Evaluation of fine fescues as alternative golf course fairway turfgrasses

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Dedication

This thesis is dedicated to my friends and family in Minnesota.

Abstract

In the cool-season region of the United States, golf courses traditionally grow high-input grasses like creeping bentgrass (*Agrostis stolonifera*, L.), Kentucky bluegrass (*Poa pratensis,* L.), annual bluegrass (*Poa annua,* L.), and/or perennial ryegrass (*Lolium perenne*, L.) on fairways. Grass species exist that are more sustainable than those currently being used for golf course fairway turf. Low-input fine fescue species could be able to withstand the pressure from typical turfgrass disease and stresses while producing acceptable turf and excellent playing quality with fewer overall inputs of pesticides, water, and fertilizer. Little research has been conducted on these species in a fairway setting, so golf course managers have been hesitant to use fine fescues. This project conducted research to overcome these barriers and thus begin using low-input fine fescues for fairways on golf courses throughout the northern United States.

The objective of the first experiment was to evaluate fine fescue species' performance as fairway turfgrass under an acute drought. Field trials were conducted at two locations under a rainout shelter. Mixtures that contained large proportions (>33%) of Chewings fescue [*Festuca rubra* ssp. *commutata* (Thuill.) Nyman] had the greatest green cover at the end of the drought period. The marginal effects summary revealed no significant differences among species success after drought. Overall, this study found that fine fescues can provide acceptable turf quality and playability on golf course fairways resulting in lower irrigation inputs.

The objectives of the second project were to determine the effect of the plant growth regulator trinexapac-ethyl on the performance of fine fescue mixtures when managed as a golf course fairway and identify fine fescue mixtures that perform well under traffic stress. The marginal effects summaries showed hard fescue [*Festuca trachyphylla* (Hack.) Krajina], slender creeping red fescue *[Festuca rubra* ssp. *litoralis* (G.F.W. Meyer) Auquier.], strong creeping red fescue (*Festuca rubra* ssp. *rubra* Gaudin), and sheep fescue (*Festuca ovina*, L.) had the greatest component effect on visual turfgrass quality, and were all statistically similar. Strong creeping red fescue was more susceptible to dollar spot disease (caused by *Sclerotinia homoeocarpa* F.T. Bennett) than the other species.

The third experiment evaluated fine fescue species and mixtures for snow mold resistance on three golf courses in Minnesota. In the spring of 2013, 2014, and 2015, there was no damage from snow mold. These grasses may be resistant to the pathogens; however, our observations in higher cut fine fescue suggest that snow mold and snow scald diseases can be a problem in these grasses. Although the objective to determine if fine fescue fairways require fungicides at currently-recommended application rates to survive winter snow mold pressure was not accomplished, turf quality data taken over 2 years was analyzed. Mixtures maintained significantly better turfgrass quality than any of the five species alone.

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LITERATURE REVIEW

Introduction

Water, fertility, and pest control products are required to manage a golf course landscape. These inputs are needed to maintain healthy, functional turfgrass that can provide valuable ecosystem services like soil stabilization, carbon sequestration, capturing runoff for ground water recharge, heat dissipation, and noise reduction (Beard, 1973). These inputs are becoming less available and more costly, which is a threat to managed turfgrass areas. Golf is an outdoor recreational activity that utilizes turfgrass area to support an industry of nearly 2 million jobs and 76 billion dollars in goods and services (SRI, 2008).

Water use

Water scarcity is both a national and international issue. The U.S. Drought Monitor gauges parts of the Midwest as measuring from -1.0 to -2.9 on the Palmer Drought Severity Index (Palmer, 1965; National Drought Mitigation Center, 2015). The Palmer is a comprehensive measurement that compares drought severity across different climates. On this index, a value of 0 is normal and any value below -4.0 is an extreme drought that would result in economic disaster. In the western United States the climate varies tremendously throughout the year, but entire states are considered to be in some level of drought. The Intergovernmental Panel on Climate Change predicts that the frequency and magnitude of unusual drought events will increase (IPCC, 2013). Water issues also bear an economic burden, as exemplified by the situation in California. At present, the estimated cost of the 2015 California statewide drought is 2.7 billion dollars and 21,000 job losses (Howitt et al., 2015).

The United States Geological Survey regularly measures national water withdrawals. Irrigation use for all agricultural and horticultural crops was 159 billion cubic meters in 2010, and was at the lowest level since 1965. Total hectares of irrigated crops increased from 2005, but total amount of water drawn for irrigation use is decreasing (USGS, 2014). The price of agricultural water is increasing throughout many regions of the country, especially in areas that rely on groundwater resources (Wichelns, 2010).

Water use rates for desired turfgrass quality often exceed natural precipitation. Golf courses have employed better management practices to achieve lower irrigation water use for environmental and economic savings. A seminal survey by the Golf Course Superintendents Association of America estimated water use practices on golf courses in 2005 and 2013 based on self-reported data from golf course superintendents. The survey found that U.S. golf courses used an estimated 2.29 billion cubic meters of water in 2013, a 22% decrease from 2.93 billion cubic meters in 2005. The first survey estimated golf courses used 1.66% of all the irrigation water withdrawn in the U.S. 2005. In the follow-up survey for 2013, this number declined to 1.44% of all irrigation water withdrawals (GCSAA, 2015). Data collected also showed a decline in water volume per area. An average 18-hole golf course used 1.33 acre-feet of water per acre in 2005 and 1.14 acre-feet of water per acre in 2013. While reducing water use rates, the golf course industry has continued to maintain irrigated acreage. Total hectares of irrigated area for a typical 18-hole golf course has barely decreased from 32.7 irrigated hectares in 2005 to 32.5 irrigated hectares in 2013. Furthermore, the number of golf courses using recycled water increased from 10.9% of survey respondents in 2005 to 15.3% in 2013. Increasing recycled water use lowers the amount of water drawn from open sources, canals, rivers, streams, creeks, wells, and municipal systems (GCSAA, 2015).

Nutrient and pesticide use

Nutrients like nitrogen, phosphorus, and potassium are a key ingredient for turfgrass growth. Few soils possess enough natural fertility to maintain healthy, functional landscapes through the entire growing season. Overuse of these nutrients has jeopardized water quality. High phosphorous levels can cause excessive algal blooms that harm aquatic life and compromise recreational use. In 2004, the state legislation in Minnesota banned fertilizer that contains phosphorous (State of Minnesota, 2004). Over 10 states have followed suit with similar restrictions in the last few years (State of Maine, 2008; State of Wisconsin, 2010; State of Illinois, 2010; State of Michigan, 2013). Nitrates can contaminate groundwater and jeopardize drinking water quality. In order to curb this negative impact, states are starting to restrict nitrogen fertilizer applications (State of Maryland, 2013) and proposed extra taxes on nitrogen (Canada et al., 2012).

Several provinces in Canada have banned all synthetic pesticides (Government of Quebec, 2006; Government of Ontario 2009). New York State has banned pesticide use on the grounds of schools and daycare centers (New York State, 2011). Montgomery County, Maryland was the first major locality in the United States to ban pesticides on lawns (Montgomery County Government, 2016). Legislation limiting fertilizer and pesticide use will likely continue to expand in geographical area, and golf course managers can expect these types of restrictions to include them. Golf courses need to adapt to reduced input levels. Another survey by the Golf Course Superintendents Association of America estimated pesticide use practices on golf courses in

2013. Self-reported data from golf course superintendents showed 26% percent of average 18-hole golf facilities had one or more restrictions on their pesticide applications enacted by a local government or tribal authority (GCSAA, 2013).

As inputs decrease, the performance of some turfgrass species will decrease (Carrow, 1996; Perdomo et al, 1996; Su et al., 2008). In order to sustain turfgrass quality and playability with lower input systems, new biological tools are required. Alternative grass species have been evaluated in various landscapes types and with varying desired functions (Diesburg et al., 1997; Meyer and Pedersen, 2000; Mintenko et al., 2002), including lower irrigation water use rates (Aronson et al., 1987), lower fertility rates (Turgeon, 2008; Watkins et al., 2008), and no pesticides (Minner et al., 2013). Fine fescues are one of these alternative options.

Fine fescues

There are over 450 species in the *Festuca* genus (Clayton and Renvoize, 1986). These grasses originated in Europe and now exist across temperate regions of the world, including mountaintops, hills, plains, and meadows. The *Festuca* genus is large and variable (Clayton and Renvoize, 1986). Some species are grouped into the “fine-leaved fescues” or “fine fescues” for their thin leaf blade (2-7 mm wide), shade tolerance, low fertility requirements, and low water use (Ruemmele et al., 1995). Fine fescues are difficult to distinguish from one another with the naked eye, and are usually distinguished from one another through plant morphology (Hubbard, 1954), sclerenchyma strands (Clayton and Renvoize, 1986), or cytological tools (Jones et al., 2008).

The five cool-season species or subspecies commonly used as managed turfgrass in the temperate regions are hard fescue, sheep fescue, Chewings fescue, strong creeping red fescue, and slender creeping red fescue. Within these fine fescues, the species can be grouped into two aggregates: the *F. rubra* complex and the *F. ovina* complex. The *F. rubra* complex includes strong creeping red fescue, slender creeping red fescue, and Chewings fescue. Both creeping red fescues are rhizomatous, while Chewings fescue has a bunch type growth with extensive tillering (Beard, 1973). The *F. ovina* aggregate includes hard fescue and sheep fescue.

Advantages of fine fescues

Fine fescues have shown a range of water needs compared to several popular cool-season grasses. Aronson et al. (1987) measured water use rates of Kentucky bluegrass and perennial ryegrass as greater than ‘Tournament’ hard fescue and ‘Jamestown’ Chewings fescue. Grasses were maintained at a 5 cm mowing height through the study. In Norway, Aamlid et al. (2015) measured relative water requirements for fine fescues maintained at 0.5 cm (green) and 1.5 cm (fairway) mowing heights. At the greens height, relative water use of ‘Center’ Chewings fescue and ‘Cezanne’ slender creeping red fescue were not significantly different from bentgrass (*Agrostis* spp.) species mowed at 0.3 cm. One day after irrigation in their fairway trial, water requirements for ‘Center’ Chewings fescue were significantly lower than ‘Barcrown’ slender creeping red fescue and ‘Celianna’ strong creeping red fescue. However, the Chewings fescue was not significantly different from Kentucky bluegrass. The mean values of the following days were not significant among any species. Blankenship (2011) presented data on cool-season grasses in Oregon mowed at 1.6 and 5.1 cm. Chewings fescue, slender creeping red fescues, and strong creeping red fescues had higher water requirements at the 16 mm mowing height than the 51 mm height. Among the species, these fine fescues all required more daily water than the tall fescue, perennial ryegrass, Kentucky bluegrass, and bentgrass varieties tested. Aamlid et al. (2015) suggested that the water-saving effect of narrow leaves may become less important at low mowing heights. It is important to note that while Blankenship (2011) and Aamlid et al. (2015) conducted experiments on fine fescues managed as fairways, irrigation was regularly applied. Thus, turfgrass response after a prolonged water shortage was not measured.

The fine fescues are declared to have superior drought resistance relative to other cool-season species (Fry and Huang, 2004; Ruemmele et al., 1995). The fine fescues do well in low-input field research where no supplemental irrigation is provided beyond establishment (Dernoeden et al., 1994). Dernoeden et al. (1998) carried out a low-input field trial to evaluate fine fescues in mixtures and monocultures. Mowing heights were 6.5 cm and 9.0 cm. The tall fescue, ‘Reliant’ hard fescue, and ‘Bighorn’ blue fescue monostands performed equal to or better than the mixtures, while the ‘Flyer’ creeping red fescue and ‘Jamestown II’ Chewings fescue seemed to lower the quality of some mixtures. A comprehensive eight-location trial by Watkins et al. (2011) indicated ‘Berkshire’ hard fescue and ‘Blacksheep’ sheep fescue performed well in a low-input study where no irrigation was employed after establishment. Hard fescue achieved higher ratings at both mowing heights (5.1 cm and 10.2 cm) for all years, except locations where rainfall was low compared to historical trends. Among the 12 species and multiple environments, hard fescue, sheep fescue, ‘Grande II’ tall fescue, and ‘SR 7150’ colonial bentgrass (*Agrostis capillaris*, L.) performed well. At a fairway mowing height, Watkins et al. (2010) tested several cool-season species exposed to traffic treatments. The two-year study required only one fertilizer application and one irrigation event beyond natural precipitation. The traditional fairway species used in the northern United States—creeping bentgrass, Kentucky bluegrass, and annual bluegrass—did not provide the same level of quality as the fine fescue species after two years, especially ‘Jamestown II’ Chewings fescue and ‘Quatro’ sheep fescue. These experiments rarely employed supplemental irrigation because rainfall provided adequate moisture; no experiments have withheld water in attempts to measure the success of fine fescue fairways after a prolonged dryspell.

Gardner and Taylor (2002) tested species with little fertilizer inputs over 6 years. Results showed red fescues, Chewings fescues, and hard fescues maintained better turf quality than Kentucky bluegrasses and perennial ryegrasses, but no species did as well as tall fescue. After a three year trial with no fertilizer after establishment, Dernoeden et al. (1998) found that ‘Reliant’ hard fescue, ‘Bighorn’ sheep fescue, and ‘Jamestown II’ Chewings fescue were not statistically different and maintained acceptable turfgrass quality at a 9.5 cm mowing height. ‘Flyer’ creeping red fescue did not achieve acceptable levels. Watkins et al. (2008) published cultivar performance of low-input grass species, with no fertilizer, irrigation, or pesticides after establishment. The top performing species for turf quality was Chewings fescue. Hard fescues maintained adequate turf quality less often, and sheep fescues did poorly. The fine fescue species are also tolerant to acidic soils with a pH from 4.5 to 6.5 (Juska and Hanson, 1959; Juska et al., 1965; Beard 1973) and soils with toxic metals (Huff and Wu, 1985; Brown and Brinkman, 1992).

Diseases

Gray snow molds (caused by *Typhula incarnata* Fr. or *T. ishikariensis* Imai), pink snow mold [caused by *Microdochium nivale* (Fr.) Samuels & I.C. Hallett], and snow scald [caused by *Myriosclerotinia borealis* (Bubak & Vleugel) L.M. Kohn] are cold-weather diseases that can be problematic in Minnesota. A group of Minnesota golf course superintendents were surveyed and asked which diseases pose a major problem. Snow molds were top-ranking, along with dollar spot (Orshinsky, 2014). Disease susceptibility can be a limit to the adaptation of fine fescues for golf course fairways and an area that necessitates research.

Snow molds and snow scald symptoms can be devastating in the springtime after snow melt. Damage on high-value fairway turf requires resources and time to repair. Control of these pathogens requires fungicide applications every fall, to protect the turf from disease throughout the winter. Fine fescues have shown some potential for genetic resistance to snow molds, and could be a strategy to reduce pesticide inputs on golf course fairways. Gregos et al. (2011) found that fine fescue cultivars had significantly less snow mold disease damage than colonial bentgrasses or creeping bentgrasses, but fine fescues still suffered disease ranging from 12 to 83% of a plot area. Other observations suggest that snow mold disease can be a problem on these grasses and breeding efforts are needed to improve disease resistance (Ruemmele et al., 1995). To date, there has not been enough research on fine fescue response to snow mold pathogens when managed as fairways.

It is worth mentioning that fine fescues are lauded for containing a beneficial *Epichloë* endophyte. Chewings fescue, strong creeping red fescue, and hard fescue have been found to contain *Epichloë* endophytes (Funk and White, 1997). Clarke et al. (2006) showed significantly higher resistance to dollar spot in *Epichloë* endophyte-infected Chewings fescue, hard fescues, and strong creeping red fescues compared to related endophyte-free lines. Within endophyte-free germplasm, strong creeping red fescues were consistently more susceptible to dollar spot than the Chewings or hard fescue entries. Red thread [*Laetisaria fuciformis* (McAlpine) Burds.] has also been suppressed with endophyte-enhanced Chewings fescue and strong creeping red fescue lines (Bonos et al., 2005). Moreover, endophytes in strong creeping red fescue and Chewings fescue suffered a lesser degree of herbivory than endophyte-free plants (Clay et al., 1993; Bazely et al, 1997; Garrison and Stier, 2010).

Use on fairways

Because of their low input requirements, there has been some transition to employ fine fescues in rough and out-of-play areas on golf courses (Lyman et al., 2007). Beyond roughs, fairways comprise the largest area of maintained turfgrass on golf courses on which to start integrating fine fescues on a large scale. A 1996 golf course pesticide census in New Jersey reported that fairways used more total pesticides (57,600 kg of active ingredient) than roughs, greens, and tees combined (50,000 kg of active ingredient) (NJ Department of Environmental Protection, 1996).

In spite of the stellar potential for savings, fine fescues occupy less than 1% of fairway acreage in the United States (Lyman et al., 2007) and information is limited on management of fine fescues on fairways. A 2007 survey of golf courses throughout the United States calculated 608,732 total hectares of maintained turf for golf courses. About 29% (179,300 hectares) of the turfgrass area is fairway, and less than 1% (1,208 hectares) of the national fairway area is fine fescues. Fairways in the cool-season regions of the United States are dominated by annual bluegrass, creeping bentgrass, Kentucky bluegrass, and perennial ryegrass. Golf course managers use these species on fairways because of their superior green color, shoot density, ability to repair injury, and traffic tolerance.

Disadvantages of fine fescues

Trials comparing wear tolerance of turfgrass species ranked red fescue and colonial bentgrass lowest among other entries of annual bluegrass, Kentucky bluegrass, perennial ryegrass, and Timothy (*Phleum pratense* L.). After two months of regular traffic, the red fescue and colonial bentgrass had virtually bare soil with less than 7% of ground cover remaining. The red fescue that was established 2 years earlier had a slightly higher wear tolerance (Canaway, 1978). Gore et al. (1979) tested some of the same species subjected to wear treatments, and also found that red fescue and colonial bentgrass were almost eliminated (Gore et al., 1979).

A major stress on golf course fairway turf is the removal of verdure and thatch as divots. Therefore, any turfgrass used in these areas needs to possess strong recuperative ability. Fine fescues maintain a very slow growth rate (Grime and Hunt 1975) and recovery from injury may be slow. Divot repair is a management area that demands study, and previous research suggests that plant growth regulators (PGR) could improve divot recovery and recovery from traffic. PGRs generally suppress vertical shoot growth, and the effect on lateral growth depends on the PGR used.

Trinexapac-ethyl is PGR that inhibits gibberellin biosynthesis and decreases leaf elongation rates (Ervin and Koski, 1998). Trinexapac-ethyl does not inhibit other forms of growth, like lateral shoots and rhizomes (Fagerness and Penner, 1998). Consequently, trinexapac-ethyl has been shown to increase plant density (Stier and Rogers, 2001) and promote lateral tillering (Ervin and Koski, 2001). Turfgrass treated with trinexapac-ethyl grows fuller and more prostrate, which results in thicker turf canopy, improves quality, and encourages better injury recovery. There is a void of recent research involving growth regulator treatments on fine fescues. Turfgrass growth regulator work has focused on increasing turf quality, stress tolerance, or annual bluegrass control on intensively managed creeping bentgrass, Kentucky bluegrass, and perennial ryegrass stands (Ervin and Koski, 1998; Ervin and Koski, 2001; Burgess and Huang, 2014). PGRs like trinexapac-ethyl should be examined on fine fescues fairways for better injury recovery.

