AN INVESTIGATION OF *CAREX*:
A LOOK AT SEED DORMANCY, USE AS A LOW INPUT LAWN, AND LOCAL STAND CHARACTERIZATION

By

GODWIN SHOKOYA

Bachelor of Science in Plant Biology

Oklahoma State University

Stillwater, Oklahoma

2020

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2022

AN INVESTIGATION OF *CAREX*:

A LOOK AT SEED DORMANCY, USE AS A LOW INPUT LAWN, AND LOCAL STAND CHARACTERIZATION

Thesis Approved:

Charles Fontanier

Thesis Adviser

Dr. Bruce Dunn

Dr. Dennis Martin

Acknowledgments

I would like to thank Anna Ready, Grace Rembold, Ashton Franks, Becky Cheary, Abigail Hobbs, and Stephen Stanphill for help throughout my projects and because without them I would not be here, they are the literal definition of taking a village to complete a thesis, so thanks again.

A big thanks goes to Dr. Charles Fontanier for accepting a Plant Biology student with a mid GPA and helping him get through his Master's program sacrificing many late nights and a few weekends to do it. I would also like to thank my committee for their valuable comments

I would also like to thank my fiancé Kaitlyn McNiel for all the small things like helping in the field when my battery pack died in Perkins and running me a new one, helping me plant on weekends when I didn't want to get out of bed, and being there when it mattered both physically and mentally. A wise man (me) once said, behind (almost) every great researcher there is a spouse telling them to chill out and write emails tomorrow, and I couldn't ask for a better one.

Name: Godwin Shokoya

Date of Degree: JULY, 2022

Title of Study: AN INVESTIGATION OF *CAREX*:
A LOOK AT SEED DORMANCY, USE AS A LOW INPUT LAWN,
AND LOCAL STAND CHARACTERIZATION

Major Field: Horticulture

Abstract: *Carex* has been an underutilized genus across multiple industries due, in part, to poor germination resulting from a strong primary dormancy. Dormancy can usually be broken using stratification or plant hormones, but the optimal stratification conditions have not been described for many *Carex* species. Therefore, our objectives for this research were to make observations on the most efficient way to improve seed propagation in local species. A 2-year study was conducted to improve germination and decrease time until germination in *Carex blanda* (common wood sedge), *C. brevior* (oval plains sedge), *C. eburnea* (ivory sedge), *C. muskingumensis* (palm sedge), and *C. pensylvanica* (Pennsylvania sedge) by testing germination in two soil temperatures, seven stratification lengths, and three concentrations of the plant hormone gibberellic acid (GA_3). A germination improvement study was conducted in-between years to determine if seed depth improved germination for the three worst performing species. In the primary study, common wood sedge performed the worst in both years averaging ≈2% germination, and palm sedge performed the best with ≈70% germination. For the germination improvement study, light with a surface level seed depth contributed most to improved germination in the three species tested. Stratification treatments influenced both germination rate as well as time until germination. Planting depth and stratification were important in increasing germination for the majority of species, and is suggested to further improve marketability.

Consumers have shown preference for low input turfgrasses that have tolerance to both shade and drought stresses. *Carex* species and nimblewill (*Muhlenbergia schreberi*) are native plants adapted in Oklahoma and may have potential as alternatives to popular turfgrass species in dry shaded environments. To evaluate the potential for native perennial ground covers common in dry woodland ecosystems in Oklahoma, a multi-location field trial was conducted in Stillwater and Perkins, Oklahoma. Four species of *Carex* [*C. amphibola* (gray sedge), *C. leavenworthii* (Leavenworth's sedge), a dwarf cultivar of palm sedge named 'Little Midge', and *C. texensis* (Texas sedge)] and two sources of nimblewill were used for the study. These alternative turfs were compared against *Zoysia japonica* 'El Toro' (Japanese lawngrass) and *Cynodon dactylon* 'Riley's Super Sport' (bermudagrass), which served as representative standards. In 2020, plant materials were established as a randomized complete block. In 2021, irrigation treatments (irrigated or not irrigated) were randomly assigned to plots using a split plot structure. Data quantifying growth was measured monthly during the growing season. By the end the second growing season, the conventional turfgrasses outperformed each *Carex* species and nimblewill. Most *Carex* showed excellent persistence but lacked the ability to spread quickly enough by the end of the two-year trial. This study demonstrated *Carex* species and nimblewill have potential to be grown in low maintenance lawns but need unique management practices to be efficient.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

Improving Germination in Select *Carex* Species with Varying Soil Temperature, Light, Gibberellic Acid, and Stratification Lengths

Introduction

Grass-like species in the *Carex* genus have applications within the turf, nursery, and prairie restoration industries, but further use is limited due to poor germination. *Carex* is a genus from the Cyperaceae or sedge family that includes about 5000 species, making it the third biggest family of monocots, with roughly 40% of sedge species belonging to the *Carex* genus (Goetghebeur, 1998). *Carex* is the most important genus in the sedge family (Rezniceck, 1990), as well as one of the most ecologically important species in the world due to wide adaptability and use as vegetation in many ecosystems (Kettenring et al., 2006; Ning, 2014). *Carex* can be found from the tropics to the artic, although many species prefer temperate regions (Bernard, 1990; Kettenring and Galatowitsch, 2007).

In North America, there are 600 species of *Carex* (Bernard, 1990) that are most commonly found in wetlands, although now scarcer as human infrastructure has encroached on their naturalized habitats (Houseal; 2010; Leck and Schütz; 2005, Schütz, 2000). Due to this, many prairie restoration efforts have looked to reintroduce *Carex* into their native habitats (Budelsky and Galatowitsch, 2007; Leck and Schütz, 2005; Van der Valk et al., 1999). *Carex* are common in open wetlands and prairies but are also common in dry shaded areas (McGinnis and Meyer, 2011). This adaptability has led many species to compete in areas of low light and soil moisture, environments where most turfgrasses struggle to grow (Ning et al., 2014).

Because of its grass-like appearance, the green industry has previously explored using *Carex* as an alternative turf with some species already sold for this intended use. To achieve widespread usage as a turf, *Carex* must meet certain parameters that are important to consumers, including traffic tolerance, color retention, shade tolerance, cold tolerance, and ease of establishment (McGinnis and Meyer, 2011). Despite its vast number of species, only a few *Carex* sp. are likely to demonstrate qualities desirable for a residential turf. In review of one online vendor of native plant seed, several species are routinely marketed for use as a lawn in dry shade or are naturally found in woodland ecosystems (Prairie Moon Nursery, Winona, MN). Some of these species include *C. blanda* (common wood sedge), which is adapted to USDA hardiness zones 3 to 9 (USDA, Washington D. *Carex.*) and is native to upland woodlands and woodland openings (Prairie Moon Nursery. Winona, MN). *Carex brevior* (plains oval sedge) is adapted to dry, disturbed locations in full sun or shaded locations and is hardy from USDA zones 3 to 8 (USDA, Washington D. *Carex.*). *C. eburnea* (ivory sedge) has fine leaf texture, low growth habit, is adapted to dry shade, and is hardy in USDA zone 2 to 8 (USDA, Washington D. *Carex.*). *C. muskingumensis* (palm sedge) forms dense clumps with a leaf architecture similar to many warm-season turfgrass species, and is hardy from

USDA zones 4 to 8 (USDA, Washington D. *Carex.*). Although palm sedge is naturally a taller species, there are dwarf cultivars (e.g., ‘Little Midge’) that may have promise for lawn applications. *Carex pensylvanica* (Pennsylvania sedge) is marketed as having fine leaf texture, short growth habit, and tolerance to drought and shade. This species is also among the most marketed for use as a lawn.

Whether for prairie restoration or green industries, prior evaluations of *Carex* have commonly reported poor germination across several species (Houseal, 2010; McGinnis and Meyer, 2011; Schütz, 2000; Van der valk et al., 1999). For example, a study testing the effects of stratification on 32 *Carex* species found nine species did not germinate, and only eight species managed to have a germination rate above 10% (ranged from 10 to 62%) (Schütz and Rave, 1998; Schütz, 2000). Because of this poor and inconsistent germination, research on a variety of *Carex* species has been focused on improving germination by overcoming persistent dormancy (Bernard, 1989; Hipp et al., 2006). Some commercial nurseries provide guidelines on germination requirements of their *Carex* seed, with most of the species adapted to dry shade requiring 60 days of cold, moist stratification (Prairie Moon Nursery). Further study to determine the validity of these claims is needed.

Germination rate in *Carex* is affected by multiple factors including species, light, growing temperature, and stratification duration. And while *Carex* species number in the thousands, only a fraction of them have been researched for use in restoration efforts or germination studies (Schütz, 2000). Because *Carex* seeds are primarily found in the understory, light availability can be a major factor in germination (Schütz, 2000), with exposure to light in several cases resulting in greater germination (Schütz, 2000; Schütz and Rave 1999). *Carex* have a high relatively wide temperature requirement for germination ranging from 10°C to 30°C with most species preferring the range of 20°C to 25°C (Kettenring and Galatowitsch, 2007; Schütz, 2000). Many species respond favorably to cold stratification with increasing germination rate and with decreasing time till emergence (Hipp et al., 2006; Kettenring and Galatowitsch, 2007; McGinnis and Meyer, 2011; Schütz and Rave, 1999; Van der Valk et al., 1999). Finally, the effects of these factors have been found to be species specific, and interactions between these factors can be complex (Bernard, 1989; Budelsky and Galatowitsch, 1999; Hipp et al., 2006; Houseal, 2010; Ning et al, 2014; Schütz and Rave, 1999).

Traditionally, germination rate can be improved in difficult germinating species through soaking seeds in gibberellic acid (GA) for multiple hours. Gibberellic Acid (GA$_3$) helps to alleviate dormancy in *Carex* by reducing the amount of abscisic acid (ABA) within a seed which is another plant hormone that keeps the seed in a state of dormancy by restricting embryo growth, adding GA starts internal precursor activities to prepare for germination including the imbibition of water as well as the softening of cell walls which is a key factor in germination (Gimeno-Gilles et al., 2009; Schopfer and Plachy, 1984; Vishal and Kumar, 2018). This mechanism to remove stratification requirements in species that are difficult to germinate. Previous attempts to use GA to improve germination in *Carex* species have generally been unsuccessful (McGinnis and Meyer, 2011; Leck and Schütz, 2005; Schütz 2000), but this may be due to concentration or particular GA product used.

Prior *Carex* germination studies have shown both an improvement in germination with exposure to stratification and a decrease in time needed to germinate with exposure to stratification (Schütz, 2000; Schütz and Rave, 1998). Previous studies have also noted that 6 to 8 weeks may be too little time to alleviate dormancy (Schütz, 2000), but also germination near 90% can be seen in certain species within 4 to 8 weeks of stratification (Kettenring and Galatowitsch, 2007). These contrasting results suggest a species-specific effect, as it is common for stratification to affect *Carex* species in different ways. Previous studies have had stratification lengths that span over multiple months (McGinnis and Meyer, 2011) or are in very specific increments that cover only a few weeks (Kettenring and Galatowitsch, 2007), which limits the potential of those studies to identify the optimal time for stratification for these select species.

While numerous studies have attempted to describe ideal germination conditions for *Carex* species, many species remain untested in the literature. To address this limitation, a series of experiments were conducted to find the optimal temperature, stratification length, GA concentration, and planting depth for germination of five *Carex* species.

Materials and Methods

Experiment 1

Seeds of five *Carex* spp. [oval plains sedge (*C. brevior*), common wood sedge (*C. blanda*), Pennsylvania sedge (*C. pensylvanica*), ivory sedge (*C. eburnea*), and palm sedge (*C. muskingumensis*)] were obtained from Prairie Moon Nursery (Winona, MN) and evaluated for germination rate under two soil temperatures (21°C and 27°C) and 10 seed pre-treatments (cold stratification or gibberellic acid soak). Each year, an experiment consisted of a stratification period and a germination period. In 2020, the stratification period was 3 months (8 Aug. to 18 Nov.) and the germination period was 1 month (18 November to 18 December 2020), while in 2021, the stratification period spanned 3 months (27 July to 26 October) and germination period from 1 November to 1 December, 2021. For each experimental unit, 25 seeds of each species were planted into single 7.5 cm × 10 cm 1201 Open Pack planters (American Plant Production & Services Inc. Oklahoma City, OK). Planters were filled with horticulture propagation mix (Sun Gro®, Agawam, MA), containing Canadian Sphagnum peat moss, vermiculite, and a wetting agent. The mix was wetted to uniform moisture content at a rate of 75 ml of water to 300 ml of propagation mix resulting in a final gravimetric water content of 3.2 g/g. Each container had six replications of each combination of temperature, species, and pre-treatment. In 2020, seeds were stratified by chilling to 2°C for a duration of 0, 15, 30, 45, 60, 75, or 90 d. In 2021, stratification treatments were similar except that the 15, 30, and

45 d treatments for ivory sedge were eliminated because of the lack of seed from the vendor. Gibberellic acid (GA_3, Research Products International, Mt Prospect, IL) pre-treatments were applied to non-stratified seed the day before planting as a 24-hour soak at three concentrations (500 ppm, 1000 ppm, and 1500 ppm). After stratification and GA treatment, planters were moved to the Oklahoma State University (OSU) Horticulture Research Greenhouses in Stillwater, Oklahoma to initiate the germination period. Minimum soil temperatures were maintained at 21°C or 27°C using Redi-Heat plant propagation mats (Phytotronics, Earth City, MO). Planters were misted daily for 15 seconds every 20 minutes using automated misting nozzles. Germination was defined as at least 1 mm of the plant being visible (Schütz, 2000), and was recorded daily until for an industry standard of 30 d. Photosynthetically active radiation (PAR) was measured every 30-minutes using a quantum sensor and Watchdog 1000 series data logger (Spectrum Technologies, Bridgend, UK). All planting and greenhouse conditions were replicated for the second year of this experiment, light conditions and temperature were similarly recorded to the first year). The average temperature inside the greenhouse for the first run of the primary experiment (2020) was 12°C and for the second run (2021) was 14°C. The average daily light integral (DLI) during the second run was 7.5 $mol \cdot m^{-2} \cdot d^{-1}$ (instrument malfunctioned in the first run). At the conclusion of the germination study, surviving *Carex* plants were moved to larger containers and held as plant stock.

Experiment 2

After poor germination in the first year of the first experiment, common wood sedge, ivory sedge, and Pennsylvania sedge (< 10% germination) were subjected to a follow up experiment to evaluate other factors which might influence germination. This second experiment was conducted using three stratification lengths (0 d, 7 d, and 60 d) with two planting depths (seeds buried 0.6 cm or seeds placed on the soil surface) arranged as a factorial. This experiment was conducted in Mar. 2020 and repeated in Aug. 2021. The 7 d stratification length involved cycling seed between -2 and 20°C every other day for a week. The 60 d stratification length was comparable to methods used in the prior experiments and represented industry standard recommendations for several *Carex* species. The experiment used six replications of 25 seeds and the same wetted horticulture propagation mix as the original experiment. When stratification was finished, all containers were moved to one of the OSU Horticulture Research Greenhouses on 27 Mar. 2021. Germination and environmental conditions were recorded using the same methods used in the prior studies, with germinations recorded daily for 30 d after the first germination and environmental conditions taken every 30 minutes. This experiment was repeated the following fall with the stratification period starting on 27 Aug. 2021 and the germination period beginning on 26 Oct. 2021. Heat mats were not included in this study based on minimal effects of temperature within the first year's results. All surviving *Carex* were moved to larger containers and held as plant stock.

Statistical Analysis

When there was no evidence of a year × treatment interaction, data from both years were subjected to a combined analysis across years using PROC GLIMMIX (SAS v9.4) fitted to a Gaussian distribution, with means separated using Fisher's protected LSD. Days to first germination data were fitted to a lognormal distribution and analyzed using data from species with greater than 10% germination due to too many missing values for other species. Initially, the model fixed effects included cold stratification pre-treatment, soil temperature, species, and their interactions and only analyzed plants without GA pre-treatment. Due to the unbalanced treatment structure, separate models were fitted to test effects of GA treatments resulting in a model with fixed effects having species, temperature, and GA rate for plants receiving not cold stratification. All statistical tests were evaluated at a significance level of $P < .05$ level.

