seedhead counts were affected by ethephon timing in Expt. 1 (P <0.0001) and 2 (P <0.0001) (Table 3.1). In Expt. 1, 9 out of 11 ethephon applications and in Expt. 2, 10 out of 12 ethephon applications had statistically lower seedhead counts than the nontreated control. The lowest seedhead counts per 2.7 ft^2 were 47 and 49 in Expt.

1 and 2, respectively. The nontreated control plots had 265 and 280 seedhead counts per 2.7 ft^2 in Expt. 1 and 2, respectively.

Visual seedhead suppression (VSS) was also impacted by ethephon application date in both Expt. 1 (P <0.0001) and 2 (P <0.0001) (Table 3.1). Results ranged from 33 to 89% in Expt. 1 and 26 to 90% in Expt. 2. There was a strong correlation between VSS and PSS in both experiments. In Expt. 1 and 2, correlation coefficient (r) was 0.92 (P <0.0001; n= 44), and 0.93 (P <0.0001; n = 48), respectively. Suppression rated visually was slightly higher than the PSS calculated based upon counts on most dates. For example, ethephon application on 1 Nov. 2020 resulted in 15% PSS based upon seedhead counts, whereas VSS was 33%. The visual suppression ratings can be a rapid tool for estimation of seedhead suppression, however, it should be utilized with a caution.

Phytotoxicity

Turf injury following PGR application has been reported previously (Dernoeden, 1984; Watschke et al., 1979). Symptoms generally include discoloration of leaf tissues and stunted shoot and root growth (Cooper et al., 1987; Eggens et al., 1989; McCullough et al., 2005b). The injury symptoms in our study occurred as browning of leaves and therefore we quantified the phytotoxicity of ethephon application through turf color ratings. Ethephon application timings affected the level of injury in both Expt. 1 and 2 (Table 3.2 & 3.3). In Expt. 1, Innovation suffered injury below the commercially acceptable level for at least four weeks after the treatment when ethephon was applied on 28 August. The second timing applied on 4 Sept. resulted in slight discoloration and turf color was statistically lower than the nontreated control plots. However, discoloration was subtle and above the acceptable level of injury. The injury for the rest of the ethephon application dates was not different from the nontreated control plots. In Expt. 2, only the first two timings on 20 and 27 August resulted in Innovation injury below an acceptable level for at least 4 and 3 weeks after the treatment, respectively. Application of ethephon on 3 Sept. resulted in minimal turf discoloration for at least two weeks post-application, but the injury was above the acceptable level. The turf color for the rest of ethephon application dates was not statistically different from the nontreated control plots and was above the commercially acceptable level. The injury from ethephon on ABG has been ameliorated by tank mixing ethephon with trinexapac-ethyl (TE) (Haguewood et al., 2013; Inguagiato et al., 2010; Kane & Miller, 2003). TE does not suppress seedheads as it works by inhibiting gibberellic acid biosynthesis, and turf exhibits darker green color and improved density with TE application. Researchers have previously reported mixing of chelated Fe products on mefluidide to mask the chlorosis effect of mefluidide on ABG (Branham, 1989; Borger, 2008). The canopy discoloration on Innovation in this study was transient and more pronounced only in late-summer application timings (28 August in Expt. 1, and 20 and 27 August in Expt. 2). Future research on effects of tank mixing ethephon with TE or Fe products on zoysiagrass would be interesting.

Impact on Turf Quality after Spring Mowing

Turf quality following mowing operation in spring was reported to be affected by the ethephon application in fall (Patton et al., 2018). In our study, ethephon application timing influenced mowing quality in both Expt. 1 ($P < 0.0001$) and 2 ($P < 0.0001$) (Table 3.4). Ethephon application dates that resulted in greater seedhead suppression had higher mowing quality. The tough seedhead stalks that remained behind after mowing have affected the mowing quality. For example, Innovation treated on 4 Sept. 2019 had 82% PSS and mowing quality of 8.3 on 8 June 2020, whereas that treated on 1 Nov. 2019 had 15% PSS and mowing quality of 6.0 on the same date. In Expt. 1, four application timings between 28 August and 18 Sept., and six timings between 28 August and 3 Oct. had produced mowing quality better than the nontreated control on 2 and 8 June, respectively. Similarly, in Expt. 2, three ethephon application dates between 20 August and 3 Sept., and five between 20 August and 17 Sept. had greater mowing quality than the nontreated control plots on 9 and 15 June. Interestingly, the mowing quality for Innovation treated with ethephon in late fall was no different from nontreated control plots across both experiments. Spring green-up in April and May in the spring following ethephon application was not different from the nontreated plots on any of the dates (Table 3.5). This suggests that fall application of ethephon might not have any role in the winter injury or winter survival of Innovation zoysiagrass.

Conclusion

Ethephon applications made between 20 August and 18 September were generally effective providing > 70% Innovation zoysiagrass seedhead suppression (based on seedhead no.) on three dates across two seasons. Applications between 20 and 28 August showed effective seedhead suppression (based on seedhead no.) but created a greater chance of turf injury, although transient. A single ethephon application of ethephon provided up to 85% suppression but the application window for greater suppression was slim. Timing based on calendar dates produced some inconsistency across experiments; for example, ethephon applied on 28 Aug. 2019 resulted 55% seedhead suppression, whereas on 27 Aug. 2020 ethephon provided 81% seedhead suppression. This suggests the activity of ethephon might be dependent on environmental factors. More practical experience and research will further explain the relationship between ethephon efficacy and environment. This study was focused on finding the optimum application window in fall with single application of ethephon; however, future research on investigation of two-sequential fall applications is needed. In addition, the use of adjuvants or a pH conditioner could have some role in enhancing the efficacy of ethephon and warrant future research. The use of ethephon on golf course turf for effective suppression of zoysiagrass seedheads has received great attention primarily due to ease of including this effort with others. Ethephon can be tank mixed with other PGRs such as trinexapac-ethyl or fungicides and save operation costs to reap additional benefits. This study provides golf course superintendents and turf managers insights on how to effectively suppress Innovation zoysiagrass seedheads in the transition zone.

Table 3.1. The effect of ethephon application timing on seedhead suppression of Innovation zoysiagrass in Manhattan, KS over two growing seasons. Ethephon was applied in fall and seedhead suppression data were obtained in spring each season.

Experiment 1 (2019-20)				Experiment 2 (2020-21)			
Treatment†	Seedhead count‡ (no./2.7 ft^2)	Seedhead suppression (%, based on seedhead no.)	Visual suppression§ (%)	Treatment	Seedhead count‡ (no./2.7 ft^2)	Seedhead suppression (%, based on seedhead no.)	Visual suppression§ (%)
Nontreated	265a¶	-	-	Nontreated	280a	-	-
28-Aug	118cd	54.4	66abc	20-Aug	76cde	72.5	81ab
4-Sept	47d	82.1	89a	27-Aug	58de	80.6	88a
11-Sept	53d	79.6	88ab	3-Sep	49e	85.0	90a
18-Sept	75cd	71.1	71abc	10-Sep	162bc	41.4	51cde
25-Sept	99cd	61.9	69abc	17-Sep	89cde	67.8	75abc
3-Oct	73cd	73.2	71abc	24-Sep	84cde	68.9	74abc
10-Oct	122cd	53.4	64bc	1-Oct	165bc	41.3	49cde
16-Oct	137bc	49.5	59cd	8-Oct	146cde	50.1	63abc
23-Oct	115cd	59.6	66abc	15-Oct	258ab	11.2	33de
1-Nov	226a	15.2	33e	22-Oct	160bcd	45.0	55bcd
6-Nov	210ab	23.1	39de	29-Oct	292a	5.1	26e
				5-Nov	173bc	41.1	55bcd
P-value	<0.0001		<0.0001	*P*-value	<0.0001		<0.0001

†Proxy® (ethephon) was applied once on each treatment date at 5 fl. oz per 1000 ft^2.

‡Seedheads were counted in a random 20 x 20-inch area on each plot at peak seedhead stage, determined visually on 31 May 2020 and 8 June 2021.

§Visual suppression was rated on a scale of 0-100% compared to nontreated plots in which 0 = no suppression and 100 = complete suppression.

¶Within columns, means followed by different letters are statistically different ($P \leq 0.05$).

Table 3.2. The effect of ethephon application timing on Innovation zoysiagrass injury as determined by turf color ratings in 2019-20 growing season.

Treatment date[‡]	Turf color[†] — Measurement date — 9/4	9/11	9/18	9/25	10/3	10/16	10/23	11/1	11/6	11/13	11/20
Nontreated	9.0a[§]	8.8a	8.8a	8.5ab	9.0a	8.8a	8.5a	7.8[NS]	7.0a	6.0[NS]	5.8[NS]
28-Aug	5.0b	4.0c	4.3c	5.0c	6.0c	7.0b	7.0b	7.0	6.0b	5.8	5.8
4-Sept	-[¶]	7.0b	7.0b	7.8b	7.8b	7.8b	7.8ab	7.8	6.8ab	5.8	5.8
11-Sept	-	-	7.8ab	7.8b	8.8a	8.8a	8.8a	7.8	7.0a	5.8	5.8
18-Sept	-	-	-	8.8a	9.0a	8.8a	8.8a	7.8	6.8ab	6.0	6.0
25-Sept	-	-	-	-	8.8a	9.0a	8.8a	7.8	7.3a	5.5	5.8
3-Oct	-	-	-	-	-	8.8a	8.8a	7.8	6.8ab	6.0	5.8
10-Oct	-	-	-	-	-	-	8.8a	8.0	7.3a	5.8	5.8
16-Oct	-	-	-	-	-	-	-	7.8	7.0a	5.8	6.0
23-Oct	-	-	-	-	-	-	-	-	7.3a	5.5	6.0
1-Nov	-	-	-	-	-	-	-	-	-	6.0	5.8
6-Nov	-	-	-	-	-	-	-	-	-	-	5.5
P-value	***[#]	***	***	***	***	***	***	0.227	0.005	0.584	0.943

[†]Turf color was rated visually on a scale of 1-9 in which 1= completely bleached white leaf, 6 = minimally acceptable discoloration with some browning, and 9 = dark green leaf with no discoloration.
[‡]Proxy® (ethephon) was applied once on each treatment date at 5 fl. oz per 1000 ft^2.
[§]Within columns, means followed by different letters are statistically different ($P \leq 0.05$) and NS represents not significance.
[¶]Treatments not yet applied on this rating rate.
[#]*** indicates $P < 0.0001$.

Table 3.3. The effect of ethephon application timing on Innovation zoysiagrass injury as determined by turf color ratings in 2020-21 growing season.

	Turf color[†]										
Treatment	Measurement date										
date[‡]	8/27	9/3	9/10	9/17	9/24	10/1	10/8	10/15	10/22	10/29	11/5
Nontreated	8.7a[§]	8.7a	8.7a	8.7a	8.8a	8.8a	8.5a	8.3a	7.3a	7.0a	6.0[NS]
20-Aug	5.0b	4.2b	4.7c	5.5c	6.0b	6.5b	7.0b	7.0b	6.0b	6.0b	6.0
27-Aug	-[¶]	4.5b	4.5c	5.5c	6.3b	6.7b	6.8b	7.0b	6.0b	6.0b	6.3
3-Sep	-	-	7.0b	7.0c	8.8a	8.8a	8.5a	8.2a	7.0a	7.0a	6.5
10-Sep	-	-	-	8.0a	8.8a	8.8a	8.5a	8.0a	7.0a	7.0a	6.0
17-Sep	-	-	-	-	9.0a	9.0a	9.0a	8.0a	7.0a	7.0a	6.3
24-Sep	-	-	-	-	-	8.7a	9.0a	8.0a	7.0a	7.0a	6.0
1-Oct	-	-	-	-	-	-	9.0a	8.0a	7.0a	7.0a	6.1
8-Oct	-	-	-	-	-	-	-	8.0a	7.0a	7.0a	6.5
15-Oct	-	-	-	-	-	-	-	-	7.0a	7.0a	6.3
22-Oct	-	-	-	-	-	-	-	-	-	7.0a	6.3
29-Oct	-	-	-	-	-	-	-	-	-	-	6.0
5-Nov	-	-	-	-	-	-	-	-	-	-	-
P-value	***[#]	***	***	***	***	***	***	***	***	***	0.833

[†]Turf color was rated visually as a measure of phytotoxicity due to ethephon on a scale of 1-9 in which 1 = completely bleached white leaf, 6 = minimally acceptable discoloration with some browning, and 9 = dark green leaf with no discoloration.

[‡]Proxy® (ethephon) was applied once on each treatment date at 5 fl. oz per 1000 ft^2.

[§]Within columns, means followed by different letters are statistically different ($P \leq 0.05$) and NS represents not significance.

[¶]Treatments not yet applied on this rating rate.

[#]*** indicates P <0.0001.

Table 3.4. The effect of ethephon application timing on mowing quality of Innovation zoysiagrass over two growing seasons.

Experiment 1 (2019-20)			Experiment 2 (2020-21)		
Treatment date[†]	Mowing quality[‡]		Treatment date[†]	Mowing quality[‡]	
	2 June 2020	8 June 2020		9 June 2021	15 June 2021
Nontreated	6.8cd[§]	5.3d[§]	Nontreated	6.8c[§]	5.3c[§]
28-Aug	8.5ab	8.3a	20-Aug	8.3ab	8.3a
4-Sept	8.8a	8.3a	27-Aug	8.8a	8.5a
11-Sept	9.0a	8.3a	3-Sep	8.8a	8.5a
18-Sept	8.3ab	7.8ab	10-Sep	7.5abc	7.3ab
25-Sept	8.0abc	7.3abc	17-Sep	8.3ab	7.8a
3-Oct	8.0abc	6.8bc	24-Sep	8.0abc	6.3bc
10-Oct	7.8abcd	6.5bcd	1-Oct	7.3bc	6.3bc
16-Oct	7.3bcd	6.3cd	8-Oct	7.3bc	5.8c
23-Oct	7.3bcd	6.0cd	15-Oct	7.8abc	5.3c
1-Nov	6.5d	6.0cd	22-Oct	7.8abc	5.3c
6-Nov	6.5d	5.3d	29-Oct	7.5abc	5.3c
			5-Nov	7.5abc	5.0c
P-value	<0.0001	<0.0001	*P*-value	<0.0001	<0.0001

[†]Proxy® (ethephon) was applied once on each treatment date at 5 fl. oz per 1000 ft^2.
[‡]Mowing quality was rated visually as a measure of turf quality post-mowing on a scale of 1-9 in which 1 = canopy with abundance of white cast and 9 = green canopy with no white cast.
[§]Within columns, means followed by different letters are statistically different ($P \leq 0.05$).