Species mixtures

Polycultures are recommended over monocultures due to the benefits of enhanced genetic diversity. Observational studies and removal experiments in natural and semi-natural grasslands show that higher-species assemblages are necessary for high ecosystem functioning (Schulze and Mooney, 1994). Tilman et al. (2001) found many multi-species plots outperformed the best monocultures in grassland biomass production. Tilman and Downing (1994) found that more diverse grassland ecosystems are more resistant to, and recover more fully from, a “negative” perturbation like drought stress.

This concept extends to managed turfgrass and is supported with a small body of literature. Brede and Duich (1984) found that a mixed stand of perennial ryegrass and Kentucky bluegrass generated a higher leaf area index, percent grass cover, and spring green up rate than either species alone. Dunn et al. (2002) showed that, on occasion, polycultures of cool-season turfgrasses provided better disease resistance than a single species. Juska and Hanson (1959) reported that a monoculture of Kentucky bluegrass outperformed mixtures of Kentucky bluegrass, colonial bentgrass, tall fescue, and red fescue in the first four years of the experiment. In the fifth and final year of the study, the Kentucky bluegrass monoculture suffered from stripe smut disease and the mixture of red fescue and Kentucky bluegrass provided better turf quality ratings.

In these experiments, selection of the turfgrass mixture proportions is often based on arbitrary or convenient values, and statistical analysis will only identify the best entry in a trial. This offers little predictive ability regarding the mixture components and proportions. Experiments with mixtures should explore better experimental designs and subsequent statistical analysis to identify the best possible mixture for a fine fescue golf course fairway.

Conclusion

Fine fescues are not widely used on golf course fairways because there are major unknowns and weaknesses associated with these species. Basic management practices have not been unraveled and harmonized for easy application by golf course managers. Response to biotic stresses like snow mold pathogens and abiotic stresses like prolonged drought have not been evaluated. Turfgrass managers need research to overcome these barrier and begin using more fine fescues on golf courses.

CHAPTER 1

Drought response of fine fescue fairway mixtures under drought conditions

ABSTRACT

Fairways in the northern United States are predominately comprised of annual bluegrass, creeping bentgrass, perennial ryegrass, and Kentucky bluegrass. These grass species are used on fairways because of their superior green color, shoot density, traffic tolerance, and playability. The popular grasses also demand regular irrigation inputs to maintain turfgrass health and function. New biological tools are required to manage golf course fairways with less water inputs. Fine fescues are a group of alternative grass species that can provide acceptable turf quality and playability on golf course fairways with lower irrigation inputs. Information on fine fescue fairways is limited and these species are not widely used as fairway turfgrasses. The objective of this project was to evaluate fine fescue species' performance as fairway turfgrass under an acute drought. Twenty-five mixtures were developed with a simplex-centroid design using 'Treazure II' Chewings fescue, 'Beacon' hard fescue, 'Navigator II' strong creeping red fescue, 'Shoreline' slender creeping red fescue, and 'Quatro' sheep fescue. The mixture design and analysis was selected to identify superior mixtures and to quantify the effect of each species on the success of a fine fescue fairway under water stress. Experiments were seeded in fall 2014 at both St. Paul, MN and Madison, WI. A rainout shelter was used to employ a 60-day drought on each trial during summer 2015. Data collected included percent green cover as determined by digital images before, during, and after the drought period. Significant differences existed among percent green cover amounts throughout the drought and recovery period. A linear regression was fit to the simplex surface, with all five main effects and two-way interactions included. The marginal effects summary for drought and recovery data showed each species had a significant effect on the mixture performance. Confidence intervals developed around each species presented no significant differences among each fine fescue for green cover retention. Sheep fescue and slender creeping red fescue, when in the same mixture, had a negative interaction effect and showed significantly lower recovery after drought than all other component effects. In this study, inclusion of both slender creeping red fescue and sheep fescue significantly diminished the performance of a fine fescue mixture recovery after drought stress. Mixtures that contained large proportions (>33%) of Chewings fescue maintained the most green cover at the end of the drought period. Overall, this study found that any of the five fine fescue species can provide acceptable turf quality and playability on golf course fairways resulting in lower irrigation inputs.

INTRODUCTION

The reduction in water quality and quantity is both a national and international issue. The U.S. Drought Monitor identifies parts of the Midwest as measuring from -1.0 to -2.9 on the Palmer Drought Severity Index (Palmer, 1965; National Drought Mitigation Center, 2015). The Palmer is a comprehensive soil moisture algorithm used by many government agencies to trigger drought relief programs. On this drought index, a value of 0 is normal and -4.0 is an “extreme drought.” In the western United States the climate varies tremendously throughout the year, but entire states are considered to be in some level of drought. The Intergovernmental Panel on Climate Change (IPCC) predicts that the frequency and magnitude of unusual drought events will increase (IPCC, 2013). Water issues also bear an economic burden, as exemplified by the situation in California. At present, the estimated cost of the 2015 California statewide drought is 2.7 billion dollars and 21,000 job losses (Howitt et al., 2015). Additionally, the price of agricultural water is increasing throughout many regions of the country (Wichelns, 2010).

The sinking availability and swelling cost of water is a threat to intensely managed turfgrass areas. Water use rates to maintain a healthy, functional turfgrass matrix often exceed natural precipitation. Best management practices would achieve the lowest irrigation water use possible for environmental and economic savings. As irrigation inputs decrease, the performance of some turfgrass species will decrease, especially during drought events (Carrow, 1996; Perdomo et al, 1996; Su et al., 2008).

For sustained turfgrass quality during drought, new strategies are needed. Alternative grass species have been evaluated in various landscapes types and with varying functions (Diesburg et al., 1997; Meyer and Pedersen, 2000; Mintenko et al., 2002), including lower irrigation water use rates (Aronson et al., 1987). Fine fescues are one of these alternative options. The fine fescues are a group of cool-season grasses with similar morphological and agronomic characteristics. These species and subspecies are known for a fine leaf blade, shade tolerance, low fertility requirements, and low water use (Ruemmele et al., 1995). However, fine fescues are not widely used as golf course turf in the northern United States (Lyman et al., 2007). Current fine fescue varieties do not provide exceptional green color, shoot density, ability to repair injury, and traffic tolerance like the more common and widely used golf course turfgrasses.

More popular cool-season turfgrasses on golf courses include annual bluegrass, creeping bentgrass, perennial ryegrass, Kentucky bluegrass, and tall fescue (*Festuca arundinacea*, Schreb.); however, fine fescues (*Festuca* spp.) have the comparatively better drought tolerance (Beard, 1973; Fry and Huang, 2004; Brar and Palazzo, 1995). Fine fescue species perform well in reduced-input situations with little to no supplemental irrigation (Watkins et al., 2010; Watkins et al., 2011). Aronson et al. (1987) found that the water potential in Kentucky bluegrass and perennial ryegrass leaves decreased significantly when soil water potential fell to -80 kPa, while hard fescue and Chewings fescue maintained an adequate leaf water potential as soil water potential reached -400 kPa. Hard fescue and blue hard fescue [*Festuca ovina* L. spp. *glauca* (Lam.) W.D.J. Koch] maintained better turf quality and superior resistance to weed invasion than tall fescue, during a three-year study without irrigation (Dernoeden et al., 1994). After two years with one irrigation event, sheep fescue, hard fescue, and Chewings fescue all maintained better turfgrass quality and percent living stand density than creeping bentgrass and annual bluegrass when maintained as a golf course fairway (Watkins et al., 2010).

The low water use of fine fescues has prompted them to be employed in rough and out-of-play areas on golf courses (Lyman et al., 2007). Beyond roughs, fairways comprise the largest area of maintained turfgrass and use of fine fescues on these areas would likely have the highest impact on total water use on golf courses. In spite of this, fine fescues occupy only 1% of fairway acreage in the United States (Lyman et al., 2007) and information is limited on water use of fine fescues on fairways.

This experiment examined various blends consisting of five different fine fescue species to identify the superior mixtures and to quantify the effect of each species on the success of a fine fescue fairway under drought stress. Mixtures of grasses are recommended over monocultures of species due to the benefits of genetic diversity, like enhanced environmental stress tolerance, pest tolerance, and biomass production (Watschke and Schmidt, 1992; Schulze and Mooney, 1994; Tilman et al., 2001). Results from Tilman and Downing (1994) show more diverse grassland ecosystems are more resistant to, and recover more fully from, a drought. Drought resistance was a significantly increasing function of pre-drought species richness. Years after the drought, species-poor plots had not recovered as much pre-drought biomass as species-rich plots.

The objective of this project was to evaluate the performance of fine fescue species as fairway turfgrass under an acute drought. This research aims to improve sustainability of golf courses by reducing water requirements of fairways. Field trials were conducted to withhold water from fine fescue fairway plots. Data was collected during the experiment to measure success of each entry during a 60-day drought, followed by a 45-day recovery period. The length of the drought was selected as an extreme example of what could possibly be seen in nature since the record for consecutive days with no measureable precipitation in St. Paul, MN is 51 days in 1943 (NWS, 2015).

MATERIALS AND METHODS

Mixture design

Mixtures used in the trial were comprised of five cultivars each representing a single fine fescue species, these include: ‘Radar’ Chewings fescue, ‘Navigator II’ strong creeping red fescue, ‘Shoreline’ slender creeping red fescue, ‘Beacon’ hard fescue, and ‘Quatro’ sheep fescue. These cultivars were selected for their commercial availability and superior performance in past fine fescue fairway trials (Watkins et al., 2010; NTEP, 2013). These five cultivars were used to create mixtures for the experiment. Monocultures, consisting of only a single cultivar of a fine fescue species, were included as the standard to which multicomponent blends were compared. Mixture components summed to a constant 1.00, constraining the constituent proportions to a multidimensional simplex.

A five-component simplex-centroid mixture design was created with the *mixexp* package in R (R Core Team, 2015). Data from this design can be analyzed with Scheffe’s canonical polynomial (Scheffe, 1963) to fit the simplex surface. The polynomial model can measure the influence of each component, or species, on the response variables measured. The full simplex-centroid design included too many mixtures to be feasible in a field study. Therefore, the mixture design was fractionated to suit 25 mixtures. To select 25 mixtures that would maximize information about the entire simplex, design optimization functions were employed and a D-optimal design was selected with the *AlgDesign* package in R. The D-optimized simplex-centroid mixture design is described in Table 1.

Site design and establishment

Field plots were established 15 August 2014 in St. Paul, MN, USA and 20 August 2014 in Madison, WI, USA. The St. Paul soil was a Waukegan silt loam and the Madison soil was a Batavia silt loam. Each site was arranged as a randomized complete block with six repetitions. All plots measured 0.9 m by 0.9 m. Starter fertilizer was Andersons Contec DG (12-24-8) at a rate of 24.4 kg N, 21.5 kg P, and 13.5 kg K ha^{-1}. Seed was spread by hand at a rate of 2.5 pure live seeds cm^{-2}. Pure live seeds was calculated from germination tests previously done in a greenhouse. After seeding, the soil surface was lightly raked to promote seed to soil contact. Futerra EnviroNet blankets (PROFILE Products LLC) were placed on the seeded area immediately after seeding to control erosion and foster turf establishment. Each site was watered daily for three weeks and then no supplemental irrigation was applied after this establishment period. Five weeks after seeding another fertilizer application with Andersons Contec DG was applied at a rate of 24.4 kg N, 21.5 kg P, and 13.5 kg K ha^{-1}.

The use of two locations in the north central region selected to repeat this experiment in the same calendar year allowed for evaluation under different climatic and soil conditions. A mobile rainout shelter was used to withhold precipitation and conduct a controlled drought at each location. Before a rainfall event, the device moved along tracks to cover the experimental area. When the weather forecast presented no chance of rain, the rainout shelter rested off of the plot area. The St. Paul rainout shelter was completely automated and could be controlled both on and/or off-site. Additionally, the structure included a rain sensor that would move the cover over the plots if rain was detected. In contrast, the Madison rainout shelter was manually moved with a tractor and pulley system.

Growth conditions and management

Starting four weeks after seeding, plots were mowed two times per week at 1.27 cm with a walking reel mower and clippings were removed. In early May 2015, a broadleaf herbicide was applied at each site. The St. Paul site was subjected to 2,4-dichlorophenoxyacetic acid, (+)-(R)-2-(2 methyl-4-chlorophenoxy) propionic acid, and 3,6-dichloro-o-anisic acid (Trimec 992, PBI/Gordon Corporation) applied at a rate of 2.34 L product ha^{-1}. The Madison site was subjected to ethyl α, 2-dichloro-5-[4(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]-4-fluorobenzeneproppanoate, 2,4-dichlorophenoxyacetic acid, (+)-(R)-2-(2 methyl-4-chlorophenoxy) propionic acid, and 3,6-dichloro-o-anisic acid (SpeedZone, PBI/Gordon Corporation) applied at a rate of 3.51 L product ha^{-1}. In late May 2015, each site was fertilized with Andersons Contec DG (12-24-8) at a rate of 24.4 kg N, 21.5 kg P, and 13.5 kg K ha^{-1}. On 1 June 2015, right before the induced drought period, a second SpeedZone application was made in Madison to control persistent broadleaf weeds.

Data collection

One day before the drought period began, each site was irrigated uniformly with 2.54 cm of water. The drought, during which time the plots received no water from irrigation or precipitation, started at the beginning of June and finished at the end of July so that the total duration was 60 d. Data measuring percent green cover was collected immediately before water was applied at the start of drought and at the end of the 60-day drought period. After the drought, the area was irrigated with 2.54 cm of water to stimulate recovery, and data was collected after 45 days of recovery.

Digital image analysis was used to compute percent green cover as a quantitative measure of turfgrass health. Digital images were captured with a custom 0.6 m by 0.6 m by 0.6 m light box that contained twelve LED lights inside mounted on the roof of the box. The camera was a Nikon D300 equipped with a Nikon 35mm f/1.8G AF-S DX Nikkor Lens. One image was taken of each plot. All images were processed in ImageJ (Rasband, 2015) with a custom batch macro that utilized the *Color Thresholder* plugin in FIJI (Schindelin et al., 2012). This macro calculated the proportion of the image within the assigned green hue range, and the proportion of the image was converted to a percentage that represented percent green cover.

Mixture model analysis

Data from both locations was combined and analyzed with R (R Core Team, 2015). Three response variables were used: percent green cover at the beginning of drought, percent reduction in green cover at the end of drought, and percent recovery of original start values. Homoscedasticity and normality assumptions were met for each analysis. An analysis of variance was computed to measure effects of site, replicate, and mixture. Treatment means were separated by Fisher's protected least significant difference (LSD) at $\alpha=0.05$ level.

A second analysis was used to model the data with the quadratic form of Scheffe's canonical polynomials. A linear regression was fit to the simplex surface, with all five main effects and two-way interactions included. Higher order polynomials, like three-way and four-way interactions, were not included because they may lead to overfitting. The *lm* function in R was used to calculate the influence of each component and two-way interaction. The three aforementioned response variables were tested with three separate linear models. Variable selection was done to remove unnecessary predictors and simplify the model. A backward elimination was done using Akaike's Information Criterion (AIC) with the *stepAIC* function in the *MASS* package of R. Final coefficients were determined with p-values that measured the difference between the coefficient and zero. In order to measure the difference between coefficients, confidence intervals were calculated for each coefficient. The *boot* function in R was used to bootstrap the coefficients based on 1000 replicates, and the *boot.ci* function furnished the 90% confidence interval.

RESULTS

Climate

Mean daily temperatures for St. Paul and Madison were 22 °C and 21 °C, respectively, during the drought period, and the average daily dew point for both sites was 15°C. During the recovery period, the mean temperatures were 22 °C and 20 °C and rainfall totaled 1.12 cm and 2.47 cm in St. Paul and Madison, respectively (NOAA, 2016).

Mixture comparison

Initial establishment

The ANOVA for percent green cover at the start of drought is described in Table 2. The ANOVA revealed a significant effect of site, so each site was analyzed separately. The subsequent ANOVA for percent cover at the beginning of drought for St. Paul and Madison (Table 3) sites both exhibited a significant effect of mixture. In St. Paul, means separation with Fisher's LSD showed that mixture 25 had the greatest percent green cover at the start of the drought, with 81.97%, but was not significantly different from the next eight mixtures (Table 4). The lowest three mixtures at the start of the drought in St. Paul were not significantly different: mixture 1, 10, and 5 had 57.66%, 58.18%, and 60.07% green cover total, respectively. In Madison, the highest ranking group ranged from 89.20% to 84.24% green cover (Table 4) and contained six mixtures. Mixture 1 had the lowest percent green cover at the start of drought, with 60.28% green cover, and was not significantly different from the next 4 lowest-ranking mixtures. The top statistical groups in St. Paul and Madison contained nine different mixtures almost exclusively composed of hard fescue, sheep fescue, and Chewings fescue. Mixtures 18 and 19 each contained 33% slender creeping red fescue. Bottom ranking mixtures at each location include no Chewings fescue and at least 50% strong creeping red fescue and slender creeping red fescue.

Conclusion of drought

The analysis of variance for percent reduction in green cover at the end of drought also revealed a significant effect of site (Table 2), so each site was analyzed separately. The Madison site displayed a significant effect of mixture (Table 3), and means were separated with Fisher's LSD (Table 5). The best performing mixture, with the smallest change in green cover, was mixture 7 (100% sheep fescue) with a 68.69% reduction in green cover. The next twelve mixtures were not significantly different from one another, and each entry consisted of hard fescue, sheep fescue, and Chewings fescue. Strong creeping red fescue had the least occurrence in the top groups, in three of these mixtures at 33% or fewer proportions. Mixture 3 had the greatest loss of

93.23% green cover; however, this mixture was not significantly different than the eleven next-lowest mixtures. In this bottommost group of twelve, hard fescue, sheep fescue, and Chewings fescue each appear three times. Strong creeping red fescue and slender creeping red fescue appear in eight and seven mixtures, respectively, out of these twelve lowest mixtures. At the end of drought, there were no significant differences among mixtures at the St. Paul site (Table 3). Means for percent loss of green cover are included in Table 5.

Recovery

The ANOVA for percent recovery of starting green cover revealed a significant effect of site, so each site was analyzed separately (Table 2). Mixture had a significant effect at each location (Table 3). In St. Paul, mixture 1 recovered the most with 120.77% of original cover reached. The next five best mixtures were not significantly different, and were all over 100% (Table 6). These plots had more green area after recovery than before the whole drought period. The lowest six entries were in the same statistical group and ranged from 95.41 to 103.92% recovery. The best statistical group contained six mixtures. Five of these six mixtures contained strong creeping red fescue. The only top mixture without strong creeping red fescue was the monoculture of slender creeping red fescue. Furthermore, slender creeping red fescue was the second most-present species in the top recovery group. Chewings fescue was not present in any of the top group of mixtures, and sheep fescue was only identified once. The worst statistical group in St. Paul also contained six mixtures, and each mixture contained 33% or more of Chewings fescue. Slender creeping red fescue was not present in any of the low-recovery mixtures. Means separation for Madison showed mixture 7 rebounded the most with original green cover of 79.12% (Table 6). This top mixture was not significantly different from the next eight mixtures. The lowest ranking entry was mixture 6, with only 27.62% recovery. The bottommost five mixtures were not statistically different. Chewings fescue was the most frequent component in the top statistical group, which is the opposite of the other location. Sheep fescue was the next most popular constituent species, which is contrary to the best constituent species at the St. Paul location for recovery area. The lowest statistical group did not consist of Chewings fescue and only demonstrated one occurrence of hard fescue. While none of the poor mixtures in St. Paul contained slender creeping red fescue, each poor-performing mixture documented at the Madison site contained some portion of slender creeping red fescue.

