2024 PROGRESS REPORTS

Mike Davis Program for Advancing Golf Course Management

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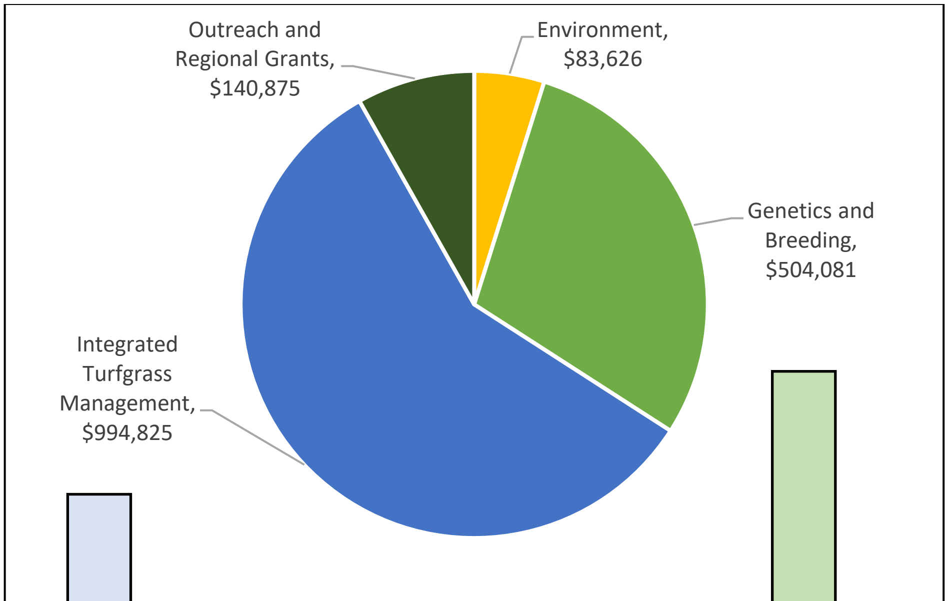
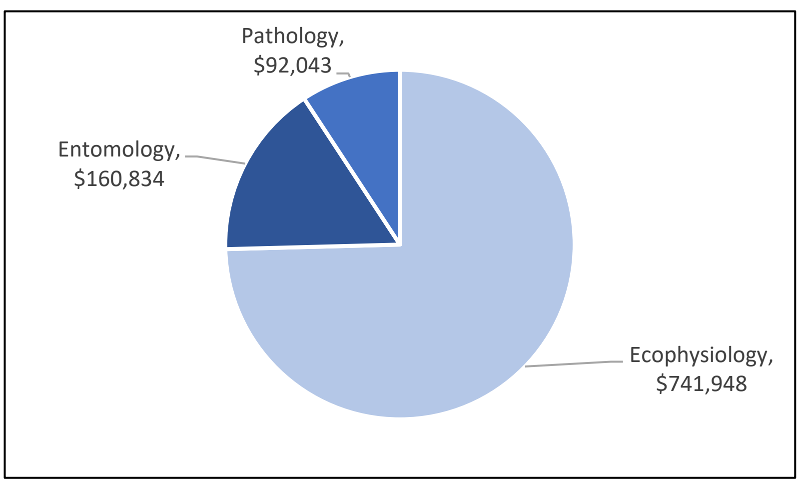
Davis Program Grants - 2024



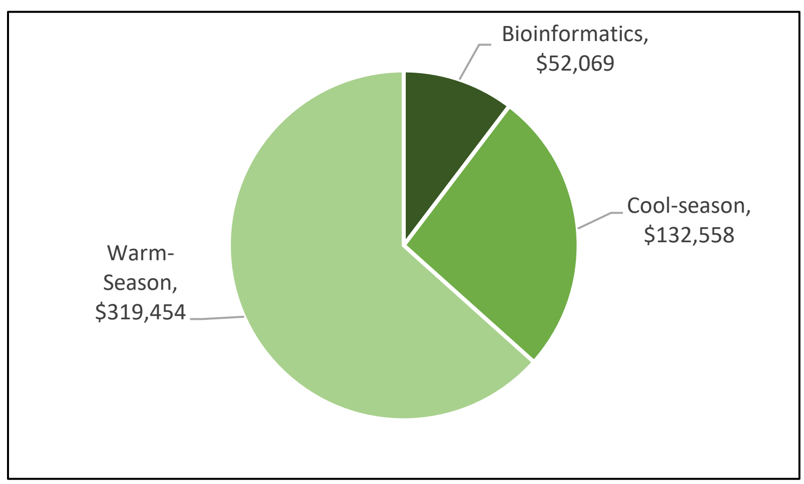
$1,723,407

Integrated Turfgrass Management



$994,825

Genetics and Breeding



$504,081

USGA ID#: 2022-01-744

Title: Transcriptome analysis of bentgrass germplasm using RNA-seq to identify novel targets for enhancement of dollar spot resistance in the field

Project Leaders: Dr. Brandon Horvath, Dr. Scott Warnke, Dr. Keenan Amundsen
Affiliation: The University of Tennessee, USDA, The University of Nebraska

Objectives:
The objectives of the proposed research are as follows:
- Evaluate differential response by bentgrasses with a range of known resistance to dollar spot via challenge inoculations.
- Evaluate the transcriptome of inoculated bentgrasses using RNA-seq to identify transcripts that are up and down regulated in response to infection.
- Compare the identified transcripts to the creeping bentgrass reference genome, and identify potential targets involved in resistance or susceptibility.
- Develop DNA markers to determine potential susceptibility of field-based plant tissue from a particular cultivar.
- Identify pathogenicity factors expressed by dollar spot during the time-course of infection

Start Date: 2021
Project Duration: 3 years
Total Funding: $99,180

Summary Points:
- Inoculation protocol optimized to yield reliable dollar spot infection. This was done by adjusting different variables such as inoculum load, and time in high humidity.
- Four time points were selected (48, 60, 72, 96 hours post inoculation) by observing the time course of infection and symptom development. Uninoculated controls were added at 48 and 96 hours as well.
- Colonial bentgrass has increased expression of genes homologous with creeping bentgrass and related to different resistance pathways. There was a lack of unique genes present in our analysis
- Colonial bentgrass gene families that are expressed higher than creeping bentgrass include: pattern recognition receptors, chitinases, thaumatin-like proteins, protease inhibitors, peroxidases, callose synthases, ribonucleases, germin proteins, and germin-like proteins.

Summary Text:

Rationale

Dollar spot (*Clarireedia spp.*) is one of the most economically and environmentally devastating diseases in turfgrass systems. Roughly 43% of the projected total acres on golf courses in the United States are composed of C3 grasses (creeping bentgrass, annual bluegrass, and Kentucky bluegrass are most common), all of which are highly susceptible to dollar spot

(USGA, 2021). This pathogen is a stressor for superintendents because it aggressively kills turfgrasses, impacts the uniform roll of the green or field, and is expensive to treat (Goodman and Burpee 1991). Due to the heavy reliance on fungicide applications, many dollar spot populations have developed resistance, limiting the ability to control large-scale disease outbreaks. Unfortunately, fungicide resistance is not easily reversible and will only become more widespread with time (Devries et al., 2008). Thus, there is a need for research that finds alternatives to fungicide control of dollar spot.

Our project is focused on one of the alternatives, genetic resistance. Genetic resistance involves harnessing the biology of creeping bentgrass (*Agrostis stolonifera*) by breeding new cultivars that are resistant to dollar spot. While creating new cultivars is the end goal, this project will advance our understanding of what creeping bentgrass genes could confer partial dollar spot resistance observed in the field. More specifically, we seek not only to characterize which genes are differentially expressed between creeping bentgrass and colonial bentgrass (*A. capillaris*) but also to examine how gene expression changes over the course of a dollar spot infection. Taken together, the results of this study will guide us in the creation of molecular markers to aid turfgrass breeders in selecting new creeping bentgrass varieties that are resistant to dollar spot.

Methodology

This study evaluated dollar spot resistance of three creeping bentgrass cultivars 'Declaration' and 'Crenshaw' and one colonial bentgrass cultivar, 'BCD'. A single seedling of each cultivar was chosen randomly after a seedling selection experiment and then clonally propagated on 80/20 sand/peat potting media using standard greenhouse management. 18 clones of each cultivar were evenly divided (3 reps each) into two non-inoculated controls sampled at 48 & 96 hours post inoculation (hpi) and four inoculated groups sampled at 48, 60, 72, and 96 hpi (Figure 1).

The inoculum was prepared by adding 60 ml of DI water to an Erlenmeyer flask containing 40 g of Kentucky bluegrass seed. The Kentucky Bluegrass was then be autoclaved on a liquid 30 cycle and allowed to cool overnight. 20-25 potato dextrose agar cubes from a pure culture of *Clarireedia jacksonii* isolate 'LWC-10' was added to the flask. The flask was then shaken once a day until it reached maturity (~21 days). After inoculum matured, all bentgrass plants will be placed in gallon sized Ziploc bags along with three wet paper towels. The canopy of each plant was misted 5 times with a spray bottle of DI water before spreading 2.5 g of inoculum on each pot except those marked non-inoculated controls. Bags were then be sealed, inflated, and all plants were be placed in a growth chamber, which was set to have daytime temperature of 26 °C, nighttime temperature of 16 °C, and a DLI ~5 mol/m^2/day (12-hour light/dark cycle).

Leaf tissue from control and treated plants were collected and immediately frozen in liquid nitrogen at the four post-inoculation time points and stored at -80°C. Once all samples were collected, they were sent to OmegaBioservices for RNA extraction and sequencing. Once the data was returned, it was checked for quality leading to low quality reads and adapters being trimmed. Dollar spot RNA was removed from each file. De novo transcriptomes were assembled for each cultivar separately before reads were mapped and counted by Salmon.

From this point, we performed three separate analysis in order to explore three possible ways colonial bentgrass is more resistant to dollar spot than creeping bentgrass (Figure 2). The first analyses determined if transcripts unique to colonial bentgrass confer dollar spot resistance. The processed data was subjected to differentially expression (DE) analysis within each genotype individually. All the unique transcript IDs of the significantly DE transcripts ($p<0.1$) were collected and then subjected to single enrichment analysis in agriGO (v2.0), assigning each transcript a functional pathway, biologic process, and cellular location. The groups were filtered for key terms linked to plant defense. Functional annotation for each of transcript was completed by creating a composite reference genome containing wheat (*Triticum aestivum* L.), purple false brome (*Brachypodium distachyon* L.), perennial ryegrass (*Lolium perenne* L.), and barley (*Hordeum vulgare* L.). Lastly, transcript expression data was obtained from the differential expression analysis and combined with the functional annotation data into a Microsoft Excel file (Redmond, WA). Transcripts that were upregulated at all time points were investigated further through a comprehensive literature review. Second run data was used to confirm the presence or absence of genes from the first run.

The second analysis determined expression differences of shared DE transcripts between the three genotypes. Using the original DE data from comparisons within each genotype individually, shared transcripts between the genotypes that were significantly DE ($p<0.1$) were collected. Using the transcript IDs, single enrichment analysis was performed, and the results were subsetted using the same key terms from the previous analysis. All these transcripts were functionally annotated and added to an Excel table containing transcript expression data. Transcripts that had higher expression in 'BCD' (colonial) compared to 'Crenshaw' and 'Declaration' (creeping) at every time point were investigated further in a comprehensive literature review.

The third analysis determined 'BCD' transcripts that were constitutively expressed in control plants using a previously published pipeline (Amaradasa & Amundsen, 2016; Ramm et al., 2013). The 48 hpi control samples were subjected to DE analysis. Single enrichment analysis was performed on all transcripts that were DE ($p<0.1$). Functional annotations were collected following the same method as the first two analyses and added to the expression Excel table produced by DESeq2. Similar to the analysis of shared transcripts, transcripts that had higher expression in colonial bentgrass compared to creeping bentgrass at every time point were subsetted and investigated further using a primary literature.

Results and Future Expectations

This study revealed many genes in creeping and colonial bentgrass localized to the cell wall or plasma membrane suggesting an important role in defense against *Clarireedia* spp. To further classify genes obtained in **Table 1-3**, they were categorized into groups: pattern recognition receptors (PRRs), pathogenesis-related (PR) proteins, or secondary defense proteins. As presented in the introduction, PRRs bind pathogen-associated molecular patterns or effectors secreted by the plant pathogen, activating PAMP triggered immunity or effector triggered immunity(ETR), respectively. Both immunity pathways result in the expression of PR proteins, which are plant proteins functioning primarily in pathogen defense that are induced upon infection. Secondary defense proteins play a role in cell development and are important in repairing pathogen damage to the plant.

From the three analyses, it became clear through our analysis that colonial bentgrass expresses genes from the families of PRRs, chitinases, thaumatin-like proteins (TLPs), protease inhibitors, peroxidases, callose synthases, ribonucleases, germin proteins, and germin-like proteins (GLPs) higher than homologous copies in creeping bentgrass in response to dollar spot infection. These proteins are localized to the extracellular matrix, apoplast, cell wall, or cytosol, directly interacting with *Clarireedia* spp., leading to increased resistance to dollar spot in the field. Interestingly, no genes were found that were unique to colonial bentgrass compared to creeping bentgrass resulting in the observation that the two species respond to dollar spot in a similar way, but colonial bentgrass responds more strongly. The gene families that future studies should focus on include PRRs, chitinases, TLPs, germin proteins, and GLPs due to their previous reports of some activity on *Clarireedia* spp. However, future studies could also ascertain if protease inhibitors, peroxidases, and ribonucleases also have activity on *Clarireedia* spp. Once a reference genome is published for both bentgrass species (relatively soon we expect), data from this study can be used to create gene annotations and begin the process of identifying markers for dollar spot resistance that could be used by breeders for marker assisted breeding.

The future for this project in order to complete the objectives of this grant includes comparing gene expression differences between the two creeping bentgrass cultivars and determining how gene expression changes in dollar spot over the time-course of infection. This will lead to three separate publications with the first being an update of Orshinsky et al. (2014) by comparing the two creeping bentgrass cultivars and how gene expression changes over time. The second will be DE transcripts present in colonial bentgrass when infected with dollar spot and how the expression profile compares to creeping bentgrass. Finally, the last publication will view the pathosystem from dollar spot's point of view by identifying genes critical in infection and destruction of plant tissue. Our expectations are the scientific and turf community will have a better understanding of the relationship between a pathogenic fungus and its host. We believe our work peels back the curtain and shines light on defense pathways these bentgrasses use and how they can be exploited through breeding efforts.

Images:

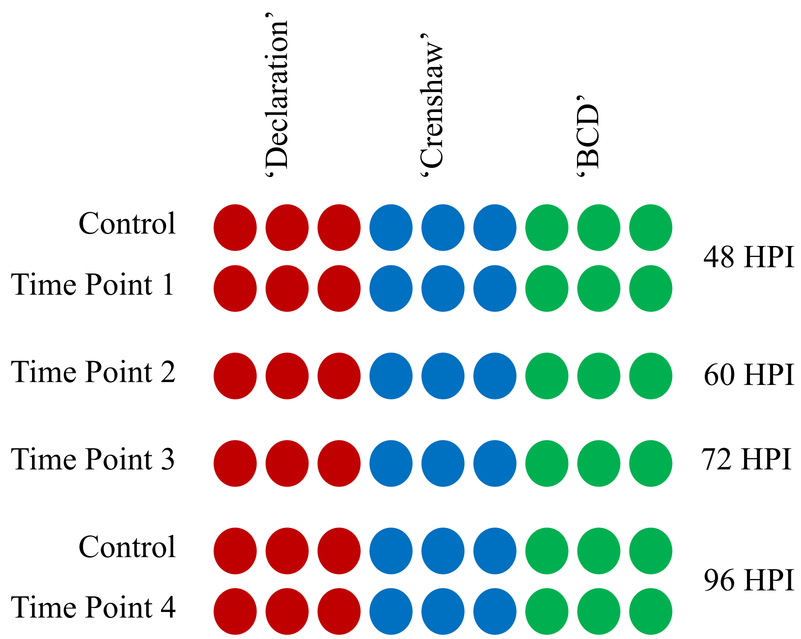


Figure 1. Design of RNAseq experiment. The top labels include two creeping bentgrass cultivars ('Declaration' and 'Crenshaw') and one colonial cultivar (BCD). The 48- & 96-hour timepoint have a non-inoculated control.

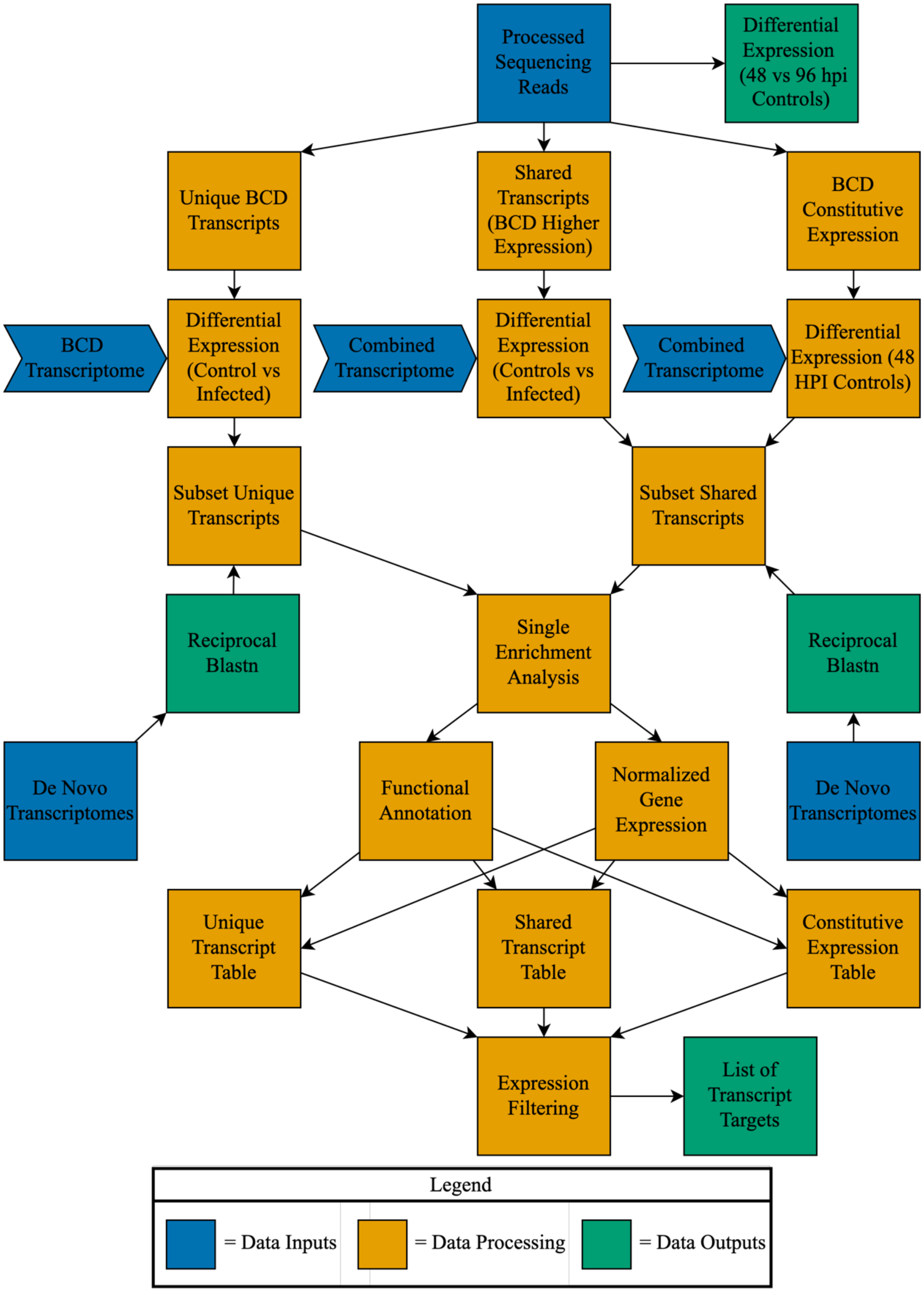


Figure 2. Statistical analysis pipeline used for analyzing processed RNA sequencing reads.

Table 1. List of gene ontology (GO) terms and functional annotations for all differentially expressed transcripts associated with unique transcripts. Red text highlights genes only found in run 1.

GO term	Functional Annotation	Gene IDs	Qt.
Cell Recognition	G-Type lectin S-receptor-protein kinase	At1g34300, At2g19130, At4g21390, ZmPK1	13
	L-type lectin-domain receptor kinase	At5g10530	1
Chitinase	Chitinase	1, 5	3
	Endochitinase	A	1
Defense Response	Barwin		1
	Major pollen allergen	Aln g 1	1
	MLO Protein	1	1
Glucan Metabolism	Callose synthase	3	1
	Cellulose synthase	A7, E6, H1	7
	Xyloglucan endotransglucosylase	6	1
Nutrient Reservoir	Germin-like protein	2-1, 4-1, 8-4, 8-7, 8-8, 8-11, 8-14	16
	Oxalate oxidase	GF-2.8	2
Oxidative Stress	Catalase	1	6
	Cationic peroxidase	SPC4	5
	Peroxidase	2, 3	5
Pattern Binding	Wall-associated receptor kinase-like	1, 2, 3, 4, 5	18

Table 2. List of gene ontology (GO) terms and functional annotations for all shared differentially expressed transcripts with increased expression in 'BCD' compared to creeping bentgrass genotypes at all time points. Red text highlights genes only found in

GO term	Functional Annotation	Gene IDs	Qt.
Cell Recognition	Wax ester synthase	11	1
	G-type lectin S-receptor protein kinase	At1g34300, At2g19130, At4g21380	8
	L-type lectin-domain receptor kinase	At5g10530	2
Chitinase	Chitinase	5, 6	5
	Endochitinase	A	3
Defense Response	MLO Protein	1, 13	4
	Pathogenesis-related protein	STH-21	1
	Pollen allergen	Aln g 1	1
Glucan Metabolism	Callose synthase	6, 8	2
	Cellulose synthase	E6, H1	4
Nutrient Reservoir	Germin-like protein	3-7, 4-1, 8-4, 8-11	11
	Oxalate oxidase	1, 2, GF-2.8	5
Oxidative Stress	Catalase	1, 2	3
	Cationic peroxidase	SPC-4	1
	L-ascorbate peroxidase	4, 6	2
	Peptide methionine sulfoxide reductase	A2, B5	3
	Peroxidase	1, 2, 5, 12, 25, 47, 50, A2, N, P7	17

Table 2. *Cont.*

GO term	Functional Annotation	Gene IDs	Qt.
Pattern Binding	Cytochrome C oxidase	Subunit A	1
	Disease resistance receptor	Lr10	5
	Wall-associated receptor kinase-like	1, 2, 3, 5	16
Wounding	Subtilisin-chymotrypsin inhibitor	2A	3

Table 3. List of constitutively expressed transcripts with increased expression in 'BCD' compared to the creeping bentgrass genotypes. Red text highlights genes only found in run 1.

GO term	Functional Annotation	Gene ID	Qt.
Cell Recognition	G-Type lectin S-receptor-like serine/threonine-protein kinase	At1g34300, At2g19130, At5g24080, At4g21390, At4g21380 At1g11300, ZmPK1	93
	L-type lectin-domain receptor kinase	At5g10530	6
Chitinase	Chitinase	1, 2, 5, 6, 8	19
	Endochitinase	A	6
Defense Response	Barwin		3
	MLO protein	1, 13	7
	Pathogenesis-related protein like	PR-4	1
	Pollen allergen	Car b 1, Aln g 1	2
	Stress-induced protein	SAM22	1
	Wheatwin	2	1
Glucan Metabolism	Callose synthase	3, 5, 6, 7, 8, 9, 10	18
	Cellulose synthase	A7, E2, E6, G3, H1	40
	Disease resistance protein	RGA5	1
	Inactive UDP-arabinopyranose mutase	1, 2	7
	Mixed-linked glucan synthase		1
	Pentatricopeptide repeat-containing protein	At1g16830	1
	Xyloglucan endotransglucosylase	6, 7, 13, 28, 31	7

Table 2.8. *Cont.*

GO term	Functional Annotation	Gene ID	Qt.
Nutrient Reservoir	11S globulin seed storage protein	2	1
	12S seed storage globulin	1	1
	Germin-like protein	2-1, 2-4, 3-7, 5-1, 8-4, 8-7, 8-8, 8-11	54
	Oxalate oxidase	1, 2, GF-2.8	16
Oxidative Stress	Catalase	1, 2	9
	Cationic peroxidase	SPC4	16
	Glutathione Peroxidase	1	7
	L-ascorbate peroxidase	2, 3, 4, 6, 7	8
	Peptide methionine sulfoxide reductase	A2, B5	5
	Peroxidase	1, 2, 4, 5, 12, 16, 17, 24, 25, 42, 47, 50, 51, 55, 65, 66, 70, A2, N, P7	79
Pattern Binding	Disease-resistance receptor	Lr-10	13
	PR5-like receptor kinase	PR5K	1
	Wall-associated receptor kinase-like	1, 2, 3, 4, 5, 6, 14, 16, 20	71
	Zinc finger BED domain protein RICESLEEPER		1
SOS Response	DNA repair protein recA	homolog 1, 2, 3	4

Table 2.8. *Cont.*

GO term	Functional Annotation	Gene ID	Qt.
Wounding	Subtilisin-chymotrypsin inhibitor	2B	5

References:

Amaradasa, B. S., & Amundsen, K. (2016). Transcriptome Profiling of Buffalograss Challenged with the Leaf Spot Pathogen Curvularia inaequalis. *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.00715

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Goodman, D. M., & Burpee, L. L. (1991). Biological Control of Dollar Spot Disease of Creeping Bentgrass. *Phytopathology*, *81*(11), 1438-1446. https://doi.org/10.1094/Phyto-81-1438

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Ramm, C., Saathoff, A., Donze, T., Heng-Moss, T., Baxendale, F., Twigg, P., Baird, L., & Amundsen, K. (2013). Expression Profiling of Four Defense-Related Buffalograss Transcripts in Response to Chinch Bug (Hemiptera: Blissidae) Feeding. *Journal of Economic Entomology*, *106*(6), 2568–2576. https://doi.org/10.1603/EC13267

USGA ID#: 2024-04-814

Title: Understanding Thatch Accumulation In Creeping And Colonial Bentgrass, And Its Association With Dollar Spot Disease Progression

Project Leader: Jinyoung Barnaby; Scott Warnke
Affiliations: USDA-ARS, U.S. National Arboretum, Floral and Nursery Plants Unit

Objectives:
1. Understand thatch development in creeping and colonial bentgrass.
2. Understand the potential relationship of thatch development with stolon vs. rhizome development and inheritance of disease resistance.
3. Identify genomic markers associated with rhizome/stolon development, dollar spot resistance, and thatch build-up by leveraging AI/ML-driven genotyping and phenotyping technologies to ultimately develop less thatch-producing bentgrass germplasm with reduced dollar spot damage.

Start Date: 2024
Project Duration: 3
Total Funding: $90,640

Summary Points:
- The hybrid population was divided into four growth rate groups, with 44% matching BCD's slow growth and 25% aligning with Providence's rapid growth.
- Rapid growth was observed in 30% of the population, with 17% showing exceptional summer expansion.
- By late September, growth peaked, with little to no expansion through October and November.
- Rhizome development occurred in 37% of large and medium plants, while 45% lacked rhizomes.
- Stolon and rhizome development varied, with 21% producing multiple stolons and 33% producing multiple rhizomes.

Summary Text:
Rationale
Thatch is a tightly interwoven layer of organic material that forms between the green vegetation and the soil surface. It develops when organic matter accumulates faster than it can naturally degrade. While a thatch layer less than ½ inch thick can be beneficial—acting as an insulating layer to moderate soil temperature and moisture fluctuations and providing a cushioning effect to protect turf and soil from traffic—thicker layers become problematic. Excessive thatch, over ½ inch, creates an ideal habitat for insect pests and diseases (e.g. dollar spot), undermining the health and longevity of dense turfgrasses. Consequently, managing thatch build-up is essential for maintaining healthy turf. Creeping bentgrass, in particular, exhibits aggressive growth that may correlate with increased thatch build-up and greater disease susceptibility. However, the precise relationships among these factors remain unclear. Our research seeks to uncover how variations in organic matter accumulation influence thatch development under fairway

management conditions. Specifically, the objectives are to: (1) investigate thatch development in creeping and colonial bentgrass, (2) examine the relationship between thatch accumulation and resistance to dollar spot disease, and (3) identify genomic regions associated with rhizome and stolon development, dollar spot resistance, and thatch build-up. By leveraging AI-driven genotyping and phenotyping technologies, this study aims to advance the development of low-input Agrostis germplasm tailored for sustainable turf management.

Methodology

The interspecific bentgrass population, derived from a cross between ‘BCD’ (colonial bentgrass) and ‘Providence’ (creeping bentgrass), was established in 10 x 10-inch square pots and grown in a greenhouse starting mid-May 2024. To assess genetic variation in growth rate and growth patterns (e.g., stolon vs. rhizome development), weekly images were captured during June, biweekly in July, and monthly from September through November. The green, healthy turfgrass pixels in these images were quantified to calculate growth rates (Figures 1 and 2). By late September, the plants exhibited maximum expansion, with growth slowing significantly in October and ceasing by November. On September 22, images of the population were analyzed to count the number of stolons and rhizomes and to measure the size of each hybrid clone, including the parental clones. In early spring 2024 (April), a total of 1,500 hybrid clones, including six replicates per clone, along with 30 replicates of the two parental clones, were transplanted into a field under a randomized design. Any plants that failed to survive the summer were replaced in September 2024 to ensure consistent evaluation.

Results

The growth rate patterns of interspecific bentgrass hybrid clones were categorized into four distinct groups (Figure 1). Approximately 44% of the population (Group II) exhibited a growth pattern similar to BCD, expanding about two-fold by September (four months after planting). In contrast, 25% of the population (Group IV) aligned with Providence, achieved up to a ten-fold expansion by September, despite their growth rate remaining below two-fold until that point. The remaining 30% of the population (Groups I and III) demonstrated rapid expansion, with 17% (Group I) showing exceptional growth during the summer months. Figure 2 illustrates the size and development of the interspecific population on June 9 (three weeks post-planting) and October 12, 2024 (when no further growth was observed). Analysis of growth patterns (Figure 3) revealed that 45% of the interspecific bentgrass population lacked rhizomes, while 37% exhibited rhizome development among large and medium-sized plants, a category that included ‘Providence’ (Figure 3a). For smaller, bunch-type plants, which included ‘BCD’, 40% developed rhizomes, and 11% did not (Figure 3a). Furthermore, 21% of the population developed more than one stolon (up to 10), while 33% produced more than one rhizome (up to 11) (Figure 3b). These findings highlight significant variation in growth patterns and morphological traits across the interspecific hybrid bentgrass population.

Future expectations

Growth rate and rhizome/stolon development patterns will continue to be monitored monthly throughout the winter season to assess their stability under dormant conditions. In the second year, growth rate and development patterns will be re-evaluated to determine year-to-year consistency and environmental influences. Additionally, the temporal progression of dollar spot disease will be tracked from May to October 2025, alongside measurements of thatch layer thickness, to establish potential correlations between disease susceptibility and thatch accumulation. Future work will also focus on quantitative trait locus (QTL) mapping to identify genetic regions associated with (1) dollar spot disease progression, (2) growth rate, (3) growth pattern differentiation (stolon vs. rhizome development), and (4) thatch layer depth. This research aims to uncover key genetic factors driving these traits, providing a foundation for developing resilient, low-input bentgrass germplasm optimized for fairway management.

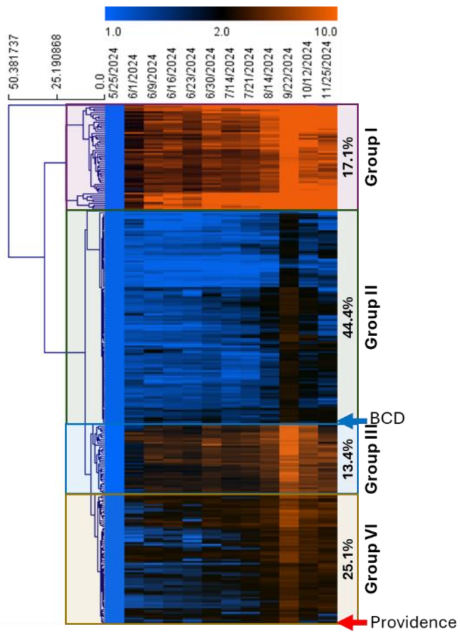

Figure 1. Heatmap showing the growth rate of interspecific bentgrass hybrid clones, including two parents: BCD (colonial bentgrass) and Providence (creeping bentgrass), from May 25, 2024, to November 25, 2024. The green, healthy turfgrass tissue pixel count on each measurement date was divided by the pixel count from the first measurement date (May 25, 2024). Blue indicates a baseline value of 1 (original size), while black and orange represent 2- and 10-fold increases in turfgrass size, respectively, compared to the initial measurement. Measurements began two weeks after transplanting the population. Blue and red arrows highlight the parents BCD and Providence, respectively. Purple and blue boxes indicate hybrid clones with rapid expansion, while the green box identifies hybrids that maintained a consistent size throughout the season, a group that includes BCD. The brown box highlights hybrids with growth rates similar to Providence.

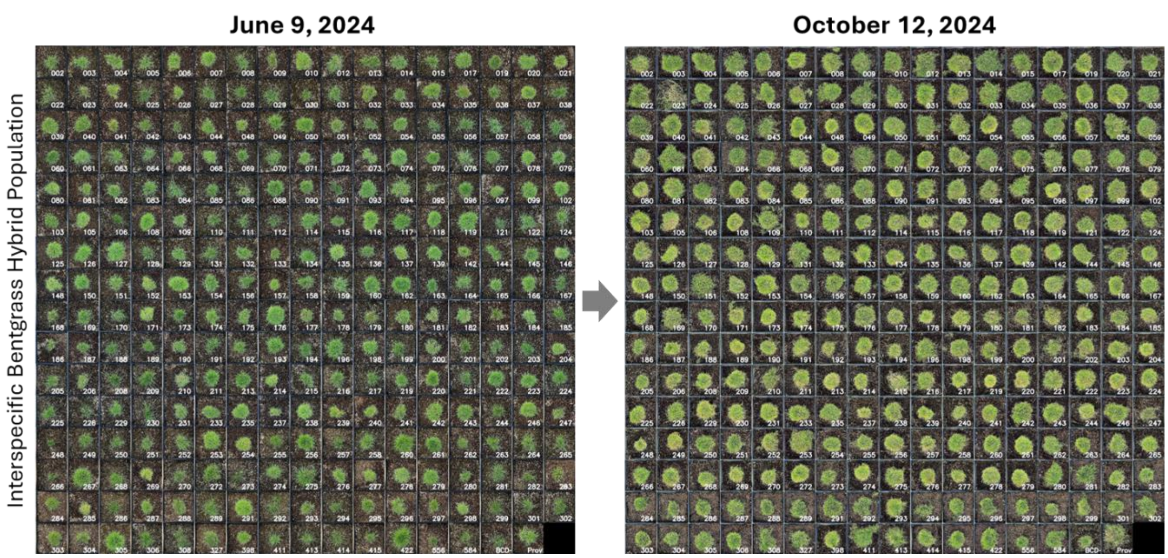

Figure 2. Growth of interspecific bentgrass hybrid population on June 9, 2024 (a) and October 12, 2024 (**b**). The concatenated images illustrate the size and development of individual hybrid clones four months (**b**) after initial planting (**a**).

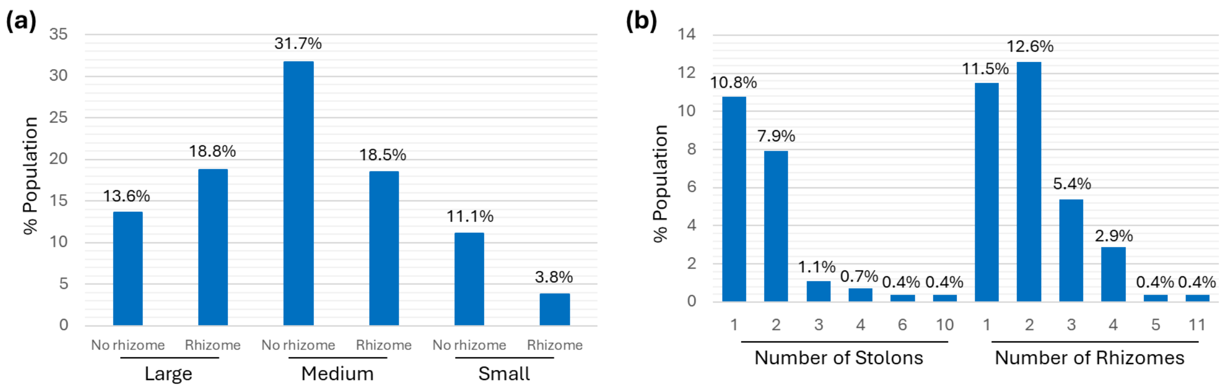

Figure 3. Distribution of hybrid clones based on rhizome presence and size, as of October 12, 2024. (**a**) Percentage of the population with or without rhizomes, categorized by plant size (large, medium, or small). (**b**) Percentage of the population with hybrid clones exhibiting either stolons or rhizomes.

Figure 4. Field establishment of the interspecific bentgrass hybrid population. Each hybrid clone was planted with six replicates, alongside 30 replicates of the two parental clones, BCD and Providence, in a randomized block design.

USGA ID#: 2022-04-747

Title: Selection and Evaluation of Shade Tolerance in Creeping Bentgrass (*Agrostis stolonifera*)

Project Leaders: Stacy A. Bonos and Eric MacPherson
Affiliation: Rutgers University

Objectives:

- Identify traits that correlate with increased shade tolerance.
- Identify creeping bentgrass cultivars that perform well under simulated foliar shade.
- Determine the inheritance of shade tolerance in creeping bentgrass.

Start Date: 2022
Project Duration: three years
Total Funding: $90,000

Summary Points:

- Plant height and chlorophyll content were correlated with increased shade tolerance following the second growth chamber experiment similar to previous results.
- There was no significant differences in biomass between creeping bentgrasses under shade in the second run of the growth chamber experiment. This is also similar to previous results.
- There were significant differences in turf quality among commercial cultivars in response to foliar shade in the growth chamber.
    - Spectrum, Diplomacy, 007XL, Piper, and Oakley exhibited good turf quality under simulated shade.
    - Penncross, PinUp, Tour Pro, AuVictory exhibited poor turf quality under simulated shade and exhibited significant shade avoidance responses, such as taller plant heights and reductions in chlorophyll concentration.
    - Results from a field study under natural shade after two full seasons of shade stress, found that cultivars- Spectrum, Diplomacy, Oakley, Piranha, and Piper, had the best quality ratings. Some of these cultivars also consistently exhibited good turf quality in the growth chamber experiments as well.
- 2,880 progeny and parental clones were evaluated this summer under natural shade and are currently being analyzed for narrow sense heritability calculations.

Summary:

Shade and its associated stresses are major problems for growing turfgrass under shade. Many golf courses have creeping bentgrass greens, tees, and fairways that experience shade during the day. A survey of golf courses with varying levels of shade stress has shown light intensity is reduced by as much as 90% and red to far red ratio is reduced by as much as 50%. This reduction in light causes weaker grass that is more susceptible to disease and other stressors. This weakened grass as a result requires extra care at the superintendent’s expense.

The most effective way for dealing with shade stress on golf courses is the removal of the trees/vegetation causing the shade. Removal of trees can greatly alleviate the shade stress, but significantly alters the playability, the aesthetics, is disruptive, and can be unpopular amongst members.

Two greenhouse and one growth chamber experiment were conducted in previous years. This year, a second growth chamber experiment was conducted to determine and confirm which cultivars perform best under foliar shade and which traits are correlated with shade tolerance. A principal component analysis (PCA) was conducted on the data collected from this growth chamber trial as well as previous trials to identify traits associated with shade tolerance and turf quality. PCA revealed that turf quality under shade is associated with moderate increases in tiller number and chlorophyll content, and smaller changes in plant height. Cultivars that possess these traits, were L93XD, 007XL, and Chinook. In addition to this experiment, a turf plot field trial managed at putting green conditions, was also evaluated for turf quality under natural shade. A heritability study including parental clones and progeny was established and evaluated under natural shade as well this year. There were significant differences among cultivars in response to shade with some consistent results across different experiments. This indicates that cultivar choice should be considered when planting in shaded environments.

Objective 1: Methodology for greenhouse and growth chamber studies

A second growth chamber study including 41 cultivars and selections grown under simulated foliar shade and non-shaded conditions was conducted in the same manner as both the previous growth chamber trial (2022) and the two prior greenhouse trials. Simulated foliar shade was provided by a photoselective film, which reduced light intensity by ~50% and Red:FarRed ratio by ~33% (Rosco E-Colour #209:.3 Neutral Density, PNTA). Light intensity and spectral compositions were collected periodically throughout the duration of the experiment.

The r^2 value for the correlation analysis of turf quality scores between the second greenhouse trial and the 2022 and 2023 growth chamber studies was 0.78 and 0.82, respectively ($p<0.005$). The 2021 greenhouse experiment was excluded from the correlation analysis because it did not include the same number of cultivars and selections. The adjusted r^2 between the two growth chamber studies was 0.75, $p<0.005$. These data indicated that there was some consistency between runs in the growth chamber and between greenhouse and growth chamber experiments.

Objective 2: Trait Identification

Results from the two greenhouse experiments and the two growth chamber experiments confirmed that plant height, chlorophyll content, and turf quality (both ratings and as calculated from Turf Analyzer from Digital Image Analysis) were useful to differentiate between cultivars and selection of creeping bentgrass in response to shade. Tiller number, height to tiller ratio, and biomass were either highly variable or not significantly different and therefore were not considered useful as a trait for breeding (Table 1).

Growth Chamber second trial results

A two-way Analysis of Variance (ANOVA) and pairwise least squared means were used to identify which of the studied traits were significantly different amongst the cultivars (Table 1). Again, there was significant variation between both the lighting conditions and amongst the cultivars themselves (Table 1.) When looking at the interaction between cultivar and light conditions, plant height and chlorophyll concentrations were significant as have been observed in the past. Both the turf quality ratings and turf quality calculated through Turf Analyzer using the digital images were also significantly different between the lighting conditions and the cultivars themselves. Biomass showed no significance between the cultivars, but foliar shade did have a significant impact on biomass production across all cultivars.

Some cultivars, such as L93XD, Chinook, Diplomacy, and Oakley performed similarly in both the 2022 and 2023 growth chamber (Figure 1), maintaining good turf quality while also having small changes in height due to shade. Cultivars such as Luminary, PennA4, and Tyee had a large positive change in height when grown under foliar shade. Cultivars that exhibited large changes in height between shade and full sun, are cultivars that would require extra inputs such as mowing or growth regulators to maintain good quality. These would be examples of cultivars poorly adapted to shade (Figure 1).

Cultivars that have higher chlorophyll concentration in the shade should be able to collect the limited sunlight for photosynthesis and therefore should also be better adapted to shade stress. However, an extreme increase in chlorophyll concentration can increase vertical growth as well. Cultivars with a moderate increase in chlorophyll concentration show the most promise for shade tolerance; these include Tillinghast, Piper, and Piranha

A principal component analysis was run on the traits measured for both greenhouse and growth chamber experiments to see relationships between these traits and turf quality under shade. PC1 explains 33.5% of the variation and PC2 explains 31.1% (Figure 2). Together with PC3, 82.8% of observed variation is captured. Height, biomass, and chlorophyll content vectors are all similarly loaded suggesting a stronger relationship between these traits. Tiller number loads opposite of height to tiller ratio, as expected do to tiller number negatively affecting the height to tiller ratio (i.e. higher tiller number results in lower height to tiller ratio). Cultivars exhibiting good turf quality across all trials are highlighted in green (Diplomacy, Spectrum, 007XL, and Piper) (Figure 2). Cultivars exhibiting lower quality ratings are highlighted in red (Penncross, PinUp, and V8) (Figure 2). Cultivars that do well in shade should possess consistency amongst traits and cluster near the left of center.

Table 1. Analysis of variance (ANOVA) for the effects of cultivar, light condition, and the interaction using a two way ANOVA on plant height, tiller number, height to tiller ratio (H/T), biomass, total chlorophyll concentration, turf quality, and digital image analysis (DIA) in a growth chamber experiment conducted in 2023.

2023	df	Height	Tiller	H:T	Biomass	Chlorophyll Concentration	Quality	DIA
Cultivar	40	***	***	***	NS	***	***	***
Light condition	1	***	*	*	***	***	***	***
Cultivar:Light Condition	40	***	**	**	NS	***	***	***

*Significant at 0.05
**Significant at 0.01
*** Significant at 0.001
NS, Not Significant

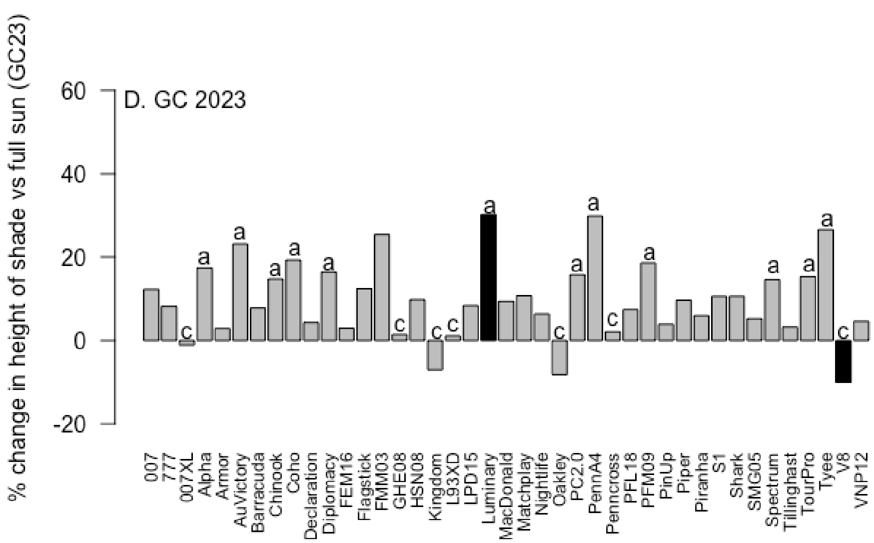

Figure 1. Percent change in plant height of creeping bentgrass cultivars and selections grown under simulated foliar shade versus full sun in a growth chamber. Black shaded bars indicate cultivars with the highest and lowest means. Means were compared using all the combinations of least squared means. a = significantly different from the lowest, not the highest; c = significantly different from the highest, not the lowest; no letter = not significantly different from either highest or lowest (p=0.05).

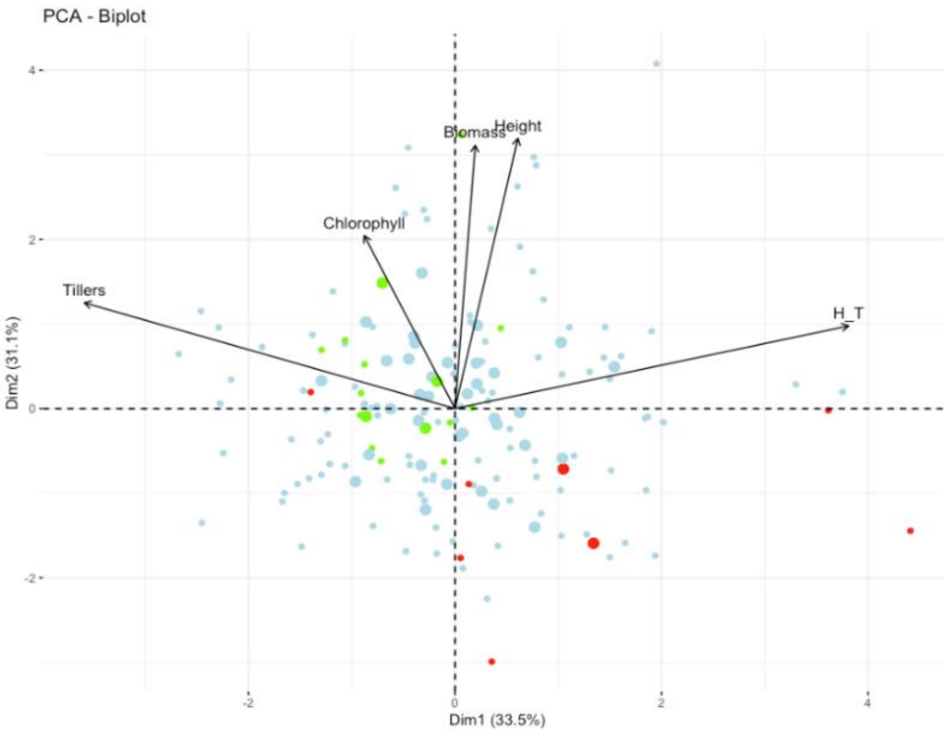

Figure 2. Variation in morphological traits of forty-one creeping bentgrass cultivars (*Agrostis stolonifera*). Cultivars in green are cultivars with high turf quality scores. Cultivars in red are cultivars with low turf quality scores under shade.

Field Trial

A field trial with 30 commercial cultivars was seeded into 3' x 5' plots at Rutgers Horticulture Farm 2 in North Brunswick on November 11, 2022. The field trial was managed as a putting green, mown at 0.110 inches. Turf quality ratings were made monthly on a 1-9 scale with 9 being the best and 1 the worst. The field is under shaded conditions provided by nearby trees from leaf out to May and again from September until leaf fall. The shade provides a 70% reduction in PPF, and a 40% reduction in Red:FarRed compared to full sun.

Cultivars with the highest turf quality rating after 2 years were Spectrum, Oakley, Diplomacy, Piranha, and Piper. These cultivars have also demonstrated good shade traits and turf quality in both the greenhouse and growth chamber studies (Figures 1&2). Cultivars such as V8, Penncross, Alpha had poor turf quality, which was also seen in the growth chamber experiments.

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	Cultivar	Turf Quality 2023-2024
1	Spectrum	6.6
2	Oakley	6.6
3	Diplomacy	6.3
4	Piranha	6.2
5	Piper	6.2
6	007XL	6.2
7	Luminary	5.9
8	Chinook	5.8
9	Matchplay	5.8
10	Tour Pro	5.7
11	Coho	5.7
12	L-93XD	5.5
13	MacDonald	5.4
14	Barracuda	5.3
15	777	5.0
16	S1	5.0
17	007	5.0
18	Shark	4.9
19	Tyee	4.9
20	Kingdom	4.7
21	Penn A4	4.3
22	AU Victory	4.3
23	Declaration	4.1
24	Nightlife	3.8
25	Flagstick	3.5
26	PC2.0	3.5
27	Armor	3.1
28	Alpha	2.9
29	Penncross	2.8
30	V8	2.6
	LSD at 5%=	1.2

Table 2. Performance of creeping bentgrass cultivars in a putting green trial under foliar shade, established in Nov 2022 at Rutgers Horticulture Research Farm 2.

Objective 3- Inheritance of shade tolerance

329 elite creeping bentgrass genotypes showing favorable traits for turf quality including density, color, growth habit, etc. were previously planted under extreme natural foliar shade from pecan trees at Rutgers Adelphia Plant Science Research Farm in 2021 (Freehold, NJ). Broad-sense heritability, calculated using a best linear unbiased prediction model in R, with corresponding ANOVA, resulted in a broad-sense heritability estimate of $H^2 = 0.54$. This is a moderate heritability estimate suggesting there is a genetic component but also a considerable amount of environmental variation affecting shade tolerance in creeping bentgrass.

Two polycross populations were developed from these creeping bentgrass clones. 22 creeping bentgrass clones with good performance and 18 creeping bentgrass clones with poor performance were open pollinated in isolation. The resulting seed was collected. Seed from each parent was harvested and germinated and 96 progeny plants from each parent plant were selected (n=2880). The progeny and parent plants were planted under the same pecan trees providing foliar shade on June 30, 2023. Light quality under the pecan trees at solar noon averaged 164.1 µmol $m^{-2}s^{-1}$ in 2023 and 167.5 µmol $m^{-2}s^{-1}$ in 2024 with a Red:FarRed ratio of 0.649 in 2023 and 0.656 in 2024. Light quality in full sun averaged 1901.4 µmol $m^{-2}s^{-1}$ in 2023 and 1899.6 µmol $m^{-2}s^{-1}$ in 2024 with a Red:FarRed ratio of 1.222 in 2023 and 1.200 in 2024. Turf quality and plant diameter measurements were taken monthly for 2023 and 2024. Monthly turf quality and diameter measurements were recorded. Figure 3 is an example of a progeny that exhibited good turf quality (1) and one that had poor turf quality (2). Data collection has been completed for 2024 in November, and data analysis is currently be completed.

Figure 3. Example of bentgrass plants with good and bad turf quality under foliar shade. Shade provided by pecan trees planted at 20’ spacings at Rutgers Adelphia Plant Science Research Farm (Freehold, NJ).

USGA ID#: 2022-08-751

Title: Evaluation and Breeding of Kentucky Bluegrass and Western Wheatgrass for Rapid Seed Germination, Salt Tolerance, and Turf Quality

Project Leader: Michael M. Neff
Affiliation: Washington State University

Objectives:

<u>Objective 1:</u> Screen Kentucky Bluegrass and Western Wheatgrass for rapid germination and perform hybridization crosses.

<u>Objective 2:</u> Screen for salt tolerance in rapid germinating Kentucky Bluegrass and Western Wheatgrass.

<u>Objective 3:</u> Perform turf trials for rapid germinating and salt-tolerant Kentucky Bluegrass and Western Wheatgrass.

Start Date: 2022
Project Duration: 3 years
Total Funding: $83,202

Summary Points:

- The top germination lines of Kentucky Bluegrass (KBG) have been advanced for hybridization and selection in breeding plots at the Washington State University (WSU) Grass Breeding and Ecology Farm.

- One hundred and seventy-six high germination lines of KBG with the highest seed yield have been subjected to salt tolerance screens with 60 surviving at a rate of 12 $dS{\cdot}m^{-1}$ (1/4 to 1/3 of sea water). All one hundred and seventy-six lines described above have been planted as turf trials along with additional selections and varieties from our breeding program.

- In the summer of 2024, we began establishing a Turf Evaluation Farm in Mt. Vernon WA which a part of the WSU Northwest Research and Extension Center (NWREC) in the Skagit Valley including 210 KBG lines from our breeding program planted as turf trials.

- Naturalized populations of KBG in western Washington, including many in salty and sandy environments, have been collected and incorporated into our breeding program.

- ‘Matchless’ a Kentucky Bluegrass variety selected for dryland production in Eastern WA without the use of postharvest burning was awarded Plant Variety Protection (PVP) status (PV #202200523) and is currently licensed and in production.

- Western Wheatgrasses and other wheatgrasses are no longer a focus of this project.

Summary Text:

Rational

This project focuses on the question of whether rapid seed germinating and salt tolerant Kentucky Bluegrass (KBG) (*Poa pratensis*) and Western Wheatgrass (*Pascopyrum smithii*) can be developed for golf courses in the Upper West, Mountain, Transition and Pacific regions of the United States. These species were chosen based on a survey from a group of Inland Empire Golf Course Superintendents regarding problems that they would like to see addressed in research projects proposed to the USGA Turfgrass and Environmental Research Program.

Methodology and Results to Date

Objective 1: Screening Kentucky Bluegrass and Western Wheatgrass for rapid germination and perform hybridization crosses.

Kentucky Bluegrass:

Two hundred and ninety-six KBG selections were planted in Pulman WA in 2022 and harvested in 2023. Eighty plants were selected for paired crosses, forty-five of which were harvested for seed. These lines were screened for percent germination on KNO_3 soaked blotter papers in a Hoffman environment chamber/seed germinator at 25°c with 16 hours/day light. Another one hundred and fifty-five plants that were harvested in 2022 with one-hundred and five planted in turf trials at our new Mt. Vernon, WA research location (see Objective 3). Fifty of these lines provided a high enough yield for planting turf trials in Pullman next spring. Another one hundred and thirty selections from previous crosses were harvested in 2023 with fifty-five planted in turf trials at our new Mt. Vernon Research location (see Objective 3). Nine of these lines provided a high enough yield for planting turf trials in Pullman next spring.

One of the varieties used in these trials, ‘Matchless’, is the product of breeding efforts from this program. ‘Matchless’ was previously selected from ‘Kenblue’ by Drs. William Johnston and R.C. Johnson for dryland production in Eastern WA without the use of postharvest burning. In 2023, ‘Matchless’ was awarded Plant Variety Protection (PVP) status (PV #202200523) and is currently licensed and in production. Matchless rates well for germination, salt tolerance and turf quality.

Western Wheatgrass:

In the past year, we shifted our focus away from western wheatgrass to other wheatgrass species for a variety of reasons (see 2023 Progress Report).

Other Wheatgrasses:

Western Wheatgrass arose as a hybrid of Streambank Wheatgrass (*Elymus lanceolatus*) and Beardless Wildrye (*Leymus triticoidies*). These species are native to the Pacific Northwest. Fifty-two accessions of Streambank Wheatgrass, thirteen accessions of Beardless Wildrye and three accessions of hybrids between the two were planted into the field. We also planted eighteen accessions of Intermediate Wheatgrass (*Thinopyrum intermedium*). Intermediate Wheatgrass is planted for erosion control and has high food value for animals. All of these have been evaluated for agronomic traits such as establishment, aggressivity and production. Unfortunately, none seem appropriate for use on golf courses.

Objective 2: Screening for salt tolerance in rapid germinating Kentucky Bluegrass and Western Wheatgrass.

Our salt tolerance analysis uses a modified version of the protocol described in Brown *et al.* (2011) in which plants are flood irrigated at pre-determined salt rates (6, 12 and 18 $dS \cdot m^{-1}$) and screened for 4 weeks as turf pots (Bushman 2016; Moxley 1978).

Kentucky Bluegrass:

The one hundred and seventy-six highest yielding lines to date were evaluated for salt tolerance at a rate of 12 $dS \cdot m^{-1}$ (1/4 to 1/3 of sea water). The sixty lines that had the highest survival will be further screened for salt tolerance at 18 $dS \cdot m^{-1}$. One hundred and seventy-six of the highest yielding lines were also planted in turf trials (see Objective 3).

We have been collecting KBG from naturalized populations in western Washington. In the spring of 2023, Dr. Neff collected flowering KBG plants found at Ediz Hook, a sandy salty sight in Port Angeles, WA (Figure 1) based on herbarium records from 1906. In the spring of 2024, Dr. Neff collected flowering KBG plants on the Kitsap Peninsula across the Puget Sound from Seattle, in Seattle on a Puget Sound beach, and at two additional sites on the Olympic Peninsula including one behind ocean dunes. All these plants have been incorporated into the project as well as our general breeding program at WSU.

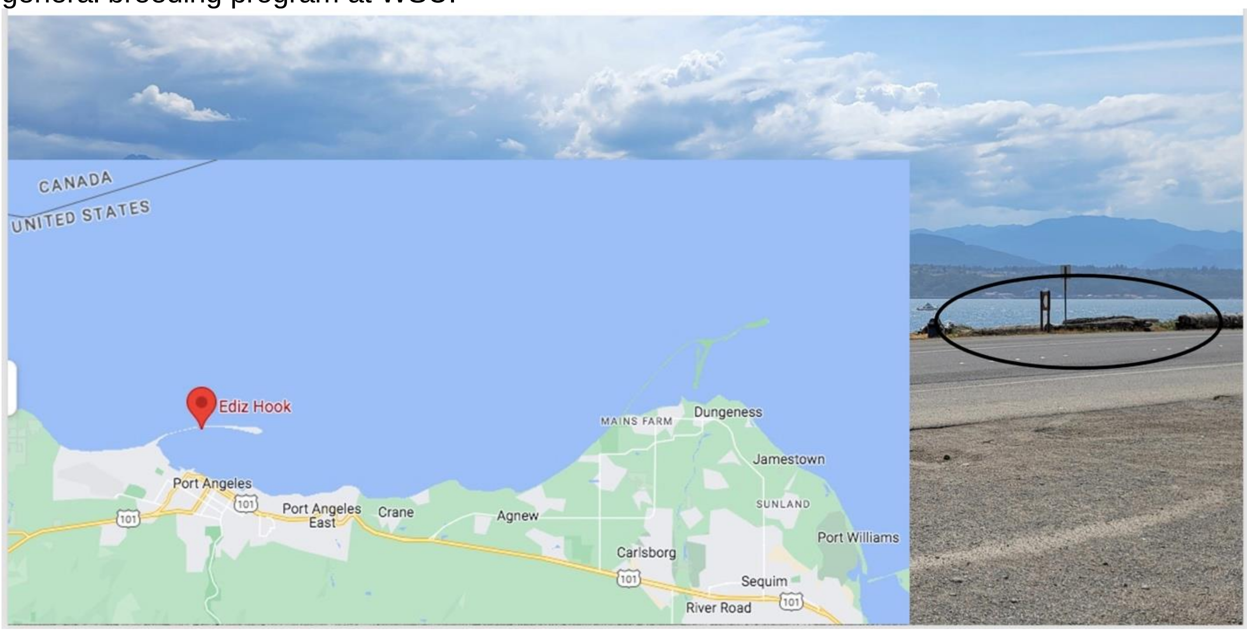

Figure 1. KBG collection site in Port Angeles, WA

Western Wheatgrass:

Due to challenges associated with establishing Western Wheatgrass turf we have postponed salt-tolerance screening for this species (see 2023 Progress Report).

Objective 3: Performing turf trials for rapid germinating and salt-tolerant Kentucky Bluegrass and Western Wheatgrass.

Kentucky Bluegrass:

The one hundred and seventy-six highest yielding KBG selections that were evaluated for salt tolerance at a rate of 12 $dS \cdot m^{-1}$ in Objective 2 were also planted as turf trials at the WSU Grass Breeding and Ecology Farm. These trials include additional selections from ‘Matchless’ and three low-vernalization selections from our current breeding program that are also in PVP trials. Plants were established on 3’ by 5’ plots at a seeding rate of 2 pounds per thousand square feet for KBG. We use augmented block designs to maximize the entries from our nursery. Turf trials will continue to be established yearly or bi-yearly depending on traits to be tested as well as the quantity of breeding lines available to produce a trial. Trials are rated NTEP style with color, establishment, turf quality, and disease, rated once monthly or as traits present themselves. The trials will be used to make evaluations of turf performance on all lines moving forward to return to Objectives 1 and 2 over time.

In the summer of 2024, we began establishing a Turf Evaluation Farm in Mt. Vernon WA which a part of the WSU Northwest Research and Extension Center (NWREC) in the Skagit Valley (Figures 2, 3 and 4). This farm location is critical since 5 of the 7 million people living in Washington State live in western Washington. The rust pressure/presence is extremely high in this region. And, KBG generally does not grow well in Western WA due to rust, low-light conditions during the winter and milder winter weather. The goal for these trials is to examine the potential use of KBG in this very large population of WA. We currently have 176 lines in turf trials in Pullman WA and 210 lines in turf trials in Mt. Vernon. These lines have varying salt tolerance.

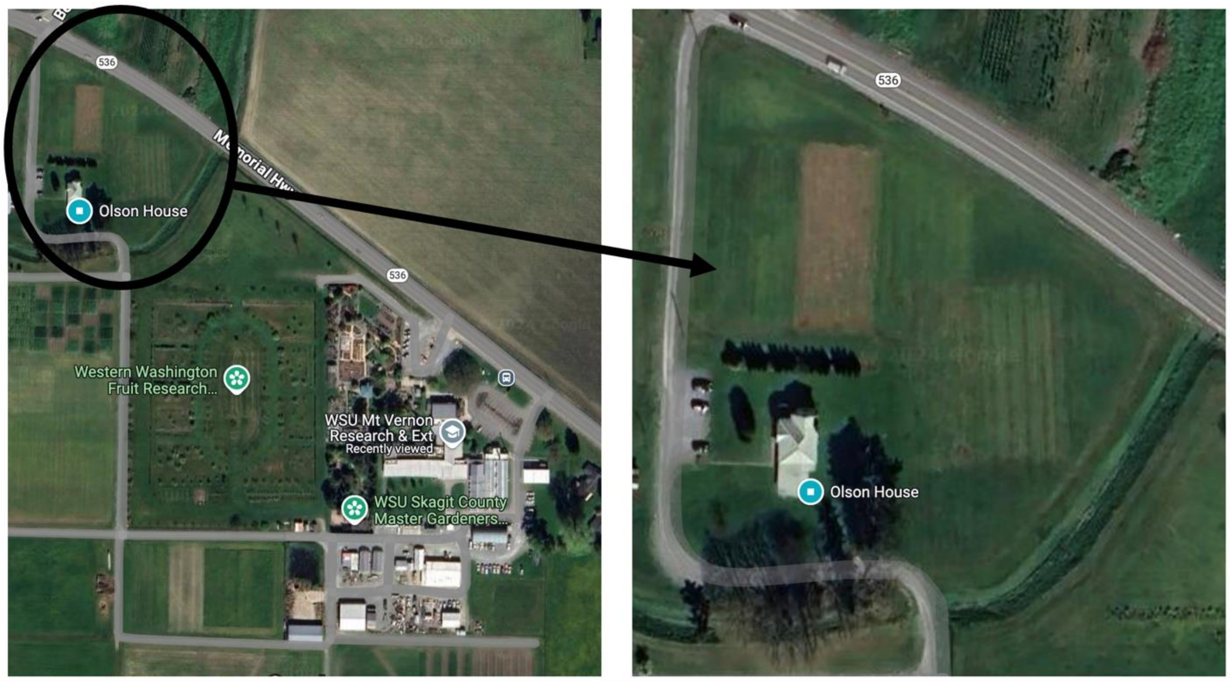

Figure 2. Site of new Turf Evaluation Farm at WSU NWREC.

Figure 3. Planting turf trials by seed at the NWREC Turf Evaluation Farm, 9/7/24.

Figure 4. NWREC 11/2/24. Tufted Hairgrass (native grass) in the front center is adjacent to KBG trials on the left foreground and background. Note rust (orange) on some KBG. Perennial Ryegrass is in the back center right and right border.

We have determined that Western Wheatgrass turf establishment is not sufficient for use on golf courses and thus will not be incorporated into future turf trials (see 2023 Progress Report).

Future Expectations of the Project

The goal of this three-year project is to determine whether rapid seed germinating and salt tolerant KBG and Western Wheatgrass can be developed for golf courses in in the Upper West, Mountain, Transition and Pacific regions of the United States.

<u>Kentucky Bluegrass:</u>

At the end of the third year, we expect to have identified KBG that has rapid seed germination, reasonable salt tolerance and turf quality. We will continue advancing the highest quality genetic material into the final steps of breeding and will ultimately perform PVP trials for any lines that we developed based on this research.

<u>Western Wheatgrass and other native grasses:</u>

Our research to date suggests that Western Wheatgrass and other native wheatgrasses are not a good choice for golf course plantings. As such, we are shifting our focus to KBG for this project and potentially to the native turfgrass Tufted Hairgrass (*Deschampsia cespitosa*) in the future.

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USGA ID#: 2016-01-551

Title: Development of New Bermudagrass Varieties with Improved Turfgrass Quality and Increased Stress Resistance

Project Leaders: Yanqi Wu, Dennis Martin, and Mingying Xiang
Affiliation: Oklahoma State University

Objectives:

1. Improve bermudagrass germplasm for seed production potential, turf performance traits, and stress resistance.
2. Develop, evaluate, and release seed- and vegetatively propagated turf bermudagrass varieties for use on fairways, tee boxes and putting greens.
3. Assemble, evaluate, and maintain *Cynodon* germplasm with potential for contributing to the genetic improvement of the species for turf.

Start Date: February 1, 2016
Project Duration: 10 years
Total Funding: $500,000

Summary Points:

- A greens-type genotype '15x9' without covering in the winter between 2023 and 2024 exhibited minimum winter kill in a field trial in the spring of 2024.
- Two new greens-type selections, '11x8' and '20x10' demonstrated ball roll distance and quality close to 'TifEagle' in 2024.
- 'OSU1101' which performed well under drought stress has been selected to advance to the coming 2025 NTEP national bermudagrass test.
- Large variations were present in late season color retention and frost resistance in the 2023 – 2026 Clonal and Seeded Bermudagrass Trial.

Summary Text:

Bermudagrass is the most widely used turfgrass on golf courses, covering up to 32% of all golf course turf acreage in the US (Shaddox et al., 2023). The 2023 USDA plant hardiness zone map indicates that many locations in the US are experiencing warmer average annual minimum temperatures. Many areas are approximately one-half zone warmer in winter (https://planthardiness.ars.usda.gov/) as compared to the map published in 2012. Climate warming has increased or is predicted to increase the use of bermudagrass in climates typically dominated by cool season turfgrasses creating various challenges for turfgrass managers. Unseasonably warm temperature spikes in winter, cold spikes in spring, along with low temperatures in winter, solely or combined with other undesirable environmental factors, such as shade or dehydration or traffic, pose a major winterkill threat to bermudagrass stands. The long-term goal of the Oklahoma State University (OSU) grass breeding program is to develop new cultivars with high turfgrass quality and improved resistance to abiotic and biotic stresses.

Developing greens-type bermudagrass cultivars is an important component of the current research grant funded by the US Golf Association. The 2021 greens-types bermudagrass mowing test was continued to evaluate winter survival in 2024. The test consisted of 12 OSU advanced selections, one genotype from the University of Florida, one from Mississippi State University, and three commercial cultivars (Tahoma 31®, 'Tifdwarf', and 'TifEagle'). A randomized complete block design (RCBD) with a 15' by 5' plot size and five replicates was used. The trial was not covered during the winter of 2023/2024 to test for winter hardiness. In spring 2024, '15x9' consistently exhibited minimal winterkill and quick spring green-up when plots were left uncovered throughout the winter. TifEagle and Tifdwarf had experienced complete winterkill in the previous year.

In 2024, we established a large Breeder class pedigree stock production block for each of two cold hardy, greens-type bermudagrasses, 'OKC 3920' and '15x9', along with another cold hardy, fairway-type selection, 'OSU1337' on the OSU Agronomy Farm. These blocks will furnish material for the establish pedigree Foundation blocks for product licensees in the future. The three advanced bermudagrass line production blocks were fertilized with 400 lbs of 19-19-19 per acre before transplanting. Plugs prepared in a greenhouse were transplanted on 2-foot centers. After transplanting, 1 gallon of Oxadiazon pre-emergence herbicide was spray applied with water in 15 gallons total spray volume per acre. The plants were watered 2-3 times per week with an irrigation reel for establishment. Since the second month following planting, the blocks were fertilized with 50 lbs N/acre applied every two weeks. The three blocks were planted in late July and not fully covered by the end of this season as the putting types grew slowly. It is expected that the three plantings will be fully covered by the early summer of 2025. We plan to produce sprigs from the three blocks for planting demonstration plots and research nurseries on golf courses, sod farms, or research facilities.

'OKC3920' produces some seedheads in May, resulting in reduced turf quality. One experiment has been conducted to develop a solution for suppressing seedheads in the bermudagrass. A research putting green was sprigged with 'OKC3920' bermudagrass in June 2022. The rootzone comprised 80% sand and 20% shredded sphagnum peat moss. The objective of this study was to assess the impact of four plant growth regulators (PGR) at different application rates on 'OKC3920' bermudagrass seedhead suppression. The experimental design followed a two-way factorial design. Each plot measured 5 by 5 ft. Plant growth regulators included trinexapac-ethyl (PrimoMaxx; Syngenta Crop Protection, Inc., Greensboro, NC), ethephon (Proxy; ENVU, Research Triangle Park, NC), prohexadione calcium (Anuew; Nufarm, Alsip, IL), and Paclobutrazol (Trimmit; Syngenta Crop Protection, Inc., Greensboro, NC). The second treatment factor involved application rates: 0.5X, 1X, and 2X label rates, applied every 2 weeks from April 28 to June 31. In 2023, seedheads emerged in late May. Our data indicated that two applications of Proxy at any rate (0.5X, 1X, or 2X) during the study resulted in over 90% seedhead control in spring. In 2024, seedhead emergence began in mid-May, approximately two weeks earlier than in 2023. Our data showed that two applications of Proxy effectively suppressed seedheads during the spring. However, when applications ceased in the summer, seedhead emergence resumed at a reduced intensity. This highlights the potential need for continuous applications, either with the same or alternative chemicals, or exploring other strategies to achieve sustained seedhead suppression.

A replicated trial established at the OSU TRC in 2017 was evaluated for spring greenup in 2024 and left in place under lower maintenance conditions than in prior years to hold the germplasm for later use. This trial was under the direction of Dr. Dennis Martin. The trial included 35 OSU vegetatively propagated experimental selections, four vegetatively propagated commercial cultivars (‘Astro’, Latitude 36®, Tahoma 31® and TifTuf®), 11 seed-propagated experimental synthetics and two seed-propagated commercial cultivars (‘Riviera’ and ‘Monaco’). In 2024 the trial was mowed once per week at 1.5 inches, fertilized with only 0.5 lbs of N per 1,000 sq. ft. per year, and was not irrigated in 2024 other than to wash in the single fertilizer event. Results from the analysis of entry responses to drought in the summer of 2022 suggested that entry ‘OSU1101’ has improved drought resistance in terms of leaf firing resistance and higher normalized difference vegetative index (NDVI) compared to many other entries but was similar to that of TifTuf. We will advance ‘OSU1101’ to the 2025 national bermudagrass test administered by the National Turfgrass Evaluation Program.

A greens-type mowing test established in 2022 continued in 2024 at the OSU TRC under the direction of Dr. Mingying Xiang. The test consisted of 13 experimental selections and two commercial cultivars (Tahoma 31®, and ‘TifEagle’). The objective of the new trial was to evaluate turf quality and ball roll distance of the new experimental selections for putting green use. In 2024, ‘11x8’ and ‘20x10’ demonstrated ball roll distance and quality close to ‘TifEagle’.

A new trial established in 2023 continued at the OSU TRC under the direction of Dr. Dennis Martin. This test consists of 52 clonal experimental genotypes with TifTuf® and ‘Astro’ as checks, and five seeded experimental synthetics with ‘Monaco’ as a commercial standard cultivar (Figure 1). The experimental design for the test is a RCBD with three replications. The objective of the test is to evaluate establishment vigor, sod tensile strength, regrowth vigor post sod harvest, turfgrass quality and its components, fall color, spring green up, winterkill, seedhead prolificacy, and diseases. Mowing height in 2023 was 1.5-inch with strip-plot mowing at 0.5-inch (typical fairway) and 1.5-inch (medium rough) mowing heights administered in 2024. Large differences were present among clonal and seeded types with the overall quality of clonal types being better than that of seeded types. Seed head expression continued to drag down the quality of seeded types as compared to high quality clonal types. Few differences were present among Monaco seeded bermudagrass and the experimental OSU lines with respect to turf quality and visual performance parameters. Large differences were present among clonal entries with respect to late-season color retention and frost resistance (Figure 1). Sod tensile strength and handling quality assessment will occur on this trial in 2025 as well as a continuation in collection of visual performance parameters.

Figure 1. Large differences were present in late season color retention and frost resistance seen on November 25, 2024, in the 2023 – 2026 Clonal and Seeded Bermudagrass Trial. Late season color retention is often better at 0.5-inch than 1.5-inch mowing height although this varies by entry.

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USGA ID#: 2023-09-776

Title: Developing new bermudagrass cultivars combining improved drought resistance, cold hardiness and high turf quality

Project Leaders: Yanqi Wu, Mingying Xiang, Shuhao Yu, and Anit Poudel
Affiliation: Oklahoma State University

Objectives:

1. To make crosses between cold-hardy parents and drought-resistant parents in common bermudagrass.
2. To identify true hybrids in the progeny populations from the target crosses.
3. To evaluate and select cold-hardy and drought-resistant progeny in field trials.

Start Date: January 1, 2023
Project Duration: 3 years
Total Funding: $109,161

Summary Points:

- We developed and evaluated 1,515 progeny from 10 crosses between cold-hardy and drought-resistant common bermudagrass parents in a greenhouse and two field nurseries.
- An experiment with 745 selected progeny genotyped with simple sequence repeat (SSR) markers indicated 331 true hybrids, 376 chance hybrids, 36 selfed progeny, and 2 with missing data.
- A field nursery was established with 147 selected progeny in a RCBD design in 2024.

Summary Text:

Bermudagrass is the most extensively used turfgrass on golf courses in the U.S. transition zone, covering approximately 45% of the turf acreage (Shaddox et al., 2023). Winterkill is a major threat to growing bermudagrass in transitional climates. The OSU turfgrass breeding program has focused on improving turf bermudagrass cold hardiness since the 1980's. The program released cold hardy cultivars 'Midlawn' and 'Midfield' collaborated with Kansas State University in 1991, 'Yukon' in 1996, 'Riviera' in 2000, 'Patriot' in 2002, Latitude 36 and 'NorthBridge' in 2010, 'Tahoma 31' in 2017, and 'OKC3920' in 2022. However, none of these cultivars has the drought resistance level comparable to some drought-resistant cultivars used in the southern regions. Accordingly, our long-term goal is to breed, test, and develop interspecific hybrid cultivars improved in drought resistance, cold hardiness, and high turfgrass quality.

Eight reciprocal single crosses between cold-hardy and drought-resistant common bermudagrass parents were established in a field nursery on the Oklahoma State University Agronomy Farm. By September 2023, all the parental plants flowered. Mature seedheads were hand harvested on each parent separately in November post a few heavy frosts. The collected seedheads from single crosses were threshed, cleaned, and stored in well-labeled paper bags. The seeds were then germinated in trays containing soil medium in February 2024. The germination involved two weeks of chill treatment followed by greenhouse exposure. The germinated seedlings were transplanted in well labeled containers in March. At the first stage, 1,302 seedlings were transplanted, which were then selected to 533 healthy looking seedlings with good roots and leaf characteristics. Additionally, 213 plants from 2021 and 2022 single-spaced nurseries were transplanted in greenhouse containers. Altogether, 745 progenies were analyzed with SSR markers to identify if they were hybrids or selfed progeny (Figure 1).

For genotyping, 72 simple sequence repeat (SSR) markers from 18 linkage groups described by Guo et al. (2017) were tested in all parental populations to identify polymorphic markers. Each progeny was then screened using 4-6 markers that were polymorphic between their respective parents (Table 1). Among the 745 screened progeny, 331 were identified as true hybrids, 376 chance hybrids, 36 selfed progenies, while 2 showed missing bands (Table 2). DNA extraction, PCR, and gel visualization in the process were carried out following the procedure described by Fang et al. (2015).

Figure 1. An M.S. graduate student, Mr. Anit Poudel, genotyping progeny DNA samples of crosses between cold-hardy and drought-resistant common bermudagrass parents with simple sequence repeat markers.

Table 1. Details of SSR markers used in genotype study

No.	Primer pair identification	Linkage Group
1.	CDGA7-1601/1602	LG2
2.	CDGA3-1135/1136	LG3
3.	CDCA3-245/246	LG3
4.	CDCA7-703/704	LG4
5.	CDCA3-263/264	LG6
6.	CDGA1-865/866	LG8
7.	CDGA1-805/806	LG9
8.	CDGA1-815/816	LG9
9.	CDGA3-1177/1178	LG11
10.	CDGA4-1347/1348	LG11
11.	CDGA2-1021/1022	LG13
12.	CDCA7-635/636	LG14
13.	CDCA5-461/462	LG17

Table 2. True hybrids identified using SSR markers

No.	Cross identification	Progeny	True hybrids verified with SSR markers
1.	A10202xA12445	84	63
2.	A12445xA10202	96	64
3.	A10202xA12400	96	35
4.	A12400xA10202	152	76
5.	A10202x21-11*2	57	19
6.	21-11*2xA10202	38	3
7.	A10202x10*15	63	6
8.	10*15xA10202	18	0
9.	A10202x1714	45	14
10.	1714xA10202	96	51
	Total	**745**	**331**

Not all the true hybrids identified with molecular markers performed well due to the differential segregation and recombination of desirable and undesirable genes. Therefore, we used the combined information of genotyping, greenhouse performance, and field performance to select progenies for a replicated field study. Plants from 2023 crosses were selected in a greenhouse based on root characteristics, while plants from 2021 and 2022 crosses were selected based on their field performance. We assumed that extensive and deep-rooted plants may have good stress tolerance. While field performance was based on drought resistance and spring green-up traits. Emphasis was given to the plants that identified true hybrids during molecular screening. Altogether, 147 progenies including 74 true hybrids, 69 chance hybrids, and 4 selfed were taken forward for the replicated field study (Figure 2).

The land preparation for the replicated field study was started in June 2024. Base fertilization (19-19-19 NPK) was provided at the rate of 100 lbs per acre. Herbicide ‘Ronstar’ was sprayed at a rate of 2 lbs a.i. per acre to control weeds in the field. Planting materials were prepared in a greenhouse in such a way that each plot received 4 plugs for establishment. The field transplanting was done on 7th and 8th of August. Total field area was 0.38 acres with plot size of 4’ x 4’ and 2’ of alleys in between. 147 experimental lines along with two parents (A12400 and A10202) were planted in a randomized complete block design (RCBD) with three replicates. During establishment, a single application of urea fertilization was done at a rate of 100 lb per acre. One application of herbicide was used to control broad leaf weeds. Additionally, one application of ‘Roundup’ was given in the alleys to prevent contamination between the plots.

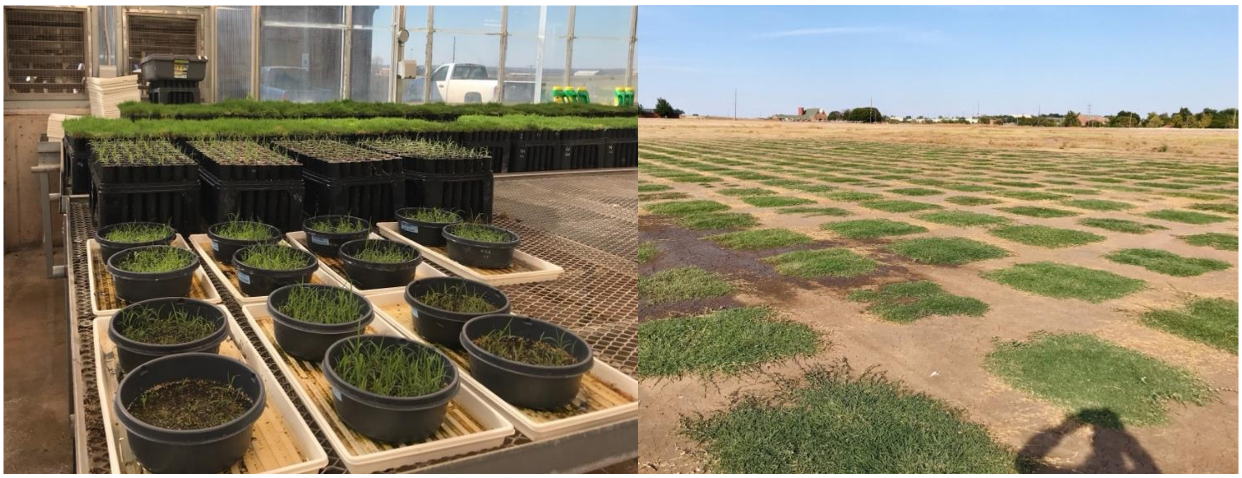

Figure 2. Seedlings at the stage of germination and transplantation (left) and establishing a replicated field nursery (right).

The visual ratings were collected for the establishment rate from 5th to 7th week post transplantation. The rating scale was from 1-9, where 1 was poorly established and 9 fully covered plots. From the analysis of variances, the LSD for establishment rate was found to be 1.01, meaning two entries are statistical different when their mean differs by 1.01. Similarly, fall color ratings of the entries were collected during the month of November. It used the same rating scale of 1-9, where 1 for complete brown color and 9 dark green color. Two entries are statistically different when their mean fall color rating differs by 0.97.

Table 3. Mean establishment rate and mean fall color of the entries rated on the scale of 1-9

Entry	Establishment rate	Fall color retention
241	6.44	7.33
586	6.22	6.83
220	6.00	7.83
298	5.78	7.67
305	5.78	7.17
377	5.78	7.83
392	5.67	7.33
720	5.56	7.83

(Table 3 continued)		
Entry	**Establishment rate**	**Fall color retention**
213	5.44	6.83
542	5.44	7.83
242	5.33	7.67
420	5.33	8.17
595	5.33	8.17
612	5.33	8.00
687	5.33	8.33
174	5.22	7.83
310	5.22	7.33
387	5.22	6.33
514	5.22	8.00
209	5.11	7.83
233	5.11	6.83
311	5.11	7.50
394	5.11	7.50
497	5.11	8.00
498	5.11	8.17
502	5.11	7.67
563	5.11	7.33
253	5.00	7.33
301	5.00	7.83
480	5.00	8.33
494	5.00	7.83
618	5.00	7.50
303	4.89	8.00
331	4.89	5.17
382	4.89	7.83
523	4.89	7.83
525	4.89	8.33
538	4.89	7.83
605	4.89	8.33
741	4.89	7.83
393	4.78	6.83
459	4.78	8.17
484	4.78	7.00
567	4.78	8.00
717	4.78	7.83
283	4.67	7.17
299	4.67	8.17

(Table 3 continued)		
Entry	**Establishment rate**	**Fall color retention**
486	4.67	8.33
511	4.67	8.33
551	4.67	7.67
580	4.67	7.50
121	4.56	7.83
126	4.56	8.00
193	4.56	7.83
234	4.56	8.33
449	4.56	7.83
530	4.56	7.00
578	4.56	8.17
142	4.44	7.83
388	4.44	5.67
597	4.44	7.00
120	4.33	7.83
416	4.33	8.33
441	4.33	8.17
656	4.33	8.17
670	4.33	7.83
60	4.22	7.50
109	4.22	8.33
157	4.22	6.83
210	4.22	8.17
281	4.22	7.50
493	4.22	8.00
519	4.22	8.33
590	4.22	8.17
24	4.11	6.67
181	4.11	7.67
373	4.11	7.50
413	4.11	8.00
691	4.11	7.50
21	4.00	6.67
127	4.00	8.17
129	4.00	7.50
456	4.00	8.17
577	4.00	8.00
589	4.00	7.17
194	3.89	7.17

(Table 3 continued)		
Entry	**Establishment rate**	**Fall color retention**
202	3.89	6.67
422	3.89	8.17
503	3.89	7.83
574	3.89	7.83
599	3.89	7.33
608	3.89	7.83
12	3.78	7.17
118	3.78	7.83
594	3.78	8.00
653	3.67	7.33
39	3.56	7.50
77	3.56	8.33
79	3.56	7.33
172	3.56	7.67
560	3.56	8.33
710	3.56	7.67
744	3.56	7.50
43	3.44	7.33
107	3.44	7.83
116	3.44	8.00
700	3.44	7.50
38	3.33	7.00
146	3.33	6.83
295	3.33	7.83
468	3.33	8.00
483	3.33	8.17
510	3.33	7.33
572	3.33	8.00
633	3.33	7.50
A10202	3.33	7.33
147	3.11	6.83
636	3.11	8.33
683	3.11	4.50
684	3.11	2.17
730	3.11	7.67
735	3.11	7.83
19	3.00	7.67
58	3.00	7.00
733	3.00	7.00

(Table 3 continued)		
Entry	**Establishment rate**	**Fall color retention**
8	2.89	5.50
140	2.89	7.17
145	2.89	8.33
155	2.89	5.00
663	2.89	7.67
685	2.89	8.33
630	2.78	7.67
99	2.67	5.83
A12400	2.67	6.33
591	2.67	3.50
628	2.67	8.17
573	2.56	7.00
632	2.56	7.50
728	2.50	6.00
26	2.44	7.33
144	2.33	8.00
631	2.33	7.83
646	2.33	7.50
666	2.28	2.00
627	2.22	5.83
660	2.22	7.17
665	2.22	7.17
587	1.83	1.00
411	1.67	1.50
5% LSD	1.01	0.97

The entries will be evaluated for winter survivability and drought resistance in the coming two years (2025 and 2026). The field will be evaluated for spring green-up and percent green cover as the measures of cold hardiness, and leaf firing and turf quality under drought stress as the measures of drought resistance. Ratings on turf quality will be recorded each month as the measure of overall turf quality. Irrigation will be halted in summer months to provide on-field drought conditions. Drone images will be taken for high-throughput selection of top entries. Additional data will be collected through a NDVI meter, and Digital Images. Statistical analysis will be performed to identify top performing entries.

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USGA ID: 2016-38-608

Title: Breeding for Resistance to Winter Dormancy in Bermudagrass and Zoysiagrass

Project leader: Kevin Kenworthy, John Erickson, Kenneth Quesenberry
Affiliation: University of Florida

Objectives:
1) Develop germplasm and cultivars of bermudagrass that are winter dormant resistant.
2) Develop germplasm and cultivars of zoysiagrass that are winter dormant resistant.

Start date 2016
Project duration 10 years
Total funding $300,000

Summary Points
- 2024 was a year of transition between ending trials and planting new trials.
- 2,500 new bermudagrass lines were planted in space plant nurseries.
- FB1628 bermudagrass is under expansion after exhibiting good performance in the 2019-2023 Bermudagrass NTEP Trial.
- Eight fine-textured zoysiagrass lines were planted in expansion blocks. Several of these lines had good performance in the 2019-2023 Zoysiagrass NTEP Trial.

In Florida, most rounds of golf are played through the winter months justifying the need for improved cultivars of bermudagrass and zoysiagrass to sustain playability through colder periods.

Bermudagrass

The 2019 bermudagrass fairway trial was terminated at the end of 2023. FB1628, FB1630, and FB1634 were selected for continued evaluation. The 2022 bermudagrass trial was also terminated, and three lines with good winter performance and color retention were selected for further evaluation (FB2239, FB2237, and FB2214). A new fairway trial with three replications was planted in October 2024 in a randomized complete block design. Plots are 3 m x 4 m. Ratings for this trial will begin in 2025.

New spaced planted nurseries of bermudagrass were planted in 2024 with 2,500 new progenies planted on 1.5 m centers.

FB1628 bermudagrass has shown good performance for many years and in several trials since it was first planted in a replicated trial in 2013. According to the 2019 Bermudagrass NTEP final report (2019-2013), FB1628 was the best performing experimental entry. We are expanding FB1628 to provide material for grower evaluations for evaluation of mowing heights and nitrogen rates (Figure 1).

Zoysiagrass

The 2019 zoysiagrass fairway trial was terminated at the end of 2023. Eight advanced lines were planted in larger 6m x 12m expansion blocks in July 2024. The 8 lines under expansion are FZ1357, FZ1367, FZ1368, FZ1722, FZ1732, FZ1727, FZ1755, and FZ1440. FZ1722 and FZ1440 were among the most consistent high performing entries in the 2019-2023 Zoysiagrass NTEP final report. When the expansions are mature, sod and sprigs will be used to establish test areas with golf courses and test production blocks with sod producers.

2017 and 2021 Zoysiagrass Spaced Plant Nurseries

Selections from these two terminated nurseries were propagated in the greenhouse for planting in 2025.

2023 Zoysiagrass Spaced Plant Nursery

The 2023 nursery was screened using SPECTICLE® FLO herbicide. Lines with less injury will be selected for use as parents and for further evaluation.

Putting Green Zoysiagrass Selections

Four putting green zoysiagrass lines are being expanded for further evaluation.

Figure 1. The image to the left is FB1628, one month (Aug 2, 2024) after planting 5 cm plugs on 32 cm centers at the Plant Science Research and Education Unit (PSREU) in Citra, FL. The image on the right is of the same area taken on Oct. 2, 2024, during the annual turfgrass field day at PSREU.

USGA ID#: 2017-21-631

Title: Improvement of Bermudagrass, Zoysiagrass, and Kikuyugrass for Winter Color Retention and Drought Tolerance

Project leaders: Adam J. Lukaszewski, Christian S. Bowman, and James H. Baird
Affiliation: University of California, Riverside

Objectives:

1. Develop bermudagrass, kikuyugrass, and zoysiagrass turf-type genotypes with improved winter color retention and drought tolerance for Mediterranean and arid climates.
2. Utilize Diversity Arrays Technology (DArT) markers to aid in breeding efforts and marker-assisted selection.
3. Develop techniques to reduce kikuyugrass ploidy level to diploid by androgenesis to reduce aggressiveness and improve turf quality and playability characteristics.

Start Date: 2017
Project Duration: 5 years
Total Funding: $250,000

Summary Points

- Two bermudagrass hybrids were patented: UCR TP6-3 under US PP35,441 P2 and UCR 17-8 under US PP35,357 P2.
- 'Coachella™' hybrid bermudagrass (UCR TP6-3) was licensed to West Coast Turf in 2024 for the U.S. and Mexico. Approximately 100 acres will be available in 2025.
- 'Presidio' hybrid bermudagrass (UCR 17-8) will be licensed in 2025/2026.
- Christian Bowman completed his Ph.D. in 2024. Dissertation: "Exploration of Genetic Diversity and Associations Between Genotype and Phenotype in Cynodon spp."
- Dr. Marta Pudzianowska was appointed as Assistant Professor of Turfgrass Breeding at Mississippi State University in October 2023.
- Dr. Bowman was appointed as a postdoctoral scholar in October 2024 and is the new quarterback of the UCR Turfgrass Breeding & Genetics program, overseeing all aspects.
- Evaluation of new bermudagrass hybrids selected for fairways/sports fields and greens and replicated test plots of kikuyugrass selected for fairways/sports fields was initiated.
- Evaluation of shade tolerance trial and test plots of bermudagrass suitable for roughs and lawns established in 2021 continued.
- Evaluation of nurseries, drought and salinity stress trials for bermudagrass, zoysiagrass, St. Augustinegrass and seashore paspalum accesions under the Specialty Crop Research Initiative (SCRI) project concluded in 2023.
- Multi-location trials in the Southwest for advanced bermudagrass hybrids were established in the summer of 2024.
- DNA markers were identified through DArTseq that may aid in screening for improved winter color retention.
- Efforts to broaden genetic diversity of kikuyugrass continue with multiple collection trips to Bogota, Colombia since 2022 and bermudagrass with an initial collection trip to Pakistan in November 2024.

Summary

Warm-season or C4 turfgrass species including bermudagrass, zoysiagrass, and kikuyugrass are much better adapted to heat, drought, and salinity compared to cool-season grasses, but they can go dormant during winter months making them less desirable choices for lawns, athletic fields, and golf courses. Clear differences in winter color retention, drought tolerance, and water use efficiency exist among warm-season grasses, and within individual species, which indicates that genetic improvements are possible. Our objectives are to develop improved genotypes of these three species with emphasis on the winter color retention and drought tolerance for Mediterranean and arid climates.

Bermudagrass

Evaluation and selection in nurseries established in 2020 and 2022 continued. Bermudagrass accessions in nurseries planted in 2018 and 2019 went through additional evaluation under mowing with rotary mower at 2 inches. Top performers were transplanted to the greenhouse for future trials, and both nurseries were terminated to clear land for new hybrids. Four parents which consistently generated hybrids with valuable traits were planted in the trays and used for crosses in the greenhouse.

Evaluation of bermudagrass hybrids suitable for roughs/lawns, planted in 2021, continued. Twenty-two bermudagrass hybrids were selected and planted at UCR in three replicates in 2021. ‘Presidio’ (UCR 17-8) and ‘Coachella’ (UCR TP6-3), as well as six cultivars (‘Bandera’, ‘Bullseye’ ‘Celebration’, ‘Midiron’ ‘Santa Ana’, ‘Tifway II’) were added as checks. Plots are mowed once a week at 2 inches. Turfgrass quality (1-9; 9=best), spring greenup (1-9;9=fastest), genetic color (1-9; 9=darkest) and seedhead production (1-9; 9=lowest) were evaluated. The highest overall quality was observed in UCRC190108, UCRC190311, UCRC180015, UCRC180661, and ‘Celebration’. ‘Presidio’, UCRC180015 and UCRC180661 had fast spring greenup, followed by ‘Celebration’ and UCRC190766. UCRC180015, UCRC190108, and UCRC190311 had also the darkest genetic color, followed by ‘Celebration’, UCRC180139, UCRC180600, and UCRC190225.

A trial of UCR bermudagrass hybrids under low light conditions was started in July 2021, and still continues. It includes 35 UCR experimental bermudagrass accessions, two recently patented UCR accessions: ‘Coachella’ (UCR TP 6-3) and ‘Presidio’ (UCR 17-8), and four checks (‘Latitude 36’, ‘Santa Ana’, ‘TifTuf’, ‘Tifway’). The trial is planted in three replicates at UCR, Riverside, CA. Plots are maintained under shade cloth (60% shade). Significant differences in establishment were observed. UCRC180211 was the fastest to establish, while ‘Latitude 36’, UCRC180041, and UCRC180133 were the slowest. UCRC180211 and ‘Presidio’ also showed high overall turfgrass quality and relatively good density, placing them as the top performers so far. Other entries with high overall quality and density were UCRC190280 and UCRC180176.

A trial to evaluate 57 UCR bermudagrass accessions for suitability for fairways/sports fields was planted in 2022 in replicated test plots; evaluation started in 2023. ‘Presidio’ (UCR 17-8) and five cultivars (‘Latitude 36’, ‘Santa Ana’, ‘Tahoma 31’, ‘TifTuf’, ‘Tifway’) were added as checks. ‘Coachella’ (UCR TP6-3) was initially included in the trial, but had to removed due to a mix-up of entries. Plots are maintained under fairway mowing height (0.5 in). The best performing entry so far is ‘Presidio’ (UCR 17-8). Other entries showing good quality were ‘Latitude 36’, ‘Tahoma 31’, UCRC180127 and UCRC180177. Among these, ‘Santa Ana’, ‘TifTuf’, ‘Tifway’, UCRC180137, and UCRC190750 had the best spring greenup.

The dry-down trial was conducted in 2020-2022 and concluded in 2023 by subjecting plots to long-term terminal drought, to evaluate how long they may survive without any irrigation. The trial included 71 of the best hybrids and collection accessions identified in previous years, together with five commercial cultivars (‘Bandera’, ‘Celebration’, ‘Santa Ana’, ‘TifTuf’ and ‘Tifway II’) as checks. Plots were established in May 2019, in a completely randomized design with three replicates. Several hybrids, UCRC180012, UCRC180037, UCRC180040, UCRC180146, UCRC180217, UCRC180229, and UCRC180557 placed consistently among the top 10 performers in their percentage of living green cover, showing remarkable drought tolerance.

After an almost 10-year long evaluation process, two bermudagrass hybrids, UCR 17-8 and UCR TP6-3, have been patented. UCR TP6-3 is registered under US PP35,441 P2 and will be available under the name ‘Coachella’. UCR 17-8 is registered under US PP35,357 P2, and will be available under the name ‘Presidio’. Currently, the area of production of these two grasses is being expanded at UCR and after a licensing agreement was signed, also by a commercial sod producer in Southern California.

After years of observation at the UCR turf facility, eight new bermudagrass hybrids have been selected for advanced trials in seven locations across the Southwest (Casa Grande, AZ; Santa Fe, NM; Las Vegas, NV; Littleton, CO; Stockton, CA; Thermal, CA; and Riverside, CA). These hybrids were selected based on their strong performance in multiple trials at UCR. ‘Presidio’ (UCR 17-8), ‘Coachella’ (UCR TP6-3), ‘TifTuf’, and ‘Tahoma 31’ or ‘Santa Ana’ were included as commercial checks. These multi-location trials were established in the summer of 2024, in a randomized complete block design with two replicates. Initial ratings of turfgrass quality (1-9; 9=best), genetic color (1-9; 9=darkest), and establishment (0-100%; 100%=fully established) were taken in August 2024. ‘Coachella’ and ‘Presidio’ had the highest overall turfgrass quality across the locations. ‘Presidio’ and ‘Tahoma 31’ had the overall best genetic color across the locations. ‘Tahoma 31’ had the highest and most consistent establishment rate across the locations. Deficit irrigation studies at all seven locations are planned for 2025.

A new nursery of 733 bermudagrass hybrids developed in 2023 was planted in June 2024. Five checks with eight replicates were included (two parents involved in the production of the hybrids, ‘Presidio’, ‘Coachella’, and ‘TifTuf’), for a total of 813 entries.

A total of 179 entries were genotyped using the DArTseq platform. The group primarily consisted of entries from the 2018 nursery, as well as six commercial entries (‘Bandera’, ‘Coachella’, ‘Presidio’, ‘Santa Ana’, ‘Tahoma 31’, ‘TifTuf’). Using data collected over multiple years for winter color retention and spring greenup, genome-wide associations were established between the field data and DNA markers. Genomic resources for bermudagrass are lacking, making genetic studies difficult; however, two significant associations were identified, with one of the markers aligning to a gene known to be involved in stress tolerance in maize. Maize was chosen for alignments as it is a warm-season (C4) grass species with a well-annotated reference genome.

Kikuyugrass

Replicated trials of kikuyugrass hybrids selected from the nursery planted in 2019 were established in the spring of 2022. Forty experimental accessions and cv. Whittet as a check are being evaluated for establishment, turfgrass quality, winter color retention, genetic color, texture and seedhead production. UCRK 190268, UCRK 190306 and UCRK 190280 have so far, the highest overall turf quality and finest texture. The dry-down study concluded in 2023, and top performing entries will be used in directed crosses to generate new hybrids. A new nursery with 406 new kikuyugrass hybrids and progenies presumed to have originated from self-pollination was also established in 2022.

One of the more bothersome aspects of kikuyugrass as turf is anther extrusion during the flower period. After several years of observation of all germplasm available at UCR for this trait, six entries were chosen with no or minimal anther extrusion, and planted for advanced trials in two locations, with cv. Whittet as a check. The two trial locations are established in Winchester, CA and Riverside, CA. Initial ratings of turfgrass quality (1-9; 9=best), anther extrusion (1-9; 9=no anthers), and turf establishment (0-100%; 100%=fully established) were taken already in the first year. While the six entries differed in anther extrusion, from trace to average, during turf multiplication under greenhouse conditions, no anthers were observed in any of the six entries in the field, while 'Whittet' produced anthers at a moderate level. UCRK190336 was ranked as the highest turf quality.

A new nursery of 112 kikuyugrass hybrids was planted in August 2024. These new hybrids will be evaluated for establishment, turfgrass quality, winter color retention, genetic color, texture, and seedhead production.

Efforts continue to reduce the ploidy level via androgenesis. With no funding dedicated specifically to this project, the efforts are limited in scale and depend on the availability of time. No success so far, but several new methods have been tested, such as shed-microspore embryogenesis. At the same time, chromosome pairing was observed in meiosis, with perfect 18 bivalents in a majority of meiocytes. This strongly suggests that kikuyugrass is an allopolyploid with strong control of chromosome pairing. If the ploidy level reduction is successful, the resulting diploids (haploids of tetraploids) are likely to be completely sterile, mitigating some concerns of spread/invasiveness of the species.

Other species

In 2019, the UCR breeding program established cooperation with five warm-season grass breeding programs under the Specialty Crop Research Initiative (SCRI) funded by the National Institute of Food and Agriculture (NIFA). The project involves North Carolina State University (NCSU), Oklahoma State University (OSU), Texas A&M AgriLife (TAMUS), the University of Georgia (UGA), and the University of Florida (UF). The accessions of four species (189 accessions of bermudagrass, 216 of zoysiagrass, 125 of St. Augustine grass and 90 of seashore paspalum) were planted in June and July 2020. UCR is the testing site for the overall performance, as well as drought and salinity tolerance. Twenty of UCR hybrids are also evaluated in single space plant nurseries (SSPNs) across all testing locations. 2023 was the last year of evaluation in all trials of this project. Dry-down was initiated in single space plant nurseries (SSPN) and in advanced drought trials in July. Bermudagrass again showed the best performance under drought and one of the UCR accessions in SSPN showed very high turf quality. In a salinity tolerance trial, irrigation with water electroconductivity at EC=4.4. dSm^{-1} was initiated again in July 2023. Under salinity stress, the entries of seashore paspalum showed higher turfgrass quality and lower leaf firing than the other species, while St. Augustinegrass had the lowest quality and the highest leaf firing. High variability in quality was observed among zoysiagrass and bermudagrass entries, which suggests that improvement of these two species through breeding efforts is possible. These results were consistent over all three years of these studies.

Figure 1. Bermudagrass (foreground) and zoysiagrass (background) entries in single space plant nursery in USDA-NIFA SCRI project after ca. 30 days without irrigation at UCR Agricultural Operations field in Riverside, CA. Photo taken on 12 August 2022. Nurseries are divided by dashed lines.

Figure 2. Variation in anther extrusion among kikuyugrass accessions in replicated test plots at UCR Agricultural Operations field in Riverside, CA. Photo taken on 16 May 2023. UCRK190336 is highlighted in blue.

Figure 3. Spring greenup of bermudagrass accessions in single space plant nursery in USDA-NIFA SCRI project at UCR Agricultural Operations field in Riverside, CA. Photo taken on 27 March 2023.

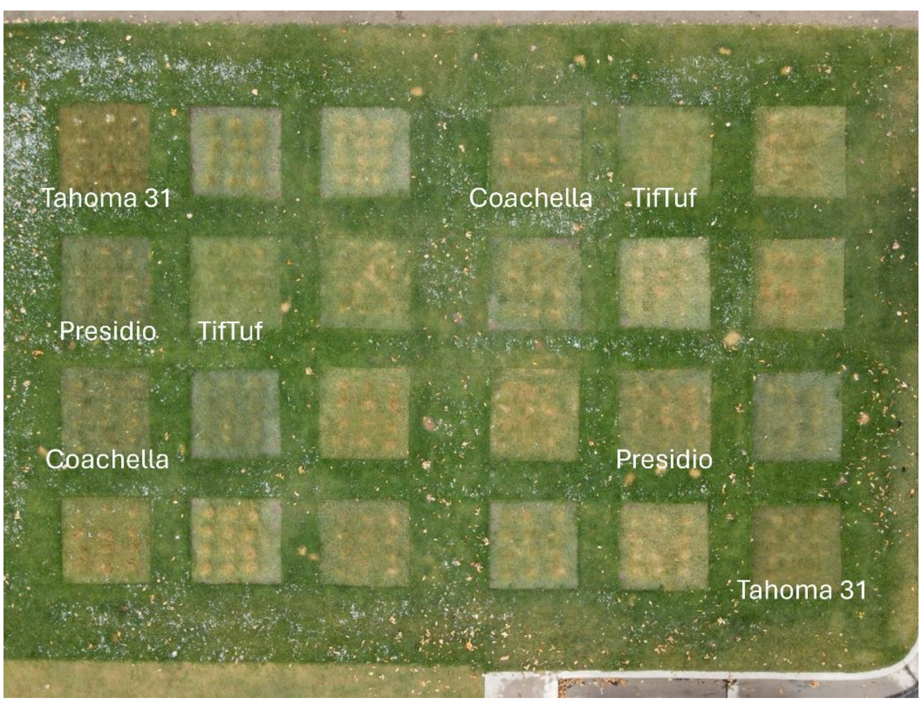


Figure 4. Advanced bermudagrass hybrids planted 12 June 2024 at Green Valley Turf in Littleton, CO. Photo taken on 4 November 2024.

USGA ID: 2017-11-621

Title: Development of Seeded Zoysiagrass Cultivars with Improved Turf Quality and High seed yields

Project Leaders: Ambika Chandra, A. Dennis Genovesi, and Meghyn Meeks
Affiliation: Texas A&M AgriLife Research – Dallas

Objectives:

1. Development of finer-textured germplasm/cultivar(s) of zoysiagrass with high seed yields that offer an economical alternative to vegetative types with the potential for rapid turf establishment.
2. Breed to improve characteristics such as turf quality, competitive ability, and persistence under biotic and abiotic stresses.