Table 3.5. The effect of ethephon (Proxy®) application timing on spring greenup of Innovation zoysiagrass over two growing seasons.

Experiment 1 (2019-20)				Experiment 2 (2020-21)				
Treatment date[†]	Spring greenup[‡]			Treatment date[†]	Spring greenup[‡]			
	17 April 2020	24 April 2020	1 May 2020		15 April 2021	23 April 2021	30 April 2021	7 May 2021
Nontreated	3.0 NS[§]	4.3 NS[§]	6.3 NS[§]	Nontreated	3.8 NS[§]	5.5 NS[§]	6.8 NS[§]	8.0 NS[§]
28-Aug	4.0	5.0	7.0	20-Aug	3.5	5.0	6.5	7.8
4-Sept	3.3	4.8	6.8	27-Aug	3.3	5.3	6.8	7.8
11-Sept	3.3	4.5	6.5	3-Sep	3.5	5.3	6.8	8.0
18-Sept	3.3	4.3	6.0	10-Sep	3.5	5.0	6.3	7.8
25-Sept	3.3	4.3	6.5	17-Sep	3.3	5.0	6.3	7.8
3-Oct	3.3	4.3	7.0	24-Sep	3.8	5.5	6.5	7.5
10-Oct	3.3	4.5	6.3	1-Oct	4.0	5.8	7.0	7.8
16-Oct	3.5	4.8	6.8	8-Oct	4.0	5.5	6.5	7.8
23-Oct	3.3	4.8	6.8	15-Oct	4.0	5.5	6.5	8.0
1-Nov	3.3	5.0	6.5	22-Oct	4.0	5.8	6.8	8.0
6-Nov	3.8	4.8	6.5	29-Oct	4.0	5.5	6.5	8.0
				5-Nov	4.0	5.3	6.5	7.8
P-value	0.931	0.568	0.399	*P*-value	0.251	0.073	0.679	0.834

[†]Proxy® (ethephon) was applied once on each treatment date at 5 fl. oz per 1000 ft^2.

[‡]Spring greeenup was rated visually on a scale of 1-9 in which 1= no green up and 9 = fully greenup.

[§]Within columns, means followed by different letters are statistically different ($P \leq 0.05$) and NS represents not significance.

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Chapter 4 - Developing Models to Optimize Seedhead Suppression in ‘Meyer’ Zoysiagrass using Ethephon in the U.S. Transition Zone

This chapter has been prepared using style guidelines for the journal Crop Science.

Abstract

'Meyer' zoysiagrass is widely used on golf course fairways in the U.S. transition zone. Meyer produces seedheads in the spring that deteriorates aesthetics and disrupts playability. Managing seedheads on Meyer with the use of ethephon has been promising but results are inconsistent. A practical tool for predicting the optimum ethephon application timing for effective seedhead suppression would be beneficial to turf managers. Five separate studies were conducted over four locations during 2018-2020 in the transition zone to develop a model. Several models were fit to describe seedhead suppression variability observed across four locations. The candidate variable, daylength, 3-d average mean air temperature (T_{avg}), cumulative growing degree-days (GDD), and cumulative cooling degree-days (CDD) were sought to fit a multiple linear regression model. A multiple linear regression model using GDD and T_{avg} as predictors was identified as the best combination to explain seedhead suppression in a linear fashion (adjusted determination coefficient = 0.44, root mean square error = 23.8, $P < 0.0001$). A second-degree polynomial and a Gaussian model, which incorporated GDD, were identified as better alternative models to predict ethephon application timing for seedhead suppression. These two models were compared for the quality of fitness. Akaike information criterion (AIC), Bayesian information criterion (BIC), and Root mean square error (RMSE) were used as fitness evaluators in addition to graphical residual analysis. The Gaussian model had a slightly better fit than the second-degree polynomial model. Furthermore, all three models were evaluated through an independent, new field study to test the predictive capability of the models. The Gaussian model had better predictive capacity near the optimum suppression window, whereas the second-degree polynomial model was better at predicting near the GDD periods where seedhead suppression began to increase or decline. The

Gaussian model should be useful prediction tool for turf managers in determining ethephon application time for the management of seedheads in Meyer zoysiagrass.

Introduction

'Meyer' zoysiagrass (*Zoysia japonica* Steud.) provides high-quality turf and playing surfaces for golf course fairways and tees throughout the U.S. transition zone (Lyman et al., 2007). Zoysiagrass in general requires less water, nitrogen fertilizer, and mowing than C_3 turf species (Patton et al., 2017). Meyer also offers improved shade and cold tolerance compared to other C_4 turfgrasses; therefore, it is widely used in the U.S. transition zone (Patton et al., 2017). However, Meyer produces seedheads in late spring that impact the playing surface and aesthetics. Seedheads appear to leave a purple cast across fairways and tees on golf courses when they emerge, and after mowing seed stalks that remain leave a white cast to these areas. The poor aesthetics and disruption of uniform playing surface due to lingering seedheads are concerning to golf course superintendents and golfers (Kane & Miller, 2003).

In C_3 turfgrasses, plant growth regulators (PGRs) have been widely used to manage seedhead production. Particularly, the performance of mefluidide [N-(2,4-dimethyl-5-{[(trifluoromethyl)-sulfonyl] amino} phenyl) acetamide] and ethephon (2-Chloroethylphosphonic acid) have been extensively studied in annual bluegrass (ABG) (*Poa annua* L.), while studies evaluating their efficacy on C_4 turfgrasses are limited. Effective seedhead suppression with ethephon has been reported in several studies across a range of climates (Askew 2006; Borger, 2008; Buettner et al., 1976; Haguewood et al., 2013; Kane & Miller, 2003; Kopec & Gilbert, 2004; Patton et al., 2018; Patton et al., 2020; Raudenbush et al., 2020; Reicher et al., 2020). One of the major challenges in the use of ethephon for seedhead suppression is determining the optimum application timing. A few studies have reported inconsistent results when application is based on calendar days. For instance, Petrovic et al. (1985) found no suppression of ABG seedheads with ethephon, and Ledford (2019) reported that ethephon was ineffective in suppressing seedheads applied to ‘Diamond’ zoysiagrass (*Z. matrella* (L.) Merr.) in a greenhouse study. There is anecdotal evidence of ethephon being not effective on seedhead suppression. Due to natural climatic patterns, the optimum time for ethephon application will vary from year to year and location to location (Bigelow & Hardebeck, 2004).

Researchers have attempted to identify optimum application timing of mefluidide for ABG seedhead suppression using cumulative 2growing degree-days (GDD) (Branham & Danneberger, 1989; Danneberger et al., 1987), phenological indicators (Askew, 2006), or morphological stage of seedhead production (Kane & Miller, 2003; Watschke & Borger, 2005). The GDD-timed application of mefluidide or ethephon for seedhead suppression in C_3 turfgrasses has been successful in several studies (Branham & Danneberger, 1989; Danneberger et al., 1987; Haguewood et al., 2013; Reicher et al., 2020). Seedhead emergence in ABG has been linked with air temperatures and is therefore best predicted by a growing degree-day (GDD) model (Danneberger & Vargas, 1984). The GDDs, a unit that accounts for temperature, more accurately predicts temperature-dependent events such as germination, flowering, and maturity, compared to calendar days (Cross & Zuber, 1972). The prediction of phenology of crops utilizing the GDD model has been commonly reported in numerous field and horticultural crops. In turfgrass, the GDD was first used for predicting proper application timing of mefluidide for ABG seedhead suppression (Danneberger et al., 1987). The method of calculating GDD has evolved and been made simpler in recent years. Baskerville and Emins (1969) provided a sophisticated and more accurate sine curve method to compute growing degree that requires computer programming. Danneberger et al. (1987) modified the sine curve methods of Baskerville and Emins (1969), but that still involved complex mathematics for computation. To expand the utility of the GDD, Branham and Collins (1986), and Branham (1991) suggested a simpler average calculation method would be equally appropriate. For the sake of simplicity and intended use, this study also used a simple average method for GDD calculation.

In the turf industry, Danneberger and Vargas (1984) first developed the GDD model to explain seedhead emergence pattern on ABG based on 13 ^{0}C base temperature with summation beginning on 1 April. The mefluidide application following the GDD model of Danneberger and Vargas (1984) provided economically acceptable seedhead suppression (>76%) in ABG fairways (Danneberger et al., 1987). The effective suppression of seedheads (>86%) in Kentucky bluegrass (*Poa pratensis* L.) following mefluidide application was reported when timed following the GDD based on 10 ^{0}C base temperature with summation beginning 1 March (Barnham & Danneberger, 1989). In Missouri, seedhead suppression of ABG in creeping bentgrass (*Agrostis stolonifera* L.) putting greens ranged from 35 to 83% on the peak rating date when ethephon was applied based upon GDD with a 10 ^{0}C base temperature with summation starting on 1 January (Haguewood et al., 2013). Ethephon applied based on a GDD model, which was different from the earlier one reported by Danneberger and Vargas (1984), has been successful in controlling seedheads (< 14% seedhead cover) in an ABG fairway in Michigan (Calhoun, 2010). The GDD model in this study was determined using a -5 ^{0}C base temperature with summation starting on 1 March. It is clear from the previous studies that although the results on seedhead suppression are promising, the methodology for developing prediction models are different, which adds confusion to adopt the model.

A few studies conducted on zoysiagrass seedhead suppression with ethephon application have reported commercially acceptable results in the transition zone (Brosnan et al., 2012; Patton et al. 2018). In Meyer zoysiagrass, spring application of ethephon was found to be ineffective, whereas fall application was effective in a study across three locations (Patton et al., 2018). This suggests the application timing influences the efficacy of ethephon in Meyer. No research has been done to determine preferred application timing for ethephon based on air temperatures or GDD. A study in Georgia reported the relationship between seedhead emergence and environmental conditions in 'Diamond' zoysiagrass managed in the transition zone (McCullough et al., 2017). The peak seedhead production in Diamond zoysiagrass (maintained at 1.3 cm height of cut) was strongly correlated with GDD determined using a 10 ^{0}C base temperature with summation beginning on 1 Jan. (r = 0.79). In the same experiment, seedhead production in Diamond was also correlated with photoperiod (r = 0.64). Considering the fact that ethephon and mefluidide are most effective in suppressing annual bluegrass seedheads when timing is based upon GDD, it is plausible to surmise similar models based on environmental factors will be useful on zoysiagrass as well.

Based on the previous findings, I hypothesize that local ambient air temperatures and photoperiod at the time of application may influence the efficacy of ethephon for Meyer zoysiagrass seedhead suppression. A study was therefore conducted over multiple sites in the transition zone to develop a model that can describe the effects of ethephon application timing on seedhead suppression in Meyer zoysiagrass. I envision that such model could be utilized as a prediction tool to remotely determine the optimum ethephon application timing of ethephon to suppress Meyer seedheads in the transition zone.

Therefore, the objectives of this study were to: 1) identify models that best estimate optimum application time for ethephon to suppress Meyer zoysiagrass seedhead development; and 2) verify the efficacy of models through validation from a new field experiment.

Materials and Methods:

Experiment 1: Model Development

Field Management

Four identical experiments were conducted on ‘Meyer’ zoysiagrass maintained at a mowing height of 1.3 cm at four locations in the transition zone during 2018-19 growing season. The locations were: W.H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN (40^{0}26’19’’ N, 86^{0}56’07’’ W); Rocky Ford Turfgrass Research Center in Manhattan, KS (39^{0}13’50’’ N, 96^{0}34’46’’ W); East Tennessee Research and Education Center in Knoxville, TN (35^{0}58’14’’ N, 83^{0}51’40’’ W); and Shadow Valley Country Club in Rogers, AR (36^{0}17’17’’ N, 94^{0}13’11’’ W) (Table 4.1). Another follow-up study was conducted only in Manhattan in 2019-20 at the same site as the previous year. Each experimental area received 49 kg N ha^{-1} $year^{-1}$ and was irrigated to prevent visible wilting. The irrigation and mowing were withheld for at least 2 days after ethephon treatment application throughout the study period. Tebuconazole (Tebuconazole 3.6F, Control Solutions Inc.) was applied each year in early Sept. and Oct. at 1.4 kg ha^{-1} to prevent large patch infection.

Experimental setup

All experiments were arranged in a randomized complete block design with four replicates. In Indiana, replicates were reduced to three due to damage from winterkill. The treatments consisted of 10 to 12 application timings of ethephon (Proxy® 2L, Bayer Environmental Science) between August and December, and an untreated control (Table 4.2). The ethephon application dates began in early autumn and continued once weekly even after the first frost as grasses entered winter dormancy during 2018. Ethephon was applied at 3.8 kg ha^{-1} with a CO_2 pressurized sprayer equipped with various nozzles (TeeJet Technologies, Glendale Heights, IL) and applied at various spray volumes (Table 4.1).

Environmental data

Environmental conditions were monitored beginning 1 August. Daily maximum and minimum air temperatures were obtained from nearby weather stations located near each research site (Table 4.1). The 3-d average mean air temperatures were obtained by averaging the daily max. and min. air temperatures 3 d before the treatment application date. Daily air temperatures were utilized to determine GDD and cooling degree-days (CDD) using Equations 1 and 2, respectively.

$$GDD = \left(\frac{T_{max}+T_{min}}{2}\right) - T_{base} \quad \text{.................................Eq. (1)}$$

$$CDD = T_{base} - \left(\frac{T_{max}+T_{min}}{2}\right) \quad \text{..................................Eq. (2)}$$

where T_{max} is the daily maximum air temperature and T_{min} is the daily minimum air temperature. In Eq. (1), T_{base} is the lowest temperature at which plant growth occurs (McMaster and Wilhem, 1997). Several base temperatures ranging from 10^0C to -5^0C at 5^0C increments were used for GDD calculation. Likewise, in Eq. (2), temperatures ranging from 15 to 30^0C at 5^0C increments were utilized as base temperatures to compute CDD. The appropriate base temperatures for Eq. (1) and (2) were selected by determining the adjusted coefficient of determination (R^2 adj) value similar to the methods of Kreuser and Soldat (2011). Cumulative GDD and CDD were calculated as the summation of absolute values of daily growing degree-days and daily cooling degree days, respectively. For West Lafayette and Manhattan locations, GDD calculations started on 1 August while summations for Knoxville and Rogers locations began on August 15 because of intrinsic differences in the air temperatures across locations. Photoperiod data were obtained from NOAA (https://gml.noaa.gov/grad/solcalc/).