Mixture component effects

Conclusion of drought

The final model for percent reduction in green cover after drought was computed with both sites together. Although site had a significant effect on variable response (Table 2), there was no site by mixture interaction, and different site means were not of theoretical interest. The marginal effects summary included all main effect terms after variable selection. All other variables were eliminated from the model because they did not significantly contribute to prediction. The regression offered an adjusted R^2 of 0.6499. Coefficient estimates and p-values for green cover retention under drought stress are presented in Table 7. The magnitude of each coefficient describes the relative ability of each component to preserve green cover; for instance, hard fescue was the best fine fescue to successfully maintain cover with a -44.60 coefficient. The lowest component coefficient was strong creeping red fescue with -54.86. All coefficients produced a p-value less than 0.001, which means the coefficients are significantly different from zero and the null hypothesis that the components have no significant effect on the mixture was rejected.

The bootstrapped 90% confidence interval calculations for each coefficient after drought are presented in Table 7. All coefficients have confidence intervals that overlap each other (Figure 1). There are no significant differences among components for green cover retention.

Recovery

A separate linear regression was constructed to measure the percent recovery after a recovery period. Sites were combined for the marginal effects summary. After variable selection, all main effect terms, Chewings fescue by slender creeping red fescue interaction, and sheep fescue by slender creeping red fescue interaction were included in the model (Table 8). The interactions were included in the model because those predictors provide the best regression that balanced model fit and size with AIC. An adjusted R^2 0.8964 describes a tight fit to the regression line. The most powerful component for the success of returning to original cover was sheep fescue at 93.22. The least powerful main effect was slender creeping red fescue with 72.59. All main effects were significantly different from zero with p-values less than 0.001. The Chewings fescue by slender creeping red fescue positive interaction coefficient presents a synergistic effect when these different species are coupled together. The sheep fescue by slender creeping red fescue negative interaction coefficient displays an antagonistic effect of these species united, with a p-value of 0.1017.

The bootstrapped 90% confidence interval calculations for each coefficient after recovery are presented in Table 8. All main effect confidence intervals contain each other, so no significant difference exists among individual species components (Figure 2). Additionally, the Chewings fescue by slender creeping red fescue is not significantly different from any main effect. The Chewings fescue by slender creeping red fescue interaction has a positive coefficient at a 0.0923 p-value. These two species have a synergistic effect when combined, and the effect is significantly different from zero at $\alpha=0.10$ level. The negative coefficient for sheep fescue and slender creeping red fescue reveals an antagonistic effect when these species are coupled, although the p-value is larger (0.1017). The antagonistic -53.65 coefficient for the sheep fescue by slender creeping red fescue interaction is significantly lower than all other coefficients. Altogether, there are no significant differences among components for green cover recovery to original levels, except the sheep fescue by slender creeping red fescue two-way interaction is antagonistic and significantly lower than all other components.

DISCUSSION

Initial establishment

The objective of the study was to assess the functionality of fine fescue species mixtures utilized as fairway turfgrass within the context of an acute drought. At the start of the drought in June 2015, no mixtures had reached a 100% green cover. Plots were seeded the previous fall, and still had not completely established to a mature sod after nine months. The range of percent cover was relatively the same between sites. Significant differences existed among mixture treatments for mean percent green cover.

The differences in establishment are not consistent with reported establishment data. Percent establishment data collected for fine fescue cultivars at six locations in the United States revealed Chewings fescue and strong creeping red fescue cultivars had significantly higher percent of established area than hard fescue cultivars (NTEP, 2013). Strong creeping red fescues have better seedling vigor than Chewings fescue (Meyer and Funk, 1989) and seedlings of red fescue had a higher maximum potential growth rate than sheep fescue (Grime and Hunt, 1975). The better establishment cover from hard fescue and sheep fescue in this experiment could be due to environmental differences among the cited studies, or recent breeding efforts that have focused on improving these species.

It is important to note the significant differences in treatment green cover at the beginning of the drought, as it influenced subsequent measurements. The initial green cover values were used as a baseline to calculate the percent of initial green amount lost after the drought and the percent of initial green amount recuperated after the recovery period.

Conclusion of drought

After the drought, the distribution of means at the Madison site were lower than that of the St. Paul site (Table 5). This stratification was likely due to the different types of rainout shelter devices. In St. Paul, the apparatus rested about 1.2 m above the turfgrass surface, and allowed for airflow over the trial area. In contrast, the Madison shelter rested about 0.15 m above the grass canopy, and blocked airflow. At times, the shelters' interior chamber likely reached a higher temperature and humidity than the outside atmosphere.

Mixtures with Chewings fescue, hard fescue, and sheep fescue retained more green cover at the end of the drought period than strong creeping red fescue or slender creeping red fescue. Research by Minner and Butler (1985) also found that Chewings fescues and hard fescues were more drought tolerant than strong creeping red fescue. Aamilid et al. (2015) found that Chewings fescue had a lower water requirement than slender creeping red fescue and strong creeping fescue one day after an irrigation event. This dynamic shifted in the following days of data collection, with slender creeping red fescue requiring the least amount of water, followed by Chewings fescue and strong creeping red fescue.

The marginal effects summary for sustainment of original green cover after drought include five main effect terms (Table 7). The 90% confidence intervals drawn for each effect swamp each other and present no significant difference among the five main effects. This is very clear in Figure 1 where each plotted component overlaps. Aronson et al. (1987) measured the seasonal water requirements for hard fescue and Chewings fescue. That study showed hard fescue had a significantly lower evapotranspiration rates than other species in the first year, but was countered when the Chewings fescue had the significantly lower rates in the second year. Beard (1973) published relative ratings of drought tolerance, and rated red fescue, hard fescue, and sheep fescue equally.

Recovery

Site effects were significant after a recovery period stimulated with irrigation and continued with regular precipitation (Table 2). The range of values at the St. Paul site were higher than the Madison site, and every mixture in St. Paul recuperated at least 95% of original green cover (Table 6). The lower recovery means at Madison were likely due to more severe temperature stress inside the Madison rainout shelter compared to the St. Paul rainout shelter.

Chewings fescue was not present in the top recovery group in St. Paul, and the top group was dominated by slender creeping red fescue and strong creeping red fescue. Contrary to the St. Paul results, the Madison site presented Chewings fescue as the most frequent species in the top recovery group, with more slender creeping red fescue and strong creeping red fescue in the bottom statistical group. Carroll (1943) found that Chewings fescue had better recovery following drought stress than red fescue. This aligns well with the Madison trial of this experiment, but not the St. Paul trial.

The final model for the marginal effects summary of percent green area recovered included seven terms (Table 8). All five main effect terms were included, as well as a Chewings fescue by slender creeping red fescue interaction and a sheep fescue by slender creeping red fescue interaction. After bootstrapping confidence intervals to compare coefficients, all effect terms are not significantly different from each other, except the negative sheep fescue by slender creeping red fescue interaction was significantly lower than every other term (Figure 2). Inclusion of both slender creeping red fescue and sheep fescue would significantly diminish the performance of a fine fescue mixture under drought stress.

The Chewings fescue by slender creeping red fescue positive interaction suggests these species are cooperative and grow well together. However, it must be noted that the interaction value is not significantly different from each species alone. The sheep fescue by slender creeping red fescue negative interaction suggests these species are competitive and do not perform well when seeded together.

Mechanisms for these interactions are not immediately obvious. It is possible that the Chewings fescue and slender creeping red fescue fill different niches that use water, nutrients, light, and other resources differently. Competition for these resources could be a factor in the negative interaction between sheep fescue and slender creeping red fescue.

These interaction relationships could be possibly be explained through genetic relatedness. Chewings fescue and slender creeping red fescue are both *Festuca rubra* subspecies. Sheep fescue is in a neighboring taxonomic group called the *Festuca ovina* complex (Ruemmele et al., 1995). In a study of *Deschampsia caespitosa* (L.) interactions with neighbors of different genetic identity, Semchenko, et al. (2014) found that some plants are able to distinguish among neighbors and manage resources accordingly. Results suggest that species avoid competition with kin or closely related plants, while more different populations compete with one another to commandeer the available resources. The mechanism presented by Semchenko et al. (2014) was biochemical compounds in root exudates. Evidence also exists that plants benefit their relatives via increased mycorrhizal networks (File et al., 2012). This is a new ecological idea that demands more research before definitive conclusions can be drawn.

CONCLUSION

A number of fine fescue mixtures performed at an acceptable level (60% or greater green cover) as a fairway turfgrass throughout a 2-month drought and recovery. Results suggest that the use of these fine fescues should be possible as a healthy, functional golf course fairway under a typical summer in Minnesota and Wisconsin. Furthermore, fine fescues can tolerate and recover from “negative” ecosystem perturbations like drought. Marginal effects summaries presented few significant differences, so future research should aim to better understand why certain mixtures performed significantly different and why others mixtures did not.

Table 1. Proportions of constituent species in each mixture identified as a design point in the simplex centroid design for the fine fescue drought experiment for seed mixture analysis.

	Constituent species proportion				
Mixture ID	Chewings fescue *Festuca rubra* ssp. *commutata*	hard fescue *Festuca brevipila*	sheep fescue *Festuca ovina*	slender creeping red fescue *Festuca rubra* ssp. *litoralis*	strong creeping red fescue *Festuca rubra* spp. *rubra*
1					1
2				0.50	0.50
3				1	
4			0.33	0.33	0.33
5			0.50		0.50
6			0.50	0.50	
7			1		
8		0.33		0.33	0.33
9		0.33	0.33	0.33	
10		0.50			0.50
11		0.50		0.50	
12		0.50	0.50		
13		1			
14	0.20	0.20	0.20	0.20	0.20
15	0.25	0.25	0.25		0.25
16	0.33			0.33	0.33
17	0.33		0.33		0.33
18	0.33		0.33	0.33	
19	0.33	0.33		0.33	
20	0.33	0.33	0.33		
21	0.50				0.50
22	0.50			0.50	
23	0.50		0.50		
24	0.50	0.50			
25	1				

Table 2. Analysis of variance of combined data from two experimental sites of the fine fescue mixture drought trial. Separate ANOVAs were computed for percent green cover at the beginning of drought, percent change of green cover at the end of drought, and percent of original green cover recovered at the end of recovery.

	Source	DF	MS	Pr(>F)
Percent green cover at the beginning of drought	Site	1	224.50	0.0014
	Replicate within site	10	132.50	< 0.001
	Mixture	24	606.80	< 0.001
	Mixture x site	24	91.40	< 0.001
	Residuals	240	21.50	
Percent change of green cover at the end of drought	Site	1	354821	< 0.001
	Replicate within site	10	1495	< 0.001
	Mixture	24	260	0.0356
	Mixture x site	24	152	0.5296
	Residuals	240	159	
Percent of original green cover recovered at the end of recovery	Site	1	178876	< 0.001
	Replicate within site	10	477	< 0.001
	Mixture	24	431	< 0.001
	Mixture x site	24	961	< 0.001
	Residuals	240	110	

Table 3. Analysis of variance of data from two experimental sites of the fine fescue mixture drought trial. Separate ANOVAs were computed for two sites (St. Paul and Madison) and three response variables (percent green cover at the beginning of drought, percent change of green cover at the end of drought, and percent of original green cover recovered at the end of recovery).

		Source	DF	MS	Pr(>F)
Percent green cover at the beginning of drought	St. Paul	Replicate	5	208.34	< 0.001
		Mixture	24	267.91	< 0.001
		Residuals	120	21.09	
	Madison	Replicate	5	56.70	0.0292
		Mixture	24	430.30	< 0.001
		Residuals	120	21.90	
Percent change of green cover at the end of drought	St. Paul	Replicate	5	2765.60	< 0.001
		Mixture	24	224.90	0.706
		Residuals	120	274.40	
	Madison	Replicate	5	225.15	< 0.001
		Mixture	24	187.18	< 0.001
		Residuals	120	44.57	
Percent of original green cover recovered at the end of recovery	St. Paul	Replicate	5	88.11	0.199
		Mixture	24	275.51	< 0.001
		Residuals	120	59.21	
	Madison	Replicate	5	865.50	< 0.001
		Mixture	24	1116.6	< 0.001
		Residuals	120	161.70	

Table 4. Mean percent green cover at the beginning of drought produced by each mixture at each experimental site of the fine fescue mixture drought trial.

St. Paul			Madison		
Mixture	Mean†		Mixture	Mean†	
25	81.97	a	13	89.20	a
24	81.69	a	23	87.16	a
13	80.25	ab	24	86.80	a
7	80.04	ab	20	85.50	ab
12	79.49	ab	25	85.36	ab
23	78.99	abc	12	84.24	ab
19	78.61	abc	22	81.17	bc
20	77.96	abcd	19	80.68	bc
18	77.85	abcd	7	78.36	cd
6	75.52	bcde	14	76.95	cd
9	75.50	bcde	21	76.77	cd
22	74.23	cde	18	76.76	cd
15	74.21	cde	17	76.38	cd
17	74.04	cde	15	76.12	cd
16	73.99	cdef	11	76.03	cd
11	73.19	def	16	74.77	de
2	72.47	ef	9	70.50	ef
21	72.35	ef	10	69.88	efg
14	72.08	ef	2	66.63	fgh
3	71.29	ef	8	66.54	fgh
4	70.88	ef	4	65.60	fghi
8	68.77	f	3	64.60	ghi
5	60.07	g	6	64.20	hi
10	58.18	g	5	64.07	hi
1	57.66	g	1	60.28	i
LSD	5.25		LSD	5.35	

† Means in each column followed by the same letter are not statistically different using Fisher's Protected LSD (α=0.05).

Table 5. Mean percent change of original green cover at the end of drought by each mixture at each experimental site of the fine fescue mixture drought trial.

St. Paul		Madison		
Mixture	Mean	Mixture	Mean	
13	-1.31	7	-68.69	a
9	-9.86	12	-77.21	b
2	-10.46	13	-79.87	bc
23	-11.09	17	-80.98	bcd
22	-12.86	14	-81.95	bcd
11	-13.62	19	-83.52	bcde
3	-13.76	9	-83.62	bcde
12	-13.99	22	-83.81	bcdef
7	-14.07	15	-84.07	bcdef
15	-14.10	18	-84.36	bcdef
19	-14.25	23	-84.60	bcdefg
10	-15.47	20	-84.77	bcdefg
5	-16.31	24	-84.79	bcdefg
21	-16.75	8	-85.62	cdefgh
24	-16.95	5	-86.41	cdefgh
1	-17.24	16	-86.69	cdefgh
18	-20.19	11	-88.37	defgh
4	-20.34	25	-89.97	efgh
8	-20.61	10	-90.36	efgh
16	-21.49	1	-90.48	efgh
17	-21.85	21	-91.39	fgh
14	-23.78	2	-92.08	gh
20	-26.61	4	-92.12	gh
25	-26.85	6	-93.10	h
6	-28.66	3	-93.23	h
ns		LSD	7.63	

† Means in each column followed by the same letter are not statistically different using Fisher's Protected LSD (α=0.05).

Table 6. Mean percent of original green cover recovered at the end of recovery by each mixture at each experimental site of the fine fescue mixture drought trial.

St. Paul			Madison		
Mixture	Mean†		Mixture	Mean†	
1	120.77	a	7	79.12	a
10	119.44	ab	23	77.58	ab
5	116.91	abc	17	73.75	abc
2	113.51	abcd	24	72.04	abcd
3	113.45	abcde	20	70.34	abcde
8	113.25	abcde	15	70.31	abcde
9	111.94	bcdef	16	66.17	abcdef
11	111.58	bcdef	14	65.87	abcdef
22	111.34	bcdef	22	64.82	abcdefg
4	109.96	cdefg	5	64.45	bcdefg
13	108.79	cdefg	19	64.14	bcdefg
6	106.81	defgh	18	63.96	bcdefg
12	106.77	defgh	8	63.19	bcdefg
7	106.66	defgh	12	62.96	cdefg
16	106.34	defgh	25	58.84	defg
14	105.99	defgh	21	58.42	defg
15	105.62	defghi	13	56.61	efg
18	105.55	defghi	10	52.46	fgh
19	104.68	efghij	1	51.87	fgh
21	103.92	fghijk	9	51.12	gh
23	101.69	ghijk	2	41.31	hi
17	98.90	hijk	4	41.28	hi
24	96.89	ijk	11	41.11	hi
20	95.99	jk	3	31.94	i
25	95.41	k	6	27.62	i
LSD	8.80		LSD	14.54	

† Means in each column followed by the same letter are not statistically different using Fisher's Protected LSD (α=0.05).

Table 7. Marginal effects summary of multiple regression of percent of original green cover lost at the end of drought onto seed mixture species proportions with both locations combined.

				90% CI	
Species†	Coefficient	Std Error	Pr(>|t|)	Lower	Upper
SHF	47.29	7.131	< 0.001	57.98	37.01
HDF	44.60	7.200	< 0.001	57.47	32.49
CHF	54.77	7.131	< 0.001	65.40	41.33
STCRF	54.86	7.200	< 0.001	66.63	41.61
SLCRF	54.67	7.073	< 0.001	66.83	39.66

† SHF, sheep fescue; HDF, hard fescue; CHF, Chewings fescue; STCRF, strong creeping red fescue; SLCRF, slender creeping red fescue

Table 8. Marginal effects summary of multiple regression of percent of original green cover recovered at the end of recovery onto seed mixture species proportions with both locations combined.

				90% CI	
Species†	Coefficient	Std Error	Pr(>|t|)	Lower	Upper
SHF	93.218	6.044	< 0.001	85.54	99.41
HDF	84.543	5.479	< 0.001	75.48	93.53
CHF	79.300	6.044	< 0.001	72.60	86.66
STCRF	86.996	5.479	< 0.001	77.19	97.19
SLCRF	72.598	6.611	< 0.001	56.60	87.91
CHF:SLCRF	55.189	32.676	0.0923	-2.66	106.20
SHF:SLCRF	-53.654	32.676	0.1017	-117.59	17.37

† SHF, sheep fescue; HDF, hard fescue; CHF, Chewings fescue; STCRF, strong creeping red fescue; SLCRF, slender creeping red fescue

Figure 1. Regression coefficients and 90% confidence intervals from the model of percent change of green cover at the end of drought data showing the effect on green cover based on the inclusion of individual species in the fine fescue drought experiment including hard fescue (HDF), sheep fescue (SHF), slender creeping red fescue (SLCRF), Chewings fescue (CHF), and strong creeping red fescue (STCRF).