Results

Effects of species, temperature, and stratification length on germination rate and timing

Palm sedge demonstrated a germination rate of 74%, which was more than double the next closest species oval plains sedge (20%), and resulted in a number of significant interactions (including the three-way interaction) that were determined to be artifacts of this large difference in magnitude among species rather than an important interaction (Fig. 1). The stratification × temperature interaction was significant, but this was due to a difficult to explain increase for 45 d stratification at 21 C (24%), and otherwise did not reveal any clear pattern (Table 1 and Fig. 2). Similarly, the significant species × temperature interaction resulted in no clear pattern and can be attributed to large differences in magnitude between palm sedge (high germination rate) and to the remaining low germinating species in common wood sedge, ivory sedge, and Pennsylvania sedge (data not shown). Both species ($P < .0001$) and stratification ($P < .03$) main effects were significant for germination, while temperature showed no effects (Table 1).

Germination main effects suggested a decline in germination at the 30 d length in comparison to stratification 60 d or longer (Fig. 3). Palm sedge did not show a strong pattern related to stratification treatment but showed an inexplicable decline at the 30 d length, presumably driving the significant main effect (Fig. 4). Oval plains sedge saw a 10% difference in germination from stratification lengths 30 d or shorter (13%) compared to stratification lengths 45 d or longer 45d (23%). However, this response was affected by a year × treatment interaction, wherein the control had equal or greater germination than any of those receiving stratification in year 2 (Fig. 5). Although not significantly different from the control, ivory sedge showed greater germination at 90 d compared to the 15 d length, and Pennsylvania and common wood sedge showed no response to stratification (Fig. 4).

Time until emergence was analyzed for the two best performing species (palm sedge and oval plains sedge) to better contextualize the effect that stratification had on the time needed for germination (Fig. 6). Both stratification length (P < .0001) and species (P < .0001) main effects were highly significant, while temperature and all interactions were not significant (Table 2).

Effects of GA, species, and temperature on germination rate and timing

For analysis of the GA concentration effects, seed receiving cold stratification were excluded from the dataset. The main effect of GA and each interaction with GA had no effect on germination (Table 3). The species × temperature and species main effects were significant for germination. In contrast, the GA main effect (P < .04) and the temperature × GA interaction (P < .03) had significant effects on days to first germination (Table 4).

Gibberellic acid treatments, regardless of concentration, hastened germination from 10 d for the control to 8 d on average for GA treated seed (data not shown). Whether this is directly a product of GA or the *Carex* seed soaking for 24 hours before planting is unknown. The temperature × GA interaction was significant for day to first emergence, but upon further investigation there was little evidence to suggest a trend that deviated from the main effects.

Germination improvement study

In general, the study shows an improvement in germination for all three species used in this trial compared to the *Carex* dormancy trial, with ivory sedge performing at a germination rate of 26% (compared to 4% in the first study), common wood sedge at 13% (up from 3%), and Pennsylvania sedge at 9% (compared to 1%) (Fig. 7). Despite this, all species in this study still performed at an unacceptable rate (<50%). The three-way species × stratification × depth interaction was significant for germination (Table 5).

For each species, planting depth was the most consistent factor affecting germination, with the surface planting resulting in the best germination for each species, although there were species-specific differences in how this interacted with stratification method (Fig. 10). When pooled across species, surface level planting depth resulted in 25% germination, while the deeper planting depth resulted in 7% (Fig. 8). More specifically, the surface level planting depth resulted in common wood sedge increasing germination 5-fold compared to the deeper depth, while ivory sedge germination doubled at the surface level depth, and Pennsylvania sedge resulted in a 7-fold increase with the surface level depth (Fig. 9). For Pennsylvania sedge, the 60 d stratification with surface planting resulted in the greatest germination among treatment combinations, followed next by both other surface planting treatments and the 60 d stratification with deeper planting depth (Fig. 11). For common wood sedge, stratification had no clear improvement on germination. For ivory sedge, the 60 d stratification with surface planting resulted in the best performance, having greater germination than the other surface planting treatments. Similar to the Pennsylvania sedge, the 60 d stratification with the deeper planting depth was equal to surface planting without stratification.

The germination improvement trial saw both species and stratification play a part in the time it takes for seeds to emerge, with common wood sedge (22 d) and Pennsylvania sedge (21 d) seeing a reduction in days to germinate compared to ivory sedge (25 d). Similar to the first study, stratification saw a decrease in days to germinate with the 60-d treatment (21 d) seeing a reduction in time compared to the control (25 d). The 7d intermittent freezing cycle was not included in this analysis due to poor performance (Table 6).

Discussion

The high germination percentage of palm sedge compared to the other four species supports previous studies (McGinnis and Meyer, 2011; Schütz 2000), but oval plains sedge performed worse than previously reported (63% germination) at a similar day temperature in a diurnal cycle of 14/1°C (Kettenring and Galatowitsch, 2007). Findings were also similar to remarks posted by the seed source (Prairie Moon Nursery, Wionna, MN), which stated palm sedge does not need stratification to germinate at a high rate, while oval plains sedge and ivory sedge are difficult to propagate from seed. Despite this, the poor germination for oval plains sedge in the present study suggests other aspects of pre-treatment or environmental conditions may be important to this species. Furthermore, the inconsistent response to cold stratification between years suggests the possibility of discrepancies between how seed was harvested and handled by the nursery. Prior reports have shown oval plains sedge to perform worse in temperatures 14°C and colder germinating at 25% after four weeks and 53% after 8 weeks in these conditions (Kettenring and Galatowitsch, 2007). The present study protocol was limited to a 30 d germination period since germination beyond this was deemed economically inefficient. Based on the present results and prior evidence of increased germination after 4 weeks, follow up studies may be warranted to track germination up to 8 or more weeks after planting. The current study also utilized a constant temperature regime rather than a diurnal temperature regime, which was used in at least one study wherein oval plains sedge had relatively high germination (Kettenring and Galatowitsch, 2007). These differences may account for the germination discrepancy between previous research and the present study.

The poor performance of Pennsylvania sedge in the present study is supported by previous findings (McGinnis and Meyer, 2011), which suggests this is a species of interests within the green sector but based off of performance it is not suggested that this species be propagated by seed. Pennsylvania sedge would benefit more to be spread clonally which is a practice some nurseries have already adopted (Prairie Moon Nursery, Winona, MN). A contributing factor to this is likely presence of a perigynia, which has been shown to reduce germination in darkness as well as when buried at 0.5 cm (Haggas et al., 1987). The present study used seed “as is” in order to simulate the typical nursery practices (Kettenring and Galatowitsch, 2007; McGinnis and Meyer 2007). Follow up research on methods for commercial removal of the perigynia and its effects on germination seem warranted. Both ivory sedge and common wood sedge have very little known about their germination habits as research over them has mainly focused on their ecology in naturalized stands. This study provides some of the first information on commercial propagation of these two species by seed.

Our study supports previous work that has found no effect of GA on *Carex* germination (Leck and Schütz; 2005; McGinnis and Meyer, 2011; Schütz, 2000). The poor performance of GA is most likely due to the hard primary dormancy of *Carex* seeds, meaning that once seeds were shed off of their parent plant they were in a "hard" dormancy as opposed to more common light or intermediate dormancy and therefore has primarily been alleviated by exposure to stratification over several weeks. The rates used in this study covered a range (500 ppm -1500 ppm) not tested for these specific *Carex* species before, the proper threshold of gibberellic acid may have yet to be reached for the *Carex* used in this stud. A broader range of concentrations is suggested to fully contextualize the effects of GA_3 on *Carex*. Gibberellic acid did seem to decrease the amount of time until first emergence from 10 to 8 d, which is important because this may be an alternative method to quickly decrease the total time until emergence. The experimental design did not account for the effect of simply soaking seeds in ethanol/water before planting, but these results show promise that soaking or other seed priming techniques may be of value in future tests.

The lack of temperature effect on germination was somewhat surprising and may be due to the narrow temperature range and relatively warm ambient temperatures in the greenhouse. A study (Schütz and Rave, 1999) looking at 32 *Carex* species under five singular temperatures (10°C, 15°C, 20°C, 25°C, and 30°C) and one diurnal temperature (22/10°C) cycle under light and dark conditions found that the odds of germinating increased by a factor of 1.14, for each degree (C) increase in non-stratified seeds. Additionally, the success of singular temperatures from the 32 species was very species specific with the best performing temperature treatment (30°) producing a range from 0-58% germination under all treatments. The singular diurnal temperature regime also saw a species specific effect, but saw a better performance with germination ranging from 0-76% under all treatments. From this, both a higher temperature range and the added use of a diurnal temperature regime may be required to identify the most efficient temperatures in the future.

In the primary study, planting depth was incorporated approximately 6 mm into the soil in order to ensure seed remained moist during stratification. The germination improvement study provides evidence that seeds may need light to germinate for several *Carex* species, similar to the report by Kettenring et al. (2006), which saw 100% germination in 8 *Carex* species (*C. brevior*, *C. comosa*, *C. cristella*, *C. granularis*, *C.*

hysterica, C. scoparia, C. stipata, and C. vulpinoidea) with exposure to 14 h of white light. This information has applications for both nursery propagation as well as field applications and is among the more critical outcomes of this project. The 7-d freeze cycle treatment was tested based on findings of McGinnis and Meyer (2011) working with Pennsylvania sedge. The poor performance of this treatment in the present study was disappointing but does not eliminate the possibility that the treatment could enhance germination in other *Carex* species.

Conclusion

Carex has much potential to be used in several industries ranging from alternative turf to prairie reintroduction, but its poor germination has slowed progress on its widespread commercial adoption. Palm sedge was the easiest to germinate, with a germination rate that was nearly 4-fold greater than any other species at 74%. Stratification was found to have an effect on common wood sedge at 60 d, oval plains sedge at 45 d, and ivory sedge at 60 d, while having no effect on palm sedge and Pennsylvania sedge. While GA has shown potential to improve germination in some plants, we did not find this to be true for *Carex* species. These studies are also among the first to characterize *Carex* species like common wood sedge and ivory sedge. Overall, to utilize the most efficient methods of propagation, our suggestion for palm sedge would be no stratification due to its naturally high germination rate and for oval plains sedge would be 45 d to see benefits on germination and the reduction of time until emergence. Surface level planting depths that ensure light reaches the seed is important for a large portion of *Carex* species, particularly the ones which performed poorly in this study. Future studies interested in further improving germination of these select species should look at diurnal temperature use in combination with surface level seed placement to receive the best germination rates from these species.

Acknowledgements

This research was funded in part by an ODAFF specialty crop block grant. The authors also wish to thank Bill Harris for consulting and Becky Cheary, Grace Rembold, Anna Ready, Ashton Franks, Stephen Stanphill and Abigail Hobbs for their contributions to this project.

Literature Cited

Baskin C, Baskin J. 1998. Ecology, Biogeography, and Evolution of Dormancy and Germination. Academic Press, Cambridge, Massachusetts, United States.

Baskin C, Baskin J, 2004. Germinating Seeds of Wildflowers, an Ecological Perspective. HortTechnology. 14(4):467–473. https://doi.org/10.21273/horttech.14.4.0467.

Bernard J. 1990. Life history and vegetative reproduction in *Carex*. Can J. Bot. 68(7):1441–1448. https://doi.org/10.1139/b90-182.

Budelsky R, Galatowitsch S. 1999. Effects of moisture, temperature, and time on seed germination of five wetland Carices: implications for restoration. Restor. Ecol. 7(1): 86-97. https://doi.org/10.1046/j.1526-100x.1999.07110.x.

Crew C, Myers M, Sherrard M, Elgersma K, Houseal G, Smith D. 2020. Stratification and perigynia removal improve total germination and germination speed in 3 upland prairie sedge species. Native Plant J. 21(2):120–131. https://doi.org/10.3368/npj.21.2.120.

Gimeno-Gilles C, Lelièvre E, Viau L, Malik-Ghulam M, Ricoult C, Niebel A. 2009. ABA-mediated inhibition of germination is related to the inhibition of genes encoding cell-wall biosynthetic and architecture: modifying enzymes and structural proteins in medicago truncatula embryo axis. Mol. Plant. 2(1):108–119. https://doi.org/10.1093/mp/ssn092.

Haggas L, Brown R, Johnston R. 1987. Light requirement for seed germination of payson sedge. J. Range Management. 40(2):180. https://doi.org/10.2307/3899216.

Hipp A. 2008. Field guide to Wisconsin sedges, an introduction to the genus *Carex* (Cyperaceae). Madison (Wisconsin): University of Wisconsin Press, Madison, Wisconsin, United States.

Houseal G. 2010. Plasticulture for seed production of wetland (*Carex*) species. Native Plant J. 11(1):58–64. https://doi.org/10.2979/npj.2010.11.1.58.

Kettenring K, Galatowitsch S. 2007. Temperature requirements for dormancy break and seed germination vary greatly among 14 wetland *Carex* species. Aquatic Bot. 87(3):209–220. https://doi.org/10.1016/j.aquabot.2007.06.003.

Kettenring K, Gardner G, Galatowitsch S. 2006. Effect of Light on Seed Germination of Eight Wetland *Carex* Species. Ann Bot. 98(4):869–874. https://doi.org/10.1093/aob/mcl170.

McGinnis E, Meyer M. 2011. After-ripening, stratification, and perigynia removal enhance Pennsylvania sedge germination. HortTechnology. 21(2):187–192. https://doi.org/10.21273/horttech.21.2.187.

Ning H, Wang W, Zheng C, Li Z, Zhu C, Zhang Q. 2014. Genetic diversity analysis of sedges (*Carex* spp.) in Shandong, China based on inter-simple sequence repeat. Biochem. Syst. Ecol. 56:158–164. https://doi.org/10.1016/j.bse.2014.05.014

Schopfer P, Plachy C. 1984. Control of seed germination by abscisic acid. Plant Physiol. 76(1):155–160. https://doi.org/10.1104/pp.76.1.155

Schütz W. 2000. Ecology of seed dormancy and germination in sedges (*Carex*). Perspectives Plant Eco. Evolution Systematics 3(1):67–89. https://doi.org/10.1078/1433-8319-00005.

Schütz W, Rave G. 1999. The effect of cold stratification and light on the seed germination of temperate sedges (*Carex*) from various habitats and implications for regenerative strategies. Plant Eco. 144(2):215–230. https://doi.org/10.1023/a:1009892004730.

Simmons M. Bertelsen S, Windhager, Zafian H. 2011. The performance of native and non-native turfgrass monocultures and native turfgrass polycultures: An ecological approach to sustainable lawns. Ecol. Engineering. 37(8):1095–1103. https://doi.org/10.1016/j.ecoleng.2011.03.004.

Smith H. 1982. Light quality, photoperception, and plant strategy. Annu Rev Plant Physiol. 33(1) 481–518. https://doi.org/10.1146/annurev.pp.33.060182.002405.

Stoller E, Sweet R. 1987. Biology and life cycle of purple and Yellow Nutsedges (*Cyperus rotundus and C. esculentus*). Weed Tech. 1(1):66–73. https://doi.org/10.1017/s0890037x0002916x.

Thompson K. 1985. Emergent plants of permanent and seasonally-flooded wetlands. Geobotany. 6:88–103. https://doi.org/10.1007/978-94-009-5504-2_3.

Van der Valk A, Bremholm T, Gordon E. 1999. The restoration of sedge meadows: Seed viability, seed germination requirements, and seedling growth of *Carex* species. Wetlands. 19(4):756–764. 19(4), 756-764. doi:10.1007/bf03161782.

Vishal B, Kumar P. 2018. Regulation of seed germination and abiotic stresses by gibberellins and abscisic acid. Front Plant Sci. 9: 1–15. https://doi.org/10.3389/fpls.2018.00838.

Wang W, Haver D, Pataki D. 2013. Nitrogen budgets of urban lawns under three different management regimes in southern California. Biogeochemistry. 121(1):127–148. https://doi.org/10.1007/s10533-013-9942-1.

Yue C, Wang J, Watkins E, Bonos S, Nelson K, Murphy J, Meyer W. A., Horgan, B. 2016. Heterogeneous consumer preferences for turfgrass attributes in the United States and Canada. Can J. Agri Economics/Revue Canadienne D'agroeconomie. 65(3):347–383. https://doi.org/10.1111/cjag.12128.