Data collection

Seedhead data were collected the spring following ethephon application to evaluate efficacy of treatment dates. Seedhead suppression was quantified by counting the number of seedheads. Once formation of seedheads was visible in the canopy, mowing ceased until peak inflorescence production, determined through visual inspection. A 50 by 50 cm template was randomly placed in each experimental plot and seedheads were counted once the peak inflorescence stage was determined. Counts were done on 11 June, 18 May, 1 May, and 15 May 2019 in West Lafayette, Manhattan, Knoxville, and Rogers, respectively, and on 1 June 2020 in Manhattan. Percent seedhead suppression (PSS) was determined as:

$$PSS = \left(1 - \frac{\text{\# seedheads in treated plot}}{\text{\# seedheads in control plot}}\right) \times 100$$

Statistical analysis

Pearson's correlation coefficients were generated for percent seedhead suppression with daylength, daily average mean air temperature, 3-d average mean air temperature, GDD_0, GDD_{10}, and CDD_{25}. Three different approaches of regression models were investigated to predict seedhead suppression: multiple linear regression, polynomial regression, and Gaussian regression. A multiple linear regression test was conducted to explain the percent seedhead suppression with all candidate variables. Subset regression was conducted to test several combinations of candidate variables to determine best fit for percent seedhead suppression. ANOVA (Analysis of variance) was conducted to test the significance of the parameters for the models selected from subset regression. Percent seedhead suppression data were applied to other two regression models to determine the fit for percent seedhead suppression as a function of GDD. Models included a second-degree polynomial model described as:

$$Y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + \varepsilon_i$$

in which Y_i is percent seedhead suppression, x_i is GDD, and β_0, β_1 and β_2 are the model parameters to be estimated.

A Gaussian model was also evaluated and described as:

$$Y_i = ae^{\left\{-0.5\left[\frac{(x-x0)}{b}\right]^2\right\}}$$

in which Y_i is percent seedhead suppression, x is the GDD, a represents the peak of the curve, e = 2.718, $x0$ represents the GDD corresponding to the peak of the curve, and b represents the width of the curve. The parameters of the polynomial model were estimated by the ordinary least square method using lm function in R and generalized least squares method was used for parameter estimation of the Gaussian model using gnls function in R. Student's t-test was utilized to test the significance of estimates in the models.

All models were verified to satisfy the assumptions of residual homoscedasticity and normality through the Breusch-Pagan and Shapiro-Wilk tests, respectively, at the level of 1% significance. A visual analysis of the standardized residuals through graphical distribution was also performed. The Akaike information criterion (AIC), Bayesian information criterion (BIC), root mean square error (RMSE), variance inflation factor (VIF), and coefficient of variation (CV) were computed to compare the quality of the fit. All statistical tests including the residual analysis for this study were conducted employing the R statistical software (R Core Team, 2020), by using the packages "car", "leaps", and "nlme". The regression figures were created using SigmaPlot version 11.0 (SPSS Inc., Chicago, IL).

Experiment 2: Model Validation

Field Management

An independent field experiment was conducted at the Rocky Ford Turfgrass Research Center, Manhattan, KS, during 2020-21 on Meyer zoysiagrass at the same site as the previous experiment and maintained at a cutting height of 1.3 cm. The site received 49 kg N ha^{-1} $year^{-1}$ and was irrigated to prevent visible wilting. Tebuconazole (Tebuconazole 3.6F, Control Solutions Inc.) was applied on 1 Sept. and 2 Oct. at 1.4 kg ha^{-1} to prevent large patch infection.

Experimental setup

Treatments consisted of seven application timings of ethephon (Proxy® 2L, Bayer Environmental Science) applied between August and November, and an untreated control (Table 4.1). The treatments were arranged in a randomized complete block design with four replicates. Plots measured 1.5 by 1.5 m. Ethephon was applied at 3.8 kg ha^{-1} with a CO_2 pressurized sprayer equipped with XR8003VS flat-fan nozzle (TeeJet Technologies, Glendale Heights, IL) calibrated to deliver 815 L ha^{-1} at 276 kPa. Weather-based parameters were monitored and calculated during 2020 as described in Expt. 1. In Expt. 2, seedhead counting was done on a 50 x 50-cm randomly selected area on each plot on 1 June 2021; percent seedhead suppression (PSS) was evaluated as described in Expt. 1.

Statistical analysis:

The predictive performance of the candidate models selected from Expt. 1 was evaluated by subjecting the models to new independent data from Expt. 2. Residual or prediction error were calculated as: Observed PSS – Predicted PSS, and then used to obtain squared residuals. The squared residuals were summed to obtain total sums of error (SS) and divided by regression df to obtain mean square error (MSE). The root mean square error (RMSE) were determined as the square root of MSE.

Results & Discussion:

The daily average mean air temperature and 3-d average mean air temperature (T_{avg}) were positively correlated with percent seedhead suppression (PSS), r= 0.31 and 0.33, respectively (Table 4.3). The cumulative cooling degree-days based on 25 ^{0}C temperature (CDD_{25}) was negatively correlated with PSS (r= -0.40). However, correlation of seedhead suppression with photoperiod and growing degree-days (GDD) was not significant (Table 4.3). The nonsignificant correlation does not necessarily mean there is no relationship, it simply means the linear relationship does not exist. McCullough et al. (2017) reported that seedhead production in 'Diamond' zoysiagrass was correlated with GDD and photoperiod. However, Meyer seedhead suppression after ethephon application showed a nonlinear relationship with photoperiod and GDD in our study. Results of three models used to optimize ethephon application timing for Meyer seedhead suppression are highlighted below.

Multiple Regression Model

Four potential variables: photoperiod, T_{avg}, GDD, and CDD were considered for inclusion in a multiple linear regression model to describe percent seedhead suppression. Among all possible combinations, a two-predictor model with T_{avg} plus GDD, with a 10 ^{0}C base temperature (GDD_{10}), resulted in the best combination from the analysis of subset regression. The model selection was based on the lowest BIC and the highest R^2_{adj} statistics (data not shown). The proposed multiple linear regression model is described as:

$$\text{Seedhead suppression (\%)} = 3.80 \times T_{avg} + 0.10283 \times GDD_{10} - 93.68$$

The overall fitness of the model was significant (P < 0.0001) with R^2 = 0.44, RMSE = 23.80, and VIF = 1.93 (Table 4.4). In other words, the combination of T_{avg} and GDD could explain

44% of variability observed in seedhead suppression. Also, in multiple linear regression the issue of multicollinearity (correlation between two predictors) is important to consider as this produces unwanted redundancy in the model. The VIF lower than 5 is considered appropriate as this indicates acceptable level of correlation between the predictors to be used in the model (Welham et al., 2014). The interaction t of T_{avg} × GDD was also investigated to add in the model but was not significant (P = 0.0648) and thus only the main effects were proposed. The regression line of the model reveals the linear relationship of seedhead suppression with GDD and T_{avg} (Fig. 4.1). All three coefficients of the model were significant at 1% significance according to the t-test (Table 4.4). The assumption of normality was satisfied with Shapiro Wilk test (P = 0.267) and constant variance with Breusch-Pagan test (P= 0.979). Also, the standardized residual analysis plot depicts the acceptable level of homogeneity of variance (Fig. 4.2). This model did a fair job of describing seedhead suppression, R^2 = 0.44. This meant that 56% of the variance in seedhead suppression could not be explained from GDD_{10} and T_{avg}. The multiple linear regression model could be further strengthened with the inclusion of an additional variable; however, the identification of significant predictor is a challenge. The understanding of metabolism of ethephon and physiology of seedhead production in Meyer zoysiagrass is still limited. It is highly likely that other environmental factors, such as soil temperature, relative humidity, soil moisture, wind speed, cloud cover, and shade might have some influence on the efficacy of ethephon on seedhead suppression.

Polynomial Model

Alternatively, seedhead suppression was fit as a function of GDD through a polynomial model. Base temperatures selection analysis showed that 0 ^{0}C had the highest R^2_{adj} (0.50) and was thus considered an ideal base temperature for GDD computation (Fig. 4.3). Kreuser and Soldat (2011) used pseudo R^2 to determine the ideal base temperature for modeling the application of trinexapac-ethyl for clipping reduction on annual bluegrass (*Poa annua* L.). Second-degree polynomial model estimates were significant for all three parameters (β_0, β_1 and β_2) at 1% significance by the t-test (Table 4.5). A third-degree polynomial equation was also fitted, but a cubic term was not significant (P= 0.2717) and hence dropped. The second-degree polynomial model for percent seedhead suppression is described as:

Seedhead suppression (%) = $0.2308\,(GDD) - 0.000103(GDD)^2 - 61.58$

Seedhead number in ABG was modeled using a third-degree polynomial model by Danneberger and Vargas (1984). The mefluidide application made based on that model resulted excellent seedhead suppression in ABG (Dannerberger et al., 1987).

Gaussian Model

The Gaussian function has a characteristic symmetric bell-shaped curve where the y-variable begins to increase gradually, and once reaches the peak it declines thereafter. This nonlinear function has been utilized widely to model several phenomena such as biological, social, psychological data, among others (Sandoval-Hernandez et al., 2019). Seedhead suppression estimates for a Gaussian model were significant for all three parameters (a, x_0, and b) (Table 4.5). This indicates inferences to be made based on the models are acceptable. The equation for the Gaussian model is described as:

Seedhead suppression (%) = $79.13\, e^{\left\{-0.5\left[\frac{(\mathrm{GDD}-1153.47)}{371.58}\right]^2\right\}}$

Where e= 2.718 and GDD is the accumulated growing degree-day based on 0 ^{0}C base temperature. Kreuser and Soldat (2011), and Kresuer et al. (2017) have proposed a nonlinear regression model to describe the relative clipping yield with application of trinexapac- ethyl on annual bluegrass (*Poa annua* L.). Nonlinear models have been commonly used in studying the growth of plants. The nonlinear models have the advantage of having smaller number of parameters, generally with biological interpretation unlike linear models (Archontoulis et al., 2015).

Based on the statistics used to evaluate the models, the Gaussian model provided a better estimate for GDD and ethephon application than the multiple regression model and polynomial model. The lower RMSE, AIC, BIC, and CV and higher R^2_{adj} indicates that the Gaussian model is better at explaining the variation observed in seedhead suppression than the polynomial model (Table 4.5). Furthermore, the fitting characteristics of the models can be compared visually through how well the regression line fits around the observations (Fig. 4.4 & 4.5). The graphical observation of the regression curve for the polynomial model suggests that the curve is fairly good at predicting seedhead suppression when suppression begins to increase or decline (Fig. 4.4). However, the curve has tendency to under-predict near the optimum seedhead suppression region, which is observed around the mean of GDD. In contrast, the Gaussian curve is shifting upward near the optimum seedhead suppression region and thus provides a better fit across the optimum region of suppression (Fig. 4.5). One of the advantages of the Gaussian model over the polynomial model is the practical interpretation of the parameters. The maximum suppression was predicted as 79% and was estimated to be achieved with ethephon application at 1153 GDD_0. Also, the standard deviation (std.) of the curve was 372 GDD_0. The practical implication of std. is that 50% of the estimated maximum response will fall between $X_0 \pm 1$ std. In other words, at least 40% seedhead suppression was estimated to occur between 782 and 1525 GDD_0. The parameters of the polynomial model have no such logical interpretation. However, the curve of the first derivative of the polynomial model showed that the peak seedhead suppression was predicted as 68% and estimated to occur when GDD_0= 1120. Both the models have unique properties. The standardized residuals plot analysis showed that the polynomial model is suffering from the issue of heterogeneity of variance as residuals are higher towards the higher fitted values and vice-versa (Fig. 4.6). This creates bias in the significance. The transformation of the y and/or x variables for the polynomial model was attempted but did not produce any better results and therefore not incorporated. The Gaussian model, in contrast, has better standardized residuals plot (random distribution of residuals) showing acceptable level of homoscedasticity (Fig. 4.7). To conclude, above all three models proposed, the Gaussian model can better describe seedhead suppression in Meyer zoysiagrass with ethephon application as a function of GDD_{0}.

Model Evaluations in Manhattan, KS

Regardless of the differing fitness of the model, all three models were further subjected to a validation test and evaluated for the predictive capability. The multiple linear regression model had SS = 4131.7; MSE = 1032.9; and RMSE= 32.1. The multiple linear regression model resulted in prediction error that was too large, and thus was not considered a competitive model. The average sum of square residuals (SS), mean square error (MSE), and root mean square error (RMSE) for the polynomial model were 197.8, 49.5, and 7.0, respectively. The Gaussian model, on average, had higher error for predictions where SS = 345.8; MSE = 86.4; and RMSE= 9.3. Based on the residual statistics, the polynomial model on average had a better predictive capability than the Gaussian model. Interestingly, the predictive performance of the Gaussian model was the best (indicated by the lowest squared residuals) when seedhead suppression was at the highest level (Table 4.6). The polynomial model, despite showing lower prediction error on average, had the greatest squared residuals when seedhead suppression was at the peak. This indicated that the Gaussian model could do a better job at making predictions on new observations near the optimum suppression region and that is where we are more interested in rather than across the wide domain.

This is also depicted through the graphical analysis. In the second-degree polynomial model, the new observation from Expt. 2 is just outside the 95% confidence band when the peak suppression is observed on 23 Sept. 2021 or at 1142 GDD_0 (Fig. 4.4). On the other hand, in the Gaussian model the same peak observation passes through the estimated regression line (Fig. 4.5).

The Gaussian model was further explored to understand the recommendation for seedhead suppression in simpler terms. The model estimated that at least 50% seedhead suppression could occur with single ethephon application in fall when applied between 800 GDD_0 and 1500 GDD_0. Likewise, if applied between 900 GDD_0 and 1400 GDD_0, at least 60% suppression was achieved, and if applied between 1000 GDD_0 and 1300 GDD_0, 70% seedhead suppression occurred.