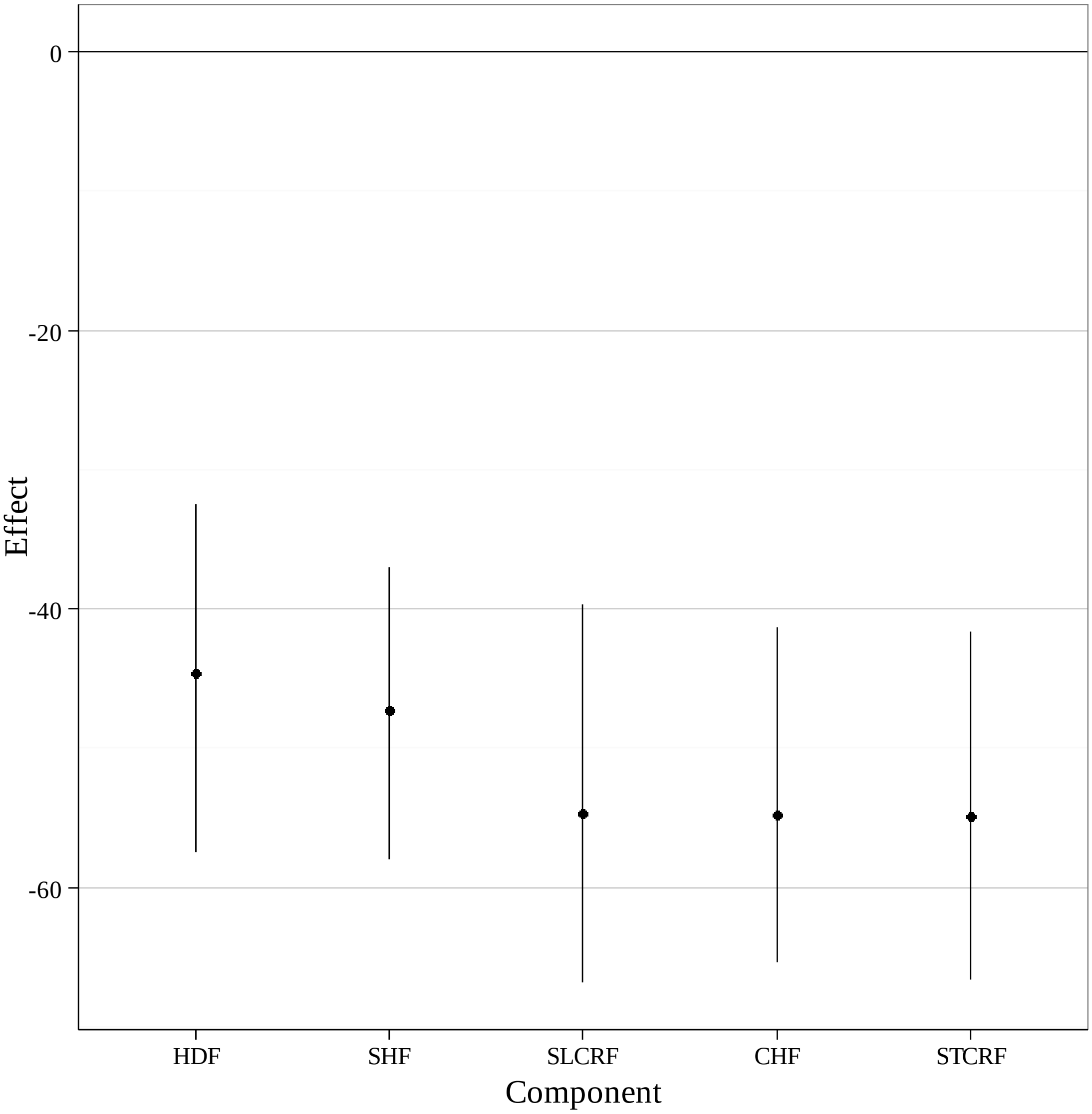
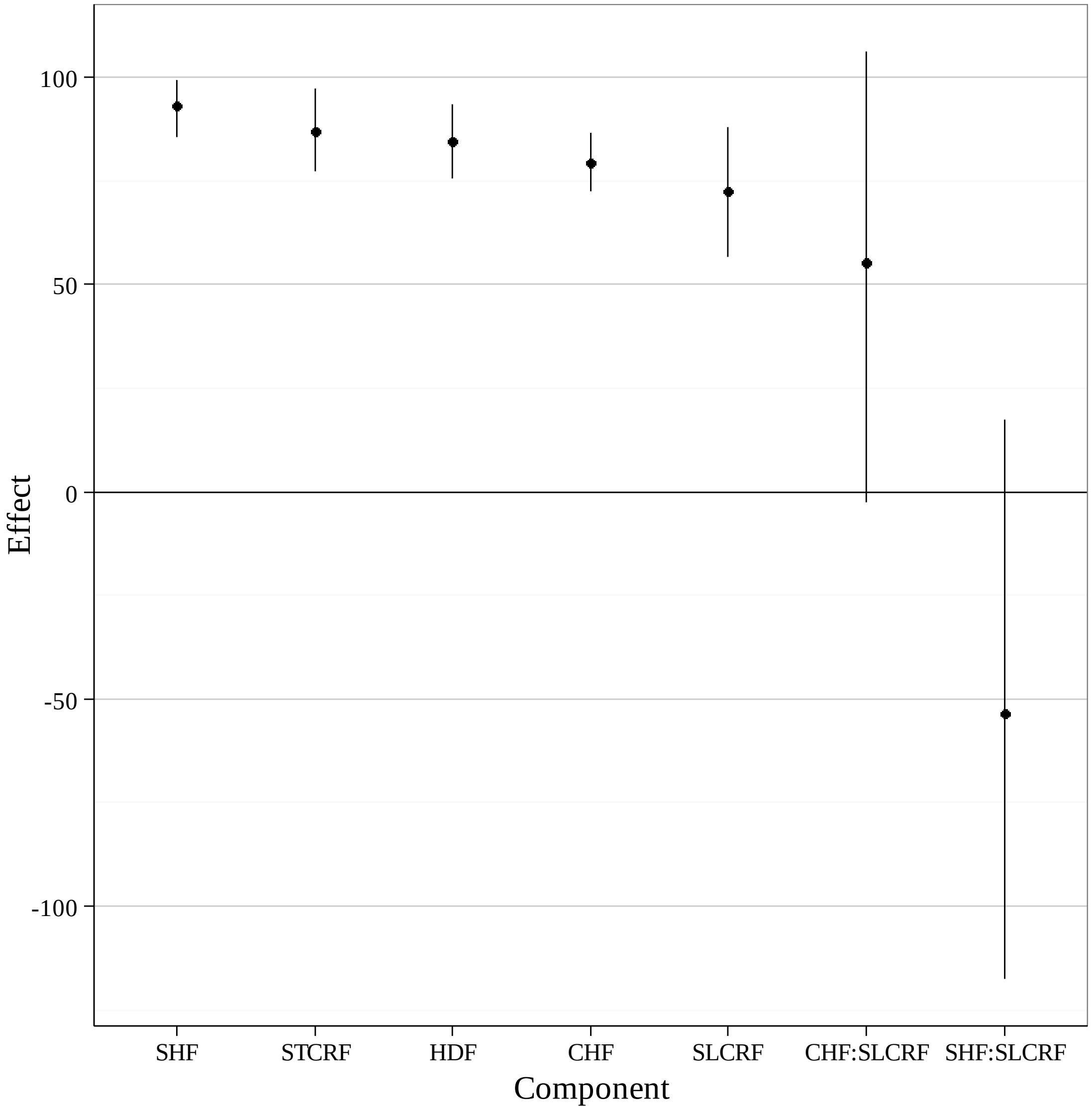


Figure 2. Regression coefficients and 90% confidence intervals from the model of percent of original green cover recovered at the end of recovery data showing the effect on green cover based on the inclusion of individual species in the fine fescue drought experiment including sheep fescue (SHF), strong creeping red fescue (STCRF), hard fescue (HDF), Chewings fescue (CHF), and slender creeping red fescue (SLCRF).



CHAPTER 2

Management practices to improve traffic tolerance and divot recovery of fine fescue species

ABSTRACT

To maintain acceptable turfgrass quality with lower water, fertilizer, and pesticide use, alternative grass species are a potential tool. Newer fine fescues cultivars may provide acceptable turf quality and playability on golf course fairways resulting in lower inputs of irrigation, fertilizer, and pesticides. The objectives of this study were to determine the effect of the plant growth regulator (PGR) trinexapac-ethyl on the performance of fine fescue mixtures when managed as a golf course fairway and identify fine fescue mixtures that perform well under traffic stress. Twenty-five mixtures were developed with a simplex-centroid design using Chewings fescue, hard fescue, strong creeping red fescue, slender creeping red fescue, and sheep fescue. The mixture design and analysis was employed to identify superior mixtures and measure the influence of each individual species on the success of a fine fescue fairway under traffic stress. To account for year-to-year environmental differences, field plots were established in two consecutive years in St. Paul, MN. A split-strip plot design was used with PGR treatment as the main plot, mixture treatment as the subplot within each main plot, and traffic treatment as the sub-subplot within each subplot. Plots treated with regular applications of trinexapac-ethyl had turf quality means greater than control plots in the spring and fall, but not the summer rating event. The marginal effects summaries revealed hard fescue, slender creeping red fescue, strong creeping red fescue, and sheep fescue had the greatest component effect on visual turfgrass quality, and were all statistically similar. Chewings fescue had the lowest species effect on performance at the end of traffic, but was significantly similar to sheep fescue. Chewings fescue had the lowest species effect, again, at the end of recovery, but was not significantly different from sheep fescue or strong creeping red fescue. There was no significant difference on divot recovery with any treatment levels, and no divots had recovered after 12 months. Strong creeping red fescue was more susceptible to dollar spot disease.

INTRODUCTION

Water, fertility, and pest control are required to manage a golf course. These inputs are not exclusive to turfgrass or golf courses, and are needed for many multifunctional landscapes to provide valuable ecosystem services, economic benefit, and recreational use. State legislation in Minnesota restricted phosphorous fertilizer use on turf (State of Minnesota, 2008). Several provinces in Canada have banned all synthetic pesticides (Government of Quebec, 2006; Government of Ontario 2009). Montgomery County, Maryland was the first major locality in the United States to ban pesticides on lawns (Montgomery County Government, 2016). Legislation limiting fertilizer and pesticide use will likely continue to expand in geographical area, and turf managers need to adapt to reduced input levels.

Water availability is also becoming scarce in some parts of the United States (National Drought Mitigation Center, 2015). The drought effects also spell economic disaster, and Howitt et al. (2015) estimated the 2015 California statewide drought to cost 2.7 billion dollars and 21,000 job losses. Furthermore, the price of agricultural water has increased for large regions of the United States that rely on groundwater (Wichelns, 2010).

Best management practices would require the least irrigation water, fertilizer, and pesticide use possible to run environmentally and economically sound golf courses. As regular inputs amounts decrease, the performance of some turfgrass species will decline (Carrow, 1996; Perdomo et al, 1996; Su et al., 2008; Watkins et al., 2011; Watkins et al., 2014). In order to maintain acceptable turfgrass quality and necessary function while preserving scarce resources, new biological tools are needed. Alternative grass species are a strategy that have been evaluated under a variety of environments and roles (Aronson et al., 1987; Diesburg et al., 1997; Meyer and Pedersen, 2000; Mintenko et al., 2002).

Fine fescues (*Festuca* spp.) are one of these alternative tools. The fine fescues are a set of grasses often grouped together because of their similar morphological and agronomic characteristics. These species and subspecies are known for a fine leaf blade (2-7 mm), shade tolerance, low fertility requirements, low water use, and low pesticide use (Aronson et al, 1987; Ruemmele et al., 1995; Miller et al., 2013; Watkins et al., 2014). Fine-leaved fescues are difficult to distinguish from one another with the naked eye, and are usually identified through plant morphology (Hubbard, 1954), sclerenchyma strands (Clayton and Renvoize, 1986), or cytological tools (Hand et al., 2013).

The five cool-season species or subspecies commonly used as managed turfgrass in the temperate regions are hard fescue, sheep fescue, Chewings fescue, strong creeping red fescue, and slender creeping red fescue. The five species can be grouped into two aggregates: the *F. rubra* complex and the *F. ovina* complex. The *F. rubra* complex consists of strong creeping red fescue, slender creeping red fescue, and Chewings fescue. The two creeping red fescues are rhizomatous, while Chewings fescue has a bunch type growth with substantial tillering. The *F. ovina* aggregate includes hard fescue and sheep fescue, and two fescues have a less aggressive bunch type growth than Chewings fescue (Beard, 1973)

Traffic stress comes from motorized cart and foot traffic, which causes wear on the turfgrass plant and compaction of the soil. Symptoms of traffic stress include a thinning turf canopy, which can result in bare spots, weed encroachment, and a greater need for fertilizer, irrigation, and pesticides (Beard, 1973). Many researchers have investigated traffic tolerance among higher cut cool-season grass species and demonstrated that fine fescues have a lower traffic tolerance than perennial ryegrass, tall fescue (*Festuca arundinacea*, Schreb.), creeping bentgrass, and Kentucky bluegrass (Shearman and Beard, 1975a; Canaway 1982; Evans, 1988; Cockerham et al., 1990; Cereti et al., 2005; Minner and Valverde, 2005). However, Watkins et al. (2010) showed that fine fescue species and cultivars can provide better quality and traffic tolerance than these aforementioned species as a fairway turfgrass when inputs are limited. Their experiment had a minimal management regime, with fertility less than 49 kg N ha^{-1} yr^{-1}, one irrigation event, and no pesticides. Hard fescue perfomed poorly in the first year, but well in the second year. Chewings fescue and sheep fescue were the best performing species species in the second year, regardless of mowing height or traffic frequency. A survey of fine fescue fairway managers reported that substantial amounts of work are dedicated to traffic control (Kvalbein et al., 2012), so research on this subject would be extremely useful to this audience.

Traffic tolerance is not the only characteristic that is necessary for adapted fine fescue fairway cultivars. A major stress on golf course fairway turf is the removal of verdure and thatch as divots. Any turfgrass used in these areas needs to possess strong recuperative ability. Fine fescues maintain a very slow growth rate (Grime and Hunt 1975) thus recovery from injury may be slow. Divot repair is a management area that demands study, and previous research suggests that plant growth regulators (PGR) could improve divot recovery and recovery from traffic. PGRs generally suppress vertical shoot growth, and the effect on lateral growth depends on the PGR used. Trinexapac-ethyl is a gibberellin biosynthesis inhibitor that decreases leaf elongation rates (Ervin and Koski, 1998), but does not inhibit other forms of growth such as lateral shoots and rhizomes (Fagerness and Penner, 1998). Consequently, trinexapac-ethyl has been shown to promote lateral tillering (Ervin and Koski, 2001) and increase plant density (Stier and Rogers, 2001). Turf treated with trinexapac-ethyl grows thicker and more prostrate, which results in fuller turf canopy, improves quality, and encourages better injury recovery.

To provide a durable turf stand under regular traffic and injury, polycultures of turfgrass species are recommended over monocultures. Each species has unique strengths that improve the performance of the mixture (Watschke and Schmidt, 1992; Friell et al., 2015). Although not managed as mowed turfgrasses, observational studies and removal experiments in grasslands show that higher-species assemblages are necessary for high ecosystem functioning and biomass production (Schulze and Mooney, 1994; Tilman et al., 2001). Tilman and Downing (1994) found that more diverse grassland ecosystems are more resistant to, and recover more fully from, “negative” perturbations (drought stress in that study).

The objectives of this study were to (1) compare fine fescue species and mixtures under traffic stress to identify mixtures that perform well and quantify the effect of each species, (2) determine the effect of trinexapac-ethyl on the performance of fine fescue mixtures when managed as a golf course fairway, and (3) evaluate species response to any disease symptoms.

MATERIALS AND METHODS

Mixture design

A cultivar was selected for each fine fescue species, these include: ‘Radar’ Chewings fescue, ‘Navigator II’ strong creeping red fescue, ‘Shoreline’ slender creeping red fescue, ‘Beacon’ hard fescue, and ‘Quatro’ sheep fescue. These cultivars were chosen because they were commercially available and provided excellent results during previous fairway trials in Minnesota (Watkins et al., 2010; NTEP, 2013). The five cultivars were used to create mixtures for the experiment. The sum of constituent proportions in each mixture must equal 1.00; this constraint confines the mixture proportions to a multidimensional simplex.

A five-component simplex-centroid mixture design was selected and mixtures were created with the *mixexp* package in R (R Core Team, 2015). Data from this this mixture design can be analyzed with Scheffe’s canonical polynomial (Scheffe, 1963) to fit the simplex surface. The polynomial model can measure the influence on the response variable of each component, or species. In addition, predictions on the response of any mixture can be made. The full simplex-centroid design included too many mixtures, beyond the resources available for a field study. Therefore, the mixture design was tailored to suit 25 mixtures total. To select 25 mixtures that would maximize information and predictive ability about the entire simplex, design optimization functions were employed and a D-optimal design was selected with the *AlgDesign* package in R. The 25 mixtures from the D-optimized simplex-centroid design are shown in Table 1. The fractionated mixture design requires the monocultures, where a plot consisted of 100% of a single species. The monocultures also provide a standard by which to compare multicomponent blends.

Site design and establishment

Field plots were established August 2012 in St. Paul, MN, USA. To account for year-to-year environmental differences, the trial was established in two consecutive years (seeded on 8

August 2012 and 15 August 2013). Mean monthly temperatures and total monthly rainfall from May to September of each year in St. Paul are shown in Table 2 (NOAA, 2016). Each trial was arranged as a split-strip plot design with PGR treatment as the main plot, mixture treatment as the subplot within each main plot, and traffic treatment as the sub-subplot within each subplot. Each sub-subplot measured 0.9 m by 0.8 m. The randomization process was assigned at each factor level, in three stages total. The levels of each factor were arranged as a randomized complete block with three repetitions.

A starter fertilizer was applied to each run using Andersons Nutri DG at a rate of 49.0 kg N, 10.8 kg P, and 40.7 kg K ha^{-1}. Seed was spread by hand at a rate of 2.5 pure live seeds cm^{-2}. Seed counts and germination rates were determined for each of the five cultivars prior to seeding. After seeding, the soil surface was lightly raked to promote seed to soil contact. Futerra EnviroNet blankets (PROFILE Products LLC, Buffalo Grove, IL) were placed on the seeded area immediately after seeding to control erosion and foster turf establishment. Each trial was watered daily for three weeks and then no supplemental irrigation was applied after this establishment period. Six weeks after seeding another fertilizer application with EC Grow was applied at a rate of 49.0 kg N, 0 kg P, and 15.8 kg K ha^{-1}.