Figures

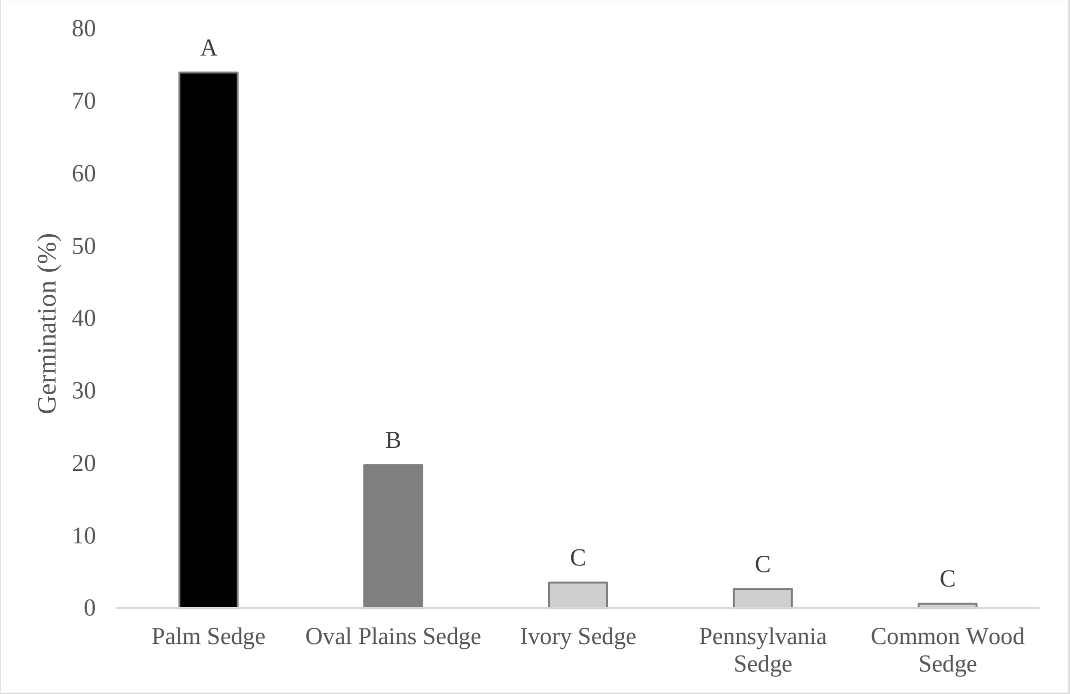

Fig. 1: *Carex* species effect on germination percentage. Data were pooled across two years, two temperatures, and seven cold stratification lengths (N=168). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05.

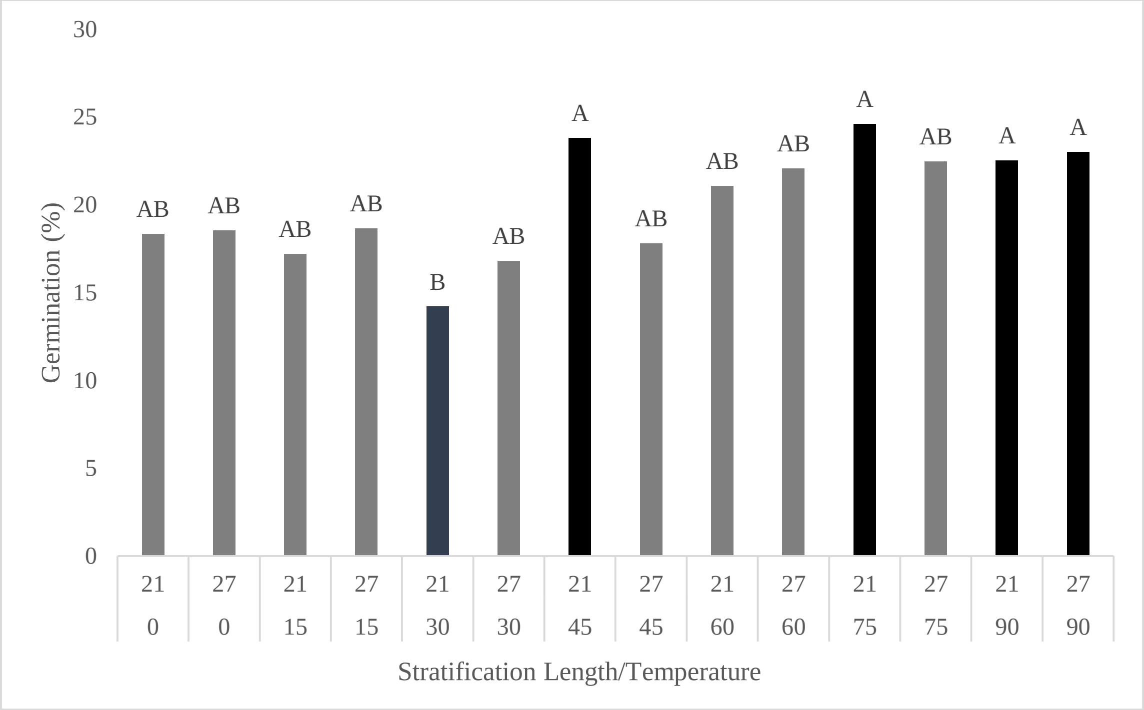

Fig 2: Stratification × temperature interaction effect on germination of selected *Carex* species. Data were pooled across two years and five species (N = 60). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05.

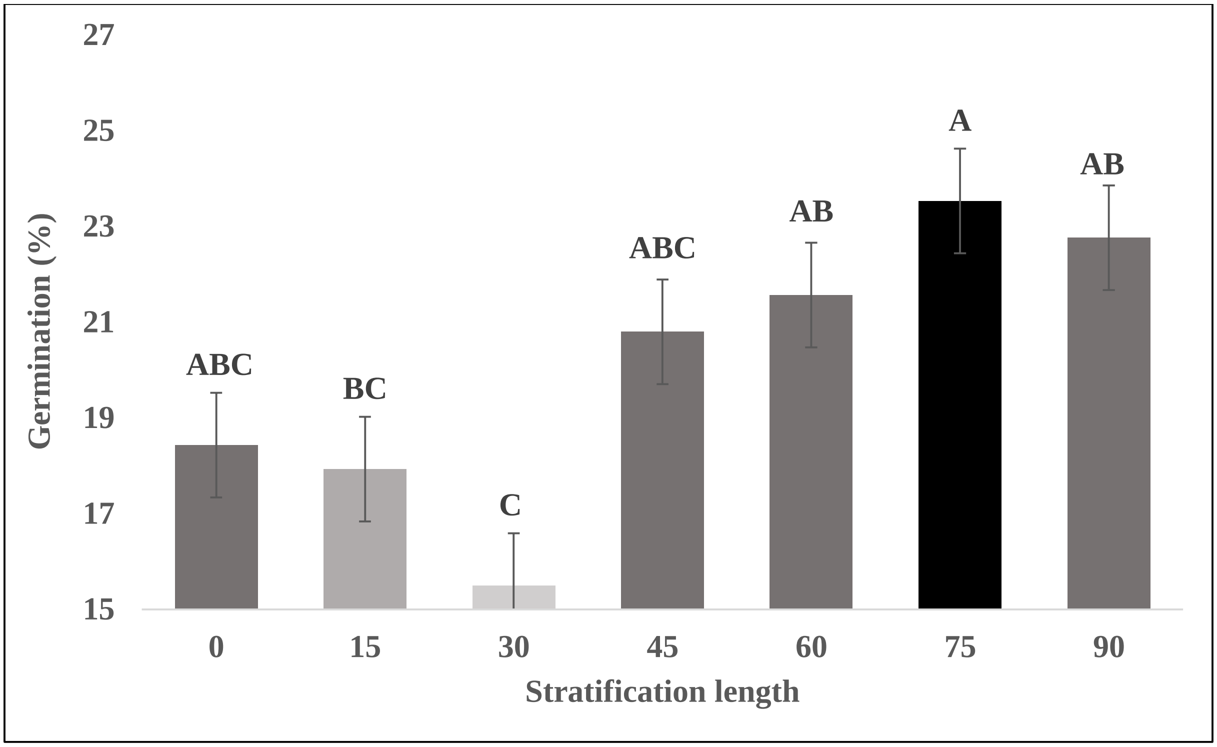

Fig. 3: Stratification main effect for germination of selected *Carex* species. Data were pooled across two years, two temperatures, and five species (N = 120). Mean labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05. Error bars represent standard error of the estimate.

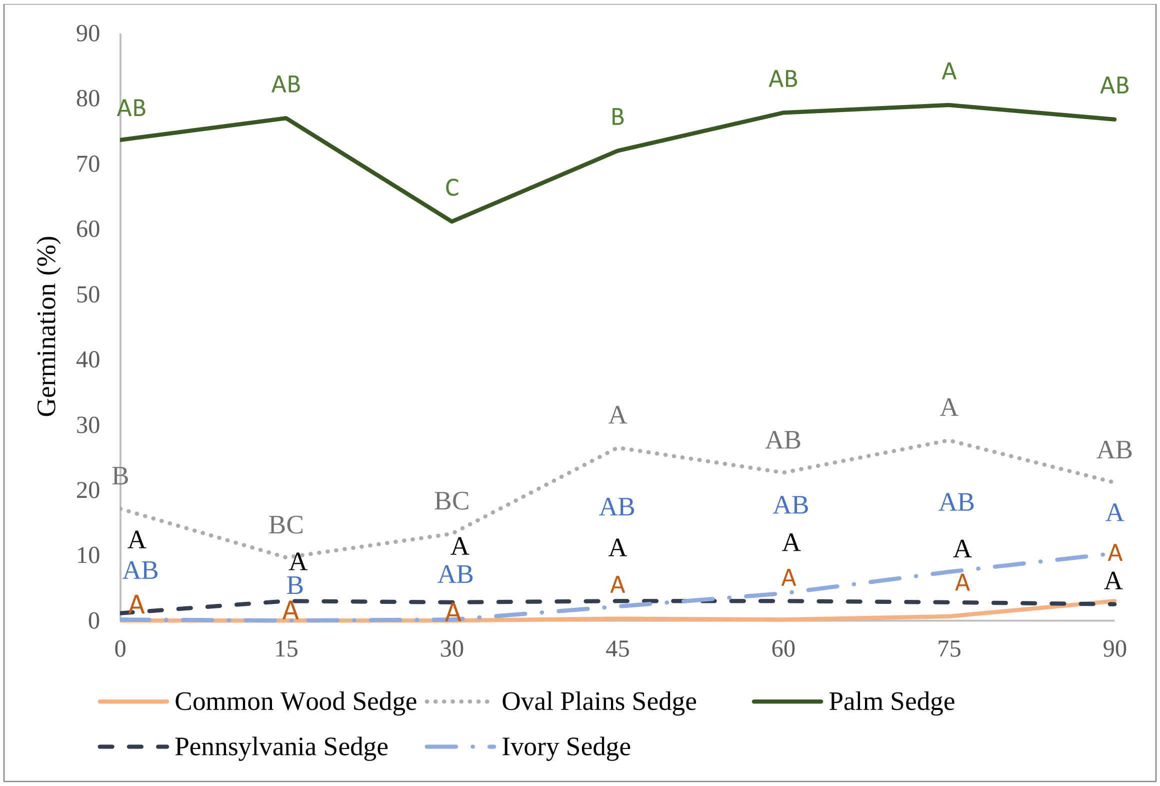

Fig. 4: Main effect of stratification length for each *Carex* species within the *Carex* germination trial. Data were pooled across two years and two temperatures (N = 24). Means labeled with different letters within the same colored line were significantly different according to Fisher's protected least significant difference test at P < .05.

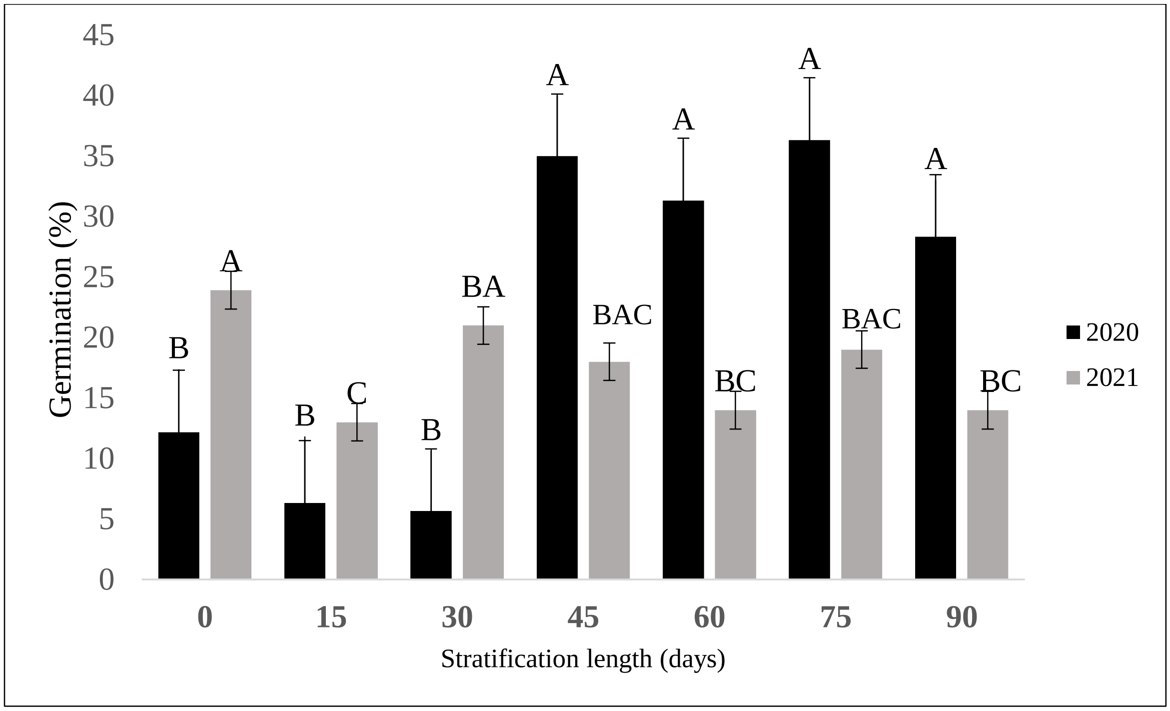

Fig. 5: Year × stratification length interaction on oval plains sedge for 2020 and 2021 for the *Carex* dormancy trial. Data were pooled across two temperatures (N = 12). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at $P < 0.05$. Error bars represent standard error of the estimate.

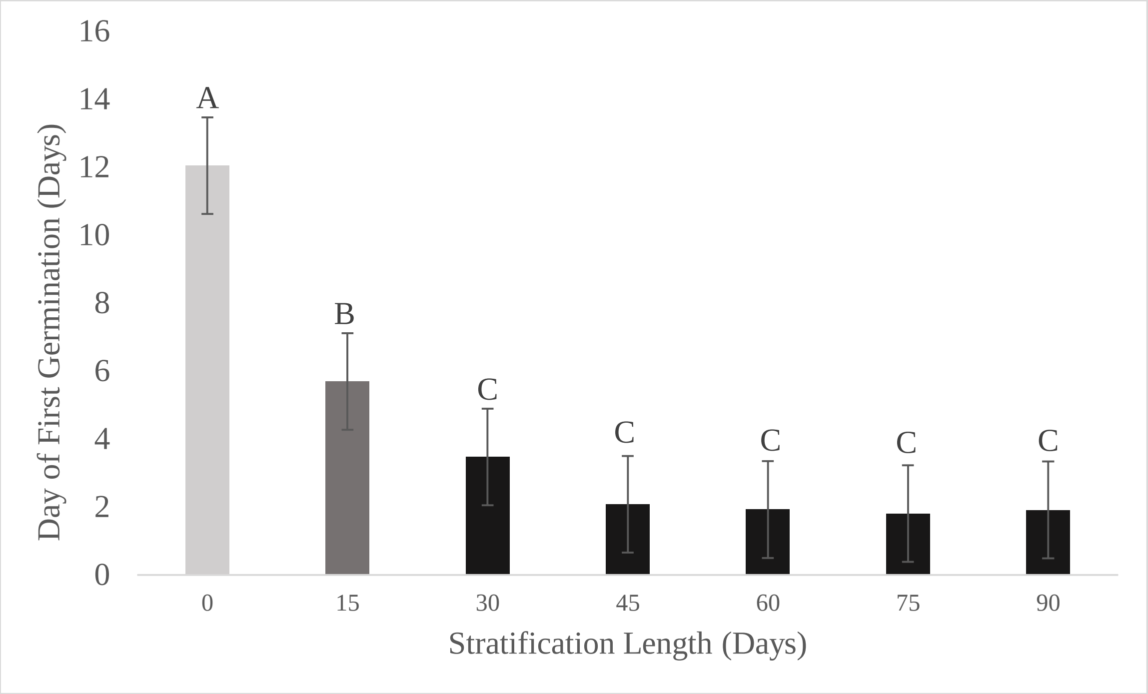

Fig. 6: Effect of stratification length on d to first germination for palm sedge and oval plains sedge. Data were pooled across two years and two temperatures (N = 24). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05. Error bars represent standard error of the estimate.