Conclusion

In summary, the Gaussian model could be useful in explaining the variations observed in the study but the domain of GDD_0 for effective predictive capability of the model is very narrow and could have limited use. The different start date for accumulation of growing degree-days for different regions of transition zone should be taken into consideration. The model might not be effective if users adopt this beyond the intended latitudinal range. Irrigation post ethephon application has been reported to affect its efficacy, and therefore precipitation within few hours of application could interfere with the model findings. The next step in refining the Gaussian model is to validate the model findings through additional field observations in golf courses and research sites. More empirical evidence would further corroborate the model and challenge its stability over wide range of conditions. It is suggested to have a control untreated plot nearby to observe comparative reduction in seedheads. Since this prediction tool is intended for operational use by the golf course superintendents, the parsimony of the model as a function of GDD was emphasized.

Furthermore, the growing degree-day calculation based on 0 ^{0}C (32 ^{0}F) is commonly available in several weather platforms including the Michigan State University's GDD Tracker (https://gddtracker.msu.edu/), which is popular in the turf industry. It is also the author's intention to improve the model output to incorporate other cultivars of zoysiagrass adapted in the transition zone, particularly the newer cultivars like Innovation™. I speculate that similar models can be deployed for other zoysiagrass cultivars in other regions of the U.S.

Figure 4.1. Regression line generated from a multiple linear regression model with cumulative growing degree-days based on 0 ^{0}C base temperature (GDD) and 3-d average mean air temperature as predictors to predict 'Meyer' zoysiagrass seedhead suppression following ethephon application. The experiment was conducted over four locations: West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN in 2018-2020.

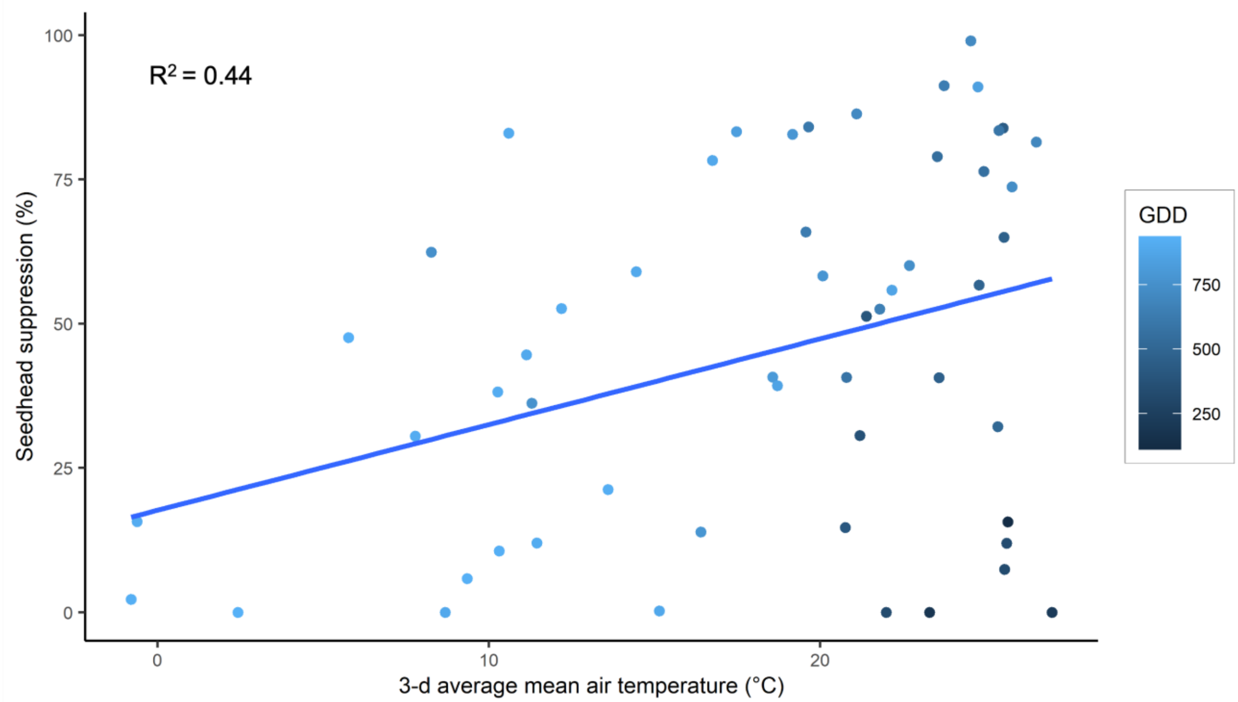

Figure 4.2. Standardized residuals plot from multiple linear regression model to predict seedhead suppression from cumulative growing degree-day and 3-d average air temperature. Data were collected across locations in Experiment 1.

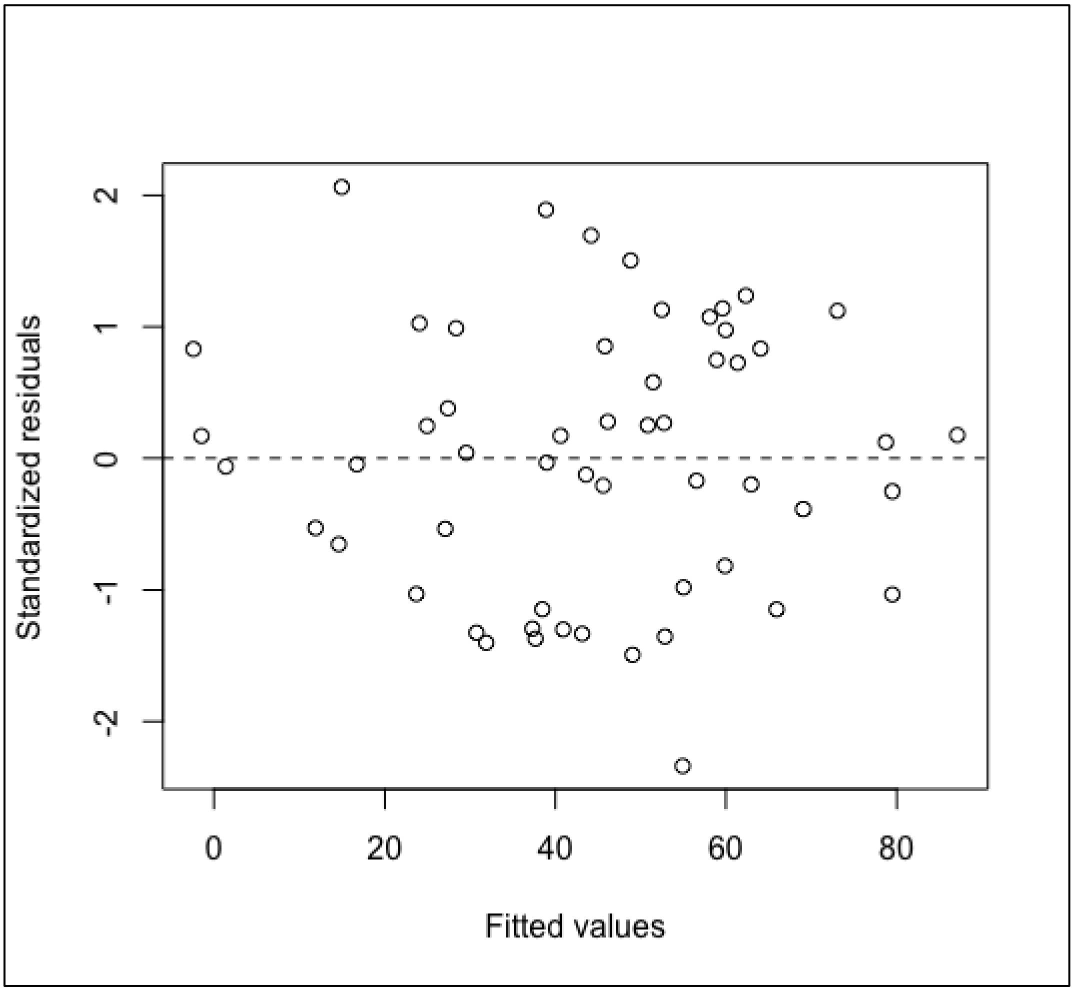

Figure 4.3. Adjusted coefficient of determination (R^2_{adj}) for the range of base temperatures on computation of growing degree days.

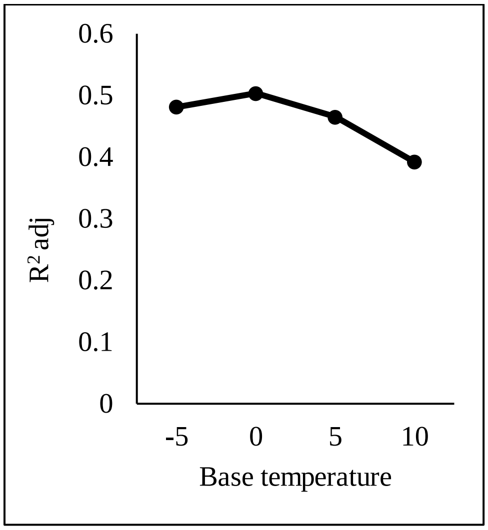

Figure 4.4. Predicted and actual zoysiagrass seedhead suppression with ethephon based on the second-degree polynomial model following results from Expt. 1 conducted over four locations: West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN in 2018-2020. Pink cross markers represent observations averaged over four replicates from Expt. 1 and were fit to develop the model. Gray triangle markers represent new observations from Expt. 2, which was conducted in Manhattan, KS in 2020-21 and were utilized to verify the model developed from Expt. 1.

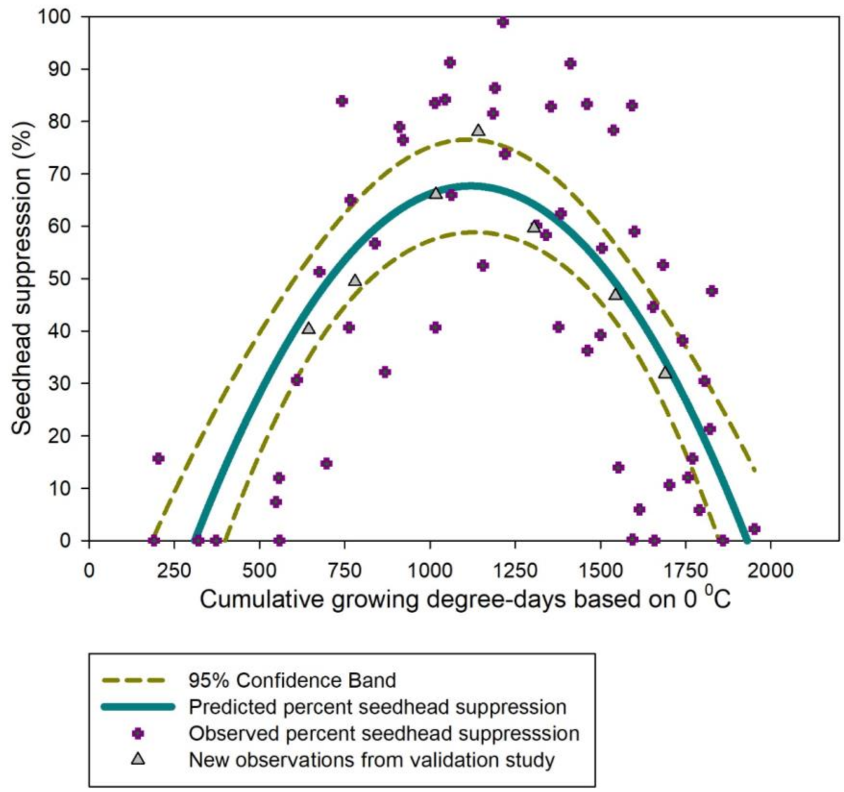

Figure 4.5. Predicted and actual zoysiagrass seedhead suppression with ethephon based on the Gaussian model following results from Expt. 1 conducted over four locations: West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN in 2018-2020. Pink cross markers represent observations averaged over four replicates from Expt. 1 and were fit to develop the model. Gray triangle markers represent new observations from Expt. 2, which was conducted in Manhattan, KS in 2020-21 and were utilized to verify the model developed from Expt. 1.

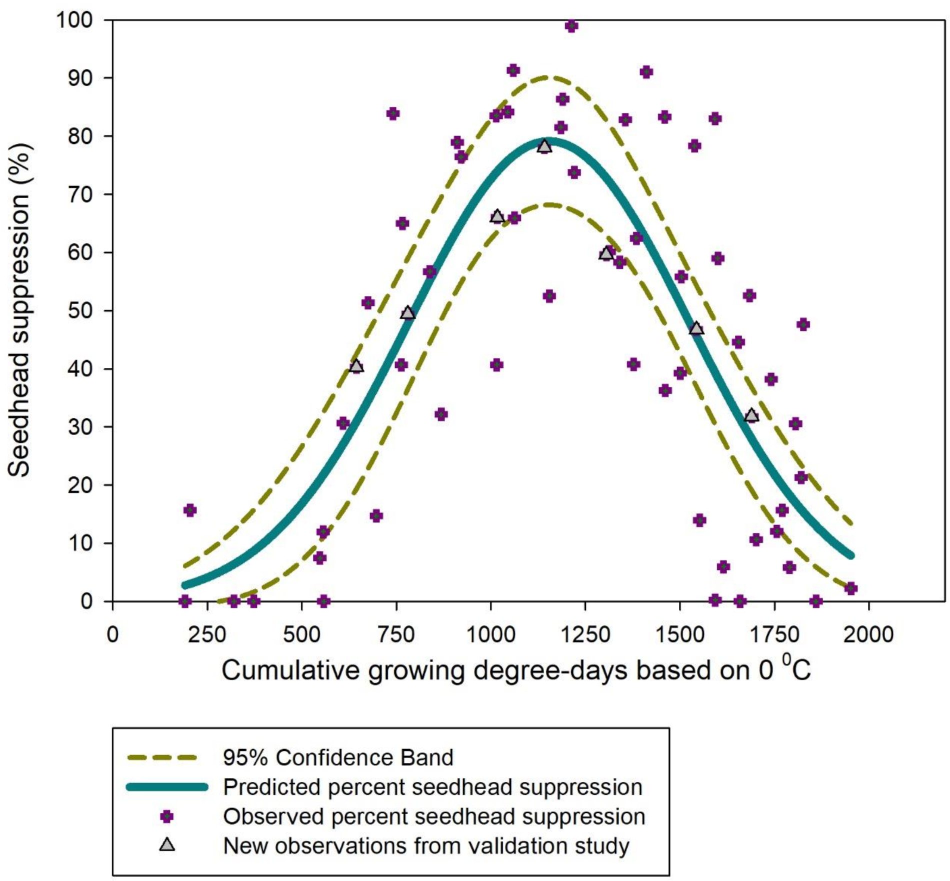

Figure 4.6. Standardized residuals plot from second-degree polynomial model to predict seedhead suppression as a function of cumulative growing degree-day; data were collected across locations in Experiment 1.