The PGR factor contained two levels: control plots did not receive trinexapac-ethyl [4-(cyclopropyl-hydroxy-methylene)-3,5-dioxo-cyclo-hexane-carboxylic acid ethyl ester] (Primo MAXX, Syngenta Professional Products) (0 L product ha^{-1}) and treated plots received 0.4 L product ha^{-1} every 200 growing degree days (Kreuser and Soldat, 2011). Plant growth regulator was applied from a backpack sprayer with a spray volume of 612 L ha^{-1}. PGR applications were initiated 1 June 2013 and continued to 15 October 2013, so plants were under regulation for the entire growing season. The mixture factor contained twenty-five levels of the aforementioned fine fescue species proportions (Table 1). The traffic factor contained two levels: control plots did not receive traffic (0 passes wk^{-1}) and treated plots received 6 passes wk^{-1}, divided into 2 passes on each of 3 days. A golf cart traffic simulator (Figure 1) weighing roughly 1800 kg was driven across the turfgrass plots. For trial 1, traffic applications were initiated 1 July 2013 and continued to 31 August 2013, for 54 total passes during 2 months of repeated traffic. Two PGR applications had occurred at the beginning of traffic treatment. The same schedule for PGR and traffic applications was employed in year 2 of the trial, and the same schedule occurred in Trial 2.

Growth conditions and management

Plots were managed as a golf course fairway. The trials were mowed two times per week at 1.27 cm with a triplex riding reel mower and clippings were removed. Each trial was fertilized with EC Grow at a rate of 98.0 kg N, 0 kg P, and 81.3 kg K ha^{-1}, split into a spring and fall application.

Data collection

Plots were visually assessed three times each year: one day before traffic treatments began, the last day of the 2-month traffic period, and one month after traffic treatments ended as a measurement of recovery. Visual turf quality ratings were taken on a 1 to 9 scale with 1 being completely dead plants or bare soil and 9 being the highest quality, dense, uniform green stand. A rating of 6 was considered minimally acceptable for a low input fairway.

On 1 August 2013 (Trial 1) and 1 August 2014 (Trial 2), one divot was mechanically removed from each sub-subplot with a custom divot-making device (Figure 2). Divots were each approximately 5 cm wide by 11 cm long by 1.3 cm deep. The sheared-off sod was discarded, and the small depression was filled to the soil surface with topdressing sand (Plaisted Companies, Inc.). Digital image analysis was used to compute divot area and recovery. Divots were photographed immediately after removal with a custom camera and light box. The light box was 0.6 m on all sides and contained twelve LED lights inside mounted on the roof of the box. The camera was a Nikon D300 equipped with a Nikon 35mm f/1.8G AF-S DX Nikkor Lens. One image was taken of each divot. All images were processed in ImageJ (Rasband, 2015). Each divot was traced with a freehand selection tool, and then area of the shape was calculated by the software. Divots were photographed and measured two months after removal, and then percent recovery was calculated with the initial divot area.

Disease was allowed to occur naturally in the field. In late August 2014 and 2015, a visual disease rating was taken for dollar spot symptoms on Trial 1 and Trial 2, respectively. Ratings were taken on a 1 to 5 scale, with 1 being no symptoms of disease and 5 being 24 or more spots per 0.9 m by 0.8 m sub-subplot. A rating of 2 was given to a plot with 1 to 6 spots, and 2 was considered a maximum acceptable disease threshold for a low input fairway. Both Trial 1 (established in 2012) and Trial 2 (established in 2013) received all described treatments for two full growing seasons after the establishment year.

Mixture model analysis

Assumptions of homoscedasticity and normality were met for each analysis. Data from both trials and both years within each trial were combined and analyzed with a linear mixed effects model (the first year after establishment for each trial was designated as year 1 and the subsequent year as year 2). The models were developed with the *lme* function in the *nlme* package in R (R Core Team, 2015). Four response variables were used: turf quality rating at the beginning of traffic, turf quality rating at the end of traffic, turf quality rating at the end of recovery, and percent divot recovery. Each model contained nested fixed effects for PGR, mixture, and traffic factors, and nested random effects for experimental run, year, and replicate. An analysis of variance (ANOVA) was computed with the *anova* function to compare models in a likelihood ratio test, and non-significant variables were removed until the simplest model with the greatest explanatory power was produced. A 95% confidence interval was estimated for fixed effect means using the *ci* function in the *gmodels* package.

A second analysis was used to measure the effect of each fine fescue species in the mixtures on overall mixture performance. The three turf quality ratings and the dollar spot rating were modeled with the quadratic form of Scheffe's canonical polynomials. A linear regression was fit to the simplex surface, with all five main effects and two-way interactions included. Higher order polynomials, such as three-way and four-way interactions, were not included because they may lead to overfitting. The *lm* function in R was used to calculate the influence of each component and two-way interaction. The three aforementioned response variables were tested with three separate linear models.

Variable selection was done with the mixture component analysis to remove unnecessary predictors and ascertain the smallest model that fits the data. A backward elimination was done with Akaike's Information Criterion (AIC) in the *stepAIC* function of the *MASS* package of R. The goal was the find the model with the smallest AIC. Final coefficients for turf quality effect were determined with p-values that measured the difference between the coefficient and zero.

In order to measure the difference between coefficients for each component, confidence intervals were calculated. The *boot* function in R was used to bootstrap the coefficients based on 2000 replicates, and the *boot.ci* function furnished the 90% confidence interval.

RESULTS

Mixture comparison

Prior to traffic

The analysis of variance for turf quality at the start of traffic on 1 June revealed no significant interactions effects, so the model was trimmed to the three main factors: PGR, mixture, and traffic. Confidence intervals were calculated for each factor level. PGR effect was not significant at $\alpha=0.05$, but was still included in the final model since it provided explanatory power. When data was averaged over the two years of the two trials, plots treated with plant growth regulator had mean turf quality ratings of 5.8 on 1 June of each year, while control plots with no trinexapac-ethyl had mean turf quality ratings of 5.7. Significant differences existed among mixtures, with all the ratings prior to traffic combined (Figure 3). The highest turf quality mean was mixture 13, the hard fescue monoculture. However, this mixture was not significantly different from the next seventeen entries, including the monocultures of slender creeping red fescue and Chewings fescue. The hard fescue monoculture was significantly better than the strong creeping red fescue monoculture and the sheep fescue monoculture. Sixteen of the 25 mixtures had confidence intervals that reached above the acceptable turf quality rating of 6.0.

Conclusion of traffic

The ANOVA for turf quality at the conclusion of traffic on 31 August showed no significant effect of PGR and no significant interaction effects. These terms were removed from the linear mixed effects model, and the final model had factors for mixture and traffic. Confidence intervals were drawn for each mixture level and each traffic level (Figure 4). The top performing mixture after traffic was mixture 13, the hard fescue monoculture. This mixture was not significantly different from the next seventeen mixtures, including the slender creeping red fescue and sheep fescue monocultures. The lowest turf quality mean was mixture 25, the 100% Chewings fescue entry, and this entry was not significantly different from the next five higher mixtures. Chewings fescue was in four of the six bottom mixtures. Hard fescue appeared one time in the lowest-ranking group of six mixtures, at a 25% proportions in mixture 15. All but one entry had confidence intervals reaching acceptable turf quality levels. The Chewings fescue monoculture did not reach an acceptable turf quality rating of 6.0. Traffic treatments had a significant effect on turf quality at the end of repeated traffic. Plots receiving traffic had means 1.1 rating units lower than plots that did not receive traffic.

Recovery

The recovery turf quality rating was measured two months after traffic treatments concluded, and the mixed effect model comparison eliminated all interaction effects. The three main factors remained for PGR, mixture, and traffic. The plant growth regulator treatments had a significant effect on turf quality, and plots under growth regulation had a means that were 0.2 ratings units greater than control plots (Figure 5). Although hard fescue and slender creeping red fescue monocultures had the highest recovery ratings, these top two mixtures were not significantly different from the next thirteen entries. The monoculture of Chewings fescue had the lowest turf quality rating, and all other monocultures had significantly higher turf quality. After the traffic recovery period, all of the mixtures achieved confidence intervals above the 6 rating of acceptable turfgrass quality. Traffic had a significant effect on the plot means. Control plots had a mean of 6.5 and regularly trafficked plots had a mean of 5.9. Additionally, the confidence intervals for the trafficked plots did not exceed an acceptable 6 rating.

Divot recovery

The analysis of variance for divot percent recovery 2 months after removal revealed no significant effects for PGR, mixture, traffic, or any interactions. The grand mean was 42.1% divot recovery after 2 months, and no divots had filled completely in 12 months after harvest.

Mixture component effects

Three marginal effects summaries were computed to determine species effects on turf quality ratings after traffic treatments, turf quality ratings after a two-month recovery period, and dollar spot disease ratings.

Conclusion of traffic

The marginal effects summary for turf quality ratings immediately after traffic included all main effect terms, the Chewings fescue by strong creeping red fescue interactions, and the Chewings fescue by hard fescue interaction after variable selection. The regression offered an adjusted R^2 of 0.9475. Coefficient estimates and p-values for turf quality ratings are presented in Table 3. The magnitude of each coefficient describes the relative ability of each component to affect turf quality ratings after traffic. Hard fescue exhibited the best traffic tolerance with a 6.02 coefficient. The lowest main effect coefficient is Chewings fescue with a 5.20 coefficient, so inclusion of Chewings fescue would diminish the tolerance of a fine fescue mixture to traffic stress. All main effect coefficients produced a p-value less than 0.001, which means the coefficients are significantly different from zero and rejects the null hypothesis that the components have no significant effect on the mixture. The interaction effects have p-values greater than 0.10, and are not statistically different from zero. In spite of this, the goal was to find the most parsimonious model based on the smallest AIC, not p-values. These interaction effects should be interpreted and attention and should be drawn to the weight of each component effect.

The bootstrapped 90% confidence interval calculations for each coefficient after traffic are presented in Table 3. The coefficients for hard fescue, slender creeping red fescue, strong creeping red fescue, and sheep fescue have confidence intervals that overlap (Figure 6). There are no significant differences among these four components for traffic tolerance. The Chewings fescue coefficient was significantly lower than hard fescue, slender creeping red fescue, and strong creeping red fescue, but is not significantly different from sheep fescue. The interaction effects are not significantly different from one another and both cross the 0 effect mark.

Recovery

A separate linear regression was constructed to measure the turf quality after a 2-month recovery period. After variable selection, all main effect terms, Chewings fescue by strong creeping red fescue interaction, and sheep fescue by slender creeping red fescue interaction were included in the model (Table 4). An adjusted R^2 of 0.9611 describes a tight fit to the regression line. The most powerful component for the mean turf quality was slender creeping red fescue at 6.60. The bootstrapped 90% confidence interval calculations for each coefficient after recovery are also presented in Table 4. This component effect was not significantly different from hard fescue at 6.52, strong creeping red fescue at 6.23, and sheep fescue at 6.16 ratings. The least powerful main effect was Chewings fescue with 5.81 rating, and this component was not significantly different from sheep fescue and strong creeping red fescue. All main effects were significantly different from zero with p-values less than 0.001. The Chewings fescue by strong creeping red fescue and the sheep fescue by slender creeping red fescue positive interaction coefficients presents a synergistic effect when these different species are coupled together.

Dollar spot disease

The final marginal effect summary created for log transformed dollar spot disease ratings incorporated all main effects and a slender creeping red fescue by strong creeping red fescue interaction (Table 5). The adjusted R^2 was 0.9387. The coefficients for all these effects are significantly different from zero with p-values less than 0.05. The most susceptible component, with the highest disease effect, was strong creeping red fescue at 0.93. A 90% confidence interval was bootstrapped around each mean to examine differences among coefficients. The strong creeping red fescue component was significantly greater than all components. The remaining four main effects were not statistically different from one another, and the slender creeping red fescue by strong creeping red fescue interaction was significantly less than all components.

DISCUSSION

The objective of this study was to determine the effect of trinexapac-ethyl on the performance of fine fescue mixtures when managed as a golf course fairway, and to identify fine fescue mixtures that perform well under traffic stress by a golf cart traffic simulator. This was accomplished with a field experiment that was repeated over two years. A split-strip plot design was required for this experiment because the PGR and traffic factors could only be applied to large plots. Data was collected with visual ratings for turfgrass quality, visual ratings for dollar spot disease, and digital image analysis to measure divot recovery.

Turf quality

Turfgrass quality is measured by visual ratings, a standard and widely accepted evaluation method for turfgrass research (Beard, 1973). The subjective method of visual scoring has been a concern to agronomists, but a study has demonstrated that turf quality ratings are valid when taken among experienced researchers. A group of turf researchers rated the same plots at a workshop on standardization of data collection. Correlation coefficients between different evaluators were strong for quality (r = 0.86 to 0.99) (Skogley and Sawyer, 1992). Horst et al. (1984) published more variable ratings that were caused by a group of evaluators. For the present experiment, visual quality ratings were made by one person so the results were effective for comparisons, but could be difficult to repeat with a different evaluator.

The visual turf quality ratings at the beginning of traffic had a main effect of PGR in the final model. Plots treated with regular applications of trinexapac-ethyl had a mean of 0.1 units greater than control plots for turf quality ratings at the beginning of traffic. The final model for turf quality at the end of a recovery period also contained a PGR term. The trinexapac-ethyl treatments had a significant effect on turf quality at α=0.05 (Figure 5), and plots under growth regulation had a means 0.2 units greater than control plots.

Trinexapac-ethyl has been shown to improve turf quality ratings on a range of turfgrass species. Steinke and Stier (2003) found that trinexapac-ethyl improved turf quality on Kentucky bluegrass, supina bluegrass (*Poa supina* Schrad.), and creeping bentgrass (on most rating dates). A reason for the higher visual ratings can be explained from darker green shoots, resulting from an increased chlorophyll concentration in treated plots. Ervin and Koski (2001) also found increased mesophyll cell density in greenhouse-maintained pots of Kentucky bluegrass. Trinexapec-ethyl can increase cell density, which would result in an increased total cell wall content. Total cell wall content has been correlated with turfgrass wear tolerance (Shearman and Beard, 1975b) and this could explain the increased turf quality ratings in the main plots of the present study. Paclobutrazol, another gibberellin biosynthesis inhibitor, applied to slender creeping red fescues, creeping red fescue, Chewings fescue, and hard fescue increased greenness, even though density of the hard fescue cultivar was reduced (Shearing and Batch, 1980; Johnston and Faulkner, 1985; Razmjoo et al., 1994).

The PGR factor was not included in the final model at the end of traffic treatments because this factor was not an important predictor for turf quality ratings. This result is interesting, since PGR factor was a worthwhile predictor at the other turf quality rating times. The optimum growth temperature for cool-season grasses is 16 to 24°C (Beard, 1973), which occurs during the spring and fall months in the northern United States. The end of traffic rating was taken on 31 August of each trial year, and the mean daily temperature in St. Paul for August ranged from 21 to 23°C (Table 2). This rating date happened in the summer months, when temperatures were highest and growth rates were slowest. The PGR may have had no statistical effect at this time point, because the turfgrass was growing more slowly and the inhibition of gibberellins caused a very slight, and not significant, difference.

The mixture performances are best described with the marginal effects summaries. At the end of traffic and at the end of recovery, hard fescue, slender creeping red fescue, strong creeping red fescue, and sheep fescue had the greatest component effect on visual turfgrass quality, and were statistically similar (Table 3 and Table 4). Chewings fescue had the lowest component effect at the end of traffic, but was not significantly different from sheep fescue (Figure 6). Chewings fescue had the lowest component effect, again, at the end of recovery, but was not significantly different from sheep fescue and strong creeping red fescue (Figure 7).

Tennis-type traffic simulated by Newell and Jones (1995) revealed slender creeping red fescues performed better than the Chewings fescues and the strong creeping red fescues. Similarly, Canaway (1982) found no difference in percent cover and total biomass between Chewings fescue and strong creeping red fescue after traffic and recovery. Both of these studies had several mowing heights ranging from 0.5 to 3 cm.

Newell and Wood (2003) measured motorized golf cart traffic effects on fine fescue species. The visual quality scores ranked slender creeping red fescues > Chewings fescues > strong creeping red fescues when subjected to traffic stress. There was overlap between species, but the mean turf quality ratings were significant. The single sheep fescue cultivar performed as well as the slender creeping red fescues and Chewings fescues. The rankings were slightly different in the present study, with Chewings fescue statistically lower than strong creeping red fescue in one marginal effects summary (Table 3). Slender creeping red fescue was never different from strong creeping red fescue (Table 3 and Table 4). The differences in performance and species rank could be the result of cultivar and environmental differences. The sheep fescue performance was in agreement, however, both studies showed sheep fescue as statistically the same to all other fine fescue species.

Watkins et al. (2010) evaluated fine fescue species response to traffic, with the same frequency (6 passes wk^{-1}) and magnitude (identical apparatus) of traffic used in the present study. In the first year of data, 'Jamestown 2' Chewings fescue had the best turf quality, but was not statistically different from 'Quatro' sheep fescue. 'SR3100' hard fescue had a significantly lower turf quality than the Chewings fescue, but was not statistically different from 'Quatro' sheep fescue. In the second year of data, 'Quatro' sheep fescue and Chewings fescue had statistically equivalent turf quality and living stand density, while hard fescue had lower values for both variables. This disagrees with the present research, which presented 'Beacon' hard fescue as significantly better than Treazure II' Chewings fescue. Again, this may be explained with germplasm and environmental differences.

In both marginal effect summaries, a positive interaction between Chewings fescue and strong creeping red fescue was present (Table 3 and Table 4). Although Chewings fescue was a poor performer, mixing this species with strong creeping red fescue increased turfgrass quality. Likewise, work from Bilgili and Acikgoz (2007) found a turfgrass mixture with Chewings fescue was not different from a mixture with Chewings fescue, strong creeping red fescue, and slender creeping red fescue for quality and percent cover after traffic. The two mixtures from this study included other cool-season grass species (Kentucky bluegrass, perennial ryegrass, and colonial bentgrass). A positive interaction, or synergism, also emerged when Chewings fescue was mixed with hard fescue, in the marginal effects summary drawn immediately after traffic (Table 3). Both interaction effects suggest that the inclusion of strong creeping red fescue and hard fescue in a mixture is more valuable than the exclusion of Chewings fescue. A negative interaction, or antagonism, materialized when sheep fescue was mixed with slender creeping red fescue, in the marginal effects summary developed after a recovery period (Table 4). Mixtures that include these two species should be avoided although there is intraspecific variability in sheep fescue (Bonos and Huff, 2013), and the current results apply only to the 'Quatro' sheep fescue used in the experiment.

All three turf quality rating events had a main effect of traffic in the final model, and the 95% confidence intervals for traffic+ and traffic- treatments were significant (Figures 3-5). Plots subjected to regular traffic produced a mean of 0.4 units less than control plots for turf quality ratings at the beginning of traffic. The final means for turf quality at the end of the traffic period resulted in trafficked plots with a means 1.1 units less than control plots, and at the end of recovery the trafficked plots sustained mean ratings 0.5 units less than control plots. Turfgrass quality and density is reduced when traffic stress is present on many turfgrass species, including fine fescues (Evans, 1988; Hacker, 1987; Newell and Jones, 1995; Cereti, 2005; Minner and Valverde, 2005; Watkins et al., 2010).