Fig. 7: *Carex* species main effect for germination of the poor performing *Carex* species. Data were pooled across two planting depths, two years, and three stratification treatments (N = 72). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05. error bars represent standard error of the estimate.

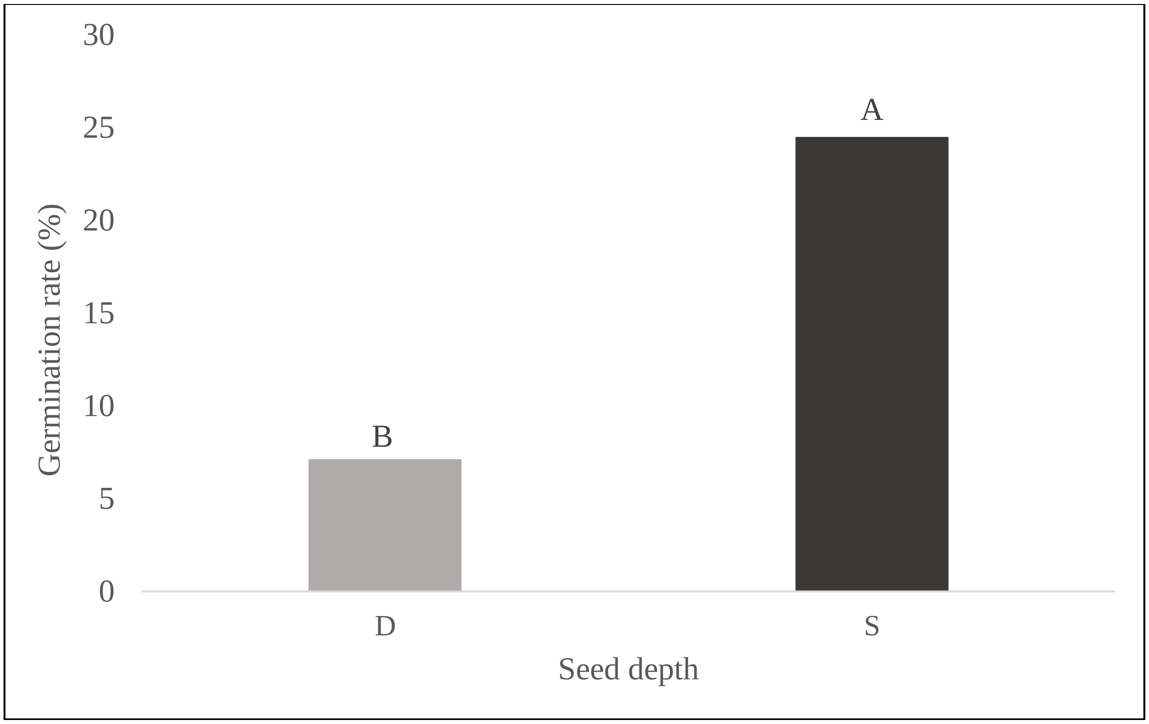

Fig. 8: Seed planting depth main effect on germination of poor performing Carex species. Data were pooled across three species, two years, and three stratification treatments (N = 108). Seed planting depth was applied at the surface (S) or deeper (D) and incorporated into the soil to a final depth of 6mm. Means labeled with different letters were significantly different according to Fisher’s protected least significant difference test at P < .05.

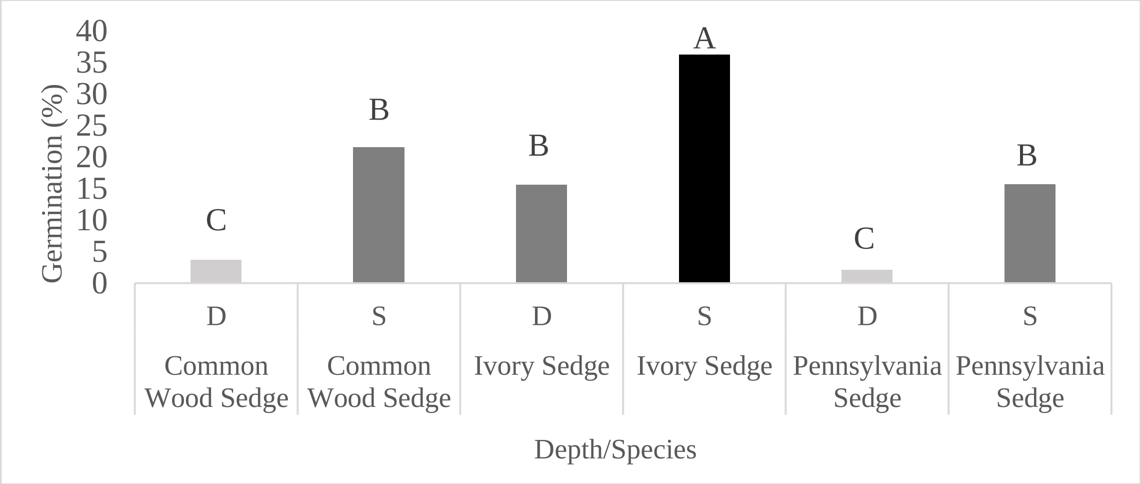

Fig. 9: Depth × species interaction for the germination of poor performing *Carex* species. Data were pooled across two years and three stratification treatments (N = 36). Seed planting depth was applied at the surface (S) or deeper (D) and incorporated into the soil to a final depth of 6mm. Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05.

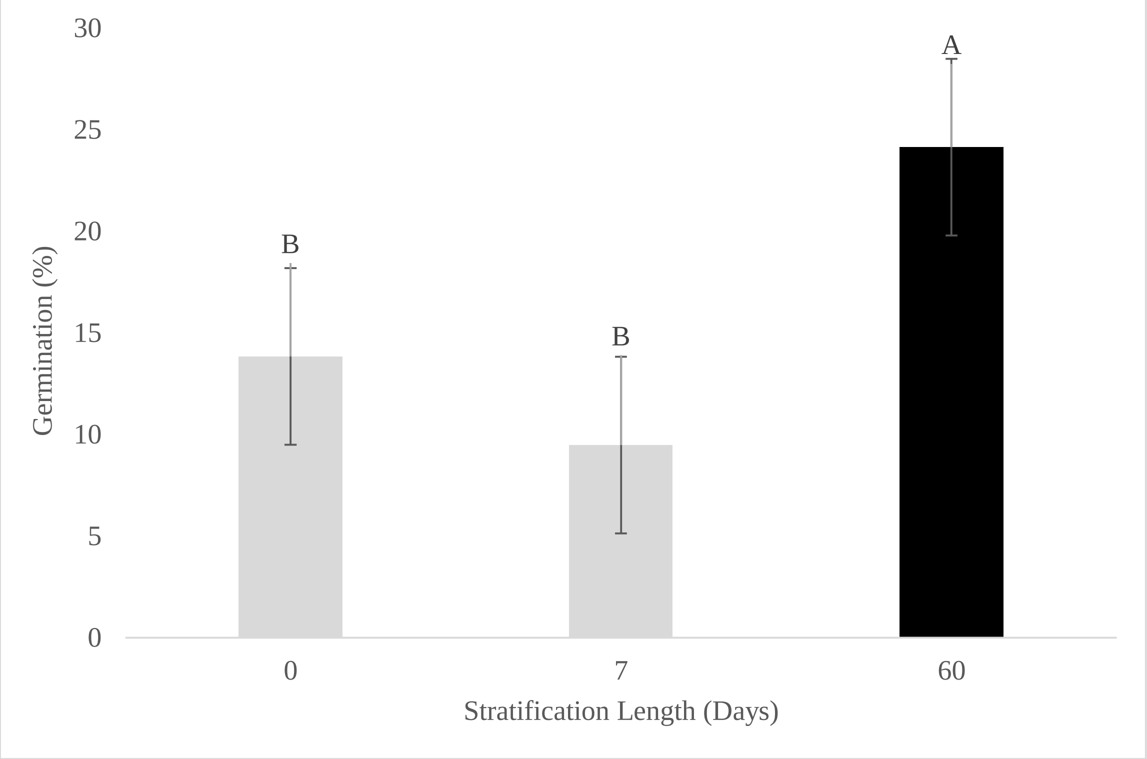

Fig. 10: Stratification main effect for germination of poorly performing *Carex* species. Data were pooled across three species, two planting depths, and two years (N = 72). The 7 d stratification involved an intermittent freezing cycle (exposing seeds to freezing conditions for 24 hr followed by room temperatures conditions for 24hr for a total of 7 d). The 60 d stratification involved placing seed in moist media and maintaining them at 2 °C. Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at $P < .05$. Error bars represent standard error of the estimate.

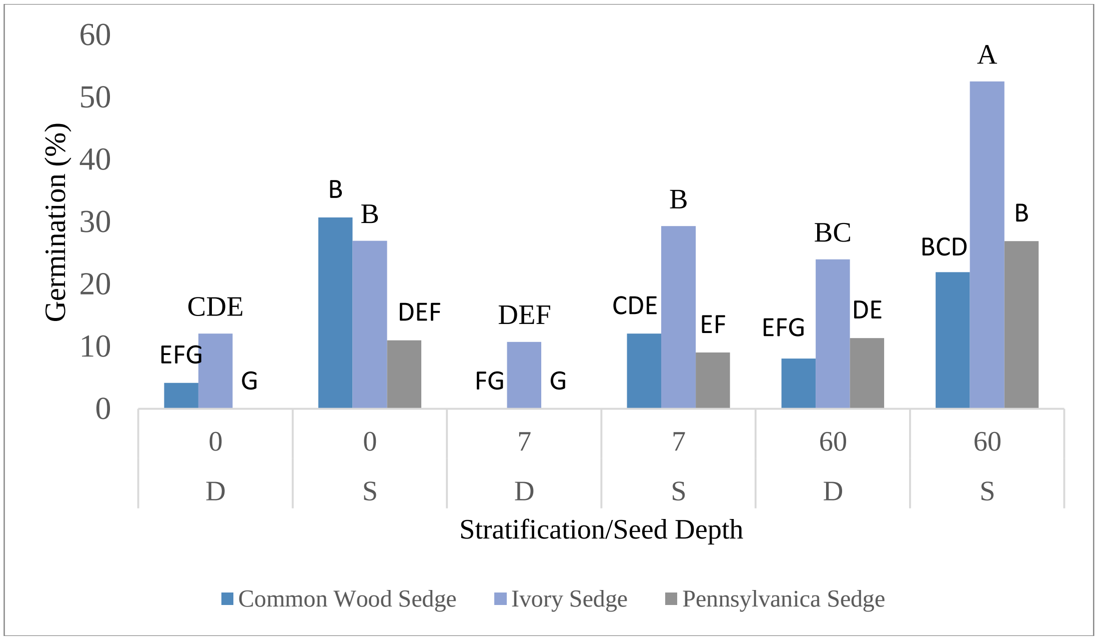

Fig. 11: The species × depth × stratification three-way interaction effect on germination of poorly performing *Carex* species. Data were pooled across two years (N = 12). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at $P < .05$.

Tables

Table 1: ANOVA table for combined analysis of germination for five *Carex* species excluding seed receiving gibberellic acid treatment.

Source	**Num DF**	**P-value**
Species	4	***[Z]
Stratification	6	*
Temperature	1	NS
Species × Stratification	24	NS
Species × Temperature	4	*
Stratification × Temperature	6	**
Species × Stratification × Temperature	24	*

[Z] *, **, ***, and NS= $P \leq 0.001$, $P \leq 0.01$, $P \leq 0.05$, and $P > 0.05$, respectively.

Table 2: ANOVA table for combined analysis of first day of germination for five *Carex* species excluding seed receiving gibberellic acid treatment.

Source	**Num DF**	**Pr > F**
Species	1	***[Z]
Stratification	6	***
Temperature	1	NS
Species × Stratification	6	NS
Species × Temperature	1	NS
Stratification × Temperature	6	NS
Species × Stratification × Temperature	6	NS

[Z] *, **, ***, and NS= $P \leq 0.001$, $P \leq 0.01$, $P \leq 0.05$, and $P > 0.05$, respectively. GA=0:

Table 3: ANOVA table for combined analysis of germination for five *Carex* species excluding seed receiving cold stratification treatment.

Effect	**Num DF**	**Pr > F**
Species	4	***[Z]
Gibberellic Acid (GA)	3	NS
Temperature	1	NS
Species × GA	12	NS
Species × Temperature	4	*
Temperature × GA	3	NS
Species × Temperature × GA	12	NS

[Z] *, **, ***, and NS= $P \leq 0.001$, $P \leq 0.01$, $P \leq 0.05$, and $P > 0.05$, respectively.

Table 4: ANOVA table for combined analysis of first day of germination for five *Carex* species excluding seed receiving cold stratification treatment.

Source	**Num DF**	**Pr > F**
Species	1	***[Z]
Gibberellic Acid (GA)	3	*
Temperature	1	NS
Species × GA	3	NS
Species × Temperature	1	NS
Temperature × GA	3	*
Species × Temperature × GA	3	NS

[Z] *, **, ***, and NS= $P \leq 0.001$, $P \leq 0.01$, $P \leq 0.05$, and $P > 0.05$, respectively.

Table 5: ANOVA for combined analyses of the germination improvement trial (additional trial created to increase germination in the 3 lowest *Carex* species from the primary dormancy trial).

Effect	**Num DF**	**Pr > F**
Species	2	***[Z]
Stratification	2	**
Depth	1	***
Species × Stratification	4	***
Species × Depth	2	**
Stratification × Depth	2	NS
Species × Stratification × Depth	4	***

[Z] *, **, ***, and NS= $P \leq 0.001$, $P \leq 0.01$, $P \leq 0.05$, and $P > 0.05$, respectively.

Table 6: ANOVA for combined analysis of the days to germinate for the germination improvement trial (additional trial created to increase germination in the 3 lowest *Carex* species from the primary dormancy trial).

Effect	**Num DF**	**Pr > F**
Species	2	*[Z]
Stratification	2	*
Depth	1	NS
Species × Stratification	4	NS
Species × Depth	2	NS
Stratification × Depth	2	NS
Species × Stratification × Depth	4	NS

[Z] *, **, ***, and NS= P ≤ 0.001, P ≤ 0.01, P ≤ 0.05, and P > 0.05, respectively.

CHAPTER II

Evaluation of *Carex* Species and *Muhlenbergia schreberi* as Low-input, Shaded Lawns in Oklahoma

Introduction

There is an estimation that 25% of turfgrass is managed under some form of shade, and the problem of shade spans parks, residential lawns, golf courses, and sports fields (Beard, 1973). Fundamentally, shade stress is the reduction in light available for photosynthesis which can be measured in terms of photosynthetic photon flux density (PPFD), which in turn reduces the carbohydrates available for normal growth and development (Bell and Danneberger, 1999; Wherley et al., 2005). Plants subjected to shade stress demonstrate surface level roots (Jiang et al., 2004; Baldwin and McCarty, 2008), increased internodal distance (Stanford et al., 2005), reduced tillering (Dudeck and Peacock, 1992), and the etiolation of shoots (Allord et al., 1991). Shade caused by trees (foliar or vegetative shade) can be especially detrimental as shade selectively filters red light, which affects plant phytochrome activity and induces a more severe shade response (Bell et al., 2000; Wherley el at., 2011). Shade ultimately leads to poor quality turf and a plant that is more susceptible to secondary stressors including drought, disease, and traffic (Baldwin et al., 2009; Tegg and Lane, 2004).