Start Date: 2017
Project Duration: 9 years
Total Funding: $269,559
Summary Points:

- Seed harvested from (1) early (two parent) and (2) late synthetic (three parent) varieties in in the fall of 2023 with a Seed Company in Oklahoma (SC-OK) has produced over 8 lbs. of breeder's seed. These two experimental synthetics varieties are under consideration for advancement in the 2025 Zoysia NTEP as DALSZ 2501 and DALSZ 2502.
- The seed sample of DALSZ 2501 and 2502 were used to test seed scarification methods to break seed dormancy. Chemical scarification agents used were sodium hydroxide and potassium nitrate. Both chemicals were useful in breaking dormancy, but potassium nitrate seemed to have a slight advantage.
- Our collaboration with a Seed Company in Alabama (SC-AL) has led to the identification of three potential seeded parents (TAES 6606-14, 6618-37 and 7327) with good seedhead production. Seed samples collected by SC-AL are currently being evaluated for percent germination following scarification.
- Another collaboration initiated in 2023 was with a Seed Company located in Oregon (SC-OR). A spaced plant nursery (SPN) consisting of 546 progeny was planted at two locations in OR in the spring of 2024 and currently under evaluation for seed traits.
- Vegetative material from nine selections made from the **2021 Seeded Zoysia SPN** have been established in 3-gallon pots for pairwise crossing in the greenhouse.
- Our **2023 Seeded Zoysia SPN** consisted of 1152 hybrid progeny (emphasizing Meyer and cold tolerant zoysiagrass germplasm like DALZ 1701and KSUZ 0806 as parental lines) was planted in Dallas in July 2023. The seed was collected from 11 red seeded types and 6 yellow seeded types. Seed was harvested from these plots in June and July of 2024 then processed in the fall. Data is presented on seed yields from each based-on plot sizes of 9 ft^2.

Project updates:

- ***Collaboration with a Seed Company in Oklahoma (SC-OK) –*** Out of the 23 intermediate-textured parental lines (cycle four of phenotypic recurrent selection) sent to SC-OK in

2018, four elite lines (TAES 6596-05, 6585-34, 6086-21, and 6087-15) were identified in 2021 with good seedhead production traits. Using these 4 elite lines, **one early flowering synthetic (TAES 6596-05 and 6086-21) and one late flowering synthetic (TAES 6596-05, 6585-34, and 6087-15) blocks** were planted in late summer 2021 in both OK and TX. Note, TAES 6596-05 is a common parent in both synthetic blocks. Anthesis began on April 13, 2022, for all three blocks. Seed was harvested from both the early and late synthetics during both the 2023 and 2024 growing seasons. Over 8 lbs. of seed have been harvested from each of the two synthetics and is under consideration for advancement and testing in the 2025 NTEP.

In preparation for NTEP testing scarification methods were compared. Samples of seed from the two synthetics were used to evaluate scarification methods.

- **a.** An experiment was designed to determine which scarification method would be the most efficient: (1) 30% NaOH, (2) 5% KNO_3, and (3) 10% Bleach with an untreated control. Also tested as checks were seed of two commercial cultivars, Zenith and Compadre.
- **b.** Each treatment was replicated four times with 25 seeds per rep. 25 seed lots were germinated in a 100 x 15 mm Petri dish containing a Whatman #4 filter paper moistened with 2.5 ml's of water.
- **c.** Data was collected by counting the number of germinated seed at two-day intervals.

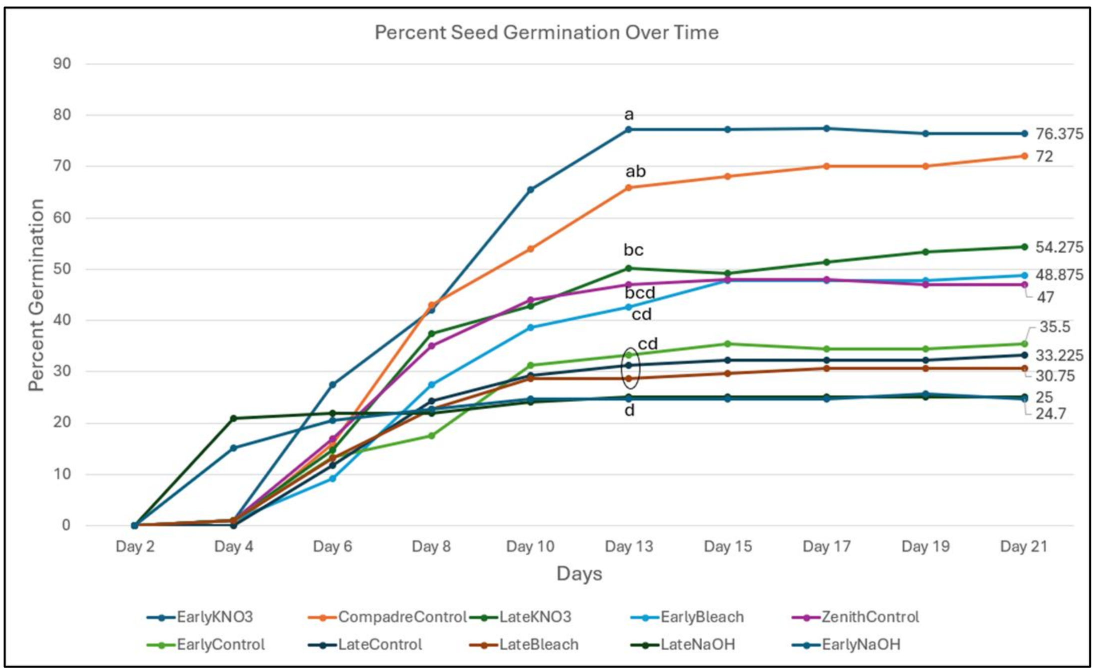


Figure 1: Percent seed germination over time of Early and Late Synthetic in comparison to Zenith and Compadre.

Seed germination over time was closely monitored across treatments, showing that the germination plateaued by day 13 across all varieties. By this point, significant differences in germination rates had emerged based on the type of treatment applied. Seeds treated with potassium nitrate (KNO_3) consistently demonstrated superior germination outcomes compared to those subjected to bleach or sodium hydroxide (NaOH). This trend held true across both the Early and Late Synthetic seed groups. In contrast, untreated seeds and those treated with NaOH exhibited the lowest germination rates.

- ***Collaboration with a Seed Company in Alabama (SC-AL)* –** Twenty-one of our advanced seeded parental lines were transferred to AL in 2021 for field evaluation. In the summer of 2024, we identified seeded parental lines they are being considered for combining into a three-clone synthetic. Those lines are 6606-14, 6618-37 (Figure 1) and 7327. Open pollinated seed samples from the three lines have been transferred to TAM AgriLife in Dallas for germination testing. Those tests are currently underway.

Figure 1. Seeded parental line 6618-37 growing in SC-AL nursery showing heavy seedhead production.

- ***Collaboration with a Seed Company in Oregon (SC-OR)* –** In the fall of 2023, a total of 546 experimental varieties were transferred to SC-OR. It was too late to plant in the field and therefore, the plants were split into two clones and kept over winter in the greenhouse.
  a) In the late spring of 2024 two spaced-plant nurseries were planted: one 546 plant nursery was planted near Albany, Oregon (a cool Mediterranean environment) and the other 546 plant nursery was planted near Madras, Oregon (a high dessert environment).
  b) The nurseries were evaluated on a maternal line basis for the following; growth rate (spreading), percent of plants flowering, percent of plants with tall seedhead exertion and fall color retention.
  c) Open-pollinated seed was harvested from plants with good seed yield potential and this seed is being tested for germination percentage.
  d) In 2025. SC-OR will continue to observe and rate the families and plants in the nurseries and then establish polycross nurseries with plants selected from the families with the best seed yield potential.

- ***2021 Spaced Plant Nursery*** – Seed harvested in 2019 from the 2017 Spaced Plant Nursery was scarified and germinated in 2020 to produce 15 to 30 progeny for each of 26 families. Progeny were transferred to 4" pots and planted 22 June 2021 as the 2021 Seeded Zoysia Spaced Plant Nursery consisting of 663 experimental entries. Plots have been rated for establishment, quality, spring greenup, and seedhead development in the spring and summer of 2022 and 2023. Selections were made on 23 August 2023 for parental lines exhibiting desirable turfgrass characteristics and seedhead production traits consistent with the goals of this project. A total of nine lines were selected representing five cycles of phenotypic selection. The nine advanced lines are currently (Fall 2024) being used as parental lines in resources cross combinations with elite germplasm.

- **2023 Seeded Spaced Plant Nursery** (SPN) consists of 1152 hybrid progeny (emphasizing Meyer and cold tolerant zoysiagrass germplasm like DALZ 1701 and KSUZ 0806 as parental lines) was planted in Dallas in July of 2023. Seed was harvested from these plots in June and July of 2024 (Figure 2) then processed in the fall. Seed was collected from 11 red seeded types and 6 yellow seeded types. Data is presented on seed yields from each based on plot sizes of 9 ft^2 and is shown in Table 1.

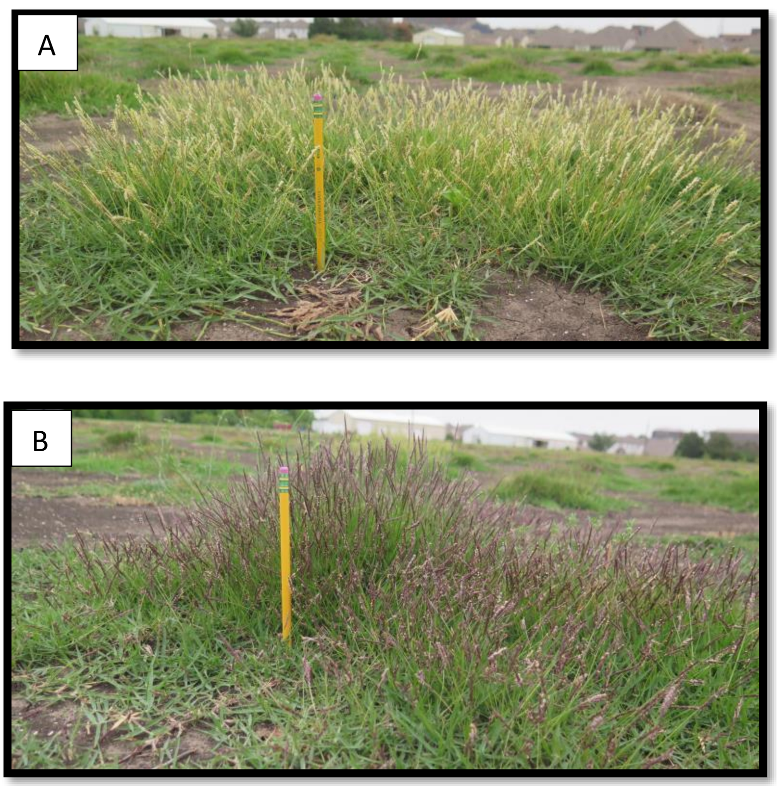


Figure 2. 2023 Seeded Zoysia SPN. A. Yellow Seeded Type; B. Red Seeded Type, photos taken on April 15. 2024

Table 1. Processed and estimated seed weight of 17 selections harvested from the 2023 Seeded SPN in 2024

No	Genotype	Group	Harvest Time	Processed Seed Weight (g)/9ft²	Estimated Seed Yield (lb)/acre
1	8211-59	red	last week of June	15.03	160.23
2	8223-59	red	last week of June	8.04	85.71
3	8224-36	red	first week of July	20.78	221.53
4	8224-61	red	first week of July	3.41	36.35
5	8224-66	red	last week of June	11.57	123.35
6	8226-63	red	last week of June	8.87	94.56
7	8228-48	red	last week of June	12.71	135.50
8	8230-69	red	first week of July	12.07	128.68
9	8238-04	red	last week of June	10.51	112.04
10	8242-04	red	first week of July	5.08	54.16
11	8243-12	red	last week of June	12.58	134.11
12	8211-56	yellow	last week of June	14.16	150.96
13	8225-21	yellow	last week of June	16.12	171.85
14	8228-34	yellow	last week of June	19.23	205.01
15	8233-31	yellow	first week of July	17.25	183.90
16	8235-32	yellow	last week of June	6.67	71.11
17	8235-52	yellow	last week of June	6.26	66.74

Goals for 2025:

- Chemically scarify the seed of DALSZ 2501 and DALSZ 2502 and test seed quality and germination for potential advancement in the 2025 Zoysiagrass NTEP in collaboration with SC-OK.
- Assemble a new experimental synthetic in partnership with SC-AL with three parental lines: TAES 6606-14, 6618-37 and 7327
- In collaboration with SC-OR, continue to evaluate seed traits and establish polycross nurseries with plants selected from the families with the best seed yield potential.
- Bulk seed by color group and establish seed increase blocks from the 2023 SPN; a portion will be used to seed a turf management trial while the remaining will be used for increase.

References:

Diesburg, K. L. 2000. Expanded germplasm collections set the stage for increased zoysiagrass breeding for turf use. Diversity 16(1):49-50).

USGA ID#: 2018-01-651, **2018-02-652**, 2018-03-653, 2021-18-742f, 2021-18-742e, 2021-18-742d, 2021-18-742c, 2021-18-742b

Title: Development of Cold Hardy Zoysiagrass Cultivars for Golf Courses in the Transition Zone

Project Co-Leaders: Ambika Chandra[1], Jack Fry[2], Aaron Patton[3], Dani McFadden[2], Meghyn Meeks[1], Dennis Genovesi[1], Ross Braun[2], Mike Richardson[4], Mike Goatley5, Dan Sandor[5], John Sorochan[6], Taylor Williams[6], Kevin Kenworthy[7], Paul Johnson[8], Kelly Kopp[8], Paul Harris[8], and Megan Kennelly[2]

Affiliation: Texas A&M AgriLife Research-Dallas[1], Kansas State University[2], Purdue University[3], University of Arkansas[4], Virginia Tech[5], University of Tennessee[6], University of Florida[7], Utah State University[8]

Objectives:
1. Phase I (year 1): Completed - Pairwise crossing of cold hardy zoysiagrasses adapted to the transition zone with under-utilized finer-textured zoysia accessions and large patch-tolerant zoysia germplasm was completed at Texas A&M AgriLife-Dallas in 2016/2017 and distributed across three test locations for evaluation in 2017: Olathe, KS, West Lafayette, IN, and Dallas, TX.

2. Phase II (year 2 and 3): Completed - Field evaluation in 2018/2019/2020 in the form of non-replicated spaced plant nurseries (SPN) comprised of the newly generated progeny populations in Olathe, West Lafayette, and Dallas. The objective of Phase II was to identify those experimental hybrids with superior cold tolerance and excellent turfgrass quality.

3. Phase III (years 4-6): Completed- A set of 65 hybrids (25 – Purdue, 20 - KSU and 20 – TAM AgriLife) were selected in fall of 2020 based on their superior performance in 2018/2019/2020. Entries were propagated into 18-cell trays in Dallas during winter 2020/2021 and distributed to eight participating trial locations across the United States. Replicated trials were planted in late summer of 2021 (Fig. 1). In year one, the rate of establishment and winter survival were evaluated. In 2022, additional data were collected on many traits that are used to characterize turfgrasses such as rate of establishment, turf quality, spring green-up, genetic color, and leaf texture. In 2022-2023, sites began evaluating individual traits including: shade tolerance in Dallas, TX; divot recovery in Fayetteville, AR; mowing height in Blacksburg, VA; thatch and traffic tolerance in Knoxville, TN; water-deficit in Citra, FL (Fig 2; observation of USGA plot area in Citra in 2024); and cold screening and adaptability in Logan, UT. Results from these evaluations are included herein.

Start Date: 2018
Project Duration: 6 years

Summary Points:
- In 2024, data collection over the past 6 years was summarized. Rather than just a focus on the transition zone, best performing zoysiagrass genotypes were identified for the transition zone and the southern U.S.

- Best performing zoysiagrass genotypes identified across transition zone and southern U.S. sites included 7 unique selections for each region; with two (TAES 6782-75 and 6782-104) selections performing well in both regions, making a total of 16 genotypes are expected to be evaluated in additional research.
- Our goal is to do additional experimental evaluation of these genotypes in the transition zone and the southern U.S. to identify a few selected genotypes that will be released as cultivars.

Summary Text:

In the summer of 2021, seventy-four zoysiagrass genotypes were planted at seven sites (Fayetteville, AR; Gainesville, FL; West Lafayette, IN; Olathe, KS; Knoxville, TN; Dallas, TX; and Blacksburg, VA). Genotypes planted in this study included sixty-five experimental lines, four elite experimental lines (DALZ 1701, 1702, 1808, and 1818) and five commercial 'standards' (Emerald, Innovation, Meyer, Palisades, and Zeon; Table 1).

Below is information regarding genotype breeding sources (Table 1); site details (Table 2); establishment (Table 3 and Figures 1 and 2); turf quality (Table 4 and Figure 2); leaf texture (Table 5); winter injury (Table 6); spring green up (Table 7); shade tolerance (Table 8); drought tolerance (Table 9); divot recovery (Table 10); traffic tolerance (Table 11).

Throughout this study, several experimental entries exhibited enhanced cold tolerance, including TAES 6844-202 and 6844-150, while TAES 6941-36 performed well throughout southern study sites suggesting good drought resistance. Elite experimental lines DALZ 1701, 1702, 1808, and 1818 show promise within a range of environments; however, no entry had exceptional performance across all seven study sites. The results of this study suggest that multiple experimental lines could perform well in specific regions, but not across all regions in the United States.

As of February 2024, nine entries were also selected for further evaluations in the transition zone, which include: 6782-75, 6782-79, 6782-104, 6829-36, 6844-36, 6844-74, 6844-104, 6844-150, and 6844-202. In addition, nine entries were selected for further evaluations in the southern region, which include: 6782-75, 6782-104, 6785-19, 6789-23, 6789-40, 6792-44, 6829-69, 6941-36, and 6942-22. TAES 6782-75 and 6782-104, were selected for both zones demonstrating a very broad range of adaptations. TAES 6782-104 and four additional southern selections (TAES 6785-19, 6789-23, 6789-40 and 6792-44), were noted as putting green candidates. Future research should focus on the adaptability and performance of these aforementioned entries under different maintenance regimes to better understand the genotype x environment x management interactions.

Fig. 1. Planting of experimental zoysiagrass plugs on June 17, 2021 in Olathe, KS.

Fig. 2. USGA zoysiagrass trial in Citra, FL on March 4, 2024.

Table 1. Texas Agricultural Experiment Station (TAES) family lineage summary

TAES Family	Lineage
DALZ 1701	(Zm x Zj) x Zj
DALZ 1702	(Zm x Zj) x Zj
DALZ 1808	Zj x Zj
DALZ 1818	(Zp x Zj) x Zj)
6782	[(Zj x Zp)/Zj) x Zp]
6783	[(Zj x Zp)/Zj] x Zp)
6784	[(Zj x Zp)/Zj] x Zp)
6785	[(Zj x Zp)/Zj] x Zp)
6786	[(Zj x Zp)/Zj] x Zp)
6787	[(Zj x Zp)/Zj] x Zp)
6789	[(Zj x Zp)/Zj] x Zp
6791	[(Zj x Zp)/Zj] x Zp)
6792	[(Zj x Zp)/Zj] x Zp)
6828	Zm x [(Zj x Zp)/Zj]
6829	[(Zj x Zp)/Zj] x Zm)
6830	((Zm x Zj) x Zm)
6831	Zm x (Zm x Zj)
6835	(Zm x Zj) x Zm
6836	[(Zmin x Zm)/Zm] x [(Zj x Zp)/Zj]
6839	Zm x [(Zj x Zp)/Zj])
6840	Zm x [(Zj x Zp)/Zj)
6844	[Zm x Zj] x [(Zj x Zp)/Zj])
6910	Zj x (Zj x Zm)
6919	[(Zm x Zp)/Zj] x [Zm x Zj]
6923	(Zj x Zm) x Zj)
6924	(Zm x Zj) x (Zm x Zj)
6925	(Zm x Zj) x (Zm x Zj)
6933	(Zm x Zj) x (Zm x Zj)
6940	(Zj x Zm)
6941	(Zj x Zm)
6942	(Zj x Zp)
Emerald	(Zj x Zp)
Innovation	(Zm x Zj)
Meyer	Zj
Palisades	Zj
Zeon	Zm

Zj: *Zoysia japonica*; Zm: *Zoysia matrella*; Zp: *Zoysia pacifica*; Zmin: Zoysia minima; Complex crosses such as double and triple crosses to introgress desirable traits require the use of x, /, () and [] to indicate hybrid parentage.

Table 2. Site information for replicated field trials during establishment of experimental zoysiagrasses from plugs in 2021.

Site info	Fayetteville, AR	Olathe, KS	Knoxville, TN	West Lafayette, IN	Blacksburg, VA	Dallas, TX	Gainesville, FL
Planting Date	21 July	17 June	17 June	21 July	18 June	24 June	30 August
Soil Type	Captina Silt Loam	Oska-Martin Silty Clay Loam	Sequatchie Silt Loam	Silty Clay Loam	Groseclose-Urban Land Complex Loam	Silty Clay Loam	Candler Sand
Fertilizer (lbs N/ 1,000ft^{-2})	21 July 2.5	6 July 0.75	1x/month 1.00	21 July, 17 Aug 0.25, 1.00	18 July 1.00	22 July, 15 Sept 1.00	27 Oct 1.00
Irrigation	As needed	2x/week	2x/week	4x/week	4x/week	2x/week	4x/week
Mowing HOC	3/4”	None	7/8”	1.75”	None	1”	None

Table 1. Establishment of experimental zoysiagrass entries in the top statistical grouping in seven replicated field trials in 2021.

	Establishment (%)[a]						
TAES entry code[b]	AR	FL	IN	KS	TN	TX	VA
6095-101	.	38.3	.	90.0	53.0	80.0	35.0
6095-83	.	35.0	46.7	.	49.7	88.3	.
6099-145	.	36.7	45.0	85.0	60.0	76.7	.
6109-87	.	.	.	78.3	.	65.0	33.3
6782-104	.	.	.	95.0	.	.	.
6782-42	.	.	.	91.7	.	.	31.7
6782-75	.	.	.	88.3	.	.	46.7
6782-79	.	.	.	96.7	.	61.7	35.0
6784-17	.	.	.	.	.	70.0	.
6789-40	.	.	.	.	.	.	31.0
6789-52	.	36.7	.	.	56.0	71.7	.
6792-44	.	.	.	.	.	.	30.0
6828-27	.	.	.	68.3	.	.	.
6828-53	.	.	.	.	53.0	75.0	.
6828-77	.	.	.	65.0	.	.	40.0
6829-02	.	.	.	81.7	.	65.0	30.0
6829-20	.	41.7	.	68.3	46.7	61.7	30.0
6829-36	.	.	.	70.0	45.3	.	.
6829-69	.	38.3	.	93.3	.	83.3	.
6830-02	.	.	.	70.0	59.0	70.0	.
6830-11	.	.	.	73.3	46.7	.	30.0
6830-39	.	36.7	.	.	71.7	68.3	.
6830-56	.	.	.	68.3	45.0	78.3	.
6831-09	50.0[c]	.	.	88.3	60.0	88.3	33.3
6835-33	.	.	.	.	54.0	.	30.0
6836-09	.	.	.	63.3	.	.	.
6839-08	.	.	.	85.0	50.3	75.0	33.3
6840-20	.	.	.	.	54.0	71.7	.
6844-04	.	.	.	.	47.7	.	.
6844-104	.	.	.	.	56.3	73.3	.
6844-141	.	.	.	78.3	.	61.7	.
6844-147	34.4	.	.	76.7	50.0	68.3	.
6844-150	.	.	.	78.3	.	.	33.3
6844-152	56.7	38.3	45.0	70.0	52.3	86.7	.
6844-154	.	.	.	.	61.3	65.0	.
6844-190	.	.	.	.	.	61.7	.
6844-202	.	.	.	.	.	.	30.0
6844-31	.	.	.	68.3	46.7	65.0	31.7
6844-34	.	.	45.0	91.7	64.7	85.0	33.3
6844-36	.	.	.	65.0	50.0	68.3	.
6844-42	.	.	.	100.0	45.0	75.0	38.3
6844-53	.	.	.	91.7	49.0	.	41.7
6844-74	.	.	.	80.0	.	.	30.0
6844-89	.	38.3	.	70.0	.	66.7	.
6910-172	.	36.7	.	73.3	.	81.7	31.7
6919-29	.	.	.	65.0	.	.	29.3
6923-11	45.0	43.3	46.7	.	73.3	90.0	.
6924-44	.	36.7	46.7	61.7	48.7	78.3	.
6924-47	.	.	.	78.3	.	60.0	.
6924-66	.	.	.	83.3	51.7	.	35.0

(Cont.)	AR	FL	IN	KS	TN	TX	VA
6925-53	.	.	45.0	.	47.3	61.7	30.0
6933-11	.	.	.	96.7	45.3	61.7	33.3
6940-15	.	.	.	.	48.3	70.0	.
6941-36	.	.	.	.	47.7	65.0	.
6942-22	.	35.0	.	70.0	58.3	68.3	31.7
Emerald	.	.	.	73.3	47.3	.	.
Innovation	.	.	.	88.3	.	.	.
Meyer	.	.	.	61.7	.	.	.
Palisades	60.0	41.7	55.0	65.0	77.0	86.7	.
Zeon	.	.	.	96.7	.	.	48.3
Average	49.2	38.1	46.9	78.7	53.5	72.4	33.8

[a] Establishment was rated on a 0 to 100% scale in which 0% = no establishment; and 100% complete establishment
[b] Texas Agricultural Experiment Station (TAES) entry code
[c] Entries with a mean presented occurred in the top statistical grouping by individual location ($P < 0.05$). Means are averages over replication, n = 3

Figure 1. Establishment distribution of experimental entries across six replicated field studies in 2022. Shaded bars within each location indicate the average establishment across all entries. Round markers within bars indicate percent establishment for each entry.

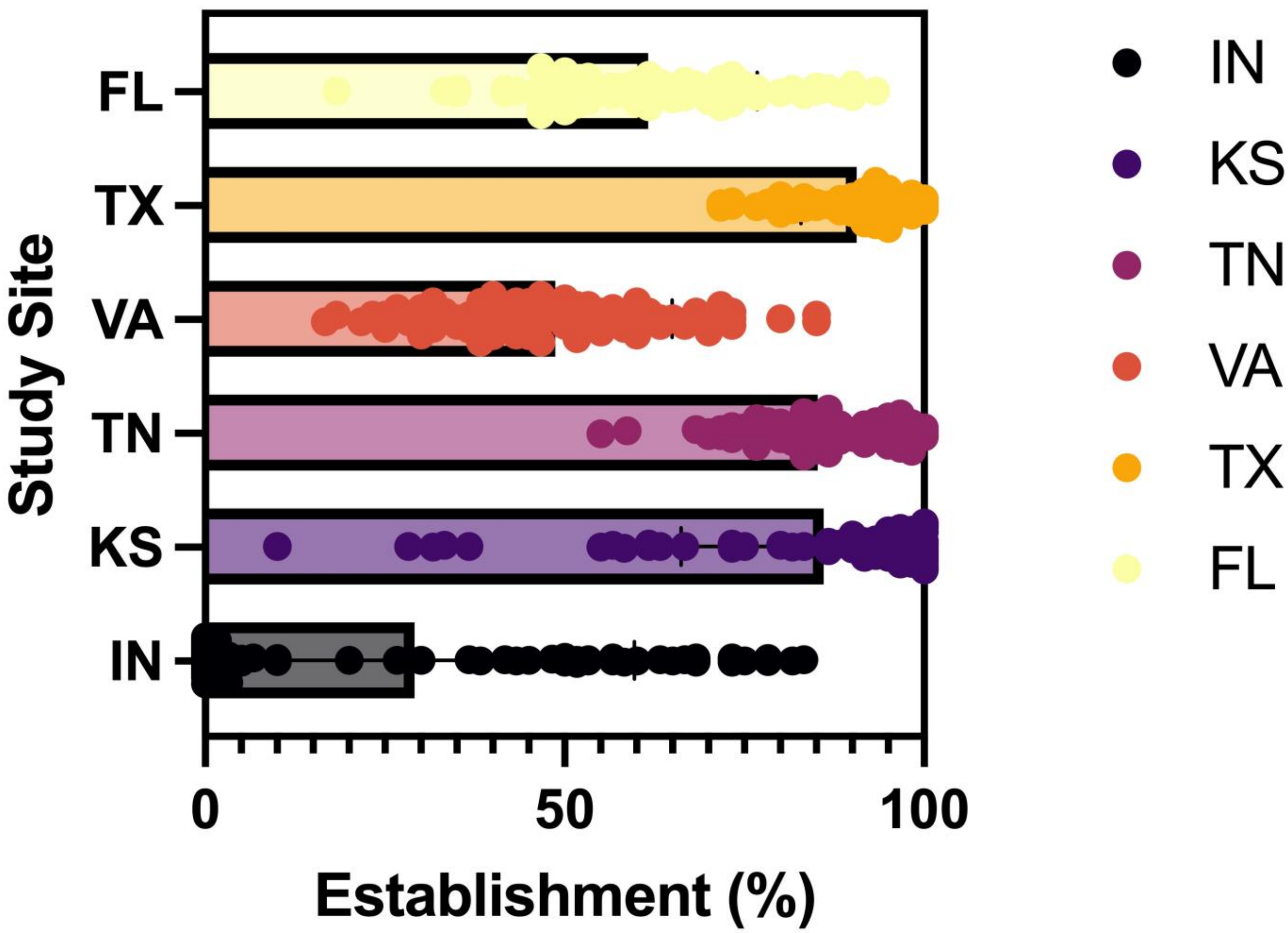


Figure 2. Loadings (locations) and principal component plots from the analysis of turfgrass establishment across ≥ 7 locations (a), and turfgrass quality across ≥ 6 locations (b) in 2022. The direction of the locations shows how much weight they have on each of the principal components (PC).

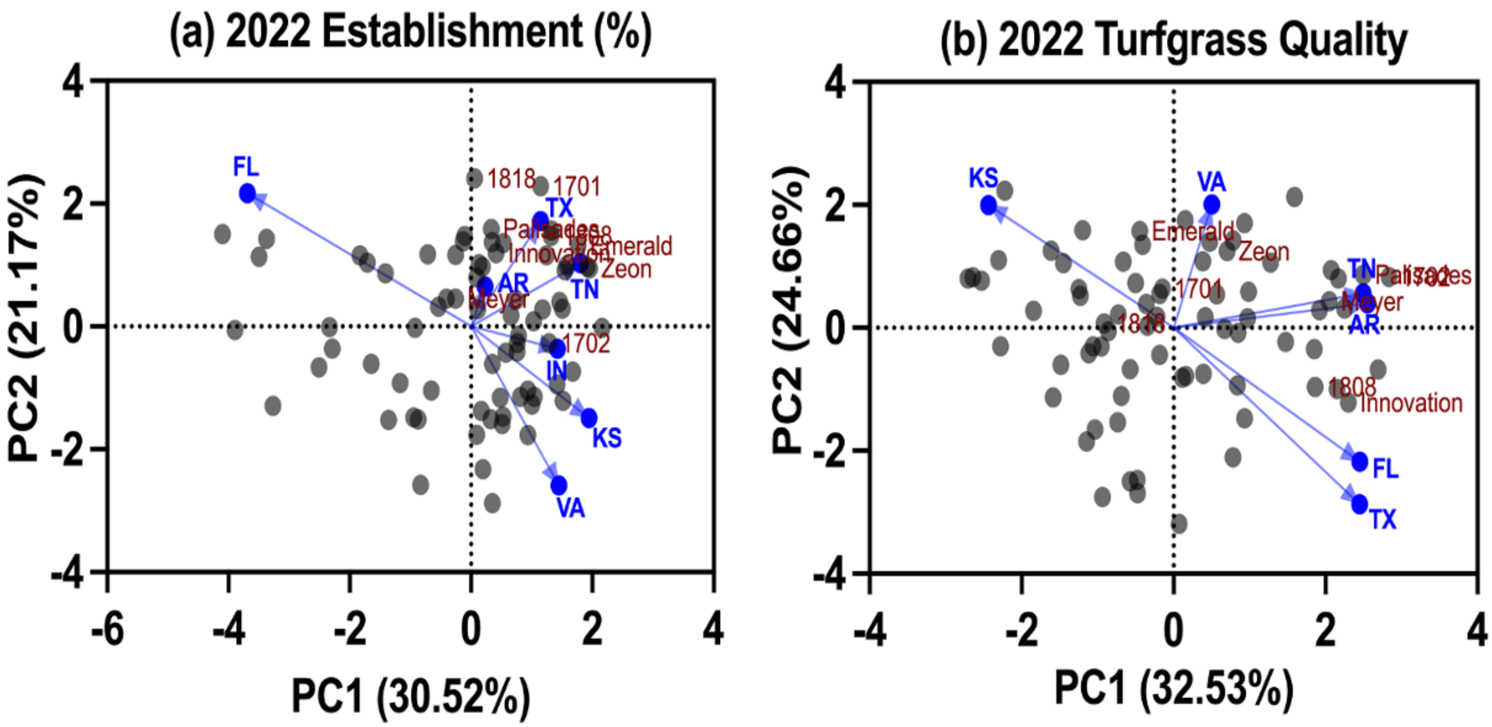


Table 2. Turf quality of experimental zoysiagrass entries in the top statistical grouping at seven locations during the summer of 2022 and 2023.

	Turf quality[a]													
	2022							2023						
TAES entry code[b]	AR	FL	IN	KS	TN	TX	VA	AR	FL	IN	KS	TN	TX	VA
DALZ 1702	7.0[c]	5.7	5.7	5.7	8.3	6.3	6.0	7.0	3.3	5.0	6.0	7.0	5.7	7.7
DALZ 1701	7.0	5.3	5.7	.	7.7	8.3	5.3	7.3	3.7	5.7	.	7.3	7.0	.
DALZ 1808	7.3	4.3	6.3	6.0	7.3	7.3	6.3	6.7	4.0	6.3	6.3	6.7	5.0	8.0
DALZ 1818	7.0	.	.	6.3	7.0	6.7	6.3	7.0	2.7	3.3	6.3	7.0	6.3	7.3
6782-104	5.7	5.0	.	6.3	7.0	7.7	4.7	5.7	3.0	.	8.0	8.3	7.3	7.3
6782-120	6.3	.	.	.	7.3	7.7	4.7	6.7	3.7	.	.	7.7	7.7	.
6782-42	5.7	.	.	6.7	6.7	6.7	5.7	.	2.3	.	7.0	7.3	5.3	7.0
6782-75	6.0	5.0	.	7.0	7.3	7.0	6.0	5.7	3.3	.	7.0	7.7	7.0	7.7
6782-79	6.0	.	.	6.3	7.0	7.0	5.7	6.3	3.7	.	6.7	8.0	7.0	7.7
6783-03	7.0	.	.	.	6.7	7.0	4.3	.	3.3	.	.	7.0	6.0	.
6784-17	6.0	.	.	.	7.0	8.7	5.7	6.7	3.3	.	.	8.0	6.7	6.3
6785-19	6.0	.	.	5.0	6.7	7.3	5.7	6.7	3.3	.	.	7.0	8.0	.
6785-22	6.3	.	.	5.7	7.0	7.0	5.3	6.7	2.7	.	.	7.7	7.3	5.3
6786-02	5.7	.	.	.	7.3	8.0	.	6.3	2.3	.	.	8.0	6.3	.
6787-18	.	.	.	5.7	.	7.0	6.3	7.3	3.7	.	.	7.3	6.3	6.0
6787-20	5.7	.	.	.	.	.	5.3	6.3	3.0	.	.	8.0	.	5.3
6789-23	6.0	4.3	.	.	7.3	8.0	4.7	7.0	3.0	.	.	8.3	8.3	5.3
6789-40	6.0	5.7	.	.	7.0	7.0	5.3	6.0	4.7	.	.	7.7	6.7	7.0
6789-52	7.3	5.0	.	5.0	8.0	7.3	5.0	6.7	3.7	.	6.3	7.0	5.3	7.0
6791-06	.	.	.	.	7.3	6.7	5.0	6.7	2.7	.	.	7.3	6.0	.
6792-44	6.3	.	.	5.0	7.3	6.7	4.7	6.3	3.3	3.1	.	7.7	6.0	7.0
6828-27	6.0	.	.	7.0	7.0	.	6.0	5.0	2.3	.	8.0	8.0	5.0	8.0
6828-53	6.7	.	.	5.0	7.0	.	4.7	6.7	3.3	2.9	6.0	7.0	.	6.3
6828-56	5.7	4.3	.	5.3	7.7	.	6.0	.	3.0	.	.	7.3	.	7.3
6828-77	.	.	.	6.0	7.3	7.0	6.0	.	2.7	.	6.7	7.3	.	7.7
6829-02	6.7	5.0	.	6.3	7.7	8.3	5.0	6.3	3.0	.	7.0	7.3	.	7.0
6829-20	7.3	4.7	.	5.7	8.0	7.0	5.7	6.7	3.7	.	6.3	7.3	5.0	6.7
6829-34	6.0	5.0	.	.	7.3	7.0	5.7	7.7	4.0	.	.	7.3	6.0	8.0
6829-36	6.7	4.3	6.7	5.7	7.7	.	4.7	6.7	4.0	6.3	7.0	7.0	5.0	5.7
6829-69	6.7	6.3	.	6.0	7.0	8.3	.	5.7	4.3	.	6.3	7.7	6.7	5.3
6830-02	6.7	5.0	.	5.7	8.3	7.3	5.3	7.3	3.3	.	7.3	7.3	.	6.3
6830-11	6.0	.	6.3	5.0	7.3	.	5.3	5.3	3.7	6.0	6.7	7.7	.	7.0
6830-39	6.3	5.7	.	6.0	8.0	6.7	5.0	6.7	3.7	.	6.7	7.3	6.0	7.7
6830-56	6.7	4.3	5.3	5.3	7.7	.	4.7	5.0	3.3	5.3	5.7	7.3	.	6.7
6831-09	6.7	5.3	.	6.0	8.3	8.3	5.7	7.0	2.3	3.7	6.0	7.7	5.0	7.3
6835-33	6.7	5.0	.	5.0	7.7	.	6.3	6.7	3.3	2.9	7.0	6.3	.	7.7
6836-09	6.7	5.0	.	6.3	7.0	6.7	5.0	6.7	2.3	.	7.0	7.7	.	8.0
6839-08	6.7	.	5.3	6.0	8.0	6.7	6.3	5.7	5.0	5.7	7.7	7.7	5.0	8.0
6840-20	6.3	4.7	.	5.3	8.3	8.3	5.3	6.7	2.7	3.4	6.7	7.3	7.7	6.7
6844-04	5.7	4.3	6.0	5.3	8.0	6.3	5.0	5.7	3.3	6.0	6.3	8.3	6.0	6.7
6844-104	7.3	.	6.3	5.7	8.0	8.3	6.0	7.0	3.0	7.0	7.7	7.7	5.7	7.3
6844-128	6.3	4.3	5.7	.	7.3	6.3	5.0	6.0	2.7	6.3	.	7.0	5.0	7.0
6844-141	6.3	.	6.0	6.0	8.0	.	.	5.7	2.3	6.0	6.7	7.7	.	.
6844-147	7.0	.	4.3	5.7	7.7	7.3	5.3	7.0	2.3	5.0	7.0	7.0	5.0	6.7
6844-150	6.7	.	.	7.0	7.3	.	5.7	5.7	3.3	4.7	7.3	7.3	5.0	8.0
6844-152	7.3	.	6.7	5.7	8.3	.	4.7	6.0	3.3	5.0	6.7	6.7	.	7.7
6844-154	6.3	4.3	5.7	.	7.7	8.0	5.0	7.0	3.3	5.7	.	7.0	5.0	5.3
6844-190	6.0	.	6.0	5.0	7.3	6.7	4.7	5.0	4.0	6.0	.	7.0	.	6.0
6844-202	6.0	4.7	6.3	6.0	7.3	7.7	6.3	6.0	2.0	6.0	7.7	7.7	5.7	7.7

	2022							2023						
(Cont.)	**AR**	**FL**	**IN**	**KS**	**TN**	**TX**	**VA**	**AR**	**FL**	**IN**	**KS**	**TN**	**TX**	**VA**
6844-31	7.0	.	5.3	6.3	7.7	7.3	5.7	6.7	2.7	5.3	6.3	7.7	5.7	7.0
6844-34	7.0	.	6.0	6.0	8.3	6.7	6.0	5.7	3.0	6.3	6.7	7.0	5.0	7.3
6844-36	6.7	.	6.3	6.0	7.7	8.3	5.7	7.3	3.0	5.7	7.7	7.3	5.3	7.7
6844-42	6.7	.	4.7	6.0	7.7	7.3	5.3	6.7	3.0	5.0	6.0	7.0	.	6.3
6844-53	5.7	.	.	6.0	7.7	6.7	6.0	5.7	3.0	3.9	6.7	8.0	6.3	8.0
6844-74	6.3	.	5.7	6.3	7.3	8.3	5.0	5.7	3.0	6.7	6.0	8.7	6.3	7.3
6844-89	6.0	.	6.0	6.0	7.7	.	4.7	.	2.7	5.3	6.7	7.3	.	7.0
6844-91	5.7	.	6.7	.	7.3	.	5.7	5.0	3.0	4.7	.	7.7	.	6.0
6910-157	7.0	.	.	5.3	7.0	7.0	6.0	6.3	3.3	3.4	.	6.3	6.0	7.3
6910-172	7.7	4.3	5.7	5.3	7.7	8.3	6.3	7.0	2.7	4.7	5.7	.	6.7	8.0
6919-29	5.7	.	6.0	5.0	7.3	.	5.3	5.7	2.7	5.3	.	7.7	.	6.7
6923-11	6.7	5.3	5.7	5.3	8.7	7.0	5.7	6.7	2.7	6.0	6.3	6.7	5.3	7.7
6924-44	6.3	.	6.0	5.7	8.3	.	5.0	6.0	2.3	5.7	7.0	7.3	.	6.0
6924-47	6.3	.	6.0	6.0	7.7	.	6.0	.	2.7	4.3	6.3	6.7	5.0	7.7
6924-66	5.7	.	4.7	5.7	7.3	.	5.7	5.7	3.0	4.3	6.3	7.7	.	6.7
6925-53	6.7	.	5.3	5.3	7.7	6.7	6.0	6.3	2.7	4.0	7.3	7.0	.	7.7
6933-11	5.7	.	.	7.3	7.3	7.7	6.0	5.3	2.7	.	7.7	8.3	.	7.3
6940-15	7.0	4.7	6.0	5.0	9.0	7.3	5.3	6.3	4.0	6.0	.	6.7	5.3	7.0
6941-36	7.0	5.3	5.7	5.3	7.7	7.7	5.3	7.3	4.3	5.7	.	6.7	7.3	7.3
6942-22	7.0	4.7	.	5.3	8.7	7.0	5.7	7.0	4.0	4.9	.	7.0	7.0	7.3
Emerald	7.0	5.0	.	6.0	8.0	7.3	6.0	7.3	3.7	3.7	6.7	7.0	7.3	7.0
Innovation	6.7	.	6.0	6.0	7.0	.	5.0	6.0	3.0	6.7	7.0	7.0	6.0	8.0
Meyer	7.0	.	6.0	6.0	7.0	.	5.7	5.7	2.0	5.3	7.3	7.3	5.3	7.3
Palisades	7.3	.	5.7	5.7	8.0	7.7	5.0	7.0	3.3	5.3	6.3	6.3	7.3	7.3
Zeon	7.0	.	.	6.0	8.3	6.3	6.7	7.0	4.0	2.9	5.7	7.3	5.3	7.3
Average	6.5	4.9	5.8	5.8	7.6	7.3	5.5	6.4	3.2	5.1	6.7	7.4	6.1	7.0

[a] Turf quality was rated visually on a 1 to 9 scale (1 = dead; 6 = minimally acceptable; 9 = optimum color, density, uniformity, and texture).
[b] Texas Agricultural Experiment Station (TAES) entry code
[c] Entries with a mean presented occurred in the top statistical grouping by individual location ($P < 0.05$). Means are averages over replications, n = 3

Table 5. Leaf texture of experimental zoysiagrass entries in the top statistical grouping at seven locations during the summer of 2022.

	Leaf texture[a]						
TAES entry code[b]	AR	IN	FL	KS	TN	TX	VA
DALZ 1702	6.3[c]	6.0	.	.	7.3	.	.
DALZ 1701	6.7	.	.	.	7.3	.	.
DALZ 1808	6.7	.	.	.	.	.	.
DALZ 1818	6.0	.	.	.	.	.	.
6782-104	6.7	.	8.0	.	9.0	9.0	.
6782-120	6.3	.	8.0	8.5	9.0	8.0	7.7
6782-42	7.0	.	8.0	.	9.0	8.0	.
6782-75	6.7	.	8.0	.	9.0	8.0	.
6782-79	6.7	.	7.3	.	8.7	8.0	.
6783-03	6.7	.	7.7	8.0	9.0	8.3	8.0
6784-17	7.0	.	7.0	8.0	8.3	8.0	7.0
6785-19	7.3	.	7.7	8.3	9.0	8.0	8.0
6785-22	6.7	.	8.0	8.0	8.7	8.0	7.0
6786-02	7.0	.	7.7	8.0	9.0	8.3	7.7
6787-18	7.3	.	8.0	8.3	9.0	8.7	6.7
6787-20	7.3	.	8.0	8.0	9.0	.	8.0
6789-23	7.7	.	7.0	7.7	9.0	8.3	7.0
6789-40	7.0	.	8.0	8.0	9.0	8.0	7.3
6789-52	8.0	.	7.3	.	8.7	8.0	.
6791-06	7.3	.	7.7	8.3	9.0	8.0	7.7
6792-44	6.7	.	7.3	8.0	9.0	8.0	6.7
6828-27	6.7	.	.	.	7.3	.	.
6828-53	6.7	.	7.0	.	8.0	.	.
6828-56	7.3	.	6.7	.	8.0	.	.
6828-77	7.0	.	.	.	7.7	.	.
6829-02	6.7	.	.	.	8.0	.	.
6829-20	7.3	.	.	6.7	7.3	.	.
6829-34	7.0	.	.	7.7	8.0	.	.
6829-36	6.3	6.7	.	6.3	7.3	.	6.7
6829-69	6.7	6.0	.	.	8.3	.	.
6830-02	7.0	.	.	.	8.0	.	.
6830-11	6.3	6.3	.	6.7	.	.	.
6830-39	7.3	.	6.7	.	8.3	8.0	.
6830-56	6.7	6.5	.	7.0	7.7	.	.
6831-09	6.3	6.9	.	6.3	8.0	.	.
6835-33	6.7	.	.	.	8.0	.	.
6836-09	7.3	.	7.0	.	8.3	.	.
6839-08	6.0	7.7	6.7	7.0	7.3	.	6.7
6840-20	6.3	.	6.7	6.7	8.0	.	.
6844-04	7.0	6.0	.	.	7.3	.	.
6844-104	6.0	6.3	.	.	8.0	.	.
6844-128	6.0	.	.	7.7	.	.	7.7
6844-141	6.7	6.0	.	6.7	7.7	.	6.7
6844-147	6.3	6.6	.	6.7	7.7	.	7.3
6844-150	7.0	7.5	6.7	.	7.7	.	.
6844-152	7.0	6.0	.	.	.	.	.
6844-154	6.7	6.1	.	8.0	7.3	.	.
6844-190	6.7	6.3	.	7.7	.	.	.

(Cont.)	AR	IN	FL	KS	TN	TX	VA
6844-202	6.3	6.7	.	6.3	7.3	.	.
6844-31	6.7	6.0	.	6.3	7.3	.	7.0
6844-34	6.3	6.0	.	7.0	.	.	6.7
6844-36	6.0	6.7	.	.	.	.	.
6844-42	6.3	7.2	.	7.0	7.3	.	6.7
6844-53	6.7	.	.	.	7.7	.	.
6844-74	6.3	7.0	.	.	7.3	.	.
6844-89	6.3	7.0	.	6.3	7.7	.	.
6844-91	6.0	.	.	6.7	7.7	.	.
6910-157	6.0	.	.	8.3	7.7	.	.
6910-172	6.0	.	.	8.0	.	.	.
6919-29	6.3	6.0	.	6.3	.	.	.
6923-11	6.7	6.7	.	6.7	.	.	.
6924-44	6.3	6.0	.	7.3	7.7	.	7.0
6924-47	6.7	6.0	.	6.3	7.3	.	.
6924-66	6.3	6.0	.	7.3	.	.	7.0
6925-53	6.7	7.0	.	.	7.7	.	.
6933-11	6.3	.	.	6.3	8.0	.	.
6940-15	6.3	.	.	6.3	.	.	7.0
6941-36	6.3	.	.	8.0	.	.	.
6942-22	6.3	.	.	6.3	7.7	.	6.7
Emerald	7.0	.	6.7	7.0	8.3	.	7.0
Innovation	6.7	6.3	.	6.7	7.7	.	.
Meyer	6.7	.	.	7.7	.	.	.
Palisades	6.3	.	.	.	.	.	.
Zeon	7.0	.	6.7	.	7.7	.	.
Average	6.7	6.5	7.4	7.3	8.1	8.2	7.1

[a] Leaf texture was visually rated on a 1 to 9 scale in which 1 = coarse; 9 = fine.
[b] Texas Agricultural Experiment Station (TAES) entry code
[c] Entries with a mean presented occurred in the top statistical grouping by individual location ($P < 0.05$). Means are averages over replications, n = 3

Table 3. Winter injury of experimental zoysiagrasses during the early spring at two locations in the transition zone in 2022.

	Winter injury (%)[a]			
TAES entry code[b]	**KS**		**IN**	
DALZ 1702	0.0		90.0	A[c]
DALZ 1701	1.7		70.0	A
DALZ 1808	0.0		56.7	
DALZ 1818	0.0		100.0	A
6782-104	0.0		100.0	A
6782-120	61.7	A	100.0	A
6782-42	0.0		100.0	A
6782-75	0.0		100.0	A
6782-79	0.0		100.0	A
6783-03	50.0	A	100.0	A
6784-17	8.3		100.0	A
6785-19	5.7		100.0	A
6785-22	5.0		100.0	A
6786-02	50.0	A	100.0	A
6787-18	0.0		100.0	A
6787-20	33.3	A	100.0	A
6789-23	39.0	A	100.0	A
6789-40	5.0		100.0	A
6789-52	0.0		100.0	A
6791-06	5.0		100.0	A
6792-44	11.7		100.0	A
6828-27	0.0		100.0	A
6828-53	2.3		100.0	A
6828-56	10.7		100.0	A
6828-77	0.0		100.0	A
6829-02	0.0		100.0	A
6829-20	0.0		100.0	A
6829-34	3.3		100.0	A
6829-36	0.0		23.3	
6829-69	0.0		100.0	A
6830-02	0.0		100.0	A
6830-11	1.7		26.7	
6830-39	0.0		100.0	A
6830-56	1.7		41.7	
6831-09	0.0		100.0	A
6835-33	0.0		100.0	A
6836-09	0.0		100.0	A
6839-08	0.0		88.3	A
6840-20	0.0		96.7	A
6844-04	0.0		8.3	
6844-104	0.0		30.0	
6844-128	1.7		13.3	
6844-141	0.0		18.3	
6844-147	0.0		71.7	A
6844-150	0.0		81.7	A
6844-152	0.0		26.7	
6844-154	5.0		53.3	
6844-190	0.0		16.7	
6844-202	0.0		56.7	

(Cont.)	KS	IN	
6844-31	0.0	43.3	
6844-34	0.0	23.3	
6844-36	0.0	31.7	
6844-42	0.0	91.7	A
6844-53	0.0	95.0	A
6844-74	1.7	45.0	
6844-89	0.0	46.7	
6844-91	3.0	5.0	
6910-157	1.7	100.0	A
6910-172	0.0	86.7	A
6919-29	0.0	18.3	
6923-11	13.3	40.0	
6924-44	5.0	21.7	
6924-47	0.0	21.7	
6924-66	1.7	85.0	A
6925-53	0.0	86.7	A
6933-11	0.0	100.0	A
6940-15	4.0	53.3	
6941-36	0.0	61.7	A
6942-22	0.0	98.3	A
Emerald	0.0	98.3	A
Innovati	0.0	36.7	
Meyer	0.0	11.7	
Palisade	0.7	86.7	A
Zeon	0.0	100.0	A
Average	4.5	73.8	

[a] Winter injury was visually rated on a 0 to 100% scale in which 0% = no winter injury; and 100% = complete winter injury

[b] Texas Agricultural Experiment Station (TAES) entry code

[c] Means followed by a capital ‘A’ in a column suffered significantly more winter injury ($P < 0.05$). Means are averages over replications, n = 3.

Table 4. Spring greenup of experimental zoysiagrass entries in the top statistical grouping at five locations during the spring of 2023.

	Spring greenup[a]				
TAES entry code[b]	FL	IN	KS	TN	TX
DALZ 1702	6.7[c]	4.7	7.0	8.3	4.7
DALZ 1701	.	4.3	7.0	8.0	5.7
DALZ 1808	5.3	4.7	8.0	8.7	5.0
DALZ 1818	.	5.0	6.7	8.0	5.0
6782-104	6.0	.	7.0	.	6.7
6782-120	6.0	.	.	.	5.3
6782-42	6.3	.	7.7	.	3.7
6782-75	6.7	.	7.0	.	6.3
6782-79	6.0	.	7.7	5.3	7.0
6783-03	6.7	.	.	.	5.0
6784-17	.	.	4.7	6.0	4.7
6785-19	5.7	.	.	6.7	7.7
6785-22	6.0	.	.	6.7	7.0
6786-02	6.0	.	.	.	5.0
6787-18	5.3	.	5.3	6.0	6.0
6787-20	5.3	.	.	7.0	.
6789-23	.	.	.	7.0	6.7
6789-40	6.0	.	.	6.0	6.0
6789-52	6.7	.	6.3	5.3	4.0
6791-06	6.0	.	.	6.3	5.7
6792-44	6.3	4.5	.	7.0	6.0
6828-27	.	3.6	6.3	8.0	3.7
6828-53	.	2.6	7.7	.	.
6828-56	.	.	5.7	7.0	.
6828-77	.	.	7.3	6.0	.
6829-02	.	.	7.0	7.3	4.3
6829-20	7.3	.	6.7	6.0	4.3
6829-34	6.3	1.9	5.3	7.0	4.3
6829-36	.	6.3	7.3	8.7	3.7
6829-69	6.0	.	6.7	8.0	5.3
6830-02	6.0	.	7.3	7.0	3.7
6830-11	.	7.3	5.7	8.7	.
6830-39	6.0	.	7.7	6.0	.
6830-56	.	5.0	5.0	7.3	.
6831-09	5.3	3.7	6.3	5.3	4.0
6835-33	.	2.8	8.0	5.3	.
6836-09	.	.	7.0	7.7	5.0
6839-08	.	6.0	5.3	7.0	5.7
6840-20	.	3.3	7.7	7.3	4.7
6844-04	.	6.7	6.7	8.7	5.0
6844-104	.	5.3	7.7	8.7	4.3
6844-128	.	5.7	6.0	9.0	5.0
6844-141	.	5.0	6.0	6.3	4.0
6844-147	.	4.3	6.0	7.7	4.3
6844-150	.	6.0	7.3	8.7	3.7
6844-152	.	5.0	7.7	8.3	5.7
6844-154	.	4.7	5.0	9.0	4.7
6844-190	.	4.0	.	8.0	4.0
6844-202	.	5.7	8.0	8.3	5.3

(Cont.)	FL	IN	KS	TN	TX
6844-31	.	4.0	6.3	8.0	6.0
6844-34	.	6.0	.	7.3	4.0
6844-36	.	4.7	7.0	8.7	5.0
6844-42	.	4.7	6.3	7.0	3.7
6844-53	.	3.8	7.0	8.0	4.0
6844-74	.	6.3	5.3	9.0	5.7
6844-89	.	6.0	6.0	7.3	4.7
6844-91	.	4.3	6.0	9.0	.
6910-157	6.3	3.8	.	5.3	4.3
6910-172	.	3.7	.	7.7	5.3
6919-29	.	6.3	5.0	9.0	3.7
6923-11	.	4.7	8.0	5.3	.
6924-44	.	5.7	7.0	6.0	.
6924-47	.	4.0	6.7	8.3	4.0
6924-66	.	3.3	.	8.7	.
6925-53	.	3.7	7.7	7.7	4.0
6933-11	.	.	7.3	7.3	3.7
6940-15	.	5.3	5.3	8.3	4.7
6941-36	5.3	3.0	5.7	8.0	6.0
6942-22	7.0	6.3	6.7	5.3	5.7
Emerald	.	4.3	5.0	7.3	7.7
Innovation	.	5.7	7.0	9.0	.
Meyer	.	5.7	7.3	9.0	4.7
Palisades	.	4.7	6.7	6.7	4.7
Zeon	5.3	.	6.7	6.7	5.3
Average	6.1	4.7	6.6	7.4	5.0

[a] Spring greenup was visually rated on a 1 to 9 scale in which 1 = brown/straw/dead; 9 = dark green.
[b] Texas Agricultural Experiment Station (TAES) entry code
[c] Entries with a mean presented occurred in the top statistical grouping by individual location ($P < 0.05$). Means are averages over replications, n = 3

Table 5. Shade tolerance[a] of experimental zoysiagrasses in Dallas, TX in 2022-2023 .

TAES entry code[b]	Turf quality[c]		Genetic color[d]		Leaf texture[e]		Spring greenup[f]	
6782-104	8.0	A[g]	8.7	A	7.3	A	5.3	A
6792-44	7.7	A	8.0	A	7.0	A	5.0	A
6789-23	7.0	A	8.7	A	7.0	A	5.3	A
6785-19	7.0	A	8.7	A	7.0	A	3.3	A
6785-22	7.0	A	8.0	A	7.0	A	3.3	A
6840-20	7.0	A	7.7	A	6.0		1.7	
6829-02	6.7	A	7.7	A	6.0		3.0	
6783-03	6.7	A	8.0	A	6.7	A	2.7	
6782-120	6.3	A	8.7	A	6.7	A	6.3	A
6789-40	6.3	A	8.3	A	7.7	A	4.0	A
6784-17	6.3	A	8.0	A	7.0	A	4.0	A
6786-02	6.3	A	8.3	A	7.0	A	3.7	A
6941-36	6.3	A	7.7	A	4.0		3.0	
6844-154	6.3	A	7.0	A	5.0		2.3	
Emerald	6.0	A	8.0	A	6.0		5.0	A
6782-42	6.0	A	8.3	A	7.3	A	4.3	A
6942-22	6.0	A	7.3	A	6.0		4.0	A
6787-18	6.0	A	8.3	A	7.0	A	3.0	
6933-11	6.0	A	8.0	A	5.3		2.3	
6782-75	5.7	A	8.7	A	7.0	A	5.3	A
6844-147	5.7	A	7.3	A	5.0		1.7	
6923-11	5.7	A	7.7	A	5.0		1.3	
Palisades	5.3	A	7.7	A	3.0		2.7	
6831-09	5.3	A	7.7	A	6.0		2.3	
DALZ 1808	5.3	A	7.0	A	5.0		2.3	
6940-15	5.3	A	7.0	A	4.3		2.3	
6844-36	5.3	A	8.0	A	5.7		2.0	
6924-66	5.3	A	7.7	A	5.0		2.0	
6844-104	5.3	A	7.0	A	6.0		2.0	
6919-29	5.3	A	7.7	A	5.3		1.7	
6844-141	5.3	A	7.7	A	5.0		1.3	
6844-202	5.3	A	7.0	A	5.3		1.0	
DALZ 1701	5.0		8.0	A	4.7		3.0	
6782-79	5.0		6.7	A	6.7	A	2.3	
6839-08	5.0		7.3	A	6.0		2.0	
DALZ 1818	5.0		7.7	A	4.7		1.7	
6844-74	5.0		7.7	A	5.7		1.3	
6791-06	4.7		7.3	A	7.0	A	5.3	A
6836-09	4.7		7.7	A	6.0		2.7	
6829-34	4.7		7.3	A	5.7		2.7	
6830-02	4.7		7.0	A	6.0		2.3	
Zeon	4.7		7.0	A	6.0		2.3	
6828-27	4.7		6.7	A	5.7		2.3	
6844-128	4.7		6.7	A	4.3		2.3	
6828-56	4.7		7.0	A	6.0		1.0	
6844-190	4.7		7.0	A	5.0		1.0	
6910-172	4.7		7.0	A	4.0		1.0	
DALZ 1702	4.3		7.0	A	5.0		3.7	A
6789-52	4.3		7.3	A	6.7	A	3.0	
6829-69	4.3		7.0	A	5.7		2.7	
6829-20	4.3		7.0	A	5.3		2.3	
6830-39	4.3		6.7	A	6.0		1.3	
6844-31	4.3		7.7	A	5.3		1.0	
Innovation	4.3		7.3	A	5.7		1.0	

(Cont.)	Turf quality	Genetic color		Leaf texture	Spring greenup
6844-04	4.0	8.0	A	5.0	2.0
6925-53	4.0	7.7	A	5.3	2.0
6844-34	4.0	7.0	A	5.0	1.7
Meyer	4.0	7.0	A	4.0	1.7
6830-11	4.0	7.0	A	5.0	1.3
6829-36	4.0	6.7	A	5.7	1.3
6844-150	4.0	7.3	A	5.3	1.0
6844-42	4.0	7.0	A	5.3	1.0
6844-91	4.0	7.0	A	5.0	1.0
6844-152	3.7	6.3		5.7	1.7
6844-53	3.7	7.0	A	5.7	1.3
6828-77	3.7	6.7	A	6.0	1.3
6924-47	3.7	6.0		5.0	1.3
6828-53	3.7	7.0	A	5.7	1.0
6910-157	3.7	6.0		5.0	1.0
6844-89	3.3	7.0	A	5.7	1.3
6835-33	2.7	5.7		6.0	1.7
6830-56	2.7	5.3		5.0	1.3
6924-44	2.7	5.7		5.7	1.0

[a] Shade tolerance was evaluated under 63% shade.
[b] Texas Agricultural Experiment Station (TAES) entry code.
[c] Turf quality visually rated on a 1-9 scale (1 = lowest quality; 6 = minimum acceptable quality; 9 = maximum quality).
[d] Genetic color visually rated on a 1-9 scale (1 = brown/straw/dead; 9 = dark green)
[e] Leaf texture visually rated on a 1-9 scale (1 = coarse; 9 = fine).
[f] Spring greenup visually rated on a 1-9 scale (1 = brown/straw/dead; 9 = dark green)
[g] Means followed by a capital ‘A’ in a column are not significantly different (*P* < 0.05). Means are averages over replications, n = 3.

Table 6. Drought tolerance of experimental zoysiagrasses in Florida in 2023.

	Green cover (%)[a,b]							
	Drought Period				Recovery Period			
TAES entry code[c]	4-May		8-May		11-May		15-May	
6829-69	93.3	A[d]	30.0	A	80.0	A	86.7	A
6942-22	86.7	A	60.0	A	85.0	A	86.7	A
6941-36	83.3	A	53.3	A	78.3	A	85.0	A
6829-34	81.7	A	33.3	A	71.7	A	81.7	A
6840-20	83.3	A	50.0	A	76.7	A	81.7	A
6789-40	85.0	A	30.0	A	71.7	A	78.3	A
DALZ 1702	93.3	A	40.0	A	66.7	A	78.3	A
6829-36	76.7	A	13.3	A	61.7	A	76.7	A
6830-02	86.7	A	18.3	A	53.3	A	76.7	A
6940-15	81.7	A	40.0	A	60.0	A	76.7	A
6782-75	63.3	A	50.0	A	68.3	A	73.3	A
6829-02	71.7	A	21.7	A	60.0	A	71.7	A
DALZ 1701	66.7	A	6.7		56.7	A	70.0	A
DALZ 1808	73.3	A	8.3		46.7	A	70.0	A
Emerald	75.0	A	46.7	A	66.7	A	70.0	A
6844-202	68.3	A	25.0	A	49.6	A	68.3	A
6844-154	60.0	A	10.0		45.0	A	66.7	A
6828-56	58.3	A	25.0	A	61.7	A	66.7	A
6787-20	68.3	A	43.3	A	60.0	A	65.0	A
6782-104	50.0	A	35.0	A	53.3	A	63.3	A
6783-03	66.7	A	43.3	A	60.0	A	63.3	A
6786-02	63.3	A	15.0	A	40.0		61.7	A
6844-104	60.0	A	15.0	A	46.7	A	61.7	A
6787-18	46.7	A	18.3	A	50.0	A	61.7	A
6784-17	56.7	A	36.7	A	55.0	A	61.7	A
6782-79	61.7	A	43.3	A	58.3	A	61.7	A
6829-20	65.0	A	50.0	A	51.7	A	61.7	A
6844-36	53.3	A	6.7		40.0		60.0	A
6789-52	76.7	A	25.0	A	46.7	A	60.0	A
6782-120	63.3	A	36.7	A	50.0	A	60.0	A
6830-39	81.7	A	5.0		20.0		58.3	A
6828-77	53.3	A	18.3	A	43.3	A	58.3	A
6789-23	58.3	A	30.0	A	51.7	A	58.3	A
6836-09	52.4	A	18.6	A	39.3		58.2	A
6910-172	55.0	A	16.7	A	46.7	A	56.7	A
Zeon	50.0	A[d]	8.3		40.0		55.0	A
6844-152	55.0	A	15.0	A	46.7	A	55.0	A
6844-34	53.3	A	18.3	A	45.0	A	53.3	A
6828-27	51.7	A	25.0	A	40.0		53.3	A
6923-11	50.0	A	3.3		30.0		51.7	A
6844-74	48.3	A	11.7		26.7		50.0	A
6828-53	56.7	A	13.3	A	40.0		50.0	A
6830-56	63.3	A	5.0		33.3		48.3	A
6830-11	46.7	A	21.7	A	38.3		48.3	A
6844-53	51.7	A	26.7	A	35.0		48.3	A
6782-42	46.7	A	30.0	A	38.3		48.3	A
6839-08	40.0	A	5.0		26.7		46.7	A
6924-44	41.7	A	8.3		43.3	A	46.7	A
6844-91	53.3	A	13.3	A	46.7	A	46.7	A
6844-128	50.0	A	21.7	A	33.3		46.7	A

(Cont.)	4-May		8-May		11-May		15-May	
Palisades	51.7	A	23.3	A	45.0	A	46.7	A
6791-06	40.0	A	26.7	A	41.7		46.7	A
6785-22	43.3	A	30.0	A	40.0		46.7	A
DALZ 1818	46.7	A	11.7		26.7		45.0	A
6910-157	40.0	A	21.7	A	35.0		45.0	A
6831-09	53.3	A	5.0		43.3	A	43.3	A
6844-04	48.3	A	11.7		40.0		43.3	A
6844-150	36.7		5.0		20.0		41.7	A
6933-11	38.3		23.3	A	38.3		41.7	A
6844-89	51.7	A	10.0		26.7		40.0	
6844-141	36.7		5.0		23.3		38.3	
Innovation	38.3		10.0		31.7		38.3	
6792-44	31.7		13.3	A	30.0		38.3	
6844-190	33.3		15.0	A	33.3		38.3	
6785-19	40.0	A	16.7	A	33.3		38.3	
6844-147	40.0	A	18.3	A	36.7		38.3	
6844-42	36.7		1.7		26.7		36.7	
6844-31	36.7		10.0		16.7		36.7	
6919-29	36.7		11.7		26.7		36.7	
6924-47	31.7		5.0		30.0		30.0	
6925-53	20.0		3.3		15.0		26.7	
Meyer	58.3	A	13.3	A	23.3		25.0	
6835-33	43.3	A	1.7		15.0		16.7	
6924-66	6.7		1.7		6.7		8.3	

[a] Experimental plots were irrigated on the morning of 1 May 2023 and then withheld for 7 days. Irrigation resumed on 8 May 2023.
[b] Green cover was visually rated on a 0 to 100% scale in which 0% = no green cover; and 100% = complete green cover.
[c] Texas Agricultural Experiment Station (TAES) entry code
[d] Means followed by a capital ‘A’ in a column are not significantly different ($P < 0.05$). Means are averages over replications, n = 3.

Table 7. Divot recovery of experimental zoysiagrass in Arkansas in 2023.

	Divot recovery (%)[a,b]			
TAES entry code[c]	**1-Sept**	**8-Sept**	**19-Sept**	
6844-34	36.8	40.4	82.9	A[d]
6844-190	35.7	32.2	81.1	A
6828-53	39.3	44.1	78.9	A
6784-17	37.6	43.5	78.6	A
6919-29	43.9	48.7	78.3	A
6924-44	39.8	44.2	77.9	A
6844-89	41.5	42.8	77.4	A
6941-36	36.9	44.3	77.0	A
6844-91	32.4	39.3	76.9	A
6828-77	33.5	36.3	76.1	A
6844-147	33.3	35.5	75.8	A
6844-31	28.8	35.8	75.3	A
6829-69	29.2	36.8	75.2	A
6844-74	39.3	44.4	74.8	A
6782-75	34.0	41.7	74.8	A
6910-172	36.8	42.4	74.8	A
6783-03	38.8	46.4	74.4	A
DALZ 1818	42.8	48.2	74.2	A
6923-11	40.2	43.3	74.1	A
6844-04	36.8	41.9	73.9	A
6844-36	34.9	39.2	73.9	A
6789-52	38.6	40.4	73.9	A
DALZ 1702	39.8	40.9	73.8	A
6844-150	41.3	41.6	73.7	A
DALZ 1701	35.1	40.5	73.3	A
6910-157	36.4	41.1	73.3	A
6925-53	40.5	43.3	73.0	A
6835-33	44.1	43.2	72.8	A
6844-42	31.5	33.9	72.7	A
6829-08	36.7	36.0	72.2	A
6785-22	38.8	43.9	71.8	A
6924-66	32.7	37.3	71.6	A
Palisades	39.2	39.8	71.4	A
6844-202	37.5	37.0	71.4	A
6924-47	44.9	45.7	71.4	A
6933-11	34.9	37.6	71.3	A
6831-09	24.2	44.5	71.2	A
6828-27	43.3	45.9	70.9	A
6829-34	32.5	44.2	70.7	A
6844-104	35.0	39.4	70.7	A
6791-06	36.7	39.4	70.5	A
6844-152	38.2	43.9	70.5	A
Emerald	37.1	43.5	70.4	A
6844-141	38.6	46.3	70.3	A
Zeon	35.2	41.7	69.8	A

(Cont.)	1-Sept	8-Sept	19-Sept	
6830-02	42.0	47.1	69.6	A
6839-08	38.8	42.5	69.3	A
6782-79	34.7	44.8	69.2	A
Meyer	36.9	41.4	69.0	A
6829-36	39.8	44.9	68.8	A
6828-56	34.8	37.2	68.8	A
6786-08	41.4	43.2	68.6	A
6782-42	37.3	39.6	67.8	A
6782-120	34.4	36.0	67.7	A
6940-15	29.6	35.6	67.6	A
6844-128	35.1	37.9	67.2	A
6840-20	41.4	42.9	67.2	A
DALZ 1808	35.8	42.6	67.2	A
6829-20	40.2	41.2	66.9	A
6782-104	39.1	41.3	66.1	A
6830-11	34.8	35.3	65.0	A
6830-39	33.6	43.5	64.9	A
6792-44	40.5	40.4	64.8	A
6836-09	35.3	38.3	63.8	A
6789-40	24.5	27.5	63.4	A
6844-154	37.8	38.8	63.0	A
6830-56	39.1	35.4	62.9	A
6942-22	34.7	37.8	62.3	A
Innovation	41.1	38.1	61.7	A
6785-19	34.3	42.1	59.6	A
6787-20	27.9	35.9	58.7	A
6787-18	38.2	44.1	57.9	A
6789-23	30.1	35.8	46.9	
6844-53	28.5	27.8	43.6	

[a] Standardized divots (5cm x 10cm) were cut from each plot on 1 September 2023 using a modified edger and then backfilled with topdressing sand.
[b] Recovery was monitored for each divot by collecting digital images and analyzed for turf coverage.
[c] Texas Agricultural Experiment Station (TAES) entry code.
[d] Means followed by a capital ‘A’ in a column are not significantly different and occurred in the top statistical group ($P < 0.05$). Means are averages over replications, n = 3.

Table 11. Traffic tolerance of experimental zoysiagrasses after simulated traffic events in Tennessee in 2022 and 2023.

	Green cover (%)[a]													
	0 traffic events[b]				10 traffic events				20 traffic events				30 traffic events	
TAES entry code[c]	2022		2023		2022		2023		2022		2023		2022	2023
6836-09	96.5	A[d]	96.3	A	81.9	A	77.9	A	70.7	A	65.5	A	44.6	42.4
6787-20	97.1	A	96.3	A	85.2	A	77.9	A	76.2	A	65.5	A	50.4	48.2
6844-190	86.3		96.2	A	68.1	A	77.8	A	56.4	A	65.4	A	49.3	47.0
6828-53	95.2	A	96.2	A	75.4	A	77.8	A	63.6	A	65.4	A	53.1	50.9
6829-02	98.4	A	96.0	A	89.1	A	77.6	A	81.8	A	65.2	A	42.0	39.8
6923-11	92.4	A	96.0	A	72.5	A	77.6	A	61.0	A	65.3	A	46.4	44.1
6828-56	94.2	A	95.7	A	69.4	A	77.3	A	57.2	A	64.9	A	40.9	38.6
6789-40	97.0	A	95.7	A	78.2	A	77.2	A	66.4	A	64.9	A	48.3	46.1
6844-36	92.4	A	95.5	A	73.2	A	77.1	A	62.8	A	64.7	A	37.2	35.0
6785-19	96.5	A	95.5	A	81.2	A	77.1	A	70.5	A	64.7	A	41.8	39.6
6844-74	96.7	A	95.4	A	83.0	A	77.0	A	74.2	A	64.6	A	39.4	33.8
6830-39	91.1	A	95.4	A	67.9	A	77.0	A	55.5	A	64.6	A	37.3	35.1
DALZ 1702	90.7	A	95.3	A	80.3	A	76.9	A	71.0	A	64.6	A	40.2	37.9
6844-91	92.3	A	95.3	A	76.2	A	76.9	A	67.3	A	64.5	A	41.8	39.6
6910-157	96.0	A	95.2	A	78.3	A	76.8	A	68.8	A	64.4	A	44.5	42.2
6787-18	96.9	A	95.1	A	83.0	A	76.7	A	73.7	A	64.3	A	46.8	44.6
6844-141	94.1	A	95.1	A	70.2	A	76.7	A	59.7	A	64.3	A	39.4	37.1
6844-31	92.6	A	95.0	A	70.9	A	76.6	A	59.2	A	64.2	A	51.5	49.3
DALZ 1701	97.2	A	94.9	A	88.4	A	76.5	A	81.5	A	64.2	A	36.4	34.2
6844-147	96.2	A	94.9	A	69.8	A	76.5	A	59.5	A	64.1	A	37.7	35.4
6791-06	97.8	A	95.0	A	83.6	A	76.5	A	73.1	A	64.2	A	36.4	34.2
DALZ 1818	98.0	A	94.8	A	82.3	A	76.4	A	72.9	A	64.1	A	42.5	40.3
6844-34	90.1	A	94.8	A	68.9	A	76.4	A	56.8	A	64.1	A	39.1	36.8
6829-20	94.8	A	94.8	A	80.0	A	76.4	A	69.2	A	64.1	A	34.7	32.5
6828-77	95.8	A	94.7	A	82.5	A	76.3	A	73.3	A	64.0	A	38.7	36.5
6782-104	98.1	A	94.7	A	86.4	A	76.3	A	76.8	A	63.9	A	34.6	32.4
6830-02	94.3	A	94.6	A	71.5	A	76.2	A	59.7	A	63.8	A	36.4	34.2
6844-128	91.8	A	94.5	A	64.8	A	76.1	A	53.5	A	63.7	A	41.3	39.0
6830-56	94.7	A	94.6	A	80.5	A	76.1	A	71.8	A	63.8	A	47.7	45.5
Zeon	96.7	A	94.5	A	74.8	A	76.1	A	63.5	A	63.7	A	42.5	40.3
6844-202	94.6	A	94.5	A	80.4	A	76.1	A	71.9	A	63.7	A	33.9	31.6
6844-53	97.3	A	94.3	A	82.6	A	75.9	A	73.0	A	63.5	A	48.3	46.1
6786-02	97.3	A	94.3	A	81.2	A	75.9	A	70.5	A	63.5	A	45.1	36.2
6789-23	99.1	A	94.2	A	91.8	A	75.8	A	85.0	A	63.5	A	38.7	36.4
6829-69	99.0	A	94.3	A	85.8	A	75.8	A	77.4	A	63.5	A	33.5	31.3
6844-04	89.9	A	94.2	A	74.7	A	75.8	A	64.3	A	63.4	A	31.1	28.8
6829-36	95.0	A	94.2	A	57.1		75.7	A	46.0		63.4	A	44.4	42.2
6789-52	93.2	A	94.1	A	52.5		75.7	A	38.1		63.4	A	33.2	31.0
6933-11	96.8	A	94.1	A	82.3	A	75.7	A	72.2	A	63.3	A	33.5	31.3
6844-154	94.0	A	94.0	A	66.4	A	75.6	A	56.1	A	63.2	A	50.4	48.2
6924-44	92.8	A	94.0	A	47.1		75.6	A	35.6		63.2	A	34.7	32.5
6844-42	91.8	A	93.9	A	61.3	A	75.5	A	49.0		63.1	A	45.8	43.5
6829-34	97.3	A	94.0	A	84.8	A	75.5	A	75.6	A	63.2	A	41.7	39.5
6782-79	96.1	A	93.7	A	80.1	A	75.3	A	69.1	A	62.9	A	42.5	40.2
6785-22	98.0	A	93.7	A	85.6	A	75.3	A	76.3	A	62.9	A	43.5	41.3
6835-33	87.8	A	93.6	A	48.1		75.2	A	35.0		62.8	A	44.8	42.5

(Cont.)	0 2022		0 2023		10 2022		10 2023		20 2022		20 2023		30 2022	30 2023
Innovation	92.1	A	93.6	A	67.3	A	75.2	A	55.3	A	62.8	A	43.7	41.5
6828-27	93.5	A	93.5	A	73.3	A	75.1	A	61.7	A	62.7	A	26.5	24.3
6919-29	91.6	A	93.5	A	78.2	A	75.1	A	69.0	A	62.7	A	42.9	40.7
6830-11	94.4	A	93.5	A	72.8	A	75.0	A	61.9	A	62.7	A	38.8	36.6
6941-36	98.4	A	93.1	A	93.9	A	74.7	A	89.9	A	62.3	A	52.5	50.2
6844-152	84.8		93.0	A	64.8	A	74.6	A	54.0	A	62.2	A	35.3	33.0
6840-20	93.1	A	92.9	A	61.1	A	74.5	A	48.3		62.1	A	29.4	27.2
6940-15	95.9	A	92.7	A	84.2	A	74.2	A	75.9	A	61.9	A	39.7	37.4
6925-53	93.6	A	92.3	A	80.9	A	73.9	A	71.9	A	61.6	A	36.9	34.7
6831-09	93.6	A	92.1	A	53.8		73.7	A	41.1		61.4	A	35.0	32.8
6784-17	93.1	A	92.2	A	56.7		73.7	A	44.4		61.4	A	50.8	48.6
6844-150	97.4	A	92.2	A	87.1	A	73.7	A	79.3	A	61.4	A	42.3	40.1
6844-104	94.8	A	92.1	A	75.4	A	73.7	A	63.6	A	61.3	A	38.0	35.8
6942-22	93.7	A	92.0	A	76.5	A	73.6	A	66.3	A	61.3	A	22.2	20.0
6782-42	94.7	A	91.9	A	80.1	A	73.5	A	69.8	A	61.1	A	42.6	40.4
6924-66	90.6	A	91.8	A	57.0		73.4	A	43.1		61.1	A	46.5	44.2
6782-75	97.9	A	91.8	A	83.4	A	73.3	A	72.8	A	61.0	A	41.3	39.1
6783-03	95.6	A	91.6	A	82.0	A	73.2	A	71.6	A	60.8	A	43.4	41.2
6782-120	96.9	A	91.5	A	82.1	A	73.1	A	72.7	A	60.7	A	42.4	40.2
6839-08	89.3	A	91.4	A	61.6	A	73.0	A	50.5		60.6	A	39.9	37.6
6924-47	93.2	A	91.0	A	64.8	A	72.5	A	53.0	A	60.2	A	31.5	29.2
6844-89	91.6	A	90.5	A	40.2		72.1	A	27.9		59.7	A	31.1	28.8
Meyer	95.3	A	90.4	A	78.1	A	72.0	A	67.7	A	59.6	A	45.1	42.9
DALZ 1808	96.9	A	90.4	A	79.9	A	71.9	A	69.9	A	59.6	A	34.4	32.2
6792-44	98.8	A	90.2	A	87.4	A	71.8	A	77.7	A	59.4	A	59.2	57.0
Palisades	95.7	A	89.4	A	79.1	A	71.0	A	70.7	A	58.6	A	22.5	20.3
6910-172	97.0	A	88.9	A	86.4	A	70.5	A	78.3	A	58.1	A	42.7	40.5
Emerald	95.6	A	87.5	A	71.4	A	69.1	A	59.1	A	56.7	A	28.4	26.2
Average	94.6		93.7		74.8		75.2		64.5		62.9		40.4	38.1

[a] Turf Analyzer Software was used to evaluate green cover on a 0 to 100% scale (0% = no green cover; 100% = complete green cover).

[b] Traffic events were simulated with a 4-ft wide modified Cody Traffic Simulator. One pass with the trafficker is equivalent to 57 cleat marks/ft^{-2}. Five simulated traffic events were initiated in August of 2022 and 2023 and applied weekly, for a total of 30 traffic events each year.

[c] Texas Agricultural Experiment Station (TAES) entry code

[d] Means followed by a capital ‘A’ in a column are not significantly different and occurred in the top statistical group ($P < 0.05$). Means are averages over replication, n = 3.

USGA ID#: 2021-18-742g

Title: 2021 Zoysiagrass Co-Op Trial: Cold Screen And Adaptability

Project Leader: Paul G. Johnson, Professor, Department of Plants, Soils, & Climate
Affiliation: Utah State University

Objective: To identify cold-hardy tees-to-green cultivars of zoysiagrass for the transition zone

Start Date: 2021
Project Duration: Four years (including no cost extension in 2024)
Total Funding: $9,000

Summary Points:

There appeared to be several top performing varieties in the trial.

- **6095-83** was top in the summer quality, near the top in fall color, and still middle but not significantly different than most top varieties in spring greenup.
- **6095-101** and **6095-152** were also among the highest in summer quality and similar to better than 6095-83 in spring.
- **6844-36** and **6844-150** also had among the highest summer quality and among the top in spring and fall color.

Background

With the increasing need to conserve landscape irrigation water in the state and with the gradually warming climate of our arid but cool region, zoysiagrass has some potential as a lower maintenance turfgrass.

Up to this point, any zoysiagrass has been Meyer, and interestingly Meyer was planted in my front yard when we moved to Logan in 1998. However the quality of Meyer leaves much to be desired.

In hopes of improved varieties, we planted a set of selections from the cooperative breeding program at Texas A&M and Kansas State University. This plot was the first research zoysia plot that has been planted in Logan Utah and probably the first anywhere in Utah.

The research plot was established in 2022 from vegetative plugs and maintained as a lawn or park turf. Mowing height at 2.5 inches, irrigation at 50-60% of ET, and herbicides to control weeds in border areas of the plot. We took ratings for turfgrass quality in spring, summer, and fall as well as spread and genetic color through fall 2024.

The winters of 2022 and 2023 were cold but also had significant snow cover. This thick snow cover (1-3 feet) likely provided significant insulation to the cold air temperatures (-

20F). The winter of 2024-2025 to the date of this writing has had very little snow cover so true cold hardiness may be evaluated among the entries in the future.

Results summary

Like all warm-season grasses in our climate, the entries were slow to greenup in spring and began to go dormant in September, however we did observe significant differences in those seasons with greenup as much as 2 weeks earlier in spring and 2 weeks later in fall. We also observed a large range in quality during the peak summer. These grasses had very good quality throughout the warmest periods and required much less water than the surrounding cool-season grasses to maintain active growth and green color. We did not lower the irrigation to the point of significant stress to the majority of the varieties in this trial.

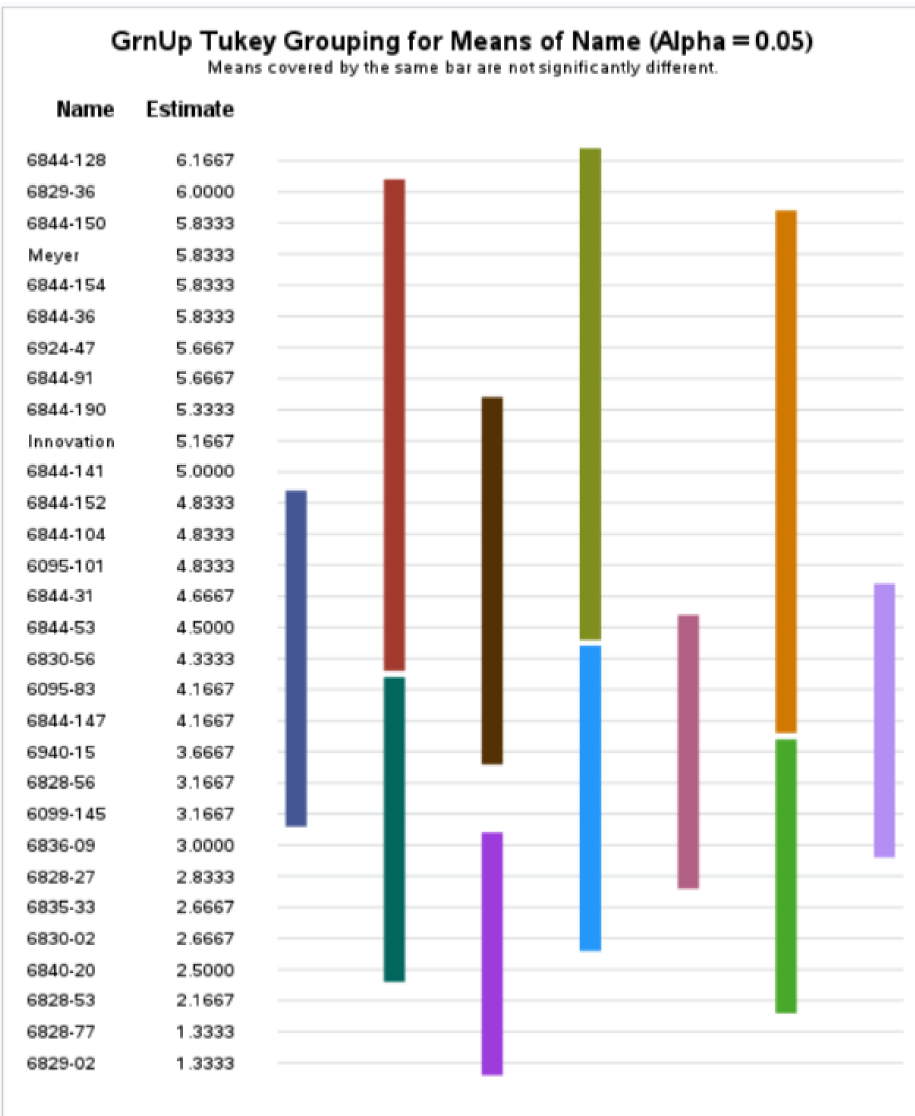


Figure 1. Spring greenup means using data from 2023 and 2024

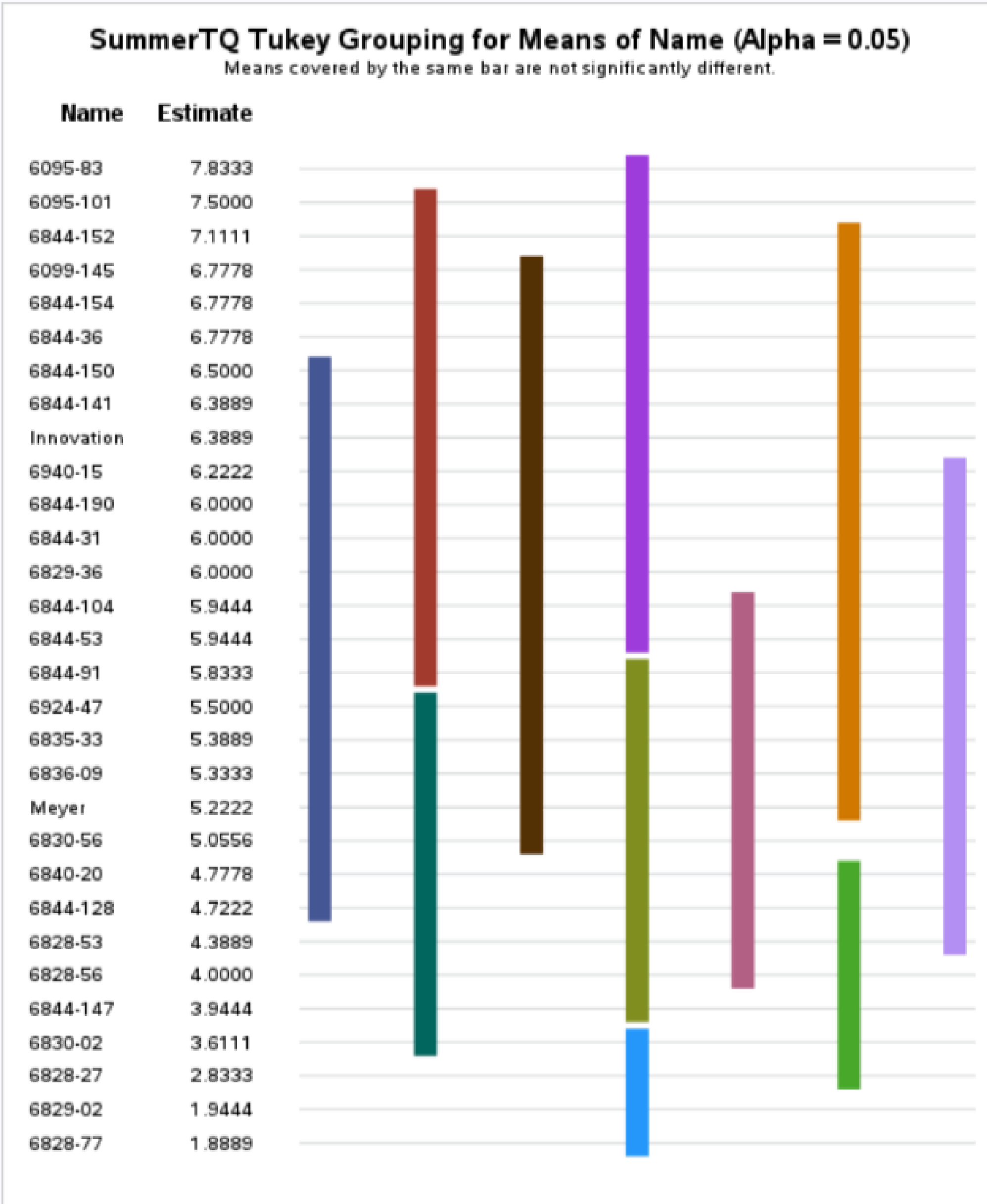


Figure 2. Summer Quality means for zoysiagrass entries in 2022-2024

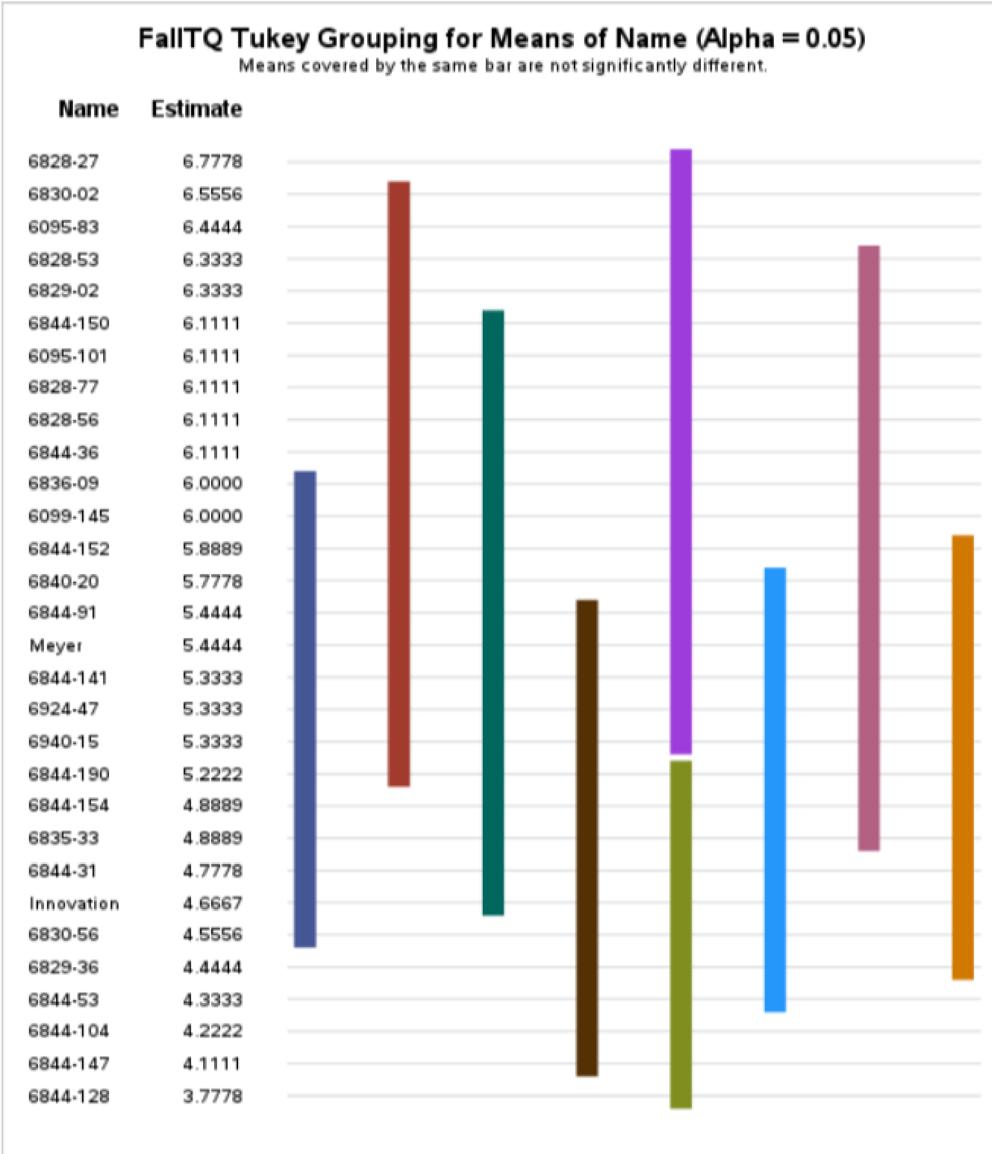


Figure 3. Fall Quality means for zoysiagrass entries in 2022-2024

USGA ID# 2021-16-740

Title: Developing Stress Tolerant Zoysiagrasses as a Low-Input Turf for Golf Course Roughs

Project Leaders: Susana Milla-Lewis[1], Aaron Patton[2], and Brian Schwartz[3]
Affiliation: [1]North Carolina State University, [2]Purdue University, [3]University of Georgia

Collaborators: Evergreen Turf (Chandler, AZ), American Sod Farms (Escondido, CA), Pfau Indiana University Golf Course (Bloomington, IN), Lonnie Poole Golf Course (Raleigh, NC), Torrey Pines Golf Course (San Diego, CA), East Lake Golf Club (Atlanta, GA) and TPC Scottsdale (Phoenix, AZ).

Objectives:
1) Expand evaluation of zoysiagrass genotypes --previously selected for their drought tolerance and aggressiveness-- to larger areas to fully assess their performance under golf conditions

2) develop materials with improved large patch tolerance through the identification of molecular markers associated with the trait

3) evaluate the performance of new experimental zoysiagrasses in warm-arid, warm-humid, transition zone climates.

Start date: 01/01/2021
Project duration: 5 years (01/01/2021-12/31/2025)
Total funding: $125,000

Summary points
- Nine experimental zoysiagrass genotypes have been planted in larger field in golf courses in NC and GA for demonstration and feedback from golf course superintendents and golfers.
- Genomic regions associated with large patch resistance were identified in a Meyer x PI 231146 mapping population.
- Preliminary evaluation new zoysiagrass hybrids has identified lines that appear very promising in terms of speed of establishment and stress tolerance.

Summary Text:
Zoysiagrass roughs are amongst some of the most easily played (improving pace of play) and easily managed (few inputs required with excellent weed suppression) of all the species used in golf course roughs. Breeding programs have germplasm available that has excellent stress and pest tolerance and fast establishment when managed with no inputs, but these materials are often discarded because current breeding efforts are more focused on “fairway” and “putting green” zoysiagrass. Our research team has evaluated zoysiagrasses for their performance and playability in multiple climates (warm-arid, warm-humid, transition zone) as a potential turfgrass for golf course roughs and other low-maintenance areas. Entries with superior drought tolerance, aggressiveness and color retention in combination with acceptable ball lie have been identified as part of those efforts.

For objective 1, nine experimental zoysiagrass genotypes were selected to be propagated alongside cultivar checks common to each state (i.e. Meyer, Zenith, Jamur, or Innovation) to be assessed in future on-site trials due to their drought resistance and aggressiveness observed at multiple locations (Braun et al., 2021). In August 2023, sod from these blocks was harvested and planted in a golf course rough (chosen in consultation with the superintendent at each location) at Lonnie Poole Golf Course in Raleigh, NC and Ansley Golf Club in Atlanta, GA (**Figure 1**). Following establishment, the plots were maintained with no to limited inputs (fertilization, irrigation, or pest control), and mown according to regular practices for other primary rough areas at each course. As plots are still establishing, only the superintendents managing the demonstration plots at each location were preliminarily surveyed (**Figure 2**) to receive feedback on overall appearance, persistence and management inputs. Results from this preliminary survey are presented in **Table 1**. A larger survey with golf professionals, members, and golf course superintendents at each course will be conducted next year to receive feedback on turf quality, ball lie (acceptable and optimal), and other potential turf golfing or turf characteristics. In addition, ball lie will be measured for each entry using the method developed by Richardson et al. (2010).

For objective 2, 229 lines were developed from crosses of large patch (LP) susceptible Meyer by LP-resistant PI 231146. Large patch response was evaluated under controlled environmental conditions across four different experimental runs through collection of final disease severity, digital image analysis-derived percent incidence (DIAPI), and the area under the disease progress curve (AUDPC). All three traits showed significant variance among individuals as well as significant genotype and genotype x run effects. Twenty quantitative trait loci (QTL) associated with LP resistance were identified which explained from 0.05% to 10.3% of the total phenotypic variance. Analysis of overlap across traits identified a potential LP "hotspot" on linkage group AH_13 (34.5 – 48.6 cM), as the region harbored significant QTL for all three traits evaluated (**Figure 3**). Several resistance genes were identified underlying QTL intervals including G-type lectin S-receptor-like serine/threonine-protein kinase LECRK1, Spotted leaf 11, CCR4-associated factor 1, and Disease resistance protein RGA5. The QTL and candidate genes identified in this study have great potential to be used in introgression breeding for the development of LP resistant zoysiagrass cultivars. A manuscript summarizing this work has been accepted by the journal Phytopathology and should be published within the next couple of months.

For objective 3, the Meyer x PI 231146 population was planted in spring 2021 at the W.H. Daniel Turfgrass Research and Diagnostic Center, West Lafayette, IN; the Lake Wheeler Turfgrass Field Lab, Raleigh NC; the Coastal Plain Experiment Station, Tifton, GA; and the Georgia Mountain Research and Education Center in Blairsville, GA with the goal of exposing the population to a wide range of environmental stresses to assess their potential for broader adaptation. In fall 2024, a combined analysis of data including percent green cover, winterkill, turfgrass quality, spring green up, leaf texture, canopy density, and fall color was conducted to identify top performers. Line 19-TZ-14433 was ranked among the top 20 at every single location and in the combined analysis across locations. Meanwhile, line TZ-19-14529, was also ranked in the top 20 across locations except for West Lafayette. Other lines ranked in the top 20 at two locations. The top 22 performing lines as well as and six commercial cultivar checks (Meyer, Zeon, Lobo, Emerald, Brazos, and DALZ 1701) will be propagated over winter in order to produce materials to plant on-farm trials at selected sod farms in NC, GA, FL, IN and AZ in spring of 2025. Twenty four plugs will be planted in 5 x 5 ft plots with 1.5

ft alleys in a randomized complete block design with three replications. At the end of year 3, data will be analyzed across years and locations to make final decisions on lines that have potential for commercial release.

References

Richardson, M.D., D.E. Karcher, A.J. Patton, and J.H. McCalla, Jr. 2010. Measurement of golf ball lie in various turfgrasses using digital image analysis. Crop Sci. 50:730–736. doi:10.2135/cropsci2009.04.0233

Braun, R.C., S. Milla-Lewis, E. Carbajal, B.M. Schwartz, and A.J. Patton. 2021. Performance and playability of experimental low-input coarse-textured zoysiagrass in multiple climates. Grass Research, 1:10 1–12. https://doi.org/10.48130/GR-2021-0010

Figure 1. Demo plots on rough area at Ansley Golf Club (Atlanta, GA).

Figure 2. Superintendent Brian Green surveying experimental zoysiagrass rough plots maintained with no inputs (zero mowing, fertilizer, irrigation, and pest control) at Lonnie Poole Golf Course (Raleigh, NC).

Table 1. Summary of survey responses from golf course superintendents at Lonnie Poole (Raleigh, NC) and Ansley Golf Club (Atlanta, GA).*

Question	Lonnie Poole Golf Course	Ansley Golf Club
5. What comments about zoysia do you hear golfers sharing	Good playability	High handicap golfers like how the ball sits up, lower handicap golfers want tighter lies
6. How would you describe the playability of zoysia for golf course uses	Easier surface to hit from	Excellent playability
7. Of the zoysiagrass varieties in the demo plots, rank from best to worst	1. 16-TZ-14114 2. XZ 14070 3. Lobo 4. 09-TZ-54-9 5. Meyer 6. Zeon 7. 16-TZ-13685	1. 09-TZ-54-9 2. Lobo 3. 1254 4. L1FS and 16-TZ-14114 5. 16-TZ-13685
8. Describe what characteristics you liked most in the top ranking entry	Established well, thicker	Density, low height

*The survey included 26 questions divided into section on perceptions, experience and preferences. Due to space limitations, we are providing just the questions more relevant to this report here. A more comprehensive report with summary statistics will be presented next year.

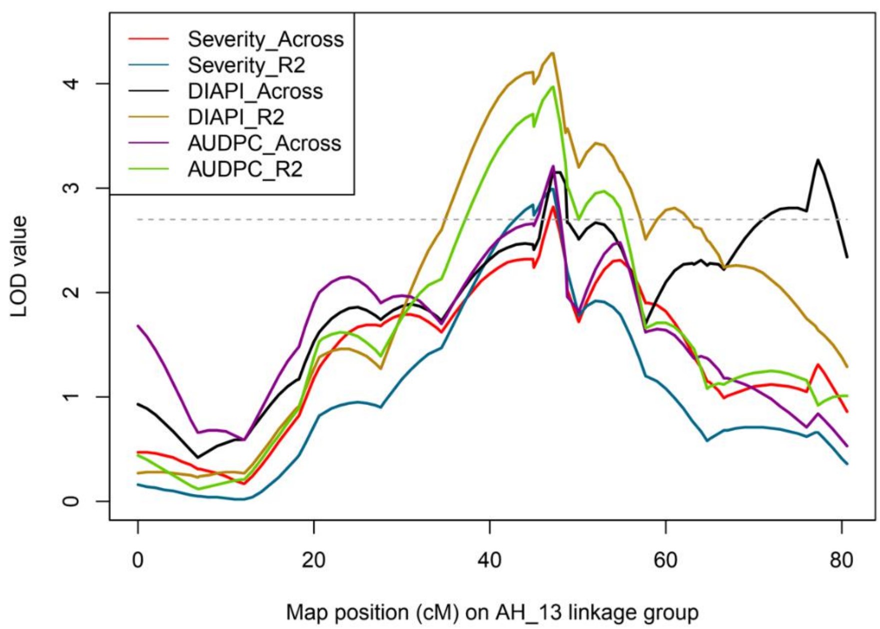


Figure 3. Quantitative trait loci (QTL) for large patch resistance co-localized in the linkage group AH_13 in the zoysiagrass Meyer x PI 231146 mapping population. Severity = visual ratings of final disease incidence, AUDPC = area under the disease progress curve, and DIAPI = digital image analysis final percent incidence. The horizontal gray line indicates a LOD threshold 2.75.

USGA ID#: 2021-04-728

Title: Buffalograss Breeding and Development

Project Leader: Keenan Amundsen
Affiliation: University of Nebraska-Lincoln

Objectives: Our primary objectives are to 1) optimize breeding schemes to improve their efficiency and reduce the cycle duration needed to release new buffalograss cultivars; 2) increase buffalograss yield and reduce production costs; and 3) continue to improve functional and visual quality of buffalograss cultivars through the application of classical and modern genetics and plant breeding techniques.

Start Date: 2021
Project Duration: 5 years
Total Funding: $150,000

Summary Points:

- A mid-season nitrogen application may significantly increase buffalograss yield and profitability.
- Five high yielding seeded populations were advanced for performance evaluation and seed increase.
- Six experimental vegetative lines were identified that surpass the performance of standard cultivars.

Summary Text:

Buffalograss is an important turfgrass species because of its natural adaptation to the United States Great Plains, and its tolerance to the desiccating winds, temperature extremes, and temperature fluctuations common to the region. There are both seeded and vegetative types of buffalograss, and the breeding approaches for developing elite varieties suitable for release as cultivars varies and is complicated by the dioecious nature of the species. Vegetative lines are clonally produced and in addition to turfgrass quality traits, internode length, stolon production, and unisexually female or little flower production are traits of interest. Seeded lines are generally developed as synthetics from clonally propagated sexually compatible female and male lines that produce high yielding uniform populations. Seeded lines are more challenging to develop due to the added need for developing compatible male parental lines. In production fields, gender expression typically approaches a near 1:1 ratio reducing seed yields due to the presence of male plants occupying valuable production field space. As such, the buffalograss breeding program at the University of Nebraska-Lincoln is committed to developing lines that are profitable for producers and desired by turfgrass managers.

In addition to working with the genetics to optimize crosses, research is also done to optimize management practices to promote profitable yields. We continued a long-term study to evaluate the effects of added nitrogen, application timing, and lime applications on buffalograss seed yields and the study is complemented with annual soil testing (). Current data suggests that an additional nitrogen application in June at our research plots, increased seed yields enough to cover the added fertility costs and increase profits. The study is established as a demonstration plot and we intend to initiate on-farm trials to determine if this is a profitable approach at production scale in the central Great Plains. A similar study was started to revisit management recommendations for mowing heights and nitrogen inputs to optimize management of new buffalograss lines. We found that current recommendations of 2 lbs N per 1,000 sq ft annually was sufficient to maintain quality, but that there was a quality increase as nitrogen rates were increased up to 4 lbs N per 1,000 sq ft annually. In these plots, the fertility treatments were split over different mowing heights (1.5, 2.5, 3.5 in) and a similar quality response to N application was observed regardless of mowing height. These findings are consistent with prior published research and recommendations.

Figure 1 Nitrogen and lime inputs to optimize buffalograss yield.

The entire area received standard fertility inputs consistent with seed production and the treatments are in excess. From left to right, plots received an extra 1) 200 lbs per acre 11-52-0, 2) 300 lbs per acre pel lime, 3) 60 lbs N per acre from urea, 4) 60# N per acre from ammonium sulfate, 5) no additional fertility, and 6) 60 lbs N from urea, 200 lbs of 11-52-0, and 300 lbs pel lime per acre.

Fourteen elite populations derived from crossing blocks designed to improve shade tolerance, chinch bug resistance and stand persistence and reduce seed dormancy were evaluated for yield over two years (Figure 2). Yields ranged from 85 to 423 lbs per acre. Five lines were identified with yields (mean=373 lbs per acre) that nearly doubled the yield of the others (mean=192 lbs per acre). These five lines were advanced along with two top performing diploid populations (development supported by USGA #2021-11-735) and five standard entries for comparison (Sundancer, Bowie, Cody, Texoca, and SWI2000). The plots will be used for comparative performance evaluations and data collection for PVP. Seed increase plots of the top performing experimental lines were established to produce enough seed for regional evaluation trials.