Divot recovery

The linear mixed effects model for divot recovery presented no significant effects for trinexapac-ethyl application, mixture composition, or traffic level. Although the main plot effect trinexapac-ethyl improved some turfgrass quality ratings, the improvement of prostrate growth and tillering required to fill in a divot was negligible. Fagerness and Penner (1998) and Gardner and Wherley (2005) showed clipping reduction in creeping red fescue and sheep fescue, respectively, from trinexapac-ethyl. Heckman et al (2005) found that trinexapac-ethyl reduced leaf elongation in tall fescue. This could result in delayed divot recovery since growth was slowed. Yemm and Willis (1962) found that the bulk vegetative growth of the red fescue was barely affected by the PGR maleic hydrazide compared to other grasses. The authors suggested that the narrow and rolled leaves of fine fescues were less likely to catch and retain the spray than grasses with broader and flatter leaves. However, there is evidence that hard fescue (McCullough et al., 2015) and creeping red fescue (Marouis et al., 1979) have similar or greater levels of glyphosate uptake compared to perennial ryegrass and reed canarygrass (*Phalaris arundinacea* L.) cultivars. This research indicates that factors other than uptake contribute to the growth regulator efficacy.

The effect of trinexapac-ethyl on divot recovery varies, in other turfgrass species managed as golf course turf. Steinke and Stier (2003) found that trinexapac-ethyl had no effect on divot recovery in Kentucky bluegrass, supina bluegrass, and creeping bentgrass. Trinexapac-ethyl effects on divot recovery in bentgrass fairways were inconsistent in research by Bigelow (2006), and Calhoun (1996) observed that trinexapac-ethyl applications stimulated lateral growth and improved divot recovery rates of treated creeping bentgrass.

No mixture differences existed among all twenty-five mixtures levels for divot recovery, so no superior mixtures could be identified. Grime and Hunt (1975) published relative growth rates for red fescue and sheep fescue and found no differences in maximum potential relative growth rate and mean relative growth rate. The equivalent growth rates among fine fescue species could explain the lack of difference among divot repair rate. The traffic factor included in the mixed effects model also had no effect on divot recovery. Evaluating traffic effects on divot recovery was not an objective of this experiment. The structure of the experimental design required divot recovery data to be collected in trafficked and non-trafficked plots.

After 12 months of regrowth, no divots had been completely filled in by the fine fescue fairway turfgrass. It is quite clear that this will be a major deficiency of these grasses when used on golf course fairways. Resource savings from utilizing a lower-input grass may need to be shifted to manual refilling on divots on courses that convert to fine fescue fairways.

Dollar spot disease

Strong creeping red fescue had a significantly greater marginal effect than all other component effects for the dollar spot disease response variable. In other words, dollar spot disease was significantly more severe on strong creeping red fescue. There were no differences among the remaining four species. Smith (1955) mentioned creeping red fescue as susceptible to dollar spot disease, and Chewings fescue inoculated with an isolate from the creeping red fescue was not as susceptible. A subsequent paper by Smith (1958) rated creeping red fescue as “very susceptible” to “moderately resistant” toward dollar spot, and Chewings fescue and sheep fescue were assigned the highest rating of “resistant.” Disease severity measurements reported by Hodges et al. (1975) revealed little blighting on sheep fescue and intraspecific variation among Chewings fescue and creeping red fescue cultivars. Similar results were collected in National Turfgrass Evaluation Program trials throughout the northern United States. No trials were inoculated, and naturally-occurring dollar spot symptoms developed. Data was collected on Chewings fescue, hard fescue, and strong creeping red fescue cultivars from 2010 to 2013 in New Jersey, Pennsylvania, and Rhode Island (NTEP, 2013). Visual disease ratings for ‘Treazure II’ Chewings fescue showed significantly less disease than ‘Beacon’ hard fescue and ‘Navigator II’ strong creeping red fescue. The latter two species were not significantly different from each other. All seven cultivars of strong creeping red fescue had greater disease severity than all twelve cultivars of Chewings fescue, but two strong creeping red fescue entries were not significantly different from five Chewings fescue entries. A different fine fescue fairway trial in St. Paul, Minnesota collected data on dollar spot disease (University of Minnesota Extension, 2015). ‘Beacon’ hard fescue and ‘Quatro’ sheep fescue had the same disease rating, and ‘Navigator II’ strong creeping red fescue had a significantly greater disease occurrence. The lowest disease was on an unnamed (DLFPS-FL/3066) hard fescue entry, and all strong creeping red fescues, slender creeping red fescues, and creeping red fescues had statistically more dollar spot disease. This is the closest geographic and temporal research on fine fescue dollar spot susceptibility to the present study, so results generally agree.

Clarke et al. (2006) showed that within endophyte-free germplasm, strong creeping red fescues were consistently more susceptible to dollar spot than the Chewings or hard fescue entries. This study also resulted in significantly higher resistance to dollar spot in endophyte-infected Chewings fescue, hard fescues, and strong creeping red fescues compared to related endophyte-free lines. The five fine fescues cultivars used in the present study offered no signs of endophyte presence when tested with a commercial immunoblot test kit.

The 0.93 coefficient effect of strong creeping red fescue and the 0.77 coefficient effect of slender creeping red fescue are not the entire effects of those terms. The interaction term for strong creeping red fescue and slender creeping red fescue reveal a biological synergism when these two species are in a mixture together. In this case, the interaction is positive, or synergistic, for greater disease severity. The inclusion of strong creeping red fescue and slender creeping red fescue together in a mixture would increase the likelihood of disease symptoms. The 0.93 coefficient for strong creeping red fescue is only the total effect when the slender creeping red fescue term equals zero, and vice versa.

CONCLUSION

A number of fine fescue mixtures performed at an acceptable level as a fairway turfgrass after a 2-month traffic and recovery period. Results suggest that the use of these fine fescues should be possible as a healthy, functional golf course fairway under period traffic stress. The plant growth regulator trinexapac-ethyl had no effect on divot recovery or traffic tolerance. Marginal effects summaries presented few significant differences, so future research should aim to better understand why certain mixtures performed significantly different and why others mixtures did not. Strong creeping red fescue is susceptible to dollar spot disease and may require control to maintain acceptable disease thresholds. No divots had recovered 12 months after harvest and this is a major limitation for a fine fescue fairway turfgrass.

Table 1. Proportions of constituent species in each mixture identified as a design point in the simplex centroid design for the fine fescue drought experiment for seed mixture analysis.

	Constituent species proportion				
Mixture ID	Chewings fescue *Festuca rubra* ssp. *commutata*	hard fescue *Festuca brevipila*	sheep fescue *Festuca ovina*	slender creeping red fescue *Festuca rubra* ssp. *litoralis*	strong creeping red fescue *Festuca rubra* spp. *rubra*
1					1
2				0.50	0.50
3				1	
4			0.33	0.33	0.33
5			0.50		0.50
6			0.50	0.50	
7			1		
8		0.33		0.33	0.33
9		0.33	0.33	0.33	
10		0.50			0.50
11		0.50		0.50	
12		0.50	0.50		
13		1			
14	0.20	0.20	0.20	0.20	0.20
15	0.25	0.25	0.25		0.25
16	0.33			0.33	0.33
17	0.33		0.33		0.33
18	0.33		0.33	0.33	
19	0.33	0.33		0.33	
20	0.33	0.33	0.33		
21	0.50				0.50
22	0.50			0.50	
23	0.50		0.50		
24	0.50	0.50			
25	1				

Table 2. Weather data during the growing season for each year. Mean daily temperatures are in ºC and total rainfall is in cm.

	2013		2014		2015	
Month	Mean daily temperature	Total precipitation	Mean daily temperature	Total precipitation	Mean daily temperature	Total precipitation
May	14	1.39	14	1.14	15	0.92
June	20	1.04	20	1.95	20	1.13
July	23	0.51	21	0.28	22	1.15
Aug.	23	0.28	22	0.75	21	1.20
Sept.	19	0.38	16	0.38	19	1.47

Table 3. Marginal effects summary of multiple regression of turfgrass quality ratings at the end of traffic onto seed mixture species proportions.

				90% CI	
Species†	Coefficient	Std Error	Pr(>|t|)	Lower	Upper
HDF	6.02	0.1437	< 0.001	5.79	6.25
SLCRF	5.87	0.1281	< 0.001	5.64	6.08
STCRF	5.69	0.1437	< 0.001	5.47	5.92
SHF	5.63	0.1284	< 0.001	5.42	5.86
CHF	5.20	0.1574	< 0.001	4.95	5.45
CHF:STCRF	1.20	0.8036	0.134	-0.03	2.60
CHF:HDF	1.16	0.8036	0.150	-0.07	2.37

† HDF, hard fescue; SLCRF, slender creeping red fescue; STCRF, strong creeping red fescue; SHF, sheep fescue; CHF, Chewings fescue

Table 4. Marginal effects summary of multiple regression of turfgrass quality ratings 2 months after the traffic period onto seed mixture species proportions.

				90% CI	
Species†	Coefficient	Std Error	Pr(>|t|)	Lower	Upper
SLCRF	6.60	0.1329	< 0.001	6.38	6.84
HDF	6.52	0.1219	< 0.001	6.32	6.70
STCRF	6.23	0.1345	< 0.001	6.01	6.47
SHF	6.16	0.1341	< 0.001	5.94	6.39
CHF	5.81	0.1327	< 0.001	5.58	6.02
CHF:STCRF	1.23	0.7425	0.097	0.04	2.49
SHF:SLCRF	-1.30	0.7224	0.072	-2.50	-0.05

† SLCRF, slender creeping red fescue; HDF, hard fescue; STCRF, strong creeping red fescue; SHF, sheep fescue; CHF, Chewings fescue

Table 5. Marginal effects summary of multiple regression of dollar spot disease ratings onto seed mixture species proportions.

				90% CI	
Species†	Coefficient	Std Error	Pr(>|t|)	Lower	Upper
SLCRF	0.77	0.03131	< 0.001	0.73	0.83
HDF	0.78	0.02871	< 0.001	0.74	0.83
SHF	0.79	0.02848	< 0.001	0.75	0.84
CHF	0.81	0.02848	< 0.001	0.76	0.87
STCRF	0.93	0.03214	< 0.001	0.87	1.00
SLCRF:STCRF	0.36	0.17207	0.0362	0.04	0.65

† SLCRF, slender creeping red fescue; HDF, hard fescue; SHF, sheep fescue; CHF, Chewings fescue; STCRF, strong creeping red fescue

Figure 1. A golf cart traffic simulator weighing roughly 1800 kg was driven across the turfgrass plots. Traffic applications were initiated 1 July and continued to 31 August, for 54 total passes during 2 months of repeated traffic.

Figure 2. Divots were mechanically removed from each plot with a custom divot-making device. The sheared-off sod was discarded, and the small depression was filled to the soil surface with topdressing sand.

Figure 3. Factor effects and 95% confidence intervals on turfgrass quality at the start of the traffic period. Factors are separated by dotted lines. From left to right, factors are: PGR, mixture, and traffic.

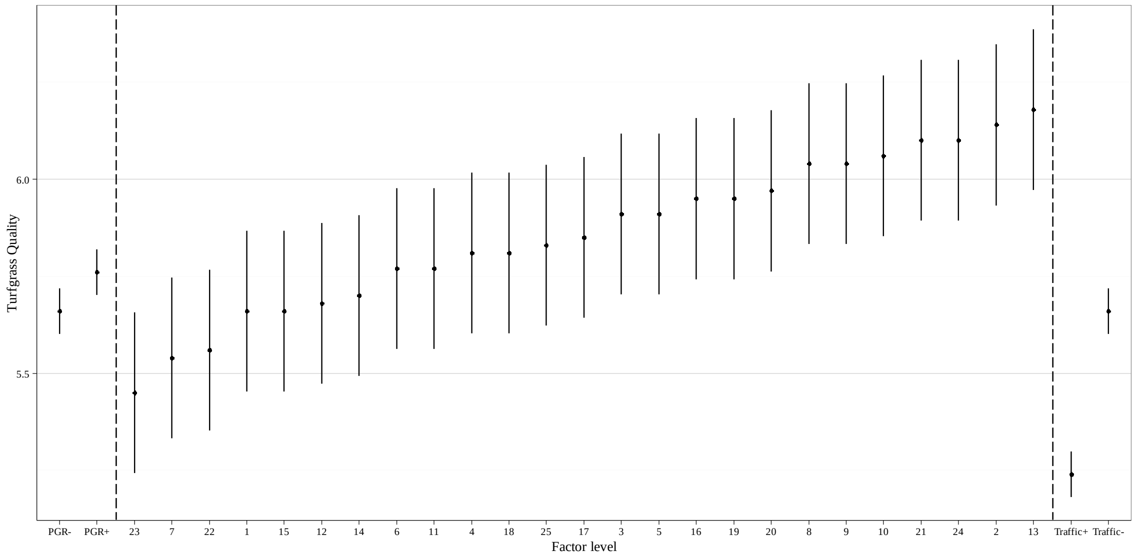


Figure 4. Factor effects and 95% confidence intervals on turfgrass quality at the end of the traffic period. Factors are separated by dotted lines. Mixture factor is on the left and traffic factor is on the right.

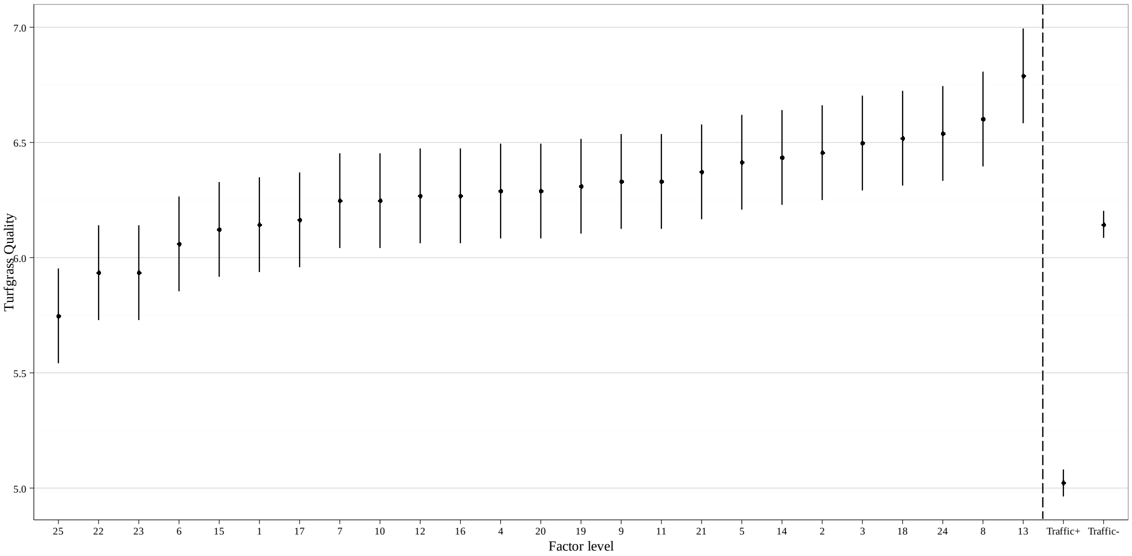


Figure 5. Factor effects and 95% confidence intervals on turfgrass quality 2 months after the traffic period. Factors are separated by dotted lines. From left to right, factors are: PGR, mixture, and traffic.

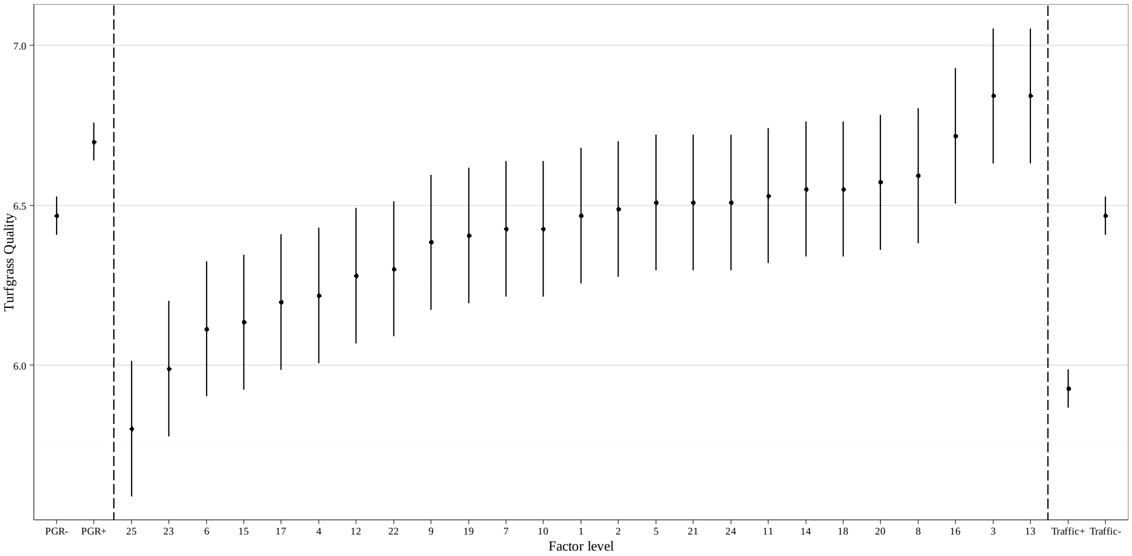


Figure 6. Regression coefficients and 90% confidence intervals from the model of turfgrass quality at the end of traffic data showing the effect on visual turfgrass quality ratings based on the inclusion of individual species in the fine fescue fairway experiment including hard fescue (HDF), slender creeping red fescue (SLCRF), strong creeping red fescue (STCRF), sheep fescue (SHF), and Chewings fescue (CHF).