Shade tolerance varies widely with turfgrass species, as well as the cultivar (Baldwin et al., 2009; Dudeck and Peacock, 1992; Trappe et al., 2011). For example, bermudagrasses (*Cynodon dactylon*) are widely regarded as having poor shade tolerance and may require over 20 mol m^{-2} d^{-1} to form an acceptable lawn (Cherti et al., 2019; Tegg and Lane, 2004). Japanese lawngrass (*Zoysia japonica*) is considered among the more shade tolerant warm-season turfgrasses having reported minimum light requirements of 10 to 15 mol m^{-2} d^{-1} (Baldwin et al., 2009; Russel et al., 2020). Cool-season turfgrasses such as tall fescue (*Lolium arundinaceum*) have excellent shade tolerance, particularly in deciduous tree shade, but typically has greater water requirements and is susceptible to devastating disease outbreaks requiring frequent renovation (Swarthout et al., 2009; Wherley et al., 2005). These traditional choices for residential lawns create a tradeoff between higher inputs and shade tolerance (Russell et al., 2020; Turgeon and Kaminski, 2019). Recent surveys of homeowners demonstrated their first preference is for turfgrasses having low maintenance requirements, with highly ranked preferences for drought and shade tolerance (Ghimire et al., 2016; Yue et al., 2016).

Development of low input plant materials that can persist as a mowed turf under dry shade would have broad application across the turfgrass industry. Improvement in adaptation of commonly used turfgrass species to dry shaded conditions is an ongoing effort at several research institutions in the United States (Bunell et al., 2005; Watkins et al., 2014; Wherley et al., 2011). In addition to turfgrass breeding, there is likely value in identifying novel species that have adaptation to regular mowing, drought, and shade. Exploration of dry woodlands and mature parks across Oklahoma, one can observe naturalized stands of perennial ground covers from the genus *Carex* persisting and, in some cases, creating near-monostands with little inputs. The genus *Carex* belongs to the sedge family (*Cyperaceae*) that is home to more than 5000 species with 600 native to North America (Bernard, 1990; Goetghebeur, 1998). *Carex* has many species with turf-like characteristics and many can be grown in full shade or sun (Bernard 1990; McGinnis and Meyer, 2011; Schütz, 2000). Several of these species are native to Oklahoma and already sold in the commercial nursery trade. *C. amphibola* (gray sedge) is a coarse-textured species having an average leaf width of 0.3 cm (Prairie Wind Nursery, Norman, OK). *C. texensis* (Texas sedge) is a medium-textured species, while *C. leavenworthii* (Leavenworth's sedge) is a medium-fine-textured species. Each of these species has shown potential for use in mowed environments, either through personal observation or marketing literature from the industry (McGinnis and Meyer, 2011; Ning et al., 2014; Wang et al., 2013). In some cases, improved cultivars have been released for traits of interest. For example, *C. muskingumensis* (palm sedge) 'Little Midge' is a dwarf-type selection from an otherwise tall species. In most cases, the Oklahoma nursery trade relies on variety not stated (VNS) nursery stock for the genus.

Published research on *Carex* has primarily focused on improving seed propagation through light and stratification (Budelsky and Galatowitsch, 1999; Crew et al., 2020; Kettenring and Galatowitsch, 2007; Schutz 2000), or ecosystem restoration studies to reintroduce *Carex* species into their native habitats (Budelsky and Galatowitsch, 1999; Leck and Schutz, 2005; Scutz and Rave 1999; Van der Valk et al., 1999). There is a lack in knowledge over how native *Carex* species perform as a low-input lawn in dry shade. Development of regional performance data for selected species may broaden their potential for wider use.

In addition to *Carex*, dry woodland areas of Oklahoma commonly host specimens of nimblewill (*Muhlenbergia schreberi*), a warm-season perennial grass traditionally regarded as a weed species in cool-season turfgrass systems (Featherly, 1938; de Moraes et al., 2014a; de Moraes et al., 2014b). As it currently stands there is a small amount of published literature on beneficial use of this species, including a few studies showing promise for control of fungal diseases when grown as a ground cover in peach (*Prunus persica*) orchards (Olien, 1995). Interestingly, seed for this native species can be purchased through online vendors, although the origin and expected performance of such products are unknown.

To create regional information on performance of native perennial ground covers for use as managed turf, a field study was conducted to compare selected *Carex* species and nimblewill to industry standard warm-season turfgrasses managed as a low-input shaded lawn.

Materials and Methods

First Year Plot Establishment and Maintenance

Field trials were planted at the Oklahoma State University (OSU) Entomology and Plant Pathology Experiment Station in Stillwater and the OSU Cimarron Valley Research Station in Perkins on 20 and 26 May, 2020 respectively. These locations were chosen for the presence of mature pecan trees (*Carya illinoinensis*) that produced relatively uniform shade in the plot area (≈73%). The soil was tilled, raked, and firmed in preparation for planting plots. The experiment was arranged as a randomized complete block design having four replications. Treatments were assigned in a split-plot structure with two irrigation regimes (whole plot), and eight plant materials (sub-plot). Of the eight entries in this study, four were *Carex* species (palm sedge, gray sedge, Texas sedge, and Leavenworth's sedge) obtained as plugs from a local nursery (Prairie Wind Nursery, Norman, OK). The other four species were from the grass (Poaceaea) family, with two being nimblewill sourced from online vendors (Ernst Seeds, Meadville, Pennsylvania; Roundstone Native Seed LLC, Upton, Kentucky) and the other two entries being Japanese lawngrass (*Zoysia japonica* 'El Toro') and bermudagrass (*Cynodon dactylon*

‘Riley’s Super Sport’), which were chosen as industry standard warm-season turfgrasses for moderately shaded lawns in Oklahoma. The Perkins plot possess loamy fine sand soil, while the Stillwater plot possess primarily loam and clay loam soil. *Carex* spp., Japanese lawngrass, and bermudagrass were established as 2.5-cm plugs on 15-cm spacing, while nimblewill was seeded using a shaker jar at rate of 5 g/m^2 and then covered with a lightweight geotextile material (American Plant Production & Services Inc. Oklahoma City, OK) until seedling emergence. All plots were fertilized with 6-2-0 (Milorganite, Milwaukee Metropolitan Sewerage District, Milwaukee, WI) immediately after planting at 48 kg/ha N, and irrigated daily using portable impact sprinklers until germination from the seeded species. After seed germinated, irrigation was applied uniformly to all plots in the establishment year, with the Perkins location watered twice per week and the Stillwater location watered once weekly and each receiving a total of 2.5 cm per week. Irrigation was discontinued at both locations on 13 Oct. 2020 due to cool wet weather conditions. Glyphosate (Buccaneer Plus®, Tenkōz inc, Alpharetta, GA) was applied as a 2% (80 ml/3.8 L) solution with a hand pump backpack sprayer as needed to prevent cross-contamination between adjacent plots as well as to reduce weed pressure, most notably, crabgrass (*Digitaria*), dallis grass (*Paspalum dilatatum*), goosegrass (*Eleusine indica*), and white clover (*Trifolium repens*). Plots were mowed every other week at a 10 cm mowing height using a rotary mower (Honda HRC216/HRC2163HXA, Minato City, Tokyo, Japan).

For second year maintenance, Oxadiazon (Ronstar 2G, Bayer, Leverkusen, Germany) was applied 19 Mar. 2021 at a rate of .001 $kg/m^{2\ to}$ reduce annual weed pressure while plots continued to become established. A slow-release fertilizer (POLYON 42-0-0 Granular Harrell's, Oklahoma City, OK) was applied 13 April. 2021. at a rate of 0.9 g/m^2. Plots were mowed weekly at 10 cm using a rotary mower and clippings returned.

A hose-end, battery-powered electric controller valve (Honda Model HRC18RNVAPRO) was used to set run times for each location. High-efficiency rotary spray nozzles (Rain Bird, Azusa, CA), were used resulting in a system that applied 1.6 cm/hr for the Stillwater location (1618 m^2) and 3.6 cm/hr for the Perkins location (2833 m^2). Run times were set to irrigate twice per week (Mondays and Thursdays) and applied a total of 2.5 cm every week. Irrigation treatments (irrigated and non-irrigated) were initiated on 4 June 2021 for Stillwater and 10 June 2021 for Perkins, and irrigation was applied through the first week of Oct. at both locations.

In Nov. 2020, an ice storm resulted in loss of several shade-inducing branches in the Perkins site. To maintain shade, a structure was installed on 26 May 2021 to simulate the return of leaves to the pecan trees. The structure was designed as a tent over the plots using steel rope mounted to the neighboring trees such that it created a top ridge in the middle of the plot area 1.8 m above the ground. A polywoven shade cloth was then hung across the top ridge and fastened to PVC pipe that had been mounted horizontally across a series of 2 m T-posts on the edge of the plot. Additional T-posts with tennis balls placed on the top were installed underneath the fabric to prevent sagging.

Data were collected every other week from 21 July 2020 to 13 Oct. 2020 to quantify canopy coverage during establishment using a spectral reflectance meter (RapidSCAN CS-45 Handheld Crop Sensor, Salfords, UK) to calculate a normalized difference vegetation index (NDVI), image analysis of green coverage using ImageJ (JIH, Java 1.8.0-172,) and pictures from a Canon PowerShot G16 (Melville, NY) mounted to a light box, and visual ratings of turfgrass quality using National Turfgrass Evaluation Program (NTEP) guidelines (Morris and Shearman, 2020). A quantum sensor connected to a Watchdog (Spectrum Technologies, Aurora, IL) 1000 series data logger with a built-in temperature sensor was used to measure PPFD and ambient temperature on 30 minute intervals.

Data were collected in the same manner and method in year 2, with the exception of a soil moisture meter (Field Scout TDR 350, Spectrum Technologies Inc., Aurora, IL) used periodically through the summer to verify the effectiveness of the irrigation system.

A combined analysis was conducted with location considered a random effect and species, irrigation, date, and their interactions considered fixed effects. Data were analyzed using PROC GLIMMIX (SAS v 9.4) with a repeated measures model, and means were separated using Fisher's protected LSD at the $P<.05$ level. There were no significant interactions between location and treatment, therefore data were pooled across location for subsequent analyses.

Results

Establishment year

Establishment rate at 15 weeks after planting was similar across species (53% coverage) with the exception of palm sedge, which had a slightly smaller green coverage value than Japanese lawngrass (Fig. 2.1). Late season coverage was also similar across most species with the exception of Leavenworth's sedge having greater coverage than bermudagrass and nimblewill obtained from the Roundstone (hereafter referred to as Nimblewill-Roundstone) seed source (Fig. 2.2). During spring-up of the second growing season (March 2021), grasses were emerging from complete dormancy, while *Carex* maintained green color through winter (Fig. 2.3). Leavenworth's sedge outperformed (28%) both palm sedge (17%) and bermudagrass (18%) on this date. Japanese lawngrass (19%) performed as well as well as the remaining *Carex* species (22%) as well as both nimblewill seed sources (23%).

Year 2: effects of species, date, and irrigation

For TQ, NDVI, and green coverage, data were affected by the species × date and irrigation × date interaction terms (Table 2.1). After July, all entries were exposed to increasingly hot and shaded conditions which resulted in poorer performances from species, such as palm sedge that were not fully established as a turf in the second growing season (Fig. 2.4-6).

Turf quality scores were low (<5) for each species, due to the low input nature of this trial (Fig. 2.7). The conventional turfgrasses outperformed other species with an average TQ of 3.8 and 4.2 for bermudagrass and Japanese lawngrass, respectively. Nimblewill obtained from the Earnst seed source (hereafter referred to as Nimblewill-Earnst) performed comparatively well with an average TQ of 3, which was greater than each of the Carex species. Gray sedge, Leavenworth's sedge, and Texas sedge, along with nimblewill-Roundstone received poor ratings (<3) but outperformed palm sedge which averaged a rating of 1.2 and did not persist in several replicates.

Similar patterns were seen for NDVI, with both Japanese lawngrass (.63) and bermudagrass (.57) demonstrating the greatest mean NDVI, and neither being significantly different from each other (Fig. 2.8). Nimblewill-Earnst (.52) was not significantly different from bermudagrass, gray sedge (.46) or the other nimblewill entry (.47). Palm sedge produced the lowest NDVI (.35), although this was not significantly different from Leavenworth's sedge.

Green coverage demonstrated similar patterns as other metrics (Fig. 2.9). Japanese lawngrass (63%) outperformed bermudagrass (57%), while nimblewill-Earnst outperformed the *Carex* species. Nimblewill-Roundstone (47%) was similar to gray sedge (46%), Leavenworth's sedge (42%), and Texas sedge (45%), with each outperforming palm sedge (36%).

Although the species main effects were largely consistent, there were a few variations across sampling dates that resulted in the significant species × date interaction for each variable. Specifically, TQ of the conventional turfgrasses generally increased from early rating dates and peaked in the middle of the summer with scores of 5.4 and 4.7 in late July for Japanese lawngrass and bermudagrass, respectively (Table 2.2). In contrast, both nimblewill entries emerged from winter dormancy well but began to decline in TQ as the summer progressed. Nimblewill-Earnst (3.9) outperformed both the bermudagrass (3.4) and Japanese lawngrass (3.6) in June before the decline, which resulted in performance equivalent to the *Carex* species by Sept. The best performing *Carex* species (gray sedge, Leavenworth's sedge, and Texas sedge) performed poorly but consistently throughout the season, which was indicative of their poor spread but acceptable persistence under the experimental conditions. Both NDVI and green coverage followed similar patterns for the species by date interaction with image analysis (Table 2.3 and Table 2.4).

The significant irrigation × date interaction saw a high level of significance in each performance response variable (Fig. 2.10). Namely, all entries similarly declined over time during the heat of summer, especially after June, where non-irrigated plots (24% green coverage) fared worse than irrigated plots (31% green coverage).

Discussion

Conventional turfgrasses performing well in this study was indicative of their creeping growth habit of both species and lack thereof for the other species (Bernard, 1990; Christians, 2003). Furthermore, these turfgrass entries have the benefit of previous breeding and selection efforts and are considered improved cultivars, whereas the other entries are either VNS, selected for non-turf usage, or, in the case of nimblewill, likely to be wild-types. Although bermudagrasses are known to lack shade tolerance, ‘Riley’s Super Sport’ is widely regarded as the most shade tolerant within the species (Baldwin et al., 2008; Chherti et al., 2021), having been ranked ahead of commonly used cultivars such as ‘Tifway’ and ‘Tift 94’ under 58% shade cover (Bunell et al., 2005; Bunell et al., 2005b; Gaussion et al., 1988). ‘Riley’s Super Sport’ averaged an NDVI of .57 under 63% shade throughout a year (Dunne et al., 2017). Japanese lawngrass, as a species, has shown good shade tolerance among warm-season turfgrasses (Baldwin et al., 2009; Russel et al., 2020; Wherley et al., 2011). ‘El Toro’ showed the ability to fill and maintain >90% turf coverage over 2 years under 49% shade cover (Trappe et al., 2011), as well as averaging .63 NDVI under 63% shade through two trials running from early fall to winter (Zhang et al., 2016).

The poor performance for all *Carex* species is due in part to the previously mentioned bunch-type growth habits. The plant spacing used in the present trial (15 cm) was chosen based on comments from the nursery providing the plant materials and is likely to be realistic for most installations of these species (Bob Faris, personal communication). The present study suggests closer spacing or higher inputs during establishment, may be required to achieve complete coverage of *Carex* species in a timely manner. Unfortunately, closer spacing decreases the economic viability of plugging as a means of establishment. Alternative propagation methods such as seed or sprigging may warrant future investigation to solve this issue. Preliminary research suggests locally collected seed of Leavenworth's sedge showed greater than 50% germination when subjected to cold, moist stratification for 60 d (Shokoya et al., 2021). However, seed readily shatters and therefore unique production systems may be required to scale up yields.

There has been little to no formal research committed to looking at the majority of these *Carex* species ability to grow as an alternative turf (Greenlee, 2010). Texas sedge has been referenced as an option for low maintenance lawns but there has been no trials or studies dedicated to growing any of the three species in low input conditions until this current study. The similar performance of gray sedge, Leavenworth's sedge, and Texas sedge suggests each of the species has similar promise for use as low input lawns, and personal preference for leaf texture should be the deciding factor. More specific screening efforts are required to determine the relative shade, drought, traffic, and mowing tolerances of individual species.