Figure 2 Multi-year evaluation plots of elite buffalograss seeded populations.

Evaluation of the sod strength study established in 2022 continued to assess persistence of the lines. Based on anecdotal observations, some buffalograss lines can begin to decline three years after establishment which was not observed in this study. That was rewarding since several of the lines were selected for stand persistence from other evaluations trials. Overall, six lines were identified that were superior to Prestige and Legacy in several evaluation categories (Table 1) and have potential as new vegetative cultivars following regional performance evaluations.

Together these studies demonstrate continued potential for genetic gain of buffalograss lines through targeted breeding. With projected increased occurrence, severity, and duration of heat and drought events, buffalograss has the unique potential to serve the increasing demand in the golf industry for turfgrasses that can survive in those challenging environments.

Table 1 Mean performance of top performing buffalograss lines for several traits important for vegetative line development

Genotypes	Fall quality		Spring Greenup		Establishment		June Sod Strength		July Sod Strength		Recovery	
NE153649AL6	7.0	ab	81.7	ab	5.0	c-f	92.2	a	60.2	ab	63.3	a-d
NEMP64	7.0	ab	63.3	d-f	6.0	a-d	66.5	b	60.3	ab	53.3	a-f
NE0709	7.0	ab	63.3	d-f	6.5	a-c	39.6	de	49.4	a-g	68.3	a-c
NE2974Advl31	6.3	b-d	60.0	d-f	6.5	a-c	50.2	b-e	57.7	a-c	58.3	a-e
NE0713	7.0	ab	90.0	a	4.5	d-f	38.7	de	50.1	a-g	21.7	f-h
NENG36	7.0	ab	53.3	f	4.5	d-f	53.4	b-e	65.1	a	48.3	a-g
Prestige	6.7	bc	66.7	c-e	6.5	a-c	42.9	c-e	52.0	a-f	76.7	ab
Legacy	6.3	b-d	76.7	bc	5.5	b-e	64.6	bc	65.4	a	80.0	a

Means separated by Fisher’s protected LSD *p=0.05*

USGA ID#: 2021-11-735

Title: Seeded Diploid Buffalograss

Project Leader: Keenan Amundsen
Affiliation: University of Nebraska-Lincoln

Objectives: The primary goals for this project are to develop 1) seeded diploid buffalograss cultivars, and 2) a genomic reference framework to support buffalograss breeding research.

Start Date: 2021
Project Duration: 3 years
Total Funding: $44,080

Summary Points:

- 10,000 sq ft seed increase plots of two elite seeded diploid buffalograss lines were established.
- Lack of diploid buffalograss winter dormancy contributes to greater fall color retention.
- Elite seeded diploid buffalograss lines have exceptional yield, vegetative growth, and turf quality.

Summary Text: The focus of the project this year was to begin evaluating elite seeded diploid populations under managed conditions in Nebraska and to establish larger seed increase plots. The seeded diploid populations under development are unique among buffalograss cultivars because they are diploid and suited to environments that experience increased and prolonged drought events that do not have severe winters. None of the diploid buffalograss lines evaluated to date by the University of Nebraska-Lincoln buffalograss breeding program have a strong winter dormancy response precluding their ability to persist over multiple years in the central Great Plains. This has complicated development of diploid lines in Nebraska. The winter survival of buffalograss diploids is significantly better than bermudagrass grown in the region and not as good as zoysiagrass, where it survives, but thins, and over multiple harsh winters it can be significantly set back; this contrasts with higher ploidy buffalograss lines with cold hardiness that is superior to either of the other warm-season species. Increasing ploidy in buffalograss is associated with winter hardiness, where hexaploids dominate northern buffalograss stands throughout the central Great Plains. The appeal of the diploid lines from a turfgrass management perspective is that they are typically a lighter and more vibrant green color,

have finer leaf texture, and lack the winter dormancy response. The winter dormancy response has value for winter survival and reduced management in the late fall and early spring when management inputs are not necessary. The downside of winter dormancy is the straw-colored canopy, which is particularly noticeable when buffalograss is grown adjacent to cool-season turf stands. In regions that do not have hard frost, the diploid lines retain their green color, increasing their visual quality in the fall (Figure 1).

The buffalograss breeding program has developed two seeded diploid populations and has begun the work of increasing seed in recent years to support local and regional evaluation trials and seed production. The seeded diploids are also a unique part of this project since there are no turf-type seeded diploid buffalograss lines on the market, and instead diploids are produced vegetatively. In previous years, while the seeded lines were advancing through the breeding program, plots were limited in size to advance populations only, but space was not dedicated to seed increase limiting seed supply for evaluation trials. The primary goal during that plant breeding phase was to determine if the diploids could be maintained in Nebraska's environment over multiple winters and to advance the breeding populations. Over the past three years, 1,000 sq ft plots were established and used to increase seed. Seed yields of the smaller plots have consistently yielded more than 600 lbs per acre which are considered high yielding for buffalograss which typically yields on average closer to half as much. Differences in harvest

Figure 1 Fall color retention in diploid buffalograss (center plot).

methods for small plots are not always good predictors of commercial production yields so the populations were increased to 10,000 sq ft plots (Figure 2) so they can be harvested using production scale methods. It is worth noting that these diploid populations also have substantial vegetative growth (Figure 3) which might complicate harvest.

Figure 2 Established 10,000 sq ft diploid buffalograss seed increase plot.

Vegetative growth can also benefit producers that use it to generate additional income from baled harvest residue. We anticipate these plots will yield a minimum of 100 lbs of seed during 2025 harvest, providing sufficient seed to begin regional turf evaluation trials and supporting commercial scale seed production.

Figure 3 Canopy growth of seeded diploid population when not mowed.

USGA ID#: 2023-02-769

Title: Evaluation of Saltgrass for Turfgrass Characteristics under Drought and Heat Stresses

Project Leader: Desalegn D. Serba
Affiliation: USDA-ARS, Maricopa, AZ

Objectives:

1. To characterize desert saltgrass (*Distichlis spicata*) accessions under different level of deficit irrigation in Maricopa, AZ field conditions.
2. To identify the most drought-and heat tolerant saltgrass genotypes with good turfgrass characteristics for use as a turfgrass in a drought/salinity stressed landscapes,
3. To identify desirable traits and reproductive characteristics for complementing desirable traits in a genotypic background through hybridization.

Start Date: 5/1/2023
Project Duration: 3 years
Total Funding: $40,866.67

Summary Points: Include 3-6 bullet points that summarize the findings of your project to date.

- Field established a total of 78 saltgrass accessions in a Split-Plot design with two replication.
- Deficit irrigation treatment of 80, 60, and 40 % ET replacement will start on May 1st, 2025.
- Genotypic variation among saltgrass accessions for establishment, density, and greenness was observed in the establishment year.
- Evaluation for color, quality, and stress tolerance will continue for the next two years using visual assessment and proximal sensing devices that collect spectral and image data.

Summary Text:

Rationale and Methodology

Recent megadroughts and substantial high temperature in southwestern USA (Williams et al., 2022) has further strained the availability of fresh water for turfgrass irrigation. Research has shown that switching from managed turfgrass to low-input alternative native grasses and ground covers on non-play areas of desert golf courses can minimize water usage and improve turf management effectiveness (Burayu and Umeda 2021).

The use of drought tolerant grass species/genotypes is one of the main strategies proposed for coping with water scarcity for turfgrass irrigation in dry lands. However, research on identification and use of adaptable native grass species that are accepted for their aesthetic and functional qualities and drought tolerance is limited in the Desert Southwestern USA. Numerous native grass species have been studied for low maintenance in various southern United States landscapes (Corley and Reynolds 1994; Aitken 1995; Ruter and Carter 2000; Dana 2002; Dunning 2014; Burayu and Umeda 2021).

Saltgrass (Distichlis spicata) is a warm-season grass grown in dry areas and has a potential to be widely used in a naturalized ecosystem with low input and maintenance requirements. Development and adoption of saltgrass on golf course fairways and roughs as well as sport fields could help conserve significant amount of potable water while maintaining attractive turf with excellent playing conditions. Roughs and fairways constitute the larger proportion of the golf courses. Adapted and evergreen native grasses with low maintenance requirement such as inland saltgrass will be an ideal product to conserve water resources and offset significant expenses for golf courses.

This project is aimed at identifying drought and heat tolerant saltgrass genotypes with good aesthetic value. A total of 78 saltgrass accessions (62 accessions obtained through Material Transfer Research Agreement with USGA and 16 accessions obtained from Germplasm Resource Information Network (USDA-GRIN)) were transplanted into the field in Maricopa on August 30, 2023. A bermudagrass and a zoysiagrass commercial cultivars were included as checks. The experiment was laid out in Split-Plot design with two replications. Necessary agronomic practices are being conducted for the establishment of the plots. Three irrigation levels (80, 60, and 40 % evapotranspiration (ET) replacement) are the main plots and the genotypes in the sub-plots. Four plug were planted at a square 0.4 m apart in center of 2.25m^{-2} (1.5 m x 1.5 m) sub-plot size. All the plots were established under 80% ET replacement irrigation. In the 2024 establishment year, irrigation was applied four times per week to meet evapotranspiration replacement. Rating for greening up started March 1st, 2024 using visual and imaging technique. RGB-image data were collected every other week from March to October 2024. The image data were analyzed using Turf Analyzer (Karcher and Richardson, 2013) and using a custom Python process to threshold green pixels and to determine percent plot cover (establishment), deep green color index (DGCI), and density metrics.

The deficit irrigation treatment will start May 1st, 2025 and the plots will be evaluated on a bi-weekly basis for color, quality, and stress tolerance for the next two years using visual assessment and proximal sensing devices that collect spectral and image data.

Results and Future Expectations

Preliminary visual assessment and imaging data analysis shows statistically significant differences among the accessions for establishment rate and turfgrass density. Percent threshold analysis using ortho-mosaics of RGB-image data revealed noticeable differences among the plots for percent area coverage (Fig. 1). Deep green color index (DGCI) analysis revealed highly significant differences among the genotypes (Fig. 2). Few genotypes with good percent of ground cover, density, and greenness were identified (Fig. 3) during the establishment year. The percent threshold analysis of the RGB-image data showed several accessions with coverage and mean DGCI comparable to TifTuf (bermudagrass control) (Fig. 4).

This study highlights the genotypic variation among accessions for establishment, density, and greenness. These results suggest that saltgrass can serve as an alternative drought- and salinity-tolerant turfgrass in the desert environment for non-play areas of golf courses, recreational areas, and home lawns providing numerous ecosystem services. The naturally adapted native grass studied is expected to also offer significant benefit by reducing irrigation water requirement. Genotype-by-irrigation treatment interaction study will be conducted the next two years.This project is expected to identify drought and heat tolerant genotypes with good turfgrass characteristic for use as a turfgrass in a drought/salinity stressed landscapes and other desirable traits.

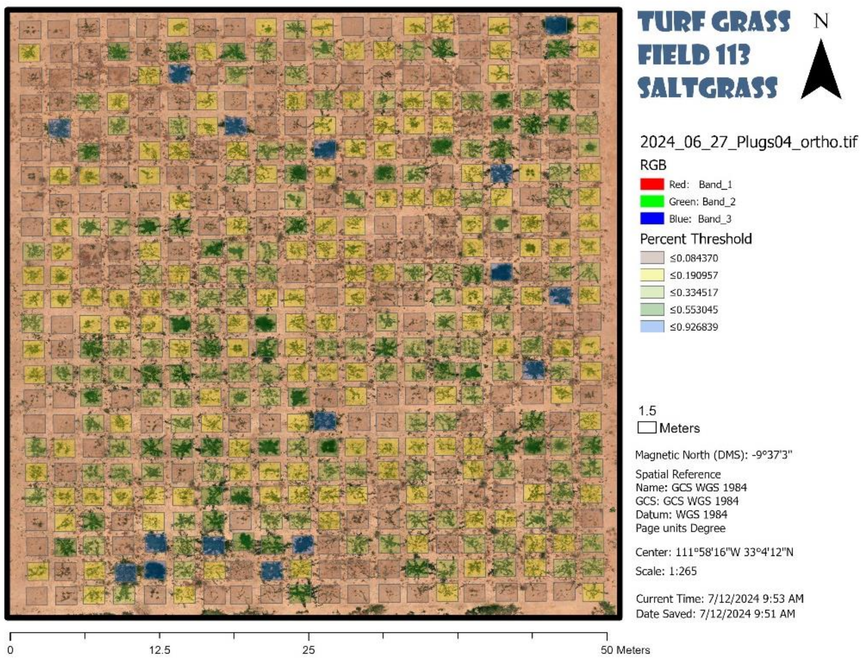


Fig. 1: Saltgrass plot coverage based on RGB-imaging analysis.

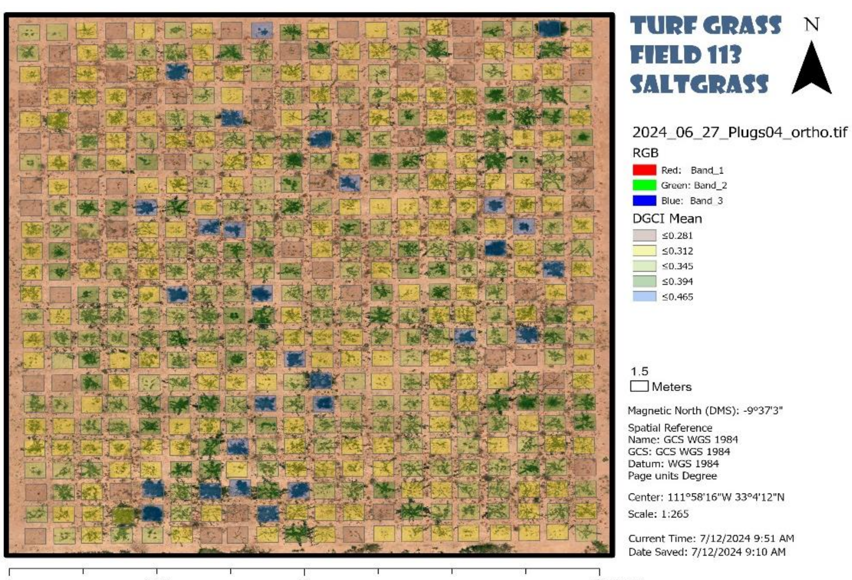


Fig. 2: Deep green color index (DGCI) of saltgrass accessions based on RGB-imaging analysis.

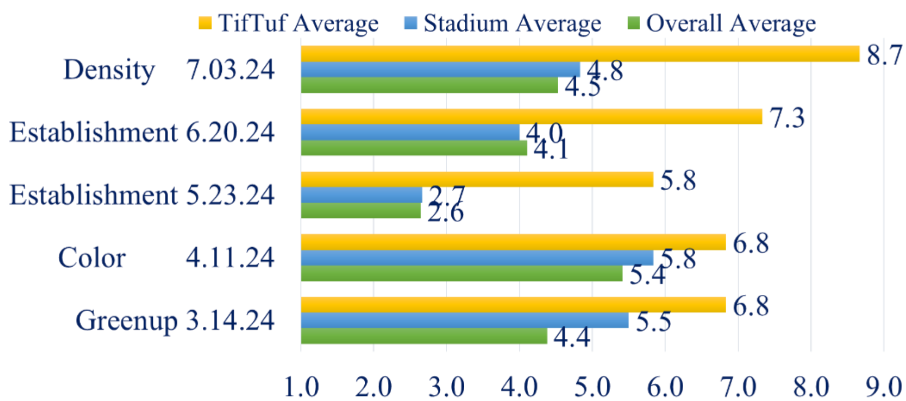


Fig. 3:Average green up, color and density scores for saltgrass accessions against bermudagrass and zoysiagrass checks during 2024 at Maricopa, AZ (1-9 scale).

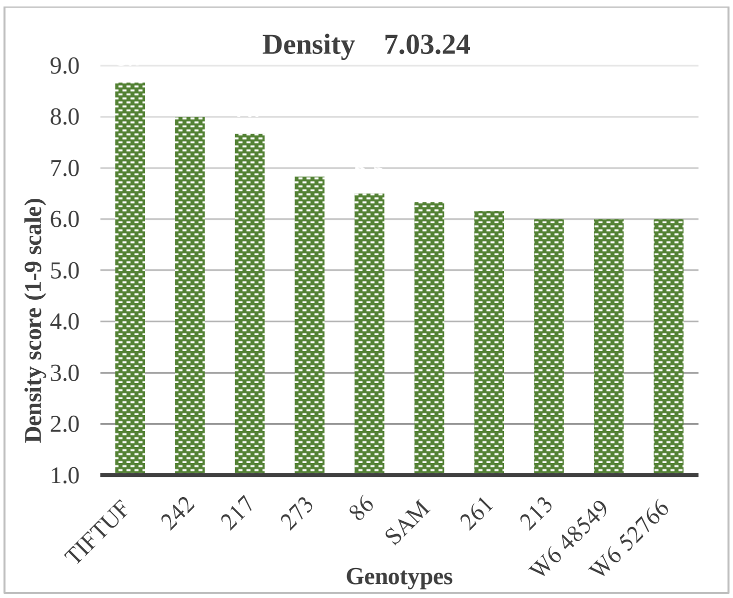


Fig. 4: Mean density of selected saltgrass accessions against bermudagrass hybrid (Tiftuf) during 2024 at Maricopa, AZ (1-9 scale).

USGA ID#: 2023-11-778

Title: New Discoveries And Methods For Complex Data Analysis

Project Leader: Keenan Amundsen
Affiliation: University of Nebraska-Lincoln

Objectives: The objectives of the project are to 1) use existing genomic and transcriptomic data to identify elements with variable responses to different conditions; 2) develop and publish workflows for genomic, transcriptomic, and fine resolution computational biology methods; and 3) test and validate the methods on other published data from turfgrass species; and 4) train a student with interest in the turfgrass industry to become a leading expert in computational biology methodologies

Start Date: 2023
Project Duration: 3 years
Total Funding: $153,970

Summary Points:

- Publicly available sequence data for turfgrass species supports ancillary studies.
- Genomic data allowed discovery of structural genome variants.
- Sequence data is supporting research to characterize bentgrass gene and genomic differences.

Summary Text:

DNA sequencing technologies have been used to study turfgrasses since the early 1990s, useful for resolving evolutionary relationships, functional genomics, understanding adaptation, structural variation, identifying genes and markers associated with traits, among other applications. A primary database of sequence data is housed by the National Center for Biotechnology Information (NCBI). Table 1 shows the number of new sequences added to the DNA database per 5-year increments for *Agrostis* spp., *Festuca* spp., *Lolium* spp., *Poa* spp., *Cynodon* spp., *Zoysia* spp., and *Bouteloua* spp., important turfgrass genera; rice is listed for comparison. In recent years, sequencing costs have lowered, and the technology has improved and become more accessible. The amount of data represented by modern high throughput sequencing (HTS) technologies is housed in the short read archive (SRA) by NCBI and the number of HTS samples for the above turfgrass genera

Table 1 Numbers of turfgrass sequences in the DNA and short read archive (SRA) National Center for Biotechnology databases

Genus	1991:1995	1996:2000	2001:2005	2006:2010	2011:2015	2016:2020	2021:2025	SRA
agrostis (46806)	6	26	16264	6298	21172	2615	425	1338
festuca (191534)	24	188	50167	99114	34517	3847	3677	5750
lolium (1028093)	27	312	61658	154143	224478	416815	170660	59430
poa (100574)	10	117	503	1175	90792	4831	3146	3860
cynodon (25478)	10	53	5098	16115	1568	1407	1227	876
zoysia (2206)	8	8	556	136	1042	278	178	431
bouteloua (9023)	0	5	127	1946	641	6076	228	1344
oryza (5407768)	12034	154759	1751015	1849093	1094807	377083	168977	179735

Genus is listed followed by the total number of sequences in parenthesis. The number of sequences in the database are shown for each 5-year window or total amount for those in the SRA.

exceed 72,000; these samples represent more than 4.57 trillion sequenced nucleotides. The substantial amount of data is at a point where it is supporting ancillary studies and allowing the industry to make comparisons not feasible a decade ago.

In collaboration with the United States Department of Agriculture, we have sequenced genomes of creeping and colonial bentgrass. Initial draft assemblies were poor quality, complicated by the genome complexity of the species, warranting additional sequencing. With the preliminary data we are still able to identify candidate genes within QTLs and structural variants (Figure 1). The data is currently useful as a framework for identifying differences between the species. As an example, we have interest in characterizing mobile genetic elements, their mobility, and how they impact gene expression. Miniature inverted repeat transposable elements (MITEs) are a sub-class of type 2 transposons because they are small and do not encode their own transposase, the enzyme that facilitates their

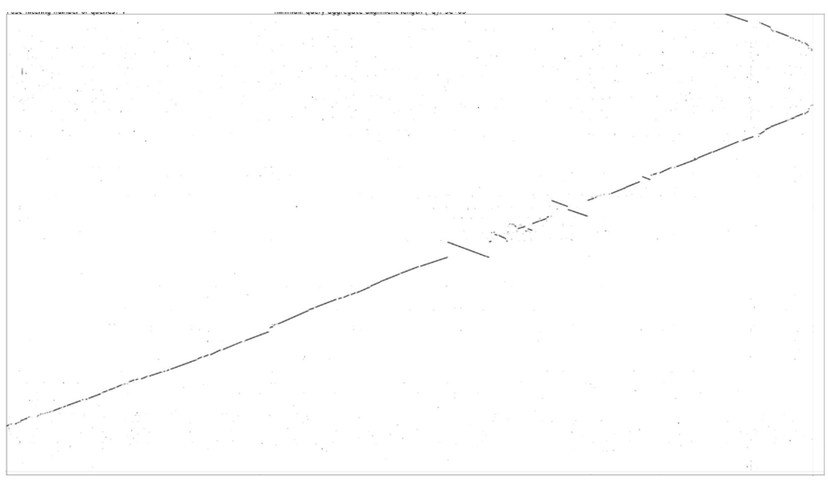
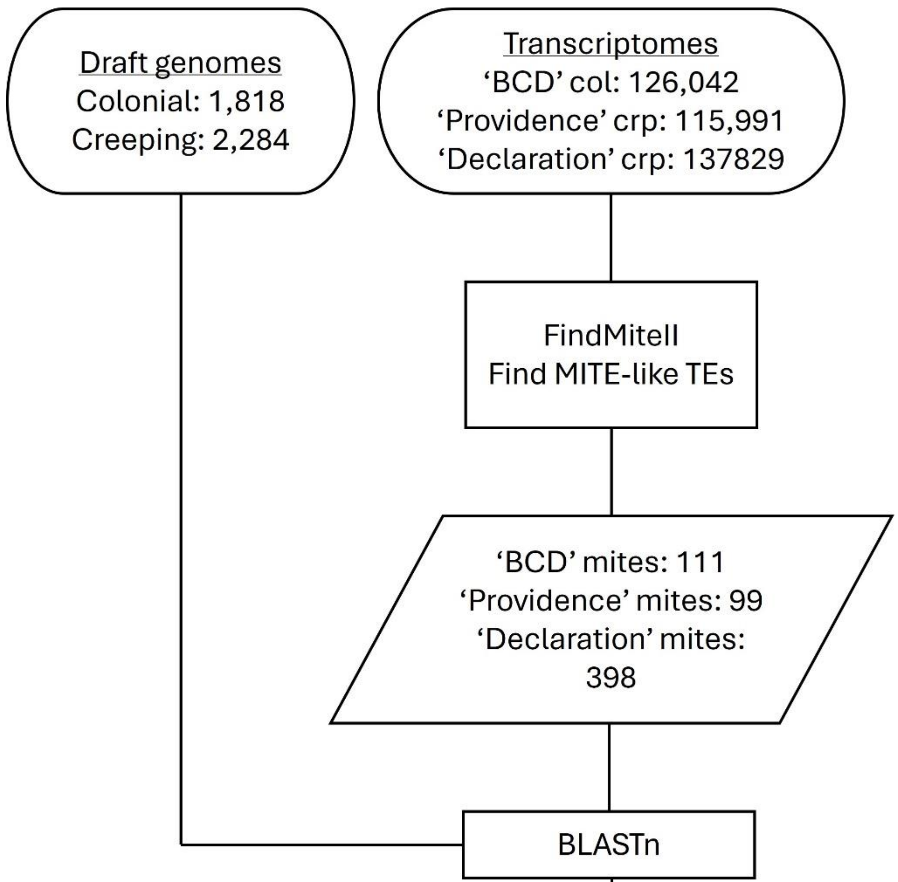


Figure 1 Dotplot represented alignment of a creeping bentgrass and colonial bentgrass genomic sequence scaffold.

Dots represent alignment between the genomic scaffolds. Dots oriented into lines represent segments of aligned sequences between the chromosomes. Duplications, inversions, insertions, and gaps in the alignment are represented by the orientation and spacing of the lines.

mobilization. The transcriptomes from a prior drought study were searched for MITEs using a software tool called FindMITEII which searches for motifs characteristic of MITEs. The found MITEs were then searched for in the colonial bentgrass and creeping bentgrass genomes demonstrating the relatively high copy number of the found MITEs distributed throughout the genomes. These candidate MITEs are interesting because they were initially discovered from expressed genes and might play a role in differential expression and function of the genes (Figure 2). Once complete, the contrasting genomes will provide more insights into the differences between creeping bentgrass and colonial bentgrass and provide a framework for developing molecular resources to further transfer desirable traits between species (dollar spot resistance and drought tolerance for example).

We have also started testing the use of linear mixed models as implemented in EchidnaMMS to identify top performing buffalograss genotypes from multiple studies and evaluation years. The advantage of the approach is that it allows for identification of top performing individuals across multiple studies instead of within a single study.



Genotype	Colonial	Creeping
'BCD'	1,511	1,579
'Declaration'	12,689	15,881
'Providence'	2,579	2,695

Figure 2 A workflow for identifying conserved miniature inverted repeat transposable elements.

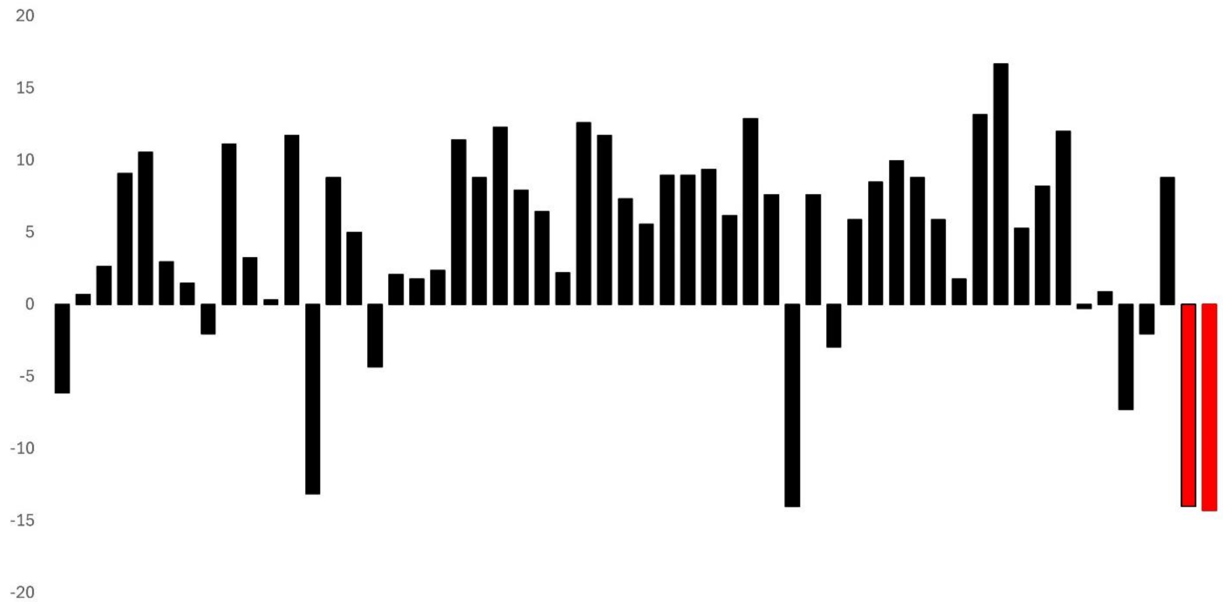


Figure 3 Buffalograss establishment rate over multiple years and studies.

Normalized mean establishment rate are shown for 54 experimental buffalograss lines along with two standard entries (red). Larger positive values represent faster establishment.

We combined data from the past three years of evaluation data, and discovered 45 entries that outperformed standard vegetative cultivars for establishment (Figure 3), 12 for spring green up, 36 for late season quality, and 3 for early season quality. We intend to apply these methods to compare historical and contemporary breeding populations to document performance gains over time and to identify top performing individuals that contribute to the best performing progeny and populations. These efforts will improve our ability to select top-performing genotypes useful to our breeding program.

USGA ID#: 2022-03-746

Title: A National Evaluation of Cool-Season Turfgrass Cultivar Water Use and Drought Tolerance under Golf Course Fairway Management

Project Leader: Kevin Morris
Affiliation: National Turfgrass Evaluation Program

Objectives: The objectives of the project are to evaluate cool-season species and cultivars under fairway management to 1) record the amount of water required to maintain a prescribed green cover, and 2) determine turfgrass quality and percent living ground cover under three replacement irrigation (ET_0) levels

Start Date: 2022
Project Duration: Three years
Total Funding: $120,000

Summary Points:

- In fall 2022 and spring 2023, eighteen total entries, encompassing creeping and colonial bentgrass, hard fescue, chewings fescue, strong creeping red fescue and perennial ryegrass were established at five sites, two under rainout shelters and three in field sites with deficit irrigation (ET_0) levels
- A minimum percent green cover threshold 75% was utilized during the drought 'season' to determine re-watering at the rainout shelter locations, thus allowing for a water needs rate for each entry
- Three deficit irrigation levels, representing high (optimum - 80% ET_o), medium (sub-optimum - 65% ET_o) and low (severe restriction - 50% ET_o) were instituted at the three deficit ET_0 sites
- 'Musket' colonial bentgrass and 'SR 4650' perennial ryegrass used 45% less water than the highest water using bentgrass and fine fescue in 2024 under the rainout shelter in West Lafayette, IN.
- Bentgrass entries were the best, with higher quality ratings required for fairway turf, under both the medium (65% ET_o) and low (50% ET_o) irrigation replacement levels in second year data collected at St. Paul, MN, .
- Perennial ryegrass entries delivered the highest turf quality, under the lowest irrigation regime in the first data from Logan, UT.

Summary Text:

In 2016, the USGA provided NTEP $500,000 to build rainout shelters and develop irrigation infrastructure at multiple locations to evaluate cultivars and experimental selections of Kentucky bluegrass and tall fescue for water use and drought tolerance. Thirty-five total entries were established and evaluated for three years at five rainout shelter locations and five deficit irrigation (ET_o) locations. In 2018, seventeen warm-season grass cultivars were established at ten locations (five rainout shelter, five deficit ET_o) with evaluations completed recently. With the completion of the cool-season trial, and because rainout shelter space limited evaluations to only Kentucky bluegrass and tall fescue, it was time to evaluate additional cool-season species. Utilizing some of the current infrastructure funded by the USGA allows us to evaluate grasses for three years at six geographically appropriate locations (three rainout shelters, three deficit ET_o) under fairway management.

We expected at least twenty paid entries of species such as bentgrass, fine fescue and perennial ryegrass to be submitted for the trial, but only received twelve paid entries. Added to the trial were six standard (unpaid) entries for a final total of eighteen entries. Entry fees paid by sponsors are utilized to cover most costs, therefore, we had to eliminate one trial location. Thus, five trial sites were established: rainout shelter sites in Amherst, MA and West Lafayette, IN measuring water needed to maintain green cover, and deficit irrigation sites in St. Paul, MN, Ft. Collins, CO and Logan, UT evaluating performance under three ET_o regimes.

Trial establishment was in fall 2022/spring 2023, with data collection for three years. Trial parameters were developed by an advisory committee consisting of USGA representatives, researchers and entry sponsors. Data is analyzed and published on the NTEP web site and uploaded into the NTEP database.

Data on percent green cover collected during the drought ‘season’, turfgrass quality and the amount of water needed by each entry to maintain a prescribed level of green cover are collected from each rainout shelter site. Data from the deficit ET_o sites include percent green cover and turfgrass quality ratings during the deficit ET_o period. The data will document performance during drought periods applicable to eastern and western US turfgrass management conditions.

Water use calculations started within the rainout shelters in either summer 2023 or 2024, depending on trial maturity. To initiate the drought ‘season’, irrigation is halted under the rainout shelter for approximately 100 days. As entries ‘dry-down’ and start to experience water stress, daily evaluation of green cover using digital image technology determines which plots have reached the 75% green cover re-watering ‘threshold’, the minimum acceptable percent green cover determined by the trial advisory committee. Using ½ - 1” of water, each plot reaching the threshold will be carefully re-watered. A daily record of plots that require water is totaled at the end of the drought ‘season’ to determine amounts of water required by each entry to maintain the threshold green level. Three years of data collection will provide water use rates under different climatic conditions.

Deficit irrigation sites calculate and replace water lost based on daily evapotranspiration (ET) rates. Three irrigation regimes based on replacement ET_o: 80, 65 and 50% are utilized at each site, representing optimum, sub-optimum and severely restricted (deficit) irrigation replacement levels. The irrigation regimes will be utilized for 100 -120 days over three years of data collection.

Data was collected and submitted in 2024 from St. Paul, MN, Ft. Collins, CO, Logan, UT (ET_0 sites) and West Lafayette, IN (shelter site). Since establishment was not sufficient by the summer of 2024, no data was submitted by the Amherst, MA (shelter) site.

Under the rainout shelter at West Lafayette, IN, two bentgrass entries and two perennial ryegrass entries required less than 203 mm to maintain 75% green cover throughout the drought ‘season’. The entries with the least water used include the bentgrasses ‘Musket’ (182.3 mm - 7.2”), and ‘Penncross’ (198.7 mm - 7.8”), and the perennial ryegrasses ‘SR 4605’ (186.3 mm - 7.3”) and ‘Helios’ (203.7 mm - 8”). As in 2023, the colonial bentgrass cultivar ‘Musket’ delivered the highest quality with less water than all other entries. Other entries with quality averages statistically equal to ‘Musket’ include bentgrasses ‘Piper’ and ‘777’, and ‘Compass II’ chewings fescue. The highest water using entries, and the only statistically inferior entries to ‘Musket’ for water use were ‘MacDonald’ creeping bentgrass and ‘Gladiator’ hard fescue, requiring 317.7 - 330.3 mm (12.5 - 13”) of water to maintain 75% green cover. These results are similar to 2023, with despite the differences in water use in 2024, most entries performed statistically equal.

At St. Paul, MN, the bentgrass entries provided the highest quality under all three irrigation regimes. As in 2023, several entries delivered a mean turfgrass quality rating of 7.0 or higher in 2024, which is the NTEP threshold for higher quality turf. Under both the medium (65% ET_o) and low (50% ET_o) irrigation replacement levels, ‘Kingdom’, finished with the highest turf quality score (7.7 and 7.4 respectively, scale is 1-9; 9=ideal turf) . ‘MacDonald’, ‘777’ and ‘Piper’ creeping bentgrass also performed very well under the low and medium ET_o replacement levels. Entries with the poorest performance under all three replacement levels include ‘Gladiator’ hard fescue, ‘Helios’ and ‘SR 4650’ perennial ryegrasses.

Data from 2024 collected at Ft. Collins, CO, correlated well with 2023 results as several of the fine fescues outperformed many of the bentgrasses. ‘PPG FRC 127’ chewings fescue, ‘Navigator II’ strong creeping red fescue and ‘Penncross’ creeping bentgrass finished in the highest turf quality statistical group under 50% ET_o irrigation replacement, with ‘Gladiator’ hard fescue, and ‘Compass II’ chewings fescue not far below. In turf quality ratings collected under 65% ET_o irrigation replacement, ‘PPG FRC 127’, ‘Compass II’, ‘Navigator II’ fine fescues, and ‘Penncross’ and ‘Oakley’ creeping bentgrass were the top performing entries. In all irrigation replacement regimes, turf quality data was well short of the minimum ratings (7.0+) preferred for high quality turf.

Our first data from the Logan, UT site was collected in 2024 with some interesting results. The top statistical entries for turf quality under the 50% ET_o irrigation replacement level were only the two perennial ryegrasses, ‘SR 4650’ and ‘Helios’ (turf quality = 6.9 and 6.2 respectively). In addition to the perennial ryegrasses, ‘Musket’ colonial bentgrass, ‘Compass II’ and ‘PPG FRC 127’ chewings fescues, ‘DLF-AP-3084’ creeping bentgrass and ‘Gladiator’ hard fescue finished in the 65% ET_o replacement top turf quality group.

The three years of results from this trial will document not only the amount of water needed to maintain a consistent green surface under a seasonal ‘acute’ drought period, but also cultivar performance under ‘chronic’ restricted irrigation replacement based on ET_o. This information is essential as golf course water use is being restricted, due to droughts and increased competition for limited water supplies due to development. Therefore, grasses that maintain high quality fairways with less water are needed for golf course superintendents, golf course owners, designers, architects, golfers and others that depend on the golf course industry for their livelihood, enjoyment and environmental protection.

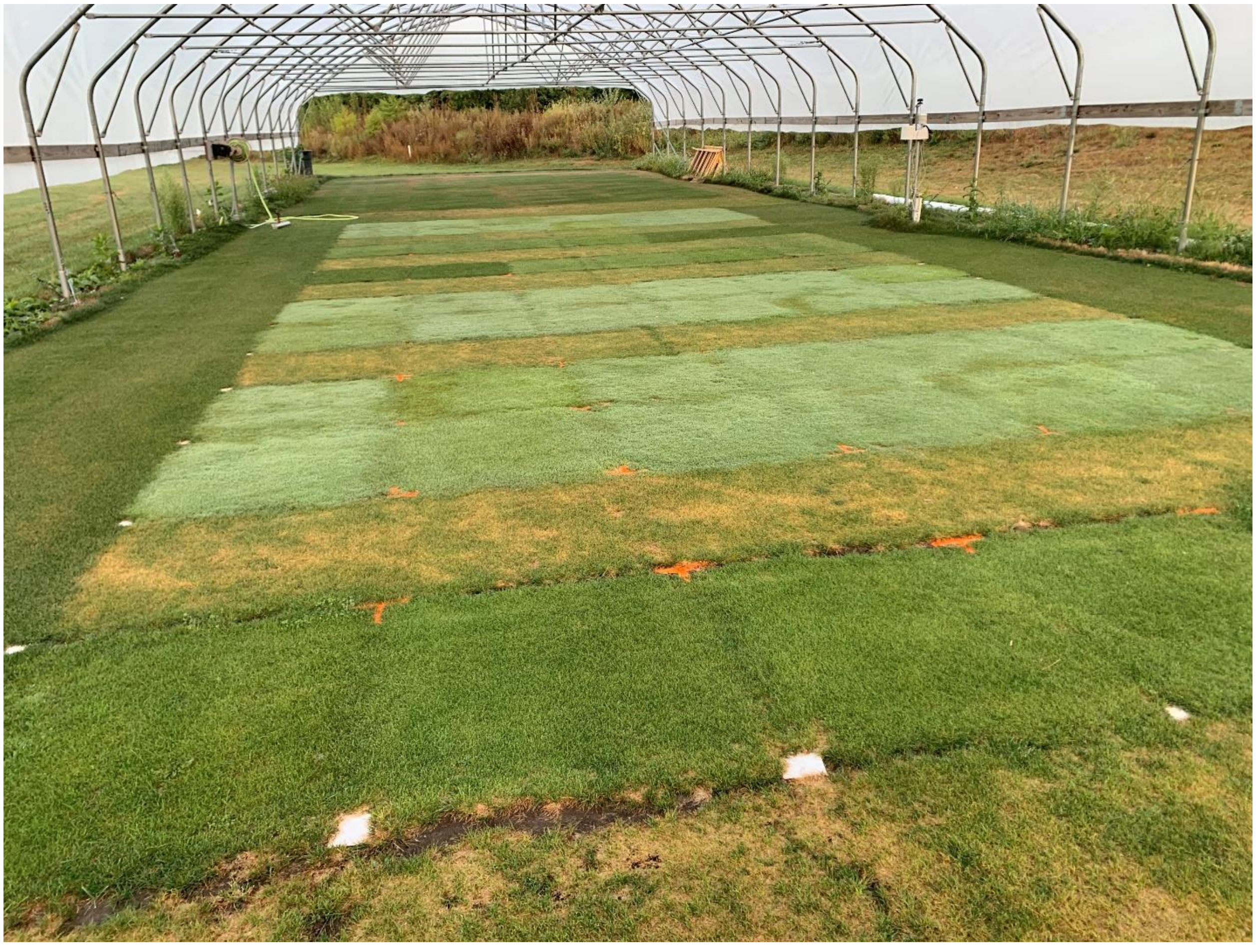


Figure 1. Plots underneath the rainout shelter in West Lafayette, IN on September 13, 2023, during dry-down.

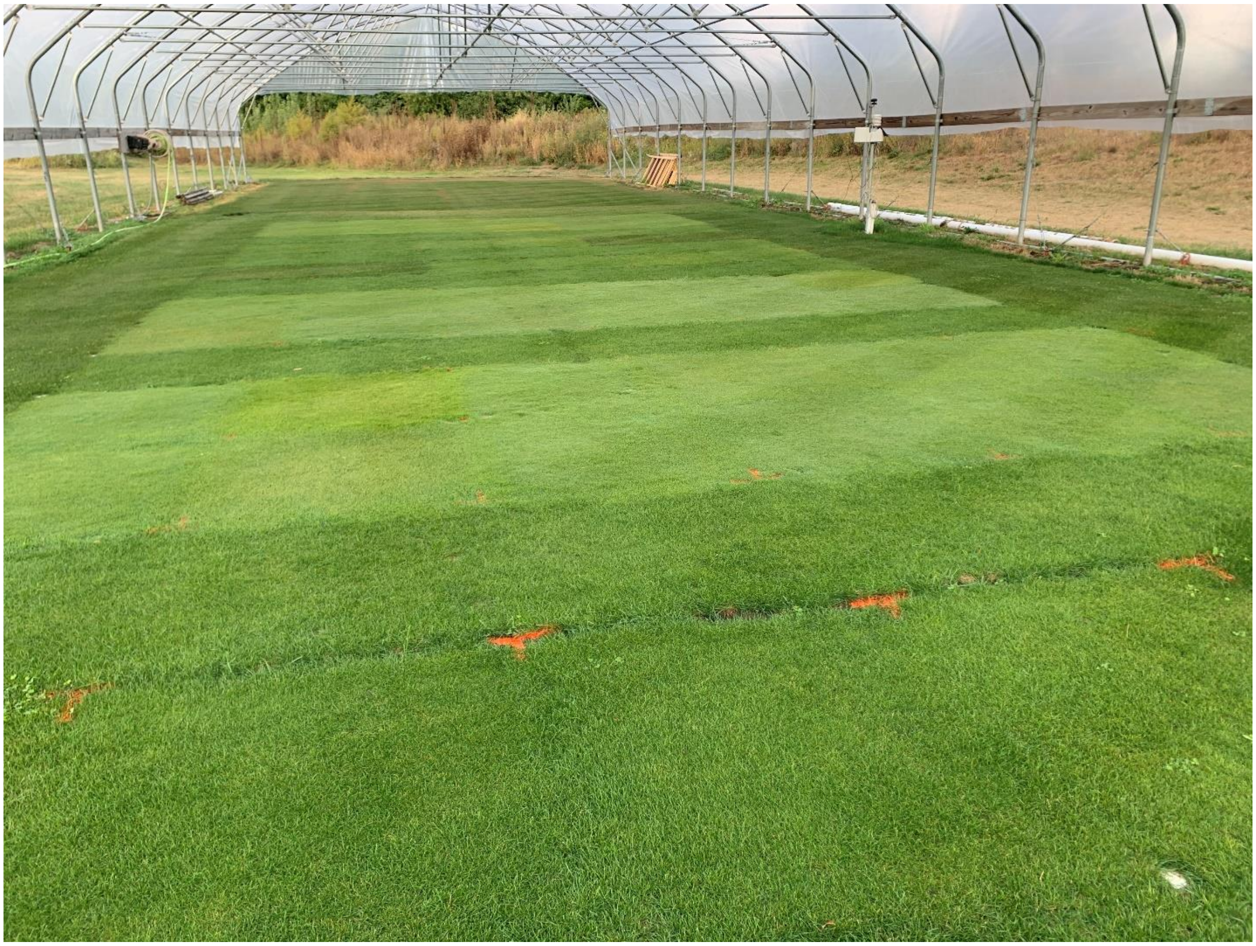


Figure 2. Plots underneath the rainout shelter in West Lafayette, IN on September 16, 2023, during rewatering.

Figure 3. Various species within reduced ET-irrigation blocks in St. Paul, MN.

USGA ID#: 2024-05-815

Title: Evaluation Of Interseeding Methods For Conversion Of Golf Fairways To Bentgrass Cultivars With Enhanced Dollar Spot Resistance

Project Leader: Gerald (Lee) Miller[1]; Paul Koch[2]; Scott Warnke[3]
Graduate Research Assistant: Justice Ruwona[1]
Affiliations: [1]Purdue University; [2]University of Wisconsin; [3]USDA REE-ARS

Objectives:
1. Evaluate the effectiveness of interseeding three dollar spot resistant cultivars into a susceptible background of fairway height bentgrass/*Poa annua*.
2. Compare conversion success among four interseeding programs using herbicide/PGRs to restrict *Poa annua* invasion, direct interseeding with no inputs, and a complete conversion.
3. Determine the return on investment for a complete renovation and interseeding programs for bentgrass fairways focused on the conversion to a dollar spot resistant phenotype and associated fungicide reduction.

Start Date: 2024
Project Duration: 3
Total Funding: $172,646

Summary Points:
- The reduction in dollar spot severity led to decreased fungicide use, though herbicide/PGR effectiveness and cultivar performance vary by region.
- Disease phenotype suggests that resistant cultivars established better in interseeding plots treated with herbicide compared to direct interseeding (without herbicide treatment)
- Combining interseeding with a selective herbicide (methiozolin, bispyribac-sodium) or PGR (paclobutrazol) may effectively reduce *Poa* invasion.

Summary Text:

Rationale

Dollar spot is the most fungicide intensive and expensive disease to control on golf courses. While fungicides are applied more frequently to golf greens, fairways account for more acreage per facility (28.1 A vs. 3.2 A). Therefore, eliminating a single application would amount to 8+ times the savings as that on greens. New bentgrass cultivars with enhanced dollar spot resistance are available but adoption has been slow due to the expense of renovation procedures and unknown agronomic attributes of the new varieties. Interseeding these newer cultivars into an existing stand may reduce or eliminate the need for course closure. Demonstration of successful conversion, whether through less disruptive interseeding methods or complete overhaul, will provide superintendents a barometer on their expected return on investment through reduction in fungicide expenditure. This information can form the basis for justification of bentgrass fairway conversion, leading to broader adoption and realization of the considerable efforts by turfgrass breeders to incorporate dollar spot resistance into modern cultivars.

Methodology

Field trials are being synchronized at three sites in Indiana, Wisconsin and Pennsylvania. Plots were established on a background susceptible bentgrass (‘Penneagle’ or ‘Penncross’) at fairway height with 10-30% encroachment of *Poa annua*. Three cultivars (007 XL, Pure Select, Coho) with varying levels of dollar spot resistance were interseeded into existing turfgrass stands at a rate of 2 lb/1000 sq ft using a Vredo Turf-Fix 25” slit seeder (Fig 1A) in two directions. This was done in conjunction with five herbicide/PGR Poa annua control programs. Treatments were arranged in a split block design, with cultivar as the main plot and herbicide/PGR program as subplots (Table 1). In May 2024, plots were divided, with one half left to natural disease development and the other half receiving the curative fungicide, fluazinam (Secure® – 0.5 fl oz/1000 sq ft), when a threshold of five dollar spot infection centers was reached (Fig 1B). Turfgrass quality, dollar spot severity, and percent *Poa annua* encroachment were assessed throughout the season both visually and with digital image analysis. Leaf clippings of each plot were collected thrice (May, July, September) and will be analyzed using molecular markers to determine integration of the new cultivar into the plant population. An economic analysis will be conducted to compare the conversion cost of seed, chemicals and playability against the potential reduction of fungicide expenditure over the trial period.

Results

Cultivar and herbicide/PGR program impact varied by location (Table 2). Wisconsin plots that did not receive herbicide had a 52% higher disease severity than plots treated with glyphosate, indicating poor establishment of resistant cultivars compared to plots receiving herbicide (Fig 2A). The reduction in dollar spot severity led to decreased fungicide use (Fig 2B). In contrast, Indiana plots saw only a 9% disease difference between glyphosate treated plots and no herbicide plots, with no difference in required fungicide applications. Plots treated with glyphosate had over three times more *Poa annua* compared to plots treated with methiozolin, paclobutrazol and bispyribac-sodium (Fig 2C). In Wisconsin, ‘Pure Select’ plots had higher dollar spot severity, requiring nearly one additional fungicide application compared to ‘007XL’ (Fig 3 A,B). No dollar spot was observed at the Pennsylvania location in 2024.

Future expectations

Disease phenotype, *Poa* counts, and fungicide use data collection will be repeated in the 2025 growing season. We anticipate that the trends in herbicide/PGR effectiveness and cultivar performance based on dollar spot-resistant phenotypes, along with the associated reduction in fungicide use, will converge across the three sites. This convergence will help us determine the return on investment for a complete renovation versus minimally disruptive interseeding programs. Future work will also involve genetic analysis of leaf clippings to track changes in the composition of the grass stand over time.

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Table 1. Herbicide/PGR program

Herbicide/PGR	Abbrev	Timing*	Rate
Amicarbazone	AMI	21 & 7 DBS	3 fl oz/A
Bispyribac sodium	BIS	14 DBS & 30 DAS	1.5 fl oz/A 0.75 fl oz/A
Methiozolin	MET	45 DBS & 84 DAS	1.2 fl oz/1000 sq
Paclobutrazol	PAC	14 DBS & 42 DAS	16 oz/A
Glyphosate	GLY	14 & 7 DBS	48 oz/A
Untreated	UT		

*DAS – Days After Seeding; DBS – Days Before Seeding

Table 2 Analysis of variance indicating significant sources of variation

		West Lafayette, IN[3]			***Madison, WI***	
Factor[1]	df	AUDPC[2]	Fung	Poa	AUDPC	Fung
Cultivar	2	*	NS	NS	NS	*
Herbicide/PGR	5	NS	NS	**	*	***
Cult x Herb/PGR	10	NS	NS	NS	NS	NS

[1]Location significantly influenced AUDPC ($p < 0.001$), necessitating separate analyses for each location

[2]AUDPC (Area Under Disease progress Curve), Fung (Fungicide), Poa (Annual Bluegrass Flower Count)

[3]Significant main effects or interactions ($p < 0.05$*, 0.001** and 0.0001***)

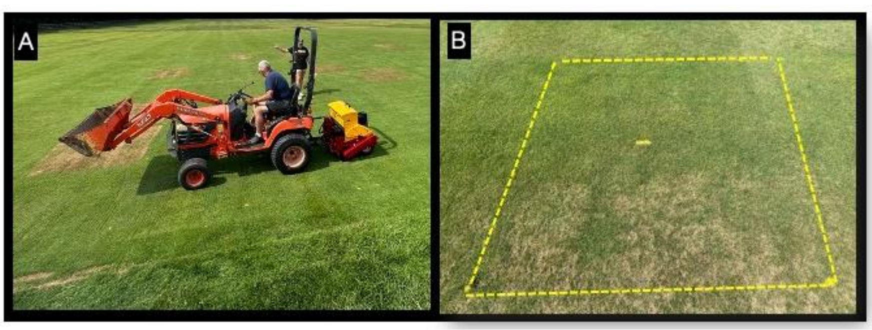

Fig 1. (A) Vredo Turf-Fix 25" interseeding study plots at W.H. Daniel Turfgrass Research & Diagnostic Center, Purdue University. (B) Example plot showing upper: Fungicide threshold;lLower: Natural dollar spot epidemic. Photo taken August 6th, 2024

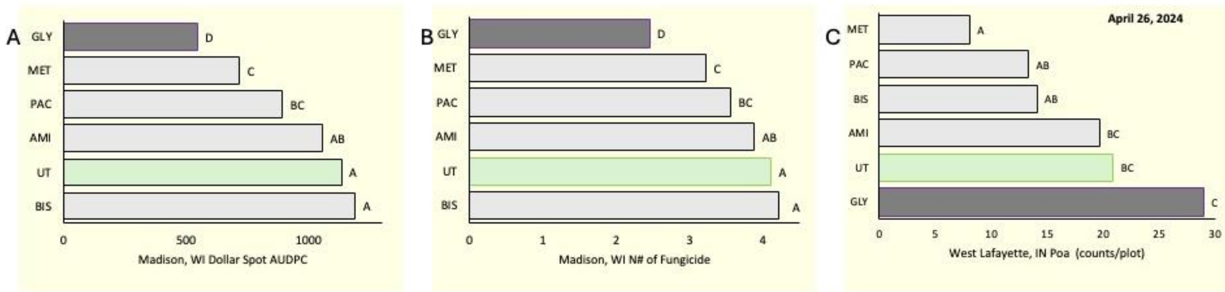

Fig 2. Herbicide/PGR effectiveness based on (A) the area under disease curve progress curve (AUDPC), (B) number of fungicide applications during the 2024 season in Wisconsin and (C) *Poa* counts conducted during *Poa* seedhead flush (GDD22) on April 26th, 2024. Columns with the same letter are not significantly different according to Fisher's Protected LSD (P = 0.05).

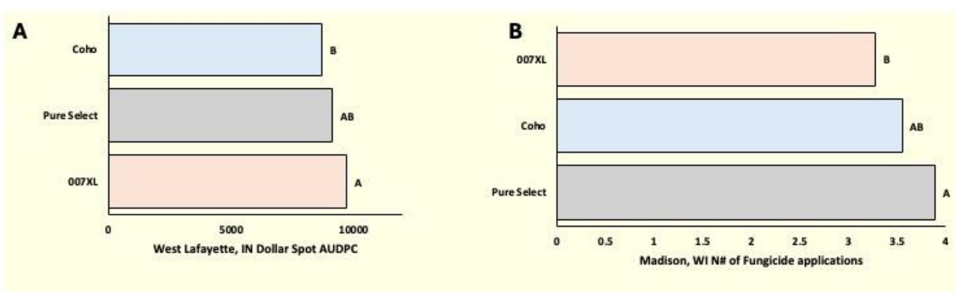

Fig 3. Cultivar performance based on (A) the area under disease curve progress curve (AUDPC), (B) number of fungicide applications during the 2024 season at Wisconsin. Columns with the same letter are not significantly different according to Fisher's Protected LSD (P = 0.05).

USGA ID#: 2023-06-773

Title: Environmental and Economic Comparison of Zoysiagrass, Bermudagrass, and Creeping Bentgrass Fairways in the Northern Transition Zone

Project leaders: Stacy Bonos and Mark LaBarge

Affiliation: Rutgers University

Objectives:
- Evaluate improved cold-hardy bermudagrass and zoysiagrass germplasm for use on fairways in the northern transition zone
- Conduct an environmental assessment comparing bermudagrass, zoysiagrass and creeping bentgrass
- Conduct an economic analysis including a return on investment calculator for fairway conversion projects
- Design, conduct, and statistically analyze a survey of golfers to determine if there is a preference on fairway turfgrass species
- Develop a decision-making framework to aid turf managers in determining if bermudagrass or zoysiagrass is a viable option for their course environment

Start Date: 2023
Project Duration: Three years
Total Funding: $90,000

Summary Points:
- Improved bermudagrass and zoysiagrass showed increased fall color retention with limited winter kill over two growing seasons
- Eight bermudagrass and five zoysiagrass entries exhibited an average of approximately 30% or less winterkill over a two-year study period
- Spring green-up was variable among entries but almost all entries showed improved spring green-up during their second green-up period
- The highest turf quality during three years of observations in New Jersey was exhibited by Tiftuf bermudagrass and DALZ 1808 zoysiagrass
- Promising bermudagrass and zoysiagrass entries were selected for further evaluation in the region

Rationale:
Plant hardiness zones provided by the USDA have undergone shifts due to climate change with increasing temperatures impacting turfgrass grown in the northern transition zone. Cold-hardy zoysiagrass and bermudagrass may provide a useful option for the region. The scope of this study aims to determine and quantify the agronomic performance, economic benefits, environmental impact, golfer perceptions, and potential shortcomings of bermudagrass and zoysiagrass. The top performing selections will be tested and maintained under fairway conditions alongside creeping bentgrass cultivars for a field-based economic and environmental comparison.

Study 1 Methodology

Improved cold-hardy zoysiagrass and bermudagrass were established via sprigs (at a 500 US bushels/acre rate) on June 30, 2022 in a randomized complete block design with three replications. Experimental plots measured approximately 100 ft^2. The trial included seven zoysiagrass cultivars, twelve bermudagrass cultivars, six zoysiagrass experimental selections, and four bermudagrass experimental selections. The trial concluded on July 1, 2024. Maintenance inputs including irrigation, fertilizer, pesticides, and labor were recorded during the trial period. Visual establishment (percent green cover), turfgrass quality (1-9 scale), fall color retention (percent green cover), spring green-up (percent green cover), and winter kill (percent damaged cover) ratings were taken throughout the trial. Digital image data was collected using a Canon PowerShot G15 with a 20 x 24-inch lightbox with four florescent bulbs. Visual ratings and image data were collected on a biweekly basis. Establishment data was statistically evaluated using non-linear regression with a sigmoid variable slope model in GraphPad Prism Version 10.1 (GraphPad Software Inc., La Jolla, CA) to model time required to reach 90% turfgrass coverage after sprigging. All other visual ratings were statistically analyzed with an ANOVA test using SAS 9.4 software (SAS Institute Inc., Cary, NC). Digital image data was evaluated using TurfAnalyzer software (Green Research Services, LLC) and the resulting quantitative outputs were statistically analyzed in SAS 9.4 software with an ANOVA test. Lastly, all visual ratings were combined for a Principal Component Analysis using GraphPad Prism Version 10.1. The results of this trial were utilized to determine promising entries for further evaluation.

Study 1 Results and Discussion

It is feasible to establish bermudagrass and zoysiagrass from sprigs in New Jersey. All bermudagrasses established within 100 days after planting and six zoysiagrasses established within 125 days after planting (Empire, DALZ 1701, FZ 1732, DALZ 1808, FZ 1727, and Lobo). Some entries did not establish during the trial period and were negated from all analyses (Emerald, Zeon, Gateway, and KSUZ 1201). Plots started to green-up in mid-April and most were fully green or exhibited winter kill by mid-May. Spring green-up was greatly improved in almost all accessions during the trials second green-up period (Figure 1). Plots began to enter dormancy in November of 2022 and 2023. Plots entered dormancy slightly earlier in 2023. Figure 2 shows how eight bermudagrass and five zoysiagrass entries exhibited an average of approximately 30% or less winterkill over a two-year study period. All established selections did grow back to full coverage in both years after the green-up period despite winter kill. The most desirable characteristic for the region is improved fall color retention, quicker spring green-up, and limited winter kill which was exhibited by several entries. Figure 3 provides an example of DALZ 1701 zoysiagrass and Tiftuf bermudagrass exhibiting these characteristics when grown in Freehold, New Jersey. DALZ 1701 and DALZ 1808 had the highest turf quality among zoysiagrass and Tiftuf and MSB-1042 had the highest turf quality among bermudagrass (Figure 4). The evaluated characteristics are useful in selecting promising zoysiagrass and bermudagrass for the region. A Principal Component Analysis of the ANOVA results for all visual ratings was conducted for dimensionality reduction. This approach helped to simplify and combine ratings to provide additional information for selecting entries for further evaluation. The Biplot of principal components 1 and 2 with the loadings of each visual rating can be seen in Figure 5.

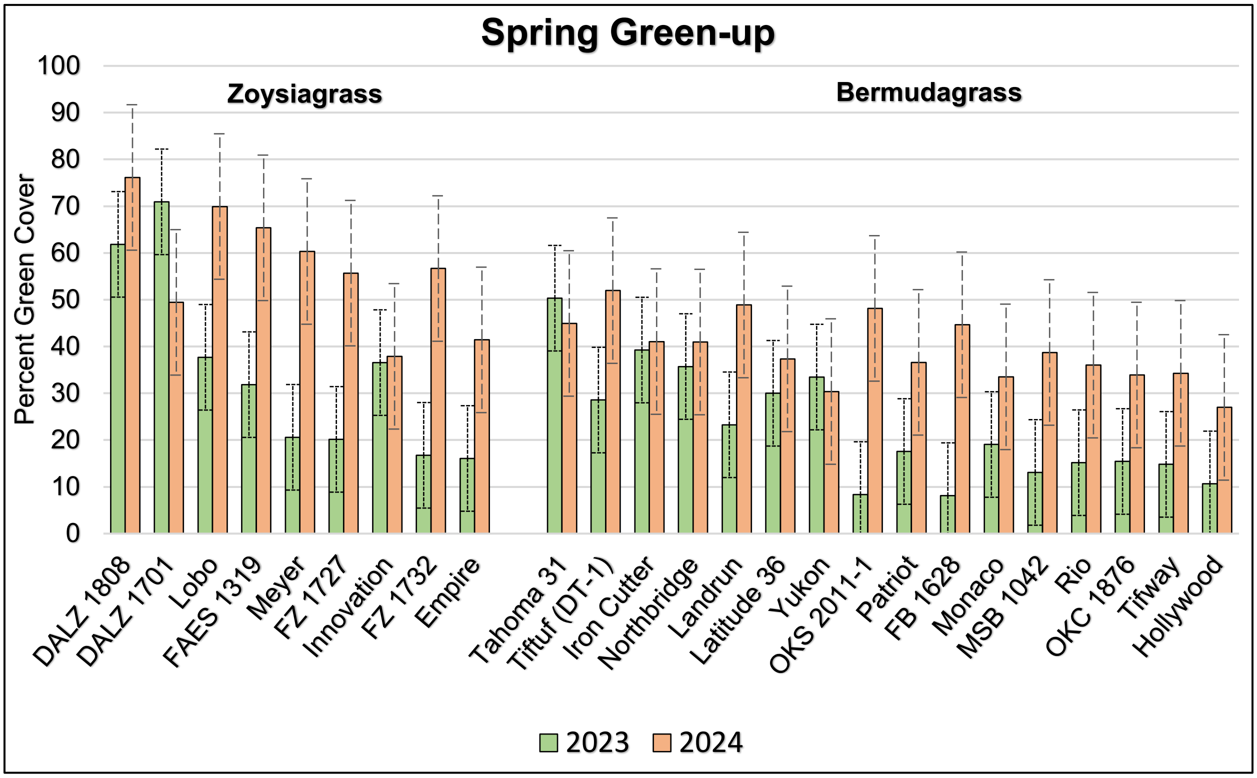

Figure 1. Digital image data evaluated with TurfAnalzyer and SAS 9.4 showing means from two years of spring green-up data with improved green-up seen in 2024. Error bars represent the LSD (0.05).

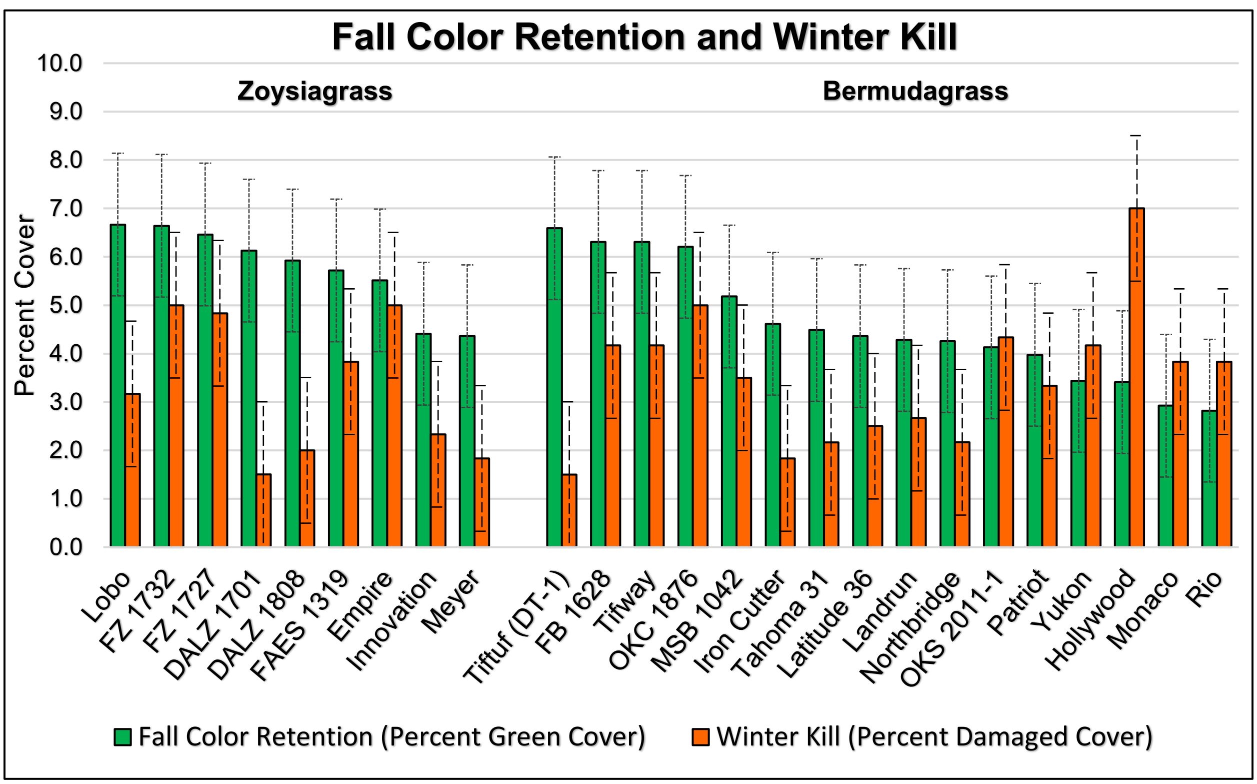

Figure 2. Means of visual ratings for fall color retention and winter kill from 2022-2024. Fall color retention is rated as percent green cover and winter kill as percent damaged cover. Error bars represent the LSD (0.05).

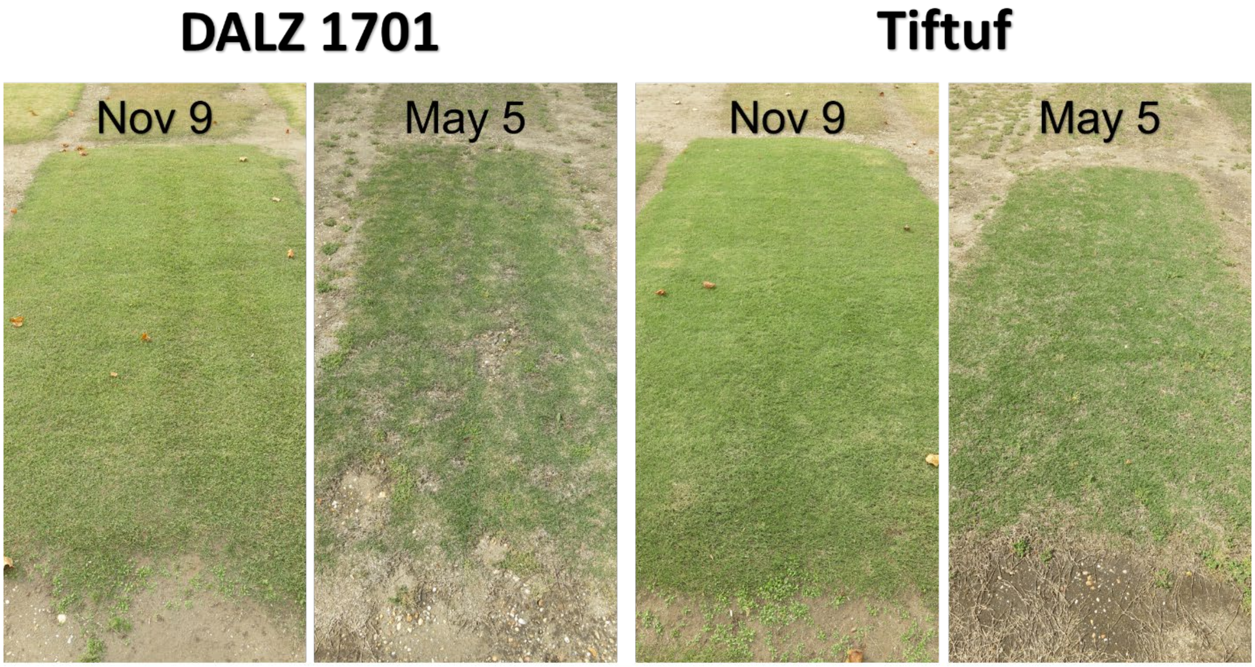

Figure 3. DALZ 1701 zoysiagrass and Tiftuf bermudagrass with the respective date of image collection exemplifying improvement in desirable traits for the region.

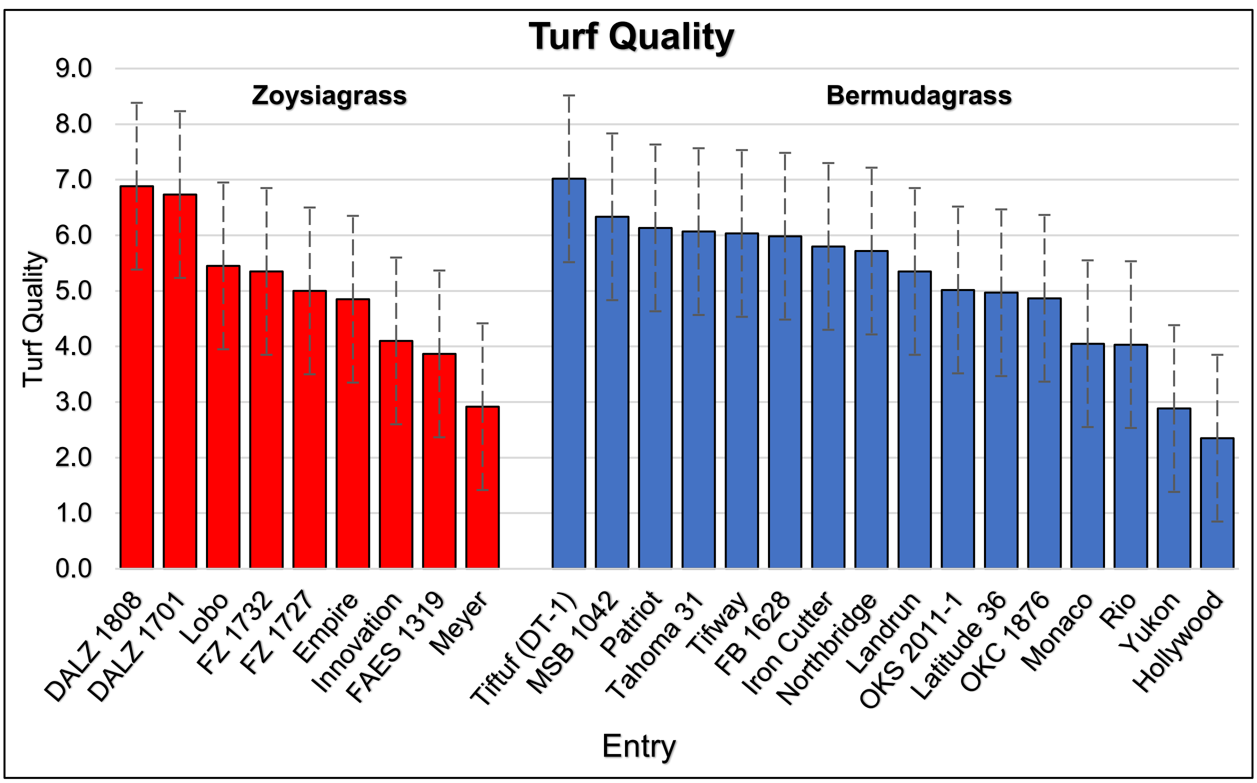

Figure 4. ANOVA means for visual ratings of turf quality from 2022-2024. Error bars represent the LSD (0.05).

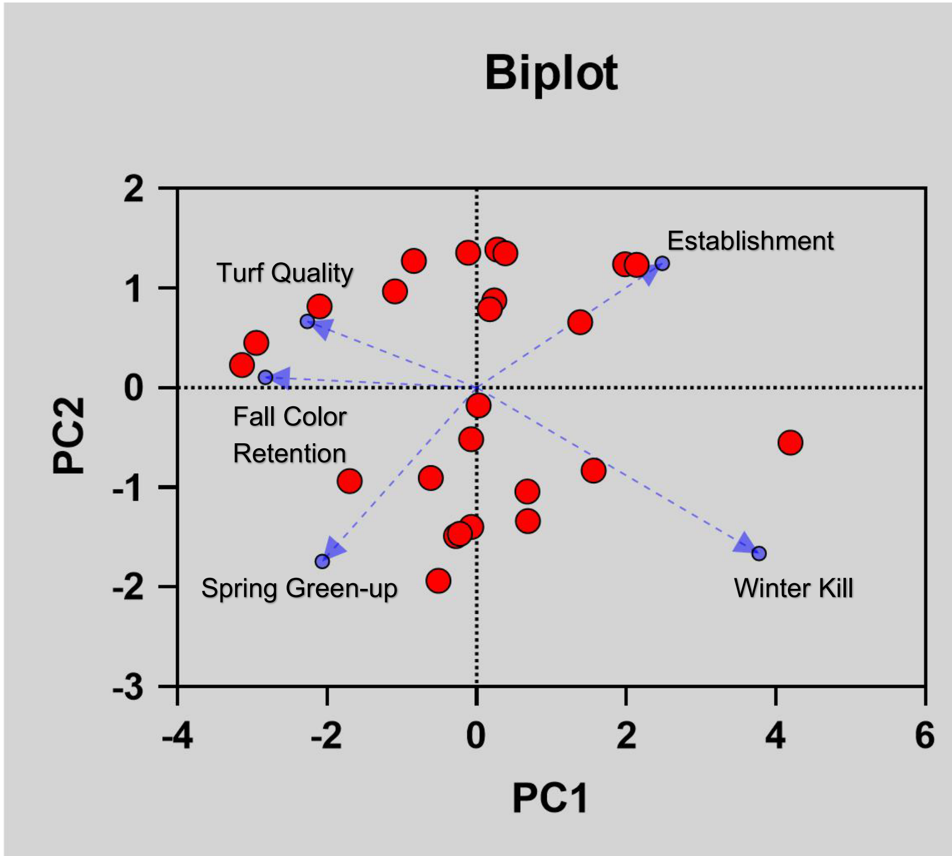

Figure 5. Principal Component Analysis of visual ratings from 2022-2024. Red dots represent each entry, and each blue arrow represents the contribution of different visual ratings to a principal component.

Future Expectations (Studies 2-4)

Two fairway trials (low and high maintenance) were established on July 1, 2024 to evaluate the top two entries and a standard from each species. Entries were selected based on study 1 results, principal component analysis, and collaboration with plant breeders. The top 2 creeping bentgrass selections were chosen from previous trials conducted in NJ. All species and plots were established as sod. Table 1 shows all entries and where sod was obtained for each. For both trials, plots are 4x6 ft and arranged in a strip plot design (by species) and include three replications of each entry. Management programs for each species and maintenance level were developed through literature reviews, interviews with turf managers, and collaboration with experts in turfgrass maintenance. Management programs will be implemented in the fall of 2024 and continue through 2026. In the low maintenance trial, the best plot from each species will be maintained at a turf quality threshold of 6. In the high maintenance trial, the best plot is each species will be maintained at a turf quality threshold of 9. All inputs will be recorded and utilized for comparisons within and between species. The Field Use Environmental Impact Quotient (EIQ) will be calculated for all pesticide applications. Pesticides will be chosen based on expert recommendations, availability, and Field Use EIQ ratings to prevent bias. All nutrient applications will also be documented.

The economic component will determine the costs associated with managing each species to demonstrate cost effectiveness of using warm-season grasses on golf courses, and to identify where savings can be made. An economic cost model will be constructed in MS Excel under conventional management systems for the three species. Cost models will be based on the following: experiment records including frequency and amount of irrigation, fertilizer, chemicals, mowing, and labor hours; interviews with golf course superintendents (approximately 3-5 with varying course budgets and management levels); and current costs for pesticides, equipment, and labor. The economic model will help determine an estimate of the cost per acre for golf course fairway renovation with each species. It will also provide estimates of how management costs differ over time between the three species of interest.

Table 1. List of selected entries for each species used in studies 2 and 3 including the sod provider for each entry.

Species	Cultivar/Experimental Selection	Sod Provider
Zoysia spp.	DALZ 1701	Study 1 (Texas A&M University)
	Lobo	Meadowspring Turf Farm
	Meyer	Meadowspring Turf Farm
Cynodon spp.	Ironcutter	Study 1 (Johnston Seed)
	Tiftuf	Study 1 (University of Georgia)
	Tahoma 31	Study 1 (Oklahoma State University)
Agrostis Stolonifera L.	007	East Coast Sod and Seed
	Coho	Rutgers Horticultural Farm No. 2
	Spectrum	Coombs Sod Farm

The same entries from Study 2 are also being utilized in Study 3 and can be found in Table 1. The trial was established from sod in a rainout shelter at the Adelphia Plant Science Research Station on July 2, 2024. Plots measure 5x5 ft and are arranged in a Randomized Complete Block Design with three replications. After the plots are fully established, each plot will be irrigated individually based on a predetermined threshold. Image data using a lightbox will be obtained weekly and analyzed using TurfAnalyzer software. When plots fall below a threshold of 60% green (according to TurfAnalyzer), irrigation will be uniformly applied on the plot area using above ground irrigation squares. Irrigation squares are constructed with 0.5 inch PVC pipe, measure 5 ft x 5 ft, and consist of 4 pressure-regulated rainbird irrigation heads in each corner. A catch can test kit will be used for calibration and to confirm uniform distribution of the irrigation squares. Each irrigation application will be recorded to help determine how much water each entry requires to maintain acceptable turf quality.

Golfer perceptions are an important consideration for golf course superintendents. We will design, conduct, and statistically analyze a survey to determine the community's opinion on fairway turf species, specifically golfer preference between warm-season and cool-season turfgrasses. The survey will consist of several short questions to assess whether golfers prefer a certain species of turfgrass. This survey will be conducted online through Google Surveys and made available to private and public courses in NJ with the target population being golfers.

USGA ID#: 2023-10-777a, 2023-10-777b, 2023-10-777c

Title: Developing management tools for new greens-type zoysiagrasses

Project Leaders: Michael Richardson, Ambika Chandra, and Jim Brosnan,
Affiliation: University of Arkansas, Texas A&M AgriLife Research, University of Tennessee-Knoxville
Key Project Personnel: John McCalla, Chase Martin, and Greg Breeden,
Affiliation: University of Arkansas, Texas A&M AgriLife Research, University of Tennessee-Knoxville

Objectives:

1. Determine the tolerance of Lazer and Prizm zoysiagrass to various chemicals commonly used for managing putting greens, including plant growth regulators, herbicides, and fungicides.
2. Determine the effects of herbicides and plant growth regulators on seedhead suppression on Lazer and Prizm zoysiagrass

Start Date: Summer 2023
Project Duration: Data collection will be completed in Spring 2025
Total Funding: $37,586

Summary Points:

<u>Pesticide / plant growth regulator (PGR) tolerance trials</u>

- Pesticide/PGR tolerance trials were repeated in 2024 at Fayetteville ('Lazer') and Knoxville ('Prizm'). Trends in injury were similar on Lazer zoysiagrass between 2023 and 2024, but no injury was observed from any treatment on Prizm in 2024
- Treatments that caused the most injury to Lazer included Fusilade II (fluazifop)+Turflon Ester (triclopyr) and a combination broadleaf herbicide, Speedzone EW (2,4-D, mecoprop, dicamba, and carfentrazone).
- For treatments where injury was observed, higher rates (2x label) caused significantly greater injury than recommended label rates, so overlaps with the sprayer could lead to unacceptable injury on zoysiagrass greens with those specific treatments

<u>Seedhead suppression on zoysiagrass putting greens</u>

- Seedhead suppression trials were conducted at Fayetteville ('Lazer') and Knoxville ('Prizm'), with treatments applied in Fall 2023 and data collection commenced in spring 2024.
- Better seedhead suppression was observed at the TN site, suggesting possible cultivar differences in sensitivity or the timing of applications were better than the AR site.
- Proxy (ethephon) and Aneuw (prohexadione-calcium) provided modest suppression at AR, while Princep (simazine) provided suppression at TN only
- None of the treatments provided complete seedhead control, so this will continue to be a challenge when managing zoysiagrass greens in the transition zone

Background: Zoysiagrass (*Zoysia* spp. Willd.) is a perennial, warm-season grass that is adapted for use in the transitional and warm climatic zones of the United States. Although its use on golf greens is limited, there is interest to golf courses in the region. Historically, 'Diamond' [*Z. matrella* (L) Merr] was the only viable zoysiagrass cultivar for golf course putting green surfaces but research from Clemson University determined ball roll speeds were generally unacceptable for tournament use (Stiglbauer et al., 2009). More recently, three *Z. matrella* cultivars ['Prizm', 'M85', and 'Trinity'] (Douget et al., 2017) and 'Lazer', the first interspecific hybrid between *Z. matrella* and *Z. minima* (ecoptype TAES 5194-5) (Chandra et al., 2020) have been released for use on golf greens. For this project, we have focused on Lazer and Prizm zoysiagrass, as these two cultivars are now commercially available and are being tested and utilized on several golf courses in the United States.

Compared to other warm-season grasses, zoysiagrass has many positive traits such as reduced fertilizer needs, enhanced cold tolerance, excellent salinity tolerance, and good shade tolerance); however, high seedhead production (McCullough et al., 2017) and lack of herbicide options for greens are a concern for superintendents and could deter early adoption. Diamond has been documented to be a prolific seedhead producer in the fall and spring seasons (McCullough et al., 2017) and early observations indicate that seedhead production can also be significant on Lazer in the spring season (Figure 1, Richardson, unpublished). Seedhead suppression research using plant growth regulators (PGRs) has recently been investigated in *Z. japonica* (Brosnan et al., 2012; McNally et al., 2024; Patton et al., 2018), but the efficacy and timing of application should be further investigated in these new hybrid cultivvars.

Figure 1. Left - seedhead production on a Lazer zoysiagrass green in early May in Fayetteville AR. Right – Lazer seedheads being produced in greenhouse in comparison to Tifeagle bermudagrass.

Currently, there are no herbicides that are labeled for zoysiagrass golf green use and most herbicides that are labeled for zoysiagrass do not even differentiate between *Z. japonica* and *Z. matrella* species. Golf course superintendents planting zoysiagrass on golf greens can only rely on information regarding fairway tolerance to herbicide applications, which may not be appropriate. Preliminary work conducted at the University of Tennessee and University of Arkansas highlighted that both Prizm and Lazer were sensitive to applications of some herbicides that are commonly used on zoysiagrass fairways, including fluazifop + triclopyr, sulfentrazone, foramsulfuron, trinexapac-ethyl and prohexadione calcium (Walton, Richardson, Carr, and Brosnan, unpublished; McElroy and Breeden, 2006). As such, a thorough investigation of pesticide tolerance was warranted.

Objectives:

This project is a multi-site effort among three universities with the following objectives:

- Determine the tolerance of Lazer and Prizm zoysiagrass to various chemicals commonly used for managing putting greens, including plant growth regulators, herbicides, and fungicides.
- Determine the effects of herbicides and plant growth regulators on seedhead suppression on Lazer and Prizm zoysiagrass

Research Methods

Pesticide tolerance studies

Pesticide tolerance work was repeated in 2024 on Lazer zoysiagrass at the Milo Shult Agricultural Research and Extension Center in Fayetteville AR (36.100674, -94.173790). Tolerance was also evaluated on Prizm zoysiagrass at the East Tennessee AgResearch and Education Center in Knoxville TN (35.902185, -83.957604). Trials at both locations were established as a randomized complete block with four replications with individual plots sizes ranging from 8-9 ft^2 at each location. Trial areas were maintained under typical putting green management practices, with a 0.125 inch height of cut, fertilization at 0.25 lb. $N/1000ft^2$/growing month, and irrigated applied as needed.

Chemical applications were made on 30 July 2024 in Knoxville and on 10 June 2024 in Fayetteville. Applications were made at a 1x and 2x labeled rate (Table 1) to take into account overlaps and/or application errors that might occur in the field. Products were applied according to label instructions, with adjuvants included if specified on the label. Nonionic surfactant (NIS) was mixed at 0.25% v/v and methylated seed oil (MOS) mixed at 0.5% v/v. All applications were made in a spray volume of 40 gallon / acre. Data collected include visual turfgrass quality and phytotoxicity (% injury) at approximately 3, 7, 14, 21, and 28 days after treatment or until injury has recovered to the acceptable threshold of <10%. For brevity, only the phytoxocity data are reported here.

Seedhead suppression studies

Seedhead suppression trials were conducted in Fayetteville, AR (cultivar – Lazer) and Knoxville, TN (cultivar – Prizm) in 2024. Trials at both locations were established as a randomized complete block with four replications with individual plots sizes of 3x3 ft in AR and 5x6 ft in TN. Trial areas were maintained under typical putting green management practices, with a 0.125 inch height of cut, fertilization at 0.25 lb. $N/1000ft^2$/growing month, and irrigated applied as needed.

Chemical applications were made near the Autumn equinox (9/25/23 in AR and TN) and / or ~28 days after the first application (10/24/23 in AR and 10/23/23 in TN). Products included Proxy (ethephon), Princep (simazine), Aneuw (prohexadione-calcium), and Klean Pik (thidiazuron) and all treatments were applied according to label rate instructions (Table 1). All applications were made using a spray volume of 40 gallon / acre and phytotoxicity (% injury) was assessed at approximately 7 and 14 days after treatment. Seedhead suppression was assessed in the spring as a visual rating of seedhead abundance and an objective seedhead count collected using a grid sampling technique.

Results and discussion

Pesticide tolerance studies

Visual phytotoxicity, including chlorosis and other discoloration of the plots, was observed with some treatments at the Fayetteville location in 2024 (Table 1). Treatments that produced unacceptable phytotoxicity included Fusilade II + Turflon Ester and Speedzone EW. With both treatment combinations, the 2X rate caused significantly more injury than the 1X rate (Table 1). These results are similar to what was observed in 2023 (presented in 2023 report to USGA) on Lazer in both Dallas TX and Fayetteville AR, although the extent of injury varied between the two years

None of the other treatments caused injury that was considered unacceptable (Table 1). It was surprising that none of the treatments caused injury to Prizm zoysiagrass in TN, but less injury was also observed on Prizm than Lazer in 2023. It is speculated that differences in weather conditions between 2023 and 2024 may have caused the lack of response, but those comparisons have not been fully investigated yet. There is also recent evidence that Prizm is more tolerant of various herbicides than Lazer (Pritchard et al., 2024).

Seedhead suppression studies

At the Arkansas site, significant differences were observed between treatments using visual assessment of seedhead reduction compared to untreated controls (Table 2). Proxy and Aneuw reduced seedheads 50-80%, while Princep only reduced seedheads when applied 2 times 28 days apart. Unfortunately, those differences were not significant when rating for seedhead counts (No. / ft^2). At the Tennsessee site, significant differences were observed for both visual assessment of seedhead production and seedhead counts (Table 2). The best treatments for both metrics were the early Princep application and the Princep application applied 2 times at a 28-day interval. Proxy applied two times also provide good seedhead suppression at this site.

The data on seedhead suppression was very inconsistent, with products and timing of application influencing the results at both sites. A second year of this trial was established in the fall of 2024 at AR, TN, and Dallas TX, so we will hopefully have a clearer picture of how these treatments influence seedhead suppression after data collection in Spring 2025. One observation that was consistent is that none of the treatments provided complete suppression of seedheads. As such, a question worth asking is how seedheads are affecting playability and how long that playability is being influenced? Similar to cultivation practices, does 1 hole / 20 in^2 have any bearing on golfer perceptions of surface conditions compared to 1 hole / 2 in^2? In most cases, the golfer would view both scenarios as having "poor quality". In relation to the current study, would a 50% or even 80% reduction in seedheads change a golfer's view of surface quality? One possible approach would be to design future studies to use the GS3 to assess how surface quality of zoysiagrasses and other putting green surfaces is disrupted by seedheads.

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Table 1. Phytotoxicity of herbicide, plant growth regulators, and fungicides applied to zoysiagrass putting greens at two locations in 2024.

				University of Arkansas - cultivar Lazer										University of Tennessee, Knoxville - cultivar Prizm							
				6/14/2024		6/17/2024		6/21/2024		7/1/2024		7/15/2024		8/5/2024		8/12/2024		8/19/2024		8/27/2024	
Trt No.	Treatment name	Rate	Rate Unit	4 DAT†		7 DAT		11 DAT		21 DAT		35 DAT		6 DAT		13 DAT		20 DAT		28 DAT	
				phytotoxicity (%)										phytotoxicity (%)							
1	Revolver	26.2	fl oz/a	0.5	e	2.0	efg	1.5	bcd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
2	Revolver	52.4	fl oz/a	1.0	de	4.0	cd	3.5	bc	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
3	Katana + NIS	3	oz wt/a	0.5	e	0.5	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
4	Katana	6	oz wt/a	2.3	de	0.5	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
5	Speedzone EW	4	pt/a	4.0	cd	2.3	d-g	1.0	cd	1.5	c	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
6	Speedzone EW	8	pt/a	10.0	b	6.8	b	4.3	b	2.8	b	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
7	Kerb	15	fl oz/a	1.0	de	0.0	h	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
8	Kerb	30	fl oz/a	0.0	e	0.0	h	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
9	Poa Cure	0.6	fl oz/1000 ft2	0.5	e	0.5	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
10	Poa Cure	1.2	fl oz/1000 ft2	0.0	e	0.0	h	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
11	Ronstar G	3	lb ai/a	1.0	de	1.0	gh	0.5	cd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
12	Ronstar G	6	lb ai/a	1.0	de	0.5	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
13	Tribute Total + MSO	3.2	oz wt/a	0.0	e	1.5	fgh	1.0	cd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
14	Tribute Total + MSO	6.4	oz wt/a	2.0	de	3.5	de	2.8	bcd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
15	Recognition	1.95	oz wt/a	1.0	de	1.0	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
	Fusilade II + NIS	12	fl oz/a																		
16	Recognition	3.9	oz wt/a	3.0	de	3.0	def	1.0	cd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
	Fusilade II + NIS	24	fl oz/a																		
17	Fusilade II + NIS	4	fl oz/a	6.3	c	5.5	bc	1.8	bcd	1.0	c	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
	Turflon Ester	32	fl oz/a																		
18	Fusilade II + NIS	8	fl oz/a	22.5	a	40.0	a	37.5	a	40.0	a	12.5	a	0.0	na	0.0	na	0.0	na	0.0	na
	Turflon Ester	64	fl oz/a																		
19	Arkon	52.5	g ai/ha	0.5	e	0.5	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
20	Arkon	105	g ai/ha	0.0	e	0.0	h	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
21	Primo Maxx	3	fl oz/a	1.0	de	0.5	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
22	Primo Maxx	6	fl oz/a	0.0	e	0.5	gh	0.5	cd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
23	Densicor	8.5	fl oz/a	0.5	e	1.0	gh	0.5	cd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
24	Densicor	17	fl oz/a	0.0	e	1.0	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
25	Banner Maxx	88	fl oz/a	0.5	e	0.5	gh	0.5	cd	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
26	Banner Maxx	176	fl oz/a	1.0	de	0.5	gh	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
27	Untreated control			1.8	de	0.0	h	0.0	d	0.0	d	0.0	b	0.0	na	0.0	na	0.0	na	0.0	na
LSD P=.05				3.2		1.9		3.0		0.6		1.3		.		.		.		.	
Treatment Prob (F)				0.0001		0.0001		0.0001		0.0001		0.0001		NA‡		NA		NA		NA	

Means followed by same letter or symbol do not significantly differ (P=.05, LSD).

† DAT = Days after treatment; ‡ NA = not applicable

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Table 2. Seedhead reduction and seedhead counts of zoysiagrass putting greens at two locations in 2024, as affected by various herbicide and growth regulator treatments

					Arkansas				Tennessee			
					5/6/2024		5/7/2024		4/15/2024		4/23/2024	
Trt No.	Treatment	Rate	Rate unit	Application Code†	Seedhead reduction		Seedhead count		Seedhead reduction		Seedhead count	
					%		No. / ft²		%		No. / ft²	
1	Untreated Check				0.0	a	239.0	-	0.0	d	199.6	a
2	Proxy	5	fl oz/1000 ft2	A	50.0	bc	215.5	-	0.0	d	200.6	a
3	Proxy	5	fl oz/1000 ft2	B	50.0	bc	235.3	-	52.5	b	115.5	b
4	Proxy	5	fl oz/1000 ft2	AB	84.0	c	166.0	-	83.8	a	38.3	c
5	Princep 4FL	0.8922	lb ai/a	A	0.0	a	190.0	-	91.3	a	115.6	b
6	Princep 4FL	0.8922	lb ai/a	B	0.0	a	218.5	-	31.3	bc	155.4	ab
7	Princep 4FL	0.8922	lb ai/a	AB	45.5	bc	165.3	-	93.8	a	44.0	c
8	Aneuw	16	oz wt/a	A	59.1	bc	193.5	-	0.0	d	199.1	a
9	Aneuw	16	oz wt/a	B	50.0	bc	214.8	-	7.5	cd	198.4	a
10	Aneuw	16	oz wt/a	AB	68.2	c	165.5	-	17.5	cd	174.0	a
11	Klean Pik	56	g ai/a	A	22.7	ab	178.0	-	7.5	cd	197.9	a
12	Klean Pik	56	g ai/a	B	50.0	bc	210.0	-	10.0	cd	194.4	a
13	Klean Pik	56	g ai/a	AB	4.5	a	205.0	-	20.0	cd	198.3	a
LSD P=.05					21.7		88.5		25.2		55.0	
Treatment Prob(F)					0.0001		0.7514		0.0001		0.0001	

Means followed by same letter or symbol do not significantly differ (P=.05, LSD).

† - Application Code A was made near the Autumn equinox (9/25/23 in AR and TN) and Code B was made ~28 days after Code A (10/24/23 in AR and 10/23/23 in TN)

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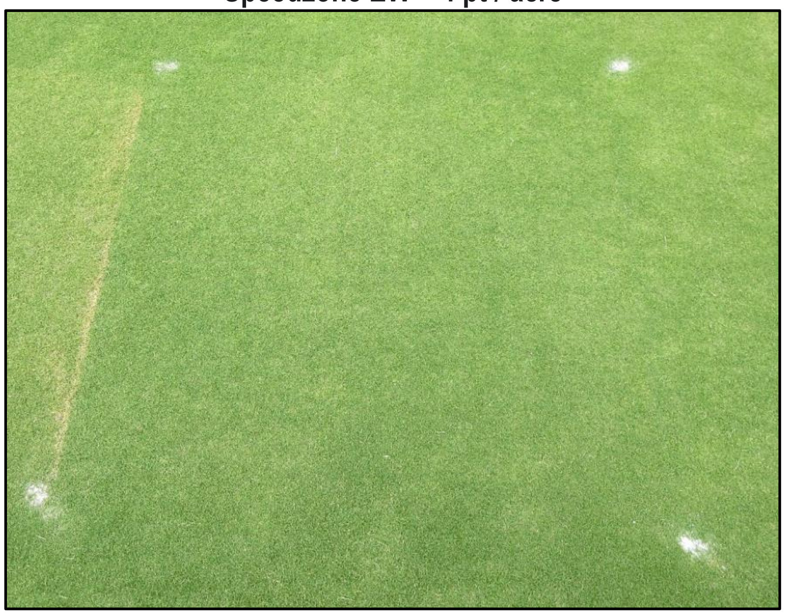
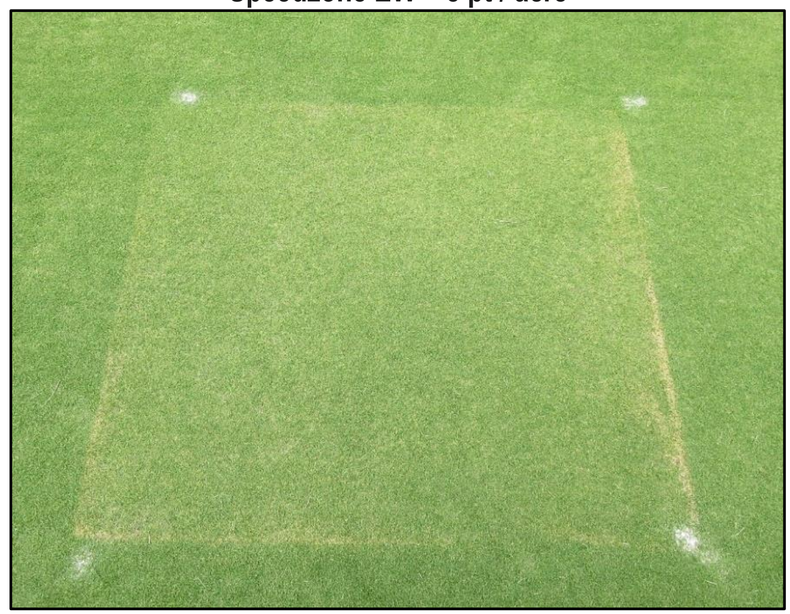
Figure 1. Herbicide injury symptoms on Lazer zoysiagrass (Fayetteville AR) at 7 days after treatment in the 2024 trial.

Speedzone EW – 4 pt / acre

Speedzone EW – 8 pt / acre



Fusilade II (4 fl oz) + Turflon ester (32 fl oz)



Fusilade II (8 fl oz) + Turflon ester (64 fl oz)

USGA ID#: 2023-05-772

Title: Effects of Equipment Traffic on Turfgrass During Frost Conditions

Project Leaders: Alec Kowalewski, Chas Schmid, Robert Starchvick, Zach Hamilton, and Brian McDonald
Affiliation: Oregon State University

Initial Objectives (2023, 2024, and 2025):
- Evaluate the effects of daily winter cart traffic applied to a creeping bentgrass, annual bluegrass, and perennial ryegrass fairway.
- Evaluate the effects of daily winter rolling applied to an annual bluegrass putting green.

Additional Objectives:
- Added in 2024 and 2025: Evaluate the effects of daily foot traffic applied to a creeping bentgrass, and perennial ryegrass fairway.
- Added in 2025: Evaluate the effects of daily winter cart traffic applied to a perennial ryegrass rough.

Start Date: 2023
Project Duration: 3 years (2023, 2024 and 2025)
Total Funding: $30,000 ($10,000 per year)

2023 Summary Points:
- After mornings with freezing soil temperatures, cart traffic and rolling applied in the morning or afternoon resulted in unacceptable turfgrass quality.
- Morning soil temperature was the greatest predictor of traffic injury and suggests that cart traffic and rolling should be avoided on days when morning soil temperatures are below freezing.

2024 Summary Points:
- Cart and rolling treatments were repeated on creeping bentgrass, annual bluegrass and perennial ryegrass.
- Foot traffic treatments were added to creeping bentgrasss and perennial ryegrass.
- Cart traffic, rolling and foot traffic applied during frost and freezing surface temperatures without freezing soil temperatures did not increase turfgrass damage when compared to afternoon treatments applied when surface and soil temperature were above freezing, and frost was not present.
- Findings support 2023 conclusion that freezing soil conditions are the greatest predictor of enhanced winter traffic damage.

2025 Research Plan:
- Repeat daily winter cart traffic applied to a creeping bentgrass, annual bluegrass, and perennial ryegrass fairway.
- Add daily winter cart traffic applied to a perennial ryegrass rough.
- Repeat daily foot traffic applied to a creeping bentgrass, and perennial ryegrass fairway.
- Repeat daily rolling applied to an annual bluegrass putting green.

Background:

Cool-season (C_3 carbon fixation) turfgrass species such as annual bluegrass (Poa annua), creeping bentgrass (Agrostis stolonifera) and perennial ryegrass (Lolium perenne) are prominent on golf courses in northern climates (Bertrand et al., 2013; Tompkins et al., 2000; Tompkins et al., 2004). Classically, winter injury is associated with freezing temperatures and snow cover, or extremely cold and dry conditions with no snow cover. These conditions lead to turfgrass injury in a variety of ways such as direct freeze damage, crown hydration, desiccation, anoxia, and snow mold. In 2022 a USDA-SCRI grant in the amount of $8 million was award to Dr. Eric Watkins at the University of Minnesota and collaborators from 7 other universities in the United States, and Norway, to explore solutions to crown hydration, anoxia, and freezing temperatures (University of Minnesota Department of Horticultural Science, 2022). A cool weather concern not included in this exploration is the effects of traffic during frost conditions.

Frost is a concern on northern and transition zone golf courses in the U.S. during the fall, winter and spring (Ackerson, et al., 2015), as well as places with moderate winter conditions like the coastal Pacific Northwest and southern U.S which allow for continued play year-round. These areas alone account for 10,004 golf courses according to the 2017 Golf Course Environmental Profile (GCSAA, 2017). This concern has become more of an issue recently with the surge in golf since the COVID pandemic, and the high demand for tee times, even during winter months. The United States Golf Association (USGA) currently has conservative recommendations with respect to frost delays, suggesting significant delays on mornings with frost to avoid turfgrass damage; but it is not well understood what causes turfgrass injury, and the environmental conditions necessary for damage (USGA, 2015; USGA 2018; USGA Green Section Record, 2021). Current recommendations are to delay the start of golf until after the frost has melted. However, there has been significant pushback from golfers who are skeptical as to whether these delays are truly necessary. It is also poorly understood how turfgrass species, mowing height, and source of traffic (foot traffic, cart traffic or maintenance equipment) affect turfgrass injury during frost. Frost delays translate to significant reductions in revenue and valuable maintenance time which is often early in the morning prior to golfer arrival.

In response to these questions, a series of preliminary studies were conducted at Oregon State University, Corvallis, OR in February of 2022 at the request of USGA Agronomy and Research staff. Results from these initial explorations determined that foot traffic, equivalent to 16 golfers on a putting green, applied during eight frost events in February did not produce visual annual bluegrass damage, or reductions in normalized difference vegetation index (NDVI) values. Findings from this initial work determined that as little as one pass of cart traffic during a frost event produced noticeable damage on a creeping bentgrass fairway. Considering these initial results, further exploration into the effects of golf cart, and golf maintenance equipment traffic, during frost is warranted. Therefore, the objectives of this project are the following: Evaluate the effects of daily winter cart traffic applied to a creeping bentgrass, annual bluegrass, and perennial ryegrass fairway, and rolling applied to an annual bluegrass putting green. In 2024, an ancillary trial evaluating the effects of foot traffic applied to creeping bentgrass, and perennial ryegrass was added. In 2025, an ancillary trail evaluating the effects of cart traffic applied to a perennial ryegrass rough will also be added.

Year 1 (2023) Results:

Effects of daily winter cart traffic on creeping bentgrass, annual bluegrass and perennial ryegrass

Frost events were followed by reductions in creeping bentgrass (Figure 1), annual bluegrass (data not shown), and perennial ryegrass (data not shown) quality when cart traffic was applied at 8:00 am and 1:00 pm. Correlation analysis between turfgrass quality and environmental factors determined that morning soil temperature was the most effective parameter for predicting cart traffic injury (Figure 2). Specifically, when morning soil temperatures are less than 32°F, traffic applied in the morning or afternoon will result in bentgrass injury at unacceptable levels. The presence or absence of frost, afternoon soil temperature, morning or afternoon surface temperature, and morning or afternoon volumetric water content were poorly correlated with turfgrass quality and thus not good predicters of cart traffic injury.

Effects of daily winter rolling on annual bluegrass

Frost events were followed by reductions in annual bluegrass quality when rolling was applied at 8:00 am and 1:00pm (Figure 3). From January 25 to Feb 17 the 8:00 am rolling regularly reduced annual bluegrass turfgrass quality compared to the 1:00 pm rolling. Again, correlation analysis determined that morning soil temperature was the most effective parameter for predicting annual bluegrass rolling injury (Figure 4). With annual bluegrass, unacceptable injury occurred when rolling was applied at morning temperatures ≤ 32°F.

Year 2 (2024) Results:

Effects of daily winter cart traffic on creeping bentgrass, annual bluegrass and perennial ryegrass

In 2024 frost and freezing surface conditions were observed on the morning of Jan 5, Jan 19, Mar 1 and Mar 6, but no freezing soil conditions were observed during the 2024 data collection period. Repeated daily cart traffic treatments applied in the morning and afternoon slowly reduced creeping bentgrass, annual bluegrass and perennial ryegrass quality over time from Jan 3 to March 8, 2024 (Figure 5 – bentgrass data only, annual bluegrass and perennial ryegrass data not shown).

When further evaluating the cart traffic treatments, no correlations were observed between turfgrass quality and soil temperature (Figure 6 – bentgrass data only, annual bluegrass and perennial ryegrass data not shown). The critical findings produced by 2024 data are that morning cart traffic applied during frost and freezing surface conditions, with soil temperature above freezing, >32 degrees F, did not increase damage compared to afternoon traffic without frost or freezing conditions.

Effects of daily foot traffic on creeping bentgrass and perennial ryegrass

Like the cart traffic research, within the foot traffic study, in 2024 frost and freezing surface conditions were observed on the morning of Jan 5, Jan 19, Mar 1 and Mar 6, but no freezing soil conditions were observed during the 2024 data collection period. Repeated daily foot traffic treatments applied in the morning and afternoon slowly reduced creeping bentgrass, and perennial ryegrass quality over time from Jan 3 to March 8, 2024 (Figure 7 – bentgrass data only, perennial ryegrass data not shown). While foot traffic produced reductions in turfgrass quality over time, quality ratings were 6 (acceptable) or higher throughout the 3-month data collection period. These findings are similar to work conducted by Gould et al (2017), which determined that repeated foot traffic during periods of cold weather will cause reduced quality on golf course putting greens. Gould et al (2017) concluded that tee markers, and cup should be used regularly moved to mitigate the effects of cumulative traffic during periods of cold weather.

Further evaluation of the foot traffic treatments determine that no correlations were observed between turfgrass quality and soil temperature (Figure 8 – bentgrass data only, perennial ryegrass data not shown). The critical findings produced by 2024 data are that morning foot traffic applied during frost and freezing surface conditions, with soil temperature above freezing did not increase damage compared to afternoon traffic without frost or freezing conditions.

Effects of daily winter rolling annual bluegrass

Like the cart and foot traffic research, within the rolling study, in 2024 frost and freezing surface conditions were observed on the morning of Jan 5, Jan 19, Mar 1 and Mar 6, but no freezing soil conditions were observed during the 2024 data collection period. Repeated daily rolling treatments applied in the morning and afternoon slowly reduced annual bluegrass quality over time from Jan 3 to March 8, 2024 (Figure 9). While rolling produced reductions in turfgrass quality over time, quality ratings were 6 (acceptable) or higher throughout the 3-month data collection period.

When further evaluating the rolling treatments, no correlations were observed between turfgrass quality and soil temperature (Figure 10). The critical findings produced by 2024 data are that morning rolling applied during frost and freezing surface conditions, with soil temperature above freezing did not increase damage compared to afternoon traffic without frost or freezing conditions.

Future Research – Year 3 (2025):

In 2025 the morning and afternoon cart traffic, foot traffic, and rolling treatments will be repeated. Cart traffic applied to rough height perennial ryegrass (2-inch height of cut) will be added to the project, as the effects of winter traffic on this height of cut have not yet been evaluated.