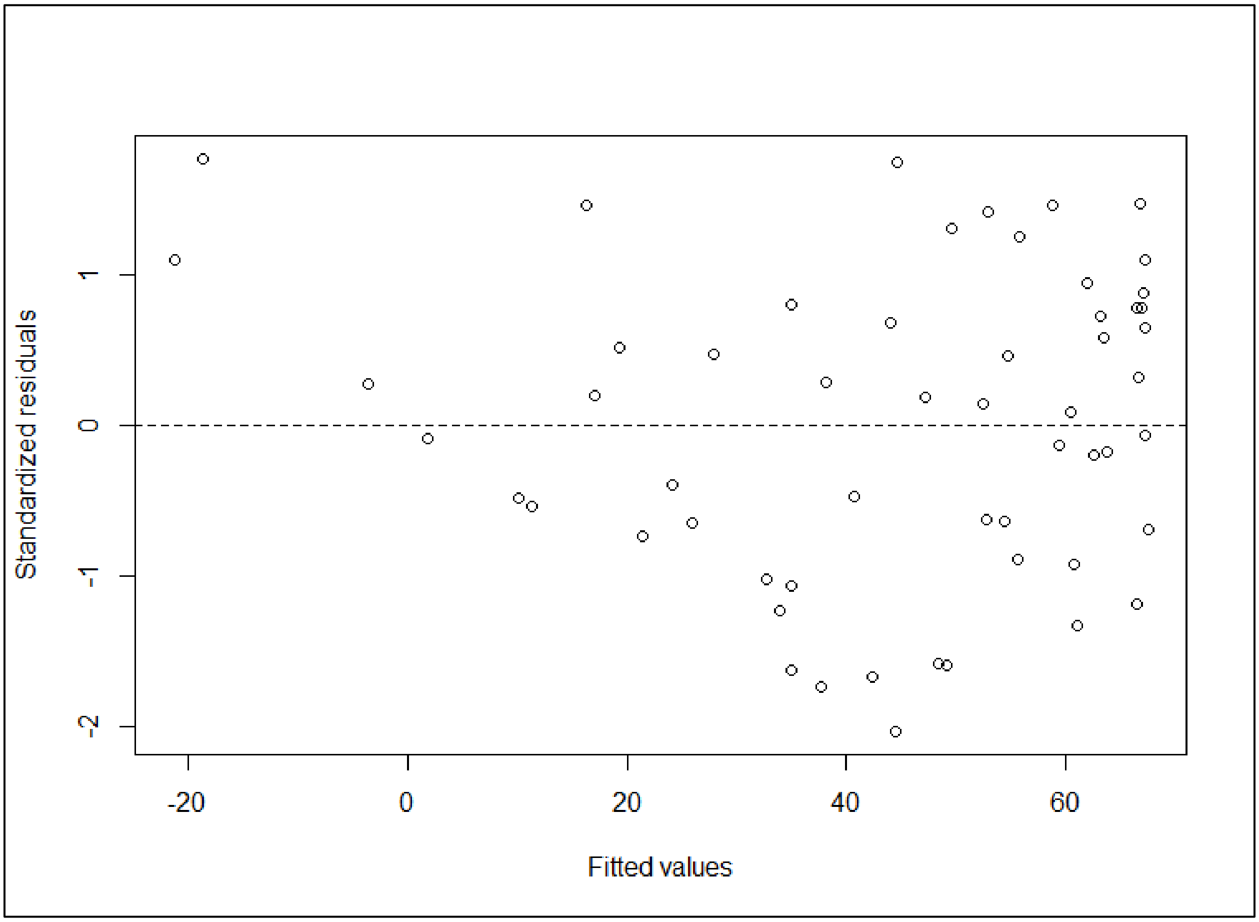

Figure 4.7. Standardized residuals plot from Gaussian model to predict seedhead suppression as a function of cumulative growing degree-day; data were collected across locations in Experiment 1.

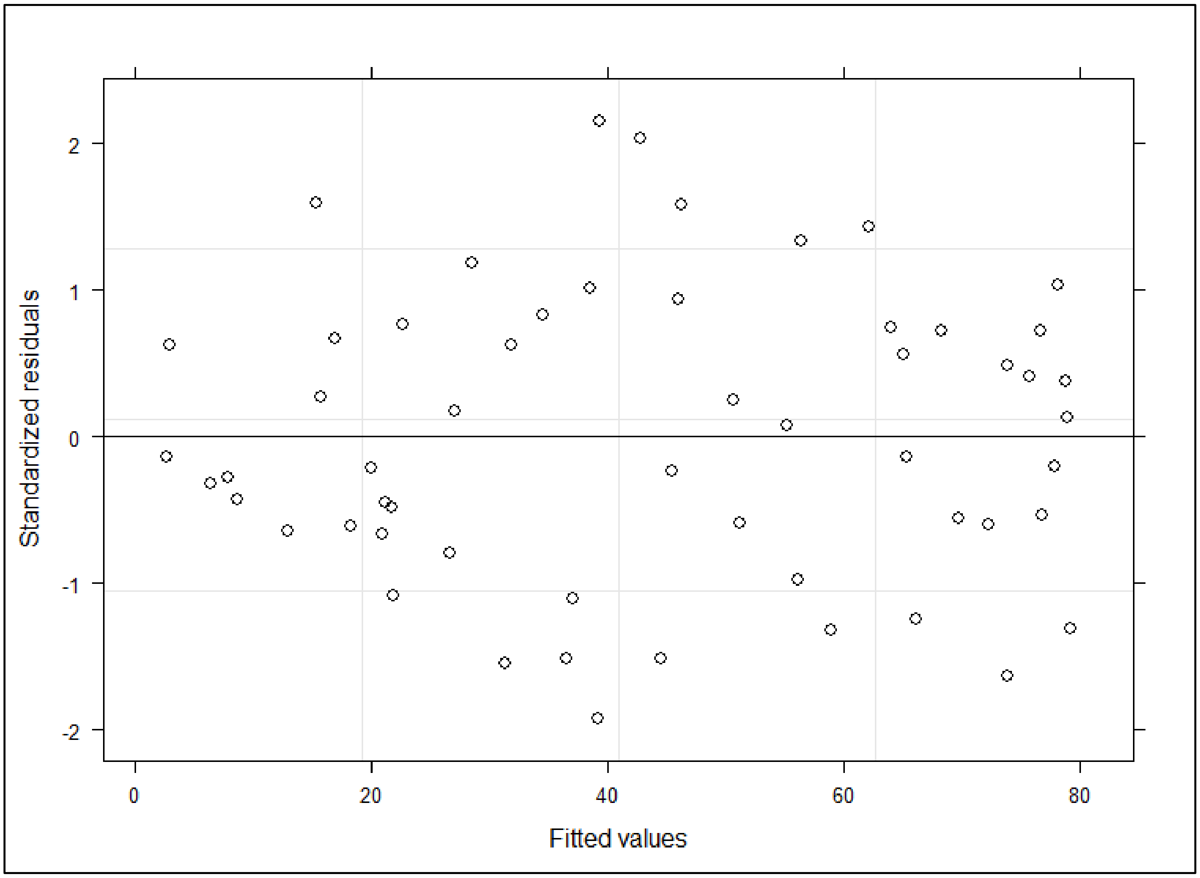

Table 4.1. Ethephon treatment information and other aspects of study locations for Experiment 1.

	Expt. 1: Model development experiment (2018–20)			
Site	WH Daniel Turfgrass Research & Diagnostic Center, West Lafayette, IN	Rocky Ford Turfgrass Research Center, Manhattan, KS	Gettysvue Polo Golf & Country Club, Knoxville, TN	Shadow Valley Country Club, Rogers, AR
Plot size	1.5 x 1.5 m	1.5 x 1.5 m	1.5 x 1.5 m	1.5 x 3.0 m
Nozzle	XR8003 VS flat-fan	XR8003VS flat-fan	TP8002 EVS flat-fan	XR8003 VS flat-fan
Spray volume (L ha^{-1})	815	815	375	703
Spray pressure (kPa)	207	276	138	276
Weather station	Purdue Mesonet https://ag.purdue.edu/indiana-state-climate/	Kansas State Mesonet https://mesonet.k-state.edu/	NOAA https://www.weather.gov/	NOAA https://www.weather.gov/
Distance to station	<200 m	<100 m	18 km	41 km

Table 4.2. Treatment application dates and cumulative growing-degree days (GDD_0) for evaluating Meyer zoysiagrass seedhead suppression with ethephon applications (3.8 kg ha^{-1}) for model development in Experiment 1 in West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN.

West Lafayette, Indiana 2018		Manhattan, Kansas 2018		Rogers, Arkansas 2018		Knoxville, Tennessee 2018		Manhattan, Kansas 2019	
Date	GDD_0[†]	Date	GDD_0	Date	GDD_0	Date	GDD_0	Date	GDD_0
23 Aug.	537.4	24 Aug.	609.2	22 Aug.	190.8	22 Aug.	203.1	28 Aug.	675.1
30 Aug.	703.4	30 Aug.	766.2	29 Aug.	372.5	27 Aug.	315.8	9 Sept.	838.1
12 Sept.	992.8	5 Sept.	921.3	5 Sept.	548.3	5 Sept.	524.4	11 Sept.	1014.5
19 Sept.	1162.0	12 Sept.	1062.5	12 Sept.	696.4	13 Sept.	729.4	18 Sept.	1185.0
26 Sept.	1303.0	18 Sept.	1219.7	19 Sept.	868.1	19 Sept.	879.7	25 Sept.	1340.5
2 Oct.	1407.8	26 Sept.	1376.8	26 Sept.	1015.3	25 Sept.	1031.7	3 Oct.	1503.9
9 Oct.	1565.6	3 Oct.	1500.3	3 Oct.	1154.7	1 Oct.	1161.7	10 Oct.	1599.5
19 Oct.	1653.9	10 Oct.	1593.4	10 Oct.	1312.8	10 Oct.	1378.1	16 Oct.	1654.8
30 Oct.	1744.0	18 Oct.	1658.7	17 Oct.	1384.2	18 Oct.	1512.5	23 Oct.	1740.8
14 Nov.	1815.5	26 Oct.	1756.2	24 Oct.	1461.4	23 Oct.	1565.6	1 Nov.	1769.9
		31 Oct.	1821.1	31 Oct.	1551.9	31 Oct.	1648.9	6 Nov.	1805.1
		8 Dec.	1951.8			16 Nov.	1786.1		

[†] GDD_0 is the accumulated degree days calculated as $\left(\frac{T_{max}+T_{min}}{2}\right)$ where T_{max} is the daily maximum air temperature and T_{min} is the daily minimum air temperature. For West Lafayette and Manhattan locations, GDD calculations started on 1 August while calculations for Knoxville and Rogers locations began on August 15.

Table 4.3. Correlation coefficients (r) of the following vs. percent seedhead suppression in 'Meyer' zoysiagrass in West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN: photoperiod; daily average mean air temperature (T_{daily}); 3-d average air temperature (T_{avg}); cumulative growing degree-days based on 0 ^{0}C temperature (GDD_0); cumulative growing degree-days based on 10 ^{0}C temperature (GDD_{10}); and cumulative cooling degree-days based on 25 ^{0}C temperature (CDD_{25}); total number of observations = 214.

Variable	Percent seedhead suppression
	r
Photoperiod	0.16^{NS†}
Daily average air temp (T_{daily})	0.31*
3-d average air temp (T_{avg})	0.33*
GDD_0	0.03^{NS}
GDD_{10}	0.14^{NS}
CDD_{25}	-0.40**

† '*' = Significant at $P < 0.05$; '**' = Significant at the .01 probability level; '***' = Significant at the .001 probability level; and NS= nonsignificant

Table 4.4. Parameter estimates of a multiple linear regression model based upon GDD_{10} and T_{avg} to predict seedhead suppression as affected by ethephon application in 'Meyer' zoysiagrass. Experiment was conducted across four locations, West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN from 2018 to 2020; total number of observations = 214.

Parameters†	Estimates	SE	*P*-value	CV
β_0 (Intercept)	-93.68	22.23	<0.0001	23.7
β_1 (T_{avg})	3.80	0.61	<0.0001	16.2
β_2 (GDD_{10})	0.10283	0.02	<0.0001	18.4
Model Fitness				
Root mean square error	23.80			
R^2	0.44			
Variance inflation factor	1.93			
P-value	<0.0001			

†T_{avg} is 3-d average mean air temperature, GDD_{10} is cumulative growing degree-days based on 10 ^{0}C temperature, and R^2 is the determination coefficient.

Table 4.5. Adjusted coefficient of determination (R^2_{adj}), root mean square error (RMSE), Akaike information criterion (AIC), Bayesian information criterion (BIC), parameter estimates, standard error (SE), *P*-values, and coefficient of variation (CV) of second-degree polynomial and Gaussian models fit to seedhead suppression in 'Meyer' zoysiagrass. Experiment was conducted across four locations, West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN from 2018 to 2020; total number of observations = 214.

Models	R^2_{adj}	RMSE	AIC	BIC	Parameters	Estimates	SE	*P*-value	CV
Polynomial	0.48	23.8	511.1	519.2	β_0	-61.58	16.10	0.0003	26.1
					β_1	0.2308	$3.12e^{-02}$	<0.0001	13.5
					β_2	$1.03e^{-04}$	$1.37e^{-05}$	<0.0001	13.3
Gaussian	0.58	20.3	500.8	508.9	a	79.13	5.46	<0.0001	6.9
					x_0	1153.47	28.91	<0.0001	2.5
					b	371.58	31.15	<0.0001	8.4

Table 4.6. Verification of the multiple linear regression, second-degree polynomial, and Gaussian model developed from Experiment 1 as evaluated with new seedhead suppression data collected from Experiment 2. Experiment 1 was conducted across four locations, West Lafayette, IN; Manhattan, KS; Rogers, AR; and Knoxville, TN from 2018 to 2020; total number of observations (n) = 214. Experiment 2 was conducted in Manhattan, KS from 2020 to 2021; n = 28.