The poor performance of palm sedge, a dwarf selection of an otherwise tall sedge species, suggests this species and/or this subspecies population are not well-adapted to low-input lawns in Oklahoma. Throughout the first growing season, palm sedge routinely demonstrated the lowest green coverage, and from there the species was never able to grow or spread at an acceptable rate. Due to the lack of research over the dwarf variety, nurseries have primarily described optimal growing conditions for palm sedge as needing moist soil conditions, which were not the conditions tested through this study as even the irrigated plots were maintained at relatively dry conditions (New Moon Nursery, Woodstown, NJ; Bohn's Farm and Greenhouse Inc, Maryville, IL).

The lack of an irrigation × species interaction effect may correspond to both treatments being relatively dry and most plots were still growing in. Alternatively, low input species such as those used in this study may not be as responsive to higher soil moisture and further study with a broader range of irrigation treatments may be necessary to understand production needs of these plants (Hilaire et al., 2008; Pincetl et al., 2018).

Examples of intentional nimblewill plantings in the literature are rare and typically associated with the plant as a weed species. de Moraes et al. (2014b), investigating chemical control options for nimblewill as a weed species, reported the plants developed slowly in both biomass and growth in its first 5 weeks after germination. Previously, Olien (1995) used a 2.2 g/m^2 rate in consecutive years in addition to mechanical mowing and annual weeding in order to establish nimblewill as a ground cover in peach production. In their report, they found they were able to create a dense enough ground cover to reduce the ring nematode *Criconemella xenoplax* to acceptable levels. As nimblewill was the only seeded entry, the present study lacks an appropriate comparison for making similar observations on establishment rate. The seeding rate used in the present study (5 g/m^2) appeared to create an appropriately dense stand quickly and could be used to guide future studies. According to the seed supplier, nimblewill has approximately 750,000 seed per pound, and similar sized turfgrass seed requires a planting rate of 30 to 40 g/m^2 (Roundstone Nursery). Follow up experiments should be used to improve these seeding rate recommendations, particularly if more turf-type nimblewill germplasm can be obtained. The late season decline in performance for nimblewill is consistent with use of upright ecotypes of the species and poor tolerance to mowing (Wherley et al., 2011). Further details on the origin of the seed is lacking, which is probably to be expected with unimproved native seed stock. Whether seed was sourced from plants that had been subjected to selection pressure from mowing or were simply non-mowed ecotypes from woodland areas is not clear. Between the two seed sources, Earnst performed slightly better than Roundstone, which suggests some variation exists within the species. Selection of genotypes persisting as weeds in fine turf may lead to better understanding of heritability of turf-type traits within the species.

This study provides evidence that gray sedge, Leavenworth’s sedge, and Texas sedge can persist under low input mowed conditions during the heat of summer under shade in Oklahoma. Furthermore, *Carex* species provide year-long green color similar to what cool-season turfgrasses provide, presumably with superior drought and disease resistance than cool-season turfgrasses (Bernard, 1990; Schütz, 2000). Continued efforts to increase stand density, either through higher planting rates or alternate propagation methods, is needed to advance these species that show promise for use as sustainable turf alternatives for dry shaded conditions.

Conclusion

This study provides one of the first descriptions of intentional establishment as mowed turf for several native perennial species. Conventional warm-season turfgrasses (bermudagrass and Japanese lawngrass) outperformed the native *Carex* species for coverage and turfgrass quality, predominantly because of their creeping growth habit and insufficient planting density. Persistence and year-long color retention were observed from the most of our *Carex* species, while fast establishment was noted for nimblewill. Nimblewill, gray sedge, Leavenworth’s sedge, and Texas sedge have the potential to be used as an alternative to conventional turfgrass species, but adjustments to establishment methods and improvement within species may be required to increase acceptance of these plants for use in fine turf culture.

Acknowledgements

Funding was provided by an ODAFF Specialty Crop Block Grant. The authors wish to thank Mr. Bill Farris for consulting on locally available sedges and the OSU Field & Research Services Unit for help maintaining field plots.

Literature Cited

Allard, G, Nelson, C, Pallardy, S. 1991. Shade effects on growth of Tall Fescue: II. leaf gas exchange characteristics. Crop Sci. 31(1):167–172. https://doi.org/10.2135/cropsci1991.0011183x003100010038x.

Allessio Leck, M, Schütz W. 2005. Regeneration of Cyperaceae, with particular reference to seed ecology and seed Banks. Perspective Plant Eco Evo Systems. 7(2):95–133. https://doi.org/10.1016/j.ppees.2005.05.001.

Baldwin, C, Haibo Liu, McCarty L. 2008. Diversity of 42 bermudagrass cultivars in a reduced light environment. Acta Hortic. (783):147–158. https://doi.org/10.17660/actahortic.2008.783.13.

Baldwin, C, Liu, H, McCarty L, Luo, Wells C, Tole J. 2009. Impacts of altered light spectral quality on warm season turfgrass growth under greenhouse conditions. Crop Sci. 49(4):1444–1453. https://doi.org/10.2135/cropsci2008.07.0412.

Beard, J. B. 1973. Turfgrass: Sci Cult. 1st EDN. Pearson, London, United Kingdom.

Bell G, Danneberger T. 1999. Temporal shade on creeping bentgrass turf. Crop Sci. 39(4):1142–1146. https://doi.org/10.2135/cropsci1999.0011183x003900040032x.

Bell G, Danneberger T, McMahon M. 2000. Spectral irradiance available for turfgrass growth in Sun and shade. Crop Sci. 40(1):189–195. https://doi.org/10.2135/cropsci2000.401189x.

Bernard J, 1990. Life history and vegetative reproduction in *Carex*. C J. Bot. 68(7):1441–1448. https://doi.org/10.1139/b90-182.

Budelsky R, Galatowitsch, S. 1999. Effects of moisture, temperature, and time on seed germination of five wetland Carices: implications for restoration. Restor. Eco. 7(1), 86–97. https://doi.org/10.1046/j.1526-100x.1999.07110.x.

Bunnell, B, McCarty L, Faust, J, Bridges W, Rajapakse N. 2005. Quantifying a daily light integral requirement of a ‘TifEagle’ bermudagrass golf green. Crop Sci. 45(2):569–574. https://doi.org/10.2135/cropsci2005.0569.

Bunnell, T, McCarty L, William B. 2005. Evaluation of three bermudagrass cultivars and meyer japanese zoysiagrass grown in shade. Int Turfgrass So. Res. J. 10:826–833.

Chhetri M, Fontanier C, Ko K, Wu Y, Moss J. 2019. Turf performance of seeded and clonal Bermudagrasses under varying light environments. Urb. Forest Urb. Greening. 43:126355. https://doi.org/10.1016/j.ufug.2019.05.017.

Chhetri, M, Fontanier C, Moss J, Wu Y. 2022. Effects of combined shade and drought stress on turf-type Bermudagrasses. Int Turfgrass Soc Res J. 14:194–204. https://doi.org/10.1002/its2.68.

Christians N, Patton A, Law Q. 2003. Fundamentals of Turfgrass Management 2nd edition. Wiley, Hoboken, New Jersey, United States.

Crew C, Myers,M, Sherrard M, Elgersma K, Houseal G, Smith D. 2020. Stratification and perigynia removal improve total germination and germination speed in 3 upland prairie sedge species. Native Plants J. 21(2):120–131. https://doi.org/10.3368/npj.21.2.120.

de Moraes P, Rossi P, Witt W, Panozzo L. 2014a. Growth and biomass allocation of *Muhlenbergia schreberi.* Am J. Plant Sci. 05(14):2188–2197. https://doi.org/10.4236/ajps.2014.514232.

de Moraes P, Witt W, Phillips T, Rossi P, Panozzo L. 2014b. Relative competitiveness of nimblewill (*Muhlenbergia schreberi*) with tall fescues and Kentucky bluegrass. Am J. Plant Sci. 05(26):3777–3787. https://doi.org/10.4236/ajps.2014.526395.

Dudeck A, Peacock C, Wildmon J. 1993. Physiological and growth responses of St. Augustinegrass cultivars to salinity. HortScience. 28(1): 46–48. https://doi.org/10.21273/hortsci.28.1.46.

Featherly H. 1938. Grasses of Oklahoma. Ok Ag Mech Co Ag Exp Stn Tec Bull 3. https://doi.org/10.31274/rtd-180813-14057.

Gaussoin B, Coffey B. 1988. Response of 32 bermudagrass clones to reduced light intensity. HortScience, 32:178–179.

Ghimire M, Boyer T, Chung C, Moss J. 2016. Consumers' shares of preferences for turfgrass attributes using a discrete choice experiment and the best–worst method. HortScience. 51(7):892–898. https://doi.org/10.21273/hortsci.51.7.892.

Goetghebeur P. 1998. Monocotyledons, 141–190. In: Kubitzki K. Cyperaceae. Flowering Plants. Springer, New York City, New York, United States. https://doi.org/10.1007/978-3-662-03531-315.

Greenlee J, Holt S. 2010. The American Meadow Garden: Creating a Natural Alternative to the Traditional Lawn. Timber Press Inc, Portland, Oregon, United States.

Hilaire R, Arnold, Wilkerson D, Devitt D, Hurd B, Lesikar B, Lohr V, Marti, C, McDonald G, Morris R, Pittenger D, Shaw D, Zoldoske D. 2008. Efficient water use in residential urban landscapes. HortScience. 43(7):2081–2092. https://doi.org/10.21273/hortsci.43.7.2081.

Hipp A. 2008. Field guide to Wisconsin sedges, an introduction to the genus *Carex* (Cyperaceae). Madison (Wisconsin): University of Wisconsin Press, Madison, Wisconsin, United States.

Jiang Y, Duncan R, Carrow R. 2004. Assessment of low light tolerance of seashore Paspalum and Bermudagrass. Crop Sci. 44(2):587–594. https://doi.org/10.2135/cropsci2004.5870.

Kettenring K, and Galatowitsch S. 2007. Temperature requirements for dormancy break and seed germination vary greatly among 14 wetland *Carex* species. Aquatic Bot. 87(3):209–220. https://doi.org/10.1016/j.aquabot.2007.06.003.

Taiz L, Zeiger E. 2006. Plant Physiology. 4th EDN. Sinauer Associates Inc, Sunderland, Massachusetts, United States. https://doi.org/10.1093/aob/mcg079.

McGinnis E, Meyer M. 2011. After-ripening, stratification, and perigynia removal enhance Pennsylvania sedge germination. HortTechnology. 21(2):187–192. https://doi.org/10.21273/horttech.21.2.187.

Olien W.1995. Nimblewill ground cover for biocontrol of ring nematode in peach orchards (abstr). HortScience. 30(4). https://doi.org/10.21273/hortsci.30.4.793d.

Pincetl S, Porse E, Mika K, Litvak E, Manago K, Hogue T, Gillespie T, Pataki D, Gold M. 2018. Adapting urban water systems to manage scarcity in the 21st century:

The case of Los Angeles. Environ Management. 63(3):293–308. https://doi.org/10.21273/horttech.21.2.187.

Russell T, Karcher D, Richardson M. 2020. Daily Light integral requirements of warm-season turfgrasses for golf course fairways and investigating in situ evaluation methodology. Crop Sci. 60(6):3301–3313. https://doi.org/10.1002/csc2.20234

Schütz W. 2000. Ecology of seed dormancy and germination in sedges (*Carex*). Perspectives Plant Eco. Evolution Systematics 3(1):67–89. https://doi.org/10.1078/1433-8319-00005.

Schütz W, Rave G. 1999. The effect of cold stratification and light on the seed germination of temperate sedges (*Carex*) from various habitats and implications for regenerative strategies. Plant Eco. 144(2):215–230. https://doi.org/10.1023/a:1009892004730.

Shokoya G, Fontanier C, Dunn B, Martin D. 2021. Species Distribution and Seed Yield for Carex Populations Colonizing Low-Input Shaded Lawns in Oklahoma (Abstr). https://ashs.confex.com/ashs/2021/meetingapp.cgi/Paper/35536

Stanford. R, White R, Krausz, J, Thomas J, Colbaugh P, Abernathy S. 2005. Temperature, nitrogen and light effects on hybrid bermudagrass growth and development. Crop Sci. 45(6):2491–2496. https://doi.org/10.2135/cropsci2005.0070

Trappe J, Karcher D, Richardson M, Patton A. 2011. Shade and traffic tolerance varies for bermudagrass and zoysiagrass cultivars. Crop Sci. 51(2):870–877. https://doi.org/10.2135/cropsci2010.05.0248

Turgeon A, Kaminiski E. 2019. Turfgrass management. Turfpath LLC, State College, Pennsylvania, United States.

Van der Valk A, Bremholm T, Gordon E. 1999. The restoration of sedge meadows: Seed viability, seed germination requirements, and seedling growth of *Carex* species. Wetlands. 19(4):756-764. https://doi:10.1007/bf03161782.

Waldrep T, Freeman F. 1964. Herbicides for nimblewill in Kentucky Bluegrass Pasture. Weeds. 12(4):317. https://doi.org/10.2307/4040767.

Wherley B, Skulkaew P, Chandra A, Genovesi A, Engelke M. 2011. Low-input performance of Zoysiagrass (zoysia spp.) cultivars maintained under dense tree shade. HortScience. 46(7):1033–1037. https://doi.org/10.21273/hortsci.46.7.1033.

Yue C, Wang J, Watkins E, Bonos S, Nelson K, Murphy J, Meyer W. A., Horgan, B. 2016. Heterogeneous consumer preferences for turfgrass attributes in the United

States and Canada. Can J. Agri Economics/Revue Canadienne D'agroeconomie. 65(3):347–383. https://doi.org/10.1111/cjag.12128.

Figures

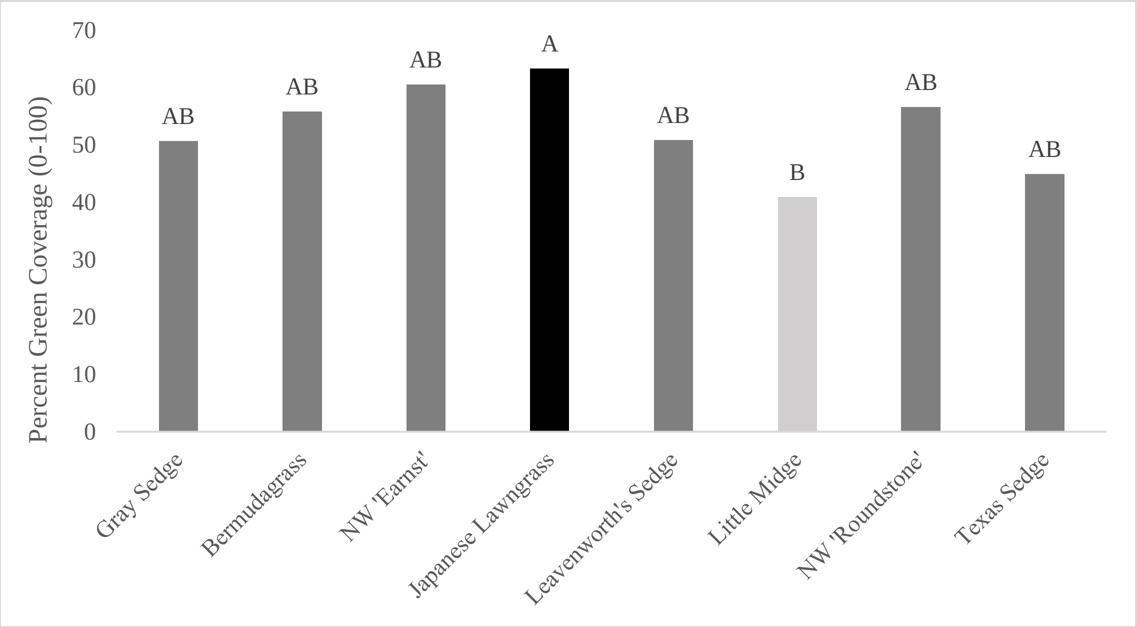

Fig. 2.1: Percent green coverage on 5 Sept. 2020 (during the establishment year) for four *Carex* species, two nimblewill (NW) sources, and two warm-season turfgrasses grown as low input turfs under moderate shade in Oklahoma. Data were pooled across two locations and two irrigation levels (N=16). Means labeled with different letters were significantly different according to Fisher’s protected least significant difference test at P < .05.