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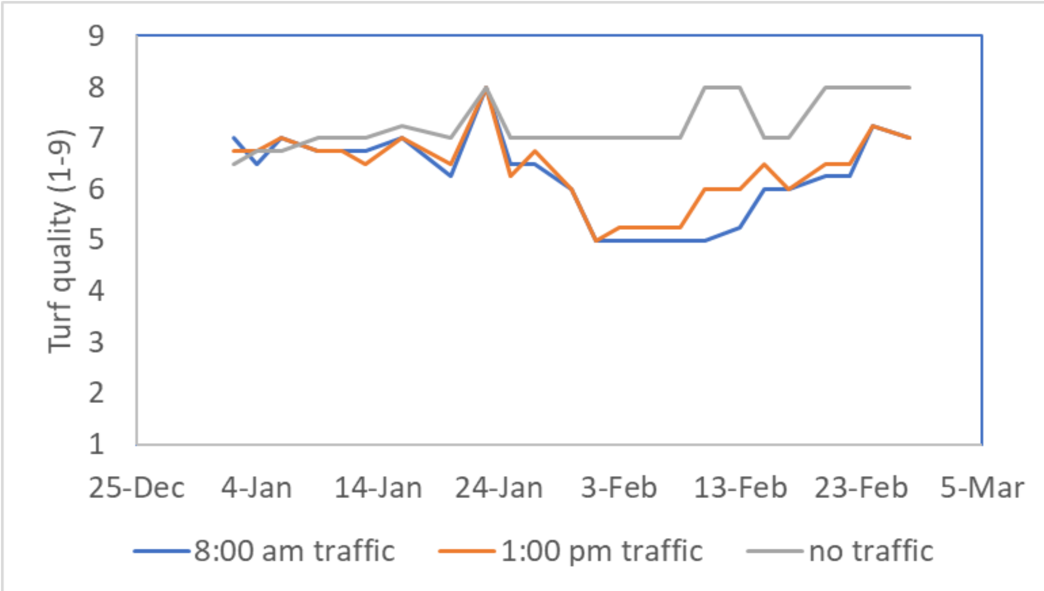

Figure 1: Creeping bentgrass fairway turf quality affected by cart traffic applied at 8:00 am or 1:00 pm over time in Corvallis, OR from Jan 2 to Feb 28, 2023.

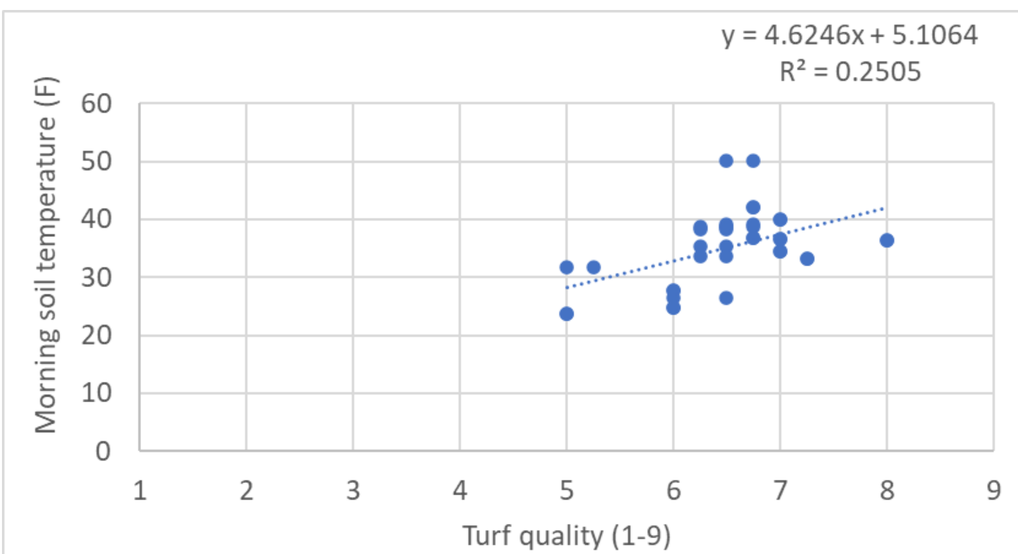

Figure 2: Relationship between morning soil temperature and creeping bentgrass fairway turf quality when traffic was applied at 8:00 am or 1:00 pm (control treatment excluded) in Corvallis, OR from Jan 2 to Feb 28, 2023.

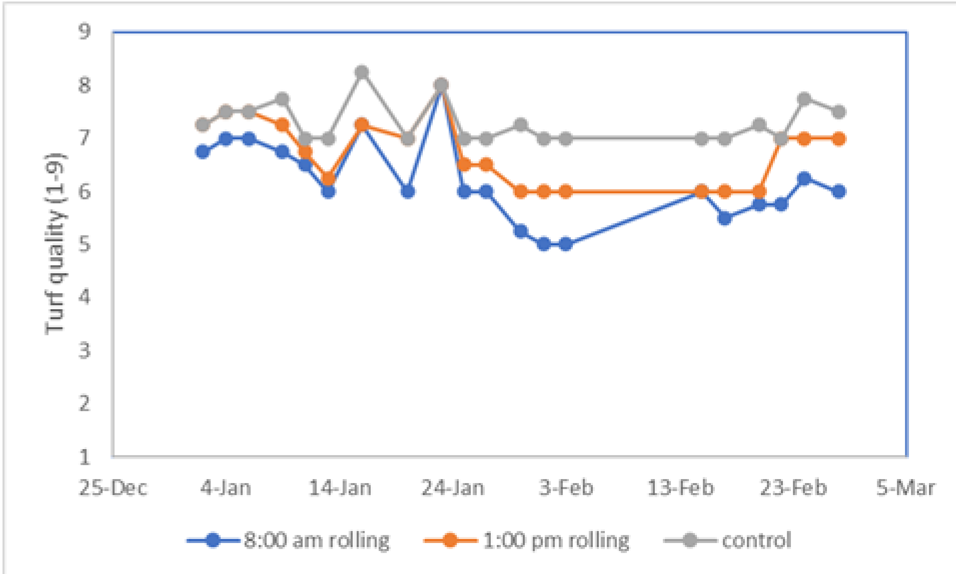

Figure 3: Annual bluegrass putting green turf quality affected by rolling applied at 8:00 am or 1:00 pm over time in Corvallis, OR from Jan 2 to Feb 28, 2023.

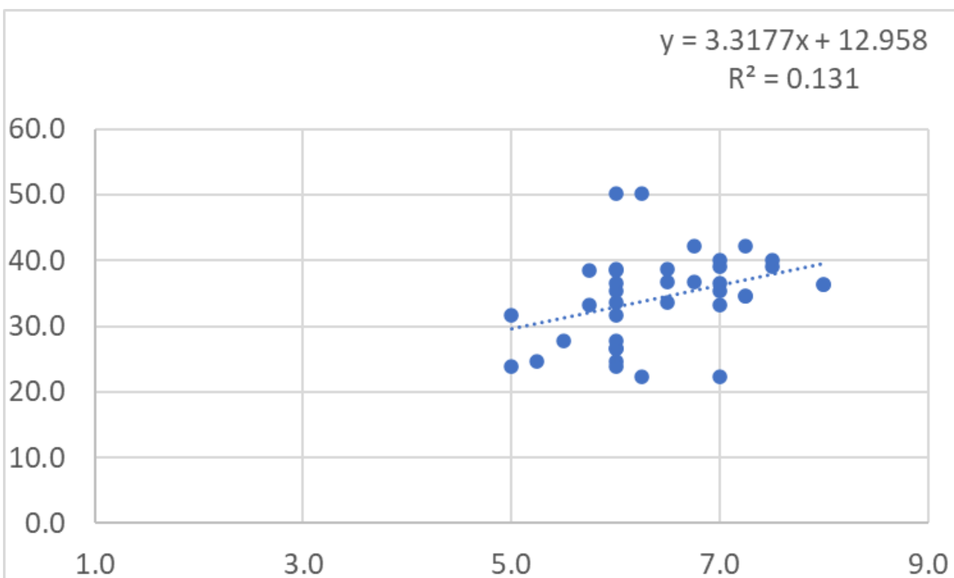

Figure 4: Relationship between volumetric water content and annual bluegrass putting green turf quality when rolling was applied at 8:00 am or 1:00 pm (control treatment excluded) in Corvallis, OR from Jan 2 to Feb 28, 2023.

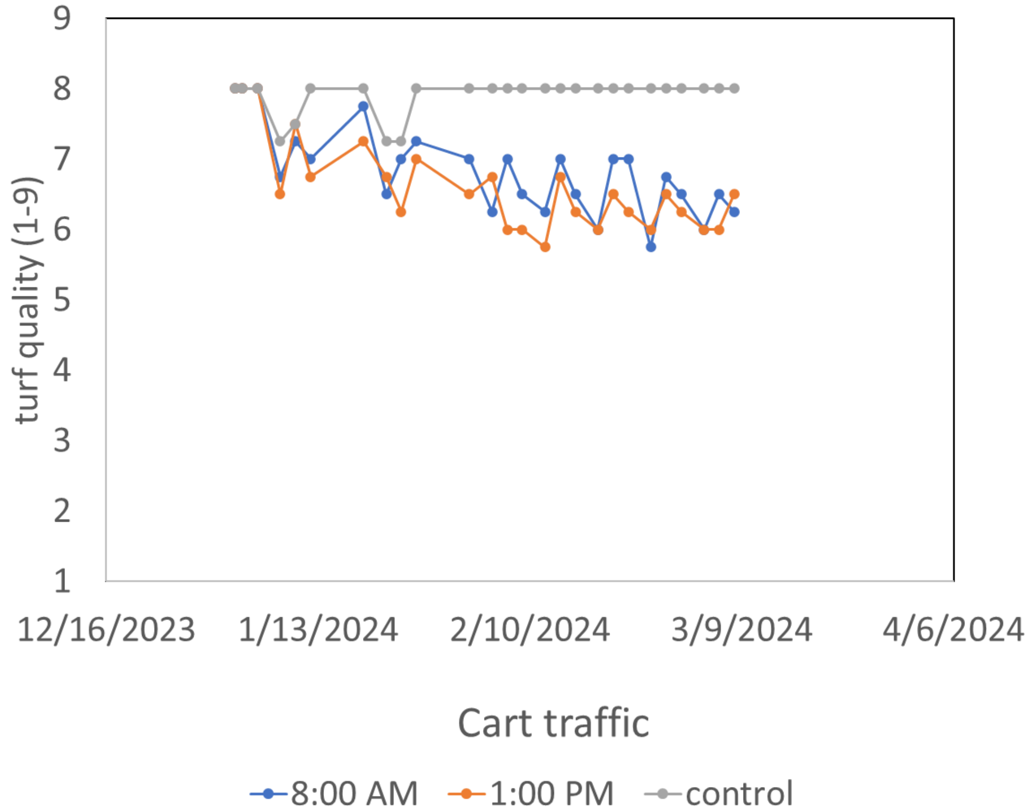

Figure 5: Effects of cart traffic on bentgrass in Corvallis, 2024. Frost was observed on Jan 5, Jan 19, Mar 1, and Mar 6, 2024.

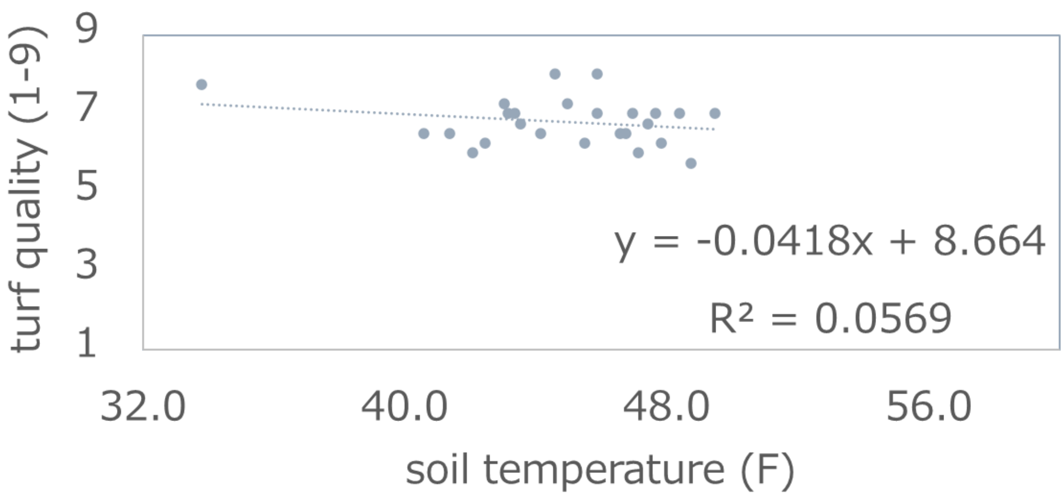

Figure 6: Interactions between soil temperature and turf quality when golf cart traffic is applied in Corvallis, OR (bottom), frost and freezing surface temperatures were observed on Jan 5, Jan 19, Mar 1, and Mar 6, 2024.

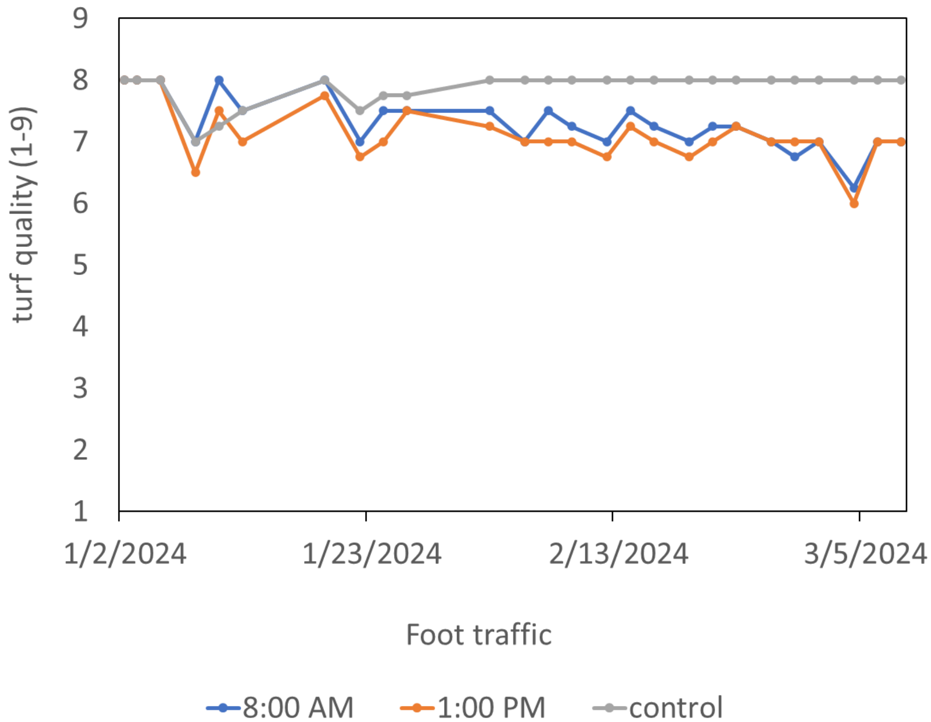

Table 7: Effects of foot traffic on bentgrass in Corvallis, 2024. Frost was observed on Jan 5, Jan 19, Mar 1, and Mar 6, 2024.

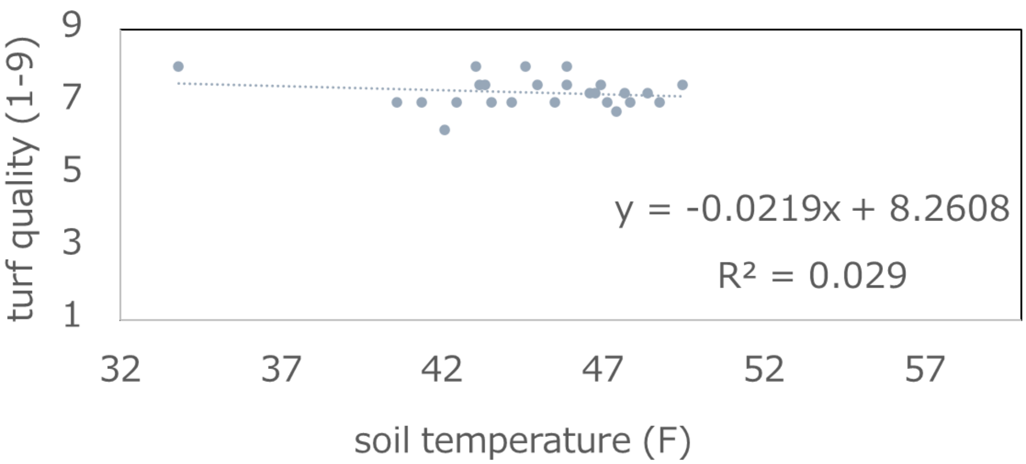

Table 8: Interactions between soil temperature and turf quality when foot traffic is applied (top), frost and freezing surface temperatures were observed on Jan 5, Jan 19, Mar 1, and Mar 6, 2024.

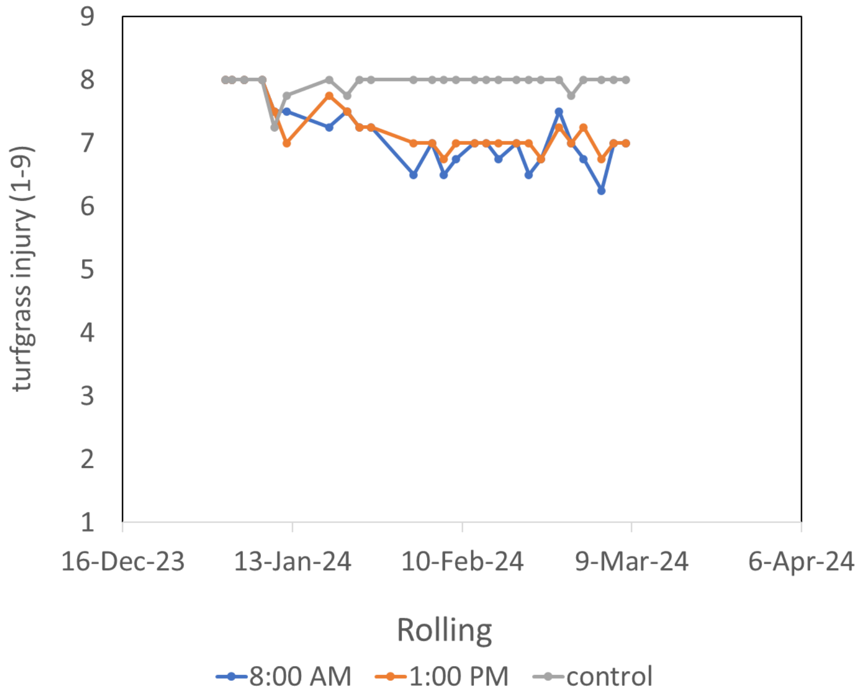

Table 9: Effects of rolling on annual bluegrass in Corvallis, 2024. Frost was observed on Jan 5, Jan 19, Mar 1, and Mar 6, 2024.

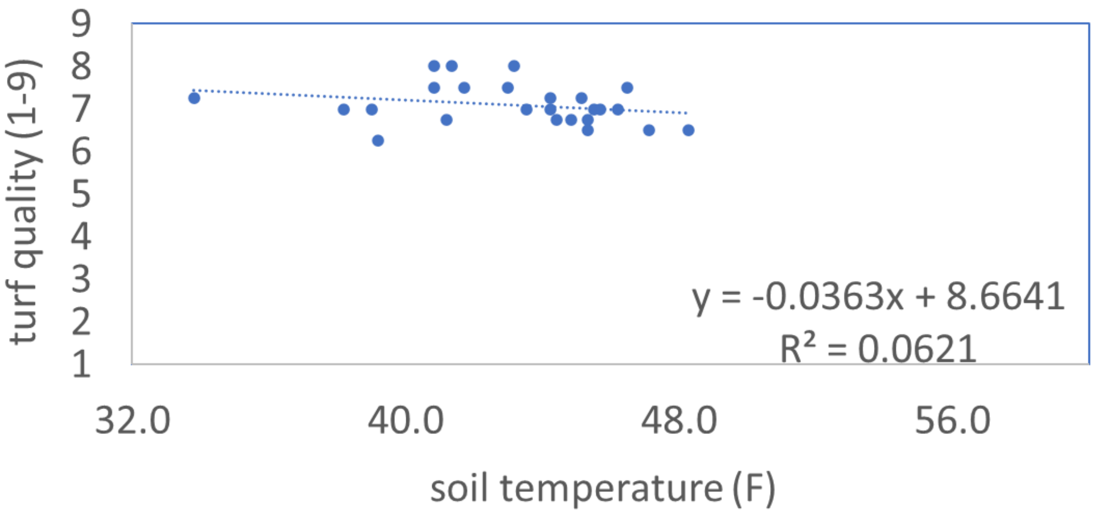

Table 10: Interactions between soil temperature and turf quality when rolling is applied, frost and freezing surface temperatures were observed on Jan 5, Jan 19, Mar 1, and Mar 6, 2024.

USGA ID#: 2023-15-782

Title: Influence of nitrogen rate on growing degree day models for plant growth regulator reapplication interval on annual bluegrass putting greens

Project Leader: Chas Schmid
Co-leader: Alec Kowalewski

Affiliation: Department of Horticulture, Oregon State University

Objectives:

1) Develop a growing degree day model for PGR (trinexapac-ethyl and prohexadione-Ca) application intervals on annual bluegrass putting greens
2) Determine if nitrogen rate has an influence on a growing degree day model for annual bluegrass putting greens

Start Date:
May 2023

Project Duration:
3 years, May 2023 to Dec 2025 (year 2 report)

Total Funding:
$90,000 ($30,000 per year)

Summary Points:

- Predicted reapplication interval for trinexapac-ethyl (TE) on annual bluegrass ranged from 309 to 217 GDD for low and high N rates, respectively; TE combined with High N was similar to previous recommendations for bentgrass.
- Predicted reapplication interval for Prohexadione-Ca on annual bluegrass ranged from 243 to 212 GDD for low and high N rates, respectively; both were much lower than previous recommendations for bentgrass.
- Trends suggest reapplication intervals for PGR varied by month of application, with PGRs applied to annual bluegrass under stressful environmental conditions during July resulting in longer reapplication intervals, particularly when combined with low N rates which increased intervals by > 130 GDD.

INTRODUCTION

Plant growth regulators (PGR) are typically applied to golf course putting greens on a calendar-based schedule, but recently growing degree-day (GDD) models for PGR reapplication interval have been developed to provide season-long growth suppression; including models for applications of trinexapac-ethyl (TE; Primo Maxx 1ME, Syngenta) (Kreuser et al., 2011) and paclobutrazol (Trimmit 2SC, Syngenta) on creeping bentgrass (Agrostis stolonifera L.) putting greens (Kreuser et al., 2018), and TE and paclobutrazol on ultradwarf hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] putting greens (Reasor et al. 2017). However, no previous research has attempted to develop a GDD model for PGRs on annual bluegrass (ABG) putting greens. Instead, superintendents managing ABG putting greens have relied on GDD models developed for creeping bentgrass as a baseline for reapplication intervals. Thus, development of GDD models for PGR reapplication interval on ABG turf is needed.

The effect of N rate on ABG putting green turf quality, disease susceptibility, and playability has been well documented (Hempfling et al., 2017; Inguagiato et al. 2008; Schmid et al. 2017), but little is known about the effect of N rate on PGRs applied to annual bluegrass. Specifically, if N rate influences PGR reapplication interval for ABG putting greens. It is possible that greater rates of N may require a more frequent (< GDD) reapplication interval compared to lower rates. Further research is needed to determine if GDD models for PGRs should be adjusted based on N rates.

MATERIALS AND METHODS

Site Description and Maintenance

This three-year field trial was initiated in June 2023. The trial is being conducted on a sand-based annual bluegrass research green constructed using the United States Golf Association rootzone specifications (USGA, 2018). The research green is managed to simulate conditions found on golf course putting greens in the Pacific Northwest. Pesticides (except DeMethylation Inhibitors) were applied preventatively to control common disease and insect pests. An onsite Campbell Scientific weather station was used to measure daily air temperatures, which were used to calculate cumulative GDD using methods described by McMaster and Wilhelm (1997), with a base temperature of 0°C and the stipulation that if the daily mean temperature is less than the base temperature, then the GDD for that day is set to zero.

Treatment Design

The treatment design for the trial was adapted from those described by Kreuser et al. (2017) and Reasor et al. (2018). The experiment was designed as 2 by 2 factorial in a randomized complete block design with four replications. Factors include PGR type, either a single application of TE at 0.125 fl oz 1000ft^{-2} or prohexadione-Ca (PH; Anuew, Nufarm) at 0.05 fl oz 1000ft^{-2}, and N rate, either 0.075 or 0.15 lb N 1,000 ft^{-2} every 7-d throughout the trial period (June through September). Multiple runs of the experiment were conducted within each year, with applications starting on June 13, July 13, and August 15, 2023; and June 18, July 11, August 15, 2024 to plots with no previous PGR application that season. Two sets of nontreated control plots were included per replication to improve the accuracy of calculating relative clipping yield based on recommendations from Kreuser et al. (2017). Plot size for the trial is 3 x 10 ft (30 ft^2).

Plant growth regulator treatments were applied with a CO_2-pressured backpack sprayer using a carrier volume of 2.0 gal 1,000 ft^{-2}.

Data Collection

Clipping collection methods were adapted from those described by Reasor et al. (2018), with clippings collected three times per week (Monday, Wednesday, and Friday) until ≈600 GDD; at which point, clippings were collected once per week until the effects of TE and PH are no longer detectable (≈1000 GDD). Clipping collection and general plot mowing were done using an electric walk-behind greens mower (eFlex 2120, Toro Company), with bench height set at 0.110 inches. The entire plot area was mowed six days per week (except Saturday), including on days when clippings had been collected from treated plots. Sand topdressing was withheld from the trial area to prevent contamination in clipping samples. Any debris was removed from collected clippings prior to weighing.

Statistical Analysis

Relative clipping yield was compared to GDD using an amplitude-dampened sine wave regression model (Kreuser et al. 2017). Data was combined across months (June, July, and August) and years (2023 and 2024) for each PGR and N rate combination and analyzed to determine their overall effect on relative growth suppression and reapplication interval. The nonlinear regression function in SigmaPlot 15 (Systat Software, 2023) was used to fit the amplitude-dampened sinewave model, which is defined by Eq. [1].

$$\text{Relative clipping yield } (\mathrm{g\ g^{-1}}) = 1 + \mathrm{A} * e^{\left(\frac{GDD}{\mathrm{D}}\right)} * \sin\left(2\pi * \frac{GDD}{\mathrm{B}} + \pi\right) \qquad [1]$$

Where A is the magnitude of the suppression and rebound growth stages, D is the amplitude decay coefficient, GDD is the cumulative GDD since the last PGR application, and B is the period of the model in GDD. In addition, data from each month (June, July, and August) was averaged across years (2023 and 2024) for each PGR and N rate combination and analyzed to determine the effect of application timing on relative growth suppression and reapplication interval.

PRELIMINARY RESULTS

All combinations of PGRs (TE and PH) and N rate (0.075 and 0.15 lb N 1,000 ft^{-2} wk^{-1}), averaged across months (June, July, and August) and years (2023 and 2024), indicated a significant relationship between relative clipping yield and GDD using a sine wave regression model with R^2 values ranging from 0.521 to 0.685 (Figure 1). Peak growth suppression for TE was observed at 238 and 167 GDD for the low and high rate of N, respectively, with predicted reapplication intervals of 309 and 217 GDD**.** Reapplication interval for TE in combination with high rates of N (217 GDD) was similar to previous reports of GDD reapplication interval for creeping bentgrass (230 GDD; Kreuser, 2016). However, when TE is combined with low rates of N (0.075 lb N/1,000 ft^2), the reapplication interval appears for be much higher (309 GDD) than previous recommendations or TE combined with high N. Differences in peak suppression and reapplication interval between N rates (low and high) in combination with PH was less dramatic than those observed in TE treatments. Prohexadione-Ca combined with high rates of N resulted in peak suppression at 163 GDD and a reapplication interval of 212 GDD, whereas PH combined with low N showed peak suppression at 187 GDD and a reapplication interval of 243 GDD (Figure 1). Interestingly, the reapplication interval for PH on annual bluegrass was much less than previous recommendations for creeping bentgrass of 280 GDD (Kreuser, 2016).

A sine wave regression model was also used to look at the relationships between relative clipping yield and GDD for each month (June, July, and August; averaged across years) to show nuance in reapplication intervals across a season (Figures 2, 3, & 4). In June, few differences in peak suppression or reapplication interval were observed between low and high rates of N for either TE or PH, but the data does indicate that TE has a longer reapplication interval than PH (Figure 2). During July, significant differences in reapplication intervals were observed between the two rates of N for both PGRs, with low rates of N extending the reapplication intervals compared to high N rates (Figure 3). Then in August, few differences were once again observed between PGRs or N rates, with reapplication intervals ranging from 199 to 209 GDD (Figure 4). These results indicate that when the turfgrass in exposed to high levels of abiotic stress (i.e. during late summer; July applications), the reapplication intervals for PGRs combined with low N rates were extended by > 130 GDD compared to high N rates. During months when the turfgrass had optimum growing conditions (early summer and early fall; June and August applications, respectively), few differences were observed between PGR types and N rates.

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Figure 1. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon averaged across June, July, and August treatments during 2023 and 2024, after a single application (within each month) of trinexapac-ethyl (left) or Prohexadione-Ca (right) combined with weekly applications of nitrogen at 0.075 lb N/1,000 ft^2 (low N; top) or 0.15 lb N/1,000ft^2 (high N; bottom). Equation and R^2 values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

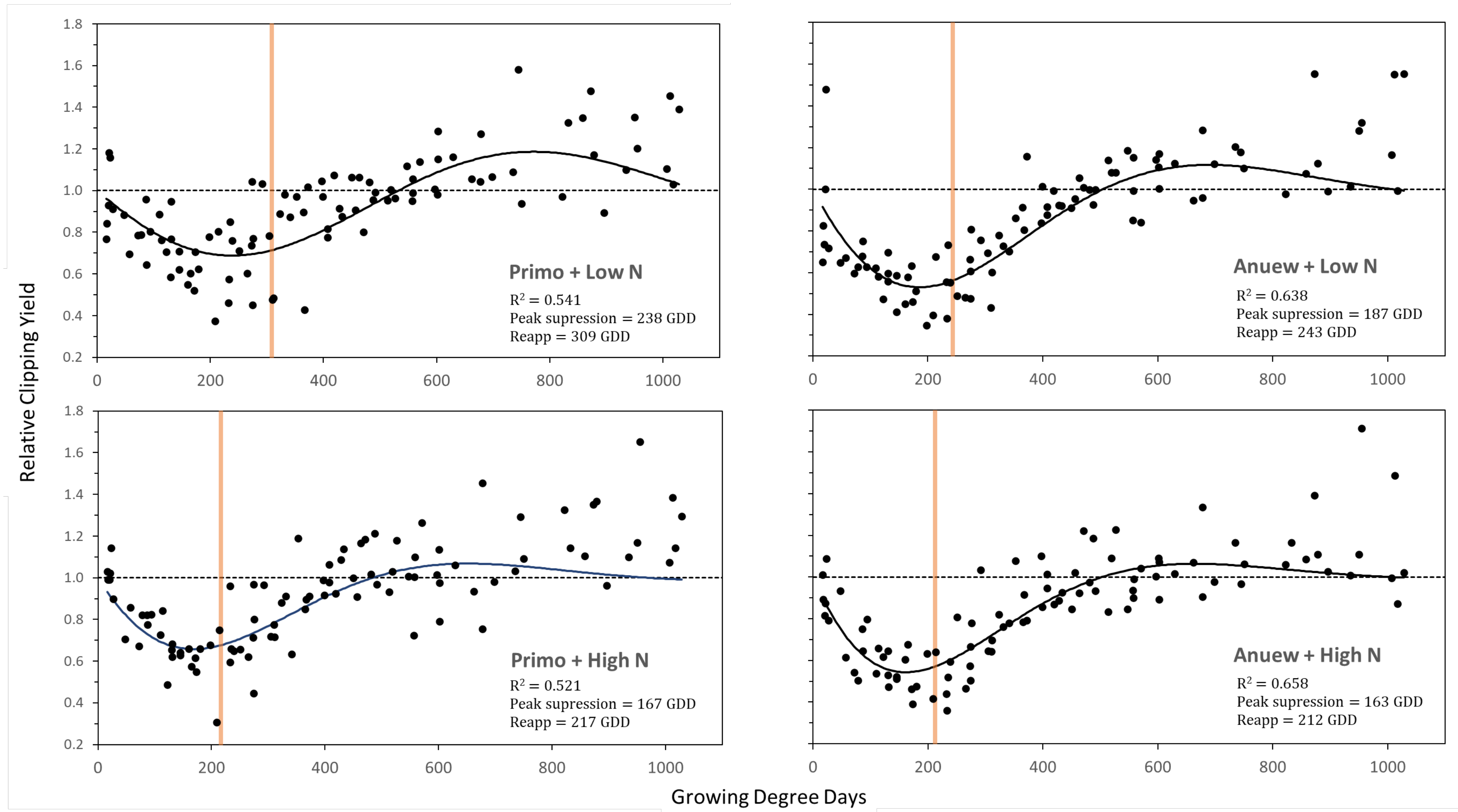

Figure 2. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon during June of 2023 and 2024 (average across years), after a single application of trinexapac-ethyl (left) or prohexadione-Ca (right) combined with weekly applications of nitrogen at 0.075 lb N/1,000 ft^2 (low N; top) or 0.15 lb N/1,000ft^2 (high N; bottom). Equation and R^2 values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

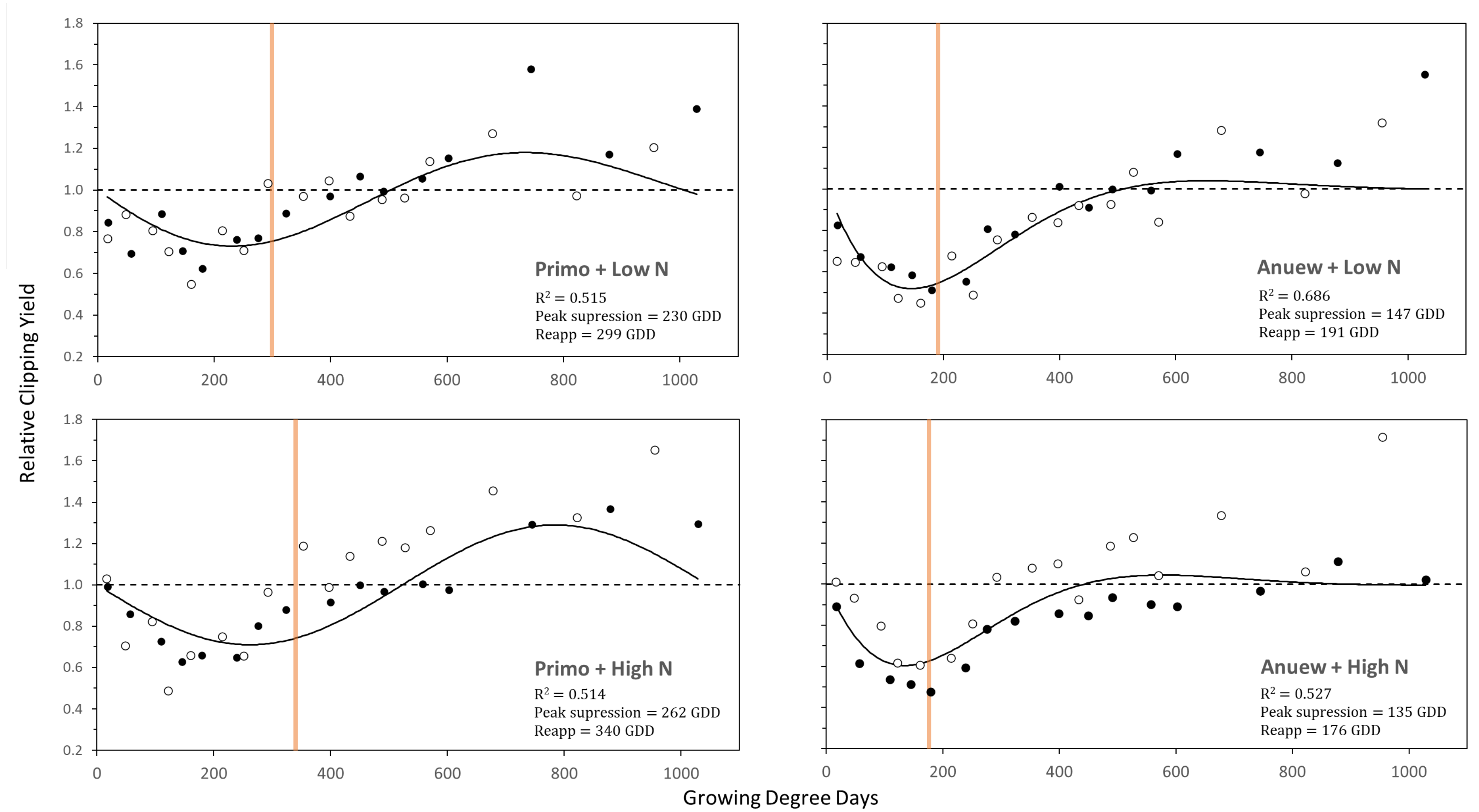

Figure 3. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon during July of 2023 and 2024 (average across years), after a single application of trinexapac-ethyl (left) or prohexadione-Ca (right) combined with weekly applications of nitrogen at 0.075 lb N/1,000 ft^2 (low N; top) or 0.15 lb N/1,000ft^2 (high N; bottom). Equation and R^2 values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

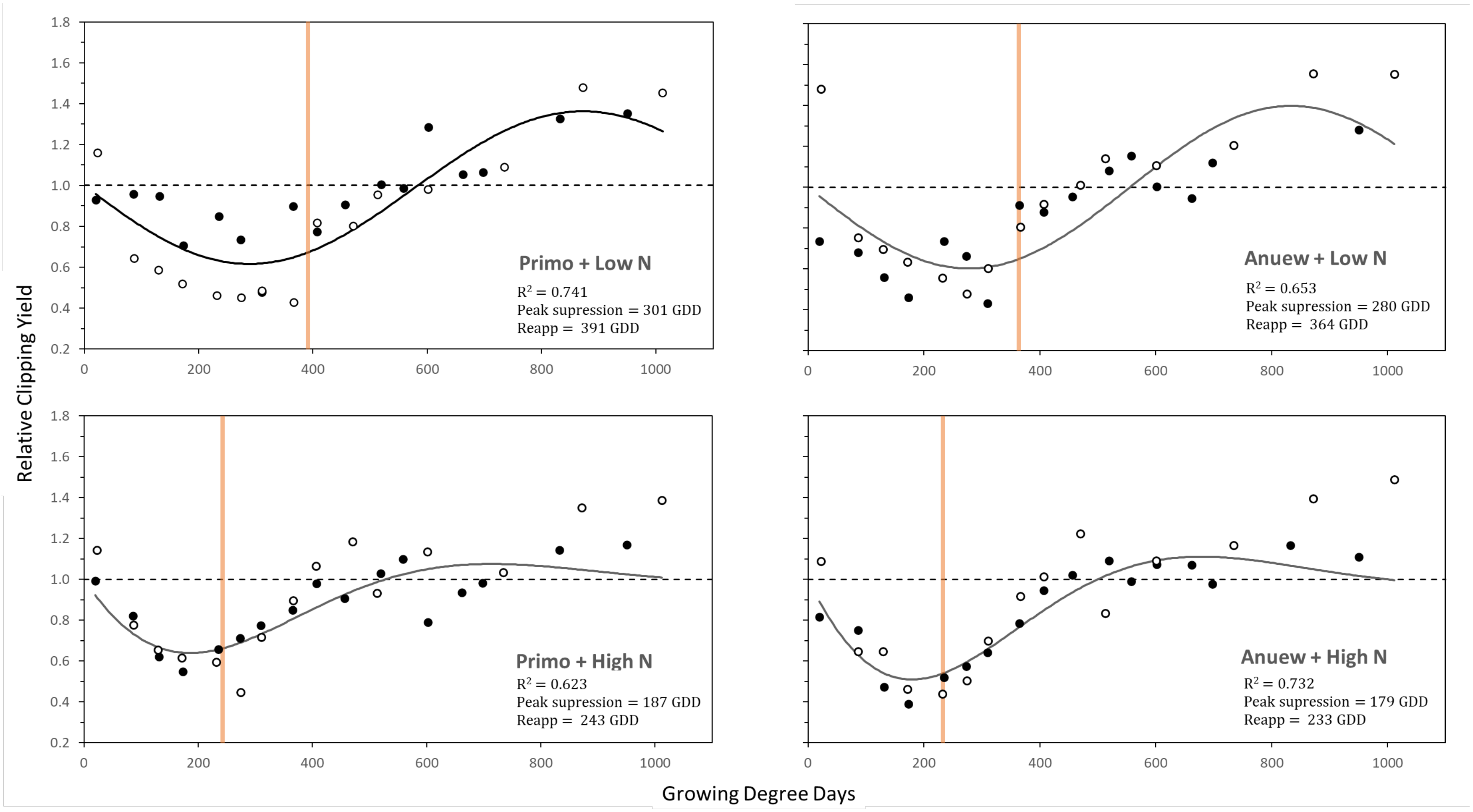

Figure 4. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon during August of 2023 and 2024 (average across years), after a single application of trinexapac-ethyl (left) or prohexadione-Ca (right) combined with weekly applications of nitrogen at 0.075 lb N/1,000 ft^2 (low N; top) or 0.15 lb N/1,000ft^2 (high N; bottom). Equation and R^2 values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

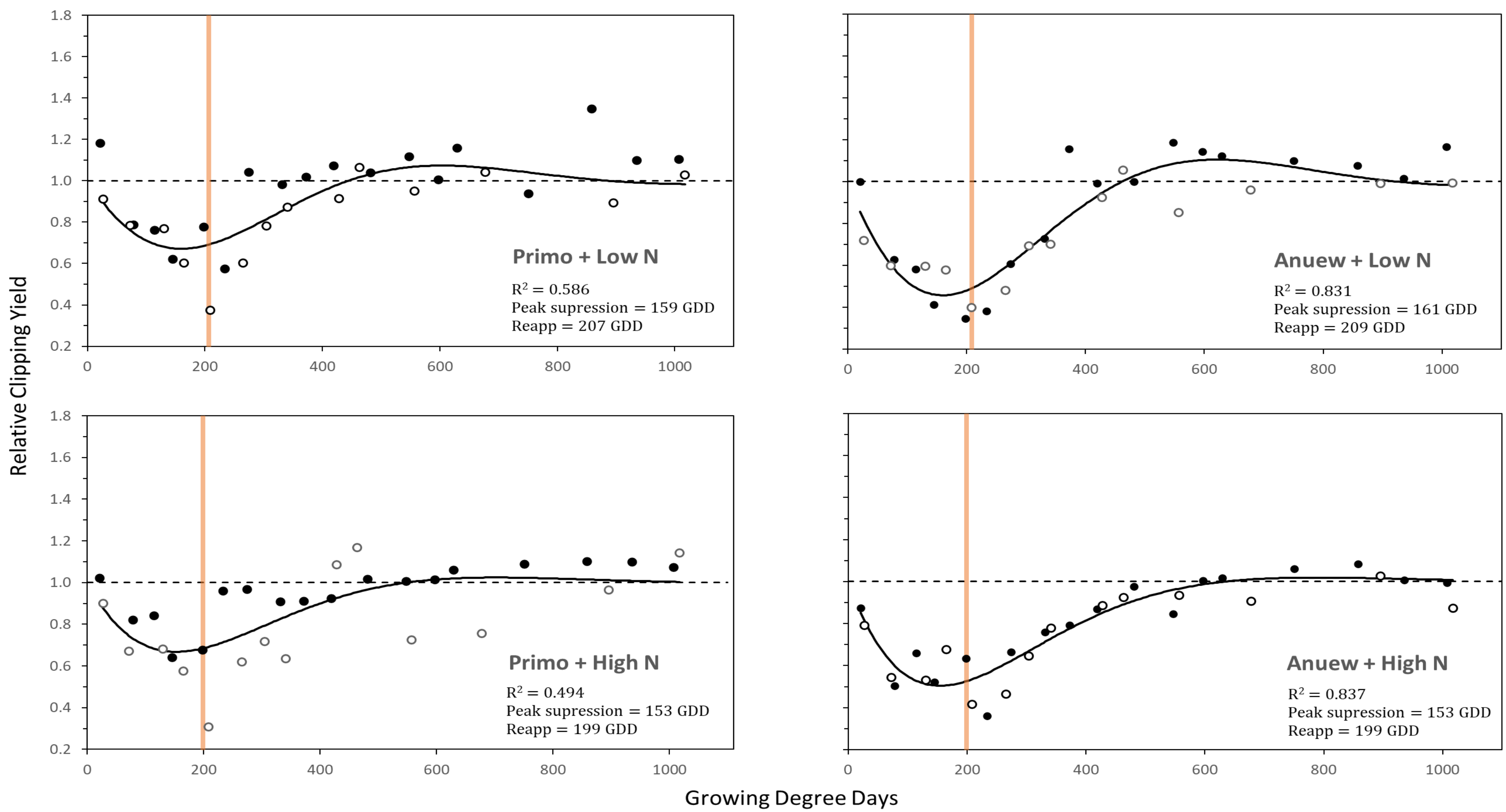

Image: Preparing PGR trial for clipping collection.

Image: Robert Starchvick presenting findings from the trial at the Oregon State University summer turfgrass field day.

USGA ID#: 2023-01-768 (altered continuation from 2020-03-708 and 2019-01-671)

Title: Switching to Solid Tine Cultivation after Seven Years of Hollow Tine Cultivation on Plots Topdressed with Three Sand Sizes

Project leader: James A. Murphy
Affiliation: Department of Plant Biology, Rutgers University

Objectives: Continue to assess the
1) long-term effects of topdressing with sand dominated by medium or fine sand particles and
2) impact of switching to solid tine cultivation and backfilling holes with medium-coarse sand on turf performance and the physical properties at the surface of a putting green root zone.

Start date: 2023
Project duration: 3 years
Total funding: $145,557

Summary Points:
- We continued applying top-dressing treatments with three sands differing in particle size distribution applied ten times during the growing season at two rates: 50 or 100 lb per 1,000 sq ft. We also continued with two levels of a cultivation factor: a ProCore® 648 setup with mini tine heads (staggered 5 tines per plate) and equipped with ⅝-inch diam. solid tines to apply the third and fourth solid tine cultivation treatment events during this grant period.
- Data analysis from the undisturbed core (3-inch diam.) samples of the mat layers removed from plots in April 2023 was completed in 2024, concluding measurements of treatments that included hollow tine cultivation (USGA ID#: 2020-03-708). These data set a benchmark for data collected during late 2025 or early 2026 for the USGA ID#: 2023-01-768 grant (solid tine cultivation).
- Seven years of topdressing and hollow tine cultivation clearly affected organic matter content, bulk density, and porosity of mat layers on creeping bentgrass turf maintained at 0.11-inch.
- The rate of topdressing sand affected the organic matter content, whereas the size of topdressing sand did not. Applying a higher topdressing rate reduced the organic matter content more than topdressing sand applied at the lower rate; this effect was most apparent when plots were not cultivated with hollow tines.
- The mat layer was densest when turf was cultivated with hollow tines compared to non-cultivated turf, regardless of the size or rate of topdressing sand. A greater application rate of sand developed a denser mat layer than the lower rate, and this effect was most evident when turf was not cultivated. However, within a given cultivation regime, the coarsest topdressing sand was or was among the sand sizes with the greatest bulk density.
- *In situ* bulk density measurements with a Troxler moisture density gauge during 2024 confirm that solid tine cultivation has maintained a greater bulk density in cultivated plots than in non-cultivated plots, similar to the effect with hollow tine cultivation.
- A peer-review publication on the surface characteristics during the first seven years of this trial is in review for Agronomy Journal.
- We are drafting a second publication focused on the physical properties within the mat layer during the first seven years of this trial and plan to submit it for review in the Agronomy Journal.

Summary:

Sand topdressing of putting greens during the season is often avoided or applied at very low application rates (dusting) due to the potential of coarse sand particles interfering with play and dulling mower blades. Topdressing with finer sand enhances incorporation, greatly reducing interference concerns, which could enable superintendents to keep pace with thatch accumulation in putting greens during the summer and reduce problems associated with excess organic matter. Results from a seven-year field trial (USGA ID#: 2016-06-556 and USGA ID#: 2019-01-671) indicate that a finer 0.05-mm topdressing sand (particles ≤ 0.5-mm) has diluted and modified thatch accumulation much like that of a coarser topdressing sand (particles ≤ 1.0-mm). However, mat layer depth and surface wetness data suggest that differences among other treatment factors in this trial have intensified over time.

Grant funding from the USGA was provided to continue a revised version of this long-term topdressing project, in which we continued applications of topdressing treatments. At the same time, one of the levels in the cultivation factor was switched from hollow tine to solid tine cultivation.

This new funding also supports initiating two complementary trials to compare hollow and solid tine cultivation. The objectives of these complementary trials were to directly compare hollow and solid tine cultivation for effects on thatch modification and associated changes in surface physical properties, including surface water retention, water infiltration, organic matter content, and pore size distribution of the mat layer.

Materials and Methods

Long-term Topdressing Trial

The long-term topdressing trial was initiated in May 2016 on a 19-month-old 'Shark' creeping bentgrass grown on a sand-based root zone. The experimental design of the trial was a 3 x 2 x 2 factorially arranged randomized complete block design with four blocks.

During 2023, the topdressing factors remained as before: sand size (medium-coarse, medium-fine, fine-medium) and quantity of mid-season topdressing (50- or 100-lb / 1,000-ft^2 every 10 to 14 days totaling ten applications from June through early October), however, one level of the cultivation factor was changed from hollow tine cultivation to solid tine cultivation with ⅝-inch diam. tines in April and October. Controls (no mid-season topdressing) at each cultivation level were included for comparisons, resulting in 14 treatments (Table 1). Four solid tine cultivation events have been performed on 18 May and 23 October 2023, and 15 April and 15 October 2024 since the initiation of this grant.

The medium-coarse sand used in this trial meets the USGA particle size recommendation for construction, whereas the medium-fine and fine-medium sands do not (Table 2). The quantity of fine and very fine particles in the medium-fine and fine-medium sands exceed the USGA recommendations and these sands contain little to no coarse particles.

Except during COVID-19 restrictions, mowing was performed with a 2.8-mm bench setting 5 to 6 days per week from late April through October. Fertilization was applied every 1 to 2 weeks at 0.1 to 0.3 lb of N per 1,000 sq ft and achieved an annual total of 2.4 lb N per 1,000 sq ft. Irrigation was applied at 50 to 80% ET_o. During select periods irrigation by handheld hose was initiated on an individual plot when the plot exhibited incipient wilt stress. Each handheld hose watering event and the gallons of water applied were recorded. Pests were preventively managed with pesticides.

Data collection during April 2023 included removing undisturbed 3-inch diam. cores of the mat layer of each plot, which was the same method used for the USGA ID#: 2019-01-671 grant. Determination and analyses of the surface bulk density, pore size distribution, organic matter content, and sand size distribution of the mat layers is underway. These data will conclude the grant activities of

USGA ID#: 2020-03-708 and set the benchmark to contrast with data collected during the grant activities of USGA ID#: 2023-01-768.

Data collection during 2024 included visual ratings of turf quality and residual sand after topdressing, volumetric water content (VWC) of the surface 0- to 3-inch depth zone; Clegg soil impact values, ball roll (GS3 device), normalized difference vegetation index (NDVI), and documentation of the number of hand-watering events and amount of water applied to individual plots. Additionally, we contracted with a geospatial consultant to develop a UAV (DJI Mavic 3 Multispectral drone) to collect remote sensing data from the trial. dual-head infiltrometers [SATURO | Automated Field Infiltrometer | METER Environment (metergroup.com), Pullman, WA] were used to measure field-saturated hydraulic conductivity of select plots. Statistical analyses of data are in progress.

Complementary Cultivation Trials

Two complementary cultivation trials were initiated on creeping bentgrass maintained as putting green turf during 2023. Mowing was performed with a 2.8-mm bench setting 5 to 6 days per week from late April through October. Fertilization was applied every 1 to 2 weeks at 0.1 to 0.3 lb of N per 1,000 sq ft. Irrigation was applied at no more than 80% ET_o once the turf had dried sufficiently after rain.

One trial, initiated on 30 June 2023, applied four treatments: non-cultivated control, ½-inch i.d. hollow tine cultivation, ½-inch diam. solid tine cultivation, and ⅝-inch diam. solid tine cultivation. All treatments were replicated four times in a randomized complete block design. All treatments were reapplied on 11 October 2023 and 5 April and 24 September 2024 (four cultivations since initiation of trial).

The second complementary trial was initiated on 18 October 2023 and three treatments were applied: non-cultivated control, ½-inch i.d. hollow tine cultivation, and ⅝-inch diam. solid tine cultivation. All treatments were replicated four times in a randomized complete block design. All treatments were reapplied on 22 April and 24 September 2024 (three cultivations since the initiation of the trial).

All cultivated treatments were applied with a ProCore® 648 setup with mini tine heads (2x5 staggered holder; 5 tines per plate) equipped with the respective tines and depth setting to reach 2 inches below the turf surface. The tine spacing affected ~5% of the turf surface area with each treatment application. All cultivation tine holes were backfilled with medium-coarse sand at 600 lb per 1,000 sq ft. At the same time cultivation treatments were applied, non-cultivated plots were topdressed with the medium-coarse sand at 400 lb per 1,000 sq ft to fill the verdure and surface thatch layers to the same extent as plots that were solid tine cultivated and backfilled with sand.

Data collection during 2024 included visual ratings of turf quality, healing of tine holes, residual sand after topdressing, normalized difference vegetation index (NDVI), VWC of the surface 0- to 3-inch depth zone, and Clegg soil impact values. Additionally, dual-head infiltrometers were used to measure field-saturated hydraulic conductivity. Finally, the USGA GS3 device was used to assess the distance, trueness, and smoothness of ball rolls and drop tests to evaluate firmness. Statistical analyses of data are in progress.

Results

Long-term Topdressing Trial

The initial analyses of the organic matter content, bulk density, and pore size distribution of mat layers – undisturbed 3-inch diam. core samples from plots in April 2023 – were completed in 2024. These analyses indicate that seven years of topdressing and hollow tine cultivation clearly affected organic matter content, bulk density, and porosity of mat layers on creeping bentgrass turf maintained at 0.11-inch (Table 3).

The sand rate was the only topdressing factor affecting the mat layer's organic matter content. Applying a greater topdressing rate (100 lb) reduced the organic matter content more than topdressing sand applied at the lower rate (50 lb); this effect was most evident when the turf was not cultivated with hollow tines (Table 4). The organic matter content was always lower (1.2 to 1.6%) when turf was cultivated twice a year with hollow tines compared to no cultivation.

Accordingly, the bulk density of the mat layer responded to topdressing and cultivation treatment combinations. The mat layer was densest when turf was cultivated with hollow tines (and organic matter content was reduced) compared to non-cultivated turf (Table 4 and 5). The greater rate (100 lb) of topdressing sand developed a denser mat layer than the lower (50 lb) sand rate, and this effect was most evident when turf was not cultivated (Table 4). Within a given cultivation regime, the coarsest topdressing sand was or was among the sand sizes that produced the greatest bulk density of the mat layer (Table 5). The finest topdressing sand (fine-medium) produced the mat layer with the lowest bulk density under non-cultivated conditions.

Air-filled and capillary porosity of the mat layer were clearly affected by the size of the topdressing sand; however, the effects depended on the topdressing rate and cultivation factors (2 two-way interactions). Under non-cultivated conditions, air-filled porosity was reduced as the size of the sand became finer (Table 5). In contrast, only the fine-medium sand reduced air-filled porosity when plots were hollow tine cultivated. Under non-cultivated conditions, capillary porosity was increased as the size of the sand became finer, and the increase with fine-medium sand was 7.1 and 9.4%—only the fine-medium sand increased capillary porosity when plots were hollow tine cultivated (Table 5). The interaction with topdressing rate indicated that air-filled porosity declined the most as sand size became finer under the greater topdressing rate (100-lb) than the lower (50 lb) topdressing rate. Capillary porosity increased the most as sand size became finer under the greater topdressing rate (100-lb) than the lower (50 lb) topdressing rate. Capillary porosity was greatest under topdressing with the fine-medium sand regardless of the topdressing rate.

Bulk density measured *in situ* with a Troxler moisture density gauge during 2024 also indicated that sand size and topdressing rate effects depended on the cultivation factor (Table 7). Plots treated with solid tine cultivation always had a greater bulk density than non-cultivated plots (Tables 8 and 9). Additionally, under non-cultivated conditions, plots that were topdressed with fine-medium sand had the lowest bulk density compared to plots topdressed with medium-coarse or medium-fine sand (Table 8). The greater topdressing rate increased bulk density compared to lower topdressing rate under the non-cultivated conditions; however, this effect was not evident when the cultivation (hollow tine and three solid tine events) impact on bulk density was present in the cultivated plots (Table 9).

Data collection during 2024 also included visual ratings of turf quality, routine volumetric water content (VWC) of the surface 0- to 3-inch depth zone; Clegg soil impact values, ball roll measurements (GS3), normalized difference vegetation index (NDVI), dual-head water infiltration, and documentation of the number of hand-watering events and amount of water applied to individual plots. Additionally, we used a DJI Mavic 3 Multispectral drone to collect remote sensing data from the trial. Statistical analyses and summarization of these data are in progress.

<u>Complementary Cultivation Trials</u>

Data collection during 2024 also included visual ratings of turf quality, routine volumetric water content (VWC) of the surface 0- to 3-inch depth zone; Clegg soil impact values, ball roll measurements (GS3), normalized difference vegetation index (NDVI), and dual-head water infiltration. Additionally, we used a DJI Mavic 3 Multispectral drone to collect remote sensing data from the trial. Statistical analyses and summarization of these data are in progress.

Table 1. Description of treatment combinations of sand size, topdressing rate, and cultivation factors, as well as two controls (no mid-season topdressing) evaluated on a 'Shark' creeping bentgrass turf seeded in 2014 and grown on a sand-based rootzone. The trial was initiated in May 2016; cultivation was switched from hollow tine to solid tine cultivation in spring 2023.

Treatment no.	Sand size [a]	Topdressing rate during mid-season [b]	Cultivation [c]	Annual quantity of sand applied
		lb / 1,000 sq ft		lb / 1,000 sq ft
1	medium-coarse	50	none	1,200
2	medium-coarse	50	Solid tine + backfill	1,700
3	medium-coarse	100	none	1,700
4	medium-coarse	100	Solid tine + backfill	2,200
5	medium-fine	50	none	1,200
6	medium-fine	50	Solid tine + backfill	1,700
7	medium-fine	100	none	1,700
8	medium-fine	100	Solid tine + backfill	2,200
9	fine-medium	50	none	1,200
10	fine-medium	50	Solid tine + backfill	1,700
11	fine-medium	100	none	1,700
12	fine-medium	100	Solid tine + backfill	2,200
13	none	0	none	0
14	none	0	Solid tine + backfill	1,200

[a] The first-mentioned size class represents the predominant size fraction in the sand.

[b] Ten applications of topdressing were applied every two weeks from June through early October. Topdressing at 50 lb per 1,000 sq ft represented a 'dusting' quantity (O'Brien and Hartwiger, 2003); whereas topdressing at 100 lb filled the surface thatch and lower verdure layers.

[c] Solid tine cultivation to the 2-inch depth was performed twice a year (April/May and October) using ⅝-inch diameter solid tines spaced to affect 10% of the surface area annually. Solid tine holes were backfilled with medium-coarse sand at 600 lb per 1,000 sq ft. During solid tine cultivation, non-cultivated plots were topdressed with the respective sand at 400 lb per 1,000 sq ft to fill the verdure and surface thatch layers to the same extent as plots cultivated and backfilled with sand.

Table 2. Sand size distributions of the three topdressing sizes, mat layer, and the underlying rootzone at the initiation of the trial; USGA construction specification provided for references. Weighted averages based on distributions of each sand delivery through October 2018.

	Particle diameter (mm)/Size class [a]				
Topdressing Sand Size	2.0-1.0 very coarse	1.0-0.5 coarse	0.5-0.25 medium	0.25-0.15 fine	0.15-0.05 very fine
	------------------------------ % retained (by weight) -----------------------------				
Medium-coarse	0	34.8	57.7	8.4	0.1
Medium-fine	0	0.1	76.7	22.7	0.5
Fine-medium	0	5.7	25.8	66.8	1.7
Mat Layer [b]	0.1	25.3	56.4	15.4	2.7
Rootzone	6.9	25.3	44.6	17.2	4.1
USGA construction specification	≤ 10	--------- ≥ 60 ---------		≤ 20	≤ 5

[a] Sieve opening and mesh: 2-mm = no. 10; 1-mm = no. 18; 0.5-mm = no. 35; 0.25-mm = no. 60; 0.15-mm = no. 100; 0.05-mm = no. 270

[b] Sand size distribution of 45 core samples of the mat layer collected before treatment initiation in May 2016.

Table 3. Analysis of variance of the organic matter content (% by weight), bulk density, and porosity (air-filled and capillary) of mat layers sampled April 2023 – before switching to solid tine cultivation – as affected by the sand size and rate of topdressing and core cultivation on a 'Shark' creeping bentgrass turf maintained at 0.11-inch mowing bench-height in North Brunswick, NJ.

ANOVA Source	Organic Matter Content [a]	Bulk Density [a]	Air-filled Porosity [a]	Capillary Porosity [a]
	-------------------------- probability of significant *F* Test --------------------------			
Sand Size	0.2191	0.0009	<.0001	<.0001
Topdressing Rate (TR)	<.0001	<.0001	0.7817	<.0001
Sand Size × TR	0.4852	0.6435	0.0064	0.0262
Core Cultivation (CC)	<.0001	<.0001	<.0001	<.0001
Sand Size × CC	0.0848	0.0443	0.0034	0.0011
TR × CC	0.0317	0.0049	0.0983	0.6231
Sand Size × TR × CC	0.3811	0.5337	0.1802	0.1210
CV(%)	7.6	2.3	9.4	4.8

[a] Data from undisturbed 3-inch diam. cores of the mat layer collected from each plot in April 2023 before switching the cultivation to solid tines.

Table 4. Topdressing rate and cultivation interaction effect on the organic matter content (by weight) of mat layers sampled April 2023 before switching to solid tine cultivation on a 'Shark' creeping bentgrass turf maintained at 0.11-inch mowing height in North Brunswick, NJ.

Factors		Organic Matter	Bulk
Topdressing Rate	Hollow Tine Cultivation	Content [a]	Density [a]
		-- % by weight --	g/cm^3
50-lb	None	6.03	0.98
100-lb	None	4.79	1.09
50-lb	Twice/year	4.36	1.11
100-lb	Twice/year	3.59	1.17
	$LSD_{0.05}$	0.03	0.02

[a] Data from undisturbed 3-inch diam. cores of the mat layer collected from each plot in April 2023 before switching the cultivation to solid tines.

Table 5. The interactive effect of topdressing sand size and cultivation on the bulk density and porosity (air-filled and capillary) of mat layers sampled April 2023 before switching to solid tine cultivation on a 'Shark' creeping bentgrass turf maintained at 0.11-inch mowing height in North Brunswick, NJ.

Factors				
Topdressing Sand Size	Hollow Tine Cultivation	Bulk Density [a]	Air-filled Porosity [a]	Capillary Porosity [a]
		g/cm^3	--------------- % ---------------	
Medium-coarse	None	1.06	17.3	40.8
Medium-fine	None	1.04	14.3	43.1
Fine-medium	None	1.00	10.1	50.2
Medium-coarse	Twice/year	1.17	19.9	34.8
Medium-fine	Twice/year	1.13	19.6	36.4
Fine-medium	Twice/year	1.14	16.5	39.0
	$LSD_{0.05}$	0.03	1.6	2.0

[a] Data from undisturbed 3-inch diam. cores of the mat layer collected from each plot in April 2023 before switching the cultivation to solid tines.

Table 6 The interactive effect of topdressing sand size and topdressing rate on the air-filled and capillary porosities of mat layers sampled April 2023 before switching to solid tine cultivation on a 'Shark' creeping bentgrass turf maintained at 0.11-inch mowing height in North Brunswick, NJ.

Topdressing Factor			
Sand Size	Rate	Air-filled Porosity [a]	Capillary Porosity [a]
		-------------------- % --------------------	
Medium-coarse	50-lb	17.9	40.2
Medium-fine	50-lb	16.5	40.9
Fine-medium	50-lb	14.3	45.0
Medium-coarse	100-lb	19.3	35.5
Medium-fine	100-lb	17.5	38.6
Fine-medium	100-lb	12.3	44.2
	$LSD_{0.05}$	1.6	2.0

[a] Data from undisturbed 3-inch diam. cores of the mat layer collected from each plot in April 2023 before switching the cultivation to solid tines.

Table 7. Analysis of variance of bulk density and volumetric water content of mat layers sampled *in situ* on April 14 and October 13, 2024, as affected by the sand size and rate of topdressing and cultivation on a 'Shark' creeping bentgrass turf maintained at 0.11-inch mowing bench-height in North Brunswick, NJ.

	April 14, 2024 [a]		October 13, 2024 [b]	
ANOVA Source	Bulk Density	Volumetric Water Content	Bulk Density	Volumetric Water Content
	-------------------------- probability of significant *F* Test --------------------------			
Sand Size	0.0003	<.0001	0.0501	<.0001
Topdressing Rate (TR)	0.0003	0.0055	0.0093	0.0011
Sand Size × TR	0.2238	0.0200	0.1200	0.7785
Cultivation (C)	<.0001	<.0001	<.0001	<.0001
Sand Size × C	0.0041	0.0003	0.0166	0.0002
TR × C	0.0085	0.1080	0.0185	0.0177
Sand Size × TR × C	0.0925	0.9744	0.1797	0.0229
CV(%)	2.3	9.7	3.5	11.5

[a] Measurements were collected with a Troxler Road Reader model 3440 moisture density gauge set in backscatter mode on April 14, 2024, before the third application of solid tine cultivation in 2024.

[b] Measurements were collected with a Troxler Road Reader model 3440 moisture density gauge set in backscatter mode on October 13, 2024, before the fourth application of solid tine cultivation in 2024.

Table 8. The interactive effect of topdressing sand size and cultivation on the bulk density and volumetric water content of mat layers sampled on April 14 and October 13, 2024, on a 'Shark' creeping bentgrass turf maintained at 0.11-inch mowing height in North Brunswick, NJ.

Factor		April 14 [a]		October 13 [b]	
Topdressing Sand Size	Hollow Tine Cultivation	Bulk Density	Volumetric Water Content	Bulk Density	Volumetric Water Content
		--- g/cm^3 ---	---- % ---	--- g/cm^3 ---	---- % ---
Medium-coarse	None	1.06	32.3	1.08	28.4
Medium-fine	None	1.02	36.3	1.09	28.0
Fine-medium	None	0.95	45.0	1.02	35.8
Medium-coarse	Twice/year	1.24	24.8	1.23	23.8
Medium-fine	Twice/year	1.25	24.5	1.25	25.0
Fine-medium	Twice/year	1.23	28.5	1.25	25.6
	$LSD_{0.05}$	0.03	3.2	0.04	2.6

[a] Measurements were collected with a Troxler Road Reader model 3440 moisture density gauge set in backscatter mode on April 14, 2024, before the third application of solid tine cultivation in 2024.

[b] Measurements were collected with a Troxler Road Reader model 3440 moisture density gauge set in backscatter mode on October 13, 2024, before the fourth application of solid tine cultivation in 2024.

Table 9. The interactive effect of topdressing rate and cultivation on the bulk density and volumetric water content of mat layers sampled on April 14 and October 13, 2024, on a 'Shark' creeping bentgrass turf maintained at 0.11-inch mowing height in North Brunswick, NJ.

Factor		Bulk Density	
Topdressing Rate	Cultivation	April 14 [a]	October 13 [b]
		------------------ g/cm^3 -----------------	
50-lb	None	1.00	1.04
100-lb	None	1.05	1.10
50-lb	Twice/year	1.23	1.24
100-lb	Twice/year	1.25	1.24
	$LSD_{0.05}$	0.03	0.03

[a] Measurements were collected with a Troxler Road Reader model 3440 moisture density gauge set in backscatter mode on April 14, 2024, before the third application of solid tine cultivation in 2024.

[b] Measurements were collected with a Troxler Road Reader model 3440 moisture density gauge set in backscatter mode on October 13, 2024, before the fourth application of solid tine cultivation in 2024.

2025 Plan of Work

USGA ID#: 2023-01-768

- We will continue treatments and data collection for visual observations of turf quality, volumetric water content (VWC) of the surface 0- to 3-inch depth zone; Clegg soil impact values, ball roll measurements (GS3), normalized difference vegetation index (NDVI); hand-watering quantification, and dual head infiltrometers (SATURO) to assess water infiltration during 2025.
- We are also scheduled to collect the undisturbed cores of the mat layers to assess bulk density, porosity, and sand size distribution at the end of the trial. We are debating when to perform this task relative to the total number of solid tine cultivation events. We have applied four solid tine cultivation events, and, by mid-October 2025, we will have six events. Waiting to sample after the sixth event is problematic due to the likely time constraints imposed by weather and the subsequent unhealed tine holes immediately after the sixth cultivation event. We are interested in comments from the research committee on this matter.
- A peer-review publication on the surface characteristics during the first seven years of this trial is in review for Agronomy Journal.
- We are drafting a second publication focused on the physical properties within the mat layer during the first seven years of this trial and plan to submit it for review in Agronomy Journal.

USGA ID#: 2022-10-753

Title: Influence of Topdressing on the Firmness and Soil Organic Matter Content of Bentgrass Putting Greens

Project Leader: Doug Soldat, Ph.D.
Affiliation: University of Wisconsin-Madison

Objectives: The objectives of this work were to 1) compare approaches for determining proper sand topdressing amounts, 2) understand how decisions about annual topdressing rate, application frequency, and sand particle size affect firmness, 3) compare the relationship among the major methods for measuring putting green surface firmness, and 4) validate the Ohio State Greens Organic Matter Management Tool.

Specific hypotheses include:

1. The USGA method will result in firmer putting surfaces than the PACE Turf and clipping volume (Woods) methods because of the greater sand topdressing volume associated with the USGA method.
2. Topdressing frequency (weekly vs. monthly) will not significantly influence putting green firmness on most measurement dates, allowing turfgrass managers to have the freedom to choose which topdressing schedules they prefer.
3. A finer topdressing sand with a greater coefficient of uniformity will result in significantly greater surface firmness than a standard sand that more closely matches the original root zone.
4. The Ohio State Greens Organic Matter Management Tool will prove useful in predicting changes in surface soil organic matter and therefore become a valuable tool for assisting turfgrass managers in their decision making for topdressing and cultivation events.

Start Date: 2022
Project Duration: 3 years.
Total Funding: $96,749

Summary Points:

- The greatest annual topdressing volume (USGA) resulted in a significantly firmer surface than the lowest volume (PACE Turf) for only one of the five firmness devices after three years.
- Topdressing weekly resulted in significantly firmer greens than monthly for two of the five firmness devices.
- The finer sand with a higher coefficient of uniformity did not result in firmer surface after three years of topdressing compared to the standard sand with all five devices.
- Greater annual sand application volume led to a significant decrease in organic matter and soil moisture in the top three inches compared to the lowest annual sand application volume.
- The Ohio State Greens Organic Matter Management Tool was able to accurately predict the surface soil organic matter across the range of topdressing treatments, and therefore has potential to be a useful tool for planning topdressing and cultivation decisions.
- While the different topdressing volumes resulted in differences in surface soil organic matter (4.4% vs 6.1% after three years of divergent management), the differences in playing surface performance (speed, firmness, quality, density) were minor across that range.

Summary Text

Rationale: Sand topdressing of putting greens is one of the most important management practices for producing high quality playing surfaces. There is some consensus about the appropriate sand topdressing rate for putting greens, yet with recommendations ranging from 16-35 ft^3 per 1000 ft^2, there remains room for refinement. Identifying the proper annual topdressing rate is important for controlling the accumulation of soil organic matter over a period of years, but across a shorter temporal interval, topdressing decisions affect putting green performance and playability. Putting green firmness is one of the most important putting green performance characteristics. Unfortunately, the factors affecting firmness remain poorly characterized. The USGA developed and utilizes the TruFirm device for quantifying putting green firmness, the R&A uses the Clegg Impact Soil Tester, and the PGA Tour measures the depth of the depression created by a steel ball dropped from a height of 6 feet. Clearly, these international golf organizations value the surface firmness of putting greens, yet the research into the factors affecting surface firmness is remarkably thin. The majority of the information on putting green firmness exists in non-peer reviewed publications. A search for "putting green" AND "firmness" on the Turfgrass Information File turned up 16 hits in the refereed literature, of 301 total hits for that search. From the reviewed literature, surface firmness is related to soil water content, soil bulk density, and soil organic matter. This research seeks to quantify how topdressing rate, frequency, and particle size decisions affect surface firmness.

Materials and Methods: Three annual sand topdressing rates were evaluated and each was applied at either weekly or monthly intervals (Table 1). In addition, two sand particles sizes were tested (properties in Table 2) in this randomized complete block design with three factors and four replications. The three topdressing rate methods include what we call the USGA method, the PACE Turf method, and the clipping volume method. The USGA method is based on the Whitlark and Thompson (2019) article that recommends 25-35 ft^3 per 1000 ft^2 for a golf course with a 30-week growing season. The bentgrass growing season in Wisconsin is approximately 26 weeks, 87% of Whitlark and Thompson's example, so for this study that method will result in the application 26 ft^3/1000 ft^2 of sand. The PACE Turf Method relies on the use of the PACE Turf Growth Potential Model, which estimates cool-season grass growth based on weather or climate inputs. This model can be used to normalize sand topdressing to climate or weather data. The default spreadsheet uses data from Hempfling et al. (2017) to establish the maximum monthly sand application (300 lbs/1000 ft^2 / month). When the estimated growth decreases, the recommended monthly sand also decreases. For example, in New Brunswick, NJ, cool-season growth potential is nearly 100% in June and September. For these months, the PACE Turf method recommends ~300 lbs/1000 ft^2 per month. In October, the estimated growth potential is about 50%, so only about ~150 lbs/1000 ft^2 of sand is recommended. Using climate data from Madison, WI, the PACE Turf Method recommends 14 ft^3/1000 ft^2 of sand, substantially less than the USGA method. Finally, many turf managers are measuring clipping volume from their putting greens, while there is little research data to suggest how clipping volume could be used to guide topdressing, Dr. Micah Woods has suggested applying 1 mm (3.3 ft^3/1000 ft^2) of sand for each L/m^2 of fresh clippings collected; this method is referred to as the clipping volume method and will vary depending on the grass growth rate. All treatments received one annual hollow-tine core cultivation event in late September or early October where ~8 ft^3/1000 ft^2 of sand was used to fill the holes left by the tines.

Table 1. List of treatments.

Treatment #	Method	Frequency	Sand Size	Approx. Annual Sand Volume
				ft^3 M^{-1}
1	USGA	Weekly	Fine	26
2	USGA	Monthly	Fine	26
3	USGA	Weekly	Standard	26
4	USGA	Monthly	Standard	26
5	Pace	Weekly	Fine	14
6	Pace	Monthly	Fine	14
7	Pace	Weekly	Standard	14
8	Pace	Monthly	Standard	14
9	Woods	Weekly	Fine	18
10	Woods	Monthly	Fine	18
11	Woods	Weekly	Standard	18

12	Woods	Monthly	Standard	18

Table 2. Particle size distribution of the two sands used.

Sand	Coefficient of Uniformity	V. Coarse	Coarse	Medium	Fine	V. Fine
			%			
Standard	2.0	0.4	31.5	56.6	9.1	1.5
Fine	2.5	0.1	22.7	42.9	26.8	7.3

We measured putting green surface firmness weekly using five devices:

1) Clegg Impact Soil Tester Hammer (2.25 kg hammer, flat bottom)
2) Clegg Impact Soil Test Hammer (0.5 kg hammer, round bottom)
3) Spectrum TruFirm
4) Precision USA Putting Green Firmness Meter
5) USGA GS3 Ball (used only during the 2024 season)

In addition to firmness measurements, we measured soil moisture, normalized difference red edge (NDRE), soil surface strength and visual turfgrass quality weekly during the growing season. Once a month, we measured ball roll distance and collected clippings from the plots. Soil organic matter was measured using loss on ignition (440℃ for 2 hours) prior to the trial initiation using a 1-inch diameter probe with five subsamples per plot. The intact samples were segmented into depths of 0-1, 1-2, and 2-3 inches. The samples were not ground or sieved prior to ignition, so the verdure and living roots were included in organic matter measurement. These measurements were repeated after the final topdressing event of the season. The verdure biomass and shoot density were quantified at this same timing using three, 2-inch diameter subsamples from each plot.

Results

At the end of the study period, we observed no significant differences in firmness from the two Clegg devices, or the GS3 Ball (Table 3). For the Spectrum Trufirm method, we found the USGA topdressing method to result in significantly firmer surface than the clipping volume method (Woods). We also observed significant differences in firmness from the Precision USA ball drop method, with USGA topdressing method resulting in a firmer surface than the Woods method, which was firmer than the PACE Turf method. In summary, it appears that higher sand application volumes are related to firmer surfaces, depending on measurement device. No differences in surface shear or ball roll distance were observed among the three topdressing volumes.

The GS3 Ball detected a significantly softer surface from the fine sand, while all other firmness devices did not detect differences in surface firmness between the two sand sizes (Table 3). This is interesting, as the finer sand had a greater coefficient of uniformity than the standard sand (Table 2), which would suggest a firmer surface from because of the fine sand topdressing. Sand size did not affect shear or ball roll distance.

Application frequency did not affect surface firmness as quantified by the Clegg devices or the Precision USA ball drop method. However, the Spectrum Trufirm and the GS3 Ball detected a firmer surface for the weekly topdressing frequency. Frequency did not affect ball roll distance or surface shear strength.

Table 3. Surface firmness strain, and ball roll results at the **final rating dates** for the study. Results followed by different letters within each column are statistically different according to Fisher's Least Significant Difference (alpha=0.05).

Treatment	Clegg (2.25 kg)	Clegg (0.5 kg)	Trufirm	Precision	GS3 Ball	Shear	Stimpmeter	GS3 Ball
	---- G force (greater is firmer) -----		Depth (inches, greater is softer)			kPa	------------ ft ------------	
Volume Method								
USGA	5.86 a	7.12 a	0.414 b	0.305 c	0.488 a	48.4 a	11.1 a	11.7 a
PACE Turf	5.76 a	7.21 a	0.428 ab	0.340 a	0.491 a	47.9 a	10.9 a	11.4 a
Woods	5.73 a	7.06 a	0.445 a	0.324 b	0.495 a	49.9 a	11.0 a	11.5 a
Sand Size								
Fine	5.71 a	7.06 a	0.436 a	0.324 a	0.500 a	49.5 a	11.0 a	11.6 a
Standard	5.86 a	7.21 a	0.422 a	0.321 a	0.483 b	48.0 a	11.0 a	11.5 a
Applic. Freq.								
Weekly	5.79 a	7.23 a	0.420 b	0.320 a	0.483 b	48.9 a	11.1 a	11.5 a
Monthly	5.77 a	7.03 a	0.438 a	0.326 a	0.500 a	48.6 a	10.9 a	11.5 a

Topdressing volume did not significantly affect turfgrass quality or tiller density (Table 4). However, topdressing with finer sand resulted in a small but statistically significant increase in turfgrass quality. Similarly, topdressing less frequently also resulted in a small but significant increase in turfgrass quality. The magnitude of these differences are small enough that they are unlikely to be discernable by any given individual on any single day. However, the differences were statistically significant because of the large number of replications for these factors. NDRE measures the reflectance of light from a surface and therefore it is not surprising to see that the highest volume of topdressing (USGA method) resulted in slightly less green color than the lower volume methods. Similarly, more frequent sand application led to less green color.

There were strong effects of topdressing volume on volumetric water content (VWC) in the top three inches of soil (Table 4). The greatest topdressing sand volume method (USGA) had the lowest average soil moisture, and the lowest sand volume topdressing method (PACE Turf) had the highest average soil moisture. These results mirror the soil organic matter in the top 1 inch (Table 4).

Table 4. Study averages for turfgrass visual quality, normalized difference red edge index (NDRE), and volumetric water content (VWC) integrated across the top 3 inches. Organic Matter (OM), turfgrass density, and verdure biomass data are all from samples taken 1 October 2024. Results followed by different letters within each column are statistically different according to Fisher's Least Significant Difference (alpha=0.05).

Treatment	Visual Quality	NDRE	VWC	OM 0-1 in	OM 1-2 in	OM 2-3 in	Tiller density	Verdure
	1-9, 9 is best	Greater is greener	--------------------------- % ---------------------------				#/cm^2	mg/cm^2
Volume Method								
USGA	6.16 a	0.297 b	23.4 c	4.36 c	2.98 a	2.13 a	14.5 a	19.8 b
PACE Turf	6.07 a	0.307 a	25.3 a	6.16 a	2.70 b	1.99 a	15.2 a	24.9 ab
Woods	6.10 a	0.306 a	24.4 b	5.76 b	2.69 b	1.99 a	15.7 a	29.2 a
Sand Size								
Standard	6.05 b	0.302 a	24.5 a	5.53 a	2.76 a	1.97 a	15.0 a	23.8 a
Fine	6.17 a	0.305 a	24.2 a	5.32 a	2.81 a	2.11 a	15.2 a	25.5 a
Applic. Freq.								
Weekly	6.04 b	0.301 b	24.5 a	5.27 b	2.89 a	2.08 a	15.7 a	23.1 a
Monthly	6.18 a	0.306 a	24.3 a	5.58 a	2.71 b	1.98 a	14.7 a	26.1 a

The Ohio State Putting Green Management Tool proved very accurate for predicting the organic matter at the end of the study period (Figure 1). The model was populated with the soil organic matter levels for the top three inches prior to study initiation. Then, the monthly topdressing and aeration operations for the USGA topdressing method (highest sand volume) and the PACE Turf topdressing method (lowest sand volume) were entered for the three years. The model allows for an adjustment of the organic matter accumulation factor. The default setting is 3.5 and the manual says that it can be adjusted down to 2.5 for situations where turf is managed to limit growth, or up to 4.5 for situations with frequent irrigation, high N levels, aggressive cultivars, or acidic soil pH. We found the closest match between the observed and predicted OM at the end of the study by using the 4.5 accumulation factor.

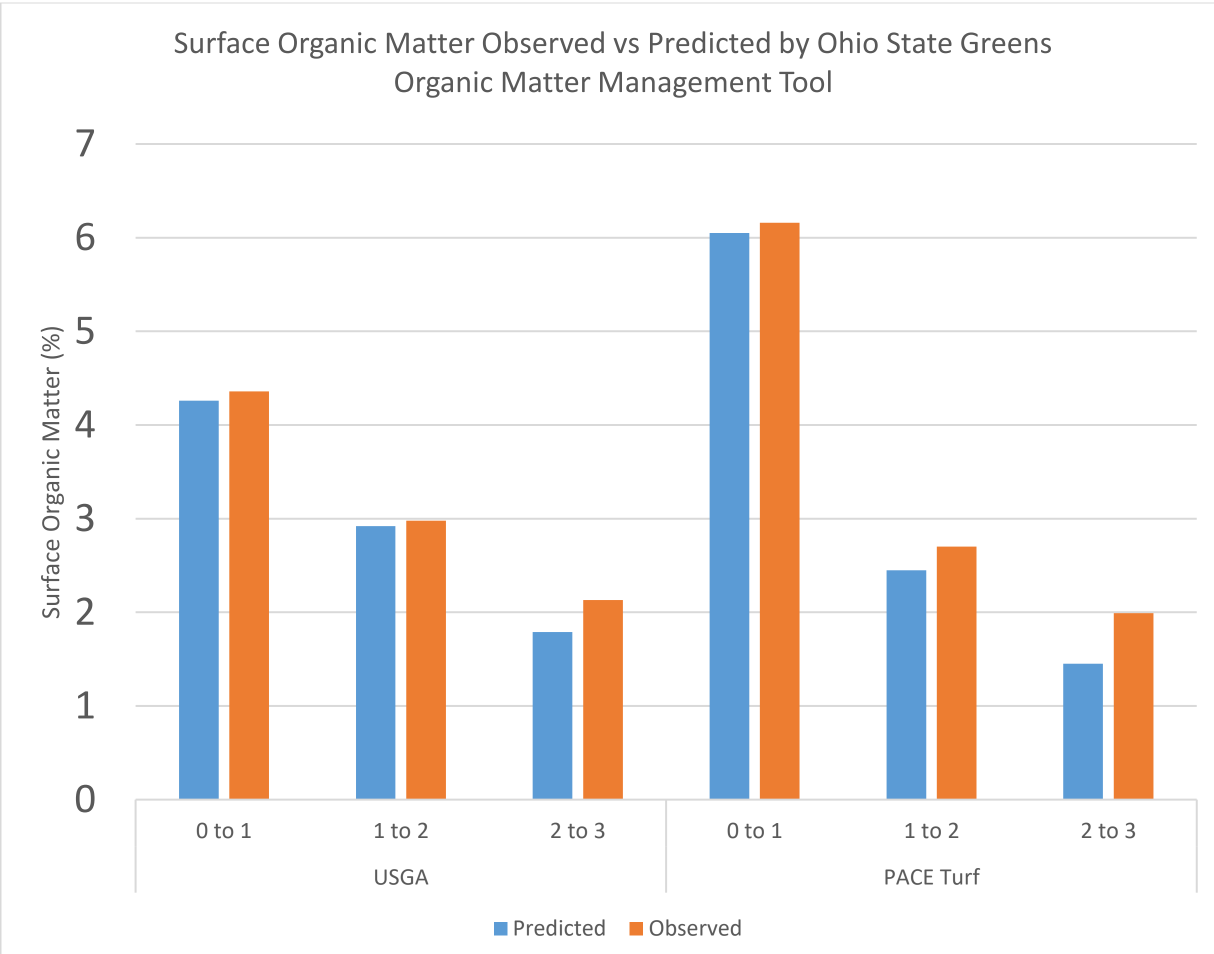

Figure 1. Comparison between the Ohio State Greens Organic Matter Management Tool and the observed soil organic matter after three seasons. The organic matter accumulation factor was set to 4.5 and the organic matter decay factor was 0.025.

The topdressing factors did not affect the average amount of grass clippings collected over the study period (Table 5). The method with the greatest sand application method resulted in significantly more sand removal by the mower than the two lower methods. None of the topdressing factors influence ball roll distance, and the regression between the GS3 Ball and Stimpmeter for ball roll speed resulted in a slope of 0.92 and an r^2 of 0.68 (Figure 2).

Table 5. Study averages for clipping mass, sand removal by mowing, and ball roll distance as affected by the topdressing factors. Ball roll distance measurements are separated because the GS3 Ball was not available prior to the 2024 season. Results followed by different letters within each column are statistically different according to Fisher's Least Significant Difference (alpha=0.05).

Topdressing Treatments	Clippings	Sand Removed	Stimpmeter 2022-2023	Stimpmeter 2024	GS3 Ball 2024
	------------- g m^{-2} -------------		-------------------------- ft --------------------------		
Volume					
USGA	8.42 a	2.29 a	10.5 a	10.4 a	10.8 a
PACE Turf	7.70 a	1.43 b	10.6 a	10.3 a	10.6 a
Woods	8.23 a	1.37 b	10.6 a	10.4 a	10.8 a
Sand Size					
Standard	7.9 a	1.97 a	10.6 a	10.3 a	10.6 a
Fine	8.3 a	1.43 a	10.5 a	10.4 a	10.8 a
Applic. Freq.					
Weekly	8.12 a	1.45 a	10.6 a	10.4 a	10.8 a
Monthly	8.11 a	1.95 a	10.5 a	10.3 a	10.7 a

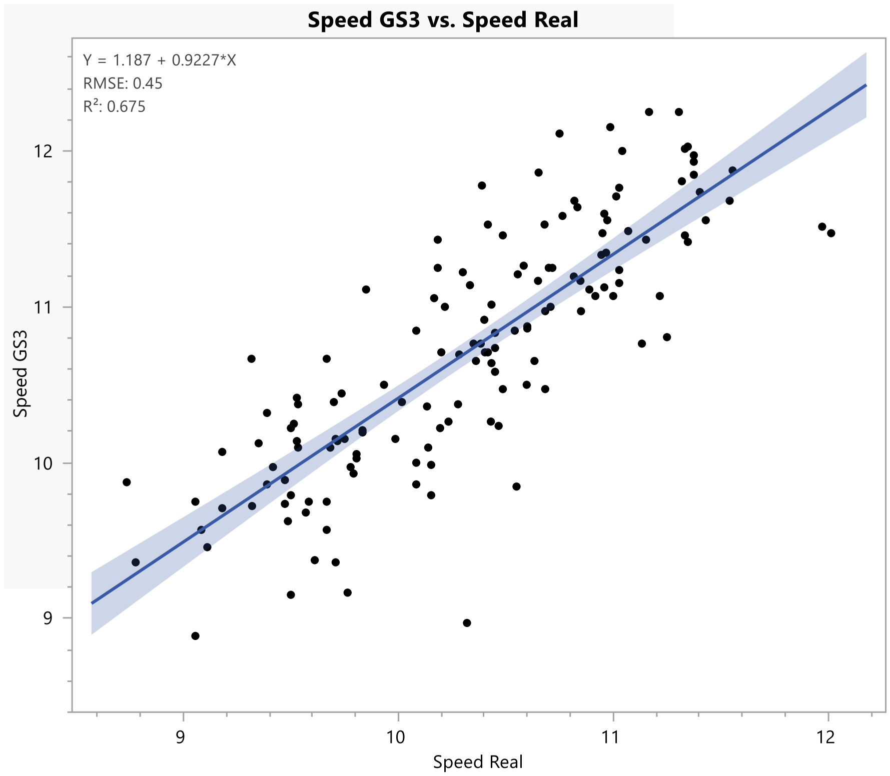

Figure 2. Relationship between USGA Stimpmeter and USGA GS3 Ball for ball roll distance. The shaded blue area shows the 95% confidence interval for the regression line.

Researchers collecting firmness data from the study area

USGA ID#: 2023-23-790

Title: Field-based putting green assessment using GS3 technology

Project Leaders: Michael Richardson and Wendell Hutchens, University of Arkansas
Key Project Personnel: William Green, Sam Kreinberg, and John McCalla, and Daniel O'Brien
Affiliation: University of Arkansas, and USGA

Objectives:
The overall goal of this project is to test the GS3 device on multiple putting green species that are being managed to produce a range of playing conditions. The GS3 will be compared to other devices or measurements that are designed to collect similar putting green performance data.

Start Date: Spring 2024
Project Duration: Data collection will be completed in December 2025
Total Funding: $20,000

Summary Points:

- The GS3 roll test was able to differentiate between foot traffic and core aerification treatments, effectively measuring vertical or horizontal movement of the golf ball after surface disruption
- The GS3 ball roll distance was well-correlated to Stimpmeter ball roll distance over all the studies conducted
- GS3 trueness measurements were found to be weakly correlated to dispersion width and dispersion area
- GS3 trueness and smoothness measurements were highly correlated to each other across a range of putting green surface quality conditions.

Background:

Putting greens have a large impact on the golfer experience and because of this, putting greens are the most intensely managed surface on a golf course. Golfers prefer to play on putting greens that provide a ball roll that is free of deviations caused by the surface, but surface deviations can be difficult to quantify for turfgrass managers. In early 2023, The United States Golf Association announced the official launch of a new technology called GS3, which is a rechargeable smart ball that is designed to measure golf course performance metrics such as green speed, trueness, and firmness. With the development of the GS3, there are new opportunities for researchers and superintendents to better understand putting green surfaces and how they respond to various cultural practices and play from golfers. Some of the unique metrics collected by the GS3 include trueness and smoothness, which aim to define how a golf ball rolls along the surface, characteristics that have previously been difficult to quantify.

The Stimpmeter is the most common way to evaluate putting greens. The Stimpmeter's ball roll distance test is used to determine how the surface interacts with the golf ball. The limitations with the Stimpmeter are that the only data collected is the ball roll distance, and not the qualities of the roll along the surface. The Sports Turf Research Institute (STRI) developed a visual bobble test to assess the smoothness and trueness of ball roll along the surface. The STRI visual bobble test uses the ball roll off of a Stimpmeter to assess vertical and lateral deviations that occur during the roll (Windows & Bechelet, 2010). This subjective test uses a 1-9 scale (1=large deviations and 9=no deviations) that is assigned by a rater that watches the roll.

Another method of evaluating putting greens is the dispersion or spread test. The dispersion test utilizes a fixed ramp device that golf balls are rolled down. For this project, the Perfect Putter golf training aid was used (Reasor et al., 2021). With the ramp fixed on the surface, 20 golf balls are rolled down the ramp and are marked at their final resting positions with chalk, as to not disturb the surface. The two furthest marks apart perpendicular to the line are measured (dispersion width), and the two furthest marks parallel to the line are measured (dispersion length). Those two metrics can be multiplied to obtain a dispersion area.

Study 1 – Comparison of GS3 to other performance metrics

Materials & Methods: Data were collected every other week over a three-month period on Pure Eclipse creeping bentgrass, TifEagle ultradwarf bermudagrass, and Lazer zoysiagrass, with each species being mown at 0.125 and 0.100 inches, with individual mowing plots measuring 3 x 15 feet. Data collected included: Stimpmeter ball roll distance, GS3 roll test (ball roll distance, trueness and smoothness), visual bobble test, dispersion test, shear strength, GS3 drop test, TruFirm drop test, Clegg Impact Tester drop test, and volumetric water content at 0.5, 1.5, and 3.0 inches using a TDR 350 (Spectrum Technologies, Aurora IL). Six data points were collected for each of the tests. The area chosen for the roll tests was a random location within the front one third of the plot. Drop tests were conducted along the ball roll line, one foot apart vertically and within one foot laterally of the roll line.

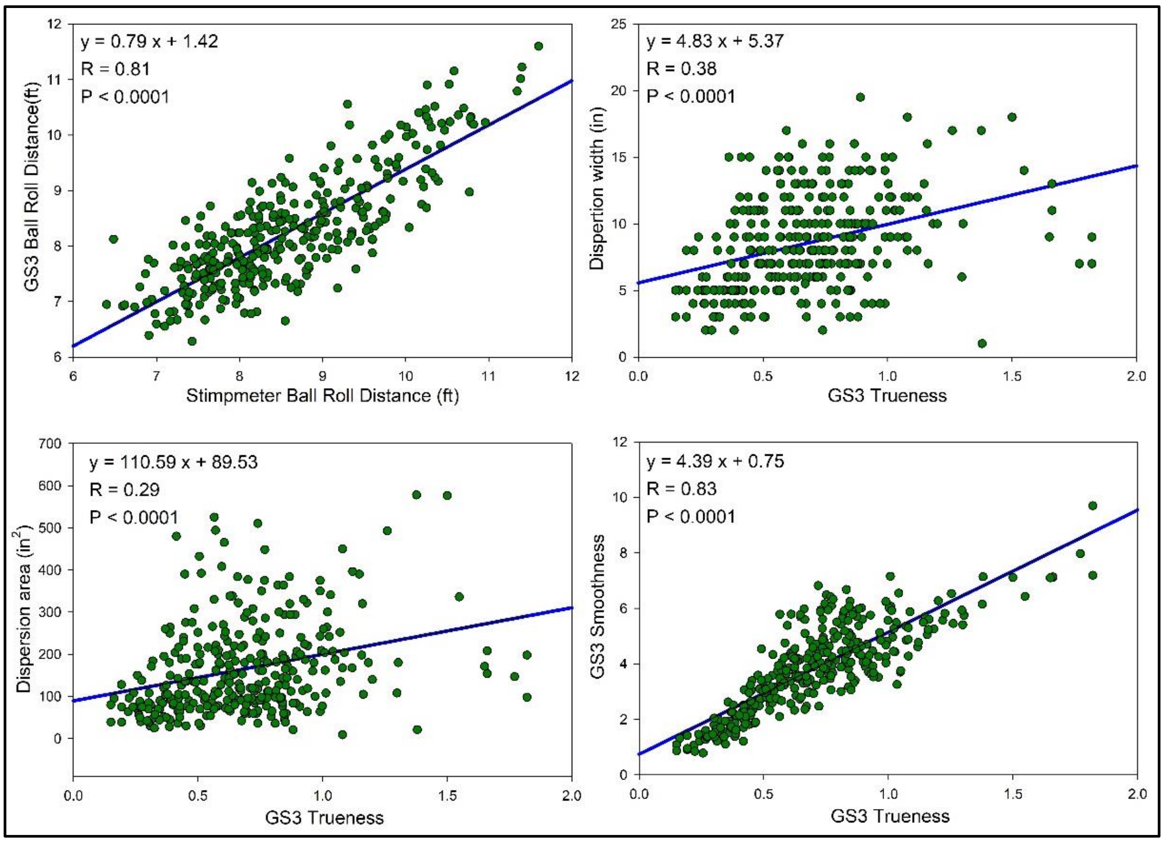

Figure 1. Comparison of various performance metrics used to assess putting green quality. For each graph, linear regression was used to determine the correlation (R) and significance of the relationship (P<0.05)

Results: There was a significant relationship between many performance metrics measured in the study (Fig. 1), but not all data were presented in this report. The GS3 ball roll test was well-correlated with the ball roll distance produced by the Stimpmeter. The GS3 Trueness measurement was also correlated to the dispertion width and dispersion area (Fig. 1), which both represent lateral deviations from the line on which the ball was rolled. Although the fit of those data (R= 0.29 or 0.38) was not as well-correlated as the ball roll distance measurements (R=0.81), these results do show that the GS3 device is picking up similar deviations than can be obtained with other objective tests. One interesting comparison in this dataset was the relationship of the GS3 trueness and smoothness measurements (Fig. 1). These metrics were highly correlated (R=0.81), which suggests that a single "deviation" measurement might be developed to simplify the results to the end-user.

Study 2 – GS3 metrics in response to foot traffic

Materials & Methods: This study was designed to mimic cumulative foot traffic over a 4-day golf tournament. This study was performed on Pure Eclipse creeping bentgrass and TifEagle bermudagrass, although data from the TifEagle plots are not included in this report. For the duration of the study, irrigation was not applied unless wilting was observed. The putting green height of cut was 0.125” and treatments included foot trafficked and non-foot trafficked plots (plot size = 4 x 15 feet). Data were collected three times each day, in the morning (before foot traffic but after mowing), afternoon (after 104 simulated rounds of foot traffic), and at night (after 156 rounds of foot traffic). To simulate foot traffic, plastic spike golf shoes were worn to simulate golfers on a putting green. Simulated traffic was performed every hour between 8 am and 5 pm. Foot traffic was simulated based upon the number of footsteps that occur within a 3-foot radius of the golf hole (Hathaway & Nikolai, 2005) under heavy play conditions. Data collected included Stimpmeter reading, GS3 ball roll test, dispersion test, GS3 drop test, and volumetric water content at 0.5, 1.5, and 3.0 inches.

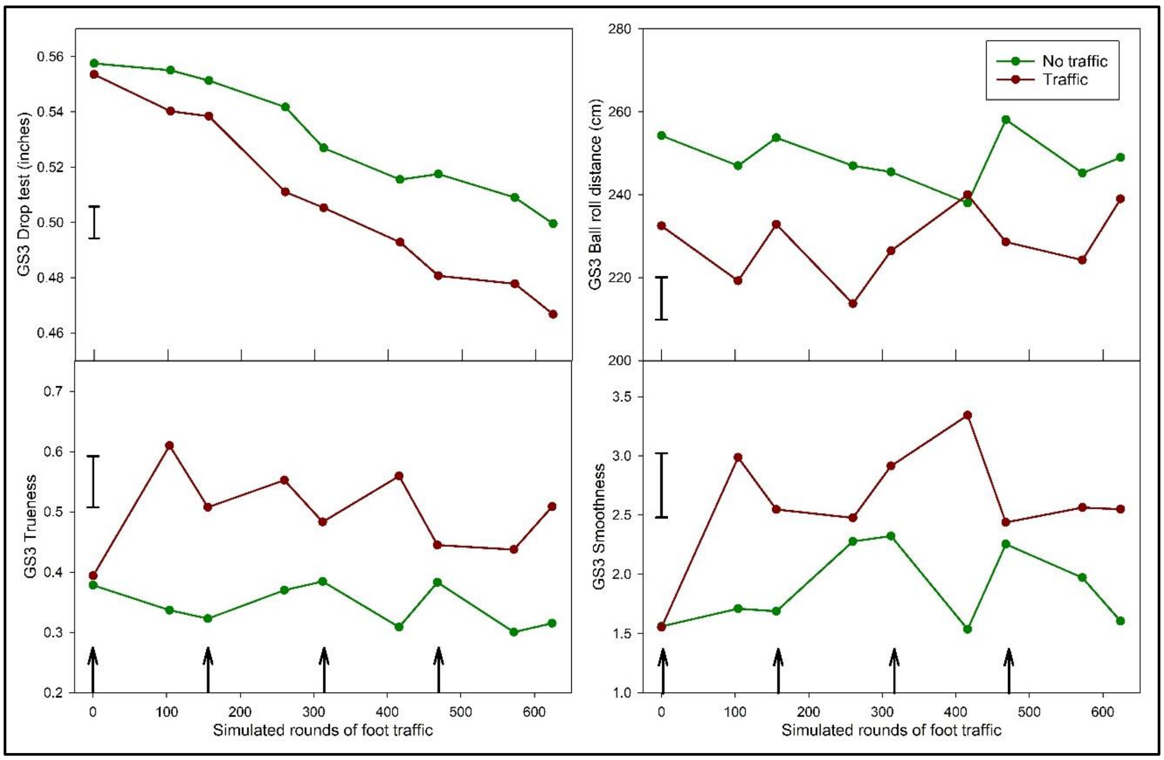

Figure 2. Response of various performance metrics to foot traffic over a 4-day period. For each graph, error bars can be used to compare traffic effects or effects of increased rounds of traffic (P<0.05). Arrows represent mowing events.

Results: The GS3 drop test was able to document an increase in surface firmness across the duration of the study, with traffic plots being consistently more firm than the non-trafficked plots (Fig. 2). GS3 ball roll distance was also signifcantly lower for trafficked compared to no traffic plots. GS3 trueness and smoothness values also responded to foot traffic treatments (Fig. 2). When compared to the non trafficked plots, GS3 smoothness and trueness values were higher in the trafficked areas across the study, although there were inconsistencies from one evaluation period to the next. Although smoothness and trueness measurements in the trafficked plots did not return to non-trafficked levels, there was a noticable drop in those values with daily mowing (Fig. 2).

Study 3 – GS3 metrics in response to core-cultivation

Materials & Methods: This study was performed on both a Pure Eclipse creeping bentgrass and TifEagle bermudagrass putting green managed at a 0.125 inch mowing height. Aerification occurred on 7/18/24 for TifEagle and 9/5/24 on Pure Eclipse and was conducted using a Toro 648 using 5/8-inch hollow tines on a 1.0 x 1.0 inch spacing. A heavy topdressing with sand was applied immediately after cultivation to fill holes. Individual aerification plots were 3 x 15 feet and data were collected before aerification (Day 0) and at days 1, 3, 5, 7, 10, 14, 21, 28, and 35 days post cultivation. Recovery was evaluated using the Stimpmeter, GS3 roll test, visual bobble test, dispersion test, and GS3 drop test and time after cultivation was considered a fixed effect in the analysis of the data. Only data on the creeping bentgrass green are reported.

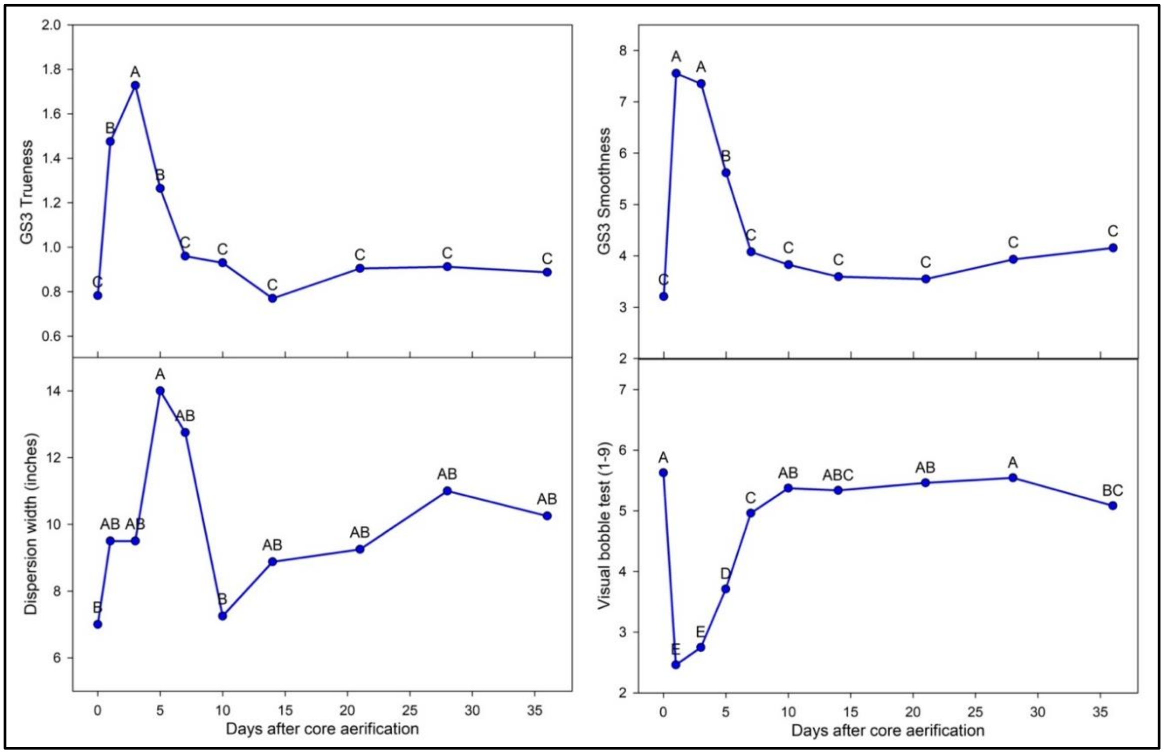

Figure 3. Response of various metrics during recovery from core-aerification over a 36-day period on creeping bentgrass. Within each graph, letters can be used to to compare days after aerification (LSD, P<0.05).

Results: GS3 trueness and smoothness values both increased significantly immediately following surface disruption by core aerification and peaked at day 3 after core aerification (Fig. 3). Values began to decline at 5-7 days following aerification, indicating recovery of the surface. Trueness and smoothness values both returned to levels that were observed before aerification at 7 days after cultivation. Dispersion width followed a similar trend to GS3 trueness and smoothness measurements, but the only significant difference in time was the 5 day after cultivation evaluation period (Fig. 3). The was the only study in which the bobble test provided any meaningful data among these trials, as the cultivaton treatments produced enough vertical and horizontal movement to be consistently picked up by the rater (Fig. 3). Interestingly, the bobble test was almost a mirror image of the trueness and smoothness data collected during the trial.

Conclusions:

After one season of data collection, we have made some initial observations that are noteworthy, but more data analysis needs to be conducted to assess other aspects of the GS3. First, the GS3 roll test was able to differentiate between treatments within our studies, especially those treatments that are know to cause surface disruption such as foot traffic and core aerification. As expected, trueness and smoothness values increased when foot traffic was applied, and when core aerification was performed. These early findings confirm that the GS3 is able to identify changes in surface characteristics that effect vertical or horizontal movement of the golf ball.

The GS3 was also observed to be correlated with other performance metrics that might be used to assess surface quality of putting greens. GS3 Ball roll distance was found to be well-correlated to Stimpmeter ball roll distance over all the studies conducted, while GS3 trueness measurements were found to be weakly correlated to dispersion width and dispersion area. When looking at a larger dataset across several studies, trueness and smoothness values were found to be highly correlated to each other, suggesting that surface disruption is causing similar changes in both vertical and horizontal deviation on the surface. This may also suggest that a single value of “deviation” might be developed moving forward.

References:

Hathaway, A. D., & Nikolai, T. A. (2005). A putting green traffic methodology for research applications established by in situ modeling. International Turfgrass Society, 10:69–70.