Model	Date	GDD†	T_{avg}	Seedhead suppression		Sq. residuals
				Observed	Predicted	
Multiple linear regression	28 Aug.	373.9	25.6	40.3	42.1	3.5
	3 Sept.	449.9	22.4	49.4	37.8	135.3
	16 Sept.	558.5	18.5	66.0	34.1	1017.1
	23 Sept.	613.3	17.8	78.0	37.1	1676.9
	2 Oct.	686.6	14.2	59.6	30.9	821.6
	17 Oct.	779.8	10.8	46.7	27.6	366.3
	6 Nov.	805.0	14.0	31.8	42.3	111.1
Polynomial	28 Aug.	643.9		40.3	44.3	16.2
	3 Sept.	779.8		49.4	55.7	40.0
	16 Sept.	1016.9		66.0	66.6	0.3
	23 Sept.	1141.6		78.0	67.6	108.6
	2 Oct.	1305.0		59.6	64.1	20.6
	17 Oct.	1543.9		46.7	49.2	5.9
	6 Nov.	1689.2		31.8	34.3	6.2
Gaussian	28 Aug.	643.9		40.3	30.9	88.0
	3 Sept.	779.8		49.4	47.7	2.9
	16 Sept.	1016.9		66.0	74.0	63.2
	23 Sept.	1141.6		78.0	79.1	1.1
	2 Oct.	1305.0		59.6	72.8	174.6
	17 Oct.	1543.9		46.7	45.6	1.4
	6 Nov.	1689.2		31.8	28.0	14.6

†GDD was calculated based on 10 ^{0}C base temperature for multiple linear regression model, and 0 ^{0}C base temperature was utilized for second-degree polynomial and Gaussian models.

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Chapter 5 - Evaluation of New Zoysiagrass Genotypes in Kansas

This chapter has been prepared using style guidelines for the journal Crop Science.

Abstract

Zoysiagrass (*Zoysia* spp. Willd.) produces high-quality turf for golf courses in the U.S. transition zone. Zoysiagrass has lower input requirements than C_3 species and improved cold tolerance than some C_4 species. Large patch, caused by *Rhizoctonia solani* (AG 2-2 LP), is a perennial disease problem in zoysiagrass and requires fungicide applications. Turf quality characteristics and large patch incidence of ten selected experimental zoysiagrass genotypes were evaluated from 2018 through 2020 in Manhattan, KS. Although plots were inoculated three different times in autumn and spring, no large patch occurred. However, the genotypes showed variability in turf performance measured by turf quality, spring greenup, fall color retention, and genetic color. The same ten progeny were established in plots on a golf course driving range in Olathe, KS and evaluated along with Meyer and Innovation zoysiagrass from 2019 to 2020. Based on the results from experiments in Manhattan and Olathe, experimental genotypes, DALZ 1701 and DALZ 1702 had overall better turf performance than Meyer or Innovation zoysiagrass. In a separate experiment, a set of 70 experimental zoysiagrass genotypes (potential cold hardy) along with three standards, ‘Meyer,' ‘Innovation,' and ‘KSUZ 1201,' were evaluated for turf performance in Olathe, KS. All 70 progeny survived the winter of 2019–2020 and a total of 20 progeny were selected based on their turf performance. The preference of selection was based first upon spring green up ratings, followed by leaf texture (finer preferred), vigor, turf quality, and wilt during dry down. The golf course industry in the transition zone would benefit from the release of cold-hardy, fine-textured and large patch-tolerant zoysiagrass cultivars.

Introduction

Turfgrasses in the United States have two broad regions of adaptation: north and south. In the northern region, cool-season or C_3 turf species are well-adapted, whereas warm-season or C_4 turfgrasses are best adapted in the southern region (Christians, 2011). The vast area between north and south is shared by both C_3 and C_4 turf species and is commonly referred to as the transition zone. The transition climate zone is a horizontal region that runs along the lower half of the country from state of Delaware in the east to California in the west, including state of Kansas (Dunn & Diesburg, 2004). This region is challenging to manage turfgrass because summers tend to be too hot for C_3 species, while winters are too cold for survival of C_4 species.

Warm-season turfgrass is attractive to turf managers in the transition zone because of lower cost of management, as they require less water and fertilizers inputs than cool-season turfgrasses (Fry et al., 2008). Zoysiagrass (*Zoysia* spp.), a warm-season turfgrass, is commonly used on home lawns and golf course fairways, tees, and roughs in the transition zone. Zoysiagrass forms a dense canopy that provides an excellent playing surface and turf quality. Zoysiagrass is recognized for heat and drought tolerance throughout the transition zone as uniform, quality playing conditions are possible through the stressful summer months (Nicoludis & Daniels, 2019).

A persistent challenge with zoysiagrass is its susceptibility to large patch disease (Green et al., 1993). Large patch is caused by the fungus *Rhizoctonia solani* Kühn (AG 2-2 LP). The disease is most active when zoysiagrass is slowly growing, i.e., before entering dormancy in autumn and after breaking dormancy in spring (Koehler et al., 2017). The cool, wet weather accompanied by poor drainage, restricted airflow, and soil compaction favors the large patch disease in zoysiagrass (Obasa et al., 2017). The initial symptoms begin with small round discolored patches that can expand up to several meters in diameter. The symptoms of large patch are reported to recur at the same location in following years with the expansion rate up to one meter annually (Aoyagi et al., 1998; Obasa et al., 2012). Although a few cultural practices have been reported to ameliorate large patch severity (Green et al., 1994; Kennelly et al., 2008; Obasa et al., 2013), most zoysiagrass managers rely on routine fungicide applications to manage large patch (Obasa et al., 2017). The cost associated with the use of fungicides in spring and fall to prevent large patch is a concern for zoysiagrass turf managers. The best fungicides for suppressing this disease can cost about \$865 ha^{-1} (Genovesi et al., 2019).

Development of large patch-tolerant zoysiagrass cultivars could be a promising alternative to fungicides. Researchers at Texas A&M AgriLife Research in Dallas, TX, crossed 22 cold-hardy zoysiagrasses with TAES 5645 (*Z. japonica*) or its derivatives that had demonstrated tolerance to large patch in breeding stock, resulting in 2,858 progeny (Genovesi & Chandra, 2015). These progeny were evaluated for cold adaptation and turf performance in non-replicated field plots in three different locations: Manhattan, KS; West Lafayette, IN; and Dallas, TX, from 2012 to 2014 (Braun, 2014). From each location, 20 progeny that performed the best were selected, and an aggregated group of 60 progeny were advanced forward for further field testing. All 60 progeny, along with eight standard cultivars, were established in replicated field trials in 2015 in Manhattan, KS, and Fayetteville, AR (Xiang, 2018). The progeny were evaluated for large patch tolerance through physical inoculation of *R. solani* AG 2-2 LP pathogen from 2015 through 2018. Additionally, all 60 progeny were established in eight other locations for turf performance evaluation. Based on the large patch tolerance and turf performance measured by percent green cover, turfgrass quality, spring greenup, and winter injury, the ten best performing progeny were selected (Xiang, 2018). This study assessed the performance of those ten best potential large patch-tolerant progeny along with eight standards for next three growing seasons from 2019 through 2021.

In addition, proper selection of a zoysiagrass cultivar is essential as their characteristics vary. For example, some of the cultivars, such as ‘Meyer’ and ‘Innovation’, exhibit good cold tolerance and survive well in northern transition zone states like Kansas. That is why Meyer zoysiagrass has been one of the most popular zoysiagrass cultivars for use on home lawns, and golf course fairways in the transition zone for more than 70 years since its release in 1952 (Grau & Radko, 1951; Fry et al., 2008). ‘Innovation’, a new cultivar was released by the collaboration between Texas A&M AgriLife Research – Dallas and Kansas State University as an alternative to Meyer as it offers finer texture and better shoot density than Meyer with cold tolerance comparable to Meyer (Chandra et al., 2017). Innovation is gaining interest among sod producers and turf managers in the transition zone for use on golf course fairways and tees (Roberts, 2019).

There are several cultivars available in the market for warmer regions in the Southern U.S. Fine-textured zoysiagrass cultivars, such as ‘Zorro’, ‘Zeon’ and ‘Trinity’ have provided excellent playing surface for golf course fairways and tees in the southern region (Roberts, 2019). Additionally, in the southeast U.S., ultra-dwarf cultivars, such as ‘Diamond’ zoysiagrass, can tolerate mowing as low as 2.5 mm. The main reason behind the popularity of finer-textured zoysiagrass in the southeast U.S. is its improved shade tolerance compared to ultra-dwarf bermudagrass (*Cynodon* spp. L.C. Rich.). In the transition zone where winters are harsh and bermudagrass often gets damage from winter kill, cold tolerance of zoysiagrass is highly valued. However, the choice of zoysiagrass cultivar in the transition zone is limited. Thus, development of finer-textured zoysiagrass that can be used on golf course tees and putting greens would open a whole new market in the transition zone.

Therefore, the objectives of this study were to: 1) evaluate performance of ten, large patch-tolerant zoysiagrass genotypes compared to eight standard zoysiagrass cultivars; and 2) on-site evaluation of performance of selected ten best progeny on a Kansas City golf course; and 3) identify new, fine-textured, cold hardy zoysiagrass genotypes.

Materials and Methods

Study 1: Large Patch-Tolerant Zoysiagrass Evaluation

Field Management

The experiment was established with plugs in July 2015 at the Rocky Ford Turfgrass Research Center in Manhattan, KS, as described by Xiang (2018). Ten experimental genotypes were developed through complex crosses at Texas A&M AgriLife Research-Dallas among *Z. japonica*, *Z. matrella*, and *Z. pacifica*, such as double and triple crosses to introgress desirable traits; each was planted in three replicates. Each plot measured 1.8 × 1.8 m with 0.6 m alleyways between the plots. Plots were fertilized with urea (46−0−0, Lesco Professional Turf Fertilizer) in June and July to provide a total of 98 kg N ha^{-1} $year^{-1}$ in 2018, 2019, and 2020. Plots were maintained under golf course fairway/tee conditions and mowed at 0.5 inches with a reel mower and irrigated to avoid visible drought stress. Dithiopyr (Dimension 2EW, Dow AgroSciences) was applied at 0.56 kg a.i. ha^{-1} on 30 April 2018, 22 April 2019, and 28 April 2020 to control crabgrass emergence. A mixture of 2,4-D, 2-ethylhexyl ester at 0.43 kg a.i. ha^{-1}, mecoprop-p acid at 0.13 kg a.i. ha^{-1}, dicamba acid at 0.04 kg a.i. ha^{-1}, and carfentrazone-ethyl at 0.01 kg a.i. ha^{-1} (Speedzone, pbi/Gordon Corporation) was applied on 19 April 2019, and 11 May 2020 to kill broadleaf weeds.

Pathogen Inoculation

Isolates of *Rhizoctonia solani* AG 2-2 LP were obtained from a naturally infected Meyer zoysiagrass area and inoculum of *R. solani* AG 2-2 LP was prepared with oat kernels as described by Obasa et al. (2013). To prepare the substrate, 150 g of oat kernels were mixed with 150 mL water in a 1 L jar and autoclaved for 30 minutes twice on two consecutive days. A pure culture of *R. solani* AG 2-2 LP maintained on the ¼ PDA (Potato Dextrose Agar) plate was sliced into small pieces and one half of the material was added to a 1 L jar. The jars were incubated at room temperature for two weeks with regular shaking every 2 days before applying in the field.

Each plot was divided into two sub-plots, one-half was randomly designated for inoculation of pathogen and the other half for a healthy check plot. On each inoculated sub-plot, a slit was cut in turf below the thatch layer using a knife, and 8 to 10 g of oat inoculum was inserted on each slit; the turf was then tamped back down. The study was inoculated on 16 September 2019, 23 April 2020, and 1 October 2020. The plots were kept wet for at least two weeks with sprinkler irrigation to foster fungal growth. On the same date, a preventive fungicide, flutolanil (N-[3-(1-methylethoxy) phenyl]-2(trifluoromethyl) benzamide, ProStar 70 WG, Bayer Environmental Science, Research Triangle Park, NC) was applied at 9.6 kg a.i. ha^{-1} only on the healthy check sub-plots. The fungicide was applied using a CO_2-compressed hand-sprayer equipped with an 8004 EVS nozzle (TeeJet® Technologies, Glendale Heights, IL) calibrated to deliver 814 L ha^{-1}.

Data Collection and Analysis

Turf performance parameters, turf quality, genetic color, fall color retention, and spring greenup were rated visually on a scale of 1–9 following National Turf Evaluation Program (NTEP) guidelines (Morris & Shearman, 1998). Turf quality, defined as evaluation of color, density, leaf texture, and uniformity, was rated as 1 = poorest quality, 6 = minimally acceptable turf, and 9 =

optimum quality. For genetic color, score of 1 = light green and 9 = dark green; fall color retention, 1 = tan brown and 9 = dark green; and spring green, 1 = brown, dormant and 9 = fully green.

The experiment was arranged in a split-plot design in which zoysiagrass entries were the whole plot (1.8 × 1.8 m) and treatment (inoculated or fungicide-treated) was the sub-plot (0.9 × 0.9 m). All data were subjected to analysis of variance (ANOVA) using Proc GLIMMIX procedure in SAS 9.4 (SAS Institute, Cary, NC). Means were separated using Fisher's protected least significant difference (LSD) test at $P \leq 0.05$.

Study 2: Golf Course On-site Evaluation

Field Management

The ten best progeny for on-site evaluation were established at Shadow Glen Golf Club, Olathe, KS, on 17 June 2019. Plots were prepared by removing the existing Kentucky bluegrass (*Poa pratensis*) swards using a sod cutter. Soil was added back to each plot and leveled smooth. Each plot measured 1.8 × 1.8 m with 0.6 m alley between the plots. The ten progeny were established by planting 24 plugs per plot, each plug measuring 5-cm diameter, whereas commercial cultivars, 'Meyer' and 'Innovation' were established using 12 plugs per plot. Oxadiazon (Ronstar G, Bayer Environmental Science) was applied immediately after planting at 2.2 kg a.i. ha^{-1}. After well established, plots were mowed at 13 mm height of cut and irrigated to prevent visible drought stress throughout the growing season. Standard golf course maintenance practices were employed, which included nitrogen applied at 49 to 98 kg $ha^{-1}yr^{-1}$ and pre- and postemergence herbicide applications as needed.