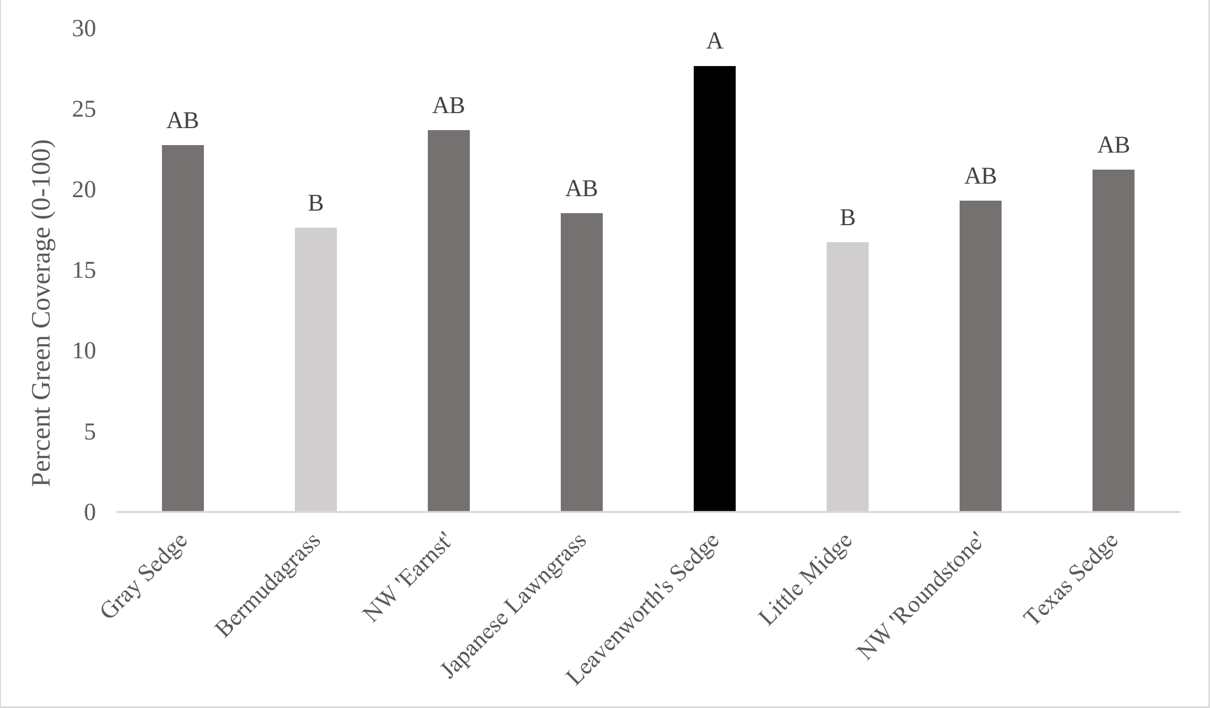

Fig. 2.2: Spring green up (percent green coverage) measured on 26 Mar. 2021 for four *Carex* species, two nimblewill (NW) sources, and two warm-season turfgrasses grown as low input turfs under moderate shade in Oklahoma. Data were pooled across two locations and two irrigation levels (N=16). Means labeled with different letters were significantly different according to Fisher’s protected least significant difference test at P < .05.

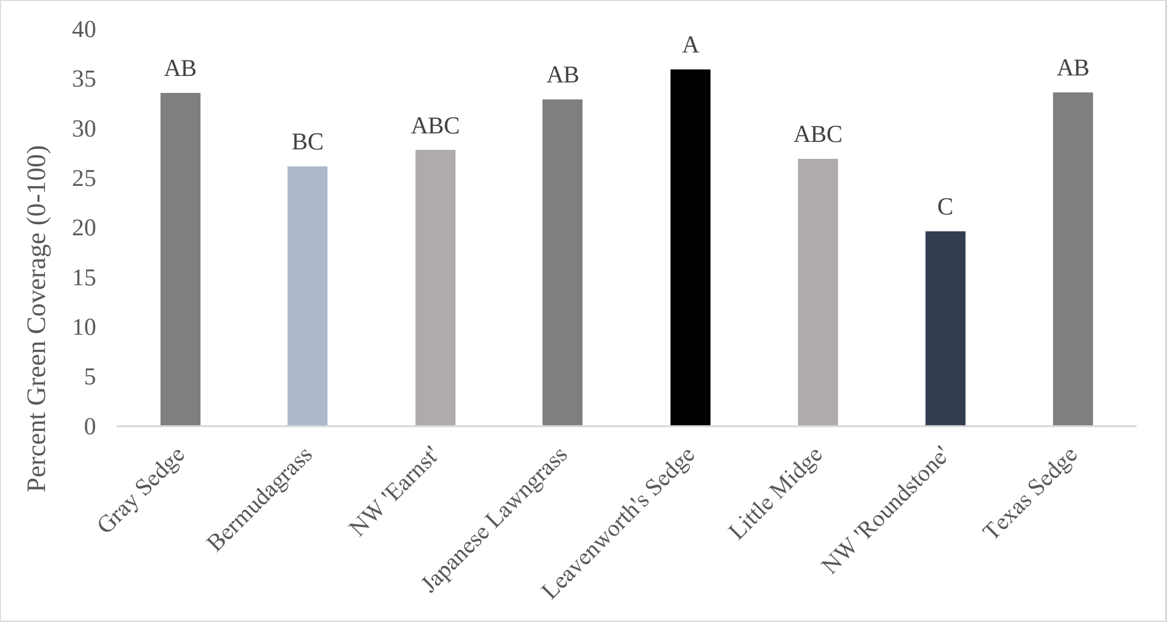

Fig. 2.3: Percent green coverage from early winter on 5 Nov. 2020 for four *Carex* species, two nimblewill (NW) sources, and two warm-season turfgrasses grown as low input turfs under moderate shade in Oklahoma. Data were pooled across two locations and two irrigation levels (N=16). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05.

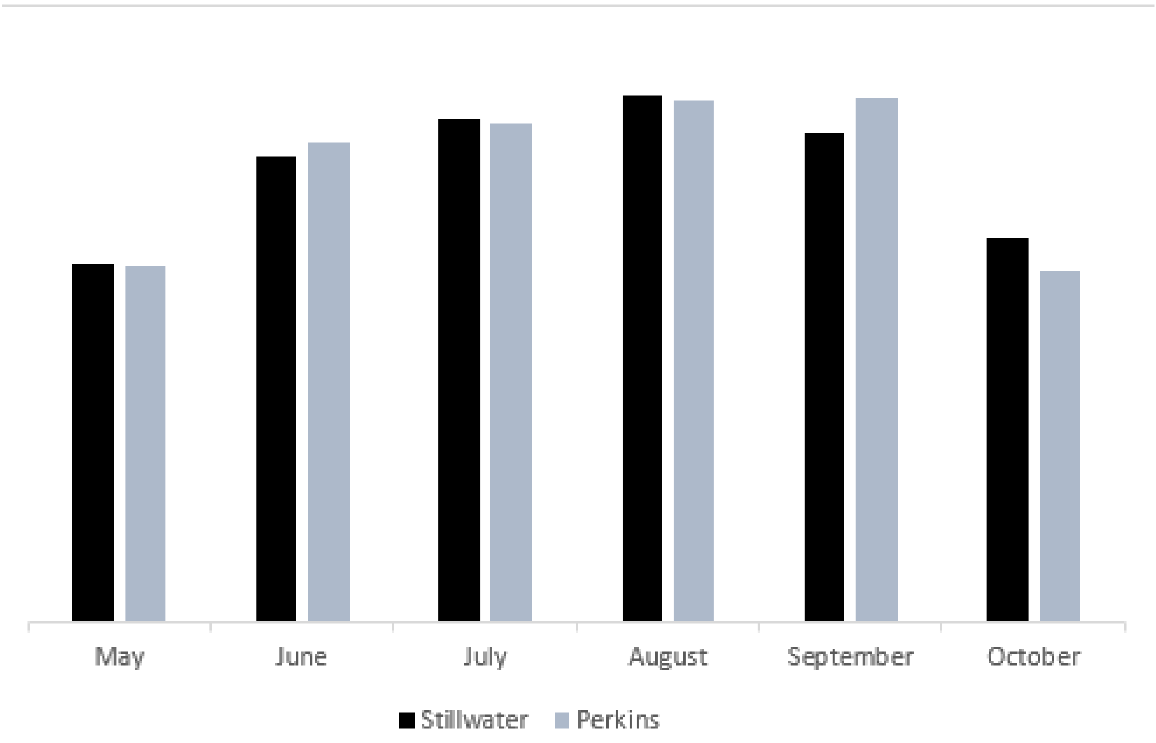

Fig. 2.4: Average temperature during the second growing season (2021) in both the Stillwater and Perkins, Oklahoma plot locations.

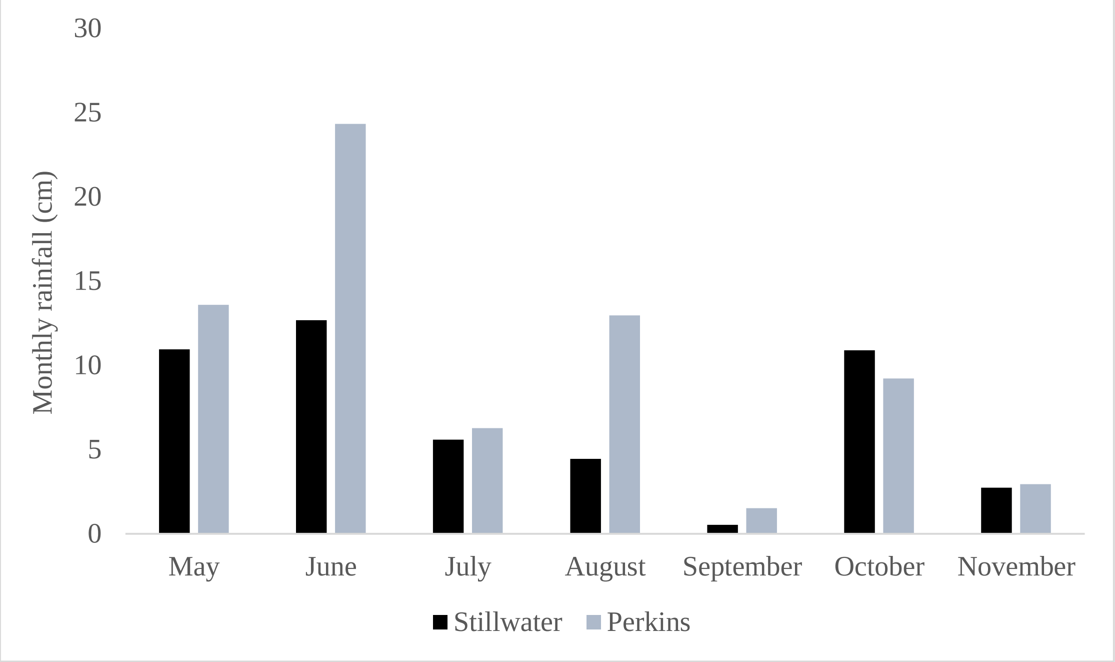

Fig. 2.5: Average rainfall during the second growing season (2021) in both the Stillwater and Perkins, Oklahoma plot locations.

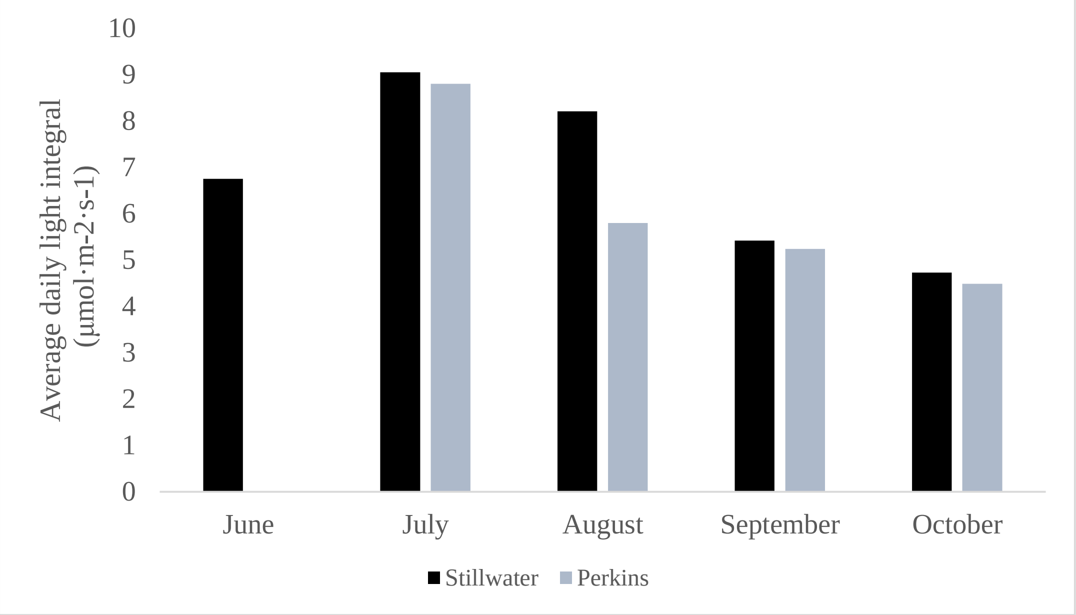

Fig. 2.6: Average daily light integral from the second growing season calculated from quantum sensors placed in representative areas in Stillwater and Perkins, Oklahoma locations. Plots were established under natural shade caused by mature pecan trees (*Carya illinoensis*).

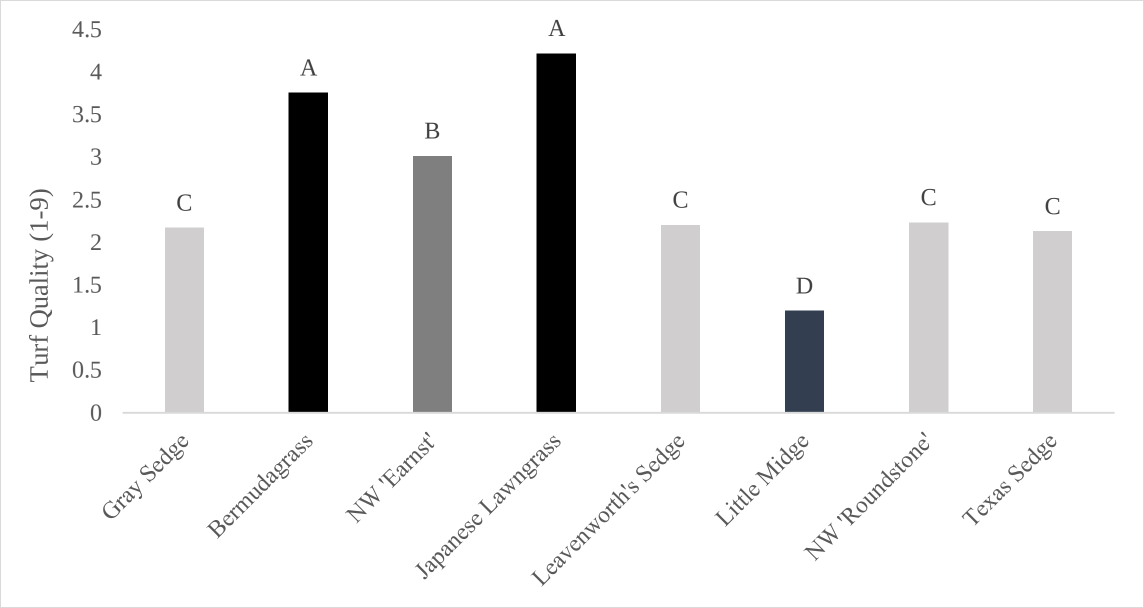

Fig. 2.7: Entry main effect on turf quality for four *Carex* species, two nimblewill (NW) seed sources, and two warm-season turfgrasses grown as low input turfs under moderate shade in Oklahoma. Scores were assigned monthly using the NTEP ratings scale which ranges from 1-worst to 9-best. Data were pooled across two locations, two irrigation levels, and seven dates (N=112). Means labeled with different letters are significantly different according to Fisher's protected least significant difference test at P < .05.