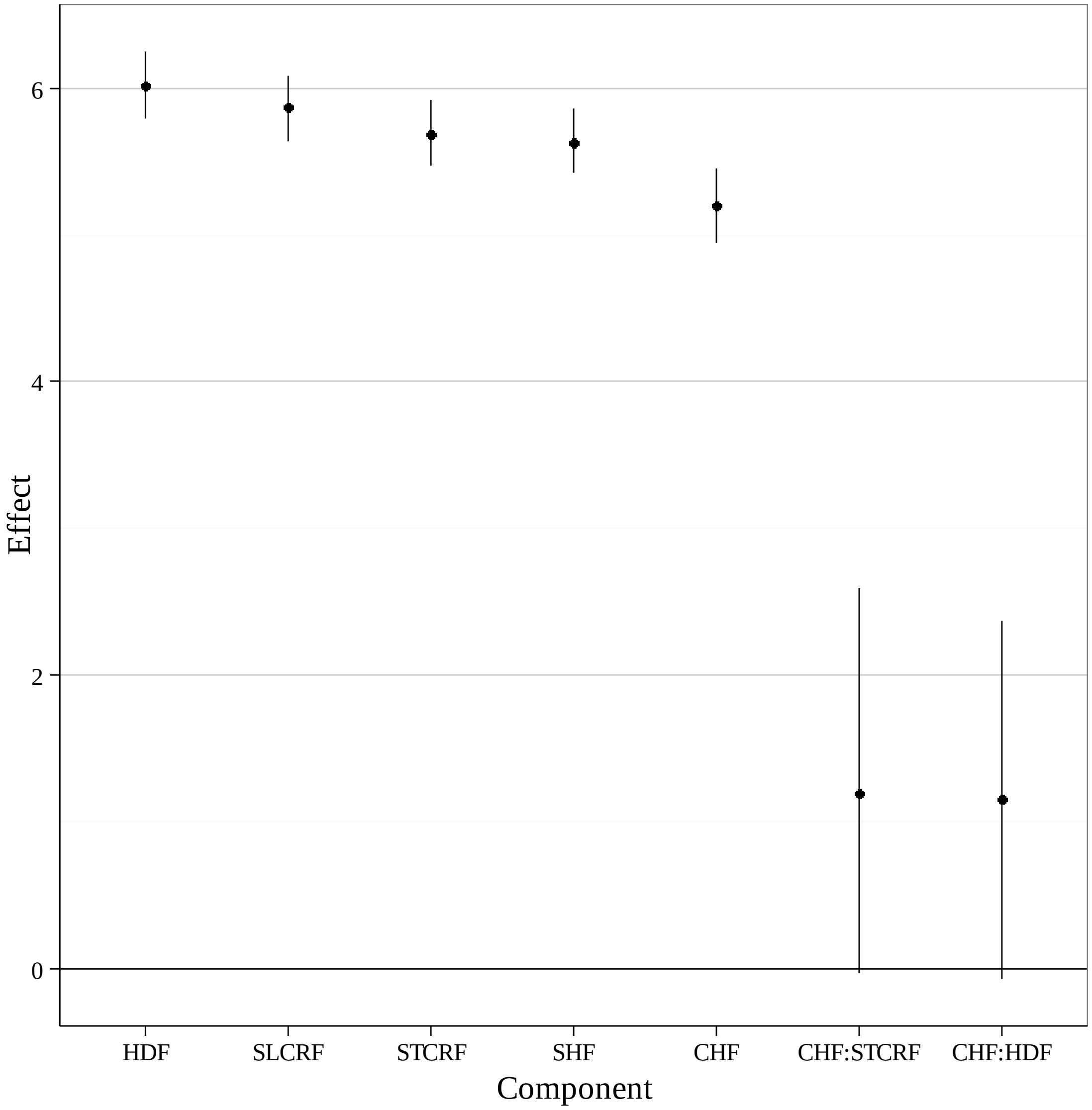
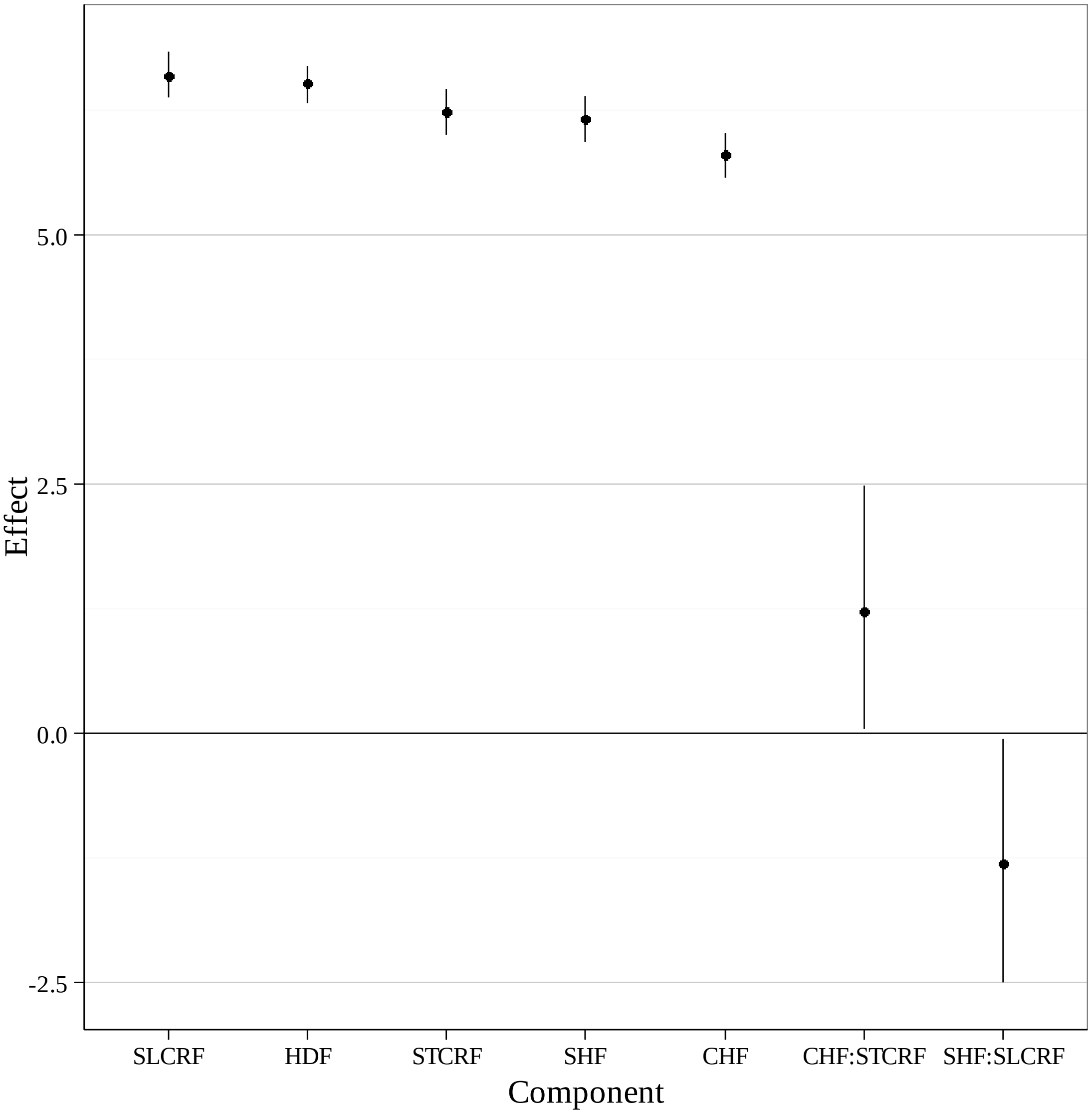


Figure 7. Regression coefficients and 90% confidence intervals from the model of turfgrass quality 2 months after the traffic period data showing the effect on visual turfgrass quality ratings based on the inclusion of individual species in the fine fescue fairway experiment including slender creeping red fescue (SLCRF), hard fescue (HDF), strong creeping red fescue (STCRF), sheep fescue (SHF), and Chewings fescue (CHF).



CHAPTER 3

Fungicide requirements for fine fescues to survive winter snow mold pressure

ABSTRACT

Fine fescue species and mixtures were evaluated for snow mold resistance on three golf courses in Minnesota: Northland Country Club (Duluth, MN); Cragun's Legacy Courses (Brainerd, MN); and Theodore Wirth Golf Club (Minneapolis, MN). Each of the three trials was arranged in a split-plot design with the main plot being fungicide treatment (fungicide or no fungicide) and the split plot being fine fescue mixture (25 different entries). In the spring of 2013, 2014, and 2015, there was no damage from snow mold. This may be that these grasses are resistant to the pathogens; however, our observations in higher cut fine fescue suggest that snow mold and snow scald diseases can be a problem in these grasses. Although the objective was not accomplished, turf quality data taken over 2 years was analyzed. Mixtures maintained significantly better turfgrass quality than any of the five species alone.

INTRODUCTION

Montgomery County, Maryland was the first major locality in the United States to ban pesticides on lawns (Montgomery County Government, 2016). This recent ban excludes golf courses. Several provinces in Canada have banned all synthetic pesticides (Government of Quebec, 2006; Government of Ontario 2009). The Canadian legislation provides an exception to golf courses, but additional conditions must be met. A nationwide survey by the Golf Course Superintendents Association of America estimated pesticide use practices on golf courses in 2013. Self-reported data from golf course superintendents showed 26% percent of average golf facilities had one or more restrictions on their pesticide applications enacted by a local government (GCSAA, 2013).

Legislation restricting pesticide use is a trend that will likely continue to expand in geographical area. Turf managers need to adapt to reduced pesticide availability, to overcome restrictions and run environmentally sound landscapes. Gray snow molds, pink snow mold, and snow scald are problematic cold-weather diseases in Minnesota. In 2014, a group of Minnesota golf course superintendents were surveyed and asked which diseases pose a major problem. The survey showed that snow molds were top-ranking, along with dollar spot (Orshinsky, 2014).

Snow molds and snow scald can be devastating in the spring when snow melts. Damage requires resources and time to repair affected turf, especially high-value golf course greens, tees, or fairways. Control of these pathogens requires fungicide applications every fall, to protect the turf from disease throughout the winter. Fine fescues (*Festuca* spp.) are a group of alternative fairway grass species that have shown some potential for genetic resistance to snow molds. Gregos et al. (2011) found that fine fescue cultivars had significantly less snow mold disease damage than colonial bentgrasses (*Agrostis capillaris* L.) or creeping bentgrasses, but fine fescues provided insufficient resistance and suffered disease ranging from 12 to 83% of a plot area. Other observations suggest that snow mold disease can be a problem on these grasses and breeding efforts are needed to improve disease resistance (Ruemmele et al., 1995).

This experiment investigated various blends of five different fine fescue species to identify the superior mixtures for a fine fescue fairway under winter disease pressure. A commercially available cultivar was selected for each species: ‘Radar’ Chewings fescue, ‘Navigator II’ strong creeping red fescue, ‘Shoreline’ slender creeping red fescue, ‘Beacon’ hard fescue, and ‘Quatro’ sheep fescue. These cultivars were selected for superior performance in past fine fescue fairway trials (Watkins et al., 2010; NTEP, 2013).

The objectives of this study was to determine if fine fescue fairways require fungicides at currently-recommended application rates to survive winter snow mold pressure.

MATERIALS AND METHODS

Mixture design

These five cultivars selected to represent each fine fescue species were blended together in varying proportions. Monocultures of a single species were still included as a baseline to compare multicomponent blends. The fact that mixture components must sum to a constant (1.00 or 100%) confines the constituent proportions to a multidimensional simplex.

A 5-component simplex-centroid mixture design was created with the *mixexp* package in R (R Core Team, 2015). The full simplex-centroid design included too many unique mixtures implemented in a field study. Therefore, the mixture design was fractionated to 25 mixtures. In order to select the 25 mixtures that would maximize prediction about the entire simplex, optimization functions were used. A D-optimal design was ultimately selected with the *AlgDesign* package in R. The D-optimized simplex-centroid mixture design proportions are described in Table 1.

Site design and establishment

Field plots were established 23 August 2012 at Northland Country Club in Duluth, MN, USA, 29 August 2012 at Theodore Wirth Golf Club in Minneapolis, MN, USA, and 31 August 2012 at Cragun's Legacy Courses in Brainerd, MN, USA. The experimental area at each golf course site was located on an in-play fairway. Each site was arranged as a split-plot design with fungicide treatment as the main plot and mixture treatment as the subplot within each main plot. The fungicide factor contained two levels: control plots did not receive snow mold fungicide (0 L product ha^{-1}) and treated plots received a snow mold fungicide each November. The mixture factor contained twenty-five levels of the aforementioned fine fescue species proportions (Table 1). Each subplot measured 0.9 m by 1.5 m. The randomization process was assigned at each factor level, in two stages total. The levels of each factor were arranged as a randomized complete block with three repetitions.

Starter fertilizer was applied using Andersons Contec DG Pro (12-24-8) at a rate of 36.6 kg N, 21.5 kg P, and 8.5 kg K ha^{-1}. Seed was spread by hand at a rate of 2.5 pure live seeds cm^{-2}. After seeding, the soil surface was lightly raked to promote seed to soil contact. Futerra EnviroNet blankets (PROFILE Products LLC) were placed on the seeded area immediately after seeding to control erosion and encourage turf establishment. Each site was watered daily for three weeks.

Three locations in Minnesota were selected to repeat this experiment. This type of repetition allows for evaluation under different climatic and soil conditions, fairways management regimes, and diverse pathogen biotypes. Soil properties for each site are described in Table 2. Fairway product rates and dates of application at Northland Country Club are listed in Table 3. Beyond this list, no fungicides or insecticides were applied, except for the snow mold fungicide treatments for this experiment. Plots were mowed at 2.54 cm. At the beginning of June and mid-September of each year, a solid tine aerification was imposed with 2.54 cm tines, spaced 7.62 cm^2, at a depth of 7.62 cm. An AerWay slicer was also used every October or early November. Fairways were never watered before mid-July or after Labor Day. Pesticide and fertilizer regimes for Cragun's Legacy Courses are included in Table 4. This trial was never aerified. Management protocols for Theodore Wirth Golf Club is not available.

Fungicide treatments and disease inoculation

In November 2012, control plots did not receive snow mold fungicide (0 L product ha^{-1}) and treated plots received Interface StressGuard plus Triton Flo (Bayer CropScience, Research Triangle Park, NC) fungicides. Interface StressGuard was applied at a rate of 22.3 L product ha^{-1} and Triton Flo was applied at a rate of 2.7 L product ha^{-1} with a Turfco T3000 (Turfco

Manufacturing, Inc., Blaine, MN) and carrier volume of 414.0 L ha^{-1}. The trial relied on natural inoculum to cause snow mold disease.

In November 2013, control plots did not receive snow mold fungicide (0 L product ha^{-1}) and treated plots received Instrata (Syngenta Professional Products, Greensboro, NC) fungicide. Instrata was applied at a rate of 17.5 L product ha^{-1} with a Turfco T3000 (Turfco Manufacturing, Inc., Blaine, MN) and carrier volume of 497.0 L ha^{-1}. Additionally, two layers of an Evergreen EVS cover (Hinspergers Poly Industries, Mississauga, ON) were used to cover the entire experimental area. The trial relied on natural inoculum to cause snow mold disease.

In November 2014, control plots did not receive snow mold fungicide (0 L product ha^{-1}) and treated plots received Secure (Syngenta Professional Products, Greensboro, NC) plus Mirage StressGuard (Bayer CropScience, Research Triangle Park, NC) fungicides. Secure was applied at a rate of 1.6 L product ha^{-1} and Mirage was applied at a rate of 3.2 L product ha^{-1} with a backpack sprayer and carrier volume of 497.0 L ha^{-1}. A Minnesota-collected snow scald colony was incubated on millet seed for 2 months, air dried, and applied to all golf course plots at a rate of 7.0 g m^{-2} with a rotary spreader. Two layers of an Evergreen EVS cover (Hinspergers Poly Industries, Mississauga, ON) were used to cover the entire experimental area.

Data collection

Plots were visually assessed three or four times each year (between April and September) for aesthetics and functional use. Visual turf quality ratings were taken to a 1 to 9 scale with 1 being poorest and 9 being the best stand. Quality ratings are based on a combination of density, color, uniformity, and environmental stress. A rating of 6 or above was considered acceptable for a low input fairway setting. After the snow cover melted each spring, plots were carefully examined for snow mold or snow scald diseases. If disease was present, visual disease ratings were taken.

Mixture model analysis

Turfgrass quality data from all three locations was combined and analyzed with R (R Core Team, 2015). A linear mixed effects model was developed with the *lme* function in the *nlme* package in R. The response variable was turf quality rating. The model used nested fixed effects for fungicide and mixture factors, and nested random effects for site, year, month, and replicate. Homoscedasticity assumptions were tested and models were compared with an analysis of variance (ANOVA) in a likelihood ratio test. Non-significant factors were removed until the simplest model with the greatest explanatory power was produced. A 95% confidence interval was estimated for fixed effect turf quality means using the *ci* function in the *gmodels* package. The same type of linear mixed effect model was created for disease data. This data was only collected one time each spring, so the model lacked the “month” random effect.

RESULTS

Turfgrass quality

The analysis of variance for turf quality revealed a significant fungicide, mixture, and fungicide by mixture interaction effect. The final linear mixed effects model, with all sites and rating times combined, included main effects for fungicide, mixture, and the fungicide by mixture interaction. Fungicide-treated plots and control plots were separated and confidence intervals were calculated for each mixture mean. Plots that were sprayed with a snow mold fungicide every fall had means that were 0.3 turf quality units lower than control plots that were not sprayed. Mixture effect was not significant in the fungicide treated plots (Figure 1). Significant differences existed among mixtures that were in control plots (Figure 2). Mixture 11 was the top-performing mixture in the control plots and was not significantly different from the next 15 mixtures. The only monoculture in the top group was mixture 3, consisting of 100% slender creeping red fescue. Mixture 7, the monoculture of sheep fescue, was the lowest ranked mean in the control plots. All monocultures were in the bottom half of ranked means (Figure 2).

Disease

After the snow cover melted each spring, there was no damage from snow mold or snow scald diseases. No disease ratings were taken.

DISCUSSION

The objective of this experiment was to determine if fine fescue fairways require fungicides at currently-recommended application rates to survive winter snow mold and/or snow scald pressure. This objective was not accomplished because there was no disease on control plots to compare. One reason for this may be that these grasses are inherently resistant to the pathogens; however, our observations in higher cut fine fescue suggest that snow mold disease can be a problem in these grasses. Another reason could be insufficient inoculum. The establishment of a new turfgrass area in fall of 2012 could have eradicated natural inoculum in that specific area. In the subsequent years, inoculum may not have reached high-enough levels to cause a disease outbreak. When inoculated with snow scald in fall of 2014, the prepared inoculum could have been defective. The snow scald pathogen had been active when plated on media in a laboratory. Lastly, environmental conditions may not have been favorable to disease development. Unsuccessful inoculations resulted when Gregos et al (2011) inoculated fine fescue cultivars with *M. nivale, T. incarnata,* and *T. ishikariensis.* In several location years, inoculated plots provided disease damage less than 8%.

Although there was no damage from snow mold or snow scald pathogens, control plots that were not treated with preventative fungicides each year maintained better turfgrass quality. This contradicts research on Kentucky bluegrass, perennial ryegrass, and creeping bentgrass where fungicides improved turf quality in the absence of disease (Kane and Smiley, 1983; Dernoeden and McIntosh, 1991; Dernoeden and Fu, 2008). Reicher and Throssell (1997) found that fungicides improved rooting and color, but did not have any “serious negative non-target effects.”

The control plots had significant differences among means (Figure 2). There was no significant difference among the monocultures slender creeping red fescue (mixture 3), Chewings fescue (mixture 25), hard fescue (mixture 13), and strong creeping red fescue (mixture 1). The sheep fescue monoculture (mixture 7) was the lowest entry, and not significantly different from the strong creeping red fescue monoculture. All monocultures were in the bottom half of mixtures. This suggests that multicomponent fine fescue mixtures performed better than single species across the three different fairway environments tested.

Evidence in the literature generally agrees that no monoculture can provide exceptional performance, and genetically diverse grass mixtures can provide several advantages to single species (Watschke and Schmidt, 1992). Experiments in grasslands show that multi-species assemblages are necessary for high ecosystem functioning, more biomass production, and better recovery from abiotic stress (Schulze and Mooney, 1994; Tilman and Downing, 1994; Tilman et al., 2001). This concept has been supported in managed turfgrasses. Brede and Duich (1984) found that a mixed culture of Kentucky bluegrass and perennial ryegrass produced a higher leaf area index, percent groundcover, and spring green up rate than either species alone. Juska and Hanson (1959) reported that a monoculture of Kentucky bluegrass outperformed mixtures of Kentucky bluegrass, tall fescue, colonial bentgrass, and red fescue. In the fifth and final year of the study, the monostand suffered from stripe smut disease and the mixture of red fescue and Kentucky bluegrass provided the best turf quality. Dunn et al. (2002) also showed that, on occasion, mixtures of cool-season grasses provided superior disease resistance compared to single species.