Data Collection and Analysis

Turf performance parameters including turf quality, genetic color, fall color retention, texture, spring greenup, and living ground cover were rated visually on a scale of 1–9 following the NTEP guidelines (Morris & Shearman, 1998). For turf quality, 1 = poorest quality, 6 = minimally acceptable turf, and 9 = optimum quality. For genetic color, 1 = light green and 9 = dark green; fall color retention, 1 = brown and 9 = dark green; and spring green up, 1 = no greenup and 9 = fully green. Percent living ground cover was assessed visually on a scale of 0–100% on 27 September 2019 and 19 May 2020. Treatments included zoysiagrass entries (ten progeny plus three standards) and were arranged in a randomized complete block design with four replicates. All data were subjected to analysis of variance (ANOVA) using Proc GLIMMIX procedure in SAS 9.4 (SAS Institute, Cary, NC). Means were separated using Fisher's protected least significant difference (LSD) test at $P \leq 0.05$.

Study 3: Fine-Textured, Cold Hardy *Zoysia*

Field Management

On 18 August 2017, 458 zoysiagrass progeny were established using plugs in a single-spaced nursery at Olathe Horticulture Research Center, Olathe, KS. Each plot measured 0.9 × 0.9 m. Progeny were evaluated visually for winter survival in May 2018. On 30 July 2018, surviving genotypes from the 2017 planting were moved to an adjacent area and planted with an additional, new 918 experimental zoysiagrass genotypes. As described for genotypes above, these progeny were developed through complex crosses at Texas A&M AgriLife Research-Dallas among *Z. japonica*, *Z. matrella*, and *Z. pacifica*, such as double and triple crosses to introgress desirable traits. Each plot measured 0.9 × 0.9 m. On 17 May 2019, entries with a winter kill score of 3 and higher were transferred to a new adjacent plot on 2 July 2019. Each plot measured 0.9 × 0.9 m. In each evaluation, standards were included for comparison, such as Meyer, Innovation, and KSUZ 1201, a cold-hardy experimental.

For the 2017 and 2018 plantings, plots were prepared by spraying glyphosate several weeks beforehand to remove existing cool-season turf growing in the study areas. Plugs were planted by drilling holes in the ground and inserting plugs. For the 2019 plantings, plugs were inserted into tilled ground and were arranged in a completely randomized design with two replicates. In all years, immediately after planting plugs, Oxadiazon (Ronstar G, Bayer Environmental Science) was applied at 2.2 kg a.i. ha^{-1} and irrigation was applied to prevent drought stress. Mowing was started only in 2019 plantings at a height of 76 mm, and once plugs were beyond that height, it was gradually reduced to 13 mm. Irrigation in summer of 2019 was withheld to impose drought stress.

Data Collection and Analysis

All visual ratings were recorded following the NTEP guidelines (Morris & Shearman, 1998). Winter kill was rated visually on a scale of 1–9 (where 1 = brown, dead turf and 9 = no injury) in May of 2018 and 2019. Leaf texture was rated on a scale of 1–9 (where 1 = coarse-textured and 9 = fine-textured) and plant vigor on a scale of 1–9 (where 1 = poor growth and 9 = best growth) were rated visually on 27 September 2019, and 6 October 2020. Spring green up (where 1 = brown, dormant and 9 = completely green) was recorded visually on 7 April 2020. Turf quality was rated visually on a scale of 1–9 (where 1 = brown dead turf, 6 = minimally acceptable, and 9 = ideal uniform turf) on 6 October 2020. Visible wilting was recorded as a measure of drought tolerance on a scale of 1–9 in which 1 = completely brown, 9 = no wilt on 27 August 2020. Since the 2019 planting was set up in just two replicates due to limited plugs available, only means of two replicates were calculated and no statistical analysis was conducted.

Results and Discussion

Evaluating Large Patch-Tolerant Genotypes

Manhattan, KS

Despite applying *R. solani* inoculum for total of three times during 2018 to 2020 growing seasons, none of the genotypes exhibited large patch symptoms. Unfortunately, there was also no incidence of natural infection. Consequently, interaction effect of inoculation treatment × genotype and main effect of inoculation treatment were not significant on any of the responses measured. Results presented herein are thus only the main effects of genotypes, including turf quality, fall color, genetic color, and spring greenup. We found some variability among the genotypes in turf performance. There was significant effect of date × genotype interaction on turf quality (P < 0.0001), fall color (P < 0.0001), genetic color (P = 0.0006), and spring greenup ratings (P = 0.0020), and thus data were analyzed by measurement date for each parameter.

Zeon and Innovation zoysiagrass were the two best genotypes in terms of turf quality throughout the study period as they were in the highest statistical group on seven and six rating dates, respectively (Table 5.1). Turf quality of Meyer zoysiagrass was in the highest statistical group on four rating dates. Experimental genotypes, DALZ 1701, DALZ 1702, and DALZ 1707 had turf quality statistically equivalent to Innovation on at least four rating dates. Fall color of these three genotypes was similar to both Meyer and Innovation in 2018 and 2019, with the exception of DALZ 1707, which was lower on 19 October 2018 (Table 5.2). Three experimental genotypes, DALZ 1701 and 1702, and KSUZ 1201 had the best fall color retention across all three rating dates. DALZ 1701, DALZ 1702, and DALZ 1707 had higher fall color than both Meyer and Innovation when measured on 22 September 2020. Likewise, genetic color also showed statistical differences among genotypes which was measured during active growth when there was no apparent stress (Table 5.2). Genetic color of Innovation and Zeon were in the highest statistical group in both 2019 and 2020, while Meyer had lower genetic color in both years (Table 5.2). DALZ 1701 had the similar genetic color to Innovation and Zeon, and genotypes DALZ 1702, DALZ 1703, DALZ 1808, DALZ 1810, DALZ 1811, and DALZ 1812 had similar genetic color to Innovation or Zeon on at least one date. Meyer zoysiagrass had the spring greenup in the highest statistical group on three of the four dates (Table 5.3). Genotypes DALZ 1701, DALZ 1702, DALZ 1703, DALZ 1707, DALZ 1808, DALZ 1809, and DALZ 1811 had spring greenup in the highest statistical group on at least three dates, which was better than that of Innovation zoysiagrass.

Golf Course Evaluation, Olathe, KS

At Shadow Glen Golf Club in Olathe, KS, ground cover among experimental genotypes ranged from 63 to 93% and 65 to 97% on 27 September 2019 and 19 May 2020, respectively (Table 5.4). The ground cover for Innovation and Meyer was lower due to use of fewer plugs/plot during establishment and therefore they were not included in the statistical analysis. Genotypes, such as DALZ 1808, and DALZ 1812 had significantly higher ground cover than DALZ 1707 and DALZ 1809 both in 2019 and 2020. Spring greenup on 8 April 2020 were statistically similar among all genotypes except DALZ 1812 and DALZ 1813, which had lower greenup ratings than the rest (Table 5.4). Leaf texture of Innovation recorded on 18 June 2020 was statistically finer compared to other genotypes (Table 5.4). On 23 July 2020, genetic color of DALZ 1701, DALZ 1702, DALZ 1707, and DALZ 1811 was statistically similar to Meyer and Innovation zoysiagrass. Turf quality recorded on 14 October 2020 showed that experimental genotypes, DALZ 1701, DALZ 1707, and DALZ 1810 had better turf quality than Meyer and Innovation zoysiagrass. On 14 October 2020, fall color of genotype DALZ 1701 was the highest and significantly better than both Innovation and Meyer, while DALZ 1808 had statistically higher fall color than Meyer zoysiagrass.

Based on the results from the study 1 and study 2, turf performance index (TPI) was generated to compare the performance of all tested genotypes similar to reported by Xiang (2018) (Table 5.5). TPI is a sum of the number of times a genotype appears in the top statistical group and was based upon visual ratings of turf quality, fall color, spring greenup, texture, and genetic color. The total possible TPI were not same for all genotypes because only three standards were used in study 2, while eight standards were included in study 1. Experimental genotypes DALZ 1701 and DALZ 1702 were the two best entries based on TPI and had higher TPI than Innovation and Meyer zoysiagrass (Table 5.5). Another experimental genotype, DALZ 1707 had higher TPI than Meyer but lower than Innovation.

Evaluating Fine-Textured, Cold Hardy Zoysiagrass genotypes

After planting 458 experimental progeny in 2017, 17 survived (4%) during the winter of 2017-2018 when evaluated in May 2018. In 2018, 918 new experimental progeny were planted along with the 17 survivors from the 2017 planting. Out of the 935 experimental progeny, 70 survived (8%) when evaluated in May 2019. The set of 70 surviving progeny varied in leaf texture (3.0 to 7.5) and vigor (2.0 to 8.0) when rated on 27 September 2019. All 70 progeny and three standard genotypes (Meyer, Innovation, and KSUZ 1201) survived the winter of 2019–2020. In addition to three cold-tolerant standards, only one experimental genotype, 6787-28, survived each winter since planting in 2017. The planting approach in 2017 and 2018 was to drill into untilled soil and insert plugs. In 2019, plugs were planted into tilled ground. Those planted in 2019 seemed more vigorous than earlier years, and this could have impacted survival. The 2017–2018 and 2018–

2019 winters were colder than 2019–2020, which may have affected survival as well (Fig. 5.1). Weather data obtained from the Kansas Mesonet system (*https://mesonet.k-state.edu/*) showed that in 2017–2018, there were 19 days with a minimum air temperature < -12.2°C and 30 days < -10.0°C; the lowest air temperature (-23.2°C) was recorded on 11 January 2018. In 2018–2019, there were 16 days with the minimum air temperature < -12.2°C and 25 days < -10.0°C; the lowest air temperature (-20.5°C) was recorded on 30 January 2019. In 2019–2020, there were 7 days with the minimum temperature < -12.2°C and 13 days < -10.0°C; the lowest air temperature (-18.9°C) was recorded on 14 February 2020.

The 70 genotypes were ranked first depending upon ratings of spring green up, followed by leaf texture, turf quality, vigor, and wilt during dry down (Table 5.6). Based upon this, 20 genotypes were selected as the top performers. Among the best 20 progeny, spring greenup ratings ranged from 3.0 to 5.0 on 7 April 2020 (Table 5.6). Leaf texture ratings ranged from 4.5 to 7.5 in 2019 and 4.5 to 8.0 in 2020. Vigor ranged from 2.0 to 8.0 in 2019 and 4.0 to 7.5 in 2020. Also, the progeny showed variation in turf quality (4.5 to 8.0), and wilt (2.0 to 7.0). Only one genotype, 6844-31, had a leaf texture rating of 8.0. The four other genotypes, 6830-56, 6844-147, 6919-29, and 6942-22, had leaf texture ratings higher than 7.0 on 6 October 2020. These 20 progeny, along with 49 additional experimental genotypes selected at Purdue and Texas A&M AgriLife Research-Dallas were recently planted in replicated plots in Olathe, KS and in Arkansas, Florida, Indiana, Missouri, Tennessee, Texas, and Virginia.

Conclusion

Turf performance of experimental genotypes, such as DALZ 1701 and DALZ 1702 were better than commercial standards Meyer or Innovation zoysiagrass when evaluated for multiple seasons in both research center and on-site golf course conditions managed as tees/fairways. Additionally, genotype DALZ 1707 performed better than Meyer zoysiagrass overall. Although our study did not have favorable conditions for large patch incidence, these genotypes had exhibited some degree of tolerance to large patch in previous research and thus have great potential to advance further in cultivar development. Another study selected 20-best new experimental zoysiagrass progeny that survived the winters from 2017 through 2020 in Olathe, KS (northern transition zone). These selected progeny showed variation in texture and spring greenup along with other turf performance parameters indicating the potential to identify cold-hardy, finer-textured zoysiagrass for use in the golf course tees and putting greens. These grasses are now under evaluation in Olathe, KS and several other states in the transition zone and southern U.S. Additional research on these potential large patch-tolerant and cold-hardy fine-textured zoysiagrass progeny is warranted. A cold-hardy, finer-textured zoysiagrass and large patch-tolerant zoysiagrass would bring benefits to zoysiagrass managers and the turf industry.

Figure 5.1. Daily averages of minimum air temperatures (^{0}C) in 2017–2018, 2018–2019, and 2019–2020 between October 1 through April 15. Data were obtained from the Kansas Mesonet system at the Olathe location (https://mesonet.k-state.edu/).

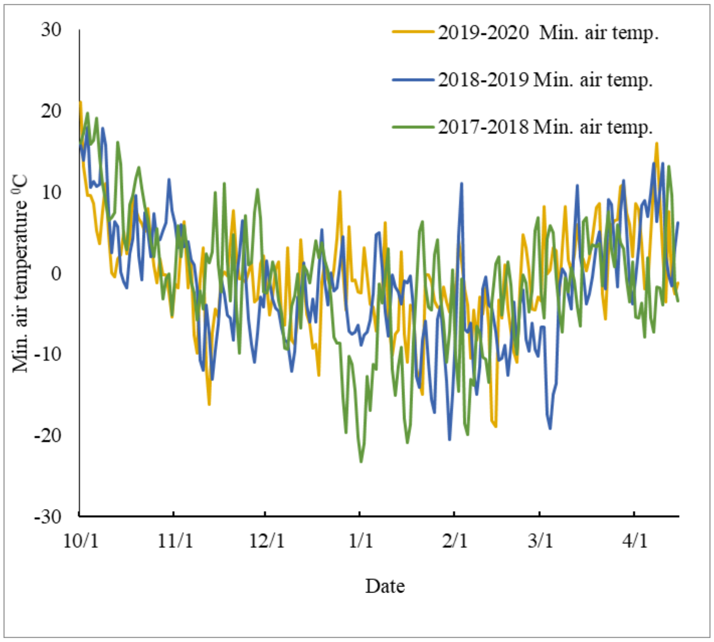

Table 5.1. Turf quality of experimental and commercial zoysiagrass genotypes evaluated in Manhattan, KS, in 2018, 2019, and 2020.