Reasor, E. H., Brosnan, J. T., & Woods, M. S. (2021). A New Method to Measure Bermudagrass (Cynodon spp.) Golf Course Putting Green Ball Roll Uniformity. Journal of Testing and Evaluation, 49:3054-3062.

Windows, R., & Bechelet H. (2010). Perfectly true. USGA Green Section Record, 48:24–27.

USGA ID#: 2022-13-756
Title: Variable-rate versus conventional nitrogen application methods to golf course fairways

USGA ID#: 2024-18-828
Title: Additional support for soil testing in variable-N rate and turfRad (2024-07-817) experiments

Project Leader: Chase Straw, Madan Sapkota, Briana Wyatt, and Julie Howe
Affiliation: Texas A&M University

Objectives:

1. Determine the relationship between vegetation indices (VIs), apparent electrical conductivity (EC_a), leaf tissue, and soil nitrogen (N) status in a practical setting on golf course fairways.
2. Developing variable-rate prescription maps for precision nitrogen management on golf course fairways
3. Compare variable-rate to conventional blanket N application methods on golf course fairways with respect to total N applied, turfgrass quality, and N volatilization.

Start Date: 2022
Project Duration: 4-years (2022-2025)
Total Funding: $90,000 (2022-13-756) and $20,000 (2024-18-828)

Summary Points:

- Preliminary data collections using a Toro Precision Sense 6000 and EM-38 were conducted at three golf facilities: The City Course at Briarcrest (Bryan, TX), The Bearkat Course (Huntsville, TX), and The Club at Carlton Woods (The Woodlands, TX).
- The Club at Carlton Woods was selected for Objective 1, featuring sand-capped fairways—one with hybrid bermudagrass and the other with zoysiagrass. Variability in EC_a was influenced by turfgrass and soil attributes. VIs were linked to soil moisture and penetration resistance but did not clearly indicate spatial variability in tissue N, highlighting the need for further research (Objective 1).
- The Bearkat Course was selected for Objectives 2 and 3. Unmanned aerial vehicle (UAV)-derived normalized difference vegetation index (NDVI) and secondary data were integrated to create and validate precise management zones, showing clear seasonal variations in site-specific management units and indicating the need for updated fertilizer prescriptions throughout the growing season (Objective 2).
- Three granular fertilization treatments (conventional, NDVI-based, and model-based) were tested in spring and fall of 2024 to assess their impact on turfgrass health and fertilizer efficiency. Data analysis is pending (Objective 3).

Summary Text:

Rationale

Precision Turfgrass Management (PTM) has the potential to improve fertilizer efficiency on golf courses by addressing variability in turfgrass and soil conditions, particularly on fairways. By employing data-driven approaches, such as NDVI-based and model-based variable-rate fertilization, PTM enables more precise nutrient delivery, reducing over-application and minimizing environmental impacts like nutrient runoff.

However, despite the availability of these technologies, adoption has been limited due to unclear benefits and a lack of comprehensive comparisons with traditional methods. This research aims to evaluate three fertilization treatments—conventional, NDVI-based, and model-based variable rate—over multiple seasons. By developing prescription maps that integrate various soil and turfgrass variables, the study seeks to enhance fertilizer application efficiency, improve turfgrass quality, and minimize environmental impacts, advancing sustainable turfgrass management practices.

Methodology

Objective 1: Data were collected on April 12, 2021, at The Club at Carlton Woods in The Woodlands, TX, focusing on two sand-capped hybrid bermudagrass and two sand-capped zoysiagrass fairways. This objective was divided into two sub-objectives: 1) to compare the spatial relationship of EC_a to other measured turfgrass and soil characteristics, and 2) to compare the spatial relationship of tissue N to other measured turfgrass and soil characteristics.

Georeferenced EC_a (mS m^{-1}) data at a depth of 0.5 m were measured using a tow-behind DUALEM-1S (D-1S; Dualem Inc., Milton, ON, Canada) equipped with an external GNSS receiver. A Toro Precision Sense 6000 (PS6000; The Toro Company, Bloomington, MN) collected ground data on soil moisture (% volumetric water content, VWC), penetration resistance, and normalized difference vegetation index (NDVI) from numerous georeferenced locations within each fairway.

For each site, a sampling grid (62–137 samples, depending on fairway size) was created and imported into a handheld GNSS device to guide further data collection. Measurements included soil moisture and EC_a at a depth of 12.2 cm using a FieldScout TDR 350 (Spectrum Technologies, Aurora, IL, USA), elevation with the handheld GNSS receiver, a single soil core for organic layer depth, and three soil cores per location for tissue N analysis in clippings, as well as soil analysis for particle size, organic carbon, and root mass.

In addition, images were captured from an altitude of 120 m using either a Quantum F90+ or Matrice 200 UAV equipped with a MicaSense Altum multispectral camera (MicaSense Inc., Seattle, WA, USA). The images were processed in Pix4D to create orthomosaics and raster maps for four VIs: NDVI, green NDVI (GNDVI), normalized difference red edge (NDRE), and enhanced vegetation index (EVI). Ground data for both sub-objectives were processed using ordinary kriging to produce raster maps. Sampling grid points were used to extract pixel values, and spatial correlations were assessed to evaluate relationships between variables (α=0.05).

Objective 2: The study was conducted at The Bearkat Course in Huntsville, TX, on fairways featuring 'Tifway 419' hybrid bermudagrass and sandy loam soils. Data were collected during four surveys in May, July, September, and October 2022 using the Precision Sense 6000 (PS6000) to measure key soil and turfgrass variables. These measurements included VWC, penetration resistance (PR), and NDVI, collected from hundreds of georeferenced locations within each fairway. The data were processed using ordinary kriging, a geostatistical method, to create raster maps of these variables for each fairway.

Aerial imagery was also captured during each survey month using a Dragonfly Commander 2 UAV equipped with a MicaSense Altum-PT multispectral camera, flown at an altitude of 120 m. The imagery was processed using Pix4D software to generate orthomosaic maps of NDVI and digital elevation models, which were further analyzed to extract slope data. NDVI values derived from UAV imagery were used in both the NDVI-based and model-based approaches for delineating management zones.

For management zone delineation, Fairways 1 and 5 (i.e., F1 and F5) were divided into 91 and 65 polygons, respectively, with each polygon representing a management unit approximately matching the width of the Texas A&M GNSS-equipped spreader (12.2 x 11.5 m). In the NDVI-based approach, three management zones were defined using UAV-derived NDVI values: low (0–0.38), medium (0.39–0.58), and high (0.59–1.0). These NDVI thresholds were determined based on historical data collected in October 2021.

In the model-based approach, additional variables—including slope, VWC, and PR—were integrated with UAV-derived NDVI values using a K-means clustering technique. This method accounted for variability in soil moisture and terrain factors, enabling the creation of management zones that reflected the complexity of the site. Validation of these management zones and their suitability was performed using historical data from October 2021 to ensure they accurately represented variations in turfgrass health and soil conditions.

Objective 3: This study was also conducted at The Bearkat Golf Course in Huntsville, TX. A randomized complete block design was used to test three treatments: conventional blanket (control) applied to fairways F7, F10, and F13; vegetation index-based variable rate (NDVI-based) applied to fairways F2, F5, and F18; and model-based variable rate applied to fairways F1, F3, and F12. Fertilizer, a slow-release N source (polymer-coated urea), was applied twice, once in spring 2024 and again in fall 2024.

Prescription maps for the NDVI-based and model-based treatments were created, similar to the approach used in Objective 2 (Figure 1), and integrated into a GNSS-guided Turfco Widespin 1550 Broadcast Topdresser. Fertilizer rates were adjusted according to these prescriptions, with low, moderate, and high rates set at 0.5, 1, and 1.5 lbs N/1,000 sq. ft., respectively, while the conventional treatment used a standard rate of 1 lb N/1,000 sq. ft.

Spreader calibration was performed using the catch pan technique. Following applications, data collection occurred at 1, 2, 4, and 8 weeks after each application. Various metrics were measured, including NDVI, soil N content, tissue N, percentage turfgrass cover (via lightbox imaging), and turfgrass quality, from six locations within each fairway.

Results to Date

Objective 1: The first sub-objective aimed to examine the relationship between EC_a and turfgrass and soil characteristics in the sand-capped fairways of the two golf courses at The Club at Carlton Woods. A positive and statistically significant correlation (in three out of four fairways) was observed between EM-38 EC_a and soil moisture measured with both the PS6000 (r=0.13 to

0.63) and the handheld TDR 350 (r=0.20 to 0.62). Negative correlations were found between EM-38 EC_a and penetration resistance, while positive but weak and non-significant correlations were noted between EM-38 EC_a and organic matter depth.

Notably, NDVI and EM-38 EC_a showed significant positive relationships in zoysiagrass fairways but exhibited mixed relationships in bermudagrass fairways. Elevation was negatively correlated with EM-38 EC_a in three fairways. Spatial maps of each parameter indicated that variability in EM-38 EC_a across sand-capped fairways is influenced by turfgrass and soil characteristics. However, the inconsistent relationships both within and between golf courses underscore the need for further research (Figure 2).

A refereed journal article detailing the complete findings from this sub-objective is in press in *Agrosystems, Geosciences, and Environment*, titled “Using electromagnetic induction to inform precision turfgrass management strategies in sand-capped golf course fairways.”

The second sub-objective explored the spatial relationship between turfgrass tissue N content and several VIs in the sand-capped fairways of the two golf courses at The Club at Carlton Woods. The VIs included NDVI, GNDVI, NDRE, and EVI. It was found that almost all VIs ($NDVI_{UAV/Ground,}$ $GNDVI_{UAV}$, $NDRE_{UAV}$, and EVI_{UAV}) showed significant and positive relationships with each. However, the relationships between VIs and tissue N were consistently weak and non-significant.

Tissue N did not exhibit any significant relationship with soil moisture or penetration resistance at any site. In contrast, the general relationship between VIs and soil moisture was significant and positive across the fairways, while the relationship between VIs and penetration resistance was generally non-significant and negative, except for one zoysiagrass fairway.

These results indicate that VIs are highly interrelated, with no clear advantage of one index over another in detecting spatial variability in tissue N. Instead, VIs were more closely associated with soil moisture and, to a lesser extent, penetration resistance (Figure 3).

Objective 2 and 3: Both the NDVI-based and model-based prescription maps revealed clear seasonal variation in site-specific management units (SSMUs) within F1 and F5, both spatially and temporally (Figure 4). From May to October, both approaches exhibited a trend where green and yellow pixels predominated in the early months, indicating healthy turfgrass. However, by August, red pixels increased, signaling turfgrass stress. These fluctuations highlight the importance of updating variable-rate prescription maps with each fertilizer application, as SSMUs shifted over the season due to factors such as moisture stress, topographical changes, soil compaction, and turfgrass quality.

For Objective 3, all data collection for the spring and fall 2024 applications has been completed, but the data have not yet been analyzed.

Future Expectations

- Data analysis will be conducted to evaluate the effectiveness of the three treatments evaluated in Objective 3.

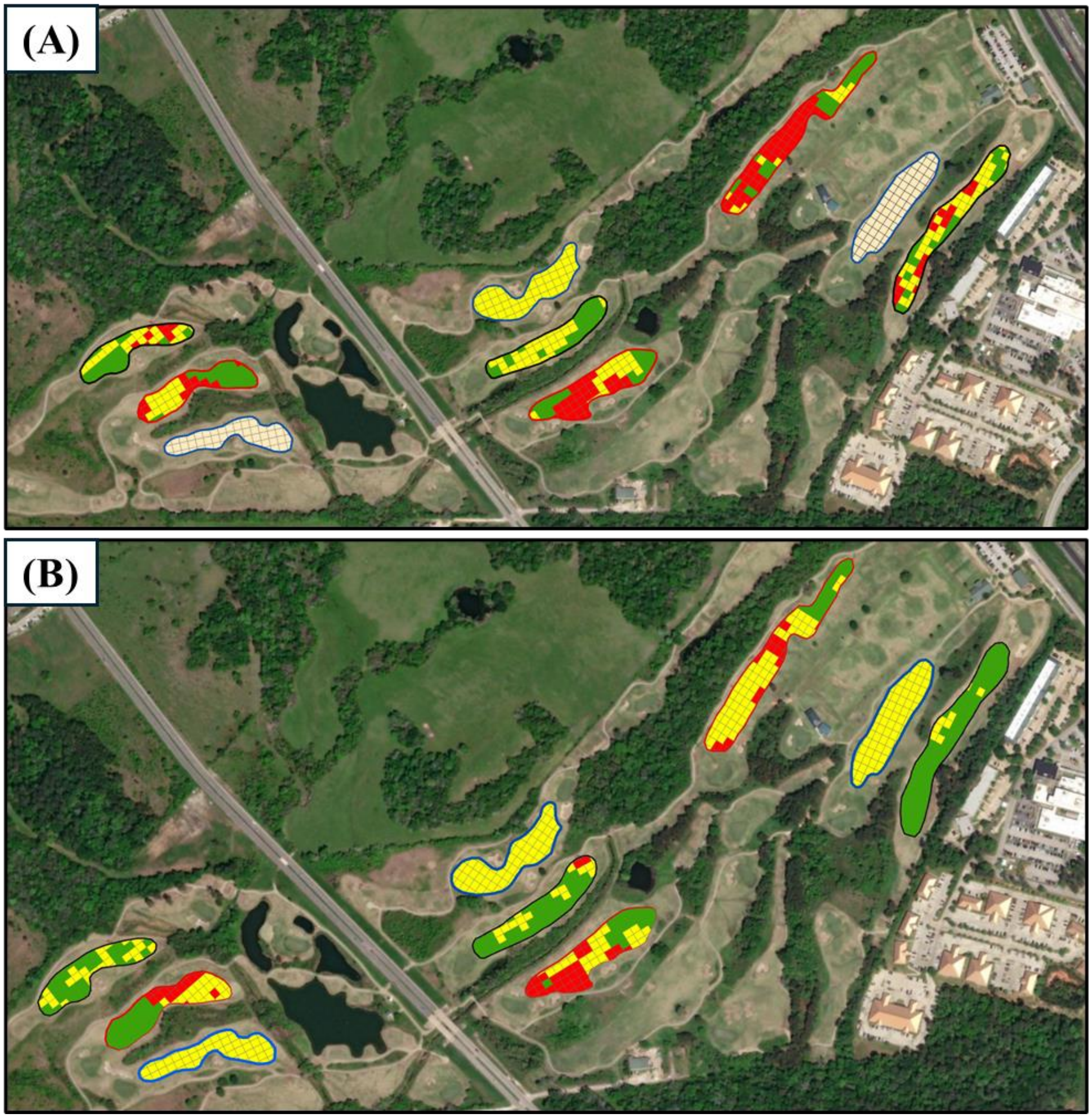

Figure 1. Nine fairways selected for fertilizer application: three each for conventional (blue outline), NDVI-based (black outline), and model-based (red outline) approaches. (A) Spring variable-rate prescription maps; (B) Fall variable-rate prescription maps.

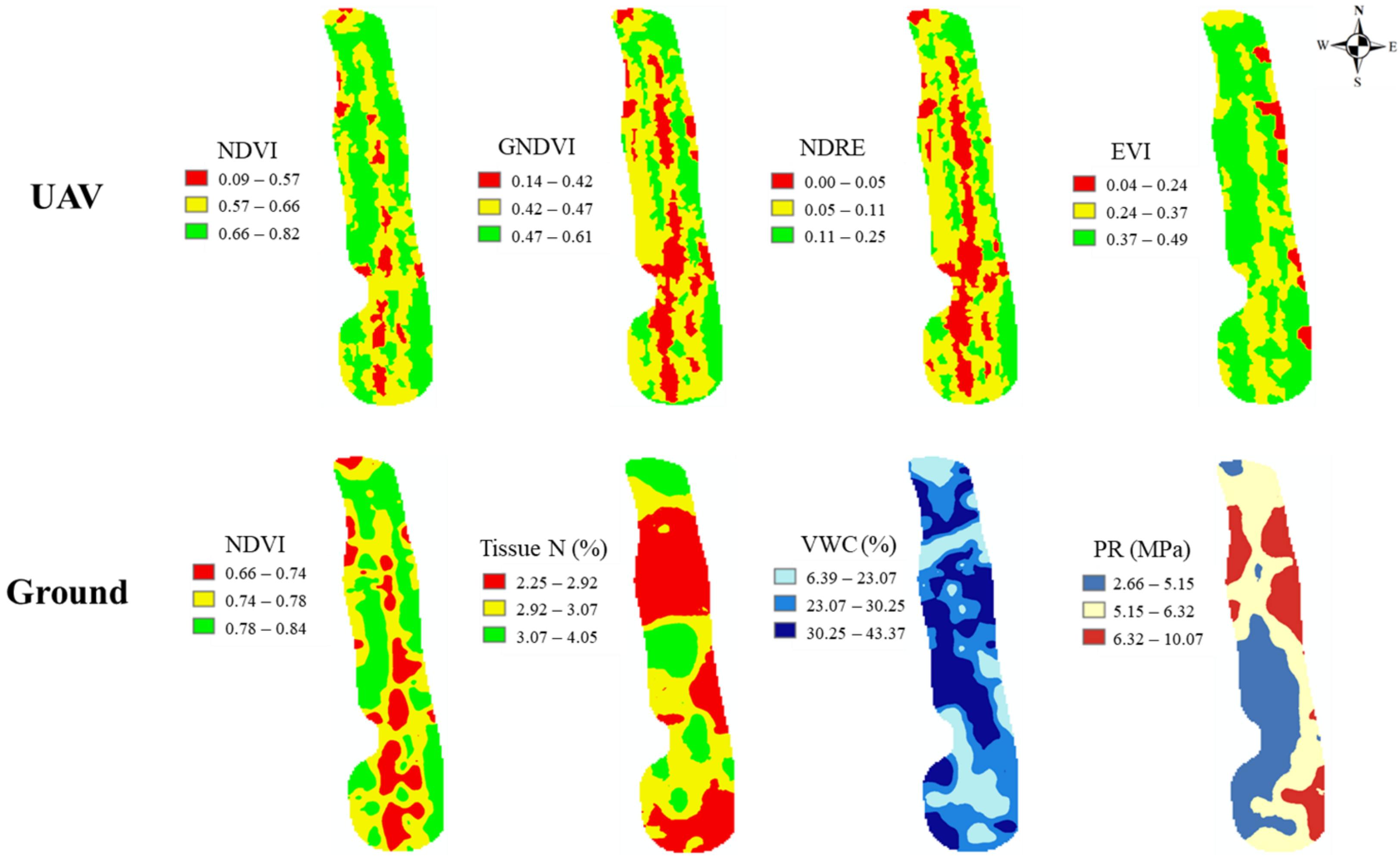

Figure 2. Spatial maps of variables collected from bermudagrass fairway 2 at The Club at Carlton Woods, The Woodland, TX.

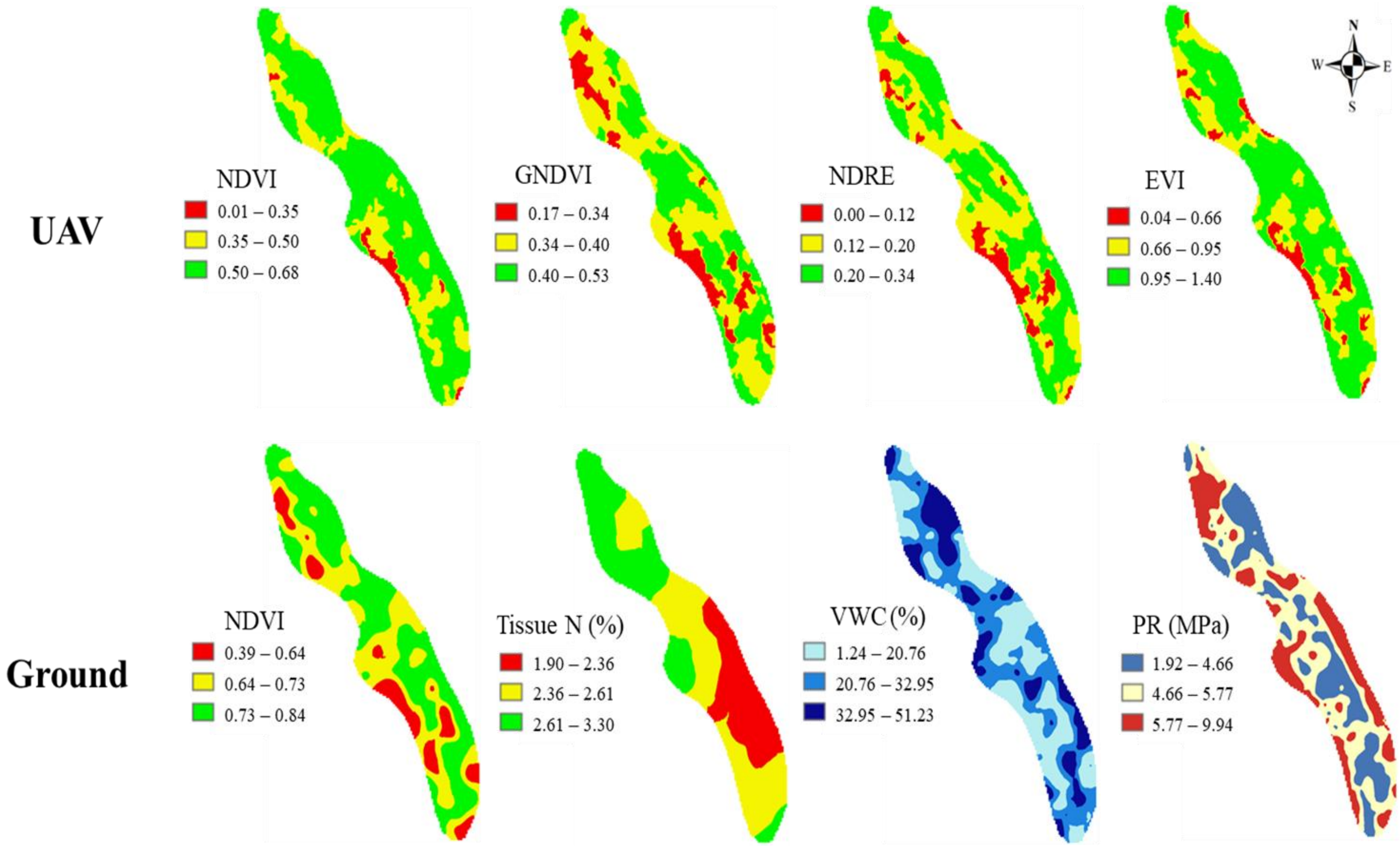

Figure 3. Spatial maps of variables collected from zoysiagrass fairway 8 at The Club at Carlton Woods, The Woodlands, TX.

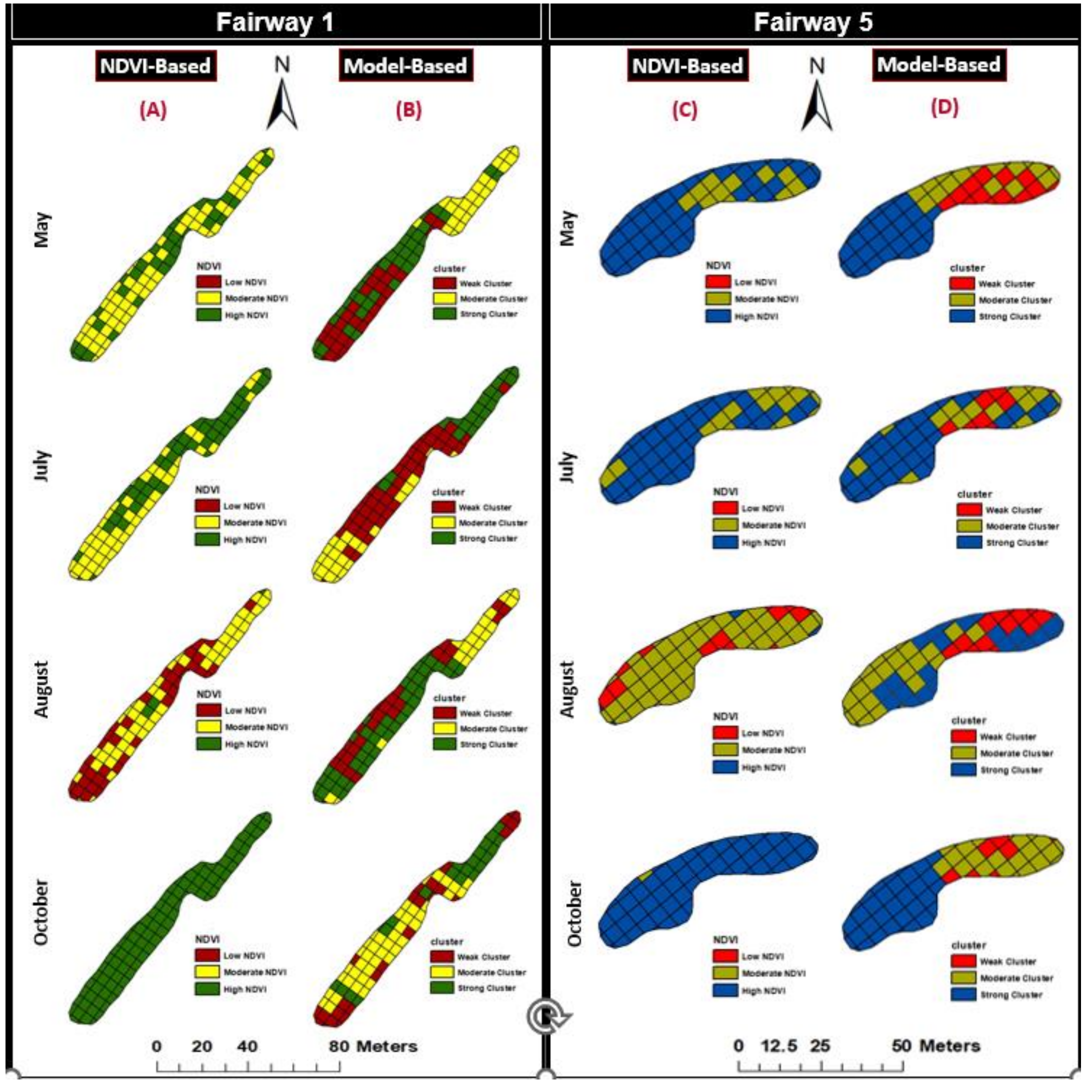

Figure 4. Spatiotemporal variation of SSMUs on golf course fairways (May–October 2022). (A, C) NDVI-based seasonal variation in fairways 1 and 5, categorized as low, medium, and high NDVI. (B, D) Cluster-based variation categorized as weak, medium, and strong.

USGA ID#: 2021-15-739

Title: Determining Irrigation Thresholds to Optimize Water Use, Turf Health, and Playability

Project Leader: Josh Friell & Eric Watkins
Affiliation: University of Minnesota

Objectives:
1) Evaluate measurement methods and devices that quantify physiological and physical responses of turfgrass swards during dry down events to determine their suitability for practical field use by superintendents
2) Determine appropriate PAW_{tt} values to optimize turf health and playability factors relative to water use on creeping bentgrass and Kentucky bluegrass fairways in cool, humid climates
3) Quantify the relationship between PAW_{tt} selection and long-term health of creeping bentgrass and Kentucky bluegrass fairways in cool, humid climates

Start Date: February 1, 2021
Project Duration: 3 years (+1 year no-cost extension)
Total Funding: $113,243.00

Summary Points: Include 3-6 bullet points that summarize the findings of your project to date.

- A reduced, third year of data was collected on drought susceptible cultivars of Kentucky bluegrass and creeping bentgrass subjected to irrigation treatments based on differing threshold-based irrigation treatments.
- Substantial precipitation during the treatment period led to somewhat different outcomes than in previous years and demonstrated the additional value of threshold-based irrigation in rainy conditions.
- A 60% PAW threshold reduced water use by 83% relative to a 75% PAW threshold while maintaining surface firmness that was not statistically different than all other lower threshold treatments.
- Normalized difference vegetation index did not change significantly over time and was not significantly different among threshold treatments at the end of the treatment period.

Plot Maintenance & Treatments:

A third year of data was collected from the plots described in our 2023 update report, which were established prior to Phase 2, Year 1. Briefly, Kentucky bluegrass (*Poa pratensis* L.) 'Shamrock' and creeping bentgrass (*Agrostis stolonifera* L.) 'Penncross' were maintained as individual plots (1.5 m x 1.5 m at the Turfgrass Research, Outreach, and Education Center on the University of Minnesota's Saint Paul Campus). The research area was maintained as a golf fairway with little-to-no weed and disease tolerance. Weeds, including invasion of the edges of Kentucky bluegrass plots by creeping bentgrass, were either removed by hand or controlled with herbicide applications outside of data collection periods. Fungicides were applied preventatively during periods of high disease pressure.

Treatments again consisted of five levels of irrigation based on plant available water (PAW) soil water thresholds levels of 15, 30, 45, 60, and 75% of the VWC range between wilt point and field capacity. Thresholds in units of percent volumetric water content were calculated from the soil water retention curve, assuming field capacity and permanent wilt point matric potential values were -10 and -1500 kPa, respectively. Three replications of each cultivar × irrigation treatment were arranged in a randomized complete block design. On 17 Jun 2024, 2.5 cm of irrigation was applied to plots prior to initiation of treatments to generate rootzone conditions near field capacity. Irrigation treatments were applied from 18 Jun – 14 Aug, 2024. Volumetric water content (VWC) was recorded every 15 minutes using the installed CS655 moisture sensors. Plots were irrigated by hand when the soil moisture content had dropped below the defined threshold for that treatment. At each irrigation application, 0.65 cm (0.25 in) of water was applied evenly to the plot using a hose-end flow meter (Model 825 Meter, Tuthill Corp., Burr Ridge, IL). Turfgrass quality, digital images, NDVI, NDRE, and surface firmness measurements were taken on each plot using the same methods as previous years; however, data was collected only weekly with the exception of surface firmness, which was measured on any day when irrigation was required for a specific plot.

Analysis & Results:

Data Analysis

Total precipitation during the 2024 treatment period was 29.4 cm and total ET_o depth was 19.9 cm. This significant rainfall during the study period created conditions that generally did not allow soil moisture to decline to threshold levels. On just 29 total occasions, any given plot required irrigation based on soil moisture levels. Of those, 24 were for plots in the 75% threshold treatment. Analysis of variance for total water use, along with NDVI and surface firmness from the final data collection date, were conducted in R with subsequent means separation using the *emmeans* and *cld* package implementation of Tukey contrasts. Effects of time and treatments on NDVI were tested using a mixed-effects model as implemented in the *lmer* function.

Soil Moisture, Canopy, & Surface Response:

At the commencement of the treatment period, soil moisture values for all plots were 34.0 – 41.6%. As of 14 Aug 2024, soil moisture values across all plots were 21.3 – 34% (Figure 1). Data collected as of 14 Aug 2024 showed significant differences between the threshold treatments for total cumulative irrigation water applied up to that date as well as surface firmness on the final data collection date but not for NDVI (Table 1).

Surface firmness at the start of the 2024 trial was 44 – 60 g and increased during the treatment period despite substantial precipitation (Figure 2). Data collected on 14 Aug, 2024 at the end of the treatment period was 51 – 65 g and showed statistically significant differences between the threshold treatments (Table 1).

No significant interaction between species and moisture threshold was found for any of the three response variables considered. Plots irrigated at higher moisture thresholds used more water and remained softer. Due to substantial precipitation, moisture thresholds of 15 - 60% plant available water resulted in significantly less water use compared to a 75% threshold and also created a firmer surface. Thresholds as low as 45% provided statistically similar surface firmness but did reduce water use relative to the 75% threshold treatment. Although water use for the 45% and 60% treatments was not statistically different than either the 15% or 30% threshold treatments, they were non-zero and so were different in a practical sense. Nonetheless, even the 60% threshold treatment reduced mean water use by 83% relative to the 75% threshold treatment. Further resolving the relationship between these and the other response variables over time is left for future analysis work.

To assess the long-term impact of the irrigation threshold selection, a model was built using the *lmer* function and included a term for species as well for main and interaction effects of irrigation treatment and days since treatment initiation. Random intercepts were allowed for each plot. The analysis of NDVI response showed that the effects for days and its interaction with irrigation threshold treatment were not statistically significant, indicating that NDVI was not changing substantially over time. Additional analyses of this type are planned to evaluate the effect of each treatment over time on other response variables.

Future Work:

This year of data collection was the final one for this project. Additional data analysis is ongoing and analysis of combined data from all years will be of particular importance. This work is being presented at regional conferences and in trade publications. In the coming year, a scientific publication of this work will be prepared in tandem with the previous research on moisture mapping and sensor-based irrigation that was the motivation for this project.

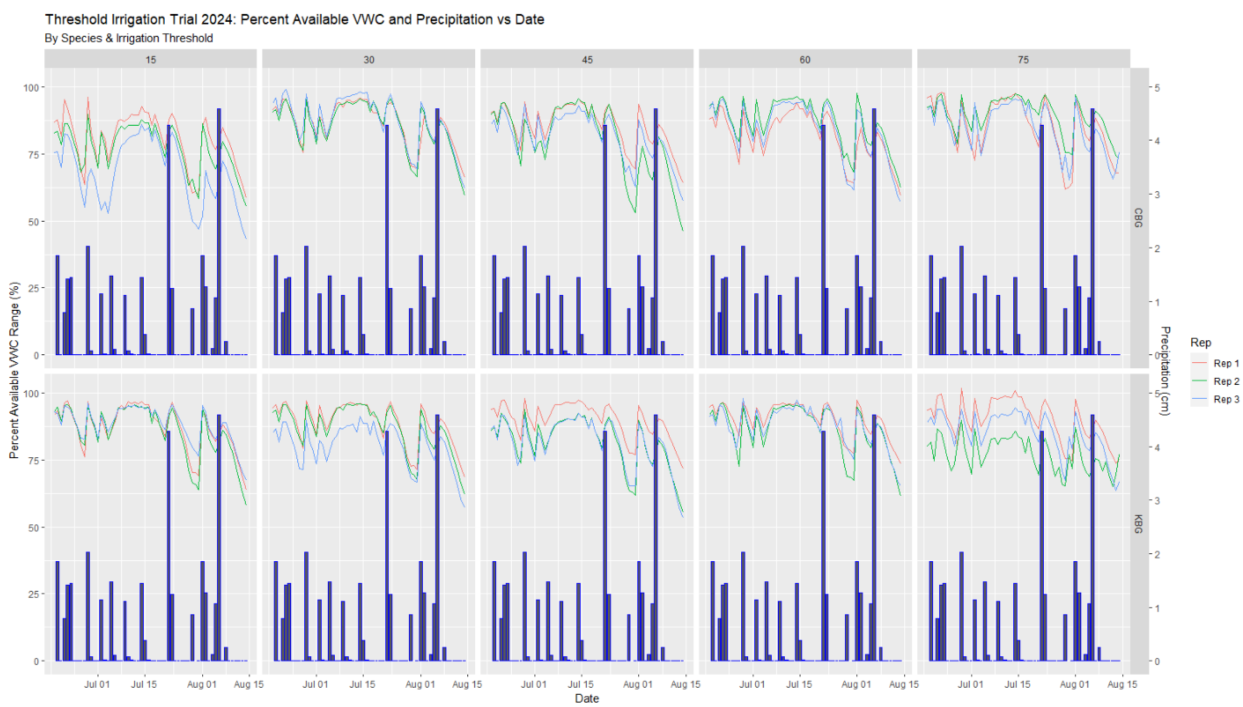

Figure 1. Percent of available volumetric water content range and precipitation versus time for creeping bentgrass and Kentucky bluegrass fairway turf plots maintained at different soil moisture thresholds in St. Paul, MN during 2024. Solid lines show time history of plant available water in the soil by species (creeping bentgrass, top row; Kentucky bluegrass, bottom row), threshold treatment (increasing left to right), and replicate (by color, within facet). Blue bars indicate daily precipitation records.

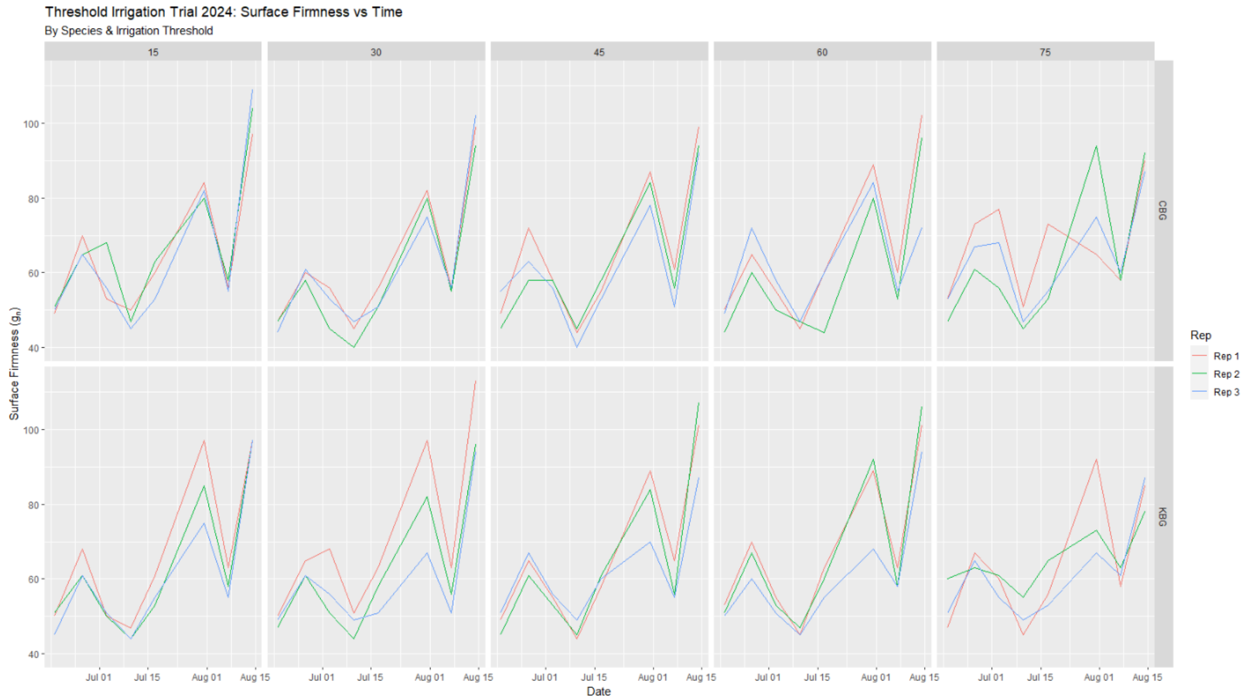

Figure 2. Surface firmness as measured using 2.5 kg Clegg Impact Hammer versus time for creeping bentgrass and Kentucky bluegrass fairway turf plots maintained at different soil moisture thresholds in St. Paul, MN during 2024. Solid lines show time history of plot surface firmness by species (creeping bentgrass, top row; Kentucky bluegrass, bottom row), threshold treatment (increasing left to right), and replicate (by color, within facet).

Table 1. Comparison of moisture threshold treatment effects on mean total water use, resulting surface firmness, and normalized difference vegetation index for creeping bentgrass and Kentucky bluegrass fairway turf plots in St. Paul, MN on 14 Aug 2024.

Moisture Threshold	Mean Total Water Use (L)	Group	Final Surface Firmness (g)	Group	Final NDVI	Group
15	0	A	100.2	B	0.802	A
30	0	A	99.7	B	0.794	A
45	2.5	A	96.7	AB	0.795	A
60	9.8	A	95.2	AB	0.807	A
75	58.8	B	86.5	A	0.806	A

USGA ID#: 2022-07-750

Title: Optimizing Irrigation Strategies Through Remote Stress Detection

Project Leader: Dr. David S. McCall and Travis L. Roberson
Affiliation: Virginia Tech

Objectives:
1. Determine the viability of thermal pixel data derived from small unmanned aerial vehicles to identify key moisture management areas for future irrigation prescription programs.
2. Thermal and digital surface model remote sensing data can potentially guide placement of in-ground soil moisture sensors for continuous feedback from precision irrigation management (PIM) programs.

Start Date: Fall 2021
Project Duration: 3 years
Total Funding: $104,495

Summary Points:
- The use of unmanned aerial vehicles (UAV) for large-scall mapping may not be feasible to build site-specific management areas for fairway moisture management due to complexities such as: proper UAV operational training, reliance on solar lighting conditions, flight avoidance during peak golf periods.
- Drone thermal data were not correlated with in-ground time-domain reflectometry data at any location other than fairway three with identified soil moisture stress during these sampling periods.
- Historical L-band radiometric data may be more useful for passive, non-destructive soil moisture estimations in a simpler manner for developing precision irrigation management areas and identify optimal, in-ground soil sensor placement.

Summary Text:
- **Rationale:**

The earth is 70% water by surface area with 97% of this being salty or brackish, making it unusable and 2% of this total is freshwater, of which is not all accessible for human consumption or use. The inaccessibility of freshwater develops an acute demand with a exponentially growing global population (Mishra, 2023). Irrigated turfgrass comprises ≥ 40 million acres and causes a large demand on the freshwater repositories that produces benefits to ecosystems but no additional yield to meet human needs (Milesi et al., 2005). This demand for freshwater has allowed certain entities to implement standards and innovations to allow for water conservation to gain more awareness while maintaining the same standards across many turfgrass surfaces.

One such example is the US EPA implementing a 'WaterSense' program that creates water prescription schedules through irrigation controllers taking into account local, on-site weather conditions that have proven to save approximately 15% of annual applied water (R Kerry et al., 2023). From this success, the EPA is considering mandating landscape irrigation through the use of soil moisture sensors like ones for irrigation systems used in variable rate applications for agriculture uses(Liakos & Vellidis, 2021). This is a viable solution for landscape situations with multiple sources reporting water savings of 22 – 72% annually using rain or soil moisture sensors for guiding irrigation applications (Cardenas-Lailhacar & Dukes, 2012; Sandor et al., 2022). These technologies prove useful for landscape use but areas such as golf courses are generally more intensively managed and face scrutiny for freshwater consumption with the United States alone using approximately six trillion gallons of water for maintaining turfgrass playing surfaces (Throssell & Norman, 2014).

Straw et al. (2022) sampled seven to fourteen fairways at nine different golf courses across eight states and found that the mean volumetric water content (VWC) using a hand-held time-domain reflectometer (TDR) was 22.4 – 48.8% and a range of 27.6-43.7% across courses. These results show the inherent variability region to region but even area to area within a single property, so climate, topography, soil physical properties, and thatch accumulation all provide influence on VWC variability (Hejl et al., 2022; Ruth Kerry et al., 2023). Documenting these variations is vital for learning the property for water management and can be done so through several options such as spatial grid sampling of VWC or penetration resistance readings or multi-spectral data through hand-held devices. Straw and Henry (2018) determined that documenting in-field soil moisture variation is best during dry periods using a penetrometer compared to VWC readings, especially for native based soils. However, when dry-down periods were implemented on golf courses fairways comparing VWC with aerial normalized difference vegetation index spectral data and only a weak negative correlation (r = -0.26) was found (Friell & Straw, 2021). This suggests that remote sensing multispectral data would not be the most reliable method to document where moisture variability occurs on a large-scale. However, when this data is incorporated with the superintendents on-site historical experience, interpolated maps can be further refined for more accurate precision turfgrass management decisions (Straw et al., 2020). An aspect that has not been considered across fairways is the use of thermal drone data across large scall areas for documenting localized management areas but has seen success in small plot research with moderate correlations between drone thermal temperature data compared to VWC (r = -0.43 to -0.63) (Hong et al., 2019). Thermal data is not as reliant on lighting conditions compared to multispectral data and could prove to be more feasible to document turfgrass canopy responses to limitations in soil moisture. Furthermore, these data could aid in identifying proper installation areas of in-ground soil moisture sensors for enhanced irrigation management decisions and what led to the stated objectives above.

- **Methodology:**

Thermal Remote Sensing: Two dry-down events (07/26/23 and 09/06/23 were initiated on three 'Champion' hybrid bermudagrass fairways (fairways 3/5/6) at Independence Golf Club located in Midlothian, Virginia. All irrigation was withheld for a minimum of 72 hours prior to anticipated field sampling to help promote soil moisture variability and a bermudagrass response to limited soil moisture availability. For all sampling events and locations, an average of 72 field sampling points of soil volumetric water content (VWC) were collected using a Spectrum time domain-reflectometer (Aurora, IL) equipped with 7.62 cm probes on a 10m x 10m sampling grid which was estimated through a serpentine fashion taken across the fairway surfaces. The TDR was calibrated between each fairway location with distilled water to ensure sampling accuracy. Field sampling points were marked with paint after taking the in-field TDR measurements for post sampling of real-time kinematic (RTK) geospatial coordinate data to ensure high accuracy of field sampling points to align with thermal canopy temperature data acquired aerial imagery. An Emlid Reach RS+ survey equipment (Richfield, OH) was used to collect spatial points with subcentimeter accuracy (Figure 1). Aerial thermal remote sensing data were collected using a Mavic 3T (Shenzhen, China) drone equipped with an uncooled VOx microbolometer thermal camera with a resolution of 640 x 512 resolution. Drone flights were taken at a 60.96m flight altitude with an average ground sampling distance of 8.88cm^2 at a flight speed of 12.8 km h^{-2}. Flights were taken with a 90% front and side overlap to consider the necessary high overlap in images required for properly making orthomosaic. All thermal images were converted from .JPEG formats to radiometric .JPEG with accessible thermal pixel data using ThermoConverter. Once images were converted to the correct file format, images were processed and stitched together using Pix4D (Denver, CO) using ground control points to ensure orthomosaic were within a ≥ 8cm spatial accuracy.

Orthomosaic were further processed to extract thermal pixel data using QGIS (Version 3.32.3-Lima). Pixel data were extracted using multipoint delimited text files to generate center points from the field spatial survey points collected during TDR sampling. A processing toolbox function *buffer* was used to extract the average thermal pixel data with a sampling radius of 1.12m around these center points with a total sampling area of 3.94m^2 (Figure 2). These spatial sampling parameters provided a total average 387 pixels sampled per TDR sampling point for each fairway location and sampling event in July and September. Comparisons of thermal pixel data and VWC% were investigated by location and sampling events

TurfRad Sampling:

A TerraRad L-band passive radiometer (TurfRad) (Zurich, Switzerland) was used to enhance data collection and expand upon the results from the drone imagery taken in 2023 for 2024 data collections sampling. The L-band radiometer samples a bandwidth of 24MHz and centered around 1414MHz. The sensor was mounted at a 150cm height at an optical angle of 40° angle (Figure 3) and traversed across three fairway locations (fairways 3/6/8) for a total of nine separate sampling events to document historical seasonal variations in soil moisture shown as follows: **3/15/24, 4/19/24, 5/17/24, 6/08/24, 6/23/24, 7/14/24, 8/01/24, 8/18/24, 9/27/24.** Fairway 5 was substituted for Fairway 8 from previous observations and superintendent input for the desire to have stress observations during key sampling periods. The TurfRad takes a measurement every one meter in the direction of motion for a travel speed of 25km hr^{-2} and since our average traverse speed was 16.8km hr^{-2} we were able to collect a robust dataset for future analysis. For example, the 3/15/24 sampling date across each fairway we are collecting an average of 2500 data points relating to soil moisture. Across these same areas three separate TurfRad periods were collected (4/30/24, 6/27/24, and 9/23/24) in conjunction with TDR and gravimetric data collection (Figure 3A and 3B), both of which were at three sampling depths of 3.81, 7.62, and 12.91cm depths. These data will aide to be incorporated into a model to calibrate the TurfRad data towards in-ground TDR measurements and by gravimetric actual moisture data. All soil cores were bagged immediately within the field post-harvesting and transported to the lab for initial weights and then oven drying for 48 hours at 121.11°C. After capturing the weight difference of water lost from oven drying, samples were then ashed in a muffle furnace for organic loss on ignition weights for 24 hours at 232.22°C.

- **Results to Date:**

At this point results are limited for this project. Due to field complications, limited dry-down stress was induced leading to what investigators believe to be an influential factor for observed weak correlations from both flight events of thermal imagery by remote sensing collection means. However, it was documented that in the field that the following fairways ranked from highest stress to least observed in the field: Fairway 3→Fairway 6 → Fairway 5 and aligns with the data in Figure 5. Thermal data acquisition is believed to be a reliable metric to document turfgrass moisture stress on a large scale compared to previous literature of seeing these results at very limited ET irrigation replacement programs of 15 and 30% ET (Hong et al., 2019). During the July sampling events, the fairway with the highest correlation was Fairway 3 between TDR and thermal pixel data ($R^2 = 0.18$), however, a stronger relationship is observed in the September sampling event ($R^2 = 0.29$) for the same fairway. This is believed to be due to the minimal rainfall occurring approximately 24 hours prior to the scheduled sampling event (Figure 4). It was also observed that Fairway 3 had less stress during the July event compared to September. Furthermore, the September sampling event had no rainfall occurring approximately 7 days prior to the scheduled data collection period. In all cases, no relationship is observed with Fairway 5 due to no turfgrass stress response from limited soil moisture for either sampling period.

- **Future Expectations:**

Overall, drones with thermal cameras have a use case for large scale sampling to document moisture stress of turfgrass areas but only after the stress has occurred. Furthermore, limitations with drones exist because the user needs knowledge of constructing proper mapping flight plans and what to do with the imagery data harvested to build the proper story for making management decisions. This is why developing site-specific management areas would be more practical with a technology related to thermal and/or radiometric data that is mower mounted and more simplistic by an end-user to take advantage of for their daily irrigation decision making. This is why the TurfRad is gaining prominence, but further research is required to compare this technology to in-field TDR data collection and aerial thermal remote sensing data to confirm the validity of using such a technology to document spatially moisture stress areas. With this data, once confirmed, we believe serves a valuable use case to not only build out site-specific management areas for further water conservation research but also to hopefully provide objective data towards knowing where to install in-ground sensors to aide in real-time data feedback for enhanced irrigation decision making.

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- **Images:**

Figure 1. Emlid Reach RS+ survey equipment collecting RTK spatial coordinate points to ensure precise sampling data within thermal orthomosaic compared to volumetric water content field sampled points.

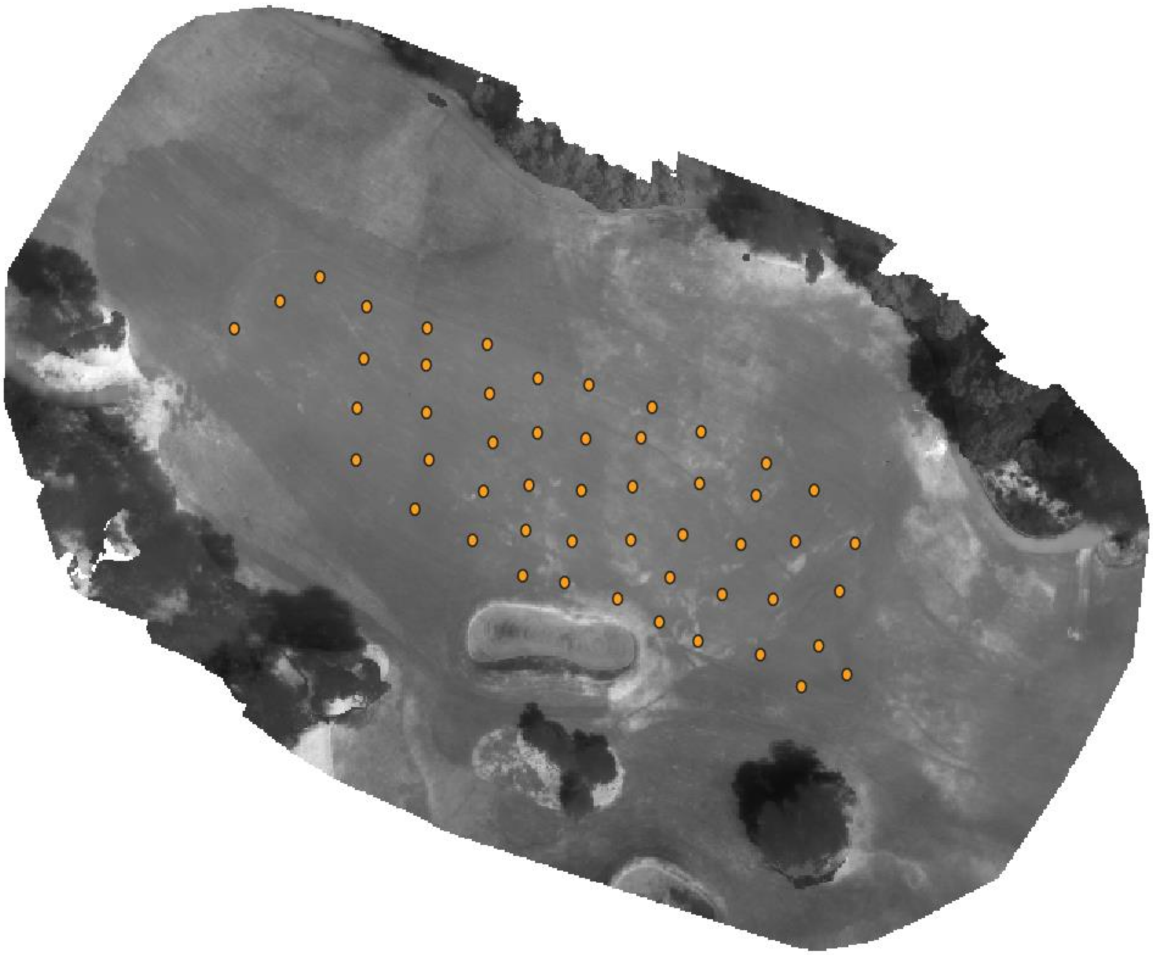

Figure 2. 10m x 10m spatial sampling points for volumetric water content with a 3.94m2 buffer centered around field sampling points (orange points) using real-time kinematic accuracy spatial data for thermal orthomosaic imagery collected by a Mavic 3T drone for fairway 3 at Independence Golf Club in Midlothian, Virginia on 09/06/23.

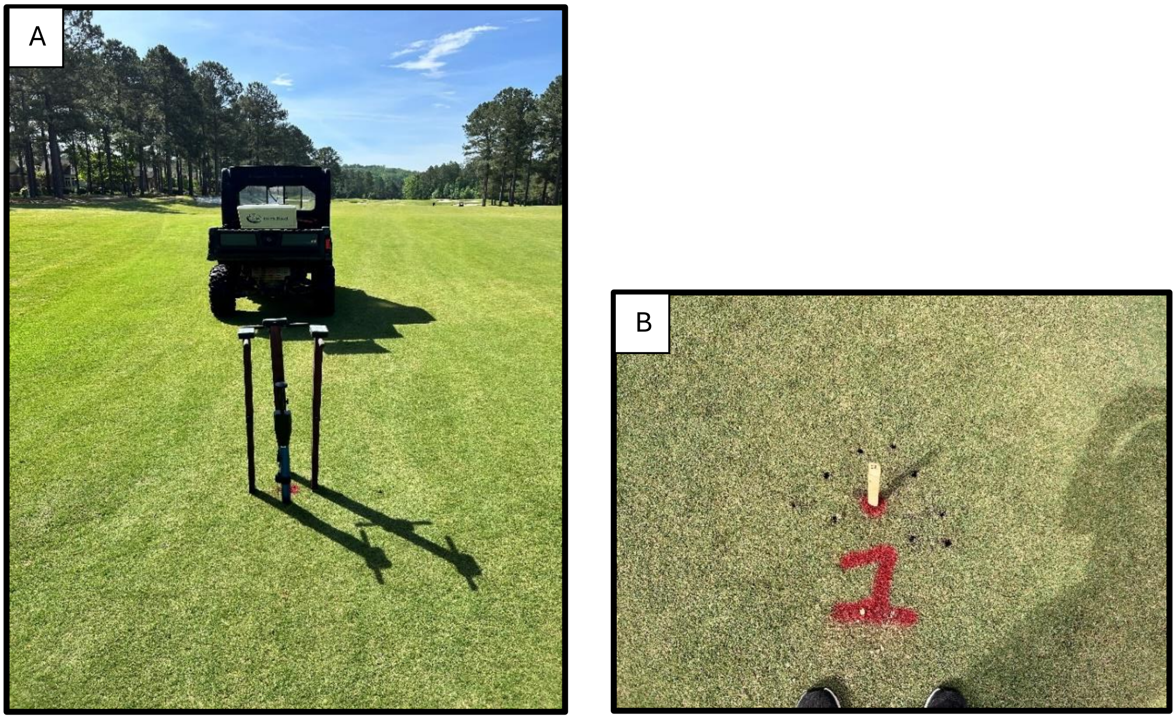

Figure 3. Representation of TurfRad mounted on a John Deere Gator at a 150cm height on a 40 degree optical angle. Calibrated Spectrum TDR (Aurora, IL) in the image represent from left to right in a clockwise rotation sampling depths of 3.81, 7.62, 12.91 cm depths (A). The red paint in the center marks the sampling location to collect RTK spatial data along with the soil cores sampled for gravimetric data at the same time of TDR sampling (B).

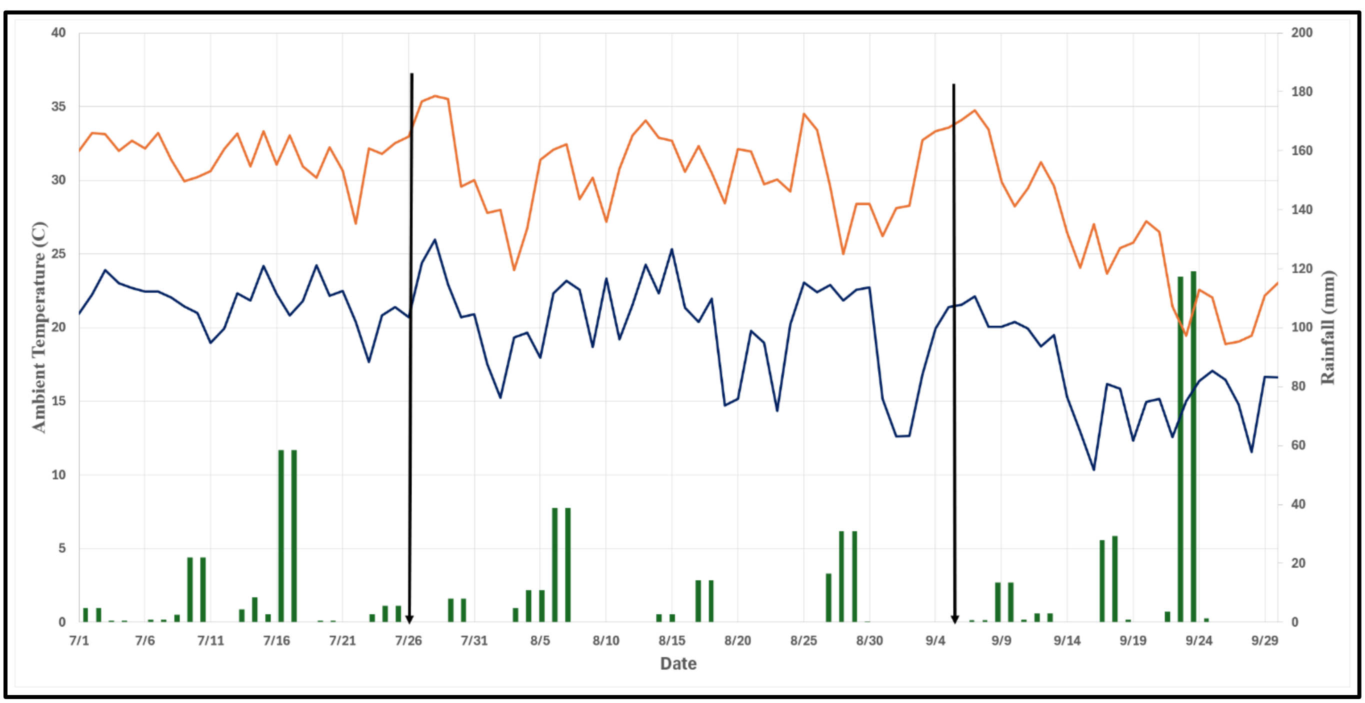

Figure 4. Ambient temperature maximum (orange line) and minimum (blue line) with average rainfall data in mm (green bars) with sampling events occurring on the dates 7/26/23 and 9/6/23 indicated by the black arrows.

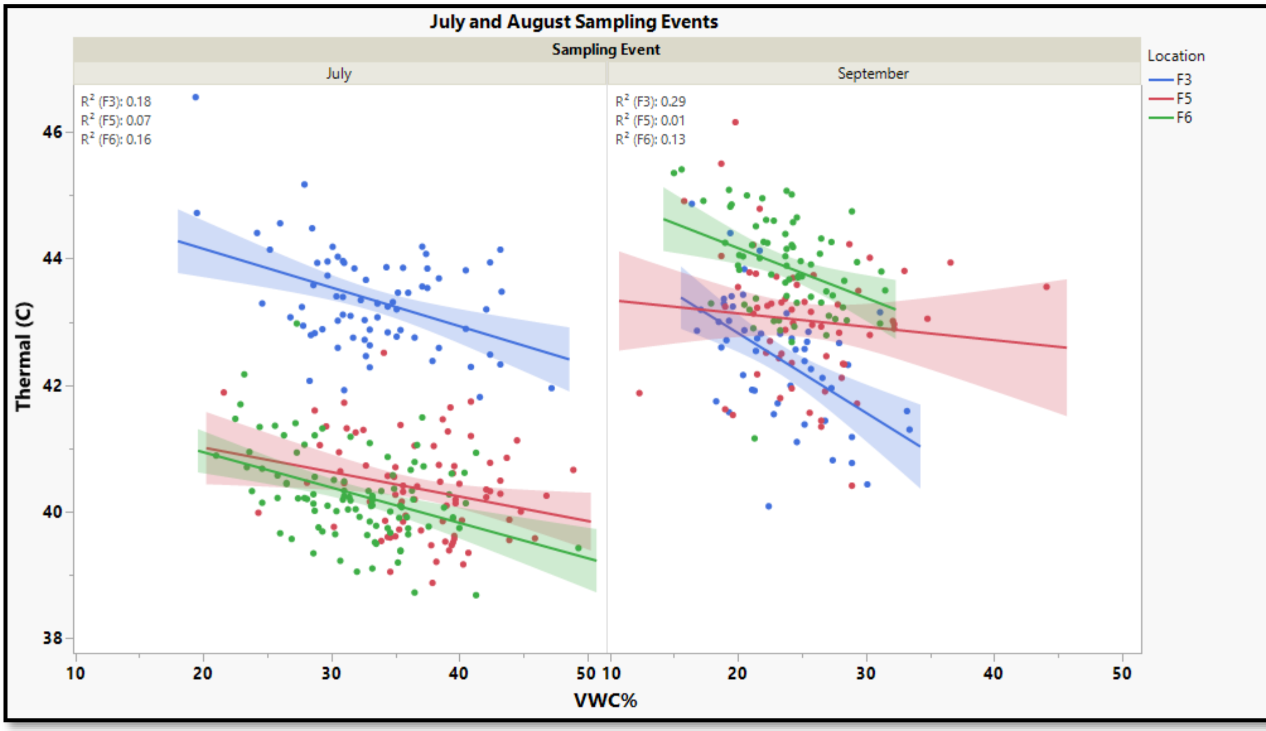

Figure 5. Thermal temperature (°C) compared to time domain reflectometry data represented as volumetric water content (VWC%) over three fairways (F3 = Fairway 3, F5 = Fairway 5, F6 = Fairway 6) at Independence Golf Club in Midlothian, Virginia for two sampling events on 07/26/23 and 09/06/23.

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USGA ID#: 2024-07-817
Title: Investigating a mower-mounted L-band radiometer for precision irrigation on golf course fairways

USGA ID#: 2024-18-828
Title: Additional support for soil testing in variable-N rate (2022-13-756) and turfRad experiments

Project Leader: Chase Straw Ph.D., Madan Sapkota, and Weston Floyd
Affiliation: Texas A&M University

Objectives:

1. Develop a rapid approach to calibrate raw turfRad radiometry measurements to in-situ soil moisture.
2. Quantify changes in water consumption between precision irrigation approaches and superintendent irrigation scheduling methods in TX.

Start Date: 2024
Project Duration: 2-years (2024-2025)
Total Funding: $75,188 (2024-07-817) and $20,000 (2024-18-828)

Summary Points:

- Data were collected from four different locations, including three golf courses in Texas (Houston, Austin, and Frisco) and one location in Virginia (Midlothian), across four distinct survey periods (Objective 1).
- Preliminary analysis at Champions Golf Club (Jackrabbit Course) in Houston indicated a moderate relationship ($R^2 = 0.48$) between turfRad brightness temperature and TDR soil moisture measurements, supporting its relevance as a predictor during the calibration process (Objective 1).
- This preliminary analysis also compared an off-the-shelf regression model with an ANCOVA model. By incorporating covariates such as brightness temperature, the ANCOVA model achieved an R^2 of 0.82 and reduced prediction errors by 78%, significantly improving accuracy and calibration (Objective 1).
- A study at Champions Golf Club (Cypress Creek Course) will employ a randomized complete block design to compare superintendent-based, ET-based, and turfRad precision irrigation methods. Fairways have been selected, treatments are planned, and data collection will begin in April 2025 (Objective 2).
- Future research will include data collection from all locations and subsequent analysis to develop a comprehensive global model (Objective 1), as well as implementing irrigation treatments and conducting further data collection (Objective 2).

Summary Text:

Rationale:

Soil moisture sensor technologies are essential for effective irrigation decision-making, yet their use is largely limited to smaller areas of golf courses, such as greens and tees, rather than larger areas like fairways. This limitation stems from challenges such as high implementation costs, time-intensive data collection, the technical expertise required for operation, and insufficient understanding of appropriate sampling intensity. These barriers highlight the need for innovative soil moisture technologies that enable rapid, large-scale, high-resolution soil moisture mapping.

The recent introduction of the Portable L-band Radiometer (PoLRa), commercially known as turfRad, which employs microwave radiometry, offers a promising opportunity for experimentation and testing. Microwave radiometry in turfgrass is influenced by several site-specific factors, including soil moisture, leaf water content, surface brightness, and temperature variations, necessitating site-specific calibrations (Scudiero et al., 2023).

This project aims to develop a calibration model for the turfRad sensor to enhance soil moisture measurements, thereby supporting precision irrigation strategies to reduce water use on golf courses. Validating the model across various Texas sites will facilitate convenient, accurate large-scale soil moisture mapping. In 2025, the calibrated soil moisture data will be used to assess water consumption variations under different irrigation scheduling techniques, demonstrating the significant water-saving potential of precision irrigation.

Methodology

Objective 1: Data for this project were collected from three golf courses in Texas—Jackrabbit Course at Champions Golf Club in Houston, Austin Country Club in Austin, and Fields Ranch East in Frisco—as well as from Independence Golf Club in Midlothian, Virginia, during four survey periods (March, June, September and December of 2023/2024). Soil moisture measurements were obtained using the turfRad sensor mounted on a utility vehicle during routine mowing operations. At each fairway, twelve random locations were selected for additional soil moisture measurements, recorded as volumetric water content (VWC) using time domain reflectometry (TDR) soil moisture sensors at depths of 3.8, 7.6, and 12.1 cm. These TDR measurements served as ground truth for calibrating soil moisture data. Gravimetric soil moisture data were also collected to further validate the measurements.

To calibrate the PoLRa readings, an ANCOVA regression model, as described by Corwin and Lesch (2014), was employed. The regression equation, $Y_{ij} = a_j + b \times X_{1,ij} + \varepsilon_{ij}$, incorporates locally estimated intercepts (a_j) for each unit (e.g., golf course fairway), while and ‘b’ represents the slope assumed constant within a specific region (e.g., Texas), and ‘ε_{ij}’ accounts for random error. This model was used to evaluate whether the relationship between turfRad and TDR measurements remains consistent across regions or varies locally. When spatial variability was identified, the slope 'b' was categorized into different levels, such as b_1 for a regional slope (e.g., all Texas golf courses) and b_2 for localized slopes (e.g., a specific golf course).

To enhance the accuracy of the ANCOVA estimations, especially in non-Gaussian variable distributions or when addressing multiplicative random errors, data transformation techniques, such as natural logarithms, were applied where necessary.

Objective 2: The study will be conducted at Cypress Creek Course at Champions Golf Club in Houston, Texas, using a randomized complete block design (RCBD). Treatments will include superintendent-based irrigation (fairways F6, F10, F15), evapotranspiration (ET)-based irrigation (F7, F11, F17), and precision irrigation using turfRad (F2, F14, F18). Fairways were selected based on preliminary seasonal data. Data collection will begin in April 2025. Irrigation amounts will be monitored using the Toro Lynx Central Control System, which will record total irrigation depths for each fairway and generate monthly water use reports. These reports will be used to compare the efficiency of turfRad-based precision irrigation, ET-based irrigation, and superintendent-based irrigation.

Additional data will be collected after irrigation applications, including soil moisture, penetration resistance, and NDVI measurements using the Toro Precision Sense 6000. Surveys will also be conducted to gather golfer feedback on fairway quality and playability. The data will be analyzed using mixed-model ANOVAs with repeated measures, spatial interpolation via ordinary kriging, and NDVI orthomosaic generation with Pix4D.

Results to Date

Objective 1: While data from all four locations are still being analyzed, data from the Cypress Course at Champions Golf Club in Houston, Texas, have been used to compare the performance of two calibration models: the off-the-shelf regression model and the ANCOVA regression model. Figure 1 shows the relationship between turfRad soil moisture readings and ground truth TDR measurements across three golf course fairways using the off-the-shelf regression calibration. This model, which correlated raw turfRad readings with TDR VWC values without considering site-specific factors, produced an R^2 value of 0.36 ($P < 0.01$), indicating moderate predictive accuracy. The mean absolute error (MAE) and root mean square error (RMSE) values of 0.08 and 0.09, respectively, suggest moderate prediction errors and indicate that incorporating site-specific factors could improve model accuracy.

Further evaluation of turfRad brightness temperature (measurements of microwave emissions from soil detected by turfRad, which serve as a proxy for estimating soil moisture) and TDR soil moisture readings yielded an R^2 value of 0.48 ($P < 0.01$), showing a moderate correlation. By applying ANCOVA regression and including brightness temperature as a covariate, the model's predictive accuracy improved significantly, achieving an R^2 value of 0.82 ($P < 0.01$) and a 78% reduction in prediction errors (with MAE and RMSE reduced to 0.02).

This highlights the potential of ANCOVA regression to enhance soil moisture calibration, as demonstrated by Scudiero et al. (2017) and Corwin and Lesch (2014).

Objective 2: Data collection for this objective will begin in 2025, with results included in the next annual report.

Future Expectations

- Develop a comprehensive global calibration model to represent diverse locations across different times of the year incorporating additional factors such as soil texture, organic matter, and turfgrass characteristics.
- Share the developed calibration algorithm with sensor manufacturers and make it publicly available for future researchers.
- Implement irrigation treatment applications and conduct data collection for Objective 2.

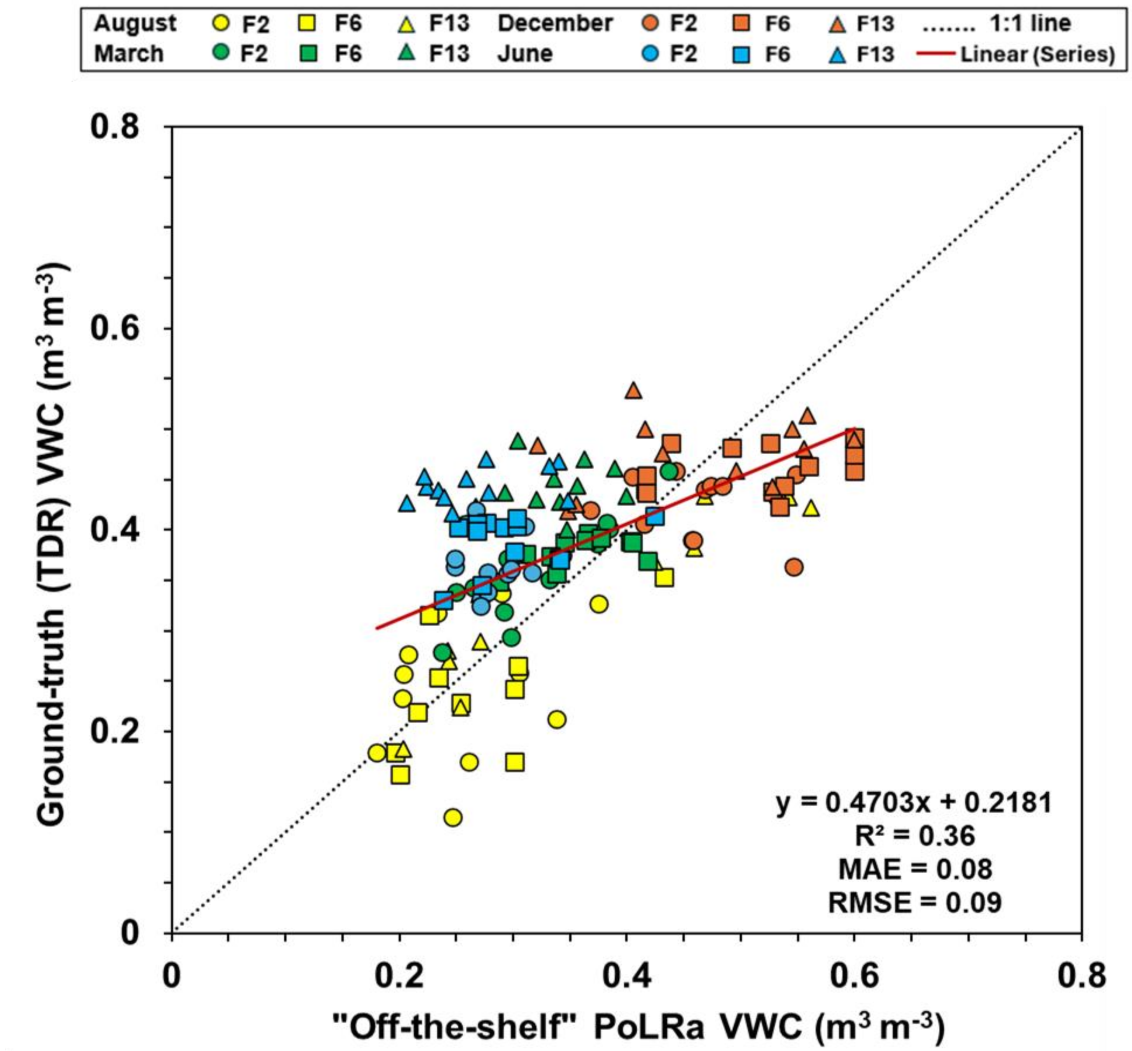


Figure 1. The relationship between the "off-the-shelf" Portable L-band Radiometer (PoLRa, commercially known as turfRad), volumetric water content (VWC), and ground truth time domain reflectometry (TDR) measurements was analyzed across three golf course fairways during four surveys at Champions Golf Club (Jackrabbit Course) in Houston, Texas.

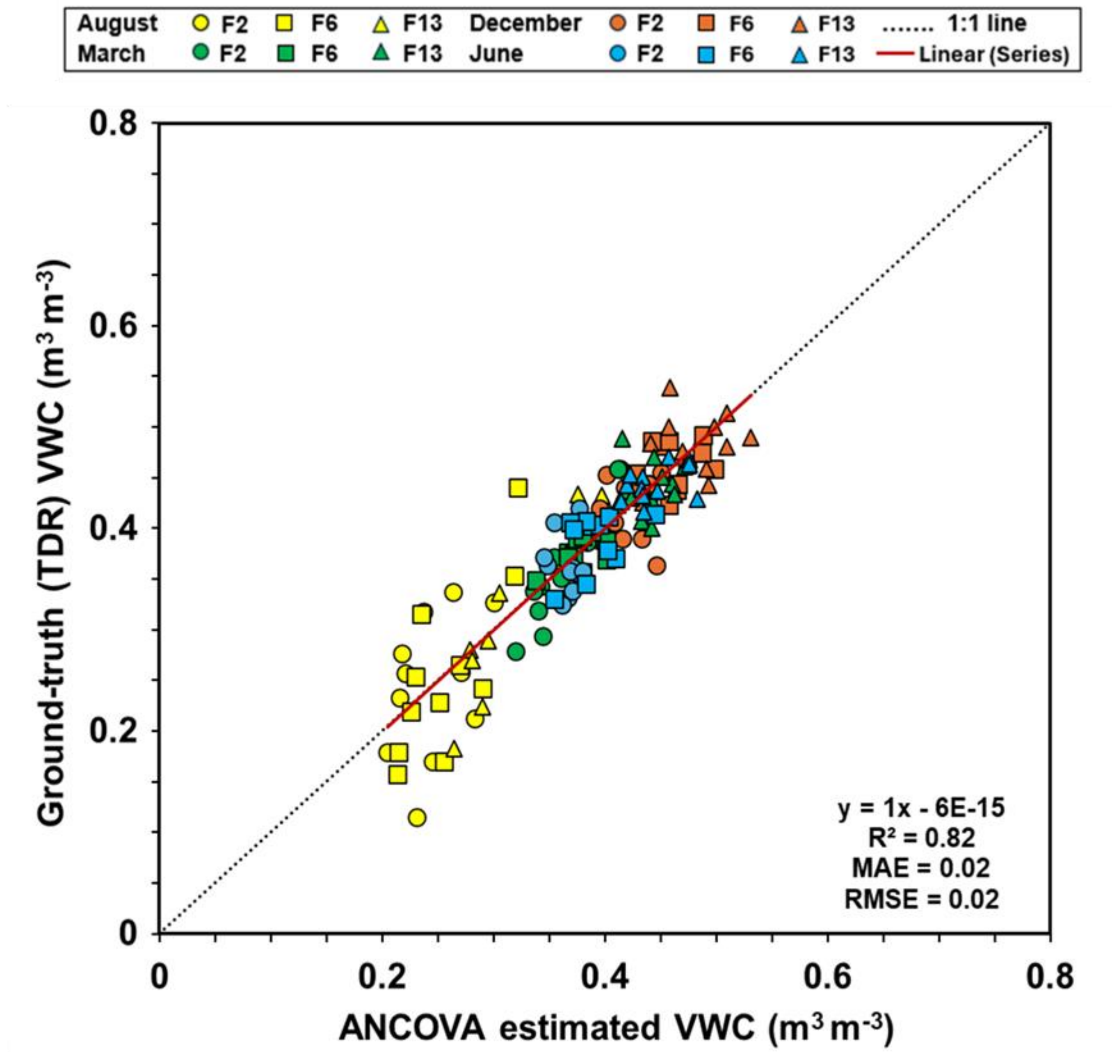


Figure 2. The relationship between "ANCOVA-estimated" Portable L-band Radiometer (PoLRa, commercially known as turfRad) volumetric water content (VWC) and ground truth time domain reflectometry (TDR) measurements was analyzed across three golf course fairways during four surveys at Champions Golf Club (Jackrabbit Course) in Houston, Texas.

USGA ID#: 2023-03-770

Title: Remote Soil Sensing of Fairways for Irrigation Water Conservation

Project Leaders: Bernd Leinauer[1], Borys Drach[2], Tatiana Kardashina[2], Tom Egelhoff[3], and Ciro Velasco-Cruz[1]
Affiliation: New Mexico State University, [1]Department of Extension Plant Sciences and [2]Mechanical and Aerospace Engineering[2]; The Club at Las Campanas, Santa Fe, NM

Objectives: 1) Determine accuracy of remote moisture sensing technologies
2) Evaluate technologies for irrigation scheduling of golf course fairways and select the most accurate to irrigate one fairway for at least one season

Start Date: 2023
Project Duration: The project is expected to run for three years.
Total Funding: $208,102

Summary Points:
1) Measurements taken with TDR 350 show a significant and strong correlation with volumetric soil moisture (θ_V) determined by loss of weight.
2) Similar to 2023, the relationship between turfRad and TDR 350 is weak, particularly when soil moisture is greater than 35%. During one sampling day we even found a significant negative linear relationship.
3) The accuracy of the turfRad sensor improved when used in a parked position compared to using it in motion. Unfortunately, using the turfRad stationary to determine soil moisture is not practical as the current standard requires to operate it on a moving fairway mower.
4) It is questionable whether the turfRad estimates soil moisture with great enough accuracy to schedule irrigation. Similar to our findings in 2023, we feel that the underlying model needs to be improved to achieve a greater accuracy, especially when soil moisture is greater than 30%.

Study

Several studies have demonstrated the water conservation potential of soil moisture sensor (SMS) -based irrigation scheduling on turfgrass areas. However, a barrier to the adoption of such technology has been the perception that too many measurement points (either by a hand-held device or from in-ground sensors) are needed to accurately determine soil moisture over a large area. Recently, alternatives to hand-held or in-ground SMS sensors have been introduced. These include Cosmic Ray Neutron Sensing (CRNS) devices placed either on a vehicle or outside of turfgrass areas. Active microwave remote sensing from a satellite orbiting the earth using Synthetic Aperture Radar (SAR) penetrates approximately 3-5 cm into the ground and has been used to estimate surface soil moisture on large landscapes and agricultural fields. The SAR sensors transmit electromagnetic pulses and record the backscattered energy from the earth's surface. A more recent advancement allows data to be collected at a resolution below the 1 m scale. More recently portable radiometers (PoLRa) operating at a wavelength of 21 cm (L-Band) that can be mounted on a fairway reel-mower have also shown promising results in estimating soil moisture to a depth of 5 to 10 cm. Nonetheless, information is lacking on the accuracy of these remote operating soil moisture sensors, their potential for irrigation scheduling and subsequently its impact on water use and turfgrass quality. A three-year field study has been initiated in 2023 to investigate accuracy and feasibility of remote SMS to schedule irrigation of golf course fairways and its water conservation potential when compared to traditional Evapotranspiration (ET) based irrigation.

Methods

Location and Maintenance

Two fairways, #2 (121,000 ft^2) and #7 (82,000 ft^2) (Figure 1) were selected from the Sunset golf course at The Club at Las Campanas in Santa Fe, NM. Both fairways are par 4 and were established in 1999 with ‘Penn Trio’ creeping bentgrass. The fairways were mowed at 0.4” (10 mm) twice per week with clippings returned. Both fairways are aerated once per year in April and de-thatched with a verti-cutter Model VC60 (First Products Inc., Tifton, GA) in September. The fairways received approximately 10 g N/m^2 (2 lbs N/1000 ft^2) annually. The surfactant ‘Revolution’ and plant growth regulators ‘Primo’ (ai Trinexapac-ethyl) and ‘Legacy’ (as Flurprimidol and Trinexapac-ethyl) were applied monthly at label rates. Weed control was achieved on a curative basis with the herbicide Trimec Bent (ais Dicamba, 2,4-D, MCPP), and Merit (ai Imidacloprid) was applied at label rate for insect control. Sand topdressing was conducted six times during the growing season (April to October). Fairways are irrigated predominately from Toro DT34 and DT35 heads installed within the center and from RainBird 750 heads around the perimeter.

Figure 1: Fairway #2 (left) and #7 (right) (courtesy of Tom Egelhoff).

Soil Moisture Equipment

Data collection started on 22 April 2024 and ended on 7 October 2024. Soil moisture sensing equipment during the 2024 research period included the Toro Precision Sense 6000 (PS6000) (The Toro Company, Bloomington, MN), turfRad (TerraRad Tech, Zürich, Switzerland), and TDR 350 (Spectrum Technologies, Aurora, IL). In addition, soil cores were collected to determine volumetric soil moisture θ_V (kg kg^{-1}) by loss of weight. On October 7 Umbra satellite reflectance data was accessed and provided by Karuna Technology UG (Wiesbaden, Germany). Umbra Space, a US-based company, develops and operates the Umbra SAR Satellite Constellation. These remote sensing satellites provide very high-resolution imagery worldwide, with a revisit rate of up to four times per day (https://docs.up42.com/data/datasets/umbra). Umbra operates in the X-band, with a wavelength of approximately 3 cm (https://www.euspaceimaging.com/blog/2024/04/05/what-is-sar-imagery/) and a bandwidth of 8–12 GHz. It captures SAR imagery at resolutions 25 cm, 35 cm, 50 cm, and 1 m (https://docs.up42.com/data/datasets/umbra). In contrast, Sentinel, part of the European Copernicus Program, operates in the C-band, with a wavelength of 5.6 cm and a bandwidth of approximately 5 GHz. It provides medium-resolution SAR imagery. More detailed information on the soil moisture measurements used in the study is provided in Table 1.

Table 1. Remote soil moisture sensing equipment used to determine accuracy of measurements compared to reference values obtained with either the Precision Sense or the TDR sensor.

				
Sensor	Precision Sense	Umbra satellite	turfRad	TDR 350 / GEODE^{TM} GN3S
Sensor Type	Capacitance	Synthetic Aperture Radar (SAR, Active microwave)	Passive reflectance	Time Domain Reflectometer / GNSS receiver
Wave-length		X-Band (3 cm)	L-Band (21 cm)	
Soil depth	10 cm		Approx. 5 cm[†]	7.5 cm (TDR)

[†]Information provided by manufacturer

Data Collection and Analysis

A combined total of 200 soil samples were collected on 22 April, 17 May, 17 June, 8 July, and 5 August. Between 10 and 30 soil cores per fairway, 5 cm in diameter and 7.5 cm in depth, were taken randomly, weighed, dried for 24 hours at 105 °C, weighed again and volumetric soil moisture was calculated. TDR 350 readings were taken at the same locations. Subsequently, θ_V (kg kg^{-1}) and TDR 350 values were compared to one another. A GEODE^{TM} GNS3S (Juniper Systems, Logan, UT) (Table 1) was used to determine exact Global Positioning System (GPS) coordinates of all measurement locations. According to the unit's manual, the GNS3S determines locations with an accuracy of 10 cm or less.

Soil moisture was measured from a moving turfRad sensor on two golf fairways (Figure 1) on 22 April and 17 May. During a meeting with Dr. Elia Scudiero and his research team at UC Riverside, it was suggested that in order to determine the exact accuracy of turfRad measurements, we take readings by means of a stationary (or parked) rather than a moving turfRad sensor. Consequently, we selected two areas (i.e. subregions) on each fairway measuring 20 m by 20 m in which ten 1 m x 1 m plots were defined randomly. turfRad readings were recorded for one minute with the sensor directing to the plots followed by ten TDR measurements taken within each plot. Data were subsequently averaged for each plot. Global Positioning System coordinates were recorded in the center of each plot. Precision Sense 6000 data were recorded with the mobile platform across the entire subregion. Data were collected on 17 June, 8 July, 5 August, 9 September, and 7 October. On 8 July, 9 September, and 7 October a second turfRad sensor was included in the investigation and moisture values were compared with all other units. Locations of turfRad readings did not align with measurements taken by the TDR 350 and PS6000 on 22 April and 17 May. Similarly, locations of PS6000 measurements did not coincide with TDR 350 locations on all sampling dates. Consequently, we implemented a Geoadditive model (Kamman and Wand, 2003) to predict turfRad values at the TDR 350 locations on 22 April and 17 May. A similar approach was used to predict PS 6000 moisture values at the TDR 350 locations on all sampling dates. The number of knots needed was a subset of the sampling locations due to the large number of measurement sites. To avoid location duplication, the coordinates of the knots were jittered using a white noise with standard deviation equal to 0.000001. The spatial covariance structure and the mean function used for this analysis were chosen based on the mean squared prediction error (MSPE) of the dataset. The isotropic Matern structure and a smoothing parameter of ν = 0.5 minimized the MSPE. The statistical analysis was performed using the R software (version 4.3.0) with a user defined function coded in C++ 17. When the number of soil moisture measurements was greater than 500, the Nearest Neighbor Gaussian Process method (Finley et al, 2022) was implemented to model the spatial data. As an assessment of simple association, the corresponding coefficient of determination values (R2), the slope of the regression line, the p-value to indicate whether it's significantly different from zero, and the root mean squared error (RMSE) are reported.

Figure 2. turfRad sensors mounted on fairway mowers in parked position recording soil moisture values.

Results

1. <u>Soil Moisture Values</u>

Figure 3 shows boxplots of soil moisture measurements recorded during 2024. Values collected on 8 July by the second turfRad unit were noticeably higher than the values of all other devices. Recorded soil moisture readings of turfRad 1 align with TDR 350 and PS 6000 values on all sampling dates Soil moisture variability was greatest on Fairway #7 on 7 October (Figure 3 and 4).

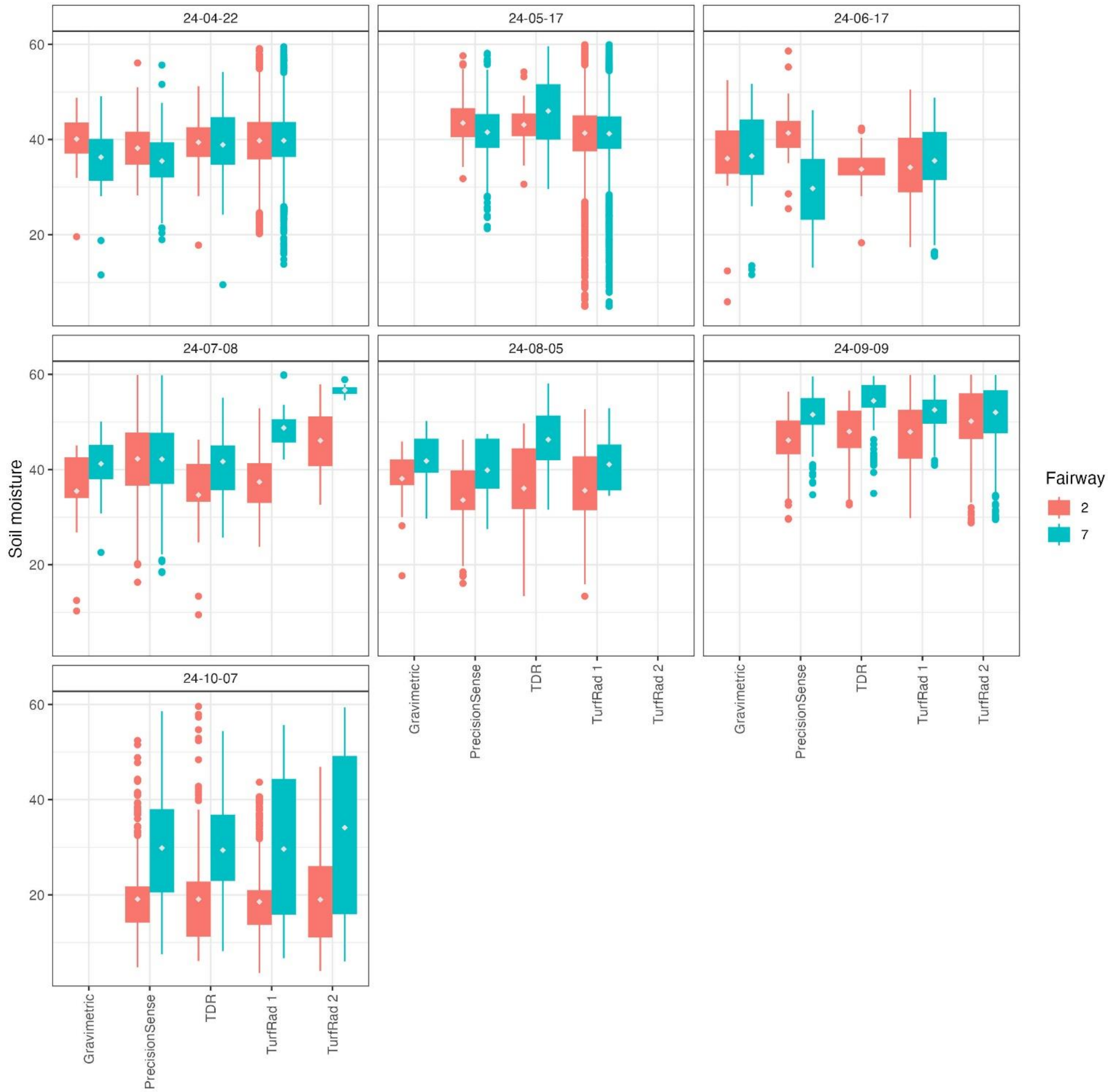


Figure 3. Volumetric soil moisture distribution at varying dates during the 2024 research period. Measurements were taken on Fairways #2 and #7 gravimetrically, with 2 portable radiometers (turfRad) installed on fairway mowers, with a capacitance sensor mounted on a mobile sampling device (Precision Sense PS6000) and a handheld TDR device (TDR 350). Box plots indicate median (line inside the box) and the 25th and 75th percentiles [length of box or interquartile range (IQR)]. Lower and upper whisker extend to the smallest and largest value of 1.5*IQR of the hinge. Data points outside the whiskers are considered outliers and are plotted individually.

Figure 4. Measurement locations on Fairway #7 marked with green flags.

2. Comparing TDR 350 to Gravimetry

Soil moisture measurements taken with TDR 350 show a significant and strong correlation with θ_V (kg kg^{-1}) determined by loss of weight (Figure 5). These results confirm our decision to use the TDR 350 as a reference or the standard against which remote sensing technologies can be compared.

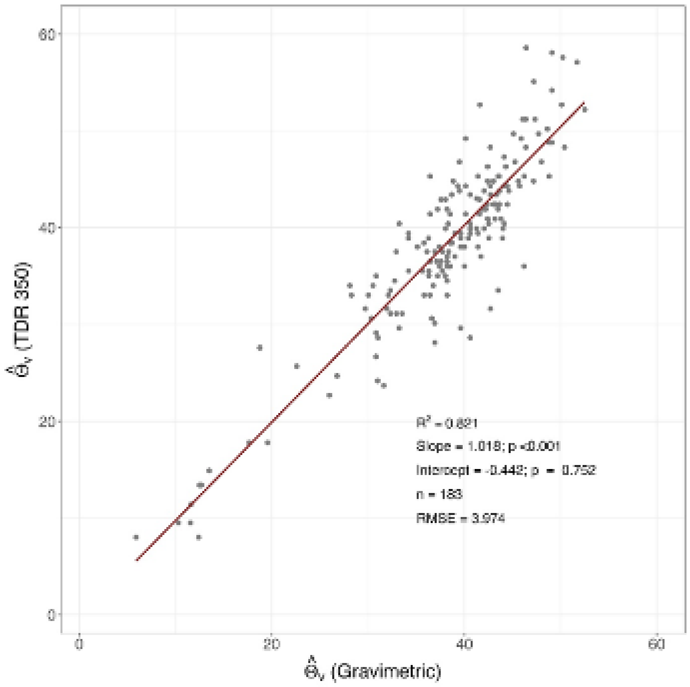


Figure 5. Relationship between volumetric soil moisture determined gravimetrically (θ_V, kg kg^{-1}) and TDR 350 values.

3. Comparing turfRad stationery to turfRad in motion

Analysis of variances of soil moisture relationship between the turfRad 1 sensor parked and in motion indicated that the relationship is different between the two conditions. None of the other treatment effects or the interactions affected the relationship (Table 2).

Table 2. P-values from ANOVA to test the effects of fairway (#2 and #7), sampling date, motion (moving vs. parked as nested factor), and their interactions on the relationship of moisture measurements collected with the turfRad 1 sensor and the TDR 350.

Effect	Pr>F
Fairway	0.3823
Motion	0.0046
Fairway*Motion	0.2723
Date(Motion)	0.1350
Date*Fairway(Motion)	0.1979

Regression analyses revealed slopes of 0.483 and 0.070 when the sensors were in parked and in motion, respectively. The values are significantly different from one another according to Tukey's Honest Significant Difference (HSD) test ($\alpha = 0.05$).

4. Comparing turfRad to TDR 350 and to Precision Sense, and Precision Sense to TDR 350

Statistical analyses of regression slopes investigating the relationships between TDR 350 and turfRad 1, TDR 350 and PS 6000, PS 6000 and turfRad 1 revealed that only sampling date affected the relationship between the variables (Table 3). The relationship between turfRad 1 and turfRad 2 was influenced by the 2 main effects Fairway and Date and by the interactions of the two variables (Table 3).

Table 3. P-values from ANOVA to test the effects of fairway and sampling date on slope of linear regression.

Effect	TDR 350 and turfRad 1	TDR 350 and PS 6000	PS 6000 and turfRad 1	turfRad 1 and turfRad 2
Fairway	0.592	0.342	0.1051	0.003
Date	0.024	0.005	0.0951	0.0001
Date*Fairway	0.214	0.337	0.8398	<.00001

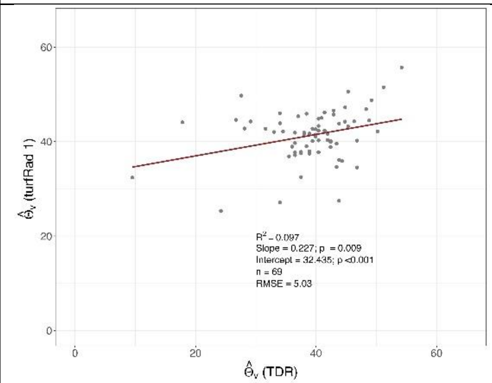
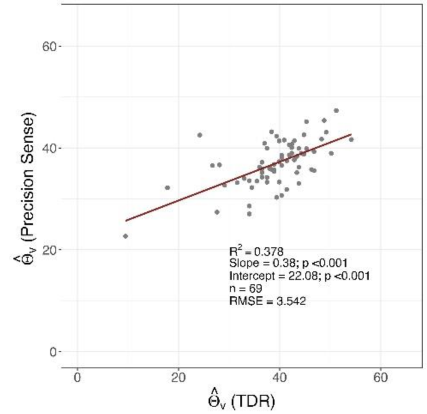
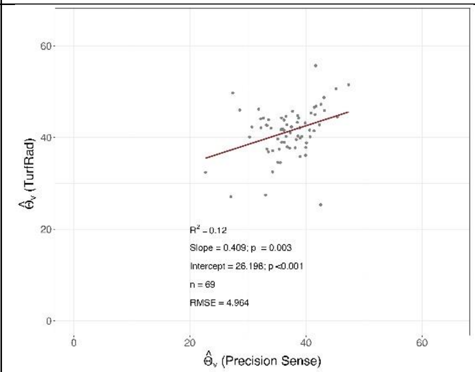
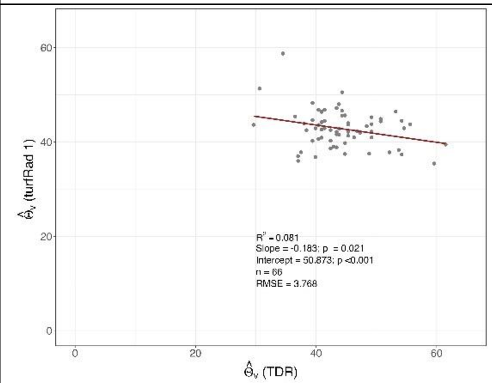
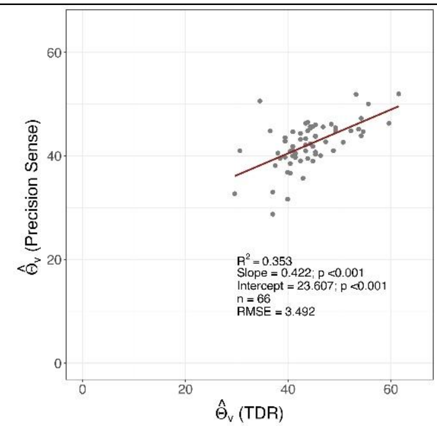
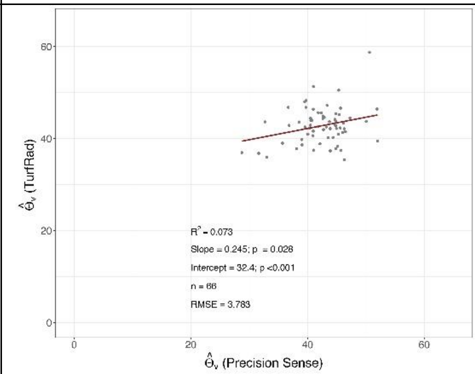
Date	TDR 350 and turfRad 1	TDR 350 and PS 6000	PS 6000 and turfRad 1
Apr 22			
May 17			

Figure 6. Linear regressions between TDR 350 and turfRad 1 (left column), TDR 350 and PS 6000 (center column), and PS 6000 and turfRad (right column) on April 22 (top row) and on May 17 (bottom row).

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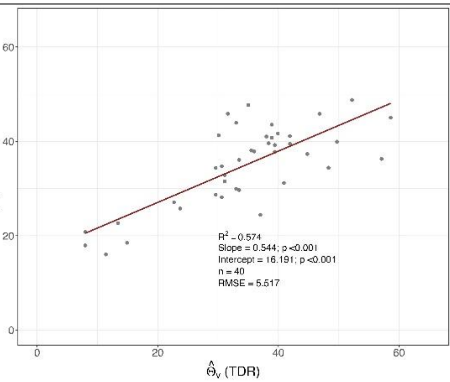
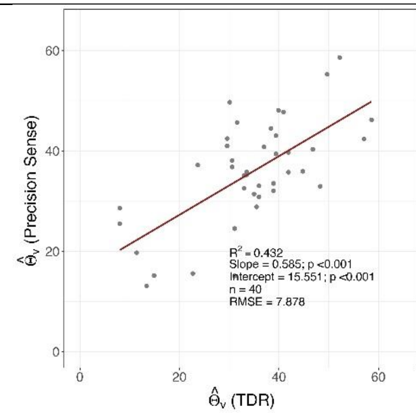
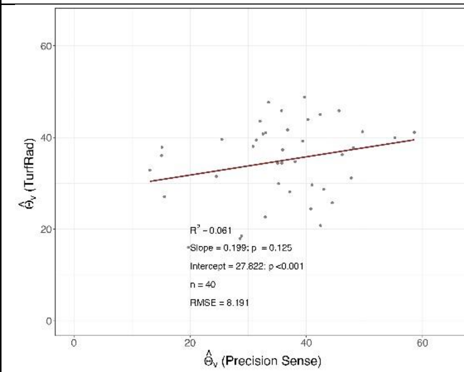
<table>
<tr><th>Date</th><th>TDR 350 and turfRad 1</th><th>TDR 350 and PS 6000</th><th>PS 6000 and turfRad 1</th></tr>
<tr><td>Jun 17</td><td>
</td><td>
</td><td>
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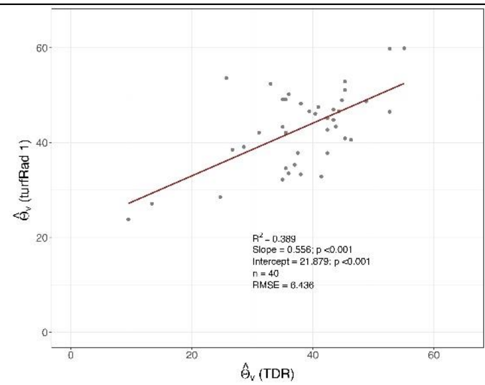
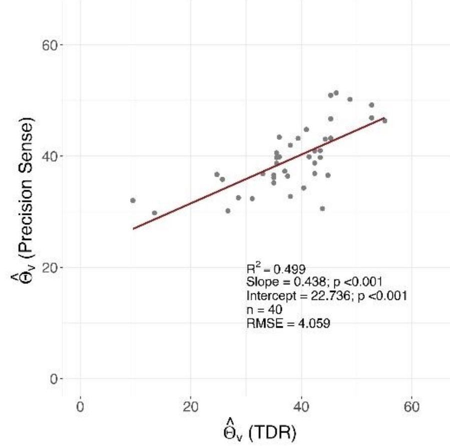
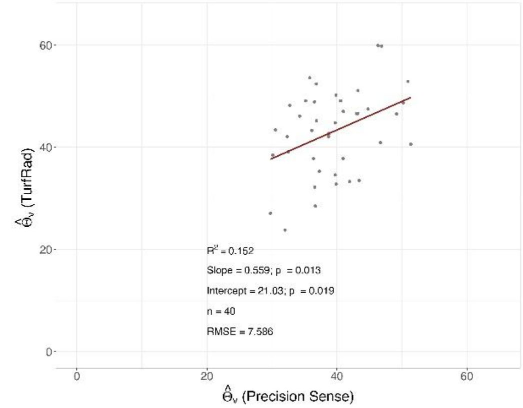
<tr><td>Jul 8</td><td>
</td><td>
</td><td>
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Figure 7. Linear regressions between TDR 350 and turfRad 1 (left column), TDR 350 and PS 6000 (center column), and PS 6000 and turfRad (right column) on June 17, 2024 (top row) and on July 8, 2024 (bottom row).

<table>
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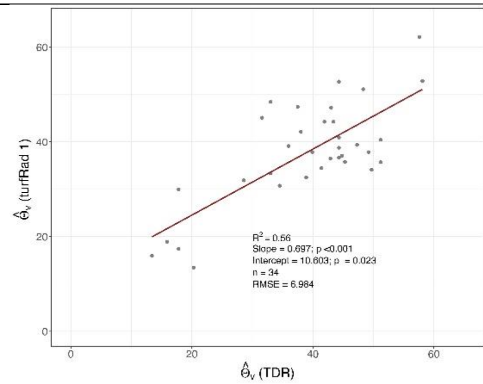
<tr><td>Aug 5</td><td>


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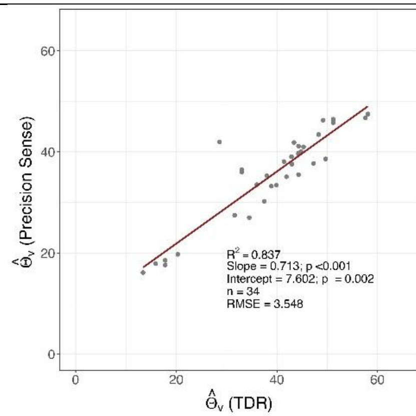

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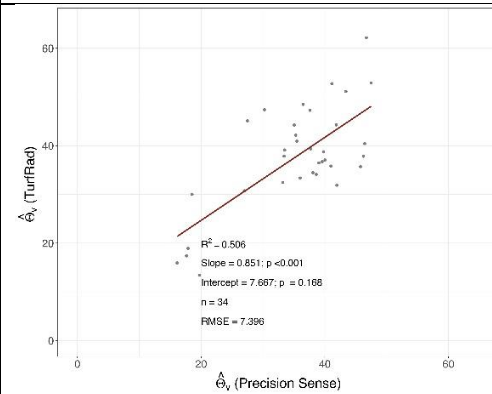

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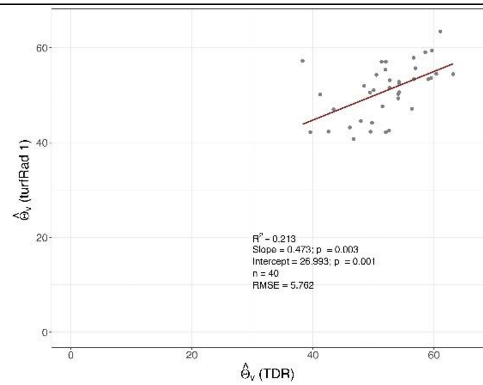
<tr><td>Sep 9</td><td>


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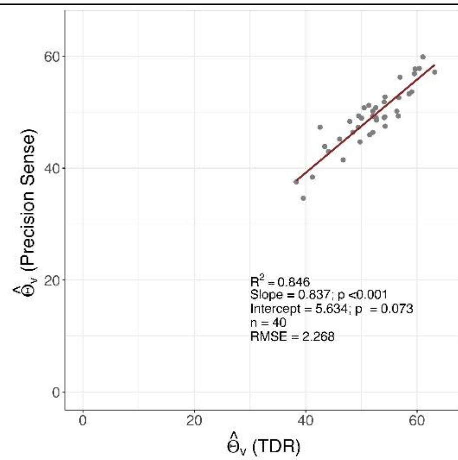

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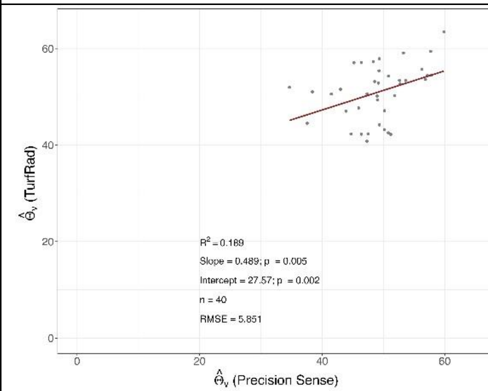

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</table>

Figure 8. Linear regressions between TDR 350 and turfRad 1 (left column), TDR 350 and PS 6000 (center column), and PS 6000 and turfRad (right column) on August 5, 2024 (top row) and on September 9, 2024 (bottom row).