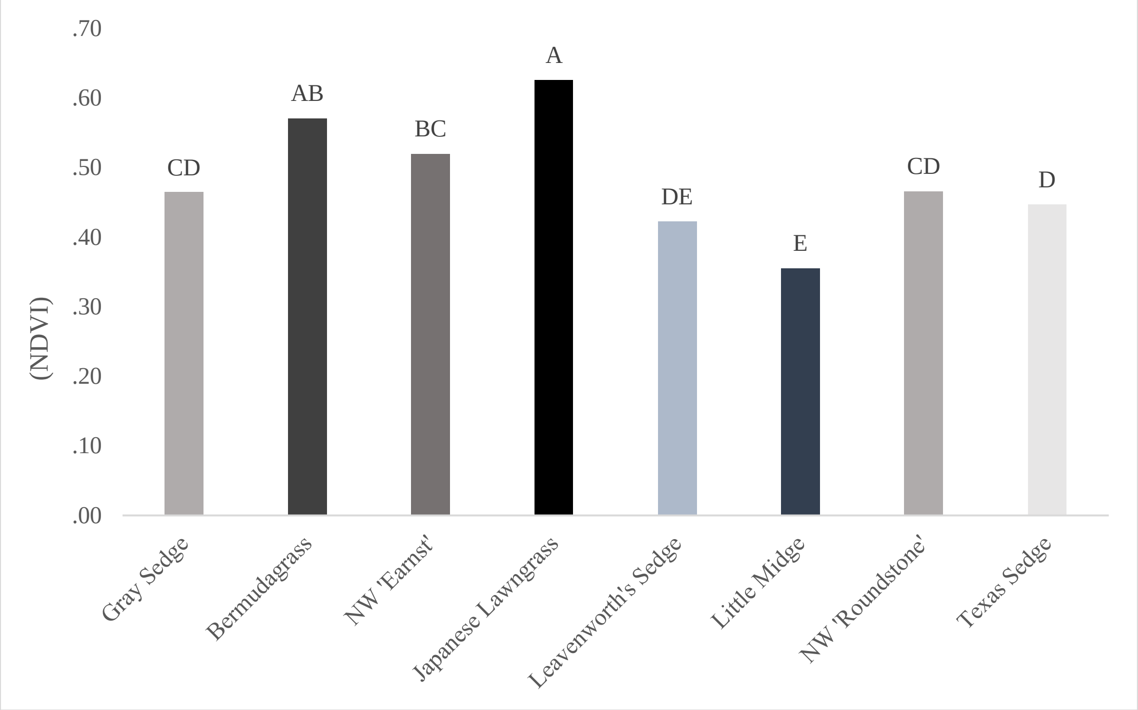

Fig. 2.8: Entry main effect on normalized difference vegetation index (NDVI) for four *Carex* species, two nimblewill (NW) seed sources, and two warm-season turfgrasses grown as low input turfs under moderate shade in Oklahoma. Measurements were conducted monthly using a spectral reflectance meter (RapidSCAN CS-45 Handheld Crop Sensor, Salfords, UK) an index and range from .00 to .99. Data were pooled across two locations, two irrigation levels, and seven dates (N=112). Means labeled with different letters are significantly different according to Fisher's protected least significant difference test at $P < .05$.

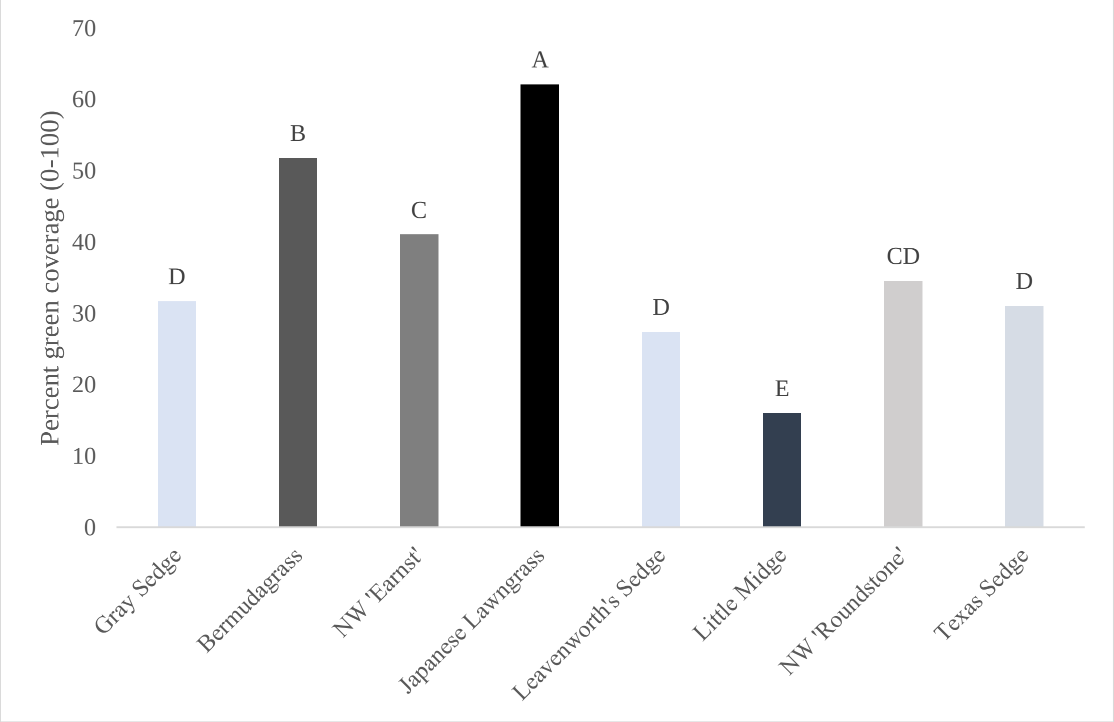

Fig. 2.9: Entry main effect on percent green coverage for four *Carex* species, two nimblewill (NW) seed sources, and two warm-season turfgrasses grown as low input turfs under moderate shade in Oklahoma. Percent green coverage is based on the amount of green coverage over a specific area and was calculated using Image J software, values range from 0% - 100%. Data were pooled across two locations, two irrigation levels, and seven dates (N=112). Means labeled with different letters are significantly different according to Fisher's protected least significant difference test at P < .05.

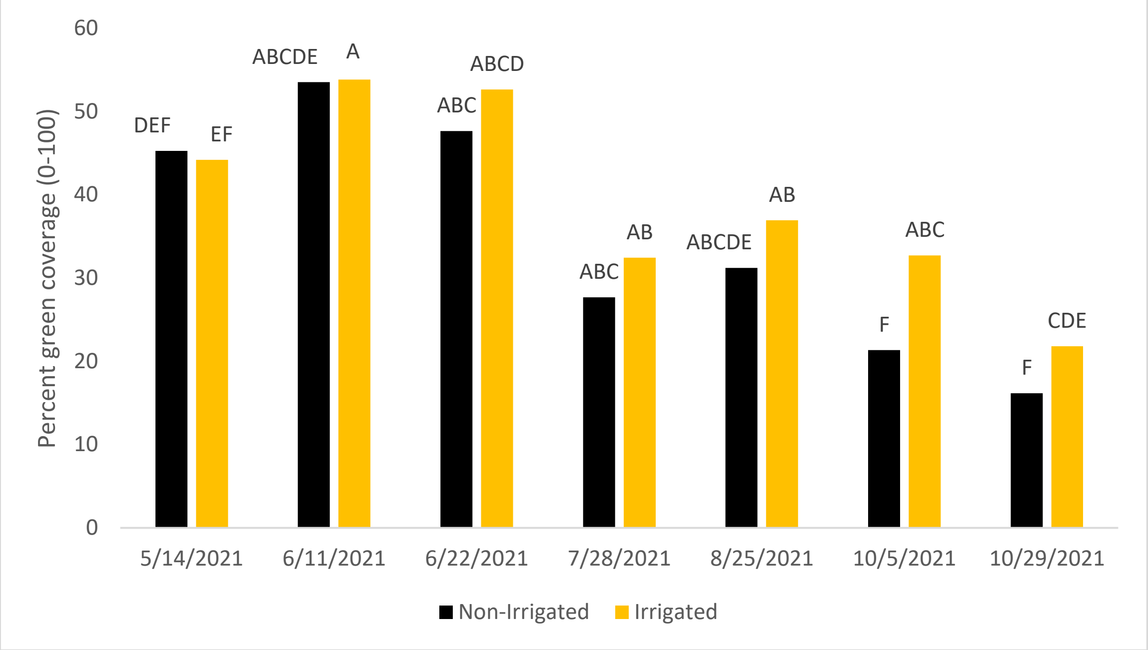

Fig. 2.10: Irrigation × Date interaction for percent green coverage for plots grown as low input turfs under moderate shade in Oklahoma. Data were pooled across two locations and eight plant materials (four *Carex* species, two nimblewill (NW) seed sources, and two warm-season turfgrasses) (N = 64). Means labeled with different letters were significantly different according to Fisher's protected least significant difference test at P < .05.

Tables

Table 2.1: Summary ANOVA table for visual turfgrass quality (TQ), normalized difference vegetation index (NDVI), and percent green coverage (measured through image analysis).

Effect	DF	Turf Quality	NDVI	Green Coverage
Species	7	***[Z]	***	***
Irrigation	1	NF	NF	NF
Date	6	***	***	***
Species × Irrigation	7	NF	NF	NF
Species × Date	42	***	***	***
Irrigation × Date	6	**	**	**
Species × Irrigation × Date	42	NF	NF	NF

[Z] *, **, ***, and NS= P ≤ .001, P ≤ .01, P ≤ .05, and P > .05, respectively.

Table 2.2: Species × date interaction effect on turfgrass quality (TQ) ratings for plots grown as low input turfs under moderate shade in Oklahoma in 2021. Data are pooled across two locations and two irrigation levels (N = 16).

Species	**14 May**	**11 Jun**	**22 Jun**	**28 Jul**	**25 Aug**	**5 Oct**	**29 Oct**
	TQ[Y]						
Bermudagrass	2.0c[Z]	3.4ab	4.1a	4.7b	4.3a	3.8a	4.2a
Gray sedge	2.3bc	1.9c	2.1c	2.0de	2.4bc	2.3b	2.2b
Leavenworth's sedge	2.7ab	2.3c	2.3c	1.7e	2.0c	2.1bc	2.3b
Palm sedge	1.2d	1.1d	1.3d	1.2f	1.2d	1.4c	1.0d
Texas sedge	2.4bc	2.0c	1.8cd	2.0de	2.3c	2.3b	2.1bc
Japanese lawngrass	3.1a	3.6a	4.0a	5.4a	4.8a	4.3a	4.3a
NW[X]-Earnst	2.8ab	4.1a	4.0a	3.6c	3.0b	2.0bc	1.7bcd
NW-Roundstone	2.3bc	2.7bc	3.1b	2.5d	2.0c	1.8bc	1.4cd

[Z] Means followed by the same letter in a given row are not significantly different according to Tukey's honestly significant difference test at P ≤ .05.

[Y] Scores assigned using the NTEP scale (1 = worst to 9 = best)

[X] NW = nimblewill sourced from either Earnst or Roundstone commercial seed suppliers.

Table 2.3: Species × date interaction for normalized difference vegetation index (NDVI) for plots grown as low input turfs under moderate shade in Oklahoma in 2021. Data are pooled across two locations and two irrigation levels (N = 16).

Species	**14 May**	**11 Jun**	**22 Jun**	**28 Jul**	**25 Aug**	**5 Oct**	**29 Oct**
	--NDVI--						
Bermudagrass	.38c[Z]	.66b	.71a	.62b	.64a	.48ab	.49a
Gray sedge	.47ab	.51d	.48c	.48cd	.46b	.42bc	.43abc
Leavenworth's sedge	.48b	.50d	.44cd	.38f	.38bc	.35cde	.4abc
Palm sedge	.38c	.47d	.38d	.41ef	.33c	.32e	.31d
Texas sedge	.46ab	.50d	.43cd	.45de	.44b	.40bcd	.44ab
Japanese lawngrass	.49ab	.72a	.76a	.72a	.67a	.52a	.51a
NW[Y]-Earnst	.53ab	.73a	.71a	.52c	.45b	.33cde	.36bcd
NW-Roundstone	.53a	.61c	.61b	.46d	.39bc	.32de	.35cd

[Z] Means followed by the same letter in a given row are not significantly different according to Tukey's honestly significant difference test at P ≤ .05.

[Y] NW = nimblewill sourced from either Earnst or Roundstone commercial seed suppliers.

Table 2.4: Species × date interaction for percent green coverage from image analysis for plots grown as low input turfs under moderate shade in Oklahoma in 2021. Data are pooled across two locations and two irrigation levels (N = 16).

Species	**14 May**	**11 Jun**	**22 Jun**	**28 Jul**	**25 Aug**	**5 Oct**	**29 Oct**
	%						
Bermudagrass	31.0c[Z]	67.8b	77.8ab	56.3b	62.9a	35.2ab	31.4ab
Gray sedge	54.5ab	37.7c	38.2d	20.5cd	28.8bc	25.9cd	16.2cd
Leavenworth's sedge	47.0b	40.4c	30.2de	13.0de	21.4bc	22.8cd	17.1cd
Palm sedge	20.03d	28.1d	19.7f	8.0e	12.8c	19.8d	3.4e
Texas sedge	49.0ab	37.0cd	26.0ef	23.8c	30.0bc	28.6bc	23.2bc
Japanese lawngrass	50.0ab	78.2a	83.7a	75.7a	65.8a	40.6a	40.7a
NW[Y]-Earnst	49.7bc	79.3a	70.6b	24.9c	31.5b	22.1cd	9.8de
NW-Roundstone	57.2a	60.7b	54.6c	18.2cd	19.2bc	22.1cd	10.0de

[Z] Means followed by the same letter in a given row are not significantly different according to Tukey's honestly significant difference test at $P \leq .05$.

[Y] NW = nimblewill sourced from either Earnst or Roundstone commercial seed suppliers.

CHAPTER III

Conclusion

Carex is a large genus of plants that has potential for use in turfgrass and prairie restoration efforts. Previously, *Carex* research and use has been limited to few species and interested industries have been dissuaded due to difficult germination, but with researched focused on improving the efficiency of seed propagation, nurseries and researchers, and previously dissuaded industries will have the opportunity to use a broader range of *Carex*. This research focused on improving the efficiency of seed propagation of select *Carex* species, including species (oval plains sedge and ivory sedge) not widely reported on previously. Surface planting depths were identified as a key contributor to higher germination for several species, while cold, moist stratification (for 45 to 60 d) decreased the time until first emergence and germination rate for some species. The research done in in this study works to improve *Carex*'s ability to be used by more industries as well as more efficiently by industries that already use them. One of those industries is turfgrass research which has looked at a few *Carex* species to be used as an alternative to turfgrasses under shade. This document describes experiments evaluating four *Carex* species, as well as a traditional weed species (nimblewill) in a low-input shaded lawn system. None of the *Carex* species perform as well as hoped, due primarily to slow establishment rates, but most species demonstrated good persistence in color, extended growing season, and overall consistency. Both of these studies work to improve *Carex*'s use to a wider audience, and specifically an audience that may have previously not considered this genus due to difficulties germinating seed or a general lack of knowledge on the many localized species. The work in these studies may help the efficiency of nurseries and advances research in this field by providing a baseline on how *Carex* performs in the Oklahoma lawn.

VITA

Godwin Shokoya

Candidate for the Degree of

Master of Science

Thesis: AN INVESTIGATION OF *CAREX*: A LOOK AT SEED DORMANCY AND USE AS A LOW INPUT LAWN

Major Field: Horticulture

Biographical:

Completed the requirements for the Bachelor of Science in Plant Biology at Oklahoma State University, Stillwater, Oklahoma in May, 2020.

Completed the requirements for the Master of Science in Horticulture at Oklahoma State University, Stillwater, Oklahoma in July, 2022.

Experience: Graduate Research Assistant at Oklahoma State University for the Department of Horticulture and Landscape Architecture

Professional Memberships: -American Society for Horticulture Science
--Phi Kappa Phi Honor Society