	Turf quality[†]						
	2018	2019			2020		
Entry ID	10/26	6/21	8/9	9/6	6/16	7/9	8/27
DALZ 1701	5.8abcd[‡]	6.2abc	7.2bc	7.0c	7.7a	8.0ab	8.4ab
DALZ 1702	5.7bcde	6.0abcd	7.2bc	7.3abc	7.4ab	8.0ab	8.7a
DALZ 1703	5.7bcde	6.0abcd	7.0c	7.0c	6.7bcd	7.7abc	7.7cd
DALZ 1707	5.2de	6.3ab	7.7ab	7.5ab	7.0abc	7.4bcd	7.7cd
DALZ 1808	5.5bcde	6.5a	7.0c	7.0c	7.0abc	7.7abc	8.0bc
DALZ 1809	5.0e	6.0abcd	7.0c	7.0c	7.0abc	6.7d	7.7cd
DALZ 1810	5.3cde	5.5d	7.0c	7.0c	7.0abc	8.0ab	8.4ab
DALZ 1811	5.3cde	5.7cd	7.0c	7.0c	6.4cd	7.0cd	7.7cd
DALZ 1812	5.2de	5.7cd	7.0c	7.0c	6.7bcd	8.0ab	7.7cd
DALZ 1813	5.2de	6.5a	7.2bc	7.2bc	6.7bcd	7.7abc	7.4de
Chisholm	6.0abc	6.2abc	7.3bc	7.0c	6.0de	6.7d	7.0ef
El Toro	6.0abc	5.7cd	7.0c	7.0c	6.0de	6.7d	6.7f
Innovation	6.5a	6.5a	8.0a	7.7a	7.7a	8.4a	8.0bc
KSUZ 1201	6.0abc	5.8bcd	7.5abc	7.3abc	6.7bcd	7.4bcd	8.0bc
Meyer	6.0abc	6.2abc	7.2bc	7.3abc	6.7bcd	8.0ab	7.7cd
TAES 5645	6.0abc	6.3ab	7.3bc	7.0c	5.4e	7.0cd	6.0g
Zeon	6.2ab	6.3ab	8.0a	7.7a	7.7a	8.4a	8.4ab
Zorro	6.0abc	6.2abc	7.0c	7.0c	6.0de	7.0cd	6.0g
$LSD_{0.05}$	0.73	0.62	0.53	0.45	0.73	0.68	0.66

[†]Turf quality was rated visually on a scale of 1–9 where 1 = poorest quality, 6 = minimum acceptable quality, and 9 = optimum color, density, texture, and uniformity. Scores were recorded on the sub-plots (inoculation treatment) and means were pooled across sub-plots.

[‡]Values within a column followed by the same letter are not statistically different at $P \leq 0\ .05$ according to Fisher's protected least significant difference (LSD).

Table 5.2. Fall and genetic color of experimental genotypes and commercial zoysiagrass cultivars evaluated in Manhattan, KS, in 2018, 2019 and 2020.

	Fall color†			Genetic color†	
Entry ID	10/19/2018	11/14/2019	9/22/2020	7/26/2019	7/9/2020
DALZ 1701	6.3abc‡	4.5ab	8.0a	8.0ab	8.7a
DALZ 1702	6.8a	4.3abc	8.0a	7.7bc	8.4ab
DALZ 1703	6.8a	3.8cd	7.4bc	7.7bc	8.0abc
DALZ 1707	6.0c	4.2abcd	8.0a	7.7bc	7.7bcd
DALZ 1808	6.3abc	3.8cd	7.4bc	8.0ab	7.4cde
DALZ 1809	6.8a	4.2abcd	7.0cd	7.3cd	7.4cde
DALZ 1810	6.2bc	4.2abcd	7.7ab	7.7bc	8.0abc
DALZ 1811	6.0c	4.3abc	8.0a	7.3cd	8.4ab
DALZ 1812	6.2bc	4.0bcd	7.4bc	7.3cd	8.0abc
DALZ 1813	6.0c	4.2abcd	7.0cd	8.0ab	6.7e
Chisholm	6.8a	4.7a	6.4e	7.7bc	7.4cde
El Toro	6.2bc	3.7d	6.7cd	7.0d	8.0abc
Innovation	6.7ab	4.2abcd	7.0cd	8.3a	8.4ab
KSUZ 1201	6.5abc	4.3abc	8.0a	7.7bc	7.7bcd
Meyer	6.3abc	4.3abc	7.4bc	7.7bc	7.7bcd
TAES 5645	6.0c	4.2abcd	7.7ab	7.7bc	7.0de
Zeon	6.8a	4.7a	7.4bc	8.0ab	8.7a
Zorro	6.5abc	4.5ab	7.4bc	7.7bc	7.7bcd
$LSD_{0.05}$	0.51	0.55	0.55	0.46	0.7

†Fall color was rated visually on a scale of 1–9, where 1 = straw brown and 9 = optimum green color and genetic color was rated visually on a scale of 1–9, where 1 = light green and 9 = dark green. Genetic color was rated when turf was actively growing and was not under stress. Each rating was recorded on the sub-plots (inoculation treatment) and means were pooled across sub-plots.
‡Values within a column followed by the same letter are not statistically different at $P \leq 0.05$ according to Fisher's protected least significant difference (LSD).

Table 5.3. Spring greenup of experimental genotypes and commercial zoysiagrass cultivars evaluated in Manhattan, KS, in 2019 and 2020.

	Spring greenup†			
Entry ID	4/26/2019	5/30/2019	4/8/2020	5/5/2020
DALZ 1701	2.3bcd‡	7.0ab	5.0a	7.7a
DALZ 1702	2.3bcd	7.0ab	4.7ab	7.0ab
DALZ 1703	2.3bcd	7.0ab	4.4ab	7.0ab
DALZ 1707	2.7abc	7.0ab	3.4cd	7.0ab
DALZ 1808	2.3bcd	7.2a	5.0a	7.4ab
DALZ 1809	2.8abc	7.0ab	4.4ab	7.7a
DALZ 1810	2.5bc	5.8bc	5.0a	7.4ab
DALZ 1811	3.0abc	6.7ab	4.4ab	6.7b
DALZ 1812	2.8abc	6.8ab	2.0f	5.7c
DALZ 1813	2.8abc	7.2a	2.4ef	7.7a
Chisholm	2.2cd	6.7ab	3.4cd	6.7b
El Toro	1.0d	4.8c	4.0bc	4.0d
Innovation	2.7abc	7.3a	2.0f	6.7b
KSUZ 1201	4.0a	6.7ab	2.7de	7.4b
Meyer	3.7ab	7.3a	4.4ab	6.7b
TAES 5645	1.0d	6.7ab	3de	3.7d
Zeon	1.7cd	6.3ab	2.0f	5.4c
Zorro	2.3bcd	6.3ab	2.0f	5.7c
$LSD_{0.05}$	1.49	1.25	0.69	0.99

†Spring greenup was rated visually on a scale of 1–9, where 1 = brown, dormant and 9 = fully green. Scores were recorded on the sub-plots (inoculation treatment) and means were pooled across sub-plots.
‡Values within a column followed by the same letter are not statistically different at $P \leq 0 .05$ according to Fisher's protected least significant difference (LSD).

Table 5.4. Ground cover, spring greenup, texture, genetic color, turf quality, and fall color of ten experimental zoysiagrass progeny established at Shadow Glen Golf Club, Olathe, KS on 17 June 2019.

Entry ID	Ground cover (%) †		Spring greenup‡	Texture‡	Genetic color‡	Turf quality‡	Fall color‡
	9/27/19	5/19/20	4/8/20	6/18/20	7/23/20	10/14/20	10/14/20
DALZ 1701	75.0bcd¶	89.3ab	4.3ab†	6.3c	8.7ab	6.7a	7.0a
DALZ 1702	74.3bcd	88.3ab	4.7a	6.0c	9.0a	6.3ab	6.3abc
DALZ 1703	92.7a	95.3ab	3.7ab	6.0c	8.0bcd	6.3ab	5.3bcd
DALZ 1707	65.0d	76.7bc	4.0ab	6.0c	8.7ab	6.7a	6.3abc
DALZ 1808	81.7abc	92.7a	4.7a	6.0c	7.0e	6.3ab	6.7ab
DALZ 1809	63.3d	65.0c	4.7a	6.0c	8.0bcd	5.3bc	5.7abcd
DALZ 1810	70.0cd	91.7a	4.3ab	6.0c	8.0bcd	6.7a	6.0abc
DALZ 1811	76.7bcd	85.0ab	4.3ab	6.0c	8.3abc	6.0abc	6.3abc
DALZ 1812	89.3ab	97.0a	2.0c	7.0b	7.3de	5.3bc	4.3d
DALZ 1813	71.7cd	85.0ab	3.3b	6.3c	7.7cde	6.3ab	5.7abcd
Innovation	38.3	50.0	4.0ab	8.0a	8.7ab	5.3bc	5.3bcd
Meyer	53.3	61.6	4.0ab	6.0c	8.7ab	5.0c	5.0cd
$LSD_{0.05}$	15.31	13.76	1.03	0.38	0.72	1.15	1.35

†Percent ground cover was rated visually on a scale of 0 to 100%. Innovation and Meyer were not included in the ground cover analysis because fewer plugs/plot were used during establishment.
‡All other visual ratings were recorded on a scale of 1–9. For spring greenup, 1 = brown, dormant and 9 = fully green; for texture 1 = very coarse and 9 = very fine; for genetic color, 1 = light green and 9 = dark green; for turf quality, 1 = poorest quality, 6 = minimum acceptable quality, and 9 = optimum color, density, texture, and uniformity; for fall color, 1 = straw brown and 9 = optimum green color. Each score was recorded on the sub-plots (inoculation treatment) and means were pooled across sub-plots.
¶Values within a column followed by the same letter are not statistically different at $P \leq 0.05$ by Fisher's protected least significant difference (LSD).

Table 5.5. Turf performance index (based upon results from two separate experiments in Manhattan† and Olathe†, KS) of experimental genotypes and commercial zoysiagrass cultivars evaluated from 2018 through 2020.

Study 1: Manhattan, KS			Study 2: Olathe, KS			Aggregate results		
Entry ID	TPI‡	Possible TPI¶	Entry ID	TPI‡	Possible TPI¶	Entry ID	TPI‡	Possible TPI¶
DALZ 1701	13	16	DALZ 1701	4	7	DALZ 1701	17	23
DALZ 1702	12	16	DALZ 1702	4	7	DALZ 1702	16	23
DALZ 1703	7	16	DALZ 1703	2	7	DALZ 1703	9	23
DALZ 1707	9	16	DALZ 1707	4	7	DALZ 1707	13	23
DALZ 1808	8	16	DALZ 1808	3	7	DALZ 1808	11	23
DALZ 1809	8	16	DALZ 1809	2	7	DALZ 1809	10	23
DALZ 1810	8	16	DALZ 1810	3	7	DALZ 1810	11	23
DALZ 1811	6	16	DALZ 1811	4	7	DALZ 1811	10	23
DALZ 1812	4	16	DALZ 1812	0	7	DALZ 1812	4	23
DALZ 1813	7	16	DALZ 1813	2	7	DALZ 1813	9	23
Chisholm	5	16	Chisholm#	0	0	Chisholm#	5	16
El Toro	2	16	El Toro#	0	0	El Toro#	2	16
Innovation	12	16	Innovation	3	7	Innovation	15	23
KSUZ 1201	8	16	KSUZ 1201	0	0	KSUZ 1201	8	16
Meyer	9	16	Meyer	2	7	Meyer	11	23
TAES 5645	5	16	TAES 5645#	0	0	TAES 5645#	5	16
Zeon	12	16	Zeon#	0	0	Zeon#	12	16
Zorro	5	16	Zorro#	0	0	Zorro#	5	16

†In Manhattan, ten experimental progeny were evaluated along with eight commercial standards from 2018 through 2020. In Olathe, ten experimental progeny were evaluated along with three standards, Meyer, Innovation, and KSUZ 1201 from 2019 to 2020.

‡TPI, turf performance index, is a sum of the number of times a genotype appears in the top statistical group. It was based upon visual ratings of turf quality, fall color, spring greenup, texture, and genetic color.

¶Possible TPI is the highest number of TPI a genotype could accumulate.

#Chisolm, El Toro, TAES 5645, Zeon, and Zorro were not established at Olathe, KS and therefore zero possible TPI in that study.

Table 5.6. Performance of best 20 interspecific hybrids selected from a set of 70 progeny from a spaced plant nursery located in Olathe, KS

Rank	Genotype	SGU†	Texture†		TQ†	Vigor†		Wilt†
		2020	2019	2020	2020	2019	2020	2020
1	6844-154	5.0‡	6.0	6.5	6.5	3.5	4.5	5.0
2	6844-91	4.5	5.0	6.5	6.5	5.0	5.5	3.5
3	6830-56	4.0	6.5	7.5	7.5	6.0	6.0	2.5
4	6844-190	4.0	6.0	6.5	6.5	4.5	6.5	3.5
5	6940-15	4.0	5.0	7.0	7.0	5.0	4.5	6.5
6	6844-128	4.0	5.0	4.5	4.5	4.0	4.5	7.0
7	6844-31	3.5	4.5	8.0	8.0	7.0	7.0	5.0
8	6844-147	3.5	5.5	7.5	7.5	4.5	5.5	4.0
9	6829-36	3.5	5.5	5.5	5.5	8.0	5.0	3.5
10	6844-141	3.5	6.0	6.5	6.5	6.5	7.5	6.0
11	6924-47	3.5	5.0	6.5	6.5	6.5	7.0	4.5
12	6844-152	3.5	6.0	7.0	7.0	4.5	6.5	3.5
13	6924-66	3.5	5.0	6.0	6.0	7.0	6.5	4.0
14	6919-29	3.5	5.0	7.5	7.5	6.0	6.0	5.5
15	6844-34	3.5	6.0	6.5	6.5	4.5	5.0	3.0
16	6830-11	3.5	6.0	7.0	7.0	2.0	4.0	4.5
17	6924-44	3.5	5.0	7.0	7.0	8.0	6.0	4.5
18	6942-22	3.0	6.5	7.5	7.5	5.0	6.0	6.5
19	6839-08	3.0	7.5	7.0	7.0	5.0	5.0	4.5
20	6925-53	3.0	6.0	7.0	7.0	4.0	5.0	4.0
-	Meyer	4.5	4.5	6.0	6.0	7.0	6.5	4.0
-	Innovation	3.5	5.5	6.0	6.0	5.0	6.0	2.0
-	KSUZ 1201	3.5	4.5	5.5	5.5	4.0	5.5	4.0

†Spring greenup (SGU) was rated visually on a 1 to 9 scale (1 = brown, 9 = fully green) on 7 April 2020; texture was rated visually on a 1 to 9 scale (1 = very coarse, 9 = very fine) on 27 September 2019 and 10 June 2020. Turf quality (TQ) was rated on a 1 to 9 scale (1 = poor quality; 9 = optimum, color, density, texture, and uniformity) on 6 October 2020; vigor was rated visually on a 1 to 9 scale (1 = least lateral spread; 9 = most lateral spread) on 27 September 2019 and 10 June 2020; and wilt during dry down was rated on a 1 to 9 scale (1 = severe wilt, 9 = no wilt) on 27August 2020.
‡All data reported for each date are the average of two replications.

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