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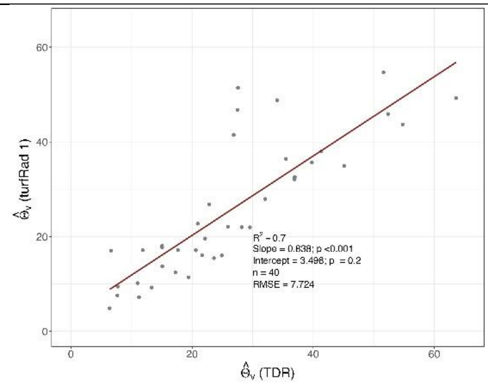
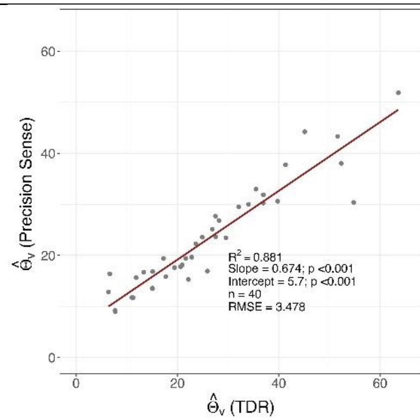
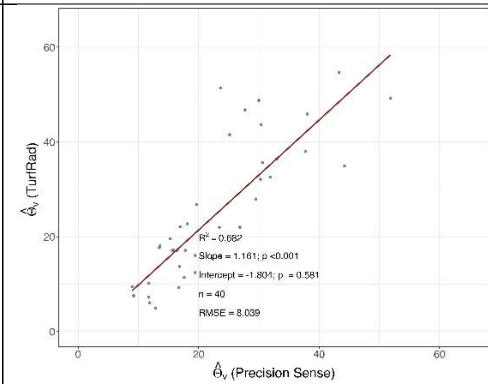
<table>
<tr><th>Date</th><th>TDR 350 and turfRad 1</th><th>TDR 350 and PS 6000</th><th>PS 6000 and turfRad 1</th></tr>
<tr><td>Oct 7</td><td>
</td><td>
</td><td>
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Figure 9. Linear regressions between TDR 350 and turfRad 1 (left), TDR 350 and PS 6000 (center), and PS 6000 and turfRad (right) on October 7, 2024.

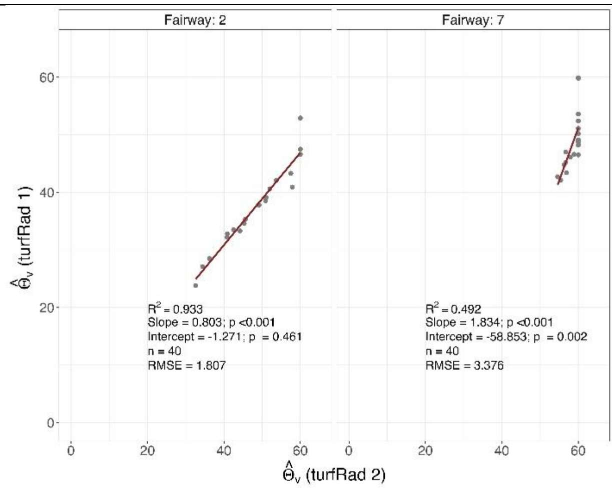
Moisture readings between turfRad 1 in motion and TDR 350 collected on April 22 showed a weak (R^2 = 0.097) but significant (p=0.009) relationship. For data collected on May 17, the regression analysis indicated a weak (R^2 = 0.081) and significant (p=0.021) but negative linear relationship between the TDR 350 and the turfRad. (Figure7). The accuracy of the turfRad improves when the sensor is used in a parked position. Regression coefficients range from 0.213 (September 9) to 0.7 (Oct 7) and RMSE from 5.517 (June 17) to 7.72 (October 7) (Figures 7,8, 9).

When compared to the TDR 350, PS 6000 tracks soil moisture more accurately than the turfRad as indicated by greater R^2 values on six and by lower RMSE values on five out seven sampling dates. Regression coefficients range from 0.353 (May 17) to 0.881 (Oct 7) and RMSE from 7.878 (June 17) to 2.268 (October 7) (Figures 7, 8, 9).

Generally, linear regression analysis indicated either a weak or no relationship between turfRad and PS6000 on five out six sampling dates. Analysis of values from June 17 showed no significant relationship (p=0.125) and for all other sampling dates R^2 ranges from 0.073 (May 17) to 0.682 (October 7) and RMSE from 3.763 to (May 17) to 8.039 (October 7).

5. Comparing turfRad 1 to turfRad 2

Two turfRad sensors to measure soil moisture were used on July 8, September 9, and on October 7. Statistical analysis revealed a significant interaction between fairway and date (Table 3). Figure 10 shows relationships between turfRad 1 and 2 for each fairway and sampling date. When values collected on all two fairways and three dates and were compared together, the Lin's Concordance test rejected the hypothesis that both measurements are in concordance. This may suggest that using both sensors to measure the same area results in different moisture values. However, both measurements appear to be in practical agreement as indicated by a high R^2 and a relatively low RMSE. Nonetheless, a greater variability was observed for soil moisture values greater than 35%. More research is needed to understand this increase of the uncertainty as soil moisture increases (Figure 11).

<table>
<tr><td>Date</td><td>turfRad 1 and turfRad 2</td></tr>
<tr><td>Jul 8</td><td>
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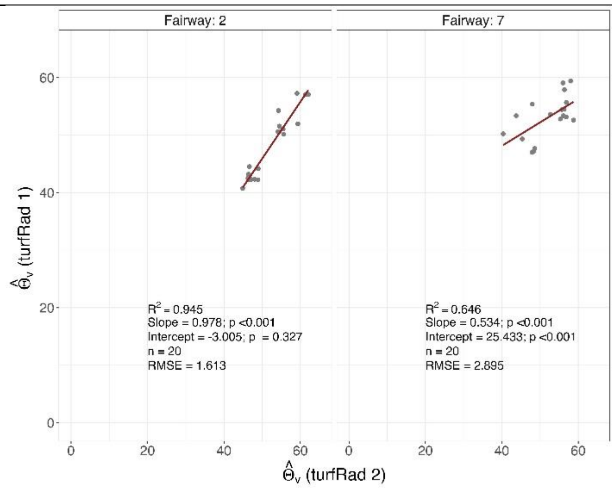
<tr><td>Sep 9</td><td>
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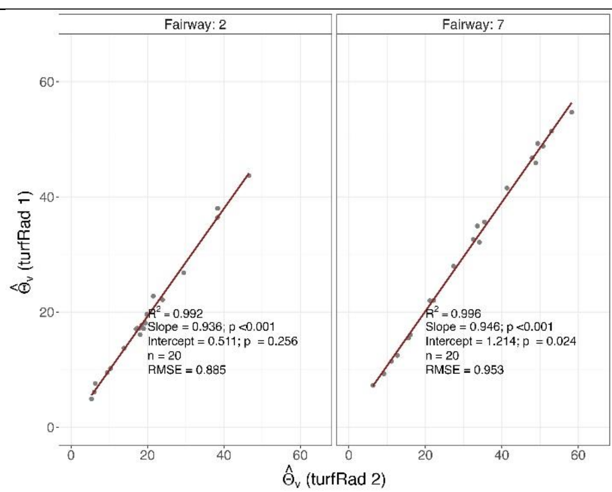
<tr><td>Oct 7</td><td>
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</table>

Figure 10. Relationships between soil moisture values of turfRad 1 and turfRad 2 on two fairways on July 8, 2024 (top), September 9, 2024 (center), and on October 7, 2024 (bottom.

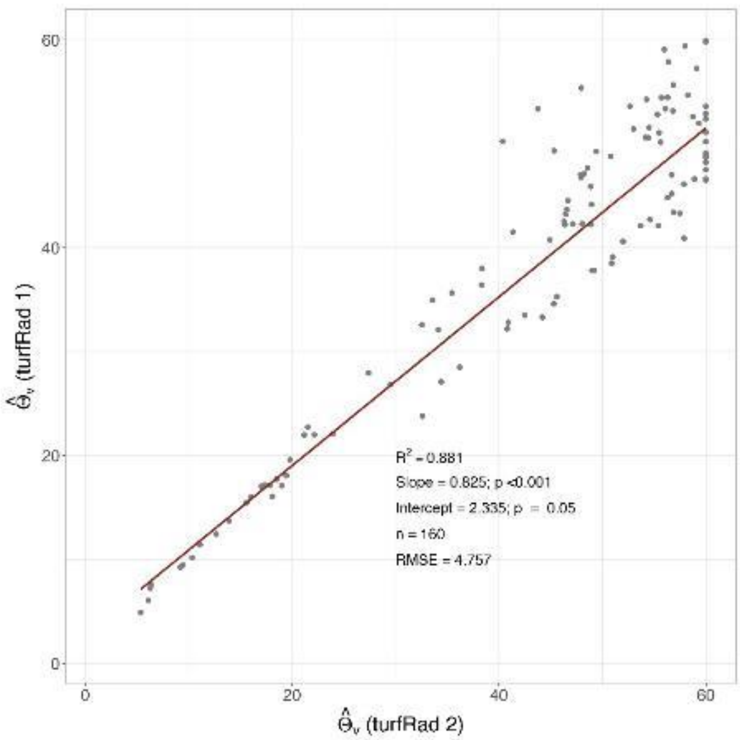


Figure 11. Relationship between volumetric soil moisture determined by turfRad 1 and turfRad 2 sensors.

6. Accuracy of GPS coordinates

Data collected included a comparison of the GPS coordinates recorded by the various instruments with the coordinates recorded by the GEODE^{TM} GNS3S receiver. A comparison of the GPS coordinates revealed that a difference between 0.5 m and up to 8 m can exist between the location shown on the turfRad and the exact location determined by a professional grade surveying equipment (Figure 12). Distance differences were much smaller for PS 6000 and range from approximately 0.2 m to 1 m. Differences were calculated with the turfRad sensors in the parked position. We were unable to provide such an evaluation with the turfRad sensor in motion.

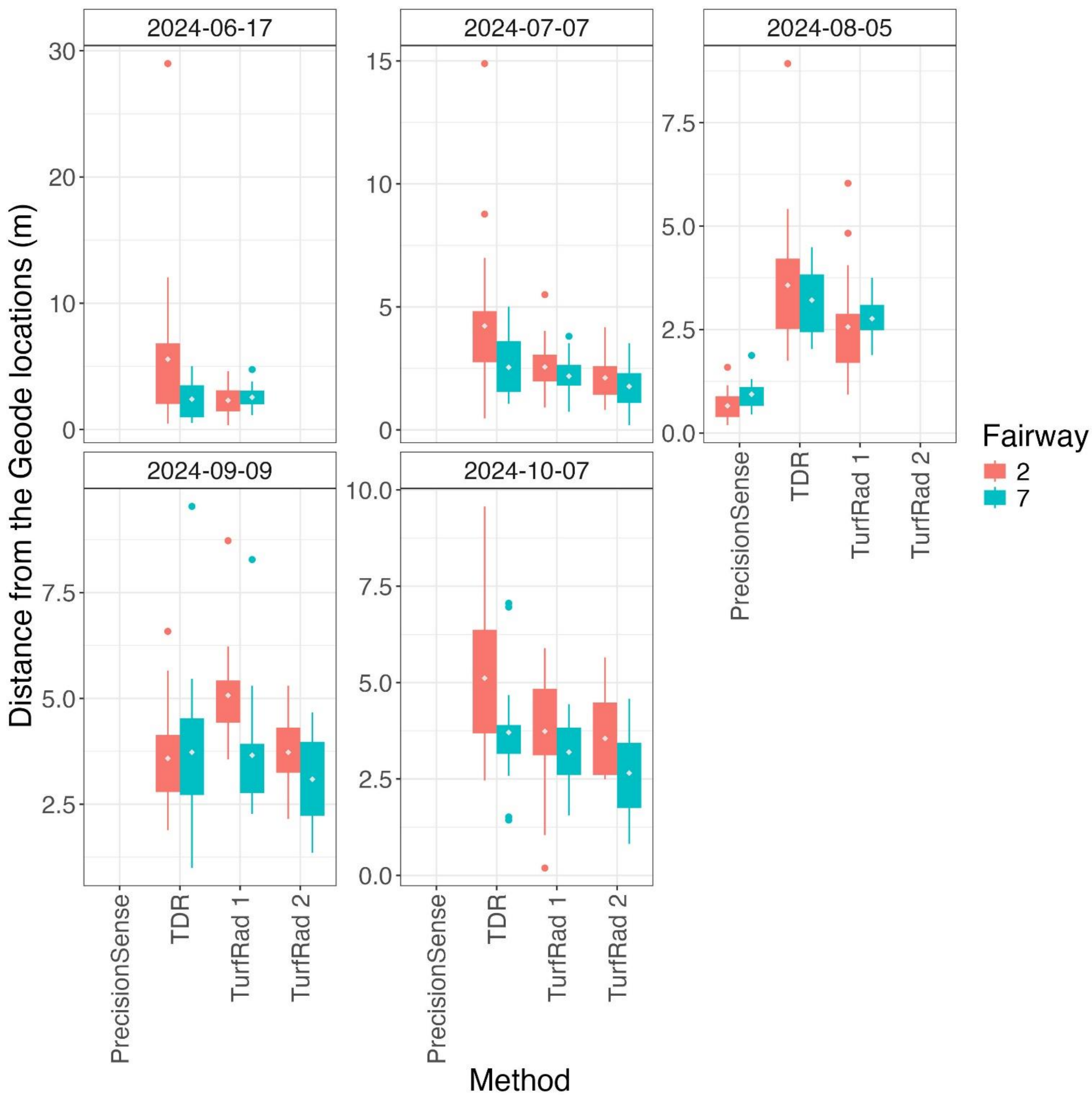


Figure 12. Distances between GPS locations recorded by varying soil moisture sensors (Precision Sense 6000, TDR 350, turfRad 1, and turfRad 2) and by a GEODE^{TM} GNS3S receiver. Precision Sense data were collected only on August 5. Box plots indicate median (line inside the box) and the 25th and 75th percentiles [length of box or interquartile range (IQR)]. Lower and upper whisker extend to the smallest and largest value of 1.5*IQR of the hinge. Data points outside the whiskers are considered outliers and are plotted individually. Scale of y-axes varies between sampling dates.

7. Soil moisture measurements with Umbra satellite

On October 7 we had the opportunity to access reflectance values collected by the Umbra satellite and develop a model to estimate soil moisture using the TDR 350 measurements collected at the Las Campanas site on both fairways as dependent variables. We used a total of 430 TDR measurements of which 90% or 387 of the data points were used to develop a model and 10% or 43 data points for validation (Figure 13). Similarly, a relationship between TDR 350 measurements and Umbra values was also established for the Sankt Leon Rot location. Of 1057 TDR data points collected over several days in October, 83% or 908 established a model and 17% or 152 data points were used for validation (Figure 14).

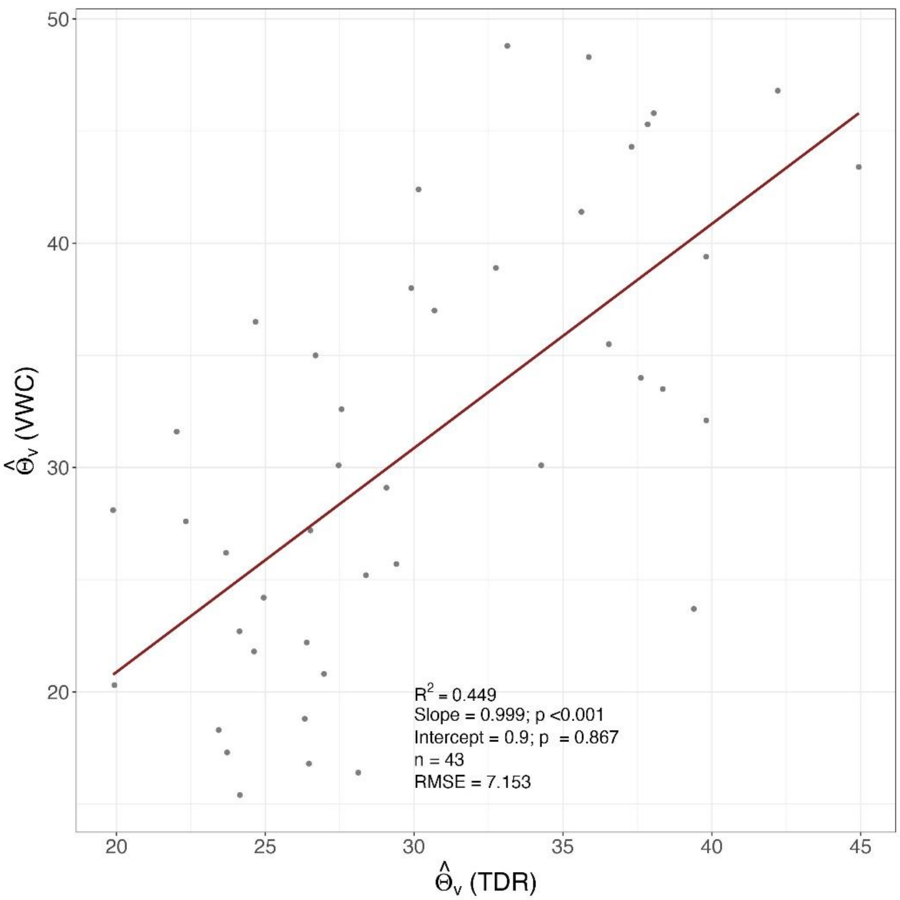


Figure 13. Relationship between volumetric soil moisture based on reflectance values collected by Umbra satellite and TDR 350 at Las Campanas.

The relationship between soil moisture measurements obtained using TDR sensors and satellite reflectance values was significant and yielded an R^2 value of 0.449 for Las Campanas and of 0.548 for Sankt Leon Rot, indicating a moderate level of correlation between the two variables.

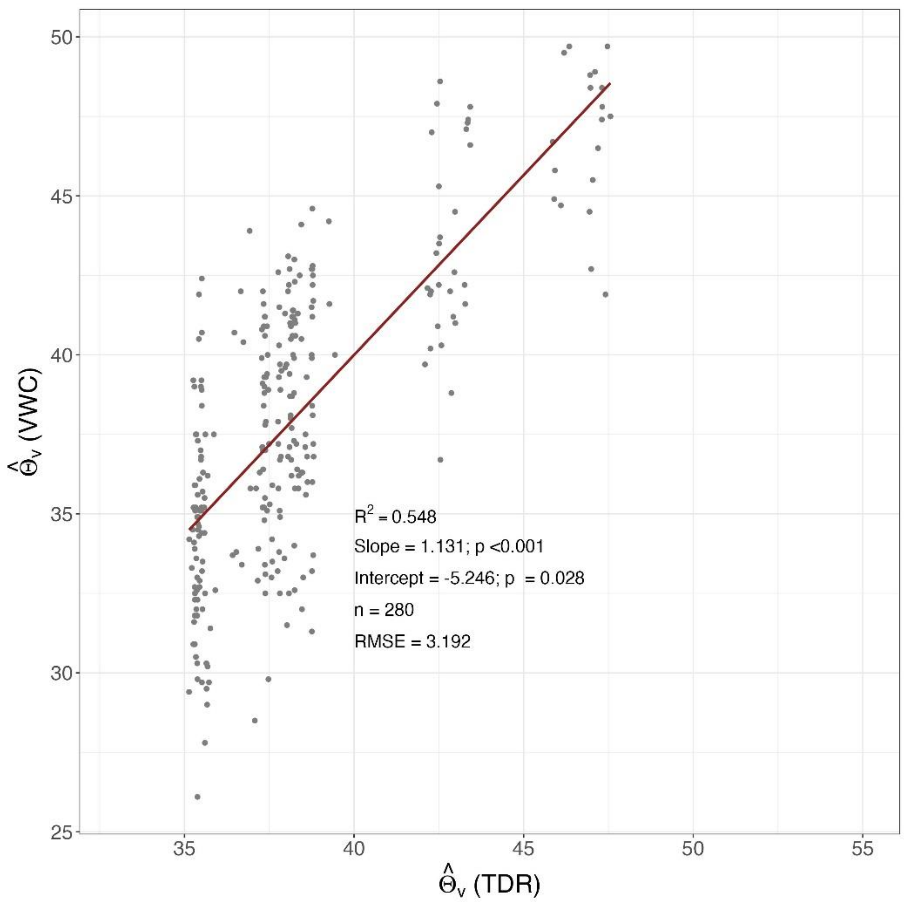


Figure 14 Relationship between volumetric soil moisture based on TDR 350 measurements and reflectance values collected by Umbra satellite at Sankt Leon Rot, Germany.

Conclusions and Future Expectations

Generally, when turfRad was compared to TDR 350, coefficients of determination are significant but low. On one sampling date (May 17), the relationship between the two variables was significantly negative! Similar results were seen during 2023. A negative relationship can be detected especially when soil moisture values are high which results in a high background scatter (Elia Scudiero, pers. communication). Such a problem may have occurred on May 17. On most sampling dates, data points were in the wet range (greater than 30% or even greater than 40%) with only a few data points in dry areas (at 20% or lower). When areas are uniformly wet (or mostly wet), there is very little variability in the dependent variable (TDR measurements) and it is difficult to establish a meaningful relationship between the measured variables. Only on October 7, after one week of no irrigation, moisture values covered a wide range from 6% to 60% and with the turfRad in a parked position regression coefficients were high and a strong relationship between TDR and turfRad could be shown.

Soil moisture based on remote sensing technologies such as the turfRad are model estimates based on soil radiation values and come inherently with some degree of error. Aside from this uncertainty, two other sources of errors may contribute to the measurement discrepancies. First, we assume that GPS coordinates assigned by the sensor unit describe the exact location. However, as Figure

12 shows, this is not the case with the turfRad in a parked position, Moreover, the extent of discrepancies varied between sampling dates. In our project we were unable to document the GPS differences between a moving turfRad and the precision instrument and we feel that it is reasonable to assume that discrepancies are even larger when sensors are in motion. More research is needed to investigate the accuracy of GPS coordinates when sensors are moving. The second source of error is the non-uniformity of the irrigation system. Low quarter Distribution Uniformity on Fairway #7 determined in 2023 reached only a 0.51. Such a low DU, in combination with a considerable difference in GPS coordinates, can result in a significant difference in moisture content when kriging is used to estimate moisture at a location that has not been measured. Considering all these sources of errors, we cannot be sure that the measurements, particularly from a moving sensor, were taken at the same location.

Satellite reflectance suggests some variability in the data but remains within an acceptable range, better than turfRad in motion. However, the significant relationship was established on a model for which data was collected on one day and on the fairways used in this study which may have provided an advantage over a general landscape model used for turfRad. Nonetheless, such an agreement highlights the same potential of satellite-based reflectance as a proxy for soil moisture estimation on golf course fairways than a turfRad sensor. Our findings suggest that satellite reflectance could replace in-situ measurements, particularly in remote monitoring scenarios.

Remote sensing technologies such as turfRad show some promise in tracking soil moisture, however accuracy needs to be improved, particularly if used when the sensor is in motion (i.e. mounted on a fairway mower). Data are uploaded and made available to the golf course superintendent almost immediately after measurements are taken and can assist in timely irrigation decisions. In the current scenario, soil moisture sensing is performed early in the morning, close to or immediately after irrigation, as the sensor is mounted on the fairway mower. Conducting measurements at noon or early afternoon, when soil moisture is at its lowest, would likely provide more meaningful data for irrigation scheduling. This timing would better capture the rootzone's drying and would make decisions for irrigation more effective. Unmanned ground vehicles or drones may be better suited to carry a sensor and scan the turfgrass area at a time when information is most useful.

Nonetheless, more studies are needed to improve the accuracy of measurements and to determine if different mathematical models should be used to estimate soil moisture based on reflectance values on turf areas, especially for the turfRad technology. The soil moisture values estimated from the models used in our study are not sufficiently accurate for them to be useful for scheduling irrigation with the aim of conserving water. These models were developed using data collected from agricultural fields and general landscape areas and not turfgrass areas. Satellite data generated by the Umbra satellite appears to be more practical for the purpose of irrigation scheduling based on the accuracy documented in this study. However, data were only available after a significant delay and fly over must be scheduled well ahead of time.

Our second objective in this study was to select the best performing technology and use it to schedule irrigation. In 2025 we will work with Tom Egelhoff, the agronomist at Las Campanas, to identify a fairway area that can be used to schedule irrigation based on soil moisture measurements. At the same time, we will continue investigating the accuracy of remote soil moisture sensing technologies and will include new ones, as they become market available.

USGA ID#: 2023-35-802

Title: Comparing The Effects of Subsurface Drip Irrigation and Soil Moisture Sensors With ET-Based Irrigation.

Project Leader: Priti Saxena, Robert Green, and Alan moss

Affiliation: California State Polytechnic University, Pomona, CA.

Objectives: 1) Analyze the performances of three subsurface drip irrigation systems (from Hunter Industries) and comparing their water savings sprinkler irrigation. 2) Evaluate the combination of soil moisture sensors and SDI capability to maintain bermudagrass quality maintained under fairway conditions. 3) Compare SDI performances against standard irrigation scheduling.

Start Date: May 1, 2023

Project Duration: Three years

Total Funding: $135,000

Summary Points:

- Bermudagrass plots were maintained by a graduate student and data was collected during the growing season (July-October 2024) to estimate the effectiveness of the subsurface drip irrigation system under traffic stress in fairway condition.

- Additionally, soil moisture sensors are installed in each plot to estimate the moisture content at root zone and manage the irrigation based on the values from SMS for the bermudagrass.

- The subsurface drip irrigation (SDI) plots showed significant variations in reduced amount of water applied to maintain the plant health. In addition, the amount of water applied is lesser as compared to sprinkler-based irrigation during the year.

- The turfgrass quality, color, density and green cover ratings showed variability in acceptable turfgrass quality under SDI fairway condition in the first year study.

Summary Text:

One of the water conserving technologies, subsurface drip irrigation (SDI) reported to save water and improve turfgrass quality by eliminating surface water evaporation and reducing the incidence of weeds and disease. The subsurface drip irrigation (SDI) can save up to 25% - 50% of water as compared to surface irrigation (Rodríguez and Gil, 2012). When SDI is used in comparison to sprinklers, the water loss reduces due to less runoff, less evaporation, and more uniform coverage.

With less moisture on the soil surface, the foot traffic will not cause much compaction than wet surface and maintains turfgrass health and quality (Ferguson, 1994). Thompson (2019) reported that subsurface drip irrigation can be efficient in providing similar turfgrass quality as by overhead sprinklers on golf courses.

The experiment will be conducted at the Center for Turf, Irrigation and Landscape Technology (CTILT), California State Polytechnic University, Pomona, CA. Hybrid bermudagrass Tahoma-31(each 10 feet × 10 feet [3 meters × 3 meters]) which were sodded in summer 2023 for the study. Twelve plots used in this study will have treatments as three SDI and one control (sprinkler). The design of the study is a randomized complete block with three replications. Each plot is individually zoned and controlled. The new hybrid Tahoma 31 bermudagrass plots are be laid on the sandy clay loam soil. A graduate student is pursuing this study as a MS thesis project.

The study is focused on comparing Subsurface Drip Irrigation Systems (SDI), which consist of simple tubing with emitters from Hunter Industries to traditional sprinkler systems that use evapotranspiration (ET)-based irrigation schedules. Each plot was equipped with a soil moisture sensor (SMS) to monitor the volumetric water content and evaluate the water requirements for each treatment. In addition to the irrigation treatments, traffic stress was applied to half of the plots to simulate the effects of mechanical stress on turfgrass. Visual ratings of turfgrass quality, including color and overall health, were collected to assess the impact of traffic stress. The results from this study will help evaluate the efficacy of SDI systems in comparison to sprinkler systems in maintaining turfgrass quality under varying levels of traffic stress and in optimizing water usage.

There were two wetting and drying cycles after sensor installation to monitor and ensure proper sensor response before final setting of control points on sensor controllers. Based on soil textural analyses (plots are sandy clay loam) and tables with general information: field capacity (F.C.) is approximately 29% volumetric; the same for a clay loam is approximately 32% volumetric). The amount of irrigation water applied will determine by recording the actual run time by an hour-meter attached to each plot valve.

Bermudagrass is continued to be maintained at the cutting height of 0.5 inch and mowed twice a week. The plots will be fertilized using 0.4 pounds N/1000 ft^2 per growing month which will be split into one application every 2 weeks to avoid the high and low peaks of shoot growth (Foy, 2014).

In the first year of the study, turfgrass plots exhibited notable variability in terms of turfgrass quality under SDI vs control. Specifically, the fairway plots exposed to traffic stress showed reduced turfgrass quality and color ratings compared to those not subjected to traffic. Additionally, control plots showed higher amount of water requirement than SDI plots. Further data collection and analysis will be necessary to gain deeper understanding of these trends and their long-term implications.

Image 1: Twelve bermudagrass plots, CPP

Image 2: Soil Scout SMS transmitter and recently one of the twelve sodded plots.

References:

Ferguson, K. R. 1994. Subsurface drip irrigation for turf. In Proc. of the 15th annual int'l Irrigation Assn. Expo and Tech. Conf., Atlanta, GA. Nov. 5-8, 1994. Irrigation Assn. pp 273-278.

Foy, H.J. 2014. Bermudagrass Fairway Management. USGA Green Section Record. 52 (11) May 30, 2014.

Rodriguez, L., & Gil, M. (2012). A Review of Subsurface Drip Irrigation and Its Management. Water Quality, Soil and Managing Irrigation of Crops. doi: 10.5772/30702

Thompson, C. (2019). Subsurface drip irrigation reduces water use on tees. United States Golf Association Green Section. Available at: http://archive .lib .msu .edu /tic / usgamisc /know /2019 -08 -02 .pdf

USGA ID#: 2024-16-826

Title: Impact of Irrigation Head Maintenance on Turfgrass Quality and Water Use of a Golf Course Fairway

Project Leader: Chas Schmid
Co-leader: Alec Kowalewski

Affiliation: Department of Horticulture, Oregon State University

Objectives:

1) Determine the impact of irrigation head maintenance (raising, leveling, and nozzle replacement) on the turf quality of golf course fairways

2) Quantify the water savings associated with irrigation head maintenance.

Start Date:
June 2024

Project Duration:
2 years, May 2024 to Dec 2025 (year 1 report)

Total Funding:
$15,000 ($10,000 year 1)

Summary Points:

- Significant labor would be required to raise and level all the fairway irrigation heads on a golf course; between 2,500 to 3,300 hours of labor.
- Raising and leveling irrigation heads improved distribution uniformity by 2.8% from 86 to 88.8%
- Replacing irrigation nozzles only improved distribution uniformity by 0.4%, increasing from 88.8 to 89.2%

INTRODUCTION

Water use is the single most important issue turfgrass managers are facing in a changing climate. To date, research trials have exclusively focused on water-use topics including evapotranspiration of turfgrass, irrigation requirements, deficit irrigation, and selection of drought tolerant plants (Braun et al., 2022), but limited research has focused on the impact of irrigation system performance. Irrigation heads and nozzles are considered the most important part of an irrigation system due to their impact on the distribution of water over the turfgrass surface (Huck and Zoldoske, 2008). However, no research is available on what impact sunken/non-level irrigation heads and/or worn nozzles have on irrigation distribution, uniformity, and water use.

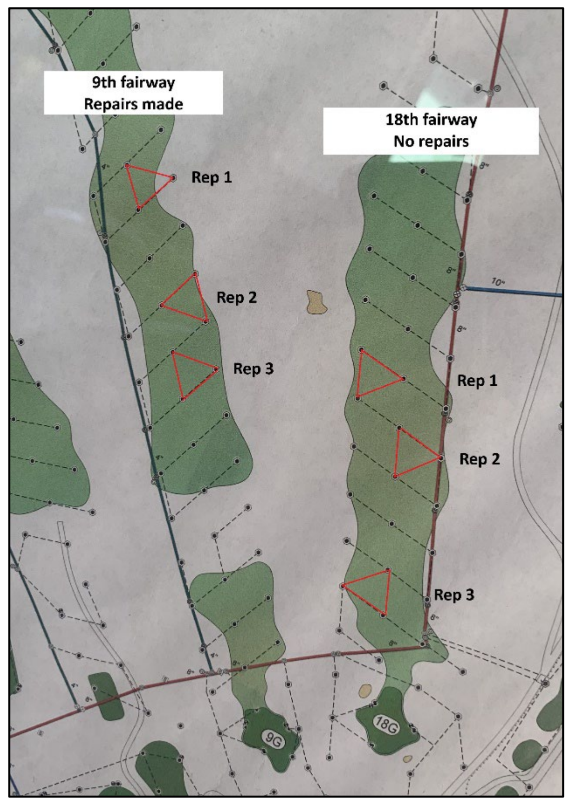
MATERIALS AND METHODS

Site Description

This two-year trial will be conducted at the Oregon State University golf course, Trysting Tree Golf Club, located < 2 miles from the OSU research farm. Trysting Tree Golf Club is an 18-hole links style golf course along the Willamette River in Corvallis, Oregon. In 2017, the golf course completed an irrigation renovation, upgrading to a triple row system (triangle spacing) with Rain Bird 700 series heads (Rain Bird A-700-IC-70, with #36 nozzles) and individual head control. Irrigation heads are on a 65' spacing and have an output of 27.5 gallons per minute at 70 psi. Since the irrigation renovation in 2017, no irrigation maintenance (raising and leveling irrigation heads, or nozzle replacement) has been completed.

Treatments

The treatments for this trial include a golf course fairway that received irrigation head maintenance (raising/leveling heads and nozzle replacement) in three locations with three irrigation heads in a triangle spacing (see image to right) and a fairway that does not receive irrigation maintenance with a similar setup. Irrigation head maintenance was performed in July of 2024, by OSU staff and Trysting Tree staff. A protocol for raising and leveling irrigation heads was established, and the project leader was responsible for final leveling of all irrigation heads.



An irrigation audit was conducted prior to irrigation maintenance, post irrigation head leveling, and post nozzle replacement (and head leveling), by placing 13 catch cans (16 in^2 surface area) within each irrigation zone (3 reps) and running the irrigation system for 10 mins to determine the average irrigation rates, as well as the low quarter average irrigation rate. Distribution uniformity (lower quarter) (DU_{LQ}), a common measurement used in irrigation audits on golf courses (Barrett et al., 2003), is calculated using the following equation:

$$DU_{LQ} = \frac{AVG_{LQ}}{AVG_T}$$

where AVG_{LQ} = low quarter of the average group of catch-can measurements and AVG_T = total average of the catch-cans measured. A suggested way to use this data is to irrigate using the low quarter average (25% of the surface area) to prevent these areas from developing drought stress. However, this means most of the remaining surface area (75%) is over irrigated. An additional irrigation audit will be performed in June 2025 prior to data collection in the summer of 2025.

Data Collection

Data collection will begin in July 2025, to allow time for differences in irrigation treatments to accumulate. Data will be collected from 2 subplots within each fairway, consisting of 9 irrigation heads and approximately 10,000 ft^2. Weekly soil moisture measurements will be collected from July to early September 2025 (10-wk period) using a spectrum soil moisture meter. Soil moisture will be measured every 5 ft on center within each subplot. Visual data, including turfgrass quality and quantity/severity of localized dry spots will be collected weekly. DJI Inspire II drone equipped with a Sentera 6x multispectral sensor with thermal imaging capabilities will be used to assess red (670-30 nm), green (550 to 20 nm), near infrared (840-20 nm), red edge (715-10 nm), RGB (20 MP) and surface temperature weekly from July to early-September 2025.

The total quantity of irrigation applied to each subplot with the fairway treatments will be estimated based on the irrigation audit (post maintenance) and scheduled run times each day. A summation of daily run times for each irrigation head within a subplot will be calculated and added up to determine the total quantity of irrigation water used. In addition, we will also attempt to measure the amount of hand watering required for each subplot by either measuring the quantity of water used to hand water localized dry spots in each subplot (using a flow meter) or the total time required to hand water.

PRELIMINARY RESULTS

On average, it took between 1.5 to 2 hrs for two people to raise and level each fairway irrigation head, not including the time spent watering and topdressing repaired turfgrass around the irrigation heads. Based on this, it would take between 2,500 to 3,400 hrs of labor to raise and level all 1,700 irrigation heads in the fairways at Trysting Tree Golf Club.

Prior to irrigation maintenance, the depth of irrigation heads below the surface ranged from 7/8" to 2 ¾", the angle of the sprinkler head ranged from 0 to 4°, and the distribution uniformity ranged from 84.7 to 87.4% (Table 1). The distribution uniformity of both the 9th and 18th fairways at Trysting Tree were within the excellent range according to water management committee of the irrigation association, with distribution uniformity of 86 and 87%, respectively. After raising and leveling of irrigation heads on the 9th fairway, the distribution uniformity increased from 86% to 88.8%. Once the nozzles were replaced, the distribution uniformity was increased another 0.4% to 89.2% at the conclusion of irrigation head maintenance. The minimal improvement in distribution uniformity of irrigation heads that received maintenance is likely due to the relatively uniform distribution of the irrigation system prior to irrigation head maintenance. Based on the results from this experiment, the golf course superintendent at Trysting Tree stated that he is not likely to conduct irrigation head maintenance on fairway heads due to the small improvement in uniformity; however, he was willing conduct irrigation head maintenance on putting green heads.

In 2025, comparisons between the fairway that received irrigation head maintenance (9th) and the one that received no maintenance (18th) will be made with respect to soil moisture uniformity, visual turfgrass quality, and drone imaging. In addition, the amount of water used in each irrigation zone will be monitored throughout the summer to determine the effect of irrigation head maintenance on water use.

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Braun, R.C., D.J. Bremer, J.S. Ebdon, J.D. Fry, and A.J. Patton. 2022. Review of cool-season turfgrass water use and requirements: I. Evapotranspiration and responses to deficit irrifafation. Crop Sci. 62:1661-1684.

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Table 1. Results from a catch-can irrigation tests at Trysting Tree Golf Club in Corvallis, OR during 2024, including average volume (ml) of water collected in each catch can, average lower quarter volume (mL), and distribution uniformity (DU) percentage measured pre-maintenance, post raising and leveling, and post nozzle replacement.

Timing	Metric	Irrigation zone			AVG
		1	2	3	
Pre	Average (ml/can)	28.6	30.4	28.5	29.2
	Average (LQ) (ml/can)	25.0	25.8	24.5	25.1
	DU %	**87.4**	**84.7**	**85.8**	**86.0**
Post raising/leveling	Average (ml/can)	26.5	26.8	28.0	27.1
	Average (LQ) (ml/can)	24.5	22.8	25.0	24.1
	DU %	**92.3**	**84.8**	**89.3**	**88.8**
Post nozzle replacement	Average (ml/can)	27.2	27.5	27.7	27.5
	Average (LQ) (ml/can)	25.5	23.8	24.3	24.5
	DU %	**93.6**	**86.5**	**87.6**	**89.2**

Image: Irrigation audit at Trysting Tree Golf Club Corvallis, OR.

Image: Measuring depth of irrigation heads below the surface of turfgrass.

Image: Measuring angle of irrigation heads, all heads were measured in two directions.

Image: Raising and leveling irrigation heads.

Image: Inspecting irrigation heads prior to maintenance.

USGA ID#: 2024-08-818

Title: Comparison of Variable Depth Rootzone and Capillary Hydroponic Greens to Promote Sustainable Irrigation Practices

Project Leaders: Thomas A Nikolai, Ph.D., Michael Rabe, Wei Zhang, Ph.D., Kevin Frank Ph.D., and Brian Horgan, Ph.D.
Affiliation: Michigan State University

Objectives:

1. Determine differences in the amount of irrigation water used between the Capillary Hydroponic System (CHS) and the Variable Depth Rootzones (VDR).
2. Determine the uniformity of soil moisture retention in the CHS and VDR.
3. Gather data including green speed, surface firmness, clipping yield, pest observations, nutrient holding capacity, organic matter build-up, and drainage water nutrient content.

Start Date: 2023
Project Duration: 2-years
Total Funding: $29,876.56

Summary Points:

- CHS greens required significantly less irrigation than VDR.
- Weather conditions impact irrigation differences between the systems.
- The CHS and VDR resulted in insignificant differences regarding green speed, surface firmness, visual appearance, clipping yield, and organic matter content in the first year of the study.

Rationale

United States golf courses use approximately 2.27 trillion liters of water per year for irrigation and water cost is significant (e.g., $1,068/Million L in the pacific region) (Gelernter et al., 2015 Shaddox et al., 2022). The need for water conservation may be further amplified by climate change (Scott et al., 2018). Furthermore, turfgrass quality and playability of golf courses must be maintained or even improved when adopting any new water and nutrient conservation practices.

Methods and Materials

Christopher Wilczynski, American Society of Golf Course Architects, drafted 6 greens with identical undulations and slopes of 1.5, 3, and 5%. Each green was constructed 11 m x 11 m separated by a concave buffer zone 6 m wide east to west and 3.5 m wide north to south to negate the possibility of runoff or overhead irrigation drifting from one green to another. All six research greens were constructed with the same sand conforming to USGA specification.

The site was seeded with T1 creeping bentgrass (*Agrostis stolonifera*) on 15 June 2022 and was grown in with overhead irrigation. Construction included block style irrigation system with heads on each corner of each green. Each Capillary Hydroponic System (CHS) includes a waterproof liner divided into 2 equal sections with a 55-gallon control basin buried beside the green connected to feed pipes that protrude to the middle of each section. The control system pumps water back and forth between sections every four hours and the control basin also houses a float valve that controls an adjustable water table. The Variable Depth Rootzone (VDR) greens diverges from United States Golf Association (USGA) recommendations by decreasing the rootzone depth at the top of slopes (8–10 inches) and increasing it in low lying areas (14-16 inches).

Maintenance practices include mowing six times per week at 3 mm, rolling 3 times per week, and sand topdressing and foliar fertility. The greens had sufficient density to initiate irrigation treatments on 21 June 2023.

Prior to study initiation irrigation triggers were determined by combining visual observations and volumetric moisture content (VMC) measurements with a TDR-350. Greens displayed visible wilting at 7% VMC, therefore 8%VMC became the irrigation trigger. VDR returned 80% relative daily evapotranspiration via overhead irrigation while CHS system was met by setting auto fill when the water table fell below 20 cm below the surface of the lowest spot (Figure 1). CHS greens only received overhead irrigation following sand topdressing, fertility, and fungicide applications receiving the same volume of irrigation as VDR on those occasions.

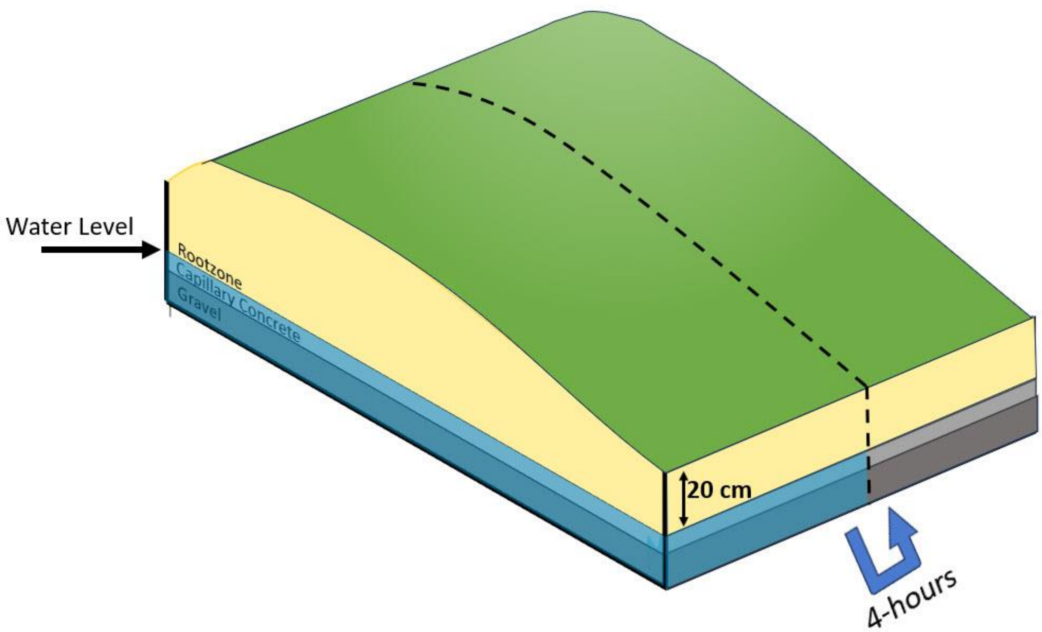

Figure 1 A cross section of the Capillary Hydroponic System

Each green was constructed with a drainage line and following significant rain events samples were collected and analyzed. When pests were observed data was collected and curative applications were made. Soil tests were conducted by collecting nine 19 mm diameter cores 7.5 cm deep and clippings yield was measured by drying and weighing clippings from a single pass with a Toro Flex 2100 in the identical location spanning elevation changes on each green.

Other data collection included green speed measurements with a USGA Stimpmeter, surface firmness on six locations on each green with a USGA TruFirm, volumetric moisture content monitored weekly at two depths, 7.5 cm, and 20 cm, with a handheld TDR 350 across the greens surface in a 1.5 m x 1.5 m grid to map uniformity of water distribution.

Results to Date

CHS greens required 59% less irrigation water to prevent surface wilting compared to VDR greens during the summers of 2023 and 2024 (Figure 2). Within that time period two 11-day intervals in each year were selected to represent two weather conditions:

1. low precipitation (<0.15 cm) and high Relative Potential Evapotranspiration (RPET) (>0.30 cm) resulting in CHS greens needing 44% and 45% less irrigation than the VDR greens in 2023, and 2024 respectively.
2. high precipitation (>0.40 cm) and high RPET (>0.30 cm) resulting in CHS greens using 76% and 74% less irrigation than the VDR greens in 2023 and 2024 respectively.

There was no significant difference regarding soil chemical analysis or organic matter content, clipping yield, green speed, or surface firmness. In 2024 VDR greens displayed signs of localized dry spot (LDS) and required a wetting agent application. However, VDR consistently demonstrated a more uniform volumetric moisture content compared to the CHS and there were some differences in nutrient content in the drainage water, but more data is required to make any conclusions. While both systems were impacted by take all patch (*Gaeumannomyces graminis*) the take all patch was more persistent in the CHS.

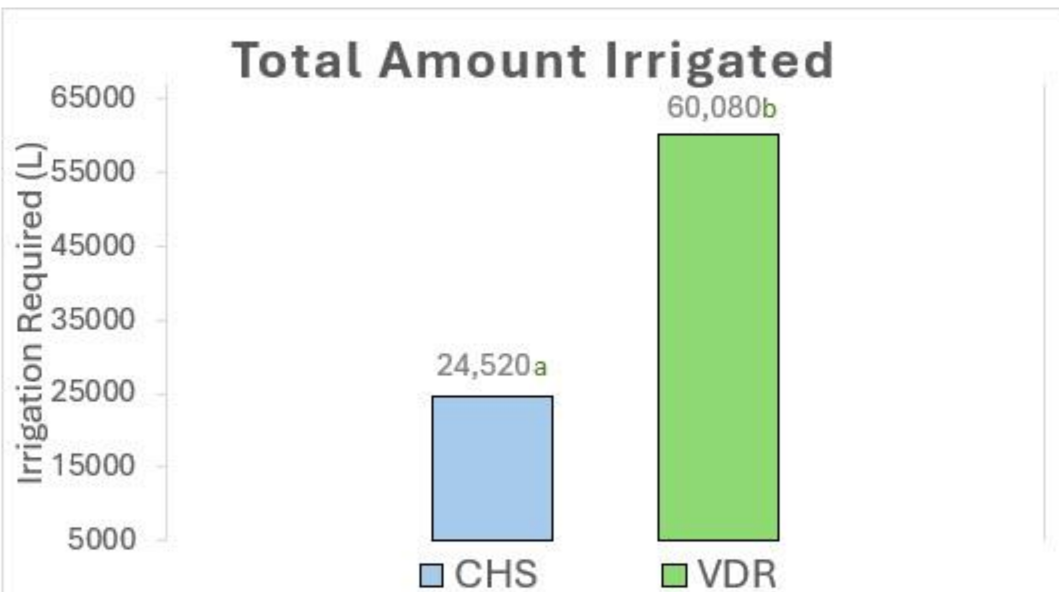

Figure 2. Irrigation applied to Variable Depth Rootzone and Capillary Hydroponic System research greens between June 21 - September 21, 2023, and 2024. Means with same letter are not significantly different (α=0.05).

Future expectations

Across the two-year trial the most significant difference between CHS and VDR is the amount of irrigation water applied. The CHS system required significantly less water than the VDR system regardless of weather conditions. It seems logical to hypothesize that greens with identical rootzone particle size and surface contours that the green receiving more than twice as much irrigation would result in greater organic matter build up, but that was not the case. However, it could be that since we are maintaining the CHS and VDR greens at a minimal amount of irrigation, to maintain 8% VMC, that there will be no changes in organic matter content and therefore very little meaningful difference between the systems going forward other than the amount of irrigation water applied, which could change as the grass matures. The wetting and drying nature of the CHS may be creating an ideal microclimate for root diseases, since the research greens were only treated with fungicide on a preventative basis it can be hypothesized that an early fungicide program could mitigate the impact of these pathogens but more data is needed to draw concrete conclusions.

Literature Cited

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USGA ID#: 2024-02-812

Title: Cultivation Strategies for Improving Soil Physical/Chemical Properties in Highly Compacted and Sodium-Degraded Fairways

Project Leader: B. Wherley, A. Franks, K. McInnes, T. Provin, M. Chavarria
Affiliation: Department of Soil and Crop Sciences, Texas A&M University

Objectives: The objectives of this project are to evaluate long-term effects of both conventional and linear decompaction cultivation strategies in combination with gypsum applications on improving soil physical/chemical properties, water retention, and turfgrass vigor under highly compacted/ sodium degraded native fairways receiving poor-quality irrigation water.

Start Date: 2024
Project Duration: 3 years
Total Funding: $135,846

Summary Points:

- The linear decompaction + hollow tine aerification treatment caused a temporary decline in turfgrass quality and cover directly following cultivation but did not differ from the untreated plots within 2-4 weeks.
- The linear decompaction treatments provide similar levels of surface hardness reduction compared to traditional aeration methods.
- All aeration and linear decompaction treatments are providing improved soil moisture levels relative to the control.
- Shockwave treatments are providing improved turfgrass quality ratings over the control plots.

Summary: Recycled water is becoming the primary source of irrigation water across the southern United States. The use of this water, which contains elevated levels of Na and bicarbonates, leads to rapid degradation of native soils leading to compaction and loss of permeability. Sand-capping can be an effective method to mitigate this problem, however it can be cost-prohibitive for many golf facilities. Gypsum applications have been the traditional recommendation for counteracting sodic soils but may only have marginal effects due to high required rates of application and low solubility. While traditional solid and hollow tine aeration are still practiced in fairways, sodic soils can be difficult to penetrate, and effectiveness may not extend below the surface, leading to development of a hard pan. Linear decompaction machines have been developed in recent years which fracture the upper soil profile to help relieve this hard pan layer. To date, there are no published studies examining linear decompaction in comparison to traditional aeration on highly degraded and trafficked sodic soils.

Golf Course Study:

On July 11, 2024, an on-course research study was initiated at a local municipal golf course (Briarcrest Golf Course, Bryan TX) to compare the effects of linear decompaction (Shockwave, Imants, Reusel, NL) to traditional solid, hollow, and/or deep solid tine aeration (Figure 1). Briarcrest Golf Course is 54-year old public course receiving over 40,000 rounds per year. Fairways are composed of 'Tifway' bermudagrass grown atop native clay loam soils. The golf course study is arranged as a randomized complete block design with treatments including 1) sold tine aeration, 2) hollow tine aeration, 3) deep solid tine aeration, 4) shockwave (perpendicular to slope), 5) shockwave (parallel to slope), 6) shockwave (different direction each event), 7) shockwave + hollow tine, and 8) control (no cultivation). All treatments except the control were implemented with and without sand topdressing following cultivation. Gypsum was applied at 3,660 kg ha^{-1} yr^{-1} in one application in August and cultivation treatments were made in July and October. To assess treatment differences, turfgrass quality, NDVI, lightbox images, soil moisture (0-5 cm), and surface firmness were measured biweekly. Soil bulk density cores were taken the first week of December to determine treatment effects on soil physical properties. At the conclusion of the study, soil samples will be taken to assess treatment effects on soil chemical properties. All data are subjected to the GLIMMIX procedure in SAS (v9.4). Means were separated using Fisher's LSD ($P \leq 0.05$).

Results to date show that the combined shockwave + hollow tine treatment is the most damaging treatment as compared to solid, hollow, or deep solid tine aerification alone. Although there is a temporary decline in green cover from this combined treatment, within 2-4 weeks after treatment, no differences in green cover are evident between any treatments (Figure 2). It was also observed that the only treatment to produce minimally acceptable turfgrass quality, when averaging across rating dates, was the shockwave treatments, regardless of direction (data not shown). The untreated control plots did not meet the minimally acceptable turfgrass quality score and were significantly lower than the shockwave treated plots. Soil moisture at the 0-2.5" depth is generally higher within all treatments as compared to the control (Figure 3). Also, surface hardness has been reduced similarly by all treatments, relative to the control (Figure 4)

Field Laboratory Study:

A parallel field laboratory study is also being conducted on 'TifTuf' hybrid bermudagrass fairway plots at the Texas A&M University Turfgrass Research Field Laboratory. The study is arranged as a split-plot design with cultivation method as the whole main plot and sand topdressing as the subplot, treatments 1-8 from above have been implemented along with a no cultivation + gypsum treatment in order to compare cultivation x gypsum interactions. In July 2024, fairway testing plots were constructed atop a native fine sandy loam soil. The fairway study area includes an east-west running 4% slope intended to simulate a sloping golf course fairway. The initial cultivation event took place on October 9th, 2024. After the treatments were imposed, the same data collection schedule was followed as the on-course study. To date, no significant treatment effects or interactions have been observed for the field lab study.

Both golf course and field laboratory studies will continue for two years, after which time a comprehensive set of results will be available. Turf species establishment into degraded, sodic soil areas will also be evaluated in the golf course study in early spring 2025. Hybrid bermudagrass, zoysiagrass, and seashore paspalum cultivars will be tested.

Figure 1. *Upper*- Core aeration and topdressing treatments being made to Tifway bermudagrass fairway plots in the golf course study at Briarcrest Golf Club, Bryan, TX. Image taken July 11, 2024. *Lower*- Image of linear decompaction scars on the hybrid bermudagrass fairway canopy. Horizontal lines are from a treatment implemented the same day the picture was taken; vertical lines are from a treatment implemented three months prior. Image taken October 3, 2024.

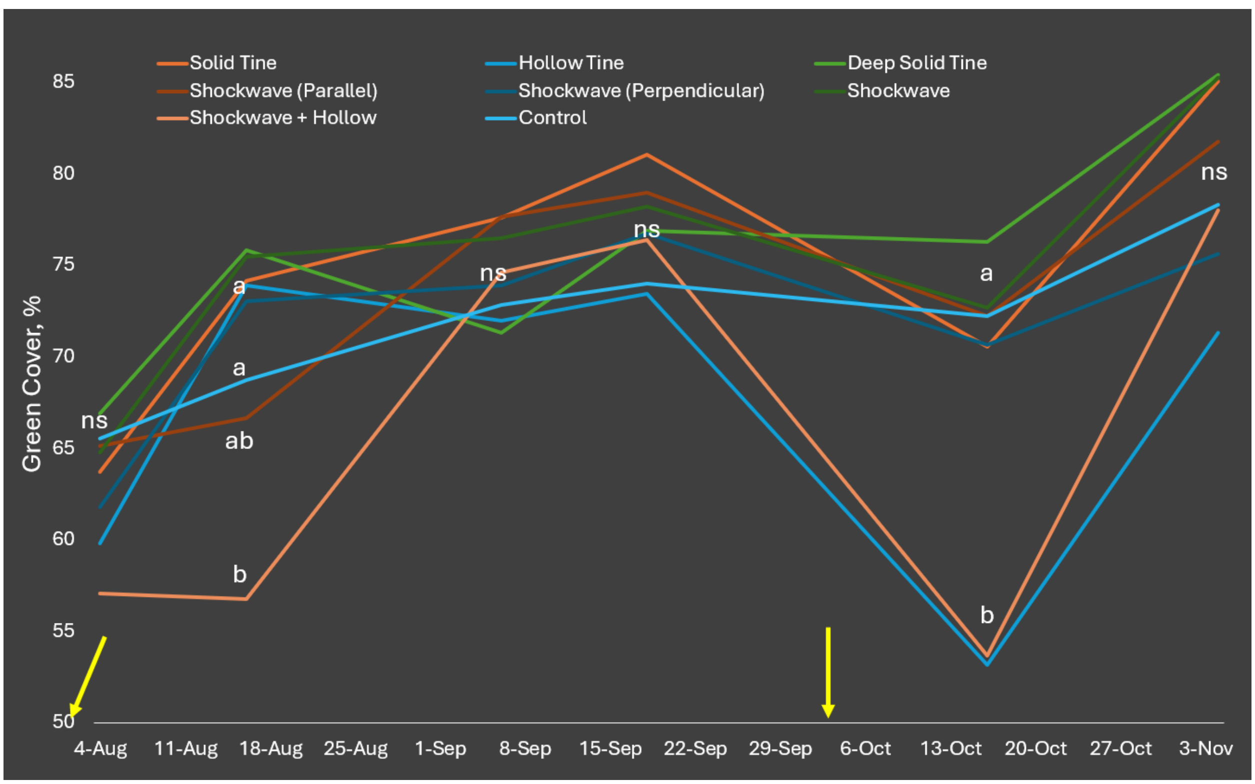


Figure 2. Date x Treatment interaction for Tifway bermudagrass fairway % Green Cover during 2024 season. Means with the same letter on a given rating dates do not differ based on Fisher's LSD (0.05).

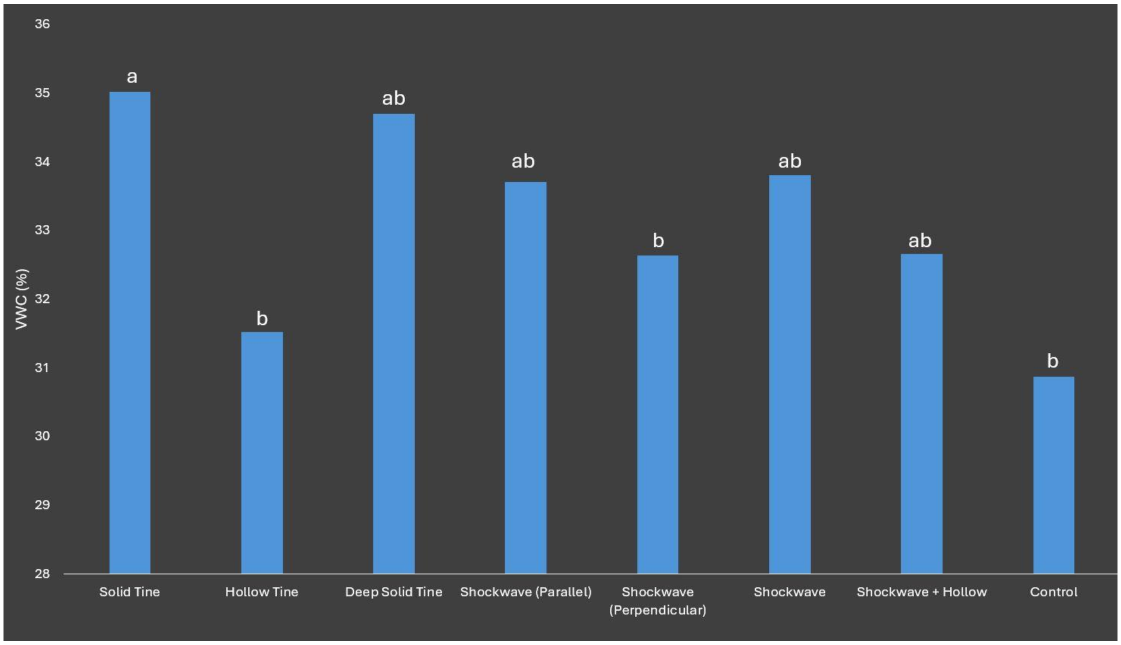


Figure 3. Main effect of cultural treatments on Tifway bermudagrass fairway soil moisture (0-2.5" depth). Data are pooled across 2024 rating dates. Means with the same letter do not differ based on Fisher's LSD (0.05).

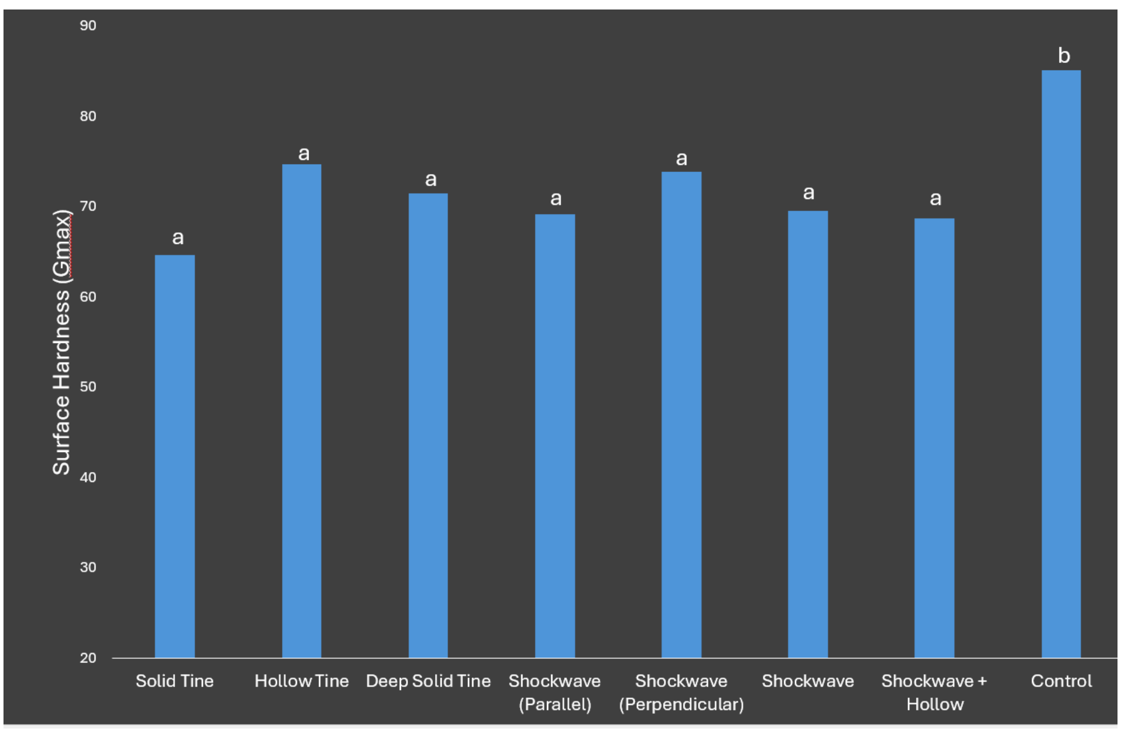


Figure 4. Main effect of cultural treatments on Tifway bermudagrass fairway surface hardness. Data are pooled across 2024 rating dates. Means with the same letter do not differ based on Fisher's LSD (0.05).

USGA ID#: 2024-06-816

Title: Bicarbonates in Irrigation Water: Effect of Acidification on Accumulation of Carbonates in Soil, Infiltration Rate and Kentucky bluegrass performance.

Project Leaders: Elena Sevostianova[1], Maria Bronnikova[2], and Bernd Leinauer[1]
Affiliation: [1]New Mexico State University, [2]Texas Tech University

Objectives:

1. Evaluate changes in infiltration rates of rootzones irrigated with water high in bicarbonates and treated with either N-pHuric acid or with WaterSOLV™ Curative.
2. Assess the impact of N-pHuric acid or WaterSOLV™ Curative on bicarbonate levels and other chemical properties of the rootzone.
3. Examine the effect of irrigation water treated with N-pHuric acid or WaterSOLV™ Curative on the quality of Kentucky bluegrass.

Start Date: 2021
Project Duration: 3 years (extended to 2024-2026)
Total Funding: $116,580.00

Summary Points:

- After 4 years, saturated hydraulic conductivity did not differ between the four water treatments.
- Despite an increase in bicarbonates levels during fall 2022 and spring 2023, there was no evidence of bicarbonate accumulation in the soil by 2024.
- Kentucky bluegrass irrigated with water high in bicarbonates plus N-pHuric acid exhibited a decline in visual quality during summertime, which persisted longer compared to grass irrigated with other treatments.
- Kentucky bluegrass tissue irrigated with water high in bicarbonates plus N-pHuric showed reduced zinc (Zn) concentration, but higher levels of sodium (Na) and total nitrogen (N_{total}).
- A six-month experiment using ceramic tiles as a matrix demonstrated that irrigation with high-bicarbonate water increases carbonate accumulation in soils compared to irrigation with potable water or soil with no irrigation.

Summary Text
Background and Rationale

Golf courses, particularly in arid regions, increasingly rely for irrigation on suboptimal water sources with elevated bicarbonate levels. In high-pH water, the abundance of hydroxyl (OH^-) ions and soluble bicarbonates can lead to the formation of carbonate ions. As water containing HCO_3^- evaporates, calcium and magnesium carbonates may precipitate. Therefore, high bicarbonates, along with sodium, calcium, and magnesium in water, contribute to issues like reduced infiltration and potential calcium carbonate deposits that seal soil pores, which is different from sodium-induced soil degradation. Despite existing guidelines, evidence on the impact of high-bicarbonate irrigation on turfgrass quality and on soil dynamics remains limited. The few available studies focused on turfgrass quality, overlooking soil effects such as calcium carbonate buildup. Addressing these gaps is essential to understanding how water quality affects soil and turfgrass health.

Methods

A study was initiated and the Kentucky bluegrass cultivar Barserati was sown in 2020 at the Turfgrass Research Center of New Mexico State University in Las Cruces, NM. The site featured a Bluepoint sandy loam soil with sixteen 2 m × 2 m plots arranged in a completely randomized block design.

Irrigation with different water sources began in 2021, using four 1,890 L (500-gallon) tanks (Figure 1). Sodium and potassium bicarbonate were added to elevate the bicarbonate concentration in the irrigation water to 500 ppm. The plots were manually irrigated five times per week at 80% of the reference evapotranspiration using respective irrigation treatments (Table 1).

Figure 1. Four water tanks containing tap water (Control), water high in Bicarbonates, water high in Bicarbonates with N-pHuric, and water high in Bicarbonates with WaterSOLV™ Curative.

Four water treatments were implemented:
Treatment 1: Potable tap water with a low bicarbonate concentration (200 ppm) served as the control treatment.
Treatment 2: Potable water with a high bicarbonate concentration (450–500 ppm).
Treatment 3: Potable water with a high bicarbonate concentration (450–500 ppm), adjusted to a pH of 6.5 using N-pHuric acid (“N-pHuric”).
Treatment 4: Potable water with a high bicarbonate concentration (450–500 ppm), amended with WaterSOLV™ Curative (“Curative”) according to label recommendations.

Table 1. Chemical analysis of water samples collected from four water tanks.

Constituents	Treatment 1	Treatment 2	Treatment 3	Treatment 4
EC (mmho/cm)	0.78	1.3	1.31	1.27
Sodium, Na (ppm)	62	116	129	124
Potassium, K (ppm)	6	93	92	95
Sulfate, SO_4-S (ppm)	37	38	80	38
Carbonate, CO_3 (ppm)	<1.0	9.2	<1.0	9.1
Bicarbonate, HCO_3 (ppm)	205	451	306	463
Total alkalinity, $CaCO_3$ (ppm)	173	382	253	392
Nitrate, NO_3-N (ppm)	0.1	0.1	0.1	<0.1
Total nitrogen, N (ppm)	0.1	0.3	42.1	0.3
Total Phosphorus, P (ppm)	0.5	0.21	0.7	0.43

Control plots and those irrigated with high-bicarbonate water, with or without Curative, were fertilized with urea to match nitrogen levels in plots treated with N-pHuric. By season's end, all plots received equal amounts of nitrogen. Soil samples were taken at 10, 20, and 30 cm depths before and after each season. In 2024, saturated hydraulic conductivity was measured using the SATURO device [SATURO | Automated Field Infiltrometer | METER Environment (metergroup.com), Pullman, WA].

Figure 2. Measurement of saturated hydraulic conductivity using SATURO (Meter Group, Inc. USA) (left) and installation of containers with basalt dust.

Turf visual quality, rated on a scale from 1 to 9, was recorded monthly from June to November. Plant tissue samples for nutrient analysis were collected in August 2024.

To explore the dynamics of calcium carbonate precipitation in soil pores, carbonate-free ceramic bisque tiles were installed in 2023 at depths of 5 cm in each plot, as well as in non-irrigated desert soil, adjacent to the research area. The accumulation of carbonate on the tiles was measured at 2, 3, 4, 5, and 6-

month intervals using a Li-Cor gas analyzer after HCl treatment of the tiles. In addition, containers filled with two media types, basalt dust and decarbonated soil (Figure 2, right), were installed to monitor calcium carbonate accumulation rates. The first measurements of the media in these containers are scheduled for March 2025.

Each water treatment was replicated four times. Data were analyzed using analysis of variance (ANOVA) with SAS Proc Mixed, and multiple mean comparisons were conducted using Fisher's LSD test at a 0.05 probability level. To meet model assumptions, soil analyses were performed on the log-transformed scale of each variable.

2021-2024 Results

Total precipitation at the research site during the years 2021- 2024 reached 162, 260, 115, and 125mm, respectively.

Saturated hydraulic conductivity

An ANOVA examining variations in saturated hydraulic conductivity among plots irrigated with different water treatments revealed no significant differences between the treatments (Table 2).

Table 2. Saturated hydraulic conductivity (cm sec^{-1}) [measured by SATURO (METER, WA, USA)] of soil irrigated with four water treatments (Control, high Bicarbonates, high Bicarbonates with N-pHuric acid, and high Bicarbonates with WaterSOLV™ Curative). Each value represents an average of four plots.

Water treatment	Value
Control	0.01255 A$^{\alpha}$
High Bicarbonates	0.01975 A
High Bicarbonates with N-pHuric	0.01608 A
High Bicarbonates with Curative	0.02130 A

$^{\alpha}$ Values with the same latter are not significantly different from one another.

Soil

P-values from the corresponding ANOVA, used to examine differences in soil chemical parameters among plots irrigated with differently treated water, are listed in Table 3. Over the course of the study, bicarbonate concentrations in soils irrigated with water high in bicarbonates were significantly higher during 4 out of 7 sampling dates (Figure 3). These peaks were most pronounced in fall 2022 and spring 2023, aligning with periods of minimal precipitation recorded during the study. By 2024, however, only soils irrigated with Curative-treated water maintained higher bicarbonate levels compared to soils irrigated with potable water. Overall, no evidence of bicarbonate accumulation in the soil was observed.

Table 3. P-values obtained from ANOVA results testing the impact of four water treatments (Control, high Bicarbonates, high Bicarbonates with N-pHuric acid, and high Bicarbonates with WaterSOLV™ Curative), seven sampling dates, soil depth (0-10, 10-20, and 20-30 cm) and their interactions on soil chemical characteristics.

Effect	HCO_3	Cl	Na	SAR	Ca	Mg
Water treatment	<.0001	0.0115	<.0001	<.0001	<.0001	0.0003
Date	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Date*water treatment	<.0001	<.0001	0.0076	0.0535	<.0001	<.0001
Depth	<.0001	0.8531	0.0215	<.0001	<.0001	<.0001
Water treatment*Depth	0.6430	0.9985	0.1343	0.0554	0.0591	0.0487
Date*Depth	0.0004	0.3917	<.0001	<.0001	0.9217	0.7229
Date*Water treatment*Depth	0.2118	0.9937	0.9806	0.9888	0.9830	0.8528

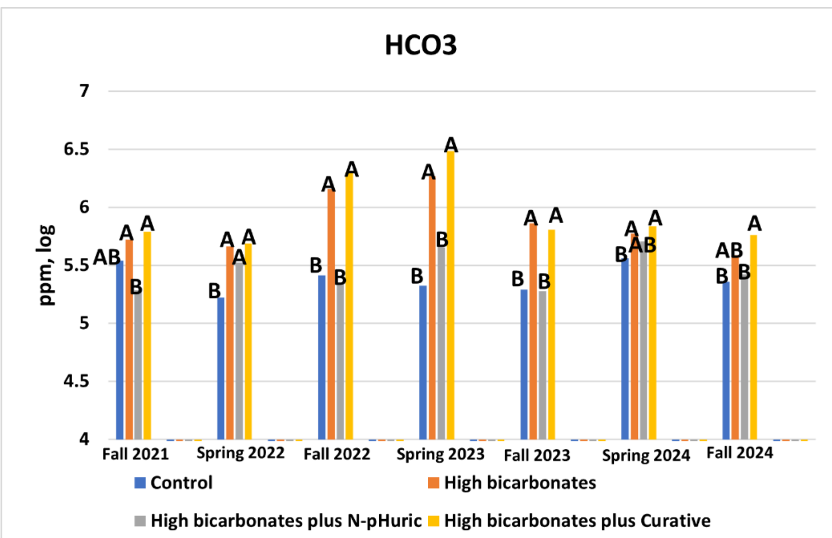


Figure 3. Bicarbonates concentrations (ppm, log scale) in soil irrigated with four water treatments (Control, high Bicarbonates, high Bicarbonates with N-pHuric acid, and high Bicarbonates with WaterSOLV™ Curative). Data are averaged over three depths (0-10, 10-20, and 20-30 cm).

Visual rating

P-values from the ANOVA evaluating Kentucky bluegrass visual quality under different water treatments are in Table 4. Starting in 2023, grass irrigated with high-bicarbonate water treated with N-pHuric acid showed significantly lower visual quality than other treatments, with differences appearing earlier and intensifying by September in 2024 (Figure 5).

Table 4. P-values obtained from ANOVA testing the effect of four water treatments in 2021-2024 (Control, high Bicarbonates, high Bicarbonates with N-pHuric acid, and high Bicarbonates with WaterSOLV™ Curative), and their interactions on visual quality of Kentucky bluegrass.

Effect	Visual quality
Water treatment	0.0016
Year*month	<.0001
Water treatment*year*month	0.0020

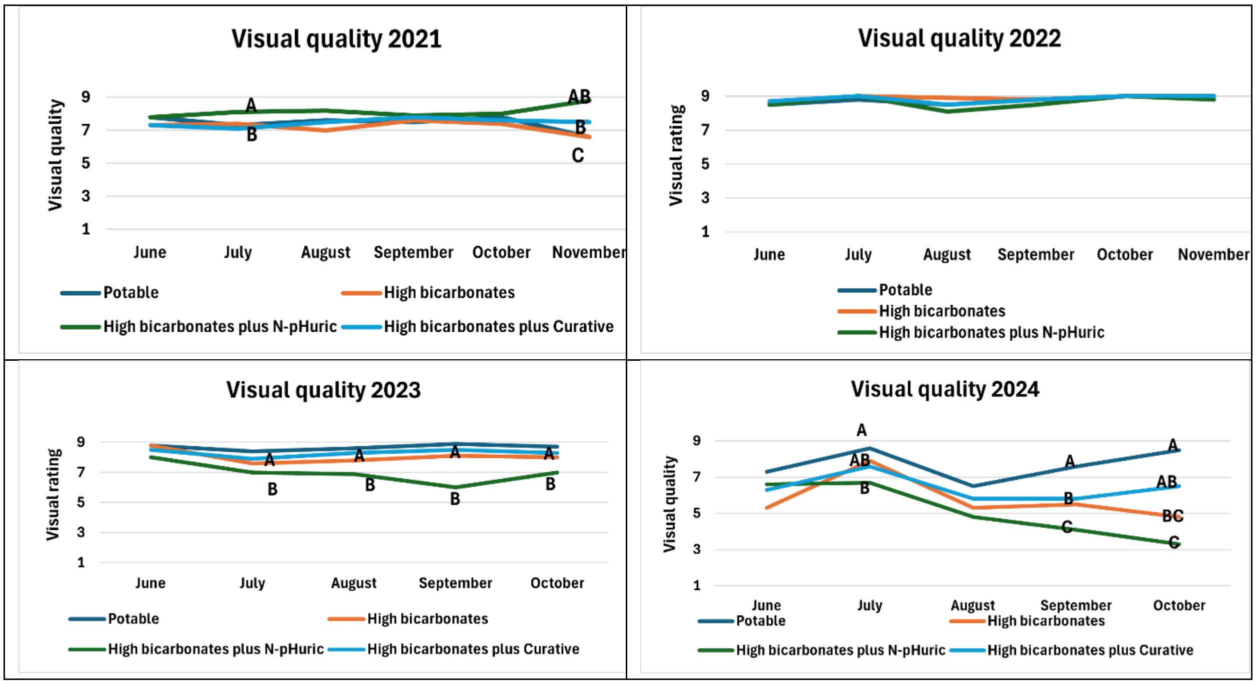


Figure 5. Quality (from 1=worst to 9=best) of Kentucky bluegrass irrigated with four water treatments (Control, high Bicarbonates, high Bicarbonates with N-pHuric acid, and high Bicarbonates with WaterSOLV™ Curative), in 2021- 2024. Data were averaged over four replications.

Plant tissue

P-values from the 2024 ANOVA (Table 5) show that Kentucky bluegrass irrigated with high-bicarbonate water and N-pHuric had higher total nitrogen and sodium but lower zinc levels than other treatments (Table 6).

Table 5. P-values obtained from ANOVA testing the effect of four water treatments (Control, high Bicarbonates, high Bicarbonates with N-pHuric acid, and high Bicarbonates with WaterSOLV™ Curative) on nutrients in grass tissue in summer 2024.

Effect	Ca	Cu	Fe	K	Zn	N_{total}	Na	P	S
Water treatment	.1036	.0002	<.0001	.0035	.0408	<.0001	<.0001	.0012	.0217

Table 6. Nutrient concentrations in Kentucky bluegrass tissue in 2024 under four irrigation treatments: Control (potable water), high bicarbonate water, high bicarbonate water with N-pHuric acid, and high bicarbonate water with WaterSOLV™ Curative. Data are averaged across four replications.

Water treatment	Ca, %	Fe, ppm	K, %	Zn, ppm	N_{total}, %	Na, %	P, %	S, %
Control	0.86A	175B	2.2B	81A	3.2B	0.12C	0.41A	0.4AB
High bicarbonates	0.79A	292A	2.6AB	73AB	3.5B	0.17B	0.2B	0.42AB
High bicarbonates with N-pHuric	0.81A	205B	2.8A	60C	4.3A	0.2A	0.29B	0.48A
High bicarbonates with Curative	0.54A	140C	2.6AB	71AB	3.4B	0.15BC	0.33B	0.31B

Accumulation of carbonates in soil

A six-month experiment using ceramic tiles as a matrix demonstrated that irrigation significantly enhances carbonate accumulation in soils under desert conditions, with noticeably higher rates observed under high-bicarbonate irrigation compared to low-bicarbonate irrigation and non-irrigated conditions (Figure 6).

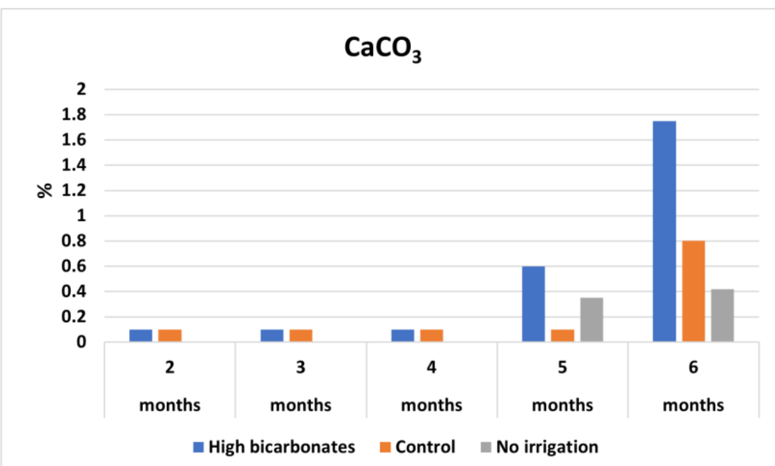


Figure 6. Calcium carbonates accumulation rate (%) in ceramic tiles in non-irrigated soil and soil irrigated with potable water (Control) and water high in bicarbonates. Data are averaged across four replications.

Future expectations of the project

The carbonate content (expressed as $CaCO_3$ equivalent) in basalt dust and decarbonated soil will be measured at 6, 12, 24, and 36 months of exposure by quantifying the CO_2 released during acidification with 2M $HClO_4$ using a coulometric titrator (CM5015, UIC). Additionally, gypsum will be applied to half of the plots to expand the comparative analysis of bicarbonate and carbonate accumulation dynamics in the soil.

USGA ID#: 2021-03-727

Title: Characterizing Immune System Responses of Select Plant Health Products for Putting Greens

Project Leader: Erik Ervin[1], Charanpreet Kaur[1], Harsh Bais[1], Beth Guertal[2], and Mike Fidanza[3]
Affiliation: [1]University of Delaware; [2]Auburn University; [3]Penn State University

Objectives:

1. To determine morphological (quality, yield, root density) and physiological (chlorophyll, elemental) effects of seasonal plant health product programs on drought-stressed creeping bentgrass.

2. To determine plant health product treatment effects on expression of pathogenesis-related genes in leaf and root tissue.

3. To determine the level of *Bacillus subtilis*-UD1022 colonization of roots via confocal microscopy and measurement of colony-forming units.

Start Date: 2021
Project Duration: 3 years
Total Funding: $132,277

Summary Points:

- PGPR *B. subtilis* UD1022 successfully colonized creeping bentgrass roots, significantly increasing bacterial populations compared to control plots.
- The tank mix, which combined full doses of PHPs showed very low pH which may have caused antagonistic interactions alongside chemical overload.
- In the growth chamber experiment, UD1022-treated plants had significantly higher shoot and root biomass as compared to the control.
- UD1022 priming upregulated defense genes *ERF1*, *NPR1*, and *MYC2* in shoots but did not significantly reduce disease severity when used alone. However, combining UD1022 priming with direct application significantly reduced dollar spot disease severity in detached leaf assays.

Summary:
Loss of putting green quality on creeping bentgrass is often associated with seasonal root decline, the prevention of which is a primary motivation for superintendents choosing to use so-called “plant health products” (PHP). Plant health product (PHP) applications have a physiological effect that enhances a plant’s immunological defense system against various biotic and abiotic stresses. Some of these materials are EPA-registered active ingredients (e.g., acibenzolar-S-methyl, fosetyl-Al, trinexapac-ethyl), while others are registered as fertilizers (e.g., kelp extract, *Bacillus* spp., phosphite). For most, potential physiological effects have been documented in referred journal articles. Rarely, however, are these materials studied on industry standard putting greens or in combination. Turfgrass consultants are often called to diagnose decline issues but are hard-pressed to determine primary causes due to confounding factors such as 3 to 10 ingredient tank-mixes.

Our target audiences are golf course superintendents, turfgrass consultants, and scientists. The overall goal of our research is to better understand why or why not one might choose to use certain plant health products, alone or in combination. If benefits are documented, our research may lead to more use of plant health products for maintaining stress-resistant putting greens and less use of pesticides. Improved drought resistance, if indicated, may result in improved superintendent confidence in their deficit irrigation practices. Less reliance on pesticides and water, while maintaining premier playing surfaces should result in measurable economic, environmental, and playability benefits.

Our field trial was conducted on a sand-based rootzone at Wilmington Country Club, Delaware (Figure 1).

Our objectives were to determine morphological and physiological effects of seasonal plant health product programs, alone and in a five-way tank mix, on creeping bentgrass and to determine treatment effects on expression of pathogenesis-related genes. Treatments were: untreated control, acibenzolar-S-methyl (50% WSP), kelp extract (0-0-1), *Bacillus subtilis* UD1022, fosetyl-Al (80% WP), trinexapac-ethyl (11.3%), and five-product tank mix. These were applied at label rates every two weeks from May to October 2021, 2022, and 2023. All plots received a uniform fertilizer program of 28-8-18 (soluble, with micronutrients) at 0.1 lb N/1000 ft^2 every 14 days. Fungicides were applied at 2-week rates every 3 weeks to result in some disease development and allowing data collection on treatment differences. For the creeping bentgrass trial at Wilmington Country Club, seven treatments (Table 1) were applied every two weeks.

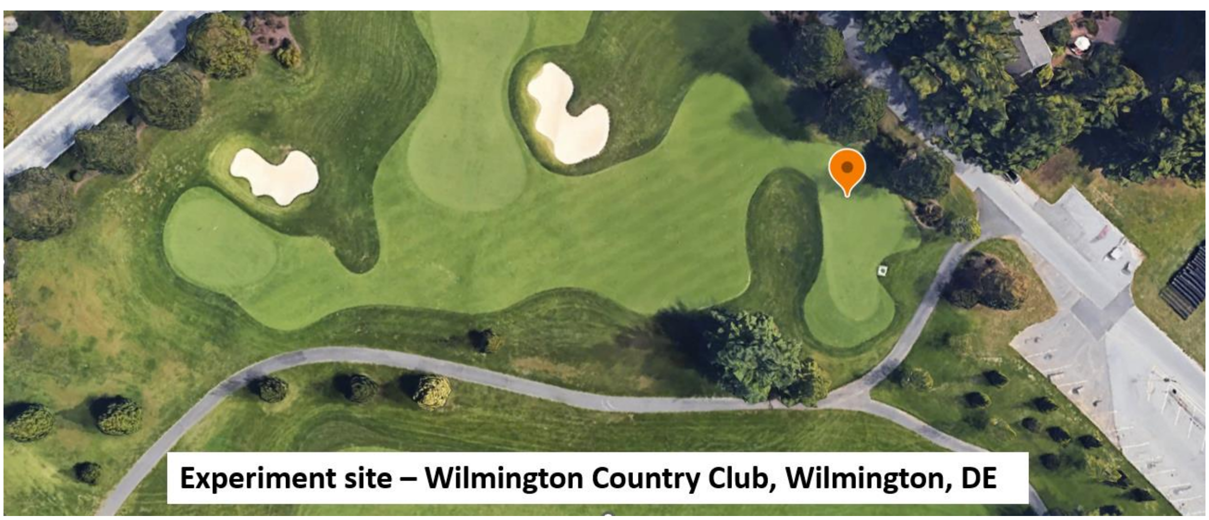


Figure 1. The study was conducted at Wilmington Country Club, DE (39.7967° N, 75.5976° W) on United States Golf Association (USGA) sand-based creeping bentgrass practice putting green.

Table 1 Plant Health Product (PHP) treatments applied to a creeping bentgrass putting green in the WCC trial.

S. No.	Treatment	Product Name	Concentration
1	Control	…….	…….
2	Acibenzolar-S-Methyl (50% WSP)	Actigard	1.08 g /100 m^2
3	Kelp Extract (0-0-1)	Guarantee Natural	95 ml/100 m^2
4	PGPR *Bacillus subtilis*	UD1022	10^6 cfu/mL in 8.2 L water/100 m^2
5	Fosetyl-Al (80% WP)	Aliette	122 g/100 m^2
6	Trinexapac-ethyl (11.3%)	Primo Maxx	4 ml /100 m^2
7.	Tank-Mix	Treatment 2,3,4,5,6	…….

Quantification of *Bacillus* in the Rhizosphere Soil for WCC trial:

Root samples (2 cm diameter, 15 cm depth) were taken from control, tank mix, and UD1022-treated plots using a soil probe and rhizospheric soil was collected. Quantification of *Bacillus* populations in the rhizosphere soil was conducted using qPCR, targeting the *gyrB* gene encoding the DNA gyrase subunit. Genomic DNA of *Bacillus subtilis* UD1022 was extracted from pure liquid cultures of UD1022 using the DNeasy® UltraClean® Microbial Kit (QIAGEN) and quantified using a NanoDrop® spectrophotometer and QUBIT® fluorometer. A standard curve was generated by serially diluting UD1022 genomic DNA (100 ng/µL) in a 1:10 ratio. Rhizosphere soil DNA from control, tank mix, and UD1022-treated plots were isolated using the DNeasy PowerSoil® Kit (QIAGEN), with quality and quantity assessed via NanoDrop®. qPCR was performed on a QuantStudio 3 system using *gyrB*-specific primers. Each reaction contained PerfeCTa SYBR® Green SuperMix, primers, template DNA, and molecular-grade water, with amplification conditions optimized for specificity. The standard curve was used to interpolate Ct values and calculate *gyrB* gene copies per gram of rhizosphere soil. The analysis revealed a comparable increase in *gyrB* copy number in UD1022-treated plots. Mean gene copy numbers for UD1022 and the tank mix were 2.4-fold (145%) higher than the control, indicating a greater abundance of *B. subtilis* in soils treated with UD1022 and the tank mix compared to the untreated control (Figure 2).

Soil and treatment pH for WCC trial:

The pH data were collected for treatment solutions as well as the soil from the treated plots using Fisher Scientific accumet AE150 pH meter (Hampton, NH). The application of PHP treatments did not significantly affect soil pH, which remained consistent across treatments, ranging from 5.74 to 5.5 (Figure 3). However, significant differences were observed in the pH of treatment solutions. ASM and the control (tap water used for mixing chemicals) had relatively higher pH values of 5.5 and 5.4. UD1022 solution had a similar pH of 5.46. In contrast, fosetyl-Al and the tank mix solutions exhibited significantly lower pH values of 2.18 and 2.26, respectively. The lower pH of fosetyl-Al and tank mix solutions indicates more acidic conditions, which may influence their chemical interactions and efficacy in sprayer-based field applications.

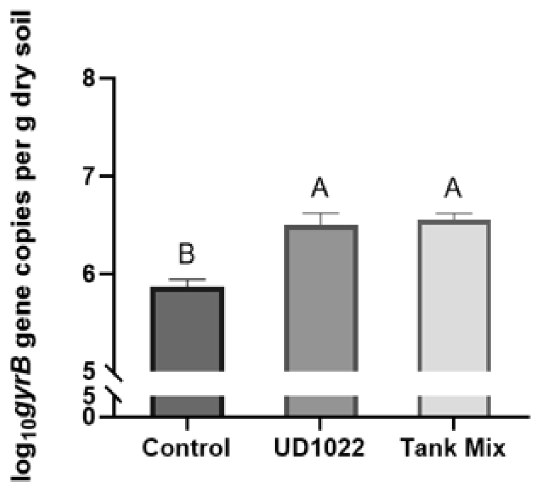


Figure 2. Quantification of *Bacillus* populations in the rhizosphere soil was performed using qPCR, targeting the *gyrB* gene. Gene copy numbers were determined based on a standard curve generated from known concentrations of *B. subtilis* genomic DNA. Bars represent the mean gene copy numbers for each treatment (control, UD1022, and five-product tank mix). Treatments were statistically grouped, with different letters denoting significant differences at $p \leq 0.05$. Error bars indicate the standard error of the mean (SEM).

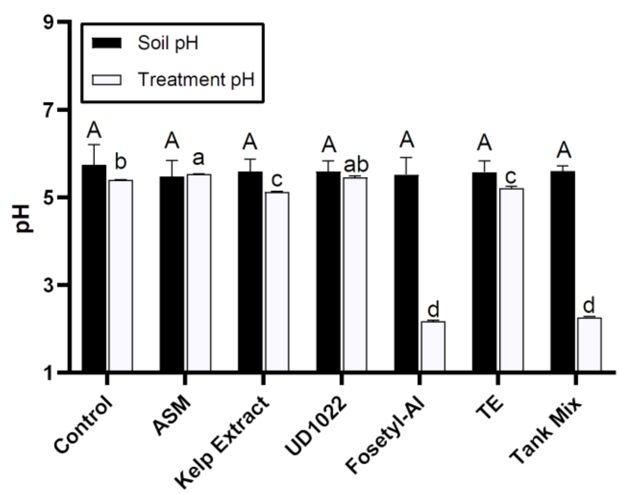


Figure 3. pH measurements of treatment spray solutions and soil from treated plots. Bars represent the mean pH values for each treatment, with different letters denoting significant differences ($p \leq 0.05$). Uppercase letters indicate soil pH comparisons, while lowercase letters represent treatment solution pH. Error bars show the standard error of the mean (SEM).

Growth chamber experiment to evaluate role of PGPR *B. subtilis* UD1022 on creeping bentgrass growth:

A growth chamber study was conducted to evaluate the role of *B. subtilis* UD1022 in creeping bentgrass growth promotion. Treatments included a control (no inoculation) and UD1022 root inoculation. UD1022 was applied at 14 days after planting (DAP), 21 DAP, 28 DAP, and 35 DAP as 10 mL inoculum (conc. 10^6 CFUs/mL) per pot as a soil drench treatment. Plants were grown in pots under controlled conditions, and data were collected on biomass and root characteristics (Figure 4). Results showed that UD1022-treated plants had significantly higher shoot and root biomass as compared to the control (Figure 5). Significant increase was also observed in UD1022 treated plants for root length, root surface area, and root volume. These findings suggest that UD1022 enhances plant growth, likely through improved root development and nutrient uptake.

The manuscript detailing the field and controlled environment trials is currently in preparation.

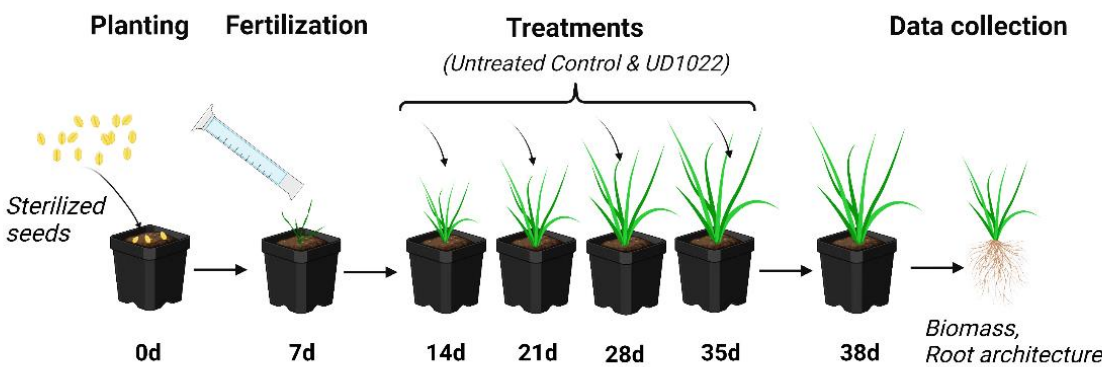


Figure 4. Growth chamber experiment set up to study the effect of PGPR UD1022 root inoculations on creeping bentgrass growth promotion.

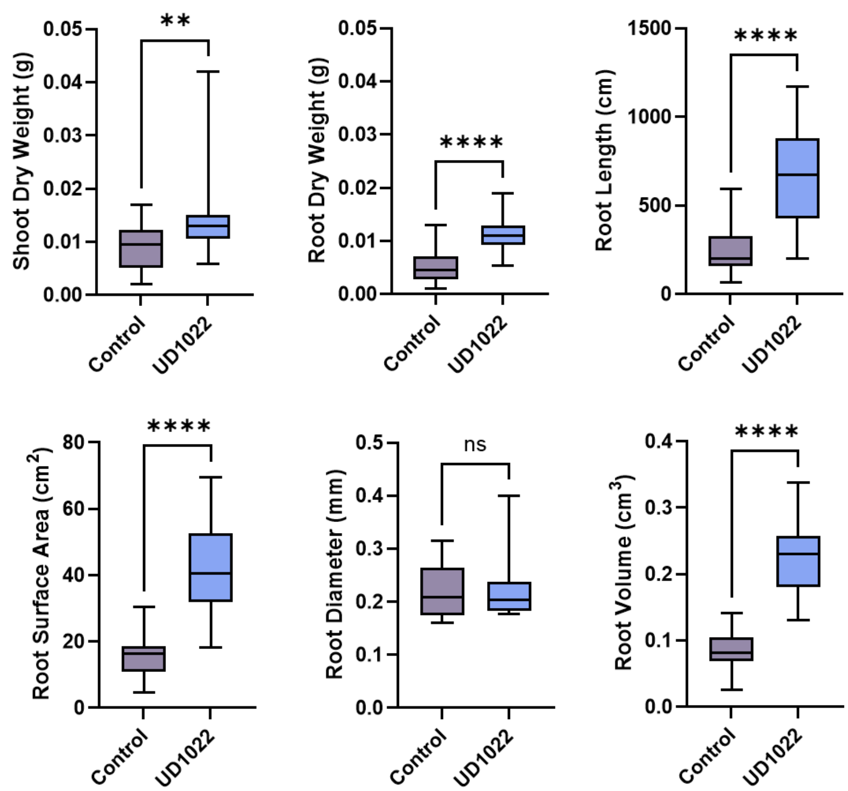


Figure 5. Effect of PGPR UD1022 root inoculation on creeping bentgrass growth. Different letters indicate significant differences ($p \leq 0.05$).

Growth chamber experiment to evaluate role of PGPR *B. subtilis* UD1022 priming on pathogenicity related/defense genes expression and dollar spot control in creeping bentgrass:

Creeping bentgrass seeds (cv. Penn A4) were surface-sterilized, germinated on MS medium, and transplanted into pots with sterile soil under controlled growth chamber conditions. Plants were primed with treatments, including UD1022, its mutants (*spo0A*⁻, *epsTasA*⁻, *srfAC*⁻), and salicylic acid, with inoculations applied at weekly intervals. RNA from treated plants was extracted for qRT-PCR analysis to evaluate defense gene expression (*ERF*, *MYC2*, *NPR1*, *PR3*). Relative gene expression was quantified using the $2^{-\Delta\Delta CT}$ method with actin as the reference gene, based on three biological replicates and technical triplicates. Disease severity was measured using detached leaf assays. UD1022 upregulated defense genes *ERF1*, *NPR1*, *MYC2* in shoots, however, there was no significant reduction in dollar spot disease severity from UD1022 priming alone (Figure 6 and 7). Combined treatment (priming + direct application) significantly reduced dollar spot disease severity in the detached leaf disease severity assays (Figure 7).

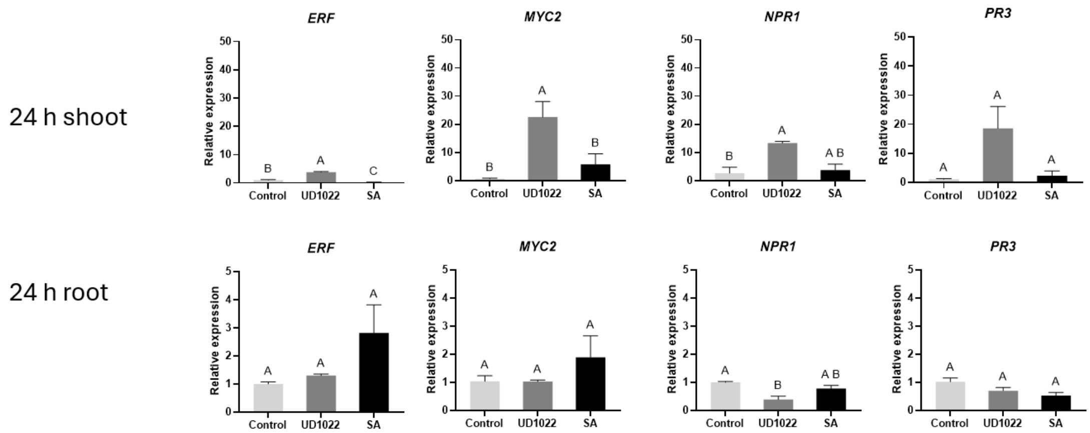


Figure 6. Relative expression of defense-related genes (*ERF*, *MYC2*, *NPR1*, *PR3*) in plant shoots and roots 24 hours after treatment with *Bacillus subtilis* UD1022, salicylic acid (SA), and control. Different letters above bars indicate significant differences ($p < 0.05$) according to Tukey's post-hoc test. Error bars represent standard error of the mean.

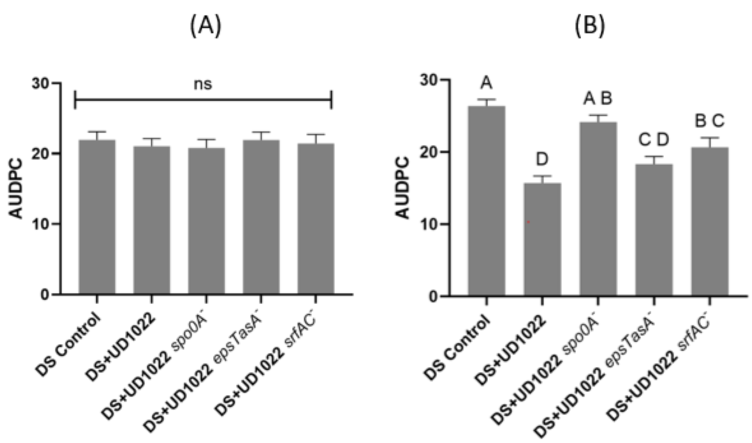


Figure 7. Effect of A) UD1022 priming and B) UD1022 priming + direct leaf treatment on *C. jacksonii* (DS) disease severity in creeping bentgrass detached leaf assays. The bar graphs illustrate the Area Under the Disease Progress Curve (AUDPC) data for each treatment. Different letters indicate significant differences at $P < 0.05$, as determined by Tukey's HSD test. Data are presented as means ± SE.

The manuscripts detailing the field and controlled environment trials are currently in preparation and a provisional patent regarding *Bacillus subtilis* UD1022's benefits to creeping bentgrass plant fitness has been filed.

USGA ID#: 2024-03-813

Title: Soil Moisture Impacts On Microbial Diversity And Dollar Spot Severity

Project Leaders: Paul Koch and Doug Soldat
Affiliation: University of Wisconsin – Madison

Objectives:

1. Quantify the relationship between soil moisture and dollar spot severity.
2. Determine the impact of soil moisture on soil-plant-microbial interactions and identify potential new dollar spot biocontrol strategies.

Start Date: 2024
Project Duration: 3 years
Total Funding: $140,000

Summary Points:

- The quotes for custom mobile rain-out shelters came back much higher than expected. Instead, we converted two shade structures previously used for alfalfa research for use in our research. It took significant time to alter the structures so that they were adequate for our usage but by mid-summer we felt they were providing adequate prevention of rain researching the research plots. We began the research project and soil moisture adjustments on June 11th.
- The first half of the summer in Madison was extremely wet with numerous thunderstorms. This resulted in a few instances of rain penetrating the rain-out shelter, including one instance in June when a thunderstorm tore the tarp off the rain-out shelter. For the sand-based putting green plot conditions dried down within a day or two, but for the soil-based fairway the instance where the tarp was torn off led to several weeks of high soil moisture.
- The fairway plot had moderate dollar spot pressure for most of the season. There were no statistical differences in dollar spot severity on any single rating date or the season-long AUDPC assessment. In general, however, dollar spot tended to be slightly higher in the higher soil moisture plots compared to the lower moisture plots. This was contrary to our expectations. The full report for this project can be accessed online at: https://tdl.wisc.edu/wp-content/blogs.dir/42/files/Interactive%20Pages/2024_Summer/Reports/UWSoilMoistureFwy_2024.pdf
- The putting green plot had modest dollar spot pressure for most of the season. Much like the fairway plot there were no statistical differences in dollar spot severity on any single rating date or the season-long AUDPC but dollar spot tended to be higher on the higher soil moisture plots compared to the lower soil moisture. Also, localized dry spot was very evident on the lowest VWC treatment (10%) which lowered the overall turf quality. The full report for this project can be accessed online at: https://tdl.wisc.edu/wp-content/blogs.dir/42/files/Interactive%20Pages/2024_Summer/Reports/UWSoilMoistureGrn_2024.pdf

- Samples for microbiome analysis were collected from each plot three times during the season and the microbial diversity in response to the various soil moisture treatments will be assessed this winter.

Summary Text:

Rationale: Moisture is a critical component in the development of most plant diseases, including dollar spot, the most economically important disease of cool-season turfgrass. Golf course superintendents often strive for the lowest soil volumetric water content (VWC) that avoids plant wilt, however past research on dollar spot and soil moisture suggests that lower soil moisture increases dollar spot severity. Soil moisture has been found to impact microbial communities in other pathosystems, and it's possible that it may also impact microbial communities and dollar spot antagonism in golf course turfgrass as well. Further investigation of this soil chemistry-plant-microbial interaction under different soil moisture regimes can provide enhanced understating of the dollar spot pathosystem and help guide more efficient disease management strategies.

Methods: The study was conducted at the O. J. Noer Turfgrass Research and Education Facility in Madison, WI on two separate stands of 'Penncross' creeping bentgrass maintained under either putting green or fairway conditions. Individual plots measured 3 feet by 5 feet and were arranged using a randomized complete block design with four replications. Beginning June 11th, every weekday morning the volumetric water content of each plot was measured using a TDR 300. When plots were deemed to be in deficit of the soil moisture target, a calculated amount of water was added back to the plot based on how much of a deficit existed. A custom-built rainout shelter was used to exclude rainfall to the best of our ability. Number of dollar spot foci per plot and turfgrass quality (1-9, 9 being excellent, 6 acceptable, and 1 bare soil) were visually assessed every two weeks. Turf quality and disease severity were subjected to an analysis of variance and means were separated using Fisher's LSD ($P = 0.05$). Area under the disease progress curve (AUDPC) and area under the turf quality curve (AUTQC) were calculated using the trapezoidal method and summarize the whole season disease severity and turf quality. Samples for microbiome analysis were collected from each plot 3 times during the season.

Results: On the putting green plot, dollar spot pressure was modest throughout the study. The high soil moisture treatment had the most dollar spot on most rating dates, but it was never statistically different than the other two treatments. The low soil moisture treatment consistently had damage from localized dry spot, which negatively affected the turf quality scores and likely impacted how much dollar spot was able to develop. On the fairway plot dollar spot pressure was moderate throughout the study. The high soil moisture treatment did have the most dollar spot on most rating dates, but it was never statistically different than the other two treatments. No treatments were of acceptable turf quality during the course of the study due to damage from dollar spot.

Future plans: This was the first of a 3-year study and it took until mid-June for us to perfect our soil moisture adjustment procedure and get the rain-out shelter to perform adequately. The microbiome samples we collected in 2024 will be processed and

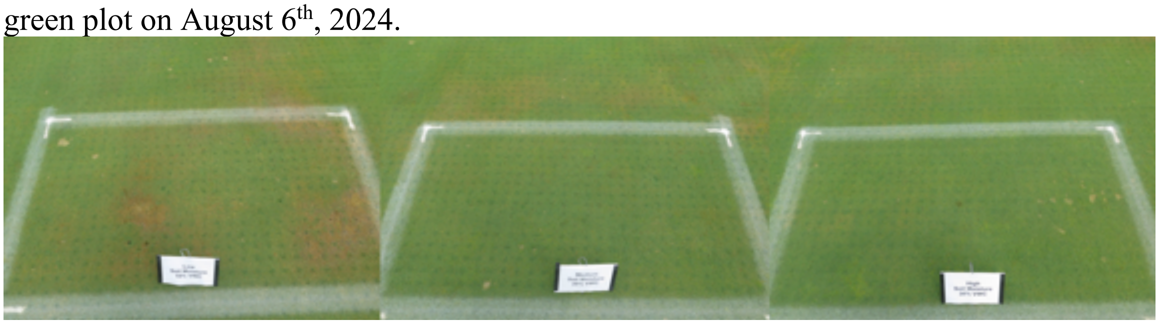
analyzed during the winter of 2024-2025. We will repeat this study in 2025 and compare the results with those obtained in 2024. There is a second project scheduled to begin in Year 2 but since that also requires a rain-out shelter and we don't have space to conduct two trials under one shelter. Because of this we will likely complete the original project in 2025 and then move to initiate the second project in 2026.