CONCLUSION

Some mixtures performed better in the multi-year, multi-site golf course trial. It is important to collect data on these grasses across multiple and diverse environments, to determine adaptation to the North Central region of the United States. Mixtures maintained significantly better turfgrass quality than any of the five species, but the top mixtures were not significantly different from the slender creeping red fescue monoculture. Snow mold and snow scald diseases did not occur naturally in the field, and snow scald did not cause damage when inoculated. The objective to determine if fine fescue species and mixtures require fungicides for snow mold and/or snow scald resistance was not accomplished.

Table 1. Proportions of constituent species in each mixture identified as a design point in the simplex centroid design for the fine fescue drought experiment for seed mixture analysis.

	Constituent species proportion				
Mixture ID	Chewings fescue *Festuca rubra* ssp. *commutata*	hard fescue *Festuca brevipila*	sheep fescue *Festuca ovina*	slender creeping red fescue *Festuca rubra* ssp. *litoralis*	strong creeping red fescue *Festuca rubra* spp. *rubra*
1					1
2				0.50	0.50
3				1	
4			0.33	0.33	0.33
5			0.50		0.50
6			0.50	0.50	
7			1		
8		0.33		0.33	0.33
9		0.33	0.33	0.33	
10		0.50			0.50
11		0.50		0.50	
12		0.50	0.50		
13		1			
14	0.20	0.20	0.20	0.20	0.20
15	0.25	0.25	0.25		0.25
16	0.33			0.33	0.33
17	0.33		0.33		0.33
18	0.33		0.33	0.33	
19	0.33	0.33		0.33	
20	0.33	0.33	0.33		
21	0.50				0.50
22	0.50			0.50	
23	0.50		0.50		
24	0.50	0.50			
25	1				

Table 2. Soil chemical properties for golf course sites in the snow mold trial.

	Northland Country Club Duluth, MN	Cragun’s Legacy Courses Brainerd, MN	Theodore Wirth Golf Club Minneapolis, MN
pH	5.0	5.9	6.6
Organic matter, %	6.4	1.9	4.4
P (Bray), mg kg^{-1}	29	90	63
K, mg kg^{-1}	109	60	119

Table 3. Management record for Northland Country Club in Duluth, MN during the snow mold trial.

Year	Date	Product	Rate
2012	August 30	Urea (46-0-0)	4.9 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	2.5 kg N ha^{-1}
		Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	9.5 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	9.5 L ha^{-1}
	September 18	Urea (46-0-0)	7.4 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	4.9 kg N ha^{-1}
		Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
	October 3	Ammonium sulfate (21-0-0)	7.4 kg N ha^{-1}
		Urea (46-0-0)	4.9 kg N ha^{-1}
		Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
	October 18	Ammonium sulfate (21-0-0)	7.4 kg N ha^{-1}
		Urea (46-0-0)	4.9 kg N ha^{-1}
		Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
	October 29	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
2013	May 29	Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Urea (46-0-0)	34.3 kg N ha^{-1}
	June 4	Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Sterling Blue (Dicamba)	12.7 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.44 L ha^{-1}
	June 18	Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Urea (46-0-0)	24.5 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	2.5 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	78.2 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Sterling Blue (Dicamba)	12.7 L ha^{-1}
	July 17	Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Urea (46-0-0)	39.2 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Sterling Blue (Dicamba)	12.7 L ha^{-1}
	July 30	Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Urea (46-0-0)	7.4 kg N ha^{-1}
		Civitas (Mineral oil)	25.4 L ha^{-1}

		Civitas Harmonizer	1.6 L ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Sterling Blue (Dicamba)	12.7 L ha^{-1}
	August 14	Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Urea (46-0-0)	4.9 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	2.5 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Sterling Blue (Dicamba)	12.7 L ha^{-1}
	August 27	Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Urea (46-0-0)	4.9 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	2.5 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Sterling Blue (Dicamba)	12.7 L ha^{-1}
	September 10	Ferrous sulfate (20% Fe)	13 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Urea (46-0-0)	2.5 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	4.9 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	9.5 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	9.5 L ha^{-1}
	September 25	Ferrous sulfate (20% Fe)	13 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Urea (46-0-0)	2.5 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	2.5 kg N ha^{-1}
	October 16	Urea (46-0-0)	4.9 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	7.4 kg N ha^{-1}
		Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
	October 22	Urea (46-0-0)	4.9 kg N ha^{-1}
		Ammonium sulfate (21-0-0)	7.4 kg N ha^{-1}
		Ferrous sulfate (20% Fe)	12.7 L ha^{-1}
2014	June 5	Ferrous sulfate (20% Fe)	22.6 L ha^{-1}
		Manganese sulfate (28% Mn)	7.6 L ha^{-1}
		Urea (46-0-0)	2.5 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.1 L ha^{-1}
		Rifle (Dicamba)	12.7 L ha^{-1}
	June 15	Ferrous sulfate (20% Fe)	22.6 L ha^{-1}
		Potassium sulfate	12.3 kg K_2O ha^{-1}

		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.1 L ha^{-1}
		Rifle (Dicamba)	12.7 L ha^{-1}
	July 2	Ferrous sulfate (20% Fe)	16.9 L ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.1 L ha^{-1}
		Rifle (Dicamba)	12.7 L ha^{-1}
	July 16	Ferrous sulfate (20% Fe)	16.9 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.1 L ha^{-1}
		Rifle (Dicamba)	12.7 L ha^{-1}
	July 29	Ferrous sulfate (20% Fe)	16.9 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Potassium sulfate	12.3 kg K_2O ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.1 L ha^{-1}
		Rifle (Dicamba)	12.7 L ha^{-1}
	August 20	Ferrous sulfate (20% Fe)	22.6 L ha^{-1}
		Ammonium sulfate (21-0-0)	2.5 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.1 L ha^{-1}
		Rifle (Dicamba)	12.7 L ha^{-1}
	September 2	Ferrous sulfate (20% Fe)	22.6 L ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
		Trimmit 2SC (Paclobutrazol)	25.1 L ha^{-1}
		Rifle (Dicamba)	12.7 L ha^{-1}
	September 22	Ferrous sulfate (20% Fe)	16.9 L ha^{-1}
		Ammonium sulfate (21-0-0)	4.9 kg N ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}
		Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
	October 9	Ferrous sulfate (20% Fe)	16.9 L ha^{-1}
		Ammonium sulfate (21-0-0)	12.25 kg N ha^{-1}
	October 15	Ferrous sulfate (20% Fe)	8.9 L ha^{-1}
		Ammonium sulfate (21-0-0)	12.3 kg N ha^{-1}
2015	May 26	Ferrous sulfate (20% Fe)	22.6 L ha^{-1}
		Manganese sulfate (28% Mn)	6.4 L ha^{-1}
		Dispatch (Wetting agent)	1.2 L ha^{-1}

	Cutless MEC (Flurprimidol)	78.2 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	17.5 L ha^{-1}
	Vanquish (Dicamba)	6.4 L ha^{-1}
June 11	Ferrous sulfate (20% Fe)	22.6 L ha^{-1}
	Manganese sulfate (28% Mn)	6.4 L ha^{-1}
	Dispatch (Wetting agent)	1.2 L ha^{-1}
	Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	17.5 L ha^{-1}
	Trimmit 2SC (Paclobutrazol)	12.6 L ha^{-1}
	Vanquish (Dicamba)	6.4 L ha^{-1}
June 29	Ferrous sulfate (20% Fe)	18.6 L ha^{-1}
	Manganese sulfate (28% Mn)	6.4 L ha^{-1}
	Dispatch (Wetting agent)	1.2 L ha^{-1}
	Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
	Trimmit 2SC (Paclobutrazol)	12.6 L ha^{-1}
	Vanquish (Dicamba)	6.4 L ha^{-1}
July 8	14-0-7	24.5 kg N ha^{-1}
July 15	Ferrous sulfate (20% Fe)	18.6 L ha^{-1}
	Manganese sulfate (28% Mn)	6.4 L ha^{-1}
	Dispatch (Wetting agent)	1.2 L ha^{-1}
	Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
	Trimmit 2SC (Paclobutrazol)	12.6 L ha^{-1}
	Vanquish (Dicamba)	6.4 L ha^{-1}
July 30	Urea (46-0-0)	4.9 kg N ha^{-1}
	Ferrous sulfate (20% Fe)	18.6 L ha^{-1}
	Manganese sulfate (28% Mn)	6.4 L ha^{-1}
	Dispatch (Wetting agent)	1.2 L ha^{-1}
	Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
	Trimmit 2SC (Paclobutrazol)	12.6 L ha^{-1}
	Vanquish (Dicamba)	6.4 L ha^{-1}
August 17	Urea (46-0-0)	7.4 kg N ha^{-1}
	Ferrous sulfate (20% Fe)	18.6 L ha^{-1}
	Manganese sulfate (28% Mn)	6.4 L ha^{-1}
	Dispatch (Wetting agent)	1.2 L ha^{-1}
	Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	12.7 L ha^{-1}
	Trimmit 2SC (Paclobutrazol)	12.6 L ha^{-1}
	Vanquish (Dicamba)	6.4 L ha^{-1}
September 2	Urea (46-0-0)	5.9 kg N ha^{-1}
	Ferrous sulfate (20% Fe)	18.6 L ha^{-1}
	Manganese sulfate (28% Mn)	6.4 L ha^{-1}
	Dispatch (Wetting agent)	1.2 L ha^{-1}
	Cutless MEC (Flurprimidol)	39.1 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	6.4 L ha^{-1}
	Trimmit 2SC (Paclobutrazol)	19.1 L ha^{-1}

	Vanquish (Dicamba)	6.4 L ha^{-1}
September 15	Ammonium sulfate (21-0-0)	6.1 kg N ha^{-1}
	Ferrous sulfate (20% Fe)	18.6 L ha^{-1}
	Manganese sulfate (28% Mn)	6.4 L ha^{-1}
	Dispatch (Wetting agent)	1.2 L ha^{-1}
	Primo MAXX (Trinexapac-ethyl)	6.4 L ha^{-1}
	Trimmit 2SC (Paclobutrazol)	19.1 L ha^{-1}
	Vanquish (Dicamba)	6.4 L ha^{-1}

Table 4. Management record for Cragun's Legacy Courses in Brainerd, MN during the snow mold trial.

Year	Date	Product	Rate
2013	June 19	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Tide Paclo 2SC (Paclobutrazol)	0.6 L ha^{-1}
		Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		PK Flight (0-0-28)	3.2 L ha^{-1}
		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
		T-NEX 1 AQ (Trinexapac-ethyl)	0.4 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
		28-0-14	36.8 kg N ha^{-1}, 18.4 kg K_20 ha^{-1}
	July 11	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Chlorothalonil 720 (Chlorothalonil)	5.9 L ha^{-1}
		Tide Paclo 2SC (Paclobutrazol)	0.7 L ha^{-1}
		PK Flight (0-0-28)	3.2 L ha^{-1}
		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
		T-NEX 1 AQ (Trinexapac-ethyl)	0.4 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
	July 30	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Chlorothalonil 720 (Chlorothalonil)	5.9 L ha^{-1}
		Tide Paclo 2SC (Paclobutrazol)	0.7 L ha^{-1}
		PK Flight (0-0-28)	3.2 L ha^{-1}
		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
		T-NEX 1 AQ (Trinexapac-ethyl)	0.4 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
	August 20	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		Tide Paclo 2SC (Paclobutrazol)	0.7 L ha^{-1}
		PK Flight (0-0-28)	3.2 L ha^{-1}
		TM 4.5F (Thiophanate-methyl)	4.0 L ha^{-1}
		T-NEX 1 AQ (Trinexapac-ethyl)	0.4 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
		28-0-14	36.8 kg N ha^{-1}, 18.4 kg K_20 ha^{-1}
	September 11	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Tide Paclo 2SC (Paclobutrazol)	0.7 L ha^{-1}
		PK Flight (0-0-28)	3.2 L ha^{-1}
		T-NEX 1 AQ (Trinexapac-ethyl)	0.4 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
	October 18	Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		Tebu-Turf 3.6F (Tebuconazole)	1.9 L ha^{-1}
		T-Pac SPC MEC (Trinexapac-ethyl)	0.1 L ha^{-1}
2014	May 21	Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
	June 12	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}

		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
		19-0-19	34.3 kg N ha^{-1}, 34.3 kg K_20 ha^{-1}
	June 30	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Chlorothalonil ETQ (chlorothalonil)	5.2 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
		PK Flight (0-0-28)	4.2 L ha^{-1}
		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
	July 30	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
		PK Flight (0-0-28)	4.2 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
	August 14	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Chlorothalonil ETQ (chlorothalonil)	5.2 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
		PK Flight (0-0-28)	4.2 L ha^{-1}
		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
		28-0-14	34.3 kg N ha^{-1}, 17.2 kg K_20 ha^{-1}
	September 9	Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		TM 4.5F (Thiophanate-methyl)	4.0 L ha^{-1}
	October 15	Offset 3.6F (Tebuconazole)	1.9 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
2015	May 26	Ferrous sulfate (20% Fe)	9.3 L ha^{-1}
		Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
	June 18	Ferrous sulfate (20% Fe)	9.3 L ha^{-1}
		Chlorothalonil ETQ (chlorothalonil)	5.2 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
		PK Flight (0-0-28)	4.2 L ha^{-1}
		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
		19-0-19	36.8 kg N ha^{-1}, 36.8 kg K_20 ha^{-1}
	July 8	Ferrous sulfate (20% Fe)	9.3 L ha^{-1}
		Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
		PK Flight (0-0-28)	4.2 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
	July 28	Ferrous sulfate (20% Fe)	9.3 L ha^{-1}
		Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}
		Legacy (Flurprimidol)	1.1 L ha^{-1}
		PK Flight (0-0-28)	4.2 L ha^{-1}
		Immerse F (Wetting agent)	1.7 L ha^{-1}
		Propiconazole 14.3 (Propiconazole)	1.6 L ha^{-1}
	August 20	Ferrous sulfate (20% Fe)	6.4 L ha^{-1}
		Iprodione Pro 2SE (Iprodione)	4.8 L ha^{-1}

	Legacy (Flurprimidol)	1.1 L ha^{-1}
	PK Flight (0-0-28)	1.3 L ha^{-1}
	Immerse F (Wetting agent)	1.7 L ha^{-1}
	TM 4.5F (Thiophanate-methyl)	4.0 L ha^{-1}
	19-0-19	36.8 kg N ha^{-1}, 36.8 kg K_20 ha^{-1}
September 15	Ferrous sulfate (20% Fe)	9.3 L ha^{-1}
	Legacy (Flurprimidol)	1.1 L ha^{-1}
	Immerse F (Wetting agent)	1.7 L ha^{-1}

Figure 1. Mixture effects and 95% confidence intervals on turfgrass quality in fungicide treated (fungicide+) plots with all locations and rating dates combined.

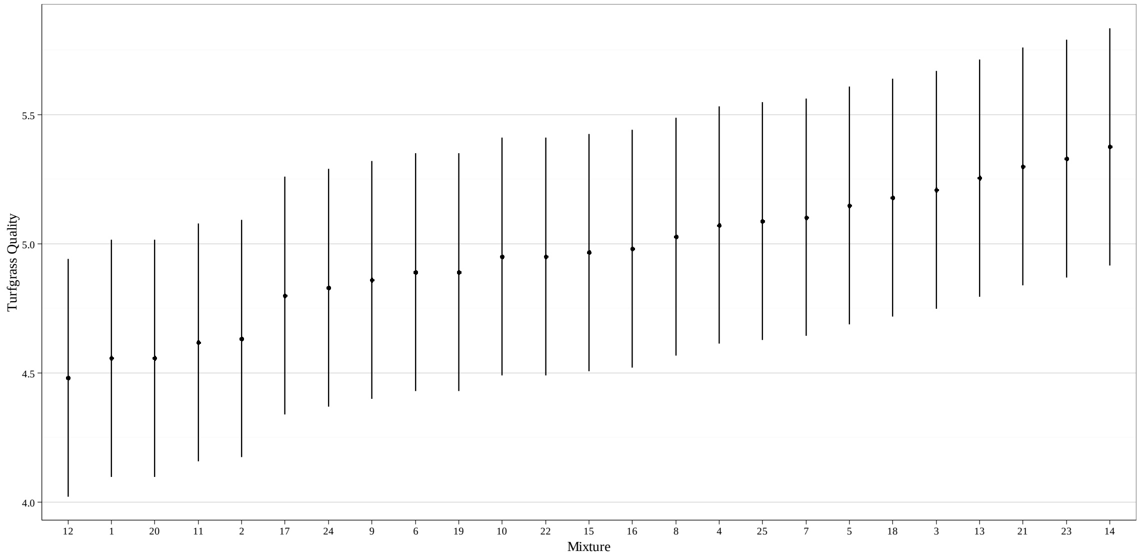
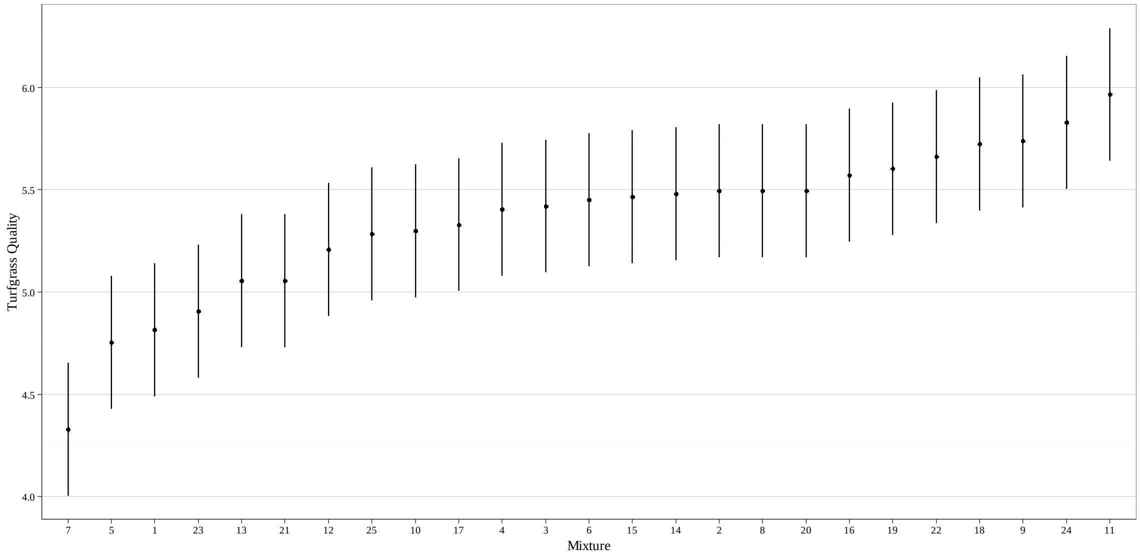


Figure 2. Mixture effects and 95% confidence intervals on turfgrass quality in control (fungicide-) plots with all locations and rating dates combined.



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