Figure 1. One of the two custom rain-out shelters created for this project.

Figure 2. The research team adjusting soil moisture.

Figure 3. Photos from the first replication of soil moisture treatments from the fairway plot on August 6th, 2024.

Figure 4. Photos from the first replication of soil moisture treatments from the putting green plot on August 6th, 2024.



USGA ID#: 2023-07-774

Title: Understanding Pacific Northwest Turfgrass Plant-Parasitic Nematode Communities to Improve Management Efficiency

Project Leaders: Hannah Rivedal[1], Emily Braithwaite[2], Alec Kowalewski[2], Inga Zasada[3]
Affiliation: [1]USDA-ARS Forage Seed and Cereal Research Unit; [2]Oregon State University Department of Horticulture; [3]USDA-ARS Horticultural Crops Disease and Pest Management Unit

Objectives:

1) Determine plant-parasitic nematode (PPN) genera and species presence across 60 golf courses in California, Oregon, and Washington (20 per state) using traditional morphological examination, and PPN community metabarcoding.
2) Evaluate survey timing (winter, spring, summer, and fall) and collection method (soil, thatch, tillers) for the most accurate detection of PPN associated with annual bluegrass, creeping bentgrass, and fine fescue putting greens.
3) Develop action thresholds and integrated pest management programs for PPN of putting greens in the PNW.

Start Date: January 2023
Project Duration: 3 years
Total Funding: $65,326

Summary Points:

- In total, 324 putting greens from 54 courses have been sampled for PPN (13 courses in California, 21 courses in Oregon, and 20 courses in Washington).
- PPN were recovered from all surveyed golf courses, at every time point, regardless of reported health of the putting green surface by superintendent.
- Sixteen unique genera were identified across California, Oregon, and Washington, with multiple species reported within each genus.
- *Meloidogyne* spp. (root knot nematode) were present in 89% of courses and had variable population densities, ranging from 4 to over 10,244 juvenile per 100 cc of soil.

Summary

***Rationale*:**

Plant-parasitic nematodes (PPN) are important pests affecting turfgrass health, playability, and maintenance. In recent years, nematodes have increasingly become a topic of interest for cool-season golf course managers in the Pacific Northwest (PNW). The distribution and species of PPN in California, Oregon, and Washington has not been extensively surveyed, though recent reports indicate that PPN are causing significant damage to cool-season putting greens managed in all three states. PPN are difficult to quickly diagnose and require expensive nematicides and management strategies to treat. In the PNW, nematode thresholds have not been established for many turfgrass PPN, leading to mis-timed control applications, and a less sustainable management strategy for turfgrass PPN. Metabarcoding, a technique that uses next generation sequencing (NGS) of a genetic region of identification for a group of organisms, is a powerful tool to help understand the community of pathogens associated with a turfgrass system. In conjunction with morphological identification methods, metabarcoding of the PPN community could reveal new species of concern and indicate PPN species of importance that are more difficult to recover using traditional methods. This project aims to establish baseline information on PPN in the PNW to improve detection strategies, associate specific PPN with identifiable symptoms, and implement management/action thresholds for PNW golf course superintendents.

***Methodology*:**

Objective 1 and 2: To determine PPN population dynamics throughout the PNW, we established a golf green survey in May 2023. The survey began with 10 courses from California, 20 courses from Oregon, and 20 courses from Washington. Courses will be sampled through August of 2025, which will allow us to have 1 full year of data on at least 20 courses per state.

In each year, sampling is conducted at four time points, February, May, August, and November, to capture temporal changes in PPN populations. At each course, 6 greens of varying turf health are surveyed. Golf greens are walked in a zig-zag fashion, collecting 20 samples per green. Soil and plant samples are bulked by green before nematode extraction. Turfgrass damage is noted when it is visible. In conjunction with visual ratings, we are collecting information on overall management practices, prior spray records, and other environmental factors that could influence the health of the putting green, to develop more detailed action threshold levels. Nematodes are extracted from samples using a Baermann funnel for 3 days. Extracted nematodes are morphologically identified with a microscope.

Individual nematodes of PPN genera and species of interest, with an emphasis on root knot nematode (*Meloidogyne* spp.) have been selected for nucleic acid extraction and molecular identification of barcoding regions. In total 96 individuals representing at least two courses in each state have been sequenced. In addition, 226 individuals representing cyst, dagger, ring, root-lesion, pin, spiral, and stubby root nematode species have also been sequenced. These individuals will be used as positive controls for the development of metabarcoding community analysis procedures.

Objective 3: Data collection is still under way for initial action threshold determinations and will be available in year 3 of the study. In the interim, we have prepared educational PowerPoints that have been presented to golf course superintendent groups, like the Northwest Turfgrass Association and Golf Course Superintendents Association of America, to provide general information on PPN and explain the scope of our research.

Results to date: Across California, Oregon, and Washington, 16 genera of PPN were identified. On average, Oregon and Washington had courses with the most detected genera, with more than five genera detected at 13 of the 21 and 20 courses, respectively. California had the lowest diversity of genera on average and had only 5 of 10 courses with more than five detected genera.

Meloidogyne has been identified as a critical PPN in the cool-season turfgrass production system. *Meloidogyne* spp. second-stage juvenile (J2) were recovered from 89% of the greens sampled (Table 2). Annual bluegrass greens were the dominant putting green host species surveyed and *Meloidogyne* incidence was high, with more than 90% positive recovery. In California, greens with routine nematicide programs had an average of 34 *Meloidogyne* J2/100 cc soil and maximum populations on a single green of 176 *Meloidogyne* J2/100 cc soil. Oregon and Washington courses, without nematicide application history, had an average of 166 and 748 *Meloidogyne* J2/100 cc soil, respectively. Maximum populations on a single green reached 3,498 and 10,244 *Meloidogyne* J2/100 cc soil, for Oregon and Washington, respectively. Thresholds have not been developed for this region, but available thresholds for creeping bentgrass in the northeast indicate 500 *Meloidogyne* J2/100 cc soil as justification for implementing control measures. Population densities of *Meloidogyne* were lower in creeping bentgrass putting greens in California and Washington with maximum population densities of 48 and 58 *Meloidogyne* J2/100 cc soil, respectively. *Meloidogyne* spp. were only recovered from 3 of the 12 fine fescue putting greens, with a maximum population density of 12 *Meloidogyne* J2/100 cc soil, suggesting it is not an ideal host for this genus. *Meloidogyne naasi* was identified in all three states and in samples collected from all three putting green hosts (Table 2). *Meloidogyne minor* was recovered from creeping bentgrass in California and annual bluegrass in Oregon.

We have identified multiple species within most genera, including a new *Heterodera* (cyst nematode) species and others that will be confirmed with molecular identification tools. We did note that reported healthy greens had lower PPN densities compared to reported unhealthy greens which had higher overall PPN densities. Based on initial findings, PPN are much more widespread than previously thought and the distribution of genera throughout the region is high.

Deliverables: A manuscript describing the initial survey efforts at an Oregon golf facility supported by this proposal is under review in *Plant Disease.* A manuscript focused on the evaluation of *Meloidogyne* spp. in PNW turfgrass systems supported by this proposal has been accepted for presentation at the International Turfgrass Research Conference in Japan in 2025. In total, 9 presentations about this work were presented in 2024 at regional industry events, national and international industry events, and scientific meetings.

Future Expectations: In the upcoming year we will continue PPN survey and identification efforts. In addition, we will begin molecular barcoding efforts of PPN communities. To do this, we will employ nanopore sequencing technology, which we believe will provide longer sequencing reads and greater ability to differentiate PPN genera and species. This technology is more accessible to other diagnostic laboratories than other NGS technologies, making it a viable option for dissemination of methods. In addition, we will start relating damage symptoms to PPN community members as we gather more sampling information. We will regularly report to golf course superintendents through extension presentations and publications.

Images:

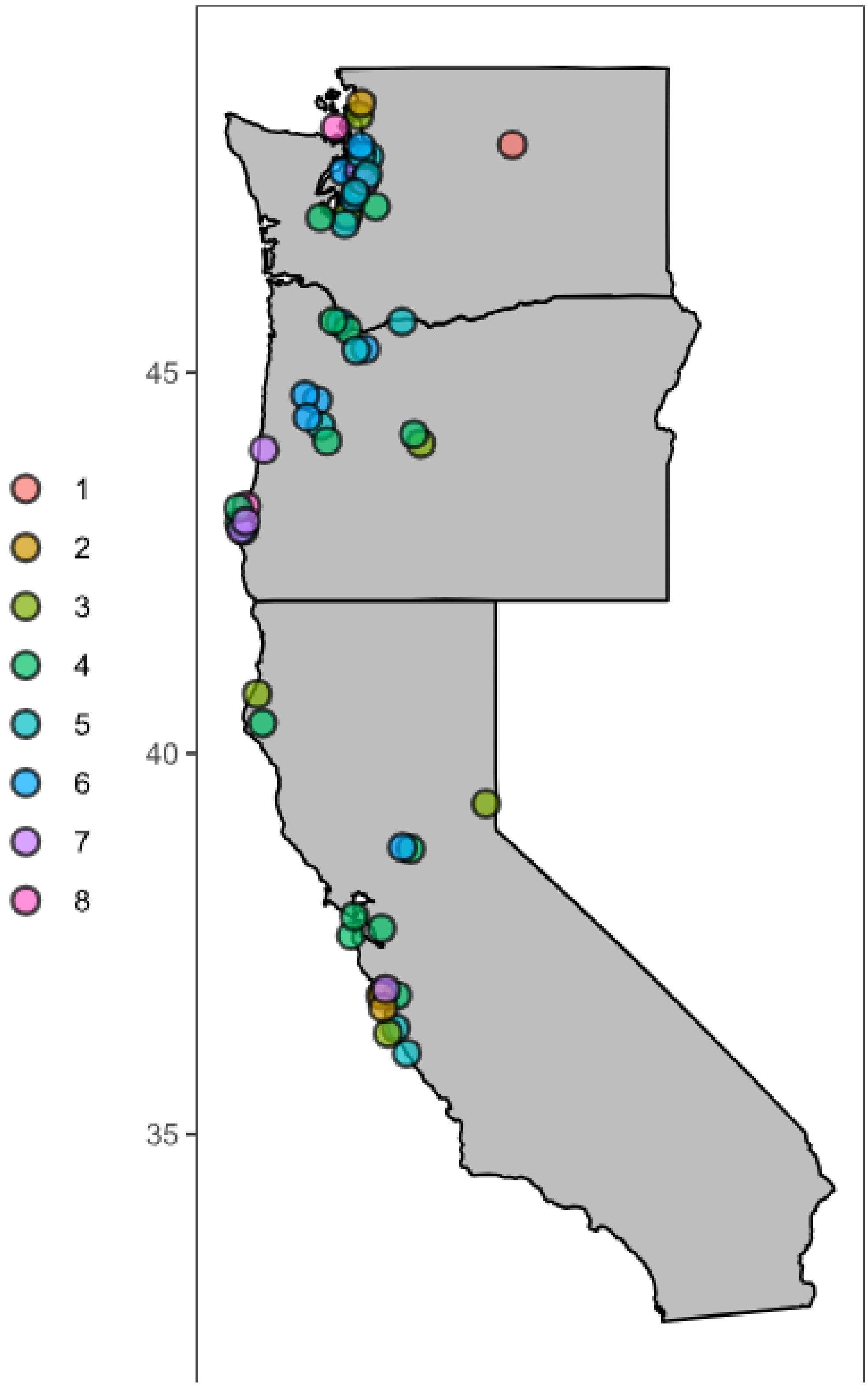


Figure 1. Locations of 2023 plant-parasitic nematode survey as of November 2024. Dot color indicates the number of recovered genera as determined by visual examination.

Figure 2. Survey location with root-knot nematode damage in 2024. Populations peaked to more than 20,000 J2 per 100cc of soil. Subsequent samples showed a decrease in population densities to 1,000 J2 per 100cc of soil after two chemical nematicide applications.

Table 1. Percentage of total sampled courses per state in January 2024 with positive recovery of plant-parasitic nematodes.

Plant-parasitic nematode genera	Survey state		
	California*	Oregon†	Washington‡
Spiral nematode *Helicotylenchus sp.*	100%	100%	96%
Root-knot nematode *Meloidogyne sp.*	90%	91%	96%
Cyst nematode§ *Heterodera sp.* *Punctodera sp.*	8%	18%	9%
Ring nematode *Criconema sp.*	20%	36%	57%
Stunt nematode *Tylenchorhynchus sp.*	13%	45%	74%
Root-lesion nematode *Pratylenchus sp.*	0%	27%	0%
Sheathoid nematode *Hemicycliophora sp.*	0%	9%	0%
Stubby root nematode§ *Trichodorus sp.* *Paratrichodorus sp.*	46%	73%	48%
Pin nematode *Paratylenchus sp.*	0%	9%	4%
Pacific shoot-gall nematode *Anguina pacificae*	38%	0%	0%

*A total of 10 courses from California, sampled in January 2024
† A total of 20 courses from Oregon, sampled in January 2024
‡ A total of 23 courses from Washington, sampled in January 2024
§ Identification to the specific genus for these nematodes requires molecular sequencing for confirmation

Table 2. Population densities and occurrence of *Meloidogyne* spp. second-stage juveniles (J2) from cool-season grass putting greens in the Pacific Northwest of the United States.

State	Host Grass	Greens samples	Greens positive for *Meloidogyne*	Average *Meloidogyne* spp. J2 per 100 cc on a single green	Max density of *Meloidogyne* spp. J2 per 100 cc on a single green	Sequence Identification
California	*Poa annua*	12	12	34	176	*Meloidogyne naasi*
	Agrostis stolonifera	18	16	24	48	*M. minor*
Oregon	*P. annua*	96	88	166	3,498	*M. naasi* *M. minor*
	A. stolonifera	12	12	184	660	*M. naasi*
	Festuca rubra ssp.	12	3	2	12	*M. naasi*
Washington	*P. annua*	120	113	748	10,244	*M. naasi*
	A. stolonifera	6	4	16	58	

USGA ID: 2024-09-819

Title: Survey of Plant-Parasitic Nematodes, Organic Matter, and Nutrients in Mid-South Golf Course Putting Green Soils

Project Leaders: Wendell Hutchens, Ph.D.; Michael Battaglia; and Mike Richardson, Ph.D.
Affiliation: University of Arkansas

Objectives:
- Survey which plant-parasitic nematode species are present and most prominent in Mid-South putting greens.
- Survey the organic matter content and soil nutrient levels in Mid-South putting greens.
- Determine if there are relationships between plant-parasitic nematode populations and soil organic matter and certain soil nutrients.

Start Date: 2024
Project Duration: 1 year
Total Funding: $20,601.60

Summary Points:
- Twelve different plant-parasitic nematode species were found in putting green soils throughout the Mid-South region of the US (Arkansas, Louisiana, Mississippi, Tennessee, and Texas).
- The plant-parasitic nematode species that were most commonly above threshold levels throughout Mid-South putting green soils were lance nematode (*Hoplolaimus galeatus*), root-knot nematode (*Meloidogyne* spp.), and sting nematode (*Belonolaimus longicaudatus*).
- Certain plant-parasitic nematode species were more prominent in creeping bentgrass putting green soils than bermudagrass putting green soils and vice versa.

Summary Text:

Rationale

Plant-parasitic nematodes (PPN) are common in golf course putting greens soils. At elevated populations, they can cause damage to putting greens by feeding on turfgrass roots (Fig. 1). Plant-parasitic nematodes are particularly problematic when turfgrasses are under severe stress. There are several PPN species that can cause damage to putting greens, but some species are more common in certain regions than others (Crow, 2017). Therefore, characterizing the PPN species present throughout a region is crucial for making informed agronomic decisions. Surveys of PPN have previously been conducted on putting greens throughout much of the US, but a survey has never been conducted in the Mid-South region (Arkansas, Louisiana, Mississippi, Tennessee, and Texas) of the US (Allan-Perkins et al., 2017; McClure et al., 2012; Shahoveisi and Waldo, 2024; Sikora et al., 2001; Walker et al., 2002; Zeng et al., 2012).

A survey of nutrients, pH, salinity, and organic matter content in putting green soils has also never been conducted in the Mid-South region of the US, so this is also important to characterize. Additionally, certain edaphic factors have been documented to correlate with certain

PPN species (Allan-Perkins et al., 2017; Walker et al., 2002). Elucidating the relationship between edaphic factors and PPN populations in Mid-South putting greens is valuable, and it will lead to greater understanding of the population dynamics of PPN in putting greens as well as improved management strategies.

Methodology

A total of 353 samples were taken from 39 golf courses across the Mid-South US (29 from Arkansas, 4 from Louisiana, 3 from Mississippi, 2 from Tennessee, and 1 from Texas). Composite soil samples (1000 cc of material) were collected from each putting green in a random pattern at a 15-cm depth with a soil probe. The 1000 cc composite soil samples were homogenized and divided into two 500 cc soil samples. Of which, one sample was used for nematode counts and the other sample was used to determine soil nutrient content and organic matter.

Nematode extractions were conducted using elutriation, and each PPN species were counted after extraction. Of the 353 samples taken across 39 golf courses, data from only 308 of the samples (34 golf courses) will be presented in this report because the final batch of 45 samples from the last five golf courses sampled are currently being processed. Additionally, soil nutrient content, pH, salinity, and organic matter content have not been measured yet (samples pending analysis with results hopefully completed by 31 Dec 2024). However, the soil nutrients will be extracted using the Mehlich III extraction technique and organic matter content by weight will be determined using loss on ignition.

Results and Future Expectations

The survey results demonstrate that there are many species of PPN in putting green soils throughout the Mid-South region of the US (Fig. 2). From the 34 golf courses sampled, 12 different species of PPN were found. The species found on most golf courses was ring nematode, followed by spiral, root-knot, stubby-root, and lance nematode, respectively. Dagger and reniform nematode were not identified in any sample in this survey.

Lance, lesion, ring, spiral, sting, stubby-root, stunt, and root-knot nematode were all above threshold in at least one sample from a putting green in this survey (Fig. 3). Sting nematode had, by far, the most samples above threshold (n = 24). Lance nematode (n = 12) and root-knot nematode (n = 14) also had many samples that were above threshold. These three PPN species are very common and problematic on golf course putting greens beyond just the Mid-South region of the US (Crow, 2021).

There were differences in PPN populations between creeping bentgrass and bermudagrass putting greens. Notably, lance, spiral, stubby-root, stunt, and sheathoid nematode were more prominent in creeping bentgrass putting greens than bermudagrass putting greens (Table 1). On the other hand, ring, sting, needle, and sheath nematode were more prominent in bermudagrass putting greens than creeping bentgrass putting greens.

These initial findings indicate that a wide variety of PPN species are present and problematic in both creeping bentgrass and bermudagrass putting greens throughout the Mid-South region of the US. Additionally, initial data also suggests that PPN species may be related to putting green turfgrass species. These findings have major implications on management decisions for PPN in golf course putting greens.

A total of 45 samples across five more golf courses with bermudagrass putting greens are pending analysis, but we expect to see similar trends as the previous golf courses sampled.

Samples are also going to be analyzed for soil nutrients, pH, salinity, and organic matter in the coming weeks. We expect to see a wide range of differences in edaphic characteristics across different golf courses depending on turfgrass species, soil type, putting green age, management intensity and history, golf course budget, etc. We also expect to observe correlations between certain edaphic factors and PPN populations similar to what Walker et al. (2002) documented.

Figure 1. Sting nematode damage on an ultradwarf bermudagrass putting green.

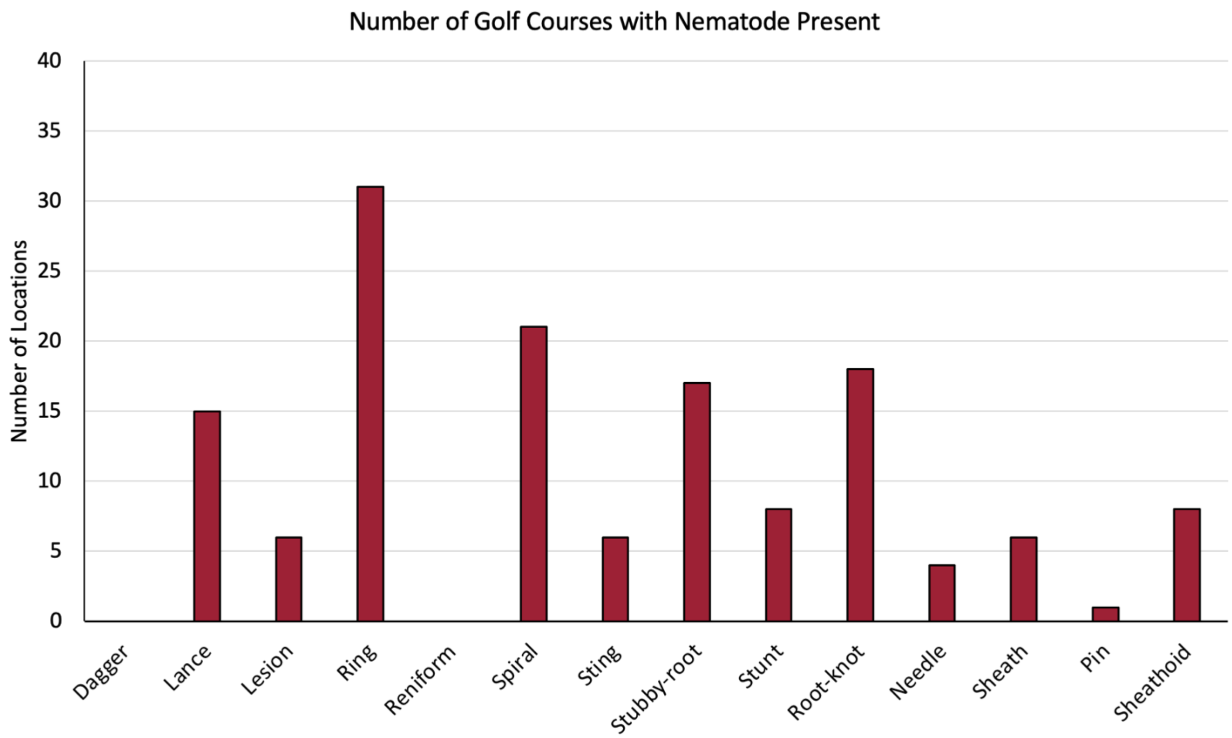


Figure 2. Number of golf courses throughout the Mid-South region of the US with presence of various plant-parasitic nematode species.

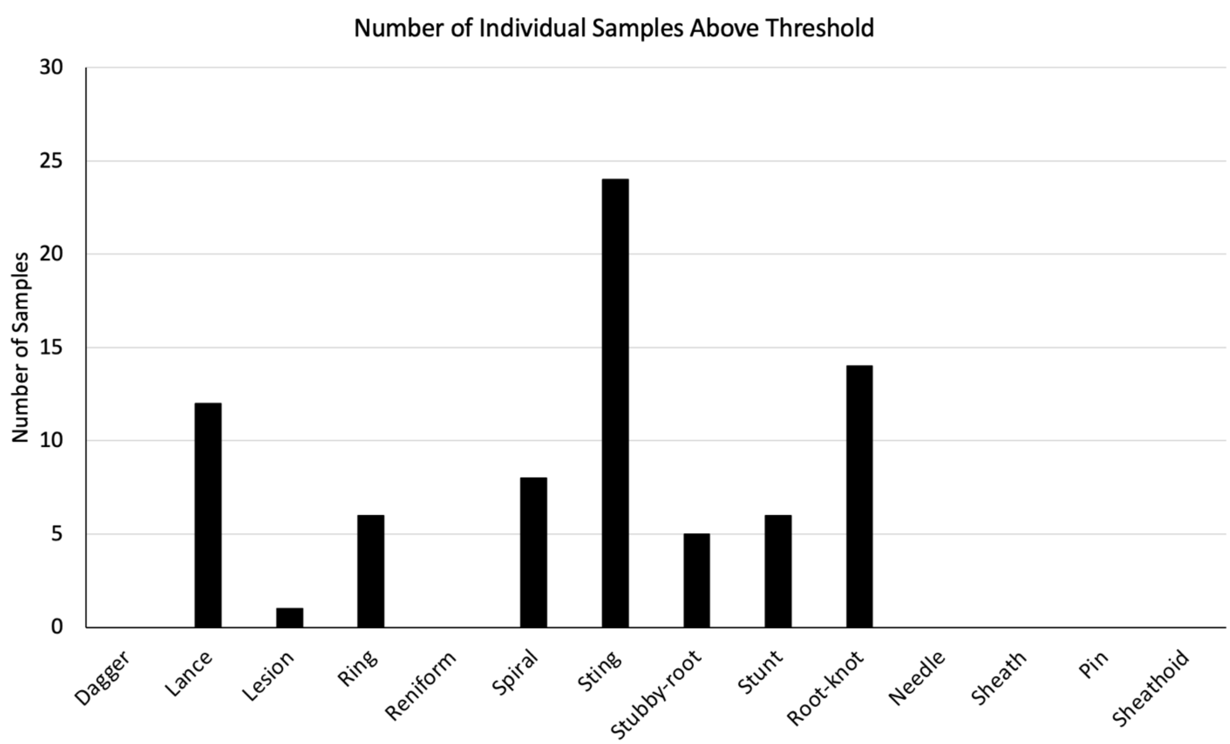


Figure 3. Number of samples from golf course putting greens throughout the Mid-South region of the US with plant-parasitic nematodes above threshold levels.

Table 1. Mean plant-parasitic nematode counts between putting green turfgrass species across all samples from survey. Means were compared between turfgrass species within nematode species. Means within a row followed by a different letter are statistically different ($p < 0.05$).

Nematode Species	Putting Green Turfgrass Species	
	Creeping Bentgrass	Bermudagrass
Dagger	0.0	0.0
Lance	38.6a	3.4b
Lesion	2.4	2.8
Ring	24.4b	60.3a
Reniform	0.0	0.0
Spiral	76.2a	36.3b
Sting	0.0b	7.4a
Stubby-root	11.6a	5.2b
Stunt	43.6a	0.2b
Root-knot	4.9	15.0
Needle	0.0b	1.7a
Sheath	0.3b	6.1a
Pin	0.3	0.0
Sheathoid	15.5a	0.6b

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USGA ID#: 2022-12-755

Title: Use of endophytic microorganisms from a nematode-tolerant Bermudagrass cultivar as nematicidal biocontrol agents

Project Leader: Ulrich Stingl, Marco Schiavon, William T. Crow
Affiliation: University of Florida, Institute of Food and Agricultural Sciences (UF/IFAS)

Objectives:

- To establish a culture collection of microorganisms from the endosphere and rhizosphere of a highly nematode-resistant turfgrass ('TifTuf') and from adjacent susceptible cultivar ('Latitude36')
- To test cultures for ability to inhibit sting (SN) and root knot nematodes (RKN)
- To identify lead strains that can be evaluated and tested for commercial application

Start Date: 2022
Project Duration: Two years
Total Funding: $116,655.69

Summary Points

- 30 fungal endophytes were isolated from two bermudagrass cultivars ('TifTuf', and 'Latitude36') and identified by molecular methods. They were grouped into 7 distinct taxa and were tested for bioactivity against sting nematodes. Seven strains showed significant nematicidal activities (Table 1 and Figure 1). Around 30 additional cultures were isolated but have not yet been identified by molecular methods.
- Extracts from the fungal strain *Colletotrichum* sp. showed strong nematicidal activity for SN and RKN. Similarly, *Cochliobolus kusanoi* and *Aspergillus terreus* achieved high mortality rate of SN.

Summary Text

Rational

All plants rely on associated microorganisms (microbiomes) to aid in acquiring nutrients, alleviating stress, and fighting pathogens (Vandenkoornhuyse et al., 2015). While microbiomes of traditional crops have been investigated to great extent for centuries, modern studies investigating microbiomes in turfgrass, and especially golf turf, are severely lacking behind thus hampering science-based efforts to make use of beneficial microbes to improve turf health (Stingl et al., 2022). In other plant systems, fungi and bacteria living inside the plant tissue ('endophytes') have shown to be very effective in protecting plants from pathogens (Sanchez-Canizares et al., 2017). In this project, we focus on analyzing fungi associated with two fairway cultivars of bermudagrass that exhibit vastly distinct tolerance to nematode infections, with the goal of developing potential microbial biocontrol agents to suppress and treat nematode infections in golf turf. The project combines cultivation-independent high-throughput DNA sequencing of microorganisms (e.g. Rashid and Stingl 2015) associated with leaves and roots of these distinct cultivars with microbial cultivation and lab testing of efficiency of nematicidal fungi from the least susceptible one and from surrounding natural grasses. Our data indicated that fungal communities differ between cultivars with different tolerance towards nematodes (Choi et al. 2022), therefore our current cultivation efforts are focused on endophytic fungi.

Methodology

This project combines high throughput sequencing using Illumina amplicon sequencing of bacterial 16S rRNA genes and fungal Internal Transcribed Spacer (ITS) regions with traditional cultivation efforts to identify and isolate fungal strains that show high activity against sting nematodes. In this project year, we expended our culture collection of fungal endophytes using sterilization and isolation methods partly described in Choi et al. (2022). Briefly, grass leaves and roots are surface-sterilized, slit open, and placed on agar plates. After incubation and colonization of the agar plates by the endophytic cultures, the strains were transferred to new plates and identified with molecular tools (ITS sequencing, Zoll et al., 2016). The sequences were analyzed by comparison against public databases of sequences containing known fungal species and environmental samples, and the strains were grouped based on sequence similarity. Agar plugs in water and glycerol stocks (stored at -80°C) were prepared for long-term preservation of the strains. We also grew cultures of sting nematodes in turf pots in the greenhouse, extracted the nematodes, and established an assay to test the supernatant of spent fungal culture media of the tested fungal strains for bioactivity against sting nematodes. For this, each fungal culture was grown in a shaking incubator at a speed of 150 rpm for 7 days in liquid media at room temperature. The fungal cells were separated from culture supernatant by centrifugation at 4000 x g and the supernatant containing potential bioactive molecules was used for the following experiment. Each assay was conducted with three replicates and one control (uninoculated media) in 24-well microtiter plates. Mortality of the sting and root-knot nematodes was checked under a microscope each day for five days.

Results

We have established a culture collection of 154 fungal endophytes that could be grouped into 20 different sequence types (‘species’) based on ITS sequencing. One representative of each species was used in a bioassay to identify bioactivity (Table 1; Figure 1). A total of seven strains (including four isolated in 2023) showed significantly higher mortality for SN or RKN than the controls. Interestingly, the majority of the isolates came from either the leaves or the roots of the susceptible cultivar. The isolated active strains belong to four different classes of fungi. The most effective strain in controlling SN (~75% of mortality) (Figure 2) and RKN (>80% of mortality) (Figure 3) was *Colletrotrichum sp.*. *Cochliobolus kusanoi* (Figure 4) and *Aspergillus terreus* (Figure 3) were able to achieve high mortality (>80% of mortality) of RKN by Day 5. Additional isolated strains did not achieve sufficient levels of mortality of any of the nematode species.

Results from this experiment demonstrated that fungal strains show promising results for plant parasitic nematodes control. New experiments should aim at the identification of bioactive compounds that are responsible for nematodes death. The identification of these compounds could lead to the creation of new nematicides for the golf industry.

Table 1. Taxonomic ID of additional fungal endophytes isolated in 2023 displaying strong nematicidal activities against sting nematodes. All experiments were done in triplicates.

Phylum	Class	Top BLAST hit	Host plants	Isolation Source
Ascomycota	Dothideomycetes	*Curvularia aeria*	TifTuf, Latitude 36	Leaves, Roots
		uncultured Pleosporales fungus	TifTuf, Latitude 36	Leaves, Roots
		Cochliobolus kusanoi	Latitude 36	Leaves
	Sordariomycetes	*Colletotrichum* sp.	Latitude 36	Leaves
	Eurotiomycetes	*Aspergillus terreus*	Latitude 36	Roots
		Aspergillus thesauricus		
Basidiomycota	Agaricomycetes	*Ceratobasidium* sp.	TifTuf	Roots

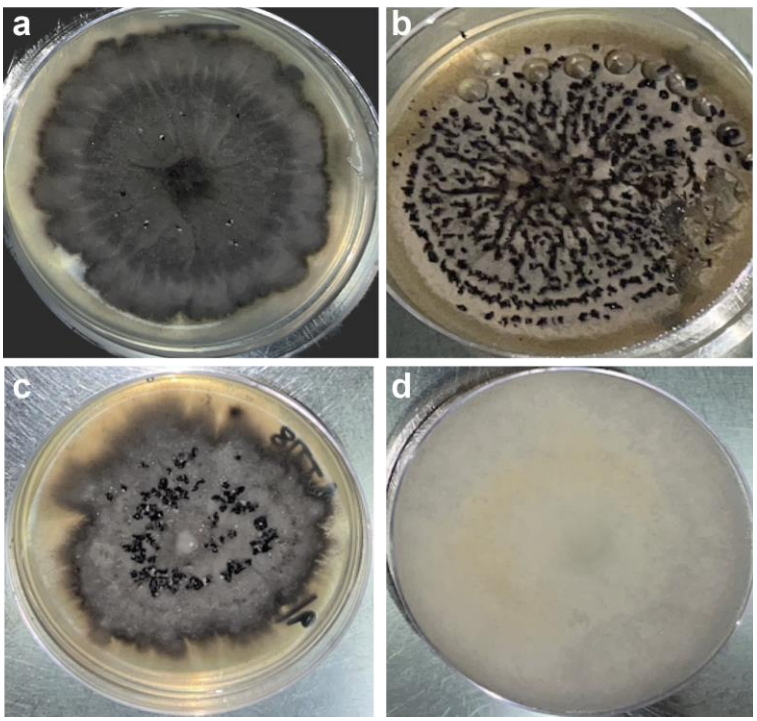

Figure 1. Cultures of endophytic fungi displaying nematicidal activities against sting nematodes.

a. *Curvularia aeria*, **b.** uncultured Pleosporales, **c.** *Colletotrichum* sp. **d.** *Ceratobasidium* sp.

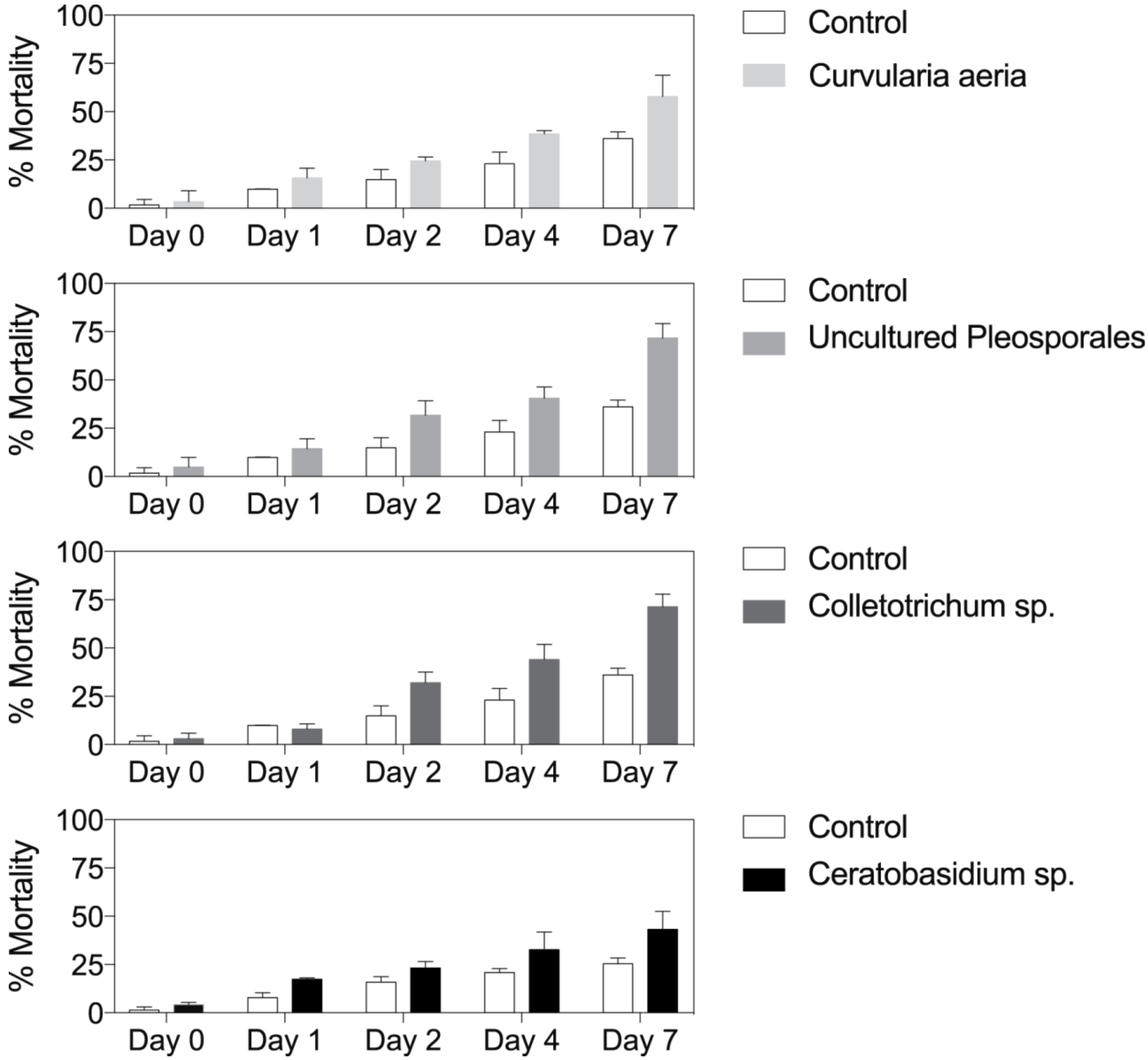

Figure 2. Mortality rate of sting nematodes against additional fungal endophytes over 7-day incubation.

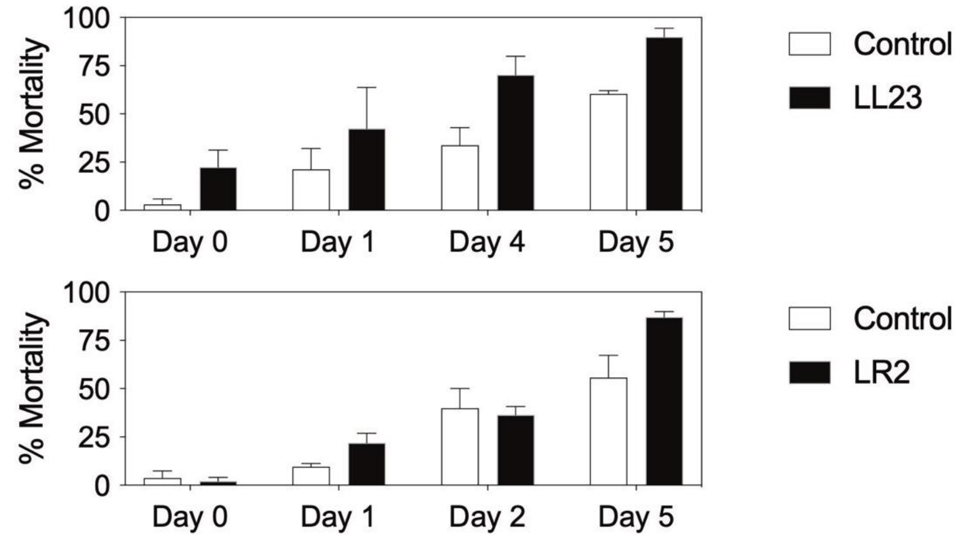

Figure 2. Mortality rate of Root Knot Nematode over 5-day incubation with *Colletrotrichum sp.* isolated from 'Latitude36' leaves (LL23) or *Aspergillus terreus* isolated from Latitude 36 roots (LR2).

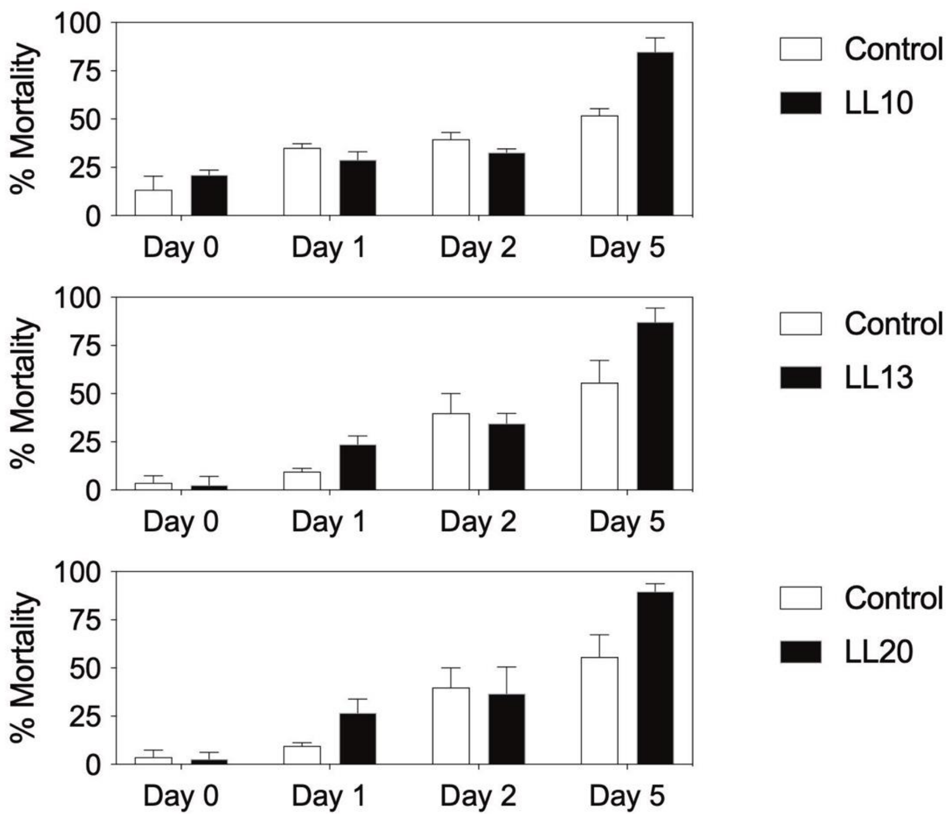

Figure 4. Effects of 3 different isolates of *Cochliobolus kusanoi* from Latitude 36 leaves (LL10, LL13, and LL20) over 5-day incubation. Root Knot Nematodes showed increased mortality on day 5 (no difference from control until day 2)

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USGA ID#: 2023-08-775

Project Title: Comparisons of early-season broad spectrum insecticide and novel insect growth regulator applications on non-target insect populations on golf courses

Principle Investigator: Benjamin A. McGraw, Ph.D.
Affiliation: Pennsylvania State University

Objectives:

(1) Determine the effect of novaluron applications on soil-dwelling and surface-active arthropod and predator populations.
(2) Determine the effect of novaluron applications on consumption of sentinel prey.
(3) Determine the effect of novaluron applications on predatory insect behavior, using the turfgrass ant (*Lasius* neoniger) as a model organism.

Start Date: 2023

Project Duration: 2 years

Total Funding: $74,050

Summary Points:

1. Diversity indices indicate that both golf course fairways harbored moderately diverse arthropod communities. Pitfall traps recovered a greater diversity of larger, surface-active arthropods, while soil core samples were dominated by Acari (mites).
2. Insecticide treatments, including novaluron and conventional products, did not significantly affect overall arthropod community composition or abundance of key taxa (e.g., oribatid and non-oribatid mites), although bifenthrin-treated plots showed increased activity of certain beetles, likely due to insecticide-induced hyperactivity.
3. Novaluron did not affect sentinel prey consumption by predators. Bifenthrin and bifenthrin+clothianidin treated plots had less sentinel prey consumption, highlighting potential short-term ecological disruptions with these broad-spectrum insecticides.
4. Novaluron did not impact ant mounding whereas bifenthrin and a bifenthrin+clothianidin significantly reduced ant mounding for a period of 7- 21 days.

Summary:

Insect Growth Regulators (IGRs) are a class of insecticides that target the endocrine system to disrupt normal growth and development of immature insects. IGRs are regarded as being relatively safe to applicators compared to most insecticides on the market which generally affect nervous system targets common to both humans and insects. Despite this general mechanism, many view IGRs as selective, reduced-risk insecticides that are compatible with IPM programs and less toxic to beneficial insects than traditional chemistries. However, few studies are available to support these claims.

Novaluron, a benzoylphenyl urea IGR, inhibits chitin biosynthesis in developing immature insects leading to abortive molting. Suprado (Control Solutions, Pasadena, TX) demonstrates superior

control of annual bluegrass weevil (ABW)(McGraw et al. in review) and has already been widely used in the Northeast for control of first-generation larvae. The impact of extensive adoption, both in area and throughout the season, of IGR insecticides on non-target and beneficial insects in the golf course environment has not been considered. Novaluron is known to be broadly toxic to several orders of insects, including Lepidoptera (moths and butterflies), Coleoptera (beetles), Heteroptera (true bugs), and Diptera (flies)(Ishaaya et al. 1996). Additionally, adult insects that contact or ingest novaluron do not perish, though egg development, fecundity, and egg hatch may be reduced (Kostyukovsky et al. 2006; Alyokhin 2008; Catchot et al. 2020). Laboratory studies conducted on ABW support these findings (McGraw et al., in review). Not surprisingly, these same effects that have been observed on pests have also been documented on several beneficial insect species (Cutler et al 2006; Cabrera et al. 2017, He et al. 2018, Santorum et al. 2019).

Objective 1: Determine the effect of novaluron applications on soil-dwelling and surface-active arthropod and predator populations.

Methodology:

Two golf courses, Mountain View Country Club (MV) (40.7837,-77.7586) and Toftrees Golf Resort (TT) (40.8225,-77.9018) in State College, Pennsylvania were selected to test the impact of IGRs and conventional insecticides on beneficial arthropod abundance over a 2 year period. Both golf courses were chosen because of their limited insecticide applications. Fairways each site consisted of primarily of *Poa annua* and *Agrostis stolonifera*. Treatments were arranged in a complete random block. Plots (3m × 3m with 1m borders) were replicated five times at each site. Treatments included an untreated control, novaluron (Suprado), bifenthrin (Talstar), clothianidin (Arena 50 WDG), bifenthrin + clothianidin combination product (Aloft LC), and acephate (Acephate 97 UP) at highest labeled rates. Treatments were chosen to represent common products used to control ABW and other turfgrass insect pests. All treatments were applied using a backpack CO_2-pressurized sprayer at a rate of 402L/ha (86 gal/ac), followed by 2.5mm (0.1”) of irrigation.

Surface-active arthropod sampling: To assess the effect of insecticide application of ground dwelling arthropods, five permanent pitfall traps (50mL centrifuge tubes, Corning) were installed. Pitfalls (150 in total) were installed in an X pattern in each plot, with one trap being in the exact center of the plot and the other four 1m extending diagonally from the center. Pitfalls were filled with 10mL of 20% propylene glycol solution to prevent degradation of insect specimens. Pitfalls were installed then replaced 7 days prior to application and 7, 14, 28, and 56 days after application to track arthropod abundance over time. Sampling began on May 9th, 2023. In the event of significant rain forecasts, pitfalls were replaced early, and specimens were combined. Once collected, insect specimens were with 70% ethanol and combined at the plot level for identification.

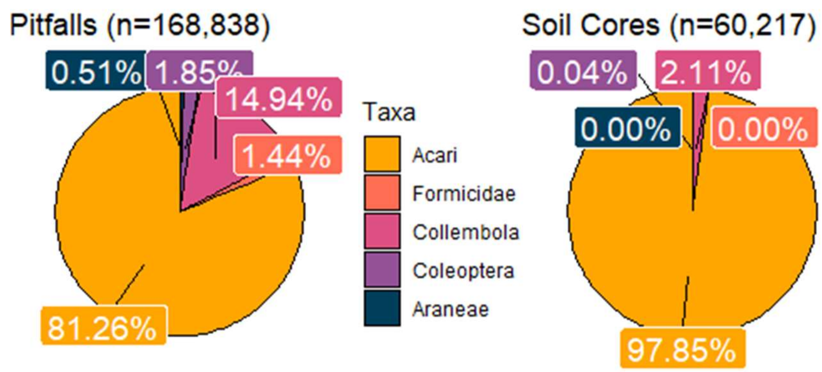
Ground-dwelling arthropod sampling: Within each plot two randomly selected turf cores were extracted from the center of the plot using a tubular turfgrass plugger (6cm diameter × 6.35cm deep) one hour before application and 7, 14, 28 and 56 days following application. Once at the lab turf cores were placed upside down on Berlese funnels and incubated at 40°C in a darkened climate-controlled incubator between 48 and 72 hours, or until soil was desiccated. Specimens that were extracted fell into a small cup of 70% ethanol then combined by plot and stored for later identification.

Results:

Differences in arthropod communities were observed across sites, sampling periods, and years, suggesting that diversity in turfgrass ecosystems is influenced not only by insecticide treatments but also by other environmental and management factors. Insecticide treatment did not have a significant effect on arthropod community composition (i.e. diversity index estimates) when analyzed across all site and year combinations. Recoveries from pitfall traps had a higher diversity of arthropods, namely larger surface-active arthropods. Collembola represented 14.94% of captures, Coleoptera 1.85%, ants 1.44% and

Araneae less than 1% (Figure 1). Arthropod captures from soil core sampling were dominated by acari (i.e. mites) with over 97% of specimens collected belonging to this taxon.

Figure 1: Pie chart showing the proportion of arthropod taxa recovered from each sampling method (pitfalls or soil cores) across the two sampling years. Taxa have been aggregated into larger groups for easier interpretation



The models indicated no significant differences in abundance between untreated controls and any of the conventional insecticide treatments for these taxonomic groups at either site during either sampling year. However, pairwise comparisons did result in some significant differences in abundance when comparing treatments within the same sampling date over both years. In 2024 carabid (ground beetle) abundance in bifenthrin treated areas was significantly increased over untreated controls during the 7DAT and 14DAT sampling periods (z=-2.04,p=0.041 | z=-2.22, p=0.026). A similar trend was observed at MV with significantly increased carabid abundance in bifenthrin-treated plots when compared to untreated controls (z=-2.08,p=0.038) in 2023 and both untreated controls (z=-2.21,p=0.027) and novaluron-treated plots (z=-2.21,p=0.027) in 2024. Similar to carabids, staphylinid (rove beetles) abundance was significantly increased in bifenthrin-treated areas when compared to untreated controls during the 14DAT sampling period at TT in 2023 (z=-2.51,p=0.012). We believe this to be due in part to insecticide-induced hyperactivity.

Acari comprised most of the captures from soil core sampling. Modelling indicated that there was no significant difference in oribatid mite abundance in 2023 between novaluron-treated plots and untreated plots at TT (z=0.81,p=0.420) and MV (z=1.23,p=0.220). In 2024, models indicated that overall, there was no significant effect of novaluron on oribatid mite abundance when compared to untreated controls at TT (z=0.49,p=0.620) and MV (z=-0.910,p=0.365). For non-oribatid mites our results were similar with non-oribatid mite abundance not being significantly different in novaluron treated areas when compared to untreated controls at TT (z=0.12, p=0.904 | z=-0.26,p=0.790) and MV (z=0.38,p=0.703 | z=-0.61,p=0.541) for the 2023 and 2024 sampling year respectively. In both years at both sites modelling indicated that the conventional insecticide treatments had no significant effect on oribatid or non-oribatid mite abundance

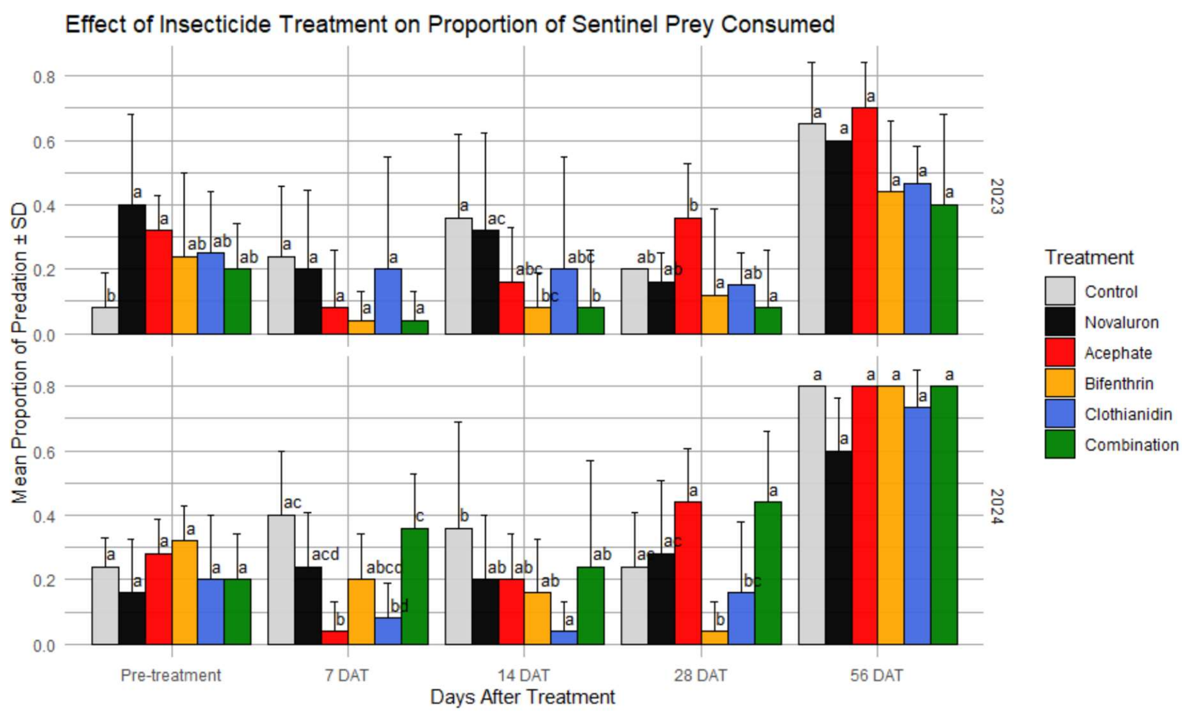
Objective 2: Determine the effect of novaluron applications on consumption of sentinel prey.

A trial designed to assess the effect of novaluron on predator behavior was held at the Joseph E. Valentine Turfgrass Research Center (40.8119,-77.8665). Insecticides had not been applied within the study area for over 3 years. Plots (3m × 3m with 1m borders) were replicated five times. The same treatments and application methods as those in Objective 1 were used. Sentinel prey (3rd-instar *Agrostis ipsilon* larvae) were pinned through the second to last abdominal segment into the turf in an X pattern, with one being in the exact center of the plot and the other four being pinned 1m from the center diagonally. A vertebrate exclusion cage was then placed over the caterpillar to exclude predation by birds and other mammals. After caterpillars had been left in the field for 24 hours their fate was assessed in situ.

Fates included: dead, alive, partially predated, or wholly predated. Caterpillars were deployed at 7, 14, 28, and 56 days after application. Sampling began on May 10th, 2023.

Results: The consumption of sentinel prey was not significantly different between novaluron-treated areas and the untreated controls in either year of the study (Figure 2). Immediately following application (7 DAT) in 2023 there were no significant differences in the proportion of sentinel prey consumed in acephate- (t=1.67,p=0.098), bifenthrin- (t=1.90,p=0.060), and combination-treated areas when compared to untreated controls (t=1.90, p=0.060). In 2024 pairwise comparisons revealed that immediately following application (7 DAT) there was a significant reduction in sentinel prey consumption in acephate- (t=3.49, p<0.001) and clothianidin-treated plots (t=2.93, p=0.004) compared to untreated controls. Sentinel prey consumption was reduced significantly in bifenthrin- (t=3.75, p<0.001 | t=- 3.78, p<0.001) and clothianidin-treated plots (t= 2.67, p=0.009 | t=-2.69, p=0.008) when compared to acephate- and combination-treated areas, respectively during the 28 DAT sampling period. No differences were observed between any treatments at 56 DAT in either year.

Figure 2: Bar graph displaying the mean proportion of sentinel prey consumed (± standard deviation) in each insecticide treatment across all sampling periods. Tukey letters represent statistical differences between treatment groups, groups that do not share the same letter are statistically significant (α = 0.05) .



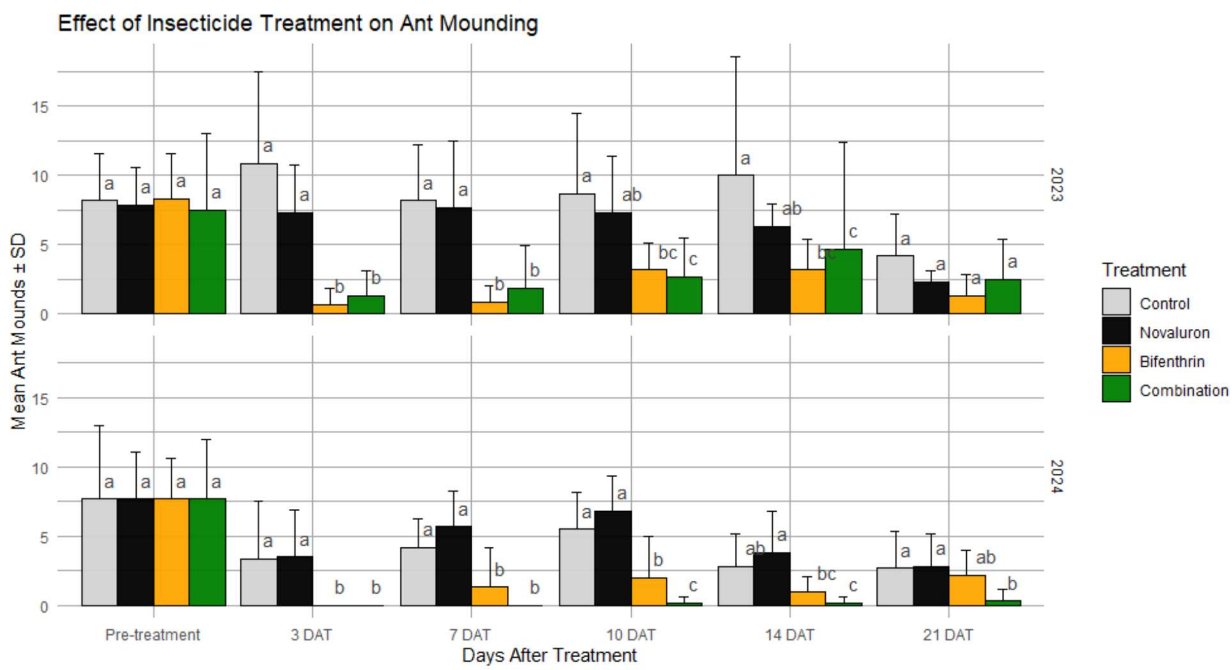
Objective 3: Determine the effect of novaluron applications on predatory insect behavior, using Turfgrass ant (*Lasius* neoniger) as a model organism.

Three research greens were selected; two at the Penn State Landscape Management Research Center (40.8240,-77.8550) and one at the Joseph E. Valentine Turfgrass Research Center (40.8119,-77.8665). Greens were surrounded by rough cut turf and had high amounts of ant mounding activity. Plots (4m × 4m) were laid out with 2.5m of the plot extending into the rough and 1.5m extending into the green where active ant mounding was occurring separated by at least a 1m untreated border region. Plots were arranged based on pre-application mound counts and blocked as necessary to avoid overlapping colonies and to balance mound counts between treatments. Each treatment was replicated six times. Plots received one of four insecticide treatments: untreated controls, novaluron (Suprado), bifenthrin (Talstar), and a combination product of bifenthrin+clothianidin (Aloft LC). Insecticide was applied at field rate for control of turfgrass ant and all treatments were applied using a backpack CO_2-pressurized sprayer at a rate of 402L/ha (86 gal/ac), followed by 2.5mm (0.1") of irrigation. We returned to the study greens 3, 7, 10, 14, and 21 days after treatment (DAT) to count active ant mounds. An ant mound was recorded as active if there were ants moving in and out of its entrance.

Results:

Novaluron did not significantly impact ant mounding activity in either year of the study (Figure 3). Pairwise comparisons revealed that bifenthrin and the combination product applications caused a significant decrease in the number of active ant mounds within plots in 2023. Bifenthrin-treated plots had significantly decreased ant mounding at the 3 DAT ($t=-5.24$, $p<0.001$ | $t=-4.24$, $p<0.001$) and 7 DAT ($t=-4.18$, $p=0.001$ | $t=--3.85$, $p=0.002$) when compared to untreated control and novaluron treated plots respectively. In 2024, the combination treatment significant decreased ant mounding across all sampling dates in 21-d observation period compared to the untreated controls and novaluron.

Figure 3: Bar graph showing the mean number of ant mounds (± standard deviation) in each insecticide treatment across all sampling periods for both sampling years. Tukey letters represent statistical differences between treatment groups, groups that do not share the same letter are statistically significant ($\alpha = 0.05$).



Conclusions:

- Community analysis showed that novaluron did not have a significant impact on the arthropod community composition, arthropod diversity, and arthropod abundance at either of our sites for the duration of the study. However, it was observed that the neurotoxic turf insecticide standards also exhibited a limited impact on beneficial arthropods, which was unexpected based each insecticide's broad spectrum of activity. Despite these findings, this study supports the hypothesis that novaluron has a limited impact on beneficial arthropods within the turfgrass system when considering a single early-season application for control of ABW.
- Novaluron was shown to have limited effects on *L. neoniger* mounding and by proxy their

foraging activity in turfgrass. Additionally, novaluron did not impact sentinel prey consumption from arthropod predators. The turf insecticide standards tested significantly reduced both ant mounding and sentinel prey consumption, although these effects were diminished by the end of both study years. These findings support the hypothesis that single early-season applications of novaluron have limited non-target effects on 1) *L. neoniger* mounding behavior and 2) sentinel prey consumption in turfgrass ecosystems when compared to conventional neurotoxic insecticides commonly used to control early-season insect pests, such as ABW.

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USGA-ID: 2023-14-781

Title: Silicon to induce resistance to annual bluegrass weevil in annual bluegrass and creeping bentgrass.

Project leaders: Albrecht M. Koppenhöfer, Ana Luiza Sousa, Tarikul Islam, Matthew S. Brown
Affiliation: Department of Entomology, Rutgers University, New Brunswick, NJ

Objectives: To enhance annual bluegrass and creeping bentgrass resistance to the annual bluegrass weevil using silicon fertilization

Start date: 2023-1-1
Project duration: 2 years
Total funding: $53,270

Summary Points:

- Silicon fertilization increased leaf Si concentrations in annual bluegrass and creeping bentgrass and suppressed ABW population growth on both grasses.
- The negative effects of silicon on ABW performance were stronger in creeping bentgrass compared to annual bluegrass.
- Silicon fertilization may support creeping bentgrass to outgrow annual bluegrass in mixed turf stands.

The annual bluegrass weevil (ABW, *Listronotus maculicollis*) is one of the most destructive insect pests of short-mown turf on golf courses in the eastern United States and southeastern Canada. ABW management has become increasingly challenging due to its extensive resistance to insecticides, necessitating the development of alternative and sustainable management strategies. One promising approach includes strengthening plant resistance through silicon (Si) fertilization. Si fertilization, either in the soil or as a topical application, can enhance plant resistance to herbivorous insect pests. Si is readily absorbed as silicic acid by plant roots and transported via the xylem to stems and leaves. Si deposition in leaf tissues as hydrated silica ($SiO_2 \cdot nH_2O$) or phytoliths can form a mechanical barrier to herbivory, impairing the ability of insects to chew and digest leaf tissues. Insect mandibles may be eroded due to the abrasiveness of silicified tissues, resulting in impaired feeding ability and retarded growth due to starvation.

Grasses are hyper-accumulators of Si, and Si fertilization has been shown to enhance the resistance to insect herbivores of several poaceous crops, including rice, wheat, and sugarcane. Both warm- and cool-season turfgrasses can accumulate significant amounts of Si in tissues, which has been linked to improvements in wear tolerance, heat stress tolerance, disease resistance, photosynthetic efficiency, growth and establishment, root development, and overall turf quality. However, the impacts of Si on turfgrass insect pests, including ABW, remain largely unexplored. A previous study involving creeping bentgrass and black cutworms reported minor negative effects of Si on larval growth. Furthermore, research on pasture grass found an inverse relationship between the density of intercostal Si deposits in leaf sheaths and the oviposition preference of the Argentine stem weevil, *Listronotus bonariensis*, a congeneric species of ABW. Given that stem and leaf silicification is a well-documented anti-herbivore defense mechanism in grasses, we hypothesize that Si fertilization enhances turfgrass resistance to ABW, reducing both oviposition and larval development.

We conducted greenhouse and field experiments to assess the effects of Si on the resistance of annual bluegrass (*Poa annua*) and creeping bentgrass (*Agrostis stolonifera*) to ABW. In the greenhouse, wild-type annual bluegrass and creeping bentgrass (cv. 007) were grown in pots for at least two months following Si fertilization before ABW exposure. Based on the results of our greenhouse experiments in Year 1, we refined the protocol for Year 2, applying Si with only wollastonite (Vansil® W-10; Vanderbilt Mineral LLC), a calcium silicate powder containing 24% Si, at three rates. Treatments included an untreated control (lime), wollastonite at the label rate (1× = 1,221 kg/ha), twice the label rate (2×), and four times the label rate (4×). Eight weeks after Si application, two male and two female ABWs were released per pot to facilitate egg-laying. Adults were removed after one week, and another four weeks larvae were extracted from the pots using the saltwater extraction method. Larval developmental stages were determined under a dissecting microscope. We also measured Si concentrations in leaves from insect-free grasses. The greenhouse experiment was conducted twice.

Fig. 1. Top view of experimental pots in the greenhouse.

Fig. 2. Extraction of ABW stages in warm salt solution.

The field experiment conducted in Year 1 was repeated in Year 2 at Rutgers Horticultural Farm No. 2, using a mixed stand of annual bluegrass and creeping bentgrass (cv. Luminary) maintained as a fairway and naturally infested with ABW. Experimental plots comprised 30.5 × 30.5 cm turf areas, separated by 30.5 cm buffer zones. In early April, four turf cores (10.8 cm diameter × 2.5 cm depth) of annual bluegrass or creeping bentgrass were implanted into each plot. Plots received one of four treatments: lime (control) or wollastonite applied at 1×, 2×, or 4× rates. For evaluation, one core per plot was extracted in early, mid, and late May. ABW stages were extracted by submerging soil cores in a warm salt solution and then counted and identified to developmental stages under a dissecting microscope. Grasses were then allowed to grow for an additional 15 days without mowing to obtain soil-free clippings for Si analysis.

Results

As in Year 1, Si fertilization effectively suppressed ABW population growth in the greenhouse experiments conducted in Year 2. Wollastonite applications at 1×, 2×, and 4× rates reduced larval populations by 46-50%, 50-56%, and 72-73% in annual bluegrass and by 45-54%, 73-77%, and 91-92% in creeping bentgrass, respectively, across experimental trials (Fig. 3). Annual bluegrass supported higher ABW population growth than creeping bentgrass. In the field, the suppressive effects of Si on ABW performance were less consistent across evaluations. Discernible reductions in ABW population were observed only at the higher wollastonite rates (2× and 4×). Wollastonite, at the highest rate, reduced ABW population by up to 49% in annual bluegrass and 85% in creeping bentgrass (Fig. 4a), although the effects varied across evaluations.

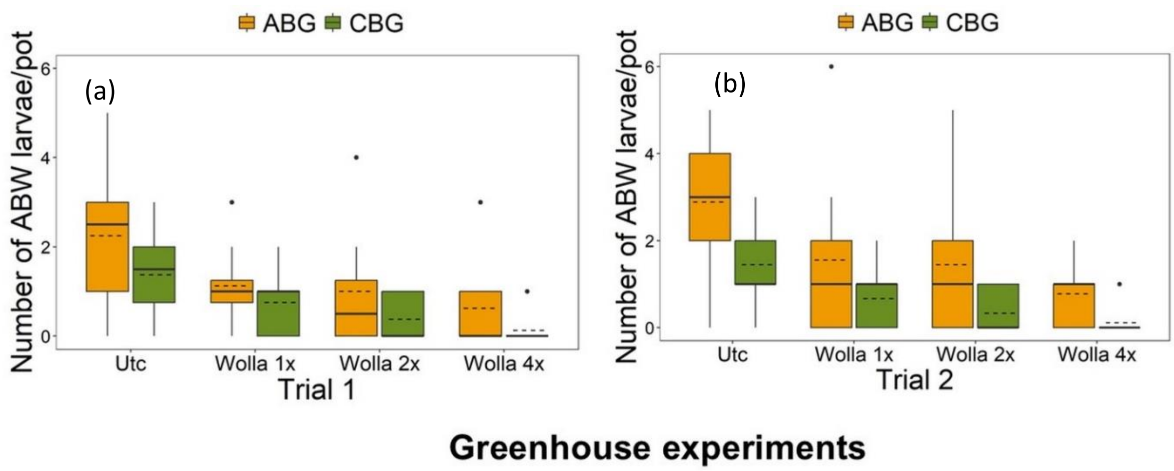

Fig. 3. Boxplots showing ABW larval counts per pot in greenhouse experiments: (a) Trial 1 and (b) Trial 2. Treatments included an untreated control (Utc) and wollastonite applied at 1×, 2×, and 4× the label rate. Dashed lines represent the mean values and dots indicate outliers. Annual bluegrass (ABG), Creeping bentgrass (CBG).

Si fertilization increased leaf Si concentrations in both turfgrass species, with creeping bentgrass accumulating more Si than annual bluegrass at 1× and 2× wollastonite rates. Specifically, 1×, 2×, and 4× rates increased leaf Si concentrations by 88%, 141%, and 276% in annual bluegrass and by 102%, 158%, and 176% in creeping bentgrass, respectively, relative to the untreated control (Fig. 4b). Overall, our two-year observations suggest that Si fertilization consistently enhances the resistance of both turfgrass species to ABW, with slightly stronger effects in creeping bentgrass than annual bluegrass. Given that annual bluegrass is a preferred host of ABW, Si fertilization could further reduce ABW preference for creeping bentgrass, potentially supporting creeping bentgrass to outgrow annual bluegrass in mixed turf stands.

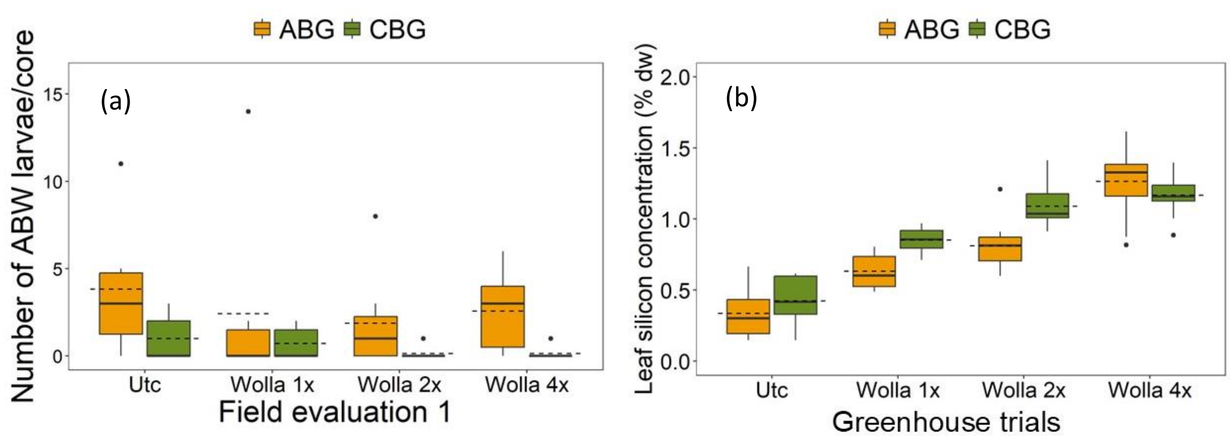

Fig. 4 (a) Boxplots showing ABW larval counts per core from the first field evaluation in year 2 and (b) leaf Si concentration (% dry weight) in grasses grown in the greenhouse. Treatments included an untreated control (Utc) and wollastonite applied at 1×, 2×, and 4× of label rate. Dashed lines represent the mean values and dots indicate outliers. Annual bluegrass (ABG), Creeping bentgrass (CBG).

USGA ID#: 2022-06-749

Title: Investigating White Grub Resistance in Turf-Type Tall Fescue

Project Leader: Stacy A. Bonos, Albrecht Koppenhöfer, Phillip L. Vines, and Jennifer L. Halterman
Affiliation: Rutgers, The State University of New Jersey

Research Objectives:

(i) Determine if there is a preference for white grubs to feed on certain tall fescue (TF) populations and assess the ability of white grubs to survive among different TF populations
(ii) Evaluate white grub feeding patterns for potential feeding preferences on roots of different TF populations
(iii) Compare and assess rooting in TF populations for their ability to compensate for white grub root feeding
(iv) Assess TF populations for fungal endophytes to determine if there is an association with white grub feeding

Start Date: August 24, 2022
Project Duration: 3 years
Total Funding: $56,746.00

Summary Points:

- Grubs were collected, counted, and identified from turf plots and lightbox images were taken for visual assessment immediately prior to turfplot rating and sampling
- Turf plots were visually rated on a 1-9 scale, with 9 being the best, monthly from May to October
- Rhizotron experiment and root cutting experiment were completed to evaluate grub feeding and root and shoot regrowth
- Drought study is currently underway to evaluate if drought resistance potentially correlates to grub resistance
- Endophyte presence was tested for each of the 20 genotypes per cultivar using microscopy methods

Summary Text:

The complex of white grub species feeding on turfgrass roots is the most destructive and widespread insect pest affecting turfgrass in the northeastern U.S. The reliance on chemical measures for control is costly and not sustainable for golf course superintendents or the environment. Increased tolerance to white grub feeding has been observed in tall fescue populations at the Rutgers Plant Science Research Farm in Freehold, NJ. Through a series of field and greenhouse studies, we hope to gain a better understanding of the contributing factors to white grub tolerance in tall fescue as a better alternative to chemical treatments.

A field trial consisting of 15 tall fescue (TF) cultivars and 1 perennial ryegrass (PR) cultivar was established at the Rutgers Adelphia Plant Science Research and Extension Farm in Freehold, NJ in August 2022. Visual turf quality ratings and lightbox images were taken throughout the growing season and grub samples were taken in July and October. The cultivars Bullseye LTZ, PPG TF-303, and Firenza II had the best turf quality while Crossfire 3, Meridian, and GO-FNKY had the poorest turf quality for the duration of the test (Table 1). White grub densities were determined in July (first and second instars) and October (third instars) by taking 10 turf plugs evenly distributed throughout each plot. Billbug damage and counts were also assessed due to evidence of billbug presence (Table 2). As initial counts in October were low, we took a 1.5 feet x 3 feet sample in the middle of the plot with a sod cutter set at 2 inch depth. Counts from both samplings in October were combined as sampling was within a week of each other (Figure 1). Initial data analysis revealed high grub counts for Crossfire 3 and PPG TF-303 in the July sampling. However, these initial counts seemed to vary from the October sampling. Line Drive II perennial ryegrass had the highest grub count, with the majority being oriental beetle followed by Degas and Firenza II tall fescue cultivars. GO-FNKY and Annapolis TF had the lowest grub counts, with the majority consisting of oriental beetle larvae. More detailed data analyses using R software are currently being conducted.

Growth chamber experiments were conducted to assess visual tall fescue characteristics that can contribute to grub tolerance. For all growth chamber experiments, 20 individual genotypes were used from each cultivar.

A rhizotron experiment was conducted to evaluate tall fescue populations when exposed to grub damage. Root length was calculated using WinRhizo, a root scanning software that can measure architectural root characteristics such as length, diameter, and volume. Shoot length was measured in millimeters. Once length data was recorded, roots and shoots were dried and weighed. Photos were taken every 3 days to assess grub feeding patterns (Figure 2). Further data analysis is currently underway.

A root cutting experiment was conducted in the growth chamber to assess tall fescue's ability to regenerate roots from physical cutting of the roots at 0.5-inch length to simulate grub feeding behavior. Roots were measured every 3 days after an 8-day establishment period (Figure 3). Root and shoot characteristics were measured the same as the rhizotron experiment and dry weights were recorded. Upon initial inspection, it appeared that some cultivars regrow roots at a faster pace, but at the end of the experiment there were no significant difference among the cultivars (Figure 4). Further data analysis is being conducted in R to accurately test for significance.

Currently, a drought study in the growth chambers is being performed to determine if there is a potential correlation with drought tolerance and grub tolerance in rooting characteristics (Figure 5).

Tall fescues were reassessed for endophyte using Bacon and White (1994) protocol for the 20 individual genotypes from each cultivar due to the low percentage of endophytes previously present and to correlate any present endophyte with growth chamber studies. Endophyte positive genotypes were identified and transformed into percentages to represent any field study correlations (Table 4).

The next steps in this process are to complete drought study, analyze data and fit models using R statistical data analysis software to identify any trends or correlations, and present the research verbally and written via thesis and publications.

Tables and Figures:

Table 1. Turf quality ratings of tall fescue cultivars seeded in August 2022 at the Rutgers Adelphia Plant Science Research and Extension Farm, Adelphia NJ.

			Turf Quality[1]				Billbug[2]
			2022-2024	2022	2023	2024	11-Jul
Rank	cult		Avg.	Avg.	Avg.	Avg.	2024
1	6	Bullseye LTZ	6.9	7.3	6.7	6.8	6.8
2	14	PPG TF-303	6.8	6.7	6.6	7.2	6.6
3	11	Firenza II	6.8	6.5	7.0	6.9	6.0
4	12	Padre II	6.7	6.5	6.3	7.3	6.8
5	2	Annapolis	6.4	6.3	6.4	6.4	5.8
6	3	Technique	6.4	6.7	6.3	6.3	6.6
7	8	Thor	6.3	6.9	6.2	5.8	6.4
8	9	Degas	6.3	7.1	5.8	6.1	5.2
9	10	Trinity	6.0	6.5	5.8	5.7	6.4
10	7	FireCracker SLS	5.9	6.3	5.8	5.7	7.2
11	16	Line Drive II	5.6	8.3	5.0	3.6	1.2
12	4	Bandit	5.6	5.9	5.5	5.5	4.2
13	5	Renegade DT	5.6	6.0	5.5	5.3	5.6
14	13	Crossfire 3	4.2	4.3	4.1	4.0	4.0
15	1	Meridian	3.9	2.7	3.7	5.2	5.0
16	15	GO-FNKY	3.3	3.9	3.4	2.7	5.0
		LSD at 5%	0.7	0.9	0.8	0.9	2.3
		CV	9.3	12.1	11.2	12.3	33.4

[1] 9 = best turf quality

[2] 9 =least billbug damage

Table 2. Early white grub larval stage sampling and billbug counts in July 2024 at the Rutgers Adelphia Plant Science Research and Extension Farm, Adelphia NJ.

	Grubs			Billbug		
Cultivar	1st instar	2nd instar		Larvae	Pupae	Adult
Annapolis	1	2		0	0	0
Bandit	0	3		2	0	1
Bullseye LTZ	0	2		0	0	0
Crossfire 3	8	7		2	1	0
Degas	3	4		0	0	1
Firecracker SLS	2	1		2	0	0
Firenza II	0	2		0	0	0
GO-FNKY	0	2		0	0	0
Line Drive II	3	5		0	0	1
Meridian	4	3		0	1	0
Padre II	7	2		0	0	1
PPG TF-303	20	3		0	0	2
Renegade DT	0	0		3	3	2
Technique	4	1		1	2	2
Thor	6	4		1	0	1
Trinity	2	3		0	0	1

Table 3. Endophyte percentage per cultivar for field correlation.

Cultivar	Percent Endophyte
Annapolis	95
Bandit	95
Bullseye LTZ	85
Crossfire 3	15
Degas	75
FireCracker SLS	70
Firenza II	75
GO-FNKY	55
Line Drive II	70
Meridian	75
Padre II	90
PPG TF-303	0
Renegade DT	90
Technique	100
Thor	80
Trinity	60

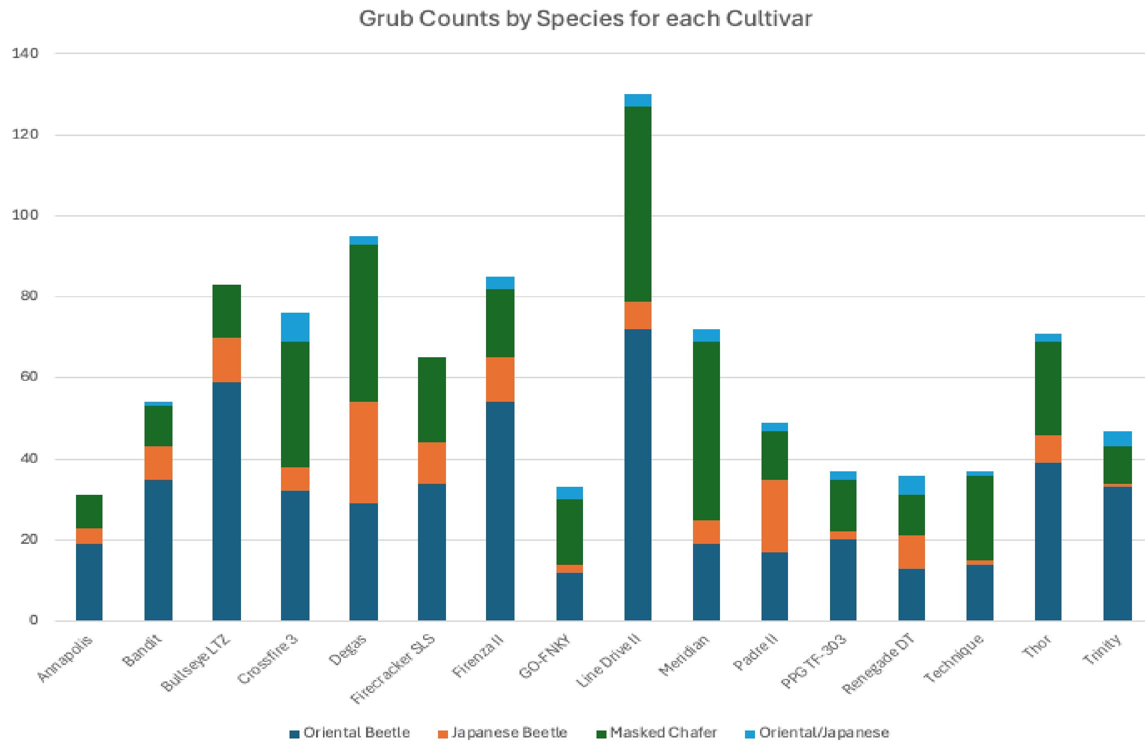

Figure 1. Total grub counts from cup cutter and sod cutter samples in October 2024 at the Rutgers Adelphia Plant Science Research and Extension Farm, Adelphia NJ.


Figure 2. Sample of photos taken of rhizotron experiment showing grub feeding patterns, root architecture and shoot growth in growth chambers at NJAES Research Greenhouse in New Brunswick, NJ.

Figure 3. Root cutting experiment. Root visualization to measure after 8-day establishment in growth chambers at NJAES Research Greenhouse, New Brunswick NJ.

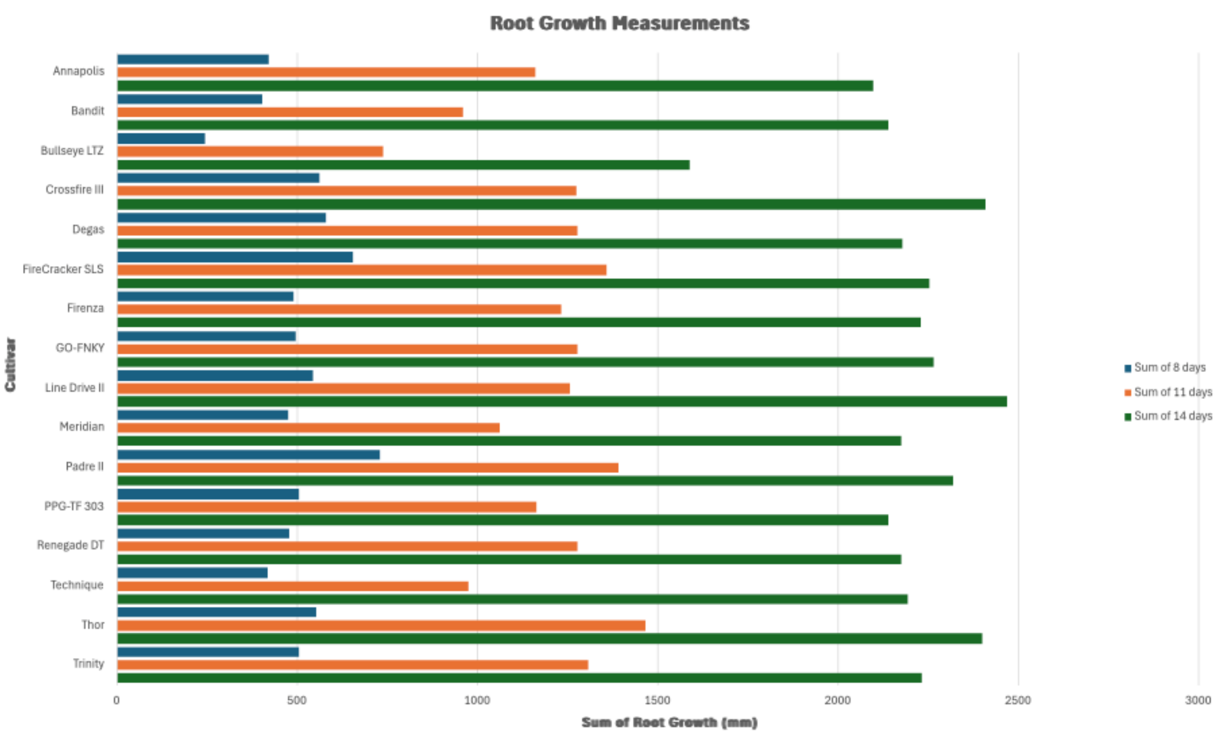

Figure 4. Root cutting experiment. Root growth measurements at 3-day increments.

Figure 5. Drought study in growth chambers at NJAES Research Greenhouses in New Brunswick, NJ.

References:

Bacon, C.W. and J.F. White. 1994. Stains, media, and procedures for analyzing endophytes. Biotechnology of endophytic fungi of grasses. 47:56.

USGA ID#: 2022-09-752

Title: Engineering Turfgrass Rhizobacteria For Selective Control Of Fall Armyworm

Project Leader: John F. Beckmann, David Held, Janiyah Cotton
Affiliation: Auburn University

Objectives:
Objective 1) Determine the best rhizobacterial killer of Fall Armyworm (FAW).
Objective 2) Equip rhizobacterial shuttle vectors with insect toxins.

Start Date: August 2022
Project Duration: 3 years (2022-2025)
Total Funding: $109,806

Summary Points:
Objective 1)

- We have successfully developed a robust bioassay testing killing efficacy of bacterial strains against FAW.
- After screening over 70 bacterial strains from an Auburn plant growth promoting rhizobacterial (PGPR) database we have detected eight natural killers of FAW.
- We have taken the four best PGPR killers of FAW and are subjecting them to grass field trials.

Objective 2)

- We have successfully synthesized and cloned the putative Lepidopteran killing gene cry1F into a shuttle vector plasmid for downstream bacterial transformations.

Summary Text:

Rational: Turfgrasses are of economic importance to Golf courses. A major pest of turfgrass is the fall armyworm. We will develop cheap and residual controls for fall armyworm in turfgrass by engineering rhizobacterial frames to deliver customizable species-specific insect killing toxins to plant herbivores.

PGPRs represent a sustainable and eco-friendly approach to enhance plant growth, improve turfgrass health and yields, while potentially mitigating the adverse impacts of conventional synthetic insecticides. Understanding the intricate mechanisms of PGPR-plant interactions is crucial for harnessing their full potential in sustainable turfgrass production. PGPRs can enhance nutrient availability through the solubilization of phosphates and the production of plant growth hormones. Additionally, PGPR can fix atmospheric nitrogen, making it accessible to plants in a usable form. Furthermore, they stimulate the plant's defense responses by inducing systemic resistance against pathogens, known as induced systemic resistance (ISR) (Bano & Muqarab, 2017; Kloepper et al., 2004; Pineda et al., 2010). As research progresses, the integration of PGPR into turfgrass management systems holds the promise of a more resilient and sustainable future.

PGPRs live in the rhizosphere. The PGPRs of turfgrass are *Bacillus* bacteria. *Bacillus subtilis* is also a model bacterium. Our research implements two redundant strategies to limit damage by FAW in turfgrass systems. The first approach is to engineer turfgrass PGPRs to kill FAW and the second approach is to screen PGPR libraries for natural killers of FAW. Thus, PGPRs serve as both a backbone for genetic engineering and a natural source of potential insecticidal activity. Some PGPRs are capable of transient colonization of turfgrass foliage. Once in the foliage the bacteria would be imbibed by insect pest herbivores. Thereupon, delivery of a toxin would kill the herbivore. This technology will be transient and not permanently damage ecosystems because the Rhizobacteria we are working on transiently colonize turfgrass for ~12 weeks then die off.

One notable potent killer of FAW is *Bacillus thuringiensis* (BT), a pathogenic microbe of caterpillars. BT expresses crystalized toxin proteins, also known as Cry proteins, on plasmids. When tested against four *Lepidopteran* species, toxins Cry1F and Cry1D showed the highest toxicity in FAW, but Cry1F had an overall higher toxin activity in all four species when compared to Cry1D (Bohorova et al., 1997). Expressing the *cry1F* gene in a turfgrass PGPR that can transiently colonize both turfgrass foliage as well as FAW's midgut could also be a possible solution. Engineering an insecticidal bacterium specific to FAW opens the door to engineering bacteria to target other major pests in different systems.

Methodology:

***Bioassays:* Original Diet-Overlay Bioassay.** Our research goal is to both find natural strains and engineer GMO strains of rhizobacteria that kill Fall Armyworm. Thus, it was necessary to develop a bioassay with controls capable of measuring FAW death. For the initial screen, PGPR strains are grown in Tryptic Soy Broth (TSB) at 37ºC, for 72 hours to allow for growth and potential production of any secondary metabolites. 1oz plastic cups are filled halfway with artificial FAW diet and left to solidify. Once solidified, the entire surface of the diet is inoculated with 50µl of the desired strain. A single 1st instar larva is placed on top of the diet and covered with a lid. The cups are then put in rearing trays and placed in a growth chamber set at 27ºC with a 14-hour day: 10-hour night photoperiod. FAW survivorship is monitored daily for 10 days.

Improved Diet Overlay Bioassay. Both the bacteria and artificial diet are prepared the same as in the original bioassay. Once solidified, the entire surface of the diet is inoculated with 250µl of the desired strain. Ten 1st (or 3rd) instar larvae are placed on top of the diet and covered with a lid. The cups are then put in rearing trays and placed in a growth chamber set at 27ºC with a 14-hour day: 10-hour night photoperiod. FAW survivorship is recorded after 5 days.

Genetic Engineering of Potential Killing Plasmids: To build a transferable FAW killing plasmid construct, we first ordered a synthesized *cry1F* gene from Genscript. Next, using restriction enzymes we cut out, purified, and ligated this gene into our shuttle vector (pMag). From there, we transformed this shuttle vector into *E. coli* for long-term storage. Mini-preps were performed to extract plasmids for cloning. Cloning success was confirmed by DNA sequencing via whole plasmid sequencing at Plasmidsaurus.

Results to Date:

Improving Previously Developed Diet-Overlay Bioassay. After identifying robust positive and negative controls for killing of FAW, we began intensive bioassay screening of PGPRs for natural insecticidal activity. The first trial and methodology yielded no PGPR strains that were significantly different from our negative TSB control, except for our positive commercial BT control (**Figure 1**). This led to revision of the protocol. Using the new and improved diet-overlay bioassay, we have screened over 70 PGPRs, against both 1st and 3rd instar larvae, to date. **Figures 2 and 3** shows survivorship data from these screened strains. Screens were performed in triplicate. In summary, we successfully identified eight statistically significant killers of 3rd instar FAW.

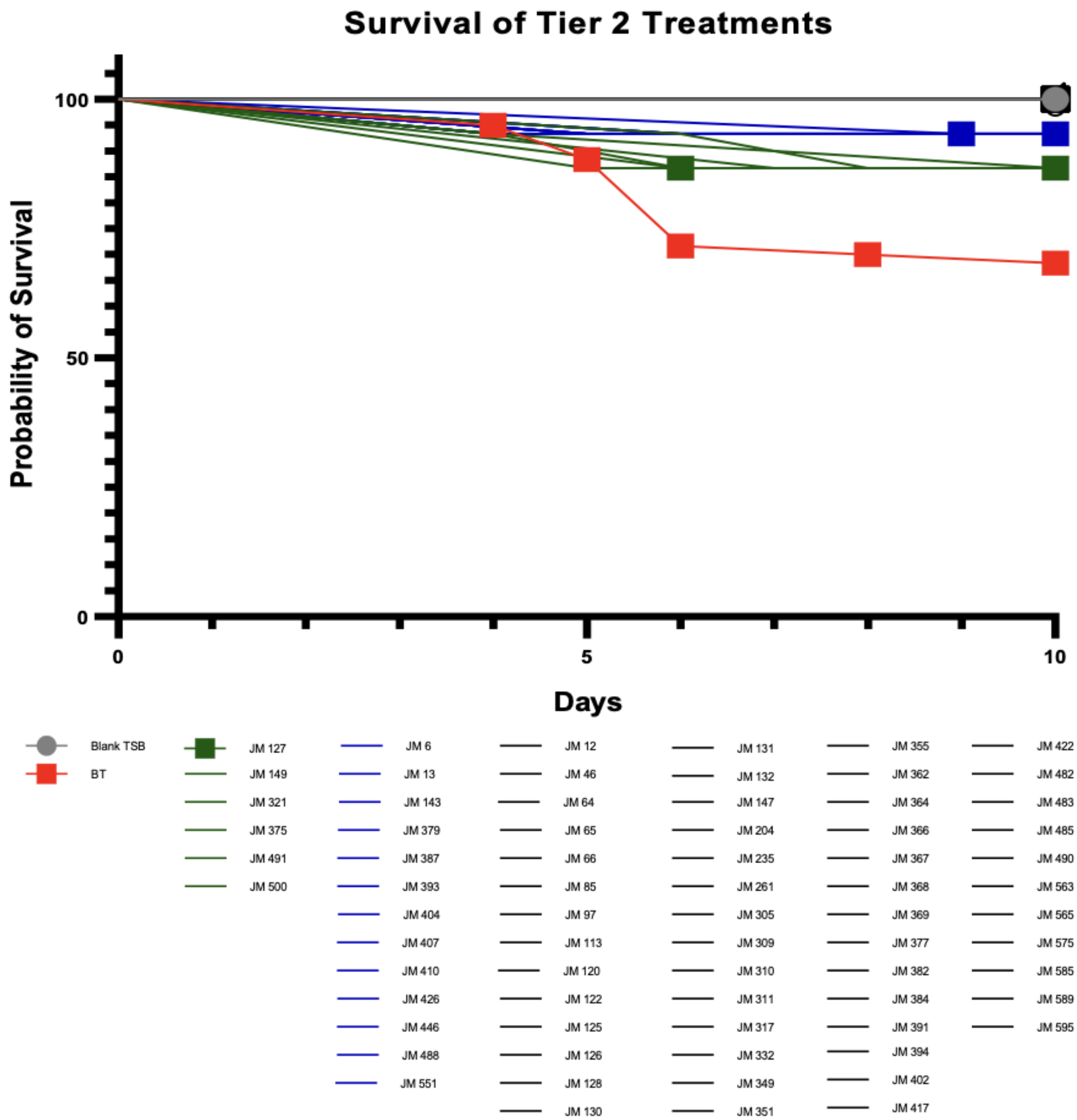

Figure 1. Survival Analysis of 1st Instar FAW. The grey line is the negative TSB control. The red line is the positive BT control. All other lines are diverse PGPR treatments. The green and blue lines are strains that expressed some killing that was not significant. The black lines are strains that expressed no killing.

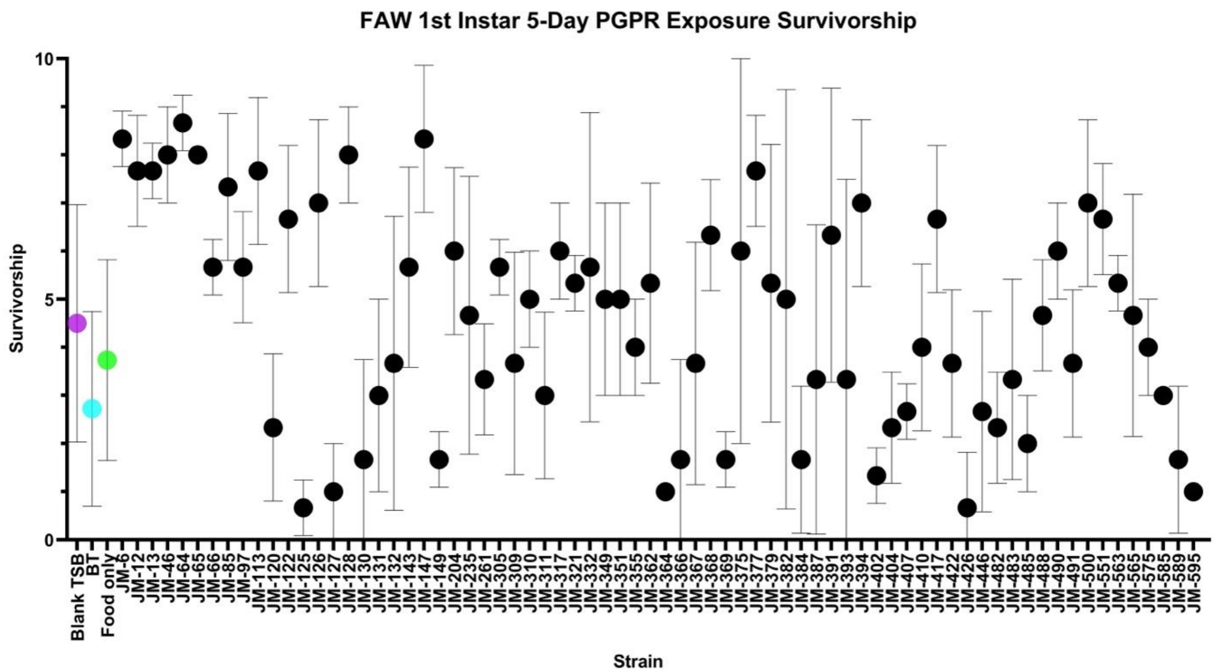

Figure 2. Survivorship of 1st instar FAW. The purple circle is negative TSB control. The blue circle is positive BT control with weak killing. The green circle is artificial diet only. All other circles received unique PGPR strain treatments. Some strains showed killing, but the variation was too great to be statistically significant. Dots are means from 3 replicates with 10 larvae each.

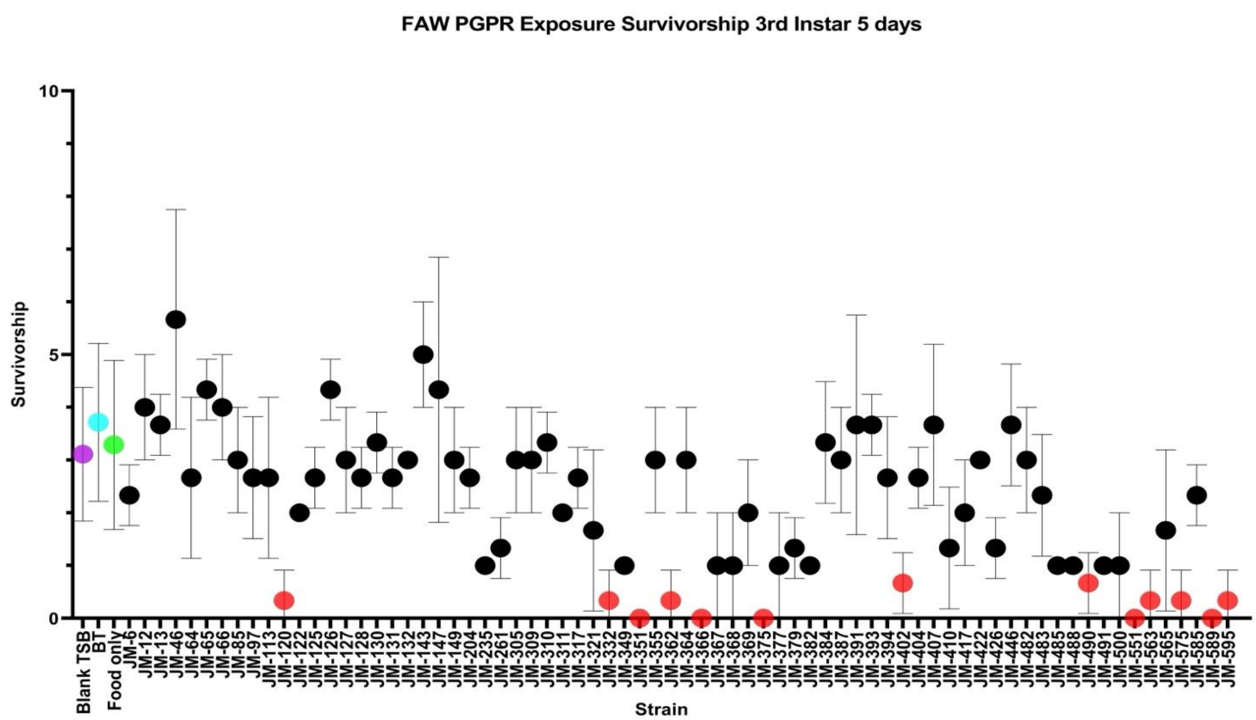

Figure 3. Survivorship of 3rd instar FAW. All circles are color coded as above. Red circles indicate potential killing strains with statistically significant results when compared against the TSB negative control. Dots are means from 3 replicates with 10 larvae each.

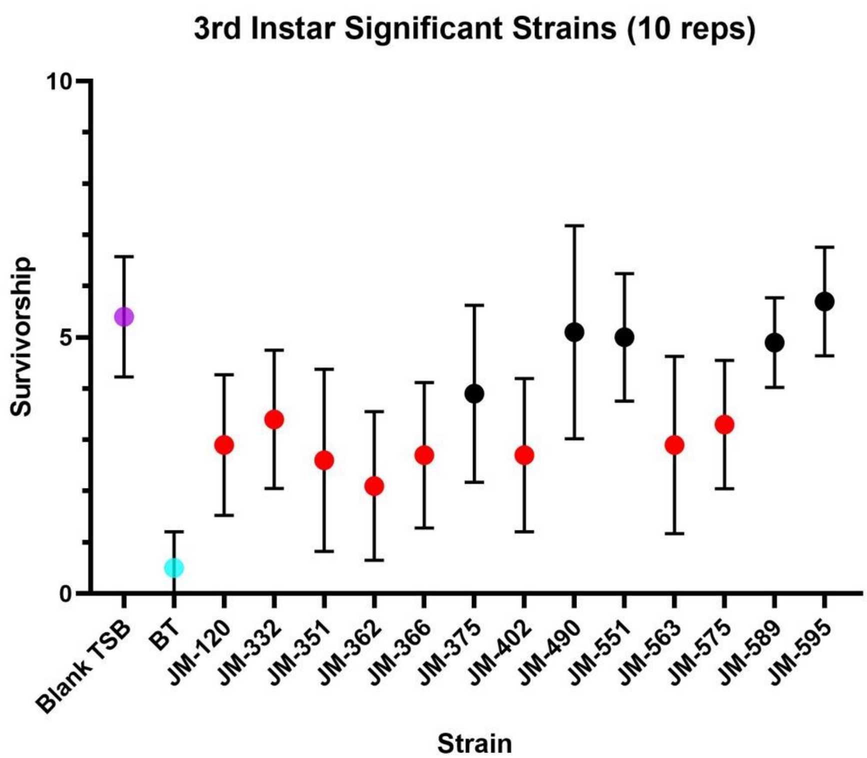

Figure 4. Survivorship 3rd instar FAW (increasing replicates of significant strains). Red circles indicate killing strains with statistically significant results compared against the TSB control with increased replicates. Dots are means from 10 replicates with 10 larvae each. This screen was conducted to rule out false positive strains.

In summary, these results reveal eight PGPR FAW killing strains (JM-120, JM-332, JM-351, JM-362, JM-366, JM-402, JM-563, and JM-575) that can be applied to turfgrass.

Using a backpack sprayer, we treated 0.25m^2 grass plots with the 4 best performing strains (JM-351, JM-362, JM-366, JM-402). We then fed hand-clipped PGPR-treated grass foliage to 3rd instar FAW larvae. **Figure 5** shows the survival analysis of the experiment.

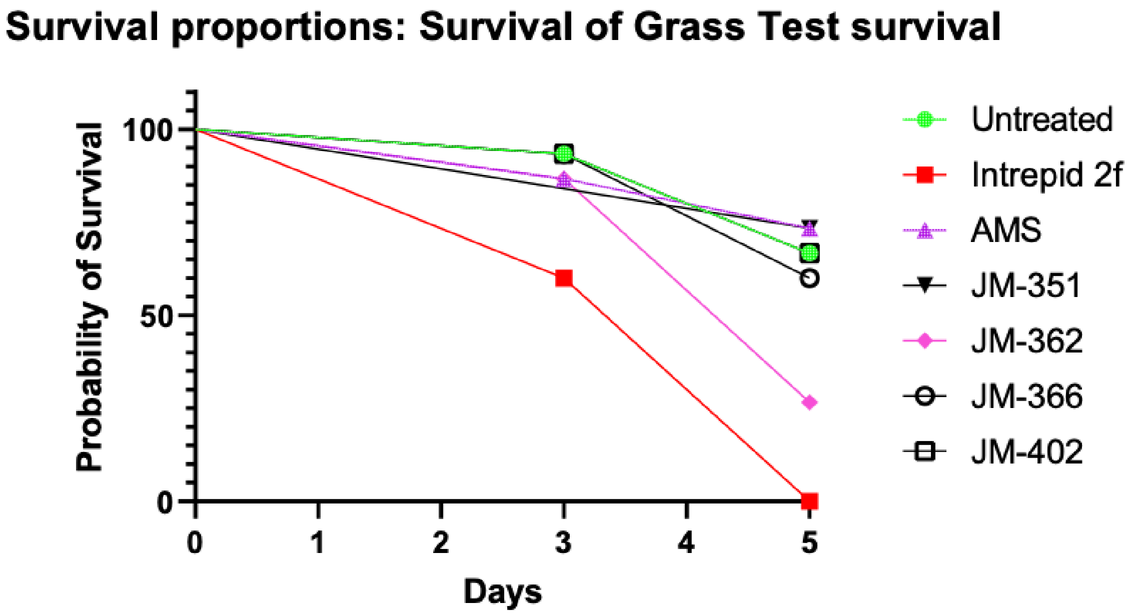

Figure 5. Grass Test Survival Analysis of 3rd Instar FAW. The green line is negative untreated control. The red line is a positive insecticide control. The purple line is a fertilizer treatment. The black lines are PGPR treatments which caused no significant difference in survivorship. The pink line (JM-362) represents the PGPR treatment which caused significantly lower survivorship in comparison to our negative untreated control group and was almost as effective as the insecticide.

Developing a Transferable *cry1F* Expressing, FAW Killing Plasmid: In an alternative redundant approach to manage FAW in turfgrass, we sought to engineer a plasmid carrying a transgene capable of killing FAW. Using restriction enzyme cloning, we have successfully integrated the *cry1F* gene into our shuttle vector **(Figure 6).**

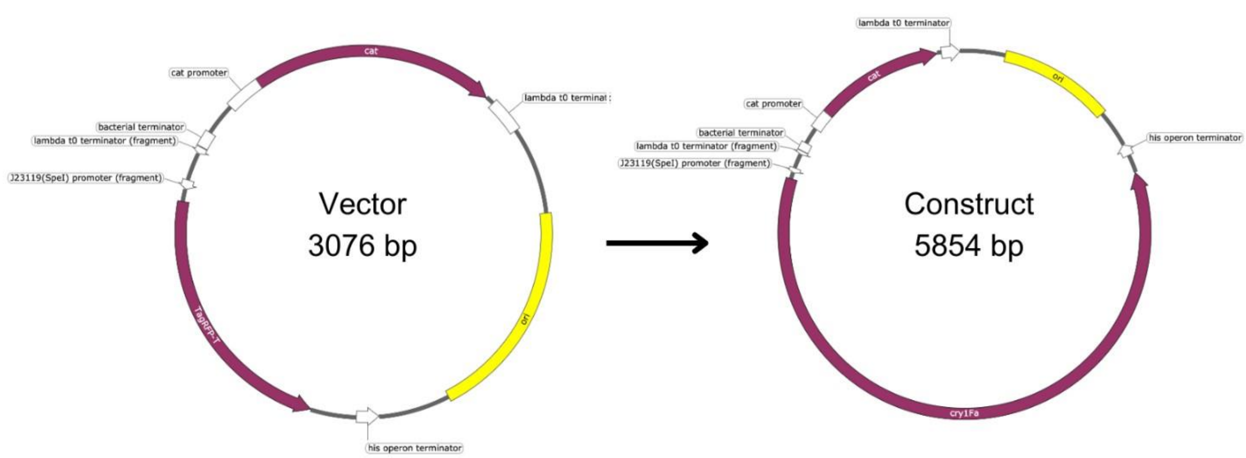

Figure 6. Plasmid map of shuttle vector before and after replacement the of florescent marker gene (*tagRFP-T*) with a Cry gene (*cry1Fa*).

The goal of constructing this plasmid is to transform it into turfgrass colonizing rhizobacterial strains from Blend 20 (AP7, AP18, AP282) which we prior discussed in our previous report from 2022. To date, these strains have yet to be successfully transformed with our new construct. We are working toward developing more efficient transformation protocols involving both biparental and triparental (transmating) conjugation methods.

Future Expectations of the Project:

The single most important discovery is that we are seeing field active PGPR treatment (JM-362) that is comparable to a modern insecticide (Intrepid 2f). These data indicate that we are close to achieving the final goal of the project which was to develop a sprayable or injectable PGPR formulation to control FAW in turfgrass.

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USGA ID#: 2023-13-780

Title: Renovating out-of-play areas to conservation habitat: Effects of seeding time and method on plant establishment and ecosystem services

Project Leader: Douglas S. Richmond and Ryan R. Beard
Affiliation: Purdue University

Objectives: The overarching goal of this research is to understand the economic, aesthetic and ecological outcomes stemming from the establishment of native, prairie vegetation on golf courses. In support of this goal, the objectives of this project are to 1) compare the effects of seeding time and seeding method on establishment of a native prairie plant community (relative abundance, richness, and diversity) and 2) quantify resulting changes in ecosystem services provided by characterizing resulting pollinator communities.

Start Date: 2022
Project Duration: 3 Years
Total Funding: $83,628

Summary Points:

- Neither seeding time, nor seeding method influenced the relative abundance or diversity of native prairie plant species during the first two years of the study.

- Although a relatively low number of plant species from the native prairie seed mixture were detected during 2023, those species comprised between 18 and 29% of the plant community.

- In 2024, native plant species introduced through seeding comprised between 24 and 48% of the plant community, marking progress over a period of two years post-seeding.

- Fall drill seeding resulted in a greater abundance of floral blooms during the fall of 2024.

- Due to its ability to capture more subtle changes in pollinator foraging activity, active sampling revealed greater bee diversity at renovated sites during May of 2024 compared to unrenovated sites, and there was tendency for greater bee diversity in renovated sites during all but one sampling period.

Summary Text

Rational:

Efforts to improve the sustainability of golf courses focus largely on practices that reduce inputs and increase the ecosystem services provided. Among these efforts, conversion of out-of-play areas for conservation purposes has received increased attention (Barden 2016, USGA Green Section 2017, Vohden 2020). The underlying reasons include a combination of economic (Janke et al. 2021), aesthetic (Turo & Gardiner 2019), and ecological (Sexton & Emery 2020) considerations, all of which must be balanced against the unique constraints and goals of golf course staff, their clientele, and the surrounding community. As such, success often hinges on the ability of golf course staff to effectively carry out the conversion process and accurately communicate expected outcomes to stakeholders. At present, there is virtually no road map to guide such efforts or characterize expected outcomes.

Methodology:
Three out-of-play areas on the Kampen-Cosler Golf Course at Purdue University totaling 6.4 acres were "burned-down" using a combination of broadleaf and grassy weed herbicides in early November, 2021. Repeated herbicide applications and mowing continued throughout the 2022 growing season to minimize weed competition during the prairie establishment phase which began in the fall of 2022. At that time, plots within each out-of-play area were established and randomly assigned one of four different seeding treatments: 1) Fall (2022) dormant seeding using a broadcast seeder, 2) Fall (2022) dormant seeding using a seed drill, 3) Spring (2023) seeding using a broadcast seeder, and 4) Spring (2023) seeding using a seed drill. Composition of the seed mixture is detailed in Table 1.

To characterize resulting plant communities, a 1.0 m point intercept frame was placed at six evenly spaced locations along a diagonal sampling transect across each plot. Ten of the sampling pins were engaged at each sampling location for a total of 60 sampling points for each plot. Each plant coming into contact with a pin was identified to species and all flower blooms associated with those plants were counted. Sampling was repeated twice in 2023 (Summer, Fall) and three times in 2024 (Spring, Summer, Fall).

Pollinator abundance and diversity were assessed using a combination of active and passive sampling. Active sampling was performed using a hand-operated, battery powered vacuum suction device. The operator walked a transect across each location for 5 minutes collecting all pollinators within 1 meter of the transect. Collection was performed on clear, calm days over the course of one week during July, August, and September of 2023 and the same procedure was repeated in 2024 during May, July, and September. Sampling was performed in the morning and again during the afternoon of each day. Passive sampling was facilitated using blue vane traps. Three traps were set at canopy height at each location, and the contents of each trap were collected at the end of each day. Passive trapping was performed for one week coinciding with each active sampling period.

Results to Date:
Neither seeding time, nor seeding method appeared to influence establishment of the conservation planting during the first or second year of the study. Although a relatively low number of plant species from the seed mixture was detected during 2023 (Fig. 1), those few species comprised between 18 and 29% of the plant community present at renovated sites (Fig. 2). By the end of the second year (2024), plant species introduced through seeding comprised between 24 and 48% of the plant community present at renovated sites. Black-eyed Susan was the most abundant species representing 16% of renovated communities by the end of 2024 (Figure 3). Fall drill seeding appeared to provide a greater abundance of floral resources for pollinators by the end of 2024 (Figure 4).

A total of 2,087 pollinator specimens (mostly bees) were collected during 2023 and 2024 with the majority (1,512) being passively collected in blue vane traps. In all, 58 different bee species representing 25 different genera have been collected over the course of the first two years of the study (Table 2). The vast majority of these specimens have been curated and identified to species level. Passive sampling indicated that local pollinator abundance and species richness were not measurably influenced by renovation, but active sampling revealed greater bee diversity at renovated sites during May of 2024 and a tendency for renovated sites to yield greater bee diversity during all but one sampling period (Figure 5).

Future Expectations:
The data collected from the previous two years will continue to be analyzed for additional trends that may be helpful to superintendents considering implementation of a renovation program for out of play areas on their course. Bees from the last sampling period (September 2024) are still being identified to species level for further analysis. A prescribed burn will be implemented by Purdue Forestry and Natural Resources students in 2025 to reduce unwanted plants and promote native plant establishment. Prescribed burns are typically beneficial for the development of native prairie communities during the third year after planting. The growth and development of the plant community after the burn will be important to document as part of a longer-term evaluation process.

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Table 1. Composition of the prairie seed mixture planted in conservation areas on the Kampen Cosler golf course at Purdue University and approximate seeding rates for each species.

Scientific Name	Common Name	Seeding rate (g)/ha
Andropogon gerardii	Big bluestem grass	35.03
Asclepias syriaca	Common milkweed	210.16
Asclepias tuberosa	Butterfly weed	210.16
Avena sativa	Oats	28021.26
Bouteloua curtipendula	Side-oats grama	420.32
Carex bicknellii	Copper-shouldered oval sedge	70.05
Coreopsis lanceolata	Sand coreopsis	210.16
Dalea candida	White prairie clover	280.21
Dalea purpurea	Purple prairie clover	490.37
Echinacea pallida	Purple coneflower	280.21
Elymus canadensis	Canada wild rye	1120.85
Juncus tenuis	Path rush	70.05
Koeleria macrantha	June grass	70.05
Monarda fistulosa	Wild bergamot	70.05
Monarda punctata	Horse mint	70.05
Panicum virgatum	Switch grass	35.03
Pycnanthemum tenuifolium	Slender mountain mint	17.51
Rudbeckia hirta	Black-eyed susan	420.32
Schizachyrium scoparium	Little bluestem	2802.13
Silphium laciniatum	Compass plant	35.03
Sorghastrum nutans	Indian grass	35.03
Sporobolus heterolepis	Prairie dropseed	70.05
Symphyotrichum novae-angliae	New-England aster	52.54
Symphyotrichum oolentangiense	Sky-blue aster	17.51
Verbena stricta	Hoary vervain	35.03
Vernonia fasciculata	Common ironweed	70.05
Zizia aurea	Golden alexanders	140.11
Total		35359.32

Table 2. Bee species collected from unrenovated areas and areas renovated to native prairie plant species on the Kampen-Cosler golf course at Purdue University during the first two years of the study.

Genus	Species
Agapostemon	*sericeus*
	texanus
Andrena	*cartini*
	crataegi
	cressonii
	miserabilis
	wilkella
Anthidium	*oblongatum*
Anthophora	*abrupta*
	bomboides
	terminalis
Apis	*mellifera*
Augochlora	*pura*
	aurata
Bombus	*auricomus*
	bimaculatus
	citrinus
	fervidus
	fraternus
	griseocollis
	impatiens
	penyslvanicus
	ternarius
	vagans
Calliopsis	*adreniformis*
Ceratina	*calcarata*
	dupla
	strenua
Chelostoma	*philadelphi*
Colletes	*thoracicus*
Diadasia	*enavata*

Genus	Species
Eucera	*atriventris*
	hamata
	ipomoeae
	pruinosa
	strenua
Florilegus	*condignus*
Halictus	*confusus*
	ligatus
	rubicundus
Heriades	*carinata*
Hoplitis	*pilosifrons*
	truncata
Hylaeus	*affinus*
Lasioglossum	*pilosum*
	tegulare
	imitatum
Megachile	*brevis*
	mendica
Melissodes	*bimaculata*
	comptoides
	denticulata
	desponsa
	trinodis
Osmia	*bucephala*
Ptilothrix	*bombiformis*
Svastra	*obliqua*
Xylocopa	*virginica*

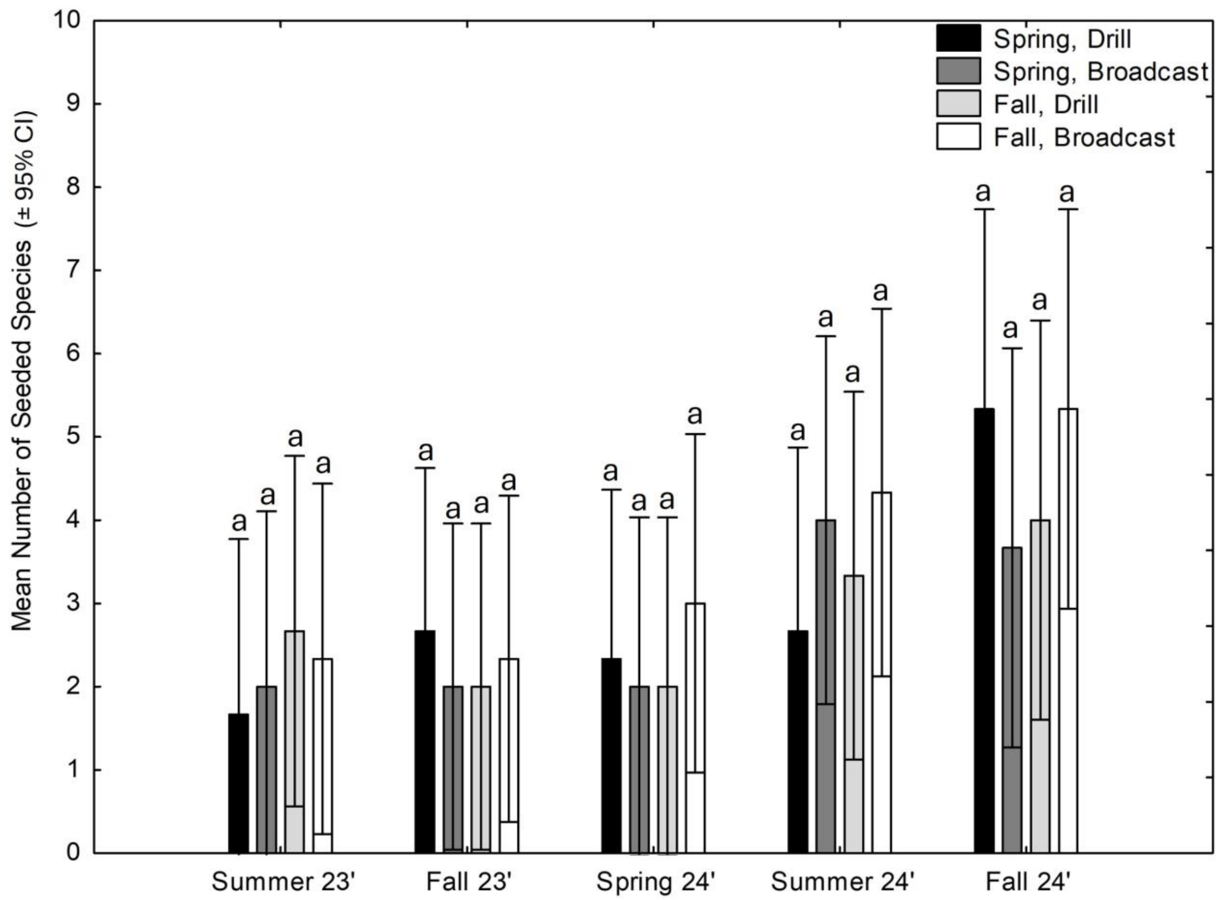


Figure 1. Number seeded species (species richness) detected over time following fall or spring seeding of a low-profile prairie seed mixture using either a seed drill or broadcast seeder.

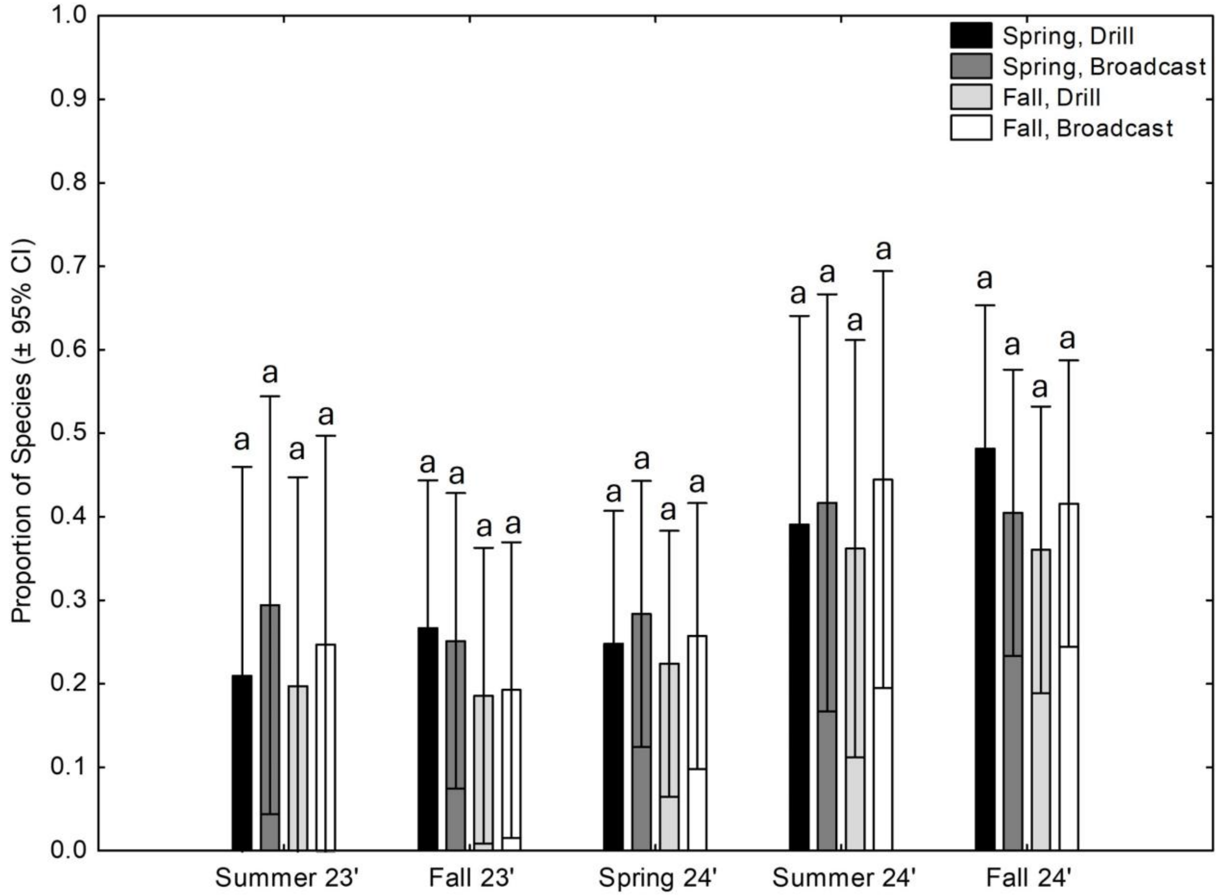


Figure 2. Proportion of the plant community (relative abundance) comprised of seeded species over time following fall or spring seeding of a low-profile prairie seed mixture using either a seed drill or broadcast seeder.

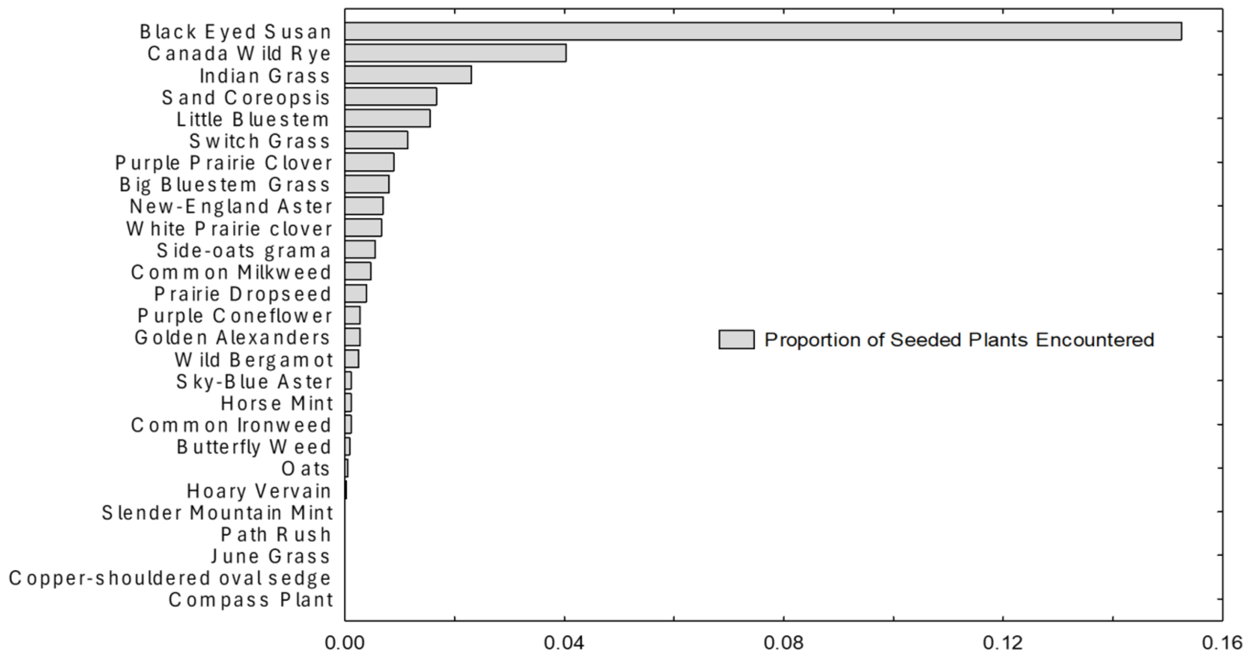


Figure 3. Mean relative abundance of seeded species in renovated areas over a two-year period.

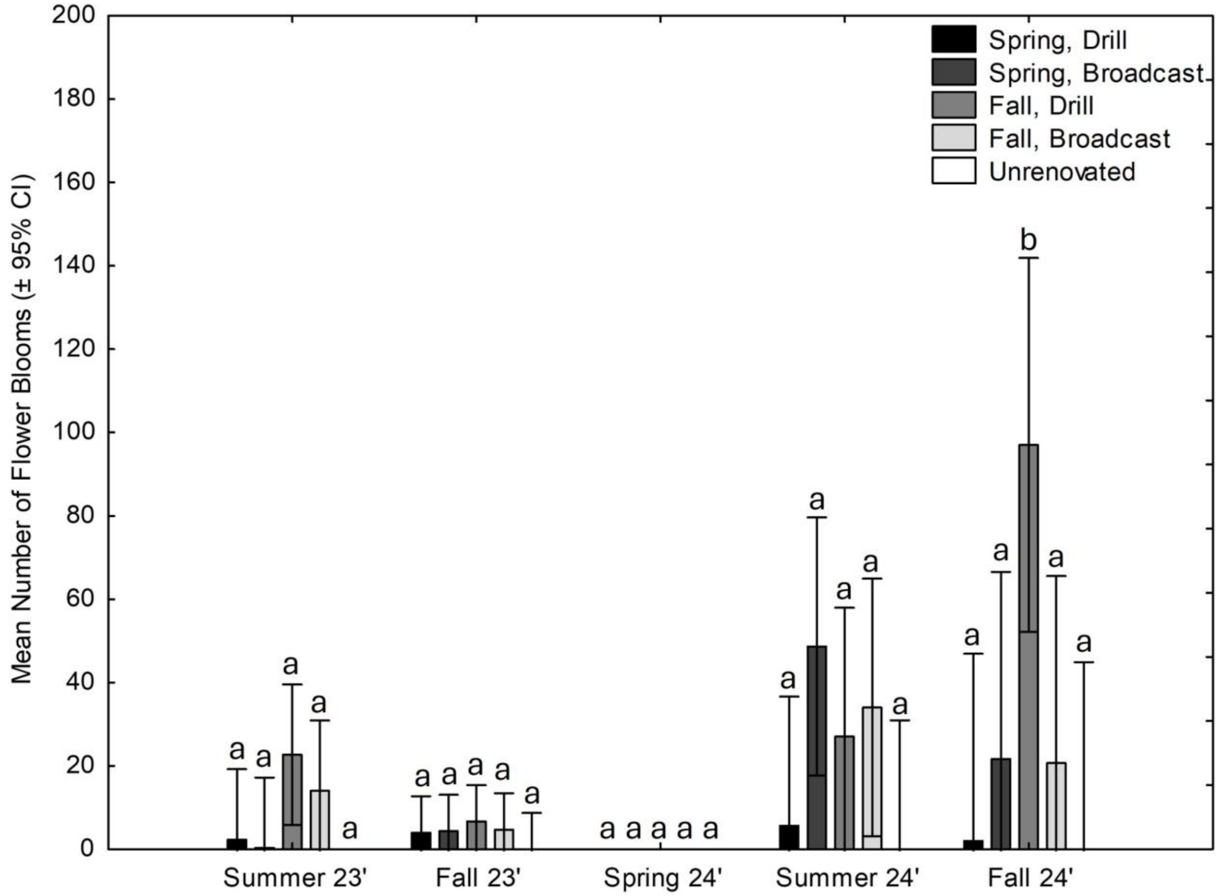


Figure 4. Number of flower blooms/linear meter over time as detected using a pin frame following fall or spring seeding of a low-profile prairie seed mixture using either a seed drill or broadcast spreader.

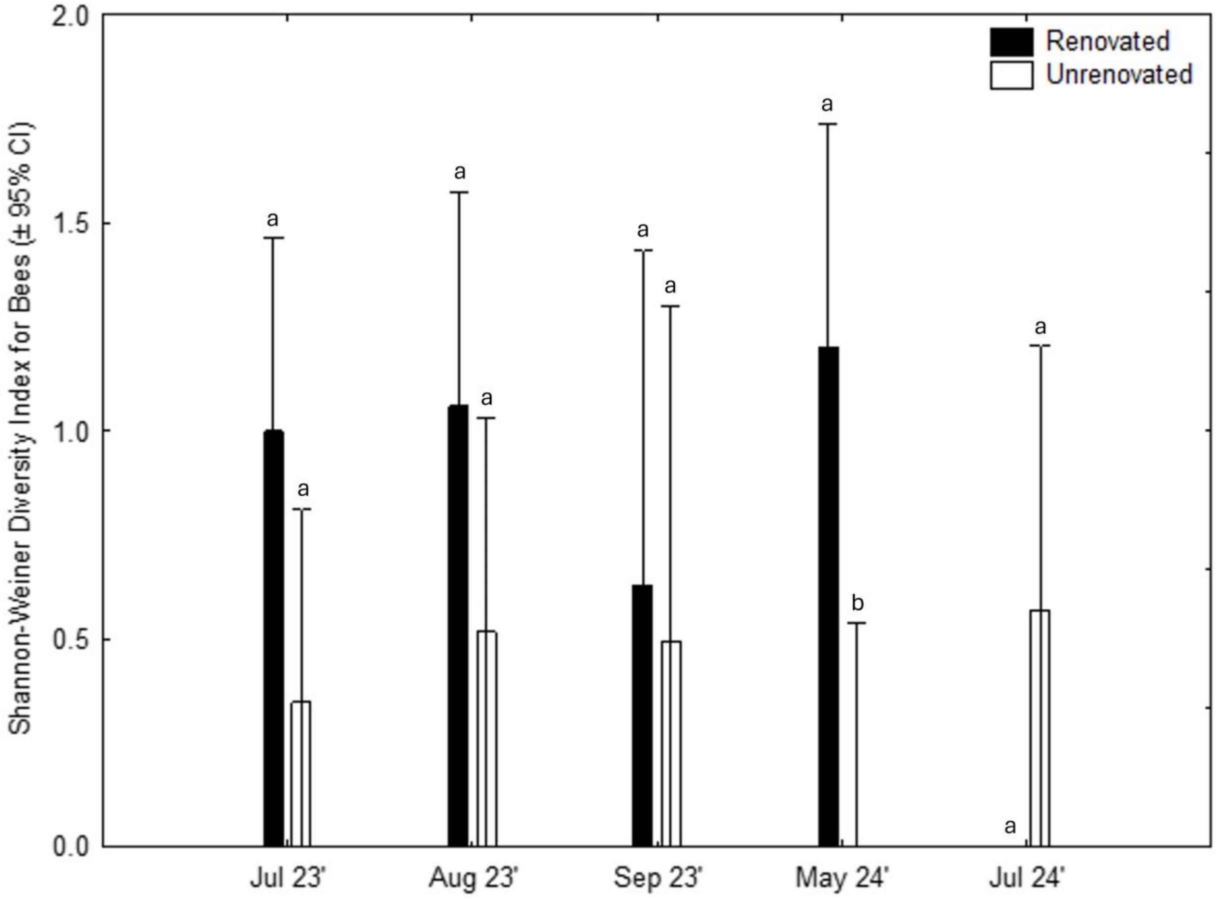


Figure 5. Shannon diversity of bees collected via active sampling in renovated sites compared to unrenovated sites.

USGA ID#: 2023-19-786

Title: Climate Change Vulnerabilities Of U.S. Golf Courses And Potential Adaptation Opportunities

Project Leaders: Laura Hilberg and Lara Hansen

Affiliation: EcoAdapt

Objectives:

Objective 1 (Year 1–2): Complete a review of climate change projections and existing scientific literature (both peer-reviewed and gray literature) to identify the primary climate change impacts that will affect golf courses, including:

- Sea level rise (e.g., inundation of low-lying properties or access to those properties, increased salinity that impacts water quality);
- Warmer temperatures and more heat waves (e.g., changes in suitability for existing turfgrass, increased heat stress for staff/managers and users, and associated changes in patterns of demand);
- Changes in precipitation patterns and flooding/drought (e.g., changes in water availability and quality, impacts to turfgrass); and
- Climate-driven increases in disease, insect pests, weeds, etc.

Objective 2 (Year 1–2): Design and conduct a survey of golf course owners, superintendents, users, and other critical stakeholders to identify existing concerns, including climate impacts already being observed as well as non-climate stressors that might interact with climate change (e.g., water availability/quality issues, invasive plants and introduced pests/disease).

Objective 3 (Year 2): Identify 4–6 golf courses representing a range of geographic regions (e.g., Northeast, Southeast, Gulf, Midwest, Southwest, Northwest) and hold focus groups or interviews to elicit more information about climate change concerns and observations as well as potential adaptation strategies.

Objective 4 (Year 2–3): Compile literature review and survey/stakeholder input into a comprehensive report outlining general vulnerabilities for U.S. golf courses, summarizing the most important concerns, and providing a case study for each region. The report will include information about priority concerns for course superintendents and suggested adaptation strategies.

Objective 5 (Year 3): Create a website with visualizations to provide managers with information about potential climate impacts that could affect their golf courses.

Start Date: 2023

Project Duration: 3 years

Total Funding: $150,000

Summary Points:

- We have identified and reviewed over 350 articles related to climate change vulnerability and adaptation in the golf industry, and have identified the primary climate change impacts likely to affect U.S. golf courses including sea level rise, warmer temperatures and heat waves, changes in precipitation patterns, flooding and drought, and climate-driven increases in pests and disease, among others.
- We conducted an online survey in spring 2024, aimed at understanding how the golf industry is experiencing and preparing for climate change. We received 59 unique responses, and are in the process of analyzing results.
- We are in the process of conducting interviews with stakeholders at golf courses that are being impacted by climate change, which will inform case studies showcasing vulnerability and adaptation at golf courses across the U.S.. To date, we have scheduled two interviews and are in contact with at least four others, representing different parts of the country.

Summary Text:

Rationale

The primary objective of this project is to assist the golf community in the United States in gaining a better understanding of the consequences of climate change on golf and its facilities, identify opportunities to decrease adverse impacts, and improve the golf community's ability to sustain site functionality and the overall experience of the participants.

Methodology

In Year 2 of this project, we have focused on completing a comprehensive literature review of the scientific literature to identify climate change impacts that may affect golf courses in the US, such as rising sea level, increasing temperatures and heatwaves, changes in precipitation patterns leading to flooding and drought, as well as climate-driven increases in disease, pests, and weeds. We used a targeted literature review approach that involved searching for a predefined set of keywords as well as a "snowballing" technique wherein results of the predefined searches identified additional sources or keywords by examining the references in the set of articles collected during the initial literature review. The keywords we defined prior to the beginning of the literature search covered a wide range of topics related to the impacts of climate change on golf courses (e.g., turfgrass and sea level rise, golf course and erosion, turfgrass and hurricane, golf course and water availability, golfers and allergies, golf course maintenance and climate change). We cataloged the search results to capture information about each article we found, including the keywords utilized, publication date, geographic location, and outcomes or recommendations mentioned.

In order to gain insight into how the golf industry is experiencing and preparing for climate change, we also conducted an online survey geared towards golf course owners, superintendents and staff, people involved in supporting industries and associations, and golfers and other recreational course users. The survey was composed of 32 questions, with a mix of multiple-choice and short answer question types designed to elicit personal observations and experiences related to experiences with direct climate changes (e.g., sea level rise, heat waves, flooding) as well as existing issues that might intersect with climate change (e.g., water availability and quality, invasive plants, pests and diseases, pollution). The questions also asked about formal and informal adaptation efforts attempting to reduce those impacts, barriers or challenges that might limit adaptation within the golf industry, and factors that might support greater adoption of adaptation initiatives. The survey was distributed through social media, newsletters, and direct email outreach by USGA and the EcoAdapt team, with an emphasis on reaching out to national audiences that would represent diverse perspectives. Survey responses were collected through Survey Monkey, a web-based survey company, between April and June 2024.

Finally, we have initiated interviews with golf course managers, superintendents, and other relevant stakeholders at several golf courses around the U.S., designed to help us gain deeper insights into current and planned actions to address climate-related challenges. A targeted list of candidate golf courses has been curated based on their involvement in efforts focused on climate adaptation and resilience. Interviews are currently being scheduled with representatives from these courses, and we have developed an interview framework that includes questions related to climate change impacts of concern, adaptation strategies that are of interest or in progress, and barriers that may hinder effective action. These interviews will be used to develop a series of in-depth case studies, which will be featured in the final report where they will serve as a resource to guide future planning and adaptation efforts across the broader golf course community in the U.S.

Results to Date

We have used the information from the literature search process (over 350 articles reviewed) to develop six adaptation strategy summaries and five vulnerability summaries. From the literature search, we identified key topics that emerged in the existing research. Adaptation-related topics so far covered in these summaries include salt-tolerant turfgrass, the impacts of sea-level rise and saltwater intrusion, as well as genetically modified and selectively bred turfgrasses designed to enhance stress tolerance. Research on these topics was synthesized and analyzed to extract relevant information that would be most useful to the golf community. These topic-specific summaries will serve as the foundation for the narrative literature review.

We received 59 unique responses from our online survey, representing 29 U.S. states as well as Canada. Washington was the most frequently reported state (12%), followed by Pennsylvania (9%), Virginia (9%), and Minnesota (7%). The vast majority of survey respondents reported that they play golf recreationally (95%) or professionally (2%). However, most survey respondents did not work in the golf industry (59%); among those who did, the most frequently reported position was golf administrator (8%). Respondents also held positions as golf course superintendents (7%), university scientists (5%), directors of agronomy (3%), course maintenance staff (3%), and industry representatives (3%), among others (Figure 1). We are in the process of analyzing the survey responses to identify trends to better understand how this group of 59 individuals characterizes their climate change concerns and priorities for adaptation. The results of this analysis will be included in the final report.

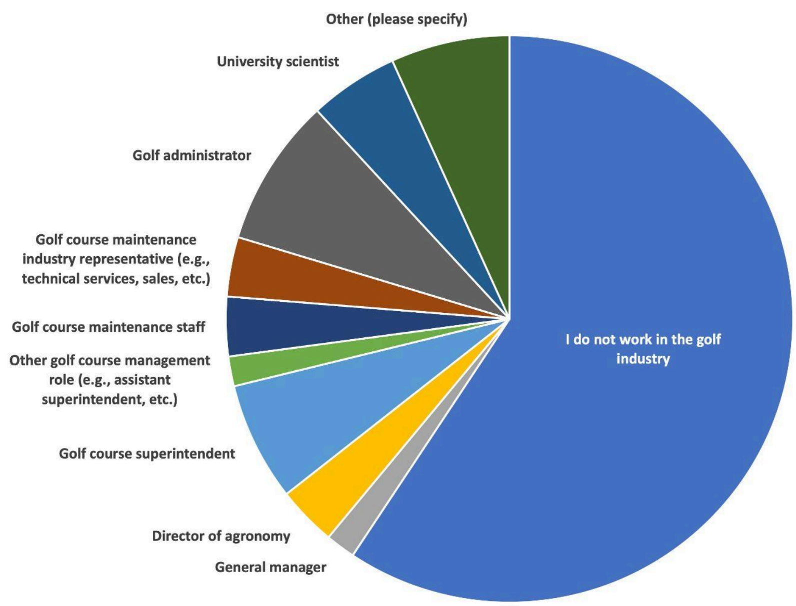


Figure 1. Reported role within the golf industry by survey respondents.

To date, we have contacted six golf courses and country clubs across the United States for interviews. The identified candidates include facilities from the northwest, midwest, southwest, southeast, and northeast regions (Figure 2). The first two interviews are scheduled for late fall 2024, marking an important milestone in our data collection process. As we continue to expand the scope of our outreach, we are actively seeking additional candidates for interviews to further diversify both the geographic representation and the range of climate change impacts experienced across different regions. This broader selection will help ensure that the insights gathered reflect a spectrum of perspectives and experiences from the golf community.

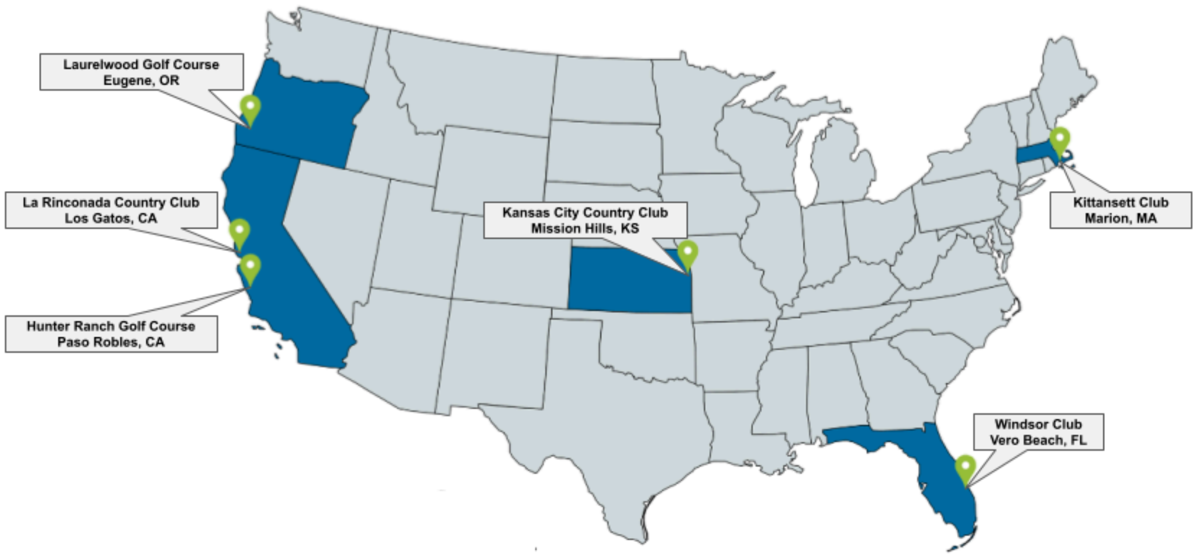


Figure 2. Map showing the golf courses and country clubs contacted for interviews, including the following locations: Windsor Club (Vero Beach, FL), Hunter Ranch Golf Course (Paso Robles, CA), Laurelwood Golf Course (Eugene, OR), Kittansett Club (Marion, MA), La Rinconada Country Club (Los Gatos, CA), and Kansas City Country Club (Mission Hills, KS).

Future Expectations

Over the next several months, we will continue to synthesize the scientific literature we collected during our review and analyze the results of the survey we conducted in the spring, both of which will be used as a basis for the final report. We will also continue conducting interviews, and then use these to develop case studies based on the information collected during these interviews. These case studies will serve a dual purpose: first, they will be integrated into the broader findings of the literature review to provide real-world context and depth to the research; second, they will be featured in a dedicated section of the report. Upon their completion, we will begin compiling all the information we have gathered into a final report and website.

USGA ID#: 2024-11-821

Original Title Submission: Impact of End-of-Season Fungicide Timing on Fungicide Inputs for Dollar Spot Control during the Subsequent Growing Season

Grant-in-Aid Project Title: Quantification of Dollar Spot Utilizing Mowing Clippings and Digital PCR

Principal Investigators: James A. Murphy, PhD; Ming-Yi Chou, PhD; Patrick A. Fardella, PhD

Affiliation: Rutgers, The State University of New Jersey, Department of Plant Biology

Objectives:

- Determine whether mower clippings from symptomatic turf and digital PCR (dPCR) could be used to quantify dollar spot compared to the previous methods of verti-cutting.
- Determine whether mowing clippings analyzed by dPCR could detect and quantify dollar spot in pre-symptomatic turf plots.
- Develop dPCR as a tool to quantify the *Clarireedia* pathogen on field samples of creeping bentgrass

Start date: 2024
Project duration: 1 year
Total funding: $10,000

Summary Points:

- Digital PCR sensitively detected and quantified dollar spot pathogen load in mowing clipping samples, yielding comparable results from verti-cutting and qPCR samples.
- *Clarireedia* quantification assay based on mowing clippings and dPCR effectively detected *Clarireedia* in dollar spot asymptomatic and symptomatic turfgrass from multiple cultivars of creeping bentgrass.
- Further exploration of the assay consistency and reliability on different populations of *Clarireedia* is required to ensure comparable assay results across place and time.

Summary:

Dollar spot, caused by fungi in the genus *Clarireedia*, is a widespread disease of turfgrasses requiring the use of chemical fungicides to maintain levels of control necessary on golf courses. Repeated applications of fungicides represent both an economic and environmental cost, which this research aims to lessen. Developing a consistent and accurate quantification tool for dollar spot disease on pre-symptomatic turfgrass will allow for better understanding of the disease epidemiology and could lead to better management practices. Research conducted by our group at Rutgers University has shown that real-time PCR (qPCR) can be used on both pre- and post-symptomatic creeping bentgrass (*Agrostis stolonifera*) to quantify the amount of dollar spot present. This technique relied on verti-cutting the plots and targeting the ITS region for qPCR.

While this method worked, verti-cutting is not a frequent practice on golf courses due to damage of the turf canopy.

The internal transcribed spacer of rRNA gene (ITS), while highly abundant in fungal genomes, is extremely dynamic and can have inter- and intra-species variation. This variation in copy number could negatively impact the consistency of the quantification over time and space with different locations and different populations of dollar spot potentially having very different amounts of ITS copies. Lastly, qPCR provides a relative amount of DNA in its Ct (cycle threshold) values which require standard curves to compare quantitative values. Also, qPCR is sensitive to PCR inhibitors which can come from environmental samples such as excess proteins, phenolics, etc.

There has been considerable progress in our group's quantification method for dollar spot in creeping bentgrass. First, mowing has been evaluated as a sampling technique; mowing is a routine practice on golf courses and far less damaging than verti-cutting. Other molecular targets within the pathogen's DNA have been in development to discern if they can be used instead of or in tandem with the current ITS target. Digital PCR (dPCR) is also being used to analyze the extracted DNA from the turfgrass samples. Compared to qPCR, the main advantages of dPCR are the detection of smaller amounts of target DNA and the increased efficiency of the reaction in the presence of inhibitors. These two benefits are achieved through the reaction being distributed over a microarray of over 20,000 wells which dilutes out any inhibitors present and the data is fit to a Poisson distribution allowing for the absolute quantification of the target without needing a standard curve.

Results

Molecular Targets

Primers have been designed and validated to amplify the following genes from *Clarireedia* species: heat shock protein (HSP), calmodulin (CAL), beta-tubulin (BT), and MCM7. Positive amplification of HSP is shown in **Figure 1** as an example. These targets are in the process of being sequenced for probe design and dPCR validation.

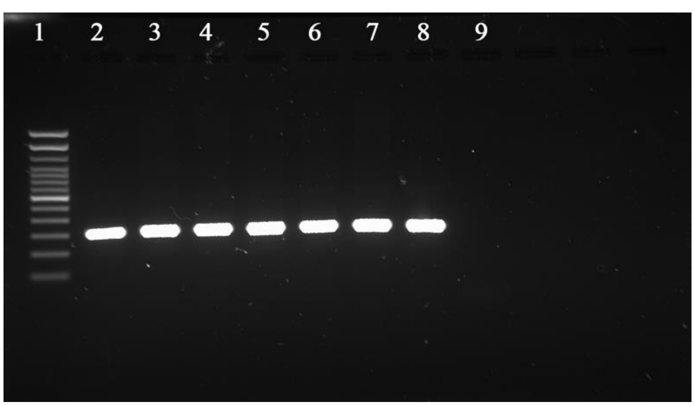


Figure 1. PCR Amplification of Heat Shock Protein from Multiple Species of *Clarireedia*.

Lane 1: DNA Ladder, Lanes 2 and 3: *C. jacksonii* isolates, Lanes 4 and 5: *C. montethiana* isolates, Lanes 6 and 7: *C. bennettii* isolates, Lane 8: *C. homoeocarpa*, Lane 9: Water negative.

2023 Field Trial

This field study was initiated on October 3rd, 2023, and ended on November 16, 2023, on creeping bentgrass cultivar 'Luminary,' which was already symptomatic for dollar spot disease. The objective was to determine whether mower clippings and dPCR could be used for quantification of dollar spot compared to the previous methods of verti-cutting and qPCR. Plots were rated every other week and then either mowed or verti-cut to collect tissue samples. These samples were then flash frozen in liquid nitrogen, ground using a mortar and pestle, and had its DNA extracted using the Qiagen DNeasy PowerSoil PowerLyzer Extraction Kit. 2 µL of DNA were used in both a qPCR and dPCR reaction allowing for a comparison of sampling and quantification methods. **Figure 2** and **Figure 3** show that both qPCR and dPCR can quantify dollar spot from creeping bentgrass samples and that dollar spot can be quantified from both verti-cut and mowed clippings.

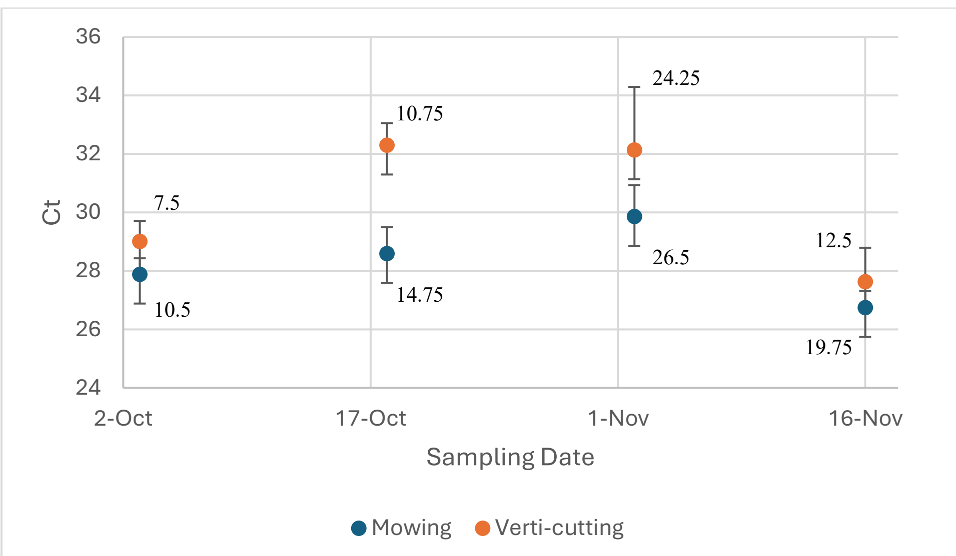


Figure 2. Average Ct Values of Mowed and Verti-cut 'Luminary'. Data points and error bars represent the averages and standard deviations of the four plots from each sampling treatment respectively. The values adjacent to each data point represent the average disease rating (average number of spots in the four plots).

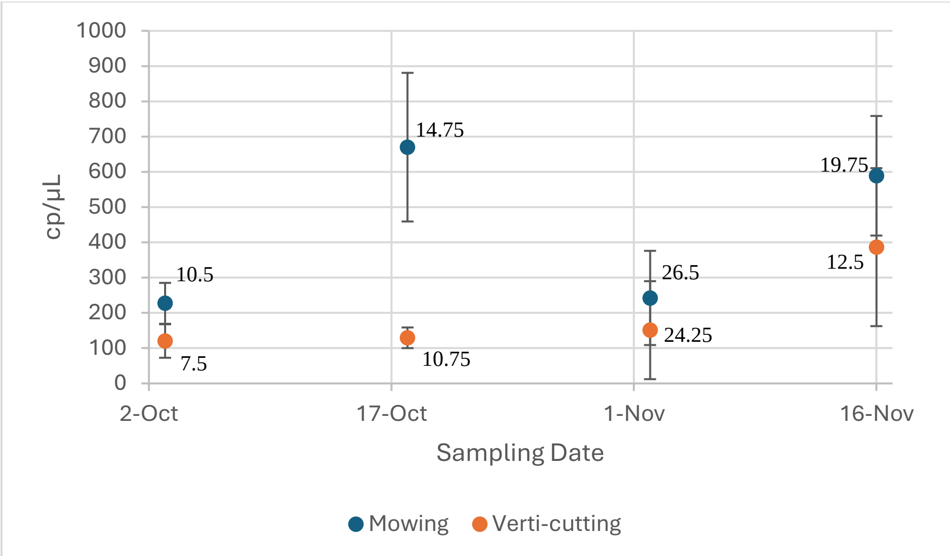


Figure 3. Average cp/µL Values of Mowed and Verti-cut 'Luminary'. Data points and error bars represent the averages and standard deviations of the four plots from each sampling treatment respectively. The values adjacent to each data point represent the average disease rating (average number of spots in the four plots).

2024 Field Trial:

This field trial was initiated on May 7th, 2024, and ended on August 20th, 2024, on creeping bentgrass cultivars 'Luminary,' 'Declaration,' and 'Independence.' The objective was to determine whether mowing clippings collected from pre-symptomatic turf plots and analyzed by dPCR could detect and quantify dollar spot. Sampling of mowing clippings and disease ratings occurred weekly until disease symptoms were observed. Verti-cutting samples were also included for comparison. From the 2023 Field Trial, we learned that bi-weekly verti-cutting of plots resulted in too much damage to the turf making disease rating difficult and recovery of the plots was too slow. To circumvent this, verti-cutting to collect tissue samples occurred every other week and rotated among four plots on 'Luminary' creeping bentgrass. Unfortunately, due to a fire at the research farm (HortFarm 2), the verti-cutter was destroyed, and we were only able to obtain a few verti-cut samplings. For a more accurate disease assessment, disease severity was assessed by estimating the infected area within a plot instead of only recording the number of infection centers as was done in 2023. The samples were analyzed using the same methods as the 2023 Field Trial, except for using 6 µL of DNA in the dPCR analysis instead of 2 µL. The rationale being that a greater amount of DNA would ensure detection of extremely low levels of the pathogen. The following data is from the mowing treatments.

The 2024 season had relatively low disease pressure for both 'Luminary' and 'Declaration' as seen in **Figure 4**. 'Independence', a more susceptible cultivar, developed a high level of dollar spot rapidly compared to the other cultivars so the rating and sampling of Independence was terminated first. Sufficient and sustained disease on 'Luminary' and 'Declaration' did not occur until near the end of the trial; the outbreak occurred on August 6th. Samples at this date and prior were analyzed first with the idea that the increase in pathogen population would be measurable. **Figure 5** and **Figure 6** show the increase of dollar spot over time leading up to the outbreak on August 6th in both 'Luminary' and 'Declaration'. Not only can mowing clippings analyzed with dPCR detect dollar spot pre-symptomatically, but there appears to be a cultivar effect; at similar disease pressure levels 'Luminary' had more quantifiable amounts of the pathogen than 'Declaration'.

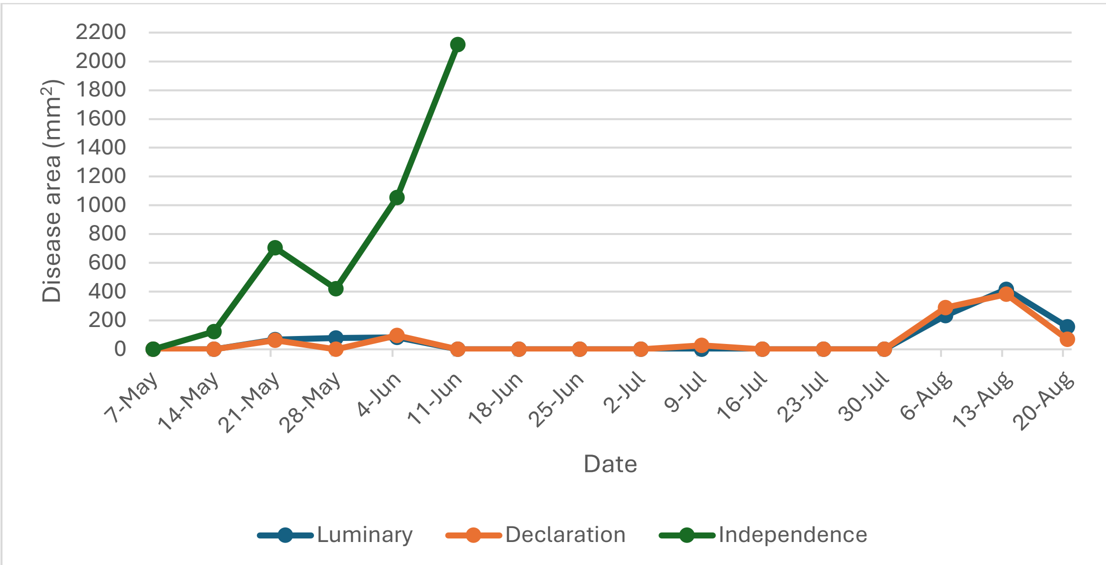


Figure 4. Average Disease Rating of Mowing Plots for Each Cultivar. Each data point represents the average disease area of four plots.

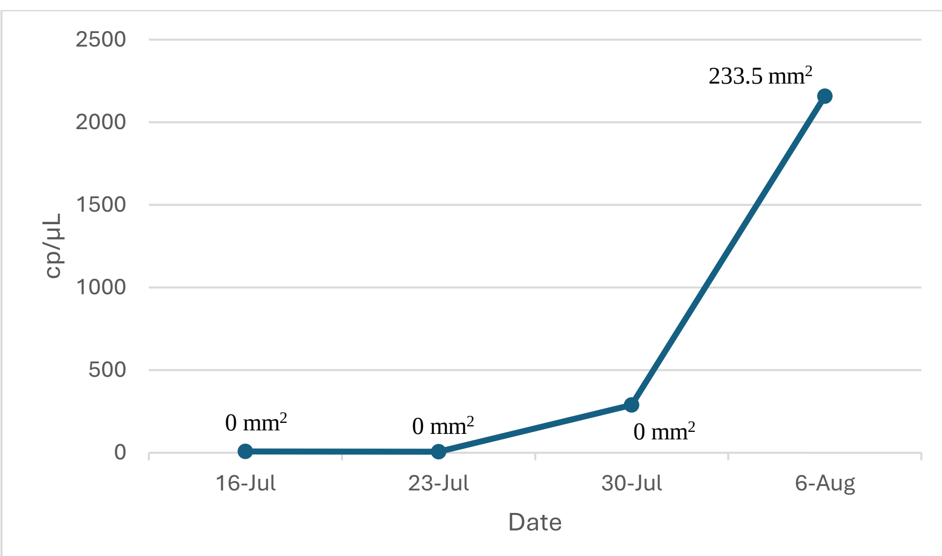


Figure 5. dPCR cp/µL of 'Luminary' Mowed Plots. Average disease areas are indicated in mm^2 with its associated date.

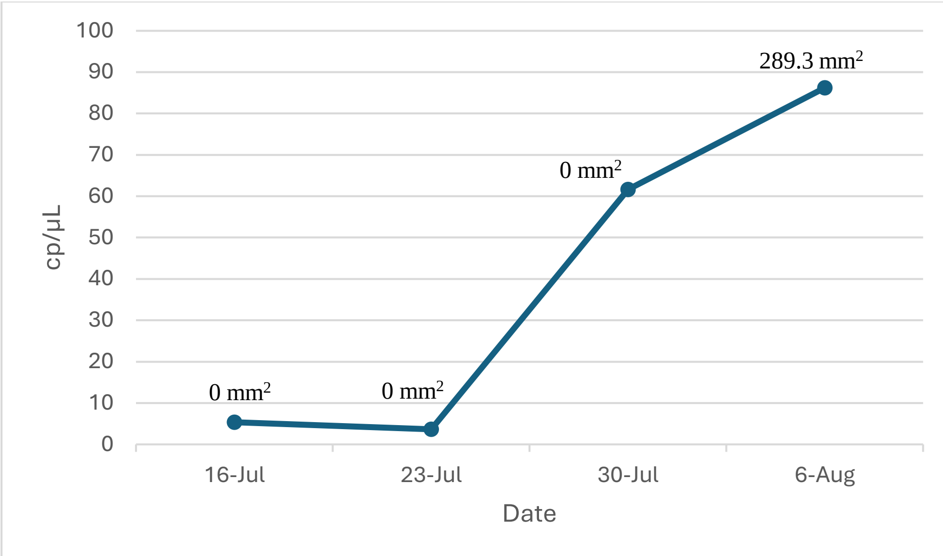


Figure 6. dPCR cp/µL of 'Declaration' Mowed Plots. Average disease areas are indicated in mm^2 with its associated date.

Plan of Work

There are mower clipping samples collected from the three cultivars in 2024 that need to be analyzed on dPCR to determine how far back from the outbreak that the pathogen can be detected. The few verti-cutting samples conducted on 'Luminary' creeping bentgrass will also be analyzed and compared to the corresponding mowing samples from those dates.

Conclusions

These data support the use of both mowing to collect tissue samples and dPCR for quantifying the dollar spot pathogen from creeping bentgrass pre- and post-symptomatic. Further work on more cultivars may provide us additional insights on the differences in disease tolerance among cultivars and the quantity of the pathogen present in leaf tissue before symptom onset.

USGA ID#: 2024-12-822

Title: The Impact Of Nitrogen Rate And Growth Regulators On Modern Creeping Bentgrass Cultivars

Project Leader: E Nangle D Petrella F Sessoms

Affiliation: The Ohio State University

Objectives: The objectives of the project were to evaluate responses of modern creeping cultivars to lower rates of nitrogen in combination with or without different growth regulators.

Objective 1. Evaluate organic matter accumulation across all the cultivars, nitrogen rates and plant growth regulators used.

Objective 2. Determine if lower nitrogen rates may be used by superintendents who are changing greens to new cultivars and understand the impact these practices have on playability of greens surfaces.

Start Date: 2023

Project Duration: 3 years

Total Funding: $10,000 from USGA – rest of trial has been self-funded.

Summary Points:

Cultivars have responded differently to lower rates of nitrogen.

Two cultivars already have displayed significantly higher levels of organic matter accumulation compared to creeping bentgrass cv ‘Penncross’.

Creeping bentgrass cv “Penncross’ has displayed lower quality turf in response to lower nitrogen rates while the new cultivars have provided higher levels of shear strength.

Creeping bentgrass cv ‘Penncross’ did provide higher firmness numbers which seem to align with less turfgrass in the canopy.

Applications of paclobutrazol and prohexadione-calcium led to enhanced shear strength.

Applications of paclobutrazol and prohexadione-calcium led to green speeds 9-12” greater than untreated control.

Oversight

New cultivars of creeping bentgrass have been released with high frequency over the last ten years with many improvements noted for responses to environmental stresses. Many golf courses have been able to renovate or construct new courses since COVID due to a dramatic increase in golfing activity. The changes however are not being matched with data for inputs that turfgrass managers would use on an annual basis. These inputs have a direct effect on the playability of the surfaces as well as their long-term competitiveness – if these cultivars can produce high quality playing surfaces at lower nitrogen rates there is both environmental as well as return on investment implications from this work.

The trial has utilized undergraduate students to give them access to data collection processes while also using equipment they may use in their careers such as stimpmeters, firmness meters and shear strength testing equipment (Image 1)

Image 1. Students have experienced data collection and have learned the practice of data collection.

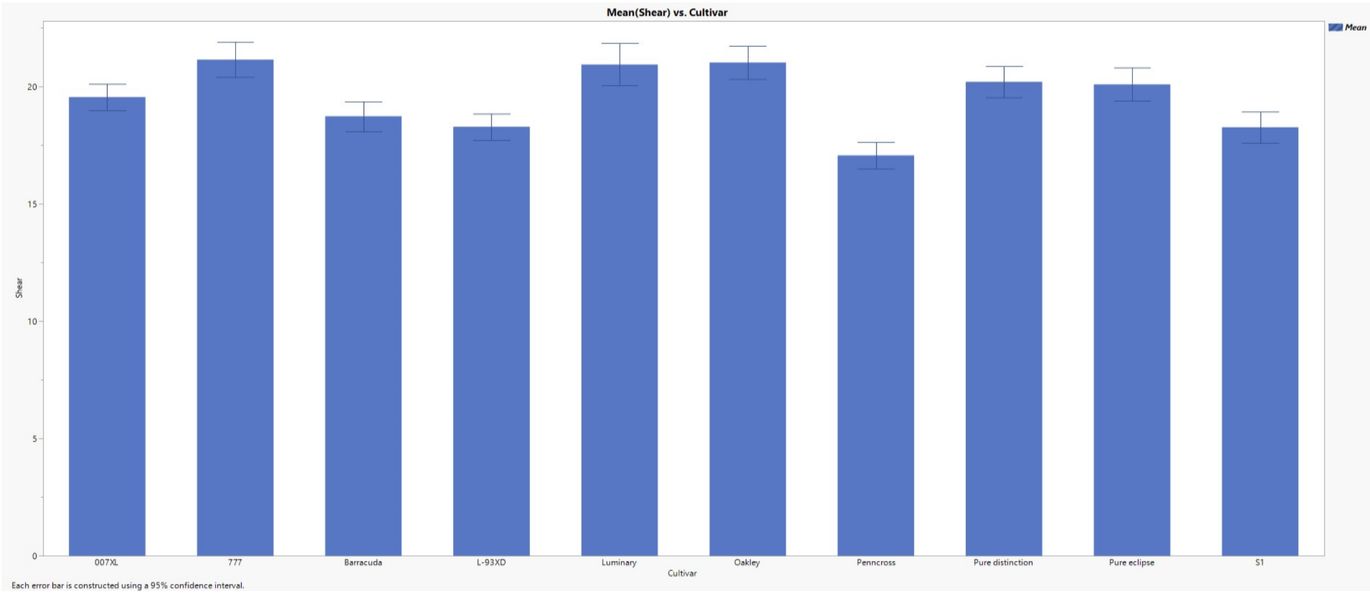
The green was constructed in Autumn of 2022 on a 10-inch rootzone of 80-20 sand - peat with cultivars seeded at that time in a randomized complete block design with four replications. The green is mowed at a height of 0.125” daily with clippings collected and irrigated through overhead irrigation. Urea (46-0-0) was used as the nitrogen source and was applied as a liquid application. Nitrogen rates have been annually ranging from 0 – 24.4 kg/ha N – 48.8 kg/ha N – 61.03 kg/ha N – 97.65 kg/ha N annually and were be applied biweekly at equal rates across all treatments during the growing season . Initial establishment of plots included the use of 48.8 kg/ha P to help with establishment. All plots received fungicides and insecticides in a preventative manner with no use of DMI fungicides occurring due to the use of growth regulators.

Two growth regulators were applied – Anuew (prohexadione calcium) and Trimmit (paclobutrazol) following recommended label rates at 280 growing degree days (GDD) base 0°C.

To date the research has shown that differences in responses to the nitrogen rates are seen across multiple parameters and between the cultivars. 'Penncross' which could still be considered the predominant creeping bentgrass cultivar in use across the United States clearly shows a need for higher rates of nitrogen as its DGCI values, color ratings (Image 2) and shear strength values (Figure 1) indicate significantly lower ratings compared to many of the newer cultivars.

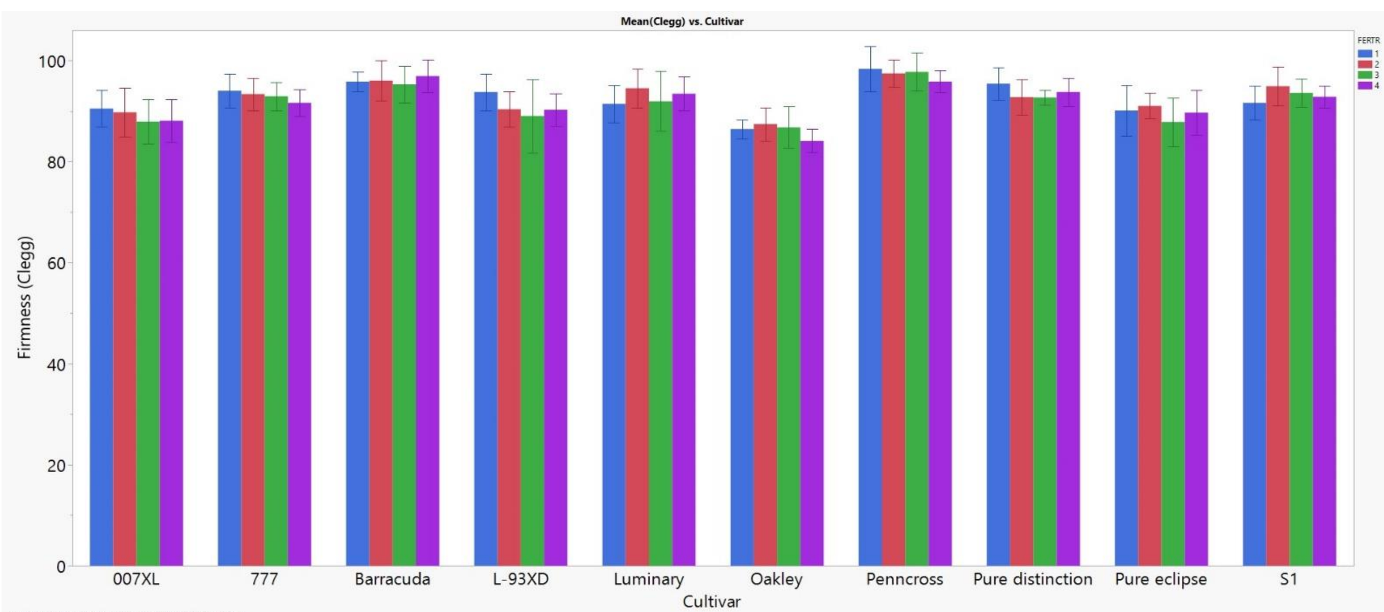
Image 2. Creeping bentgrass cv 'Penncross' clearly showing discoloration in response to lower nitrogen rates in trial evaluation of new creeping bentgrass cultivars.

Figure 1. Shear strength data (Newtons) for cultivars evaluated in trial evaluation of new creeping bentgrass cultivars Wooster OH



Conversely however due to the lack of plant material it has been found that 'Penncross' is providing firmer surface data compared to at least one of the modern cultivars across all nitrogen rates (Figure 2).

Figure 2. Firmness ratings for cultivars at 4 different nitrogen rates in trial evaluating new creeping bentgrass cultivars.



The accumulation of organic matter has shown that differences are occurring between the cultivars with ‘Barracuda’ and ‘Pure Eclipse both providing significantly higher organic matter levels* than ‘Penncross’ within 1.5 yrs of the trial initiation (Figure 3).

Figure 3. Organic matter data for cultivars at different nitrogen rates with and without plant growth regulators in trial evaluating new creeping bentgrass cultivars in Wooster OH.

*Data shows OM at 0.01442 for ‘Barracuda’ – this should read as 1.4% and same for all other cultivars.

Organic matter

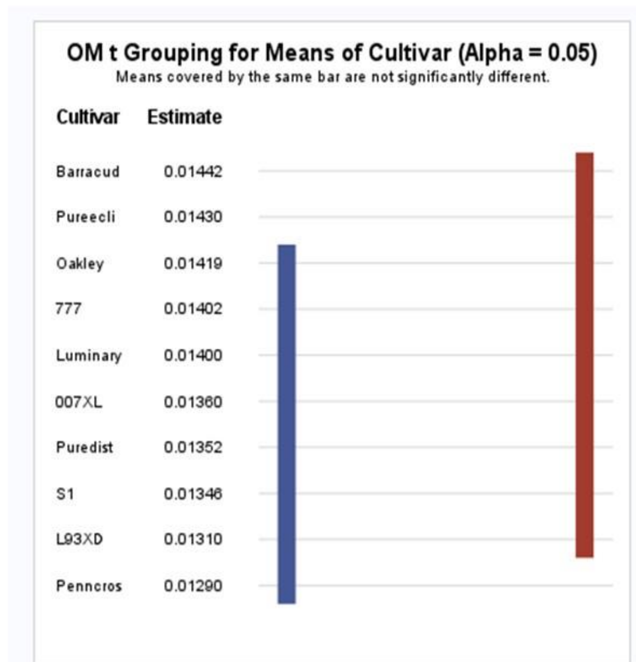
Source	DF	Type III SS	Mean Square	F Value	Pr > F
REP	3	0.00023533	0.00007844	41.52	<.0001
Cultivar	9	0.00011434	0.00001270	6.72	<.0001
REP*Cultivar	27	0.00027685	0.00001025	5.43	<.0001
PGR	2	0.00000024	0.00000012	0.06	0.9388
Cultivar*PGR	18	0.00006863	0.00000381	2.02	0.0093
REP*Cultivar*PGR	60	0.00014018	0.00000234	1.24	0.1321
FERTTR	3	0.00000465	0.00000155	0.82	0.4834
Cultivar*FERTTR	27	0.00003578	0.00000133	0.70	0.8648
FERTTR*PGR	6	0.00000847	0.00000141	0.75	0.6124
Cultivar*FERTTR*PGR	54	0.00008196	0.00000152	0.80	0.8325

Tests of Hypotheses Using the Type III MS for REP*Cultivar as an Error Term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Cultivar	9	0.00011434	0.00001270	1.24	0.3136

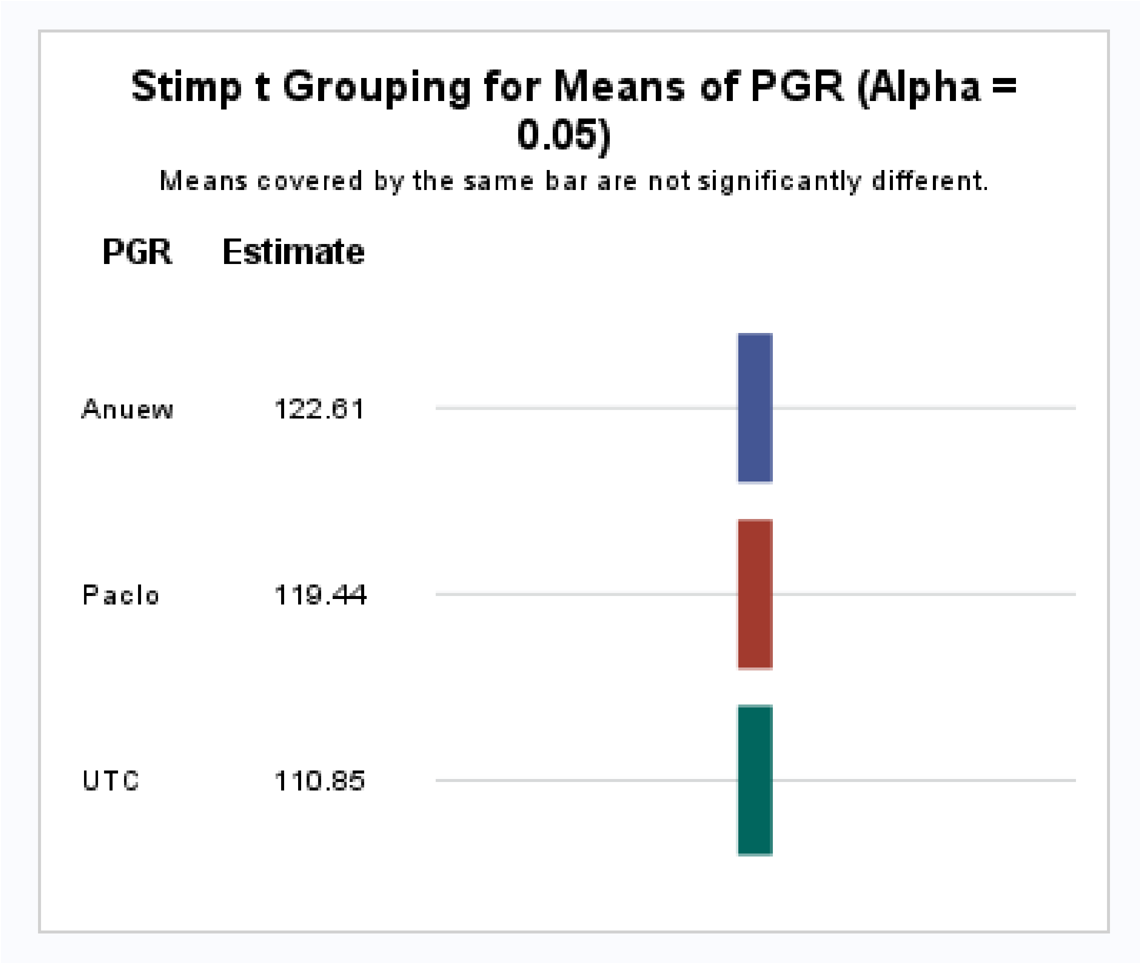
Tests of Hypotheses Using the Type III MS for REP*Cultivar*PGR as an Error Term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PGR	2	0.00000024	0.00000012	0.05	0.9503
Cultivar*PGR	18	0.00006863	0.00000381	1.63	0.0806



Data also shas shown that from a playability perspective there is clear differences between applying growth regulators and not when green speed measurements are considered. The use of Anuew and Paclobutrazol has resulted in green speeds that as between 9 and 12” longer compared to untreated plots and this would certainly be a benefit or turfgrass managers from a playability standpoint (Figure 4).

Figure 4. Average greenspeeds in response to growth regulator applications in trial evaluating new creeping bentgrass cultivars in Wooster OH.



The outlook for the project is to complete further playability data collecting in spring and fall of 2025 with completion of two further rounds of organic matter analysis. The current belief is that there will be further separation between the cultivars regarding organic matter accumulation. Playability variation may also continue to display however this is less Further to this – segregation in some of the cultivars has occurred in response to applications of paclobutrazol in particular and this warrants further investigation. The clear difference between 'Penncross' and the new cultivars is somewhat concerning however as superintendents who transition from older greens as part of high value renovations may need further guidance on where to initiate nitrogen rates on new cultivars so as not to run into quality issues and lose return on investment of the new greens while also providing a more sustainable surface with reduced inputs.

USGA ID#: 2023-38-805

Title: Integrating Phosphorus and pH Management with A Plant Growth Regulator for Annual Bluegrass Suppression

Project Leader: Matthew T. Elmore and James A. Murphy
Affiliation: Rutgers University

Objectives: The original proposed objective was to evaluate a combination of cultural (phosphorus and pH) and chemical management (paclobutrazol) for annual bluegrass suppression in bentgrass putting greens (Project 1). Our hypothesis is that a strongly acidic rootzone (pH ~5.5) combined with relatively low rootzone phosphorus (6 to 10 ppm) will promote creeping bentgrass encroachment into annual bluegrass. This objective has since been expanded with an additional field trial to study annual bluegrass and creeping bentgrass putting green population dynamics using a five-level pH gradient and ‘Penncross’ vs. ‘Oakley’ creeping bentgrass (Project 2). The primary objective for 2024 was to adjust the phosphorus and pH levels in the annual bluegrass putting green before creeping bentgrass is introduced and its encroachment measured in 2025.

Start Date: 2024
Project Duration: One year
Total Funding: $5,000

Summary Points:

- The mat layer pH has been adjusted from 6.0 to 6.3 to a mean of 5.3 in acidic plots and 6.3 in neutral pH plots (as of Nov 2024). The acidic treatments are exhibiting poorer turfgrass quality in summer.
- A mat layer pH gradient ranging from 4.8 to 7.0 has been established for Project 2. Large differences in turfgrass quality across the pH gradient are evident.
- The phosphorus depletion target for Project 1 has not been achieved despite phosphorus not being applied in over 2 years. Mat layer P averaged 47 ppm (Mehlich III) across the site in November 2024, an increase from 38 ppm in May 2024.
- ‘Penncross’ and ‘Oakley’ bentgrasses were established in 2024 for transplant in 2025.
- This project will continue from 2025 to 2027 as USGA ID# 2025-01-832.

Summary Text:
Methods

Site management: The site was managed as described in the proposal. Irrigation was monitored daily during the summer, typically with overhead irrigation to 60% of ET and hand-watering where needed to maintain VWC at 20 to 25%. The site for both projects was core-cultivated on 17 September 2024 using 1.3 cm-diameter tines on a 5 x 5 cm spacing. The site for Project 1 was core cultivated again on 17 October 2024 using 1.6 cm-diameter tines on a 5 x 7.5 cm spacing to accelerate phosphorus removal.

Amendments: Lime (3700 kg ha^{-1}) was applied to the neutral pH plots on 13 June and 8 November 2024 and gypsum (925 kg ha^{-1}) was applied to the acidic pH plots on 13 June, 7 August, and 8 November 2024 for Project 1. Lime was applied at 80, 230, 700, 2090, and 6280 kg ha^{-1} on 8 November 2024 for Project 2. Gypsum was applied to both gypsum treatments at 925 kg ha^{-1} on 29 August and 8 November 2024 for Project 2.

Data collection

Mat layer sampling occurred just prior to amendment applications in May and November 2024 following Xu's (2023) methods. Six samples per plot were collected with a 1.9 cm diameter probe from each plot, forming one composite sample sent to the Rutgers Soil Testing Lab for pH and nutrient (Mehlich III extractant) analysis. Turfgrass quality was evaluated visually on a 1 (poor) to 9 (excellent) scale. Factors that produce a high-quality playing surface, e.g., turfgrass density, texture, surface uniformity, and smoothness, more so than color, were considered in the quality ranking. Data were analyzed using the Glimmix procedure in SAS (v 9.4).

<u>Results</u>

Project 1: The effect of pH treatment on mat layer pH was highly significant ($P < 0.001$) on both sampling dates (Table 1). This indicates that exclusively using ammonium sulfate as the N source is having the intended effect of acidifying the mat layer pH and amending the neutral pH plots with lime is also having the intended effect. The pH differences were concomitant with lower turfgrass quality ($P < 0.001$) in the acidic plots (6.2) compared to neutral plots (7.3) when evaluated on 15 September. The site was monitored daily during the summer, and thus we can be fairly certain that differences in turfgrass quality are not attributed to any acute stressor (e.g., drought stress, anthracnose), but rather cumulative effects of poor vigor and summer stress in plots with low mat layer pH. The pH treatment has a significant effect on mat layer calcium (Mehlich III), likely due to high water solubility of gypsum, which limited calcium retention compared to lime (Table 1). While statistically significant, these calcium differences were expected and are probably not agronomically meaningful since calcium levels were within the moderate range of 375 to 750 ppm. There were no differences in phosphorus among plots on either sampling date ($P > 0.2$), which is expected as no phosphorus was applied. However, it is concerning that mean mat layer phosphorus across all the plots increased from 38 ppm to 47 ppm from May to November 2024. This is concerning since no phosphorus has been applied to the site since May 2023. We are investigating potential sources of phosphorus addition to the system. One explanation is that small aggregates from the native sandy loam underlying the mat layer were dislodged from soil cores brought to the turf surface during core cultivations. The sandy loam has a relatively high P content. Thus, small aggregates of the sandy loam dislodged from cultivation cores and re-integrated into the turf surface could explain the increase from 38 to 47

ppm. Note that the 38 to 47 ppm of P measured in the mat layer is within the medium (27-54 ppm) range of sufficiency (Carrow et al., 2001).

Project 2: Methods and site description for this project were not in the original proposal but are provided in the proposal for USGA ID# 2025-01-832. Mat layer sampling from both May and November 2024 indicates a range of mat layer pH sufficient for the bentgrass to be introduced in 2025 (Table 2). There was also a substantial effect of pH on turfgrass quality. The effect of pH on turfgrass quality was most apparent at the September rating. The site was monitored daily during the summer, thus we can be fairly certain that differences in turfgrass quality are not attributed to any acute stressor (e.g., drought stress, anthracnose), but rather cumulative effects of poor vigor and summer stress in plots with low mat layer pH.

Plans for 2025: The pH differences for Project 1 and pH gradient for Project 2 are established sufficiently to allow for bentgrass transplanting into the annual bluegrass putting green in spring 2025. The PGR regimen for Project 1 will also begin in spring 2025. We will assess the lack of phosphorus depletion in Project 1 and determine how to proceed with that factor before spring 2025.

Table 1. Mat layer pH and calcium as affected by pH treatment for Project 1. Means (n=16) are pooled across phosphorus and PGR treatment since those treatments will be initiated in 2025. Note, 375 to 750 ppm of Ca is considered a moderate level for the Mehlich III extractant.

	May 2024		November 2024	
pH Treatment	pH	Calcium (ppm)	pH	Calcium (ppm)
Acidic	5.7	426	5.3	624
Neutral	6.2	487	6.3	772
P-value	< 0.001	< 0.001	< 0.001	<0.001

Table 2. Mat layer pH and turfgrass quality as affected by amendments for Project 2. Turfgrass quality values >7 are shaded in green and those <6 are shaded in red.

	pH		Turfgrass quality (1 to 9)			
pH Treatment	June	November	June	July	Sep	Nov
Non-treated	5.2	4.9	6.0	5.8	5.1	5.8
Lime (80 kg ha^{-1})	5.3	5.2	6.3	6.0	5.3	5.5
Lime (230 kg ha^{-1})	5.5	5.3	7.0	6.8	5.9	6.5
Lime (700 kg ha^{-1})	6.3	5.9	7.8	7.7	7.9	7.4
Lime (2090 kg ha^{-1})	7.1	6.7	7.1	7.5	7.9	7.1
Lime (6280 kg ha^{-1})	7.3	7.0	6.7	7.7	7.6	7.1
Sulfur	5.1	5.1	5.5	5.9	5.1	6.0
Sulfur	4.8	5.1	4.8	4.3	4.2	6.3
Gypsum	5.1	4.6	5.0	5.3	5.4	6.1
Gypsum	5.2	5.1	5.4	5.5	5.6	6.8

$LSD_{0.05}$	*0.18*	*0.4*	*0.9*	0.9	0.76	0.82
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Reference

Carrow, R. N., Waddington, D. V., and Rieke, P. E. 2001. Turfgrass soil fertility and chemical problems: assessment and management. Ann Arbor Press, Chelsea, MI. p. 400.

Figure 1. Visible differences in turfgrass color on 4 September 2024 for Project 2. Select plots are labeled with the mat layer pH according to June 2024 sampling.

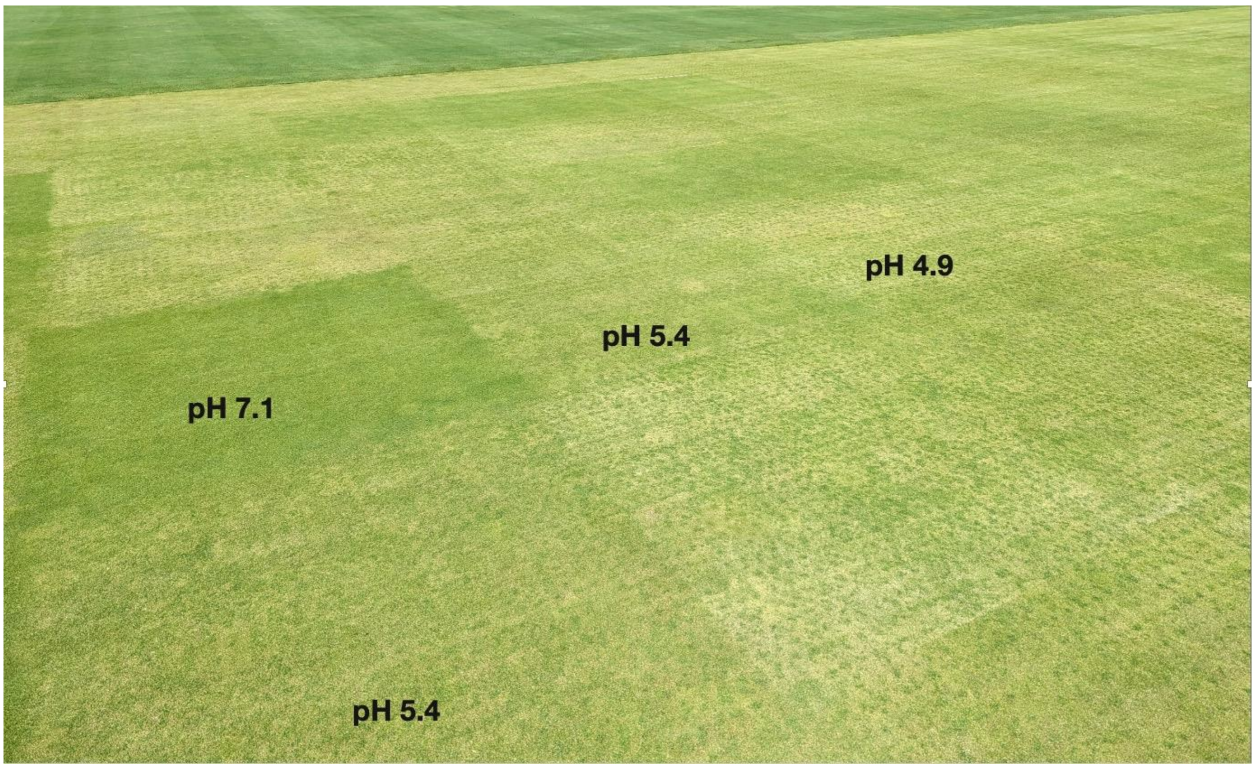


Figure 2. Amendments being applied for Project 2 on 8 November 2024.

USGA ID#: 2024-10-820

Title: Understanding the physiology of *Poa annua* death under ice cover in the field

Project Leaders: Eric Watkins, Adrian Hegeman, Katrina Freund Saxhaug, and Andrew Hollman
Affiliation: University of Minnesota

Objectives: This preliminary investigation has two primary aims:

1. Assess variability of individual experimental units
2. Optimize volatile gas collection

Start Date: January 2024
Project Duration: 18 months
Total Funding: $10,000

Summary Points:

- *Poa annua* is susceptible to complete death under extended ice encasement
- The mechanism by which turfgrass die under ice encasement is not well defined
- A new gas volatile collection system is being paired with real-time carbon dioxide and oxygen monitoring systems to improve our understanding of turfgrass death under ice

Summary Text

Poa annua on golf surfaces is susceptible to several biotic and abiotic stresses; of particular concern is its poor survival under extended ice cover, a condition that is likely to become more prevalent in some regions due to warming winters. Golf course superintendents currently have few options to prepare for or mitigate this problem. The turfgrass science team at the University of Minnesota and collaborators at several institutions are currently determining the physiological processes that lead to *Poa annua* death in this long-term ice encasement situation. This work is being done in the lab, and there are currently no efforts to determine how these grasses are dying in the field. We aim to encase a *Poa annua* (cultivar ‘Two Putt’) in ice for up to 120 days and sample the plant growing environment for gasses produced in the anoxic environment while assessing grass survival throughout the encasement period. To investigate the production of gasses produced in soil under ice encasement that may contribute to *Poa annua* death (e.g. volatile organic compounds or volatile sulfur compounds), a sampling apparatus (Figures 1 and 2) was assembled in the field that enables gas samples to be taken at a regular expanding time course. The apparatus consists of a sealed tube with a midsection that is gas permeable so that the interior of the tube will accumulate gas phase components. For volatile collection, the tube will be flushed into a trap and analyzed by gas chromatography-mass spectrometry (GC-MS) for likely volatile organic and sulfur compounds. When installed in the ground and the ice is fully formed, the apparatus is sealed at both ends, thereby excluding oxygen from above the ice-encased *Poa annua*. This allows for the accumulation of gaseous chemicals that are trapped under the ice to be accessed from the outside for gas sampling without introducing oxygen to the system.

In late fall 2023, we constructed 1.15-meter diameter aluminum frames and installed them into the turf—these frames allowed the buildup of ice over individual experimental units (Figure 3). We also installed carbon dioxide and oxygen sensors just under the soil surface, along with soil temperature sensors. Beginning in early January 2024, ice was formed on these experimental units, with the hope that duration would continue for several weeks allowing for gas sampling. Unfortunately, a very warm winter prevented ice formation beyond one week and we were not able to test the efficacy of our system. Importantly, we were able to successfully design and install the volatile collection units.

For the upcoming 2024-2025 winter, we designed a replicated experiment to learn more about our proposed system. Treatments include:

1. Volatile gas collection system + carbon dioxide and oxygen sensors from WinterTurf environmental sensing nodes + no ice encasement (control)
2. Volatile gas collection system + carbon dioxide and oxygen sensors from WinterTurf environmental sensing nodes + ice encasement of up to 100 days

Each treatment is replicated three times at the Turfgrass Research, Outreach, and Education Center on the University of Minnesota St. Paul campus. During the winter, volatiles will be collected from the sampling devices approximately bi-weekly during the ice encasement period. Using a diaphragm pump, gases from underneath the ice will be pumped out into an above ground gas collector containing adsorbent material (e.g. polydimethylsiloxane (PDMS), which has been utilized successfully in the Hegeman laboratory for capturing VOCs). The adsorbent material samples will be brought back into the lab for analysis using GC-MS. When paired with this laboratory work, results from our proposed field work will be an important step in understanding how superintendents can reduce winter risk to their *Poa annua* greens.

Figure 1. The gas collecting device consists of sintered PTFE (teflon) tubing (will allow gases but not water to diffuse in), copper or steel tubing connected to the PTFE coming out of the ground above the ice level (steel and copper chosen for their compatibility with GC analyses), a pump to flush the collected gases out, and some sort of adsorbent material for collecting the gases (like solid phase microextraction disks or fibers that gases will "stick" to).

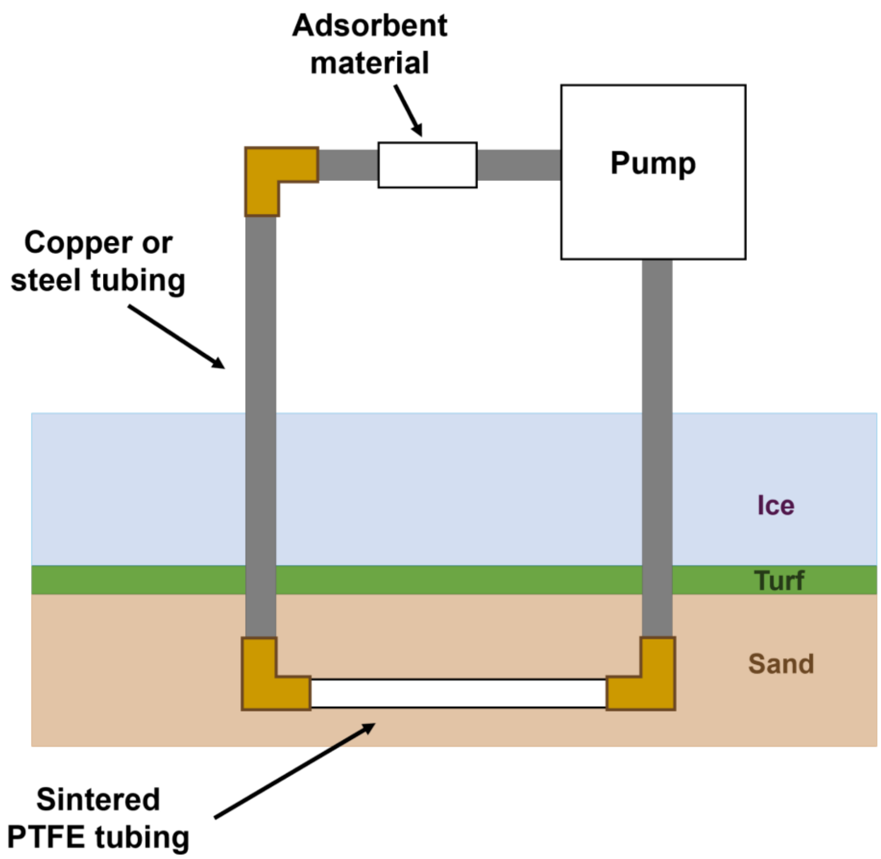

Adsorbent material
Pump
Copper or steel tubing
Ice
Turf
Sand
Sintered PTFE tubing

Figure 2. Close-up of the gas sampling device as installed in a stand of 'Two Putt' annual bluegrass in November 2023.

Figure 3. Aluminum barriers surround individual ice encased experiment units during January 2024. Due to warm winter temperatures, ice encasement did not last long enough to collect data.

USGA ID#: 2024-14-824

Title: Can Fraise Mowing Reverse Resistance For Golf Course Superintendents?

Project Leader: James T. Brosnan, Ph.D. and Gregory K. Breeden
Affiliation: University of Tennessee, Knoxville

Objective: Determine if summer fraise mowing of hybrid bermudagrass (*C. dactylon* x *C. transvaalensis*) fairways would allow golf course superintendents to regain effective use of common herbicides like prodiamine (e.g., Barricade) or foramsulfuron (e.g., Revolver) that has been lost due to the evolution of resistance

Start Date: June 18, 2024
Project Duration: One Year
Total Funding: $10,000

Summary Points:

- Research was conducted at a public golf course in Burns, TN with a known infestation of *Poa annua* that is resistant to multiple mode-of-action groups.

- The 18th fairway at this course was fraise mowed to a 0.5" depth on June 18th, 2024. The total area fraise-mowed measured 3,500 ft^2. An accompanying area adjacent to this location served as a non-fraise mowed check.

- A cohort of herbicides with efficacy for *Poa annua* control will be applied within each area throughout autumn, winter, and spring. Efficacy of these treatments will be assessed in April 2025 to determine the effects of summer fraise-mowing on control of herbicide-resistant *Poa annua* with herbicides of varying modes-of-action.

Summary

Fraise mowing can be used to effectively reduce *Poa annua* populations on hybrid bermudagrass (*Cynodon* spp.) and zoysiagrass (*Zoysia* spp.) playing surfaces.[1,2] Herbicide resistance within *Poa annua* is a widespread and complex issue that ultimately limits herbicide options available for selective control.[3] This is particularly true on golf courses where reports of herbicide-resistant *Poa annua* are significant.[4]

Research was conducted at Montgomery Bell State Park Golf Course (Burns, TN) during 2024-2025. This site is infested with a population of *Poa annua* that is resistant to several modes-of-action leading to herbicides such as indaziflam, prodiamine, pronamide, simazine, and foramsulfuron being ineffective. University of Tennessee scientists have been conducting research trials at this site since 2018.

An area (3,500 ft^2) in the center of the 18th fairway was fraise mowed on June 18th, 2024 using a KORO Field Top Maker (KTM 1200) affixed to the power take-off assembly of a tractor (Image 1). The unit was configured to remove the uppermost 12.5 mm of the surface (0.5") using 10-mm blades affixed to a universe rotor with debris discarded off-site. An adjacent area (3,500 ft^2) served as a non-fraise mowed check. Recovery from stolon growth (Image 2) was monitored throughout summer 2024.

Herbicides from varying mode-of-action groups were evaluated in the presence or absence of fraise mowing during 2024-2025. These herbicides included prodiamine (Barricade® 65WG. Syngenta Professional Products), oxadiazon (Ronstar® G. Bayer Crop Sciences), indaziflam (Specticle® Flo. Envu Turf & Ornamentals), foramsulfuron (Revolver®. Envu Turf & Ornamentals), thiencarbazone-methyl + foramsulfuron + halosulfuron (Tribute Total®. Envu Turf & Ornamentals), simazine (Princep®. Syngenta Professional Products), metribuzin (Sencor®. Envu Turf & Ornamentals), pronamide (Kerb® SC T&O. Corteva Agriscience), glyphosate (Ranger Pro®. Bayer Crop Science), glufosinate (Finale® XL T&O. BASF Corporation), diquat (Reward®. Syngenta Professional Products), and methiozolin (PoaCure®. Moghu USA) applied at the maximum labeled rate for use in hybrid bermudagrass. Herbicide treated plots (5 x 6 ft) were arranged in a randomized complete block design with four replications. Herbicides were applied via label directions with CO_2-pressurized boom sprayers calibrated to deliver 40 gpa via four, flat-fan, 8002 nozzles. Adjuvants were included with herbicides in accordance with label directions.

Poa annua control will be visually evaluated on a 0 (i.e., no injury) to 100 (i.e., complete plant death) percent scale relative to the non-treated check in each replication during spring 2025. *Poa annua* cover in treated plots will be quantified via grid count at the end of the experiment in spring 2025 as well. All data will be subjected to ANOVA with means separated using Fisher's protected least significant difference test at $\alpha = 0.05$.

Expected Results

We hypothesize that fraise mowing will restore the efficacy of certain herbicides for *Poa annua* control. It is likely that this response will vary among mode-of-action groups and that complete restoration will not be achieved via a single fraise mowing event. If warranted, the project will be continued in 2025-2026 to explore the number of fraise mowing events required to reverse resistance completely.

References

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2. Carroll DE, Brosnan JT, Unruh JB, Stephens CA, McKeithen C, Boeri PA. Non-Chemical Control of Annual Bluegrass (*Poa annua*) in Bermudagrass (*Cynodon* spp.) via Fraise Mowing: Efficacy and Barriers to Adoption. *Sustainability*. 2021; 13(15):8124. https://doi.org/10.3390/su13158124
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4. Brosnan, JT, Vargas, JJ, Breeden, GK, Zobel, JM. Herbicide resistance in annual bluegrass on Tennessee golf courses. Crop, Forage & Turfgrass Mgmt. 2020; 6:e20050. https://doi.org/10.1002/cft2.20050

Image 1. Fraise mowing (0.5" depth) a hybrid bermudagrass (*C. dactylon* x *C. transvaalensis*) fairway in Burns, TN on June 18th, 2024

Image 2. Stolon tissue remaining after fraise mowing a hybrid bermudagrass (*C. dactylon* x *C. transvaalensis*) fairway to a 0.5" depth on June 18th, 2024

USGA ID#: 2024-17-827

Title: Bermudagrass Putting Green Cultivar Evaluation

Project Leader: A.J. Lindsey and Chris Neff
Affiliation: University of Florida and UGSA Green Section

Objectives:

1. Compare new bermudagrass cultivars to a standard (i.e., commonly used) cultivar in terms of putting green establishment, performance, and playability.
2. Determine bermudagrass cultivar injury recovery from divots.

Start Date: 2024
Project Duration: Three years
Total Funding: $10,000

Summary Text:

Turfgrass breeding has resulted in the development of new commercially available bermudagrass cultivars. However, there are minimal research studies conducted to evaluate the new cultivars in putting green establishment, performance, and playability, especially in Florida. The objective of the research study is to compare three new bermudagrass cultivars to a standard (i.e., commonly used) cultivar in terms of putting green establishment, performance, and playability.

A three-year study is being conducted at the University of Florida Plant Science Research and Education Unit (Citra, FL). Four bermudagrass cultivars will be evaluated and include Celebration Dwarf (Sod Solutions; Mississippi State University), Tif3D (University of Georgia), Mach 1 and TifEagle as the standard for comparison. Each cultivar was established from sprigging at the same sprigging rate (15 bushels/1000 ft^2) on August 13, 2024. Fertilizer is being applied at UF/IFAS recommendation and all routine putting green maintenance (mowing, topdressing, aeration, irrigation, pesticide applications) are being conducted throughout the duration of the study. Pesticides will be applied as needed to prevent excessive damage. Bermudagrass cultivars were arranged in a randomized complete block with four replications (Figure 1).

During the establishment period (year 1), data collection includes monthly visual quality ratings, visual estimated percent cover, Normalized Difference Vegetation Index (NDVI), and digital images for digital image analysis (DIA) to determine percent cover. Data is being collected throughout the growing season or until the plots are fully established. After the establishment period (year 2 and 3), data collection will include monthly visual quality ratings, NDVI, digital images for DIA, clippings, ball roll (Stimpmeter), and firmness (TruFirm). Additionally, divot recovery data will occur once during the 2nd and 3rd year of study. Plots will receive a divot to determine turfgrass recovery. After the divot, bi-weekly digital images will be collected to determine percent cover until turfgrass is fully recovered from injury.

All data collected will be subjected to analysis of variance (ANOVA) using SAS (version 9.4; SAS Institute Inc.). Treatment mean comparisons will be separated using Fisher's unprotected least significant difference (LSD) at the $p \leq 0.05$ level. Data from this study will be used by the golf course industry to determine what cultivar or cultivars are best suited for use in Florida and the Southeastern region.

Preliminary bermudagrass cultivar establishment results indicate that there is a significant cultivar effect on turfgrass visual quality, estimated percent cover, NDVI, and percent green cover (Figure 2, 3, 4, 5, 6). Overall, when there were cultivar differences, Celebration Dwarf, Tif3D, and TifEagle were in the top statistical group for turfgrass visual quality, estimated percent cover, NDVI, and percent green cover. Mach 1 was in the lowest statistical group for all the parameters listed above. This indicates that Mach 1 has a slower establishment in north central Florida compared to the other cultivars tested. However, none

of the cultivars are fully established and data collection is ongoing. Turfgrass quality, cover, performance, and recovery will continue to be tracked for the following two years, and the trial is expected to conclude on December 12, 2026.

Figure 1. Overview of experimental site.

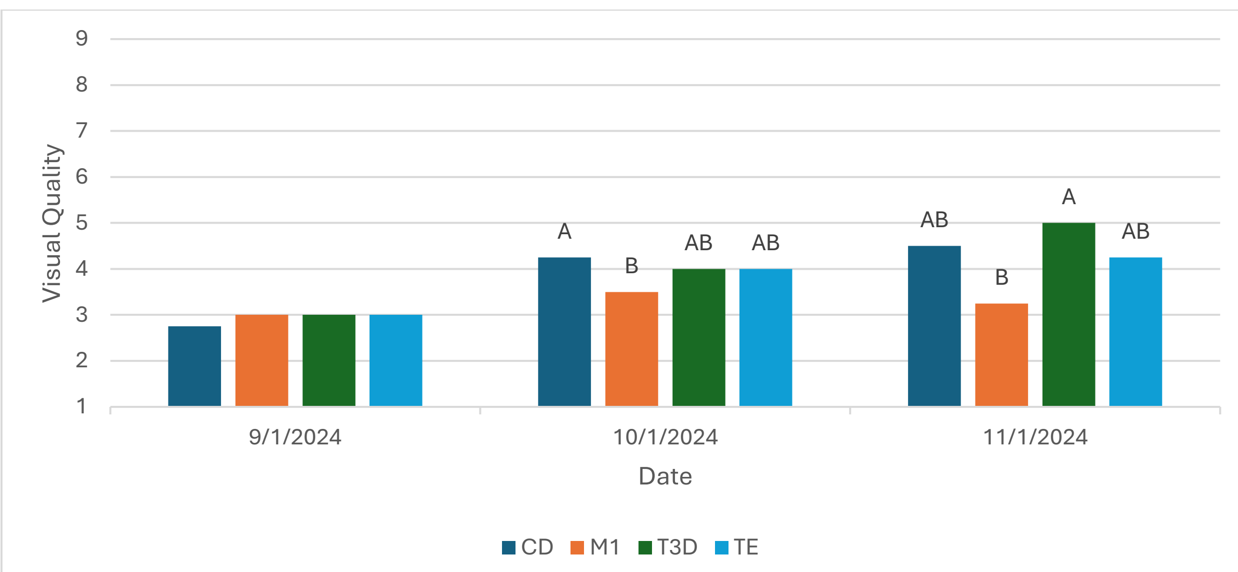


Figure 2. All Bermudagrass cultivars visual quality (1-9, 6 minimally acceptable) during establishment. Means followed by the same letter within each rating date are not significantly different from one another according to Fisher's unprotected least significant difference ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

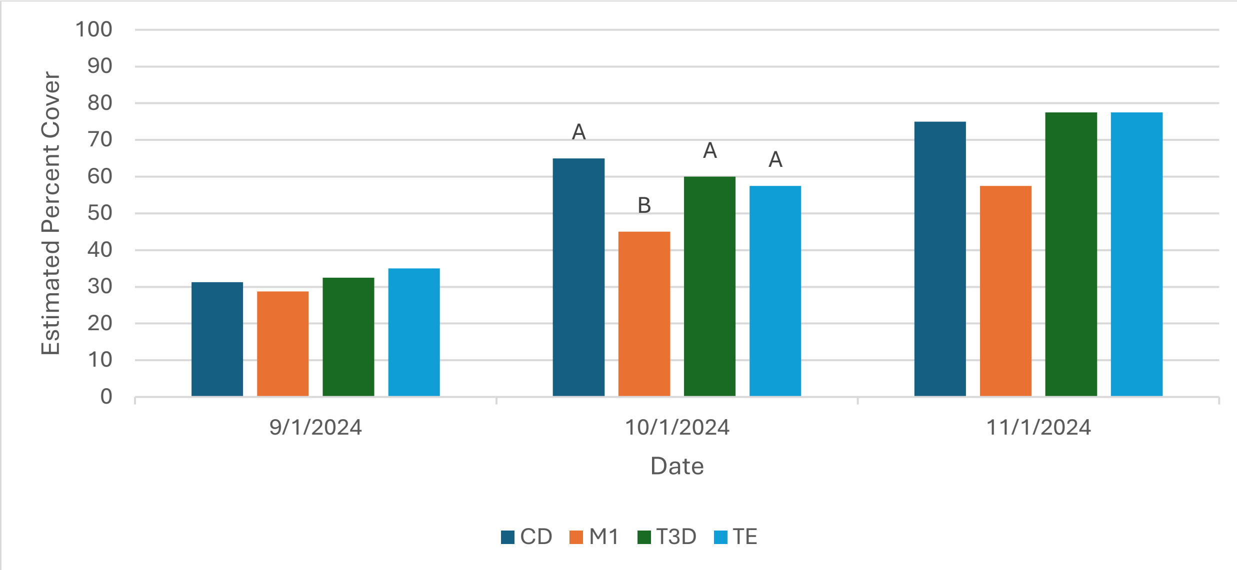


Figure 3. Bermudagrass cultivars estimated percent cover during establishment. Means followed by the same letter within each rating date are not significantly different from one another according to Fisher's unprotected least significant difference ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

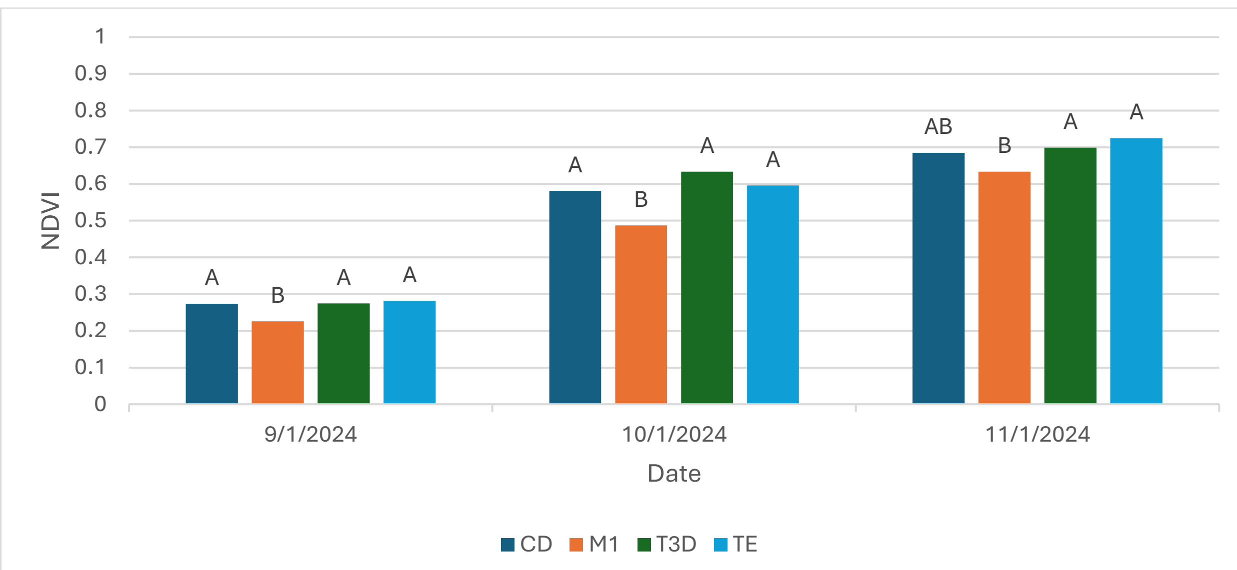


Figure 4. Bermudagrass cultivars Normalized Difference Vegetation Index (NDVI; 0-1) during establishment. Means followed by the same letter within each rating date are not significantly different from one another according to Fisher's unprotected least significant difference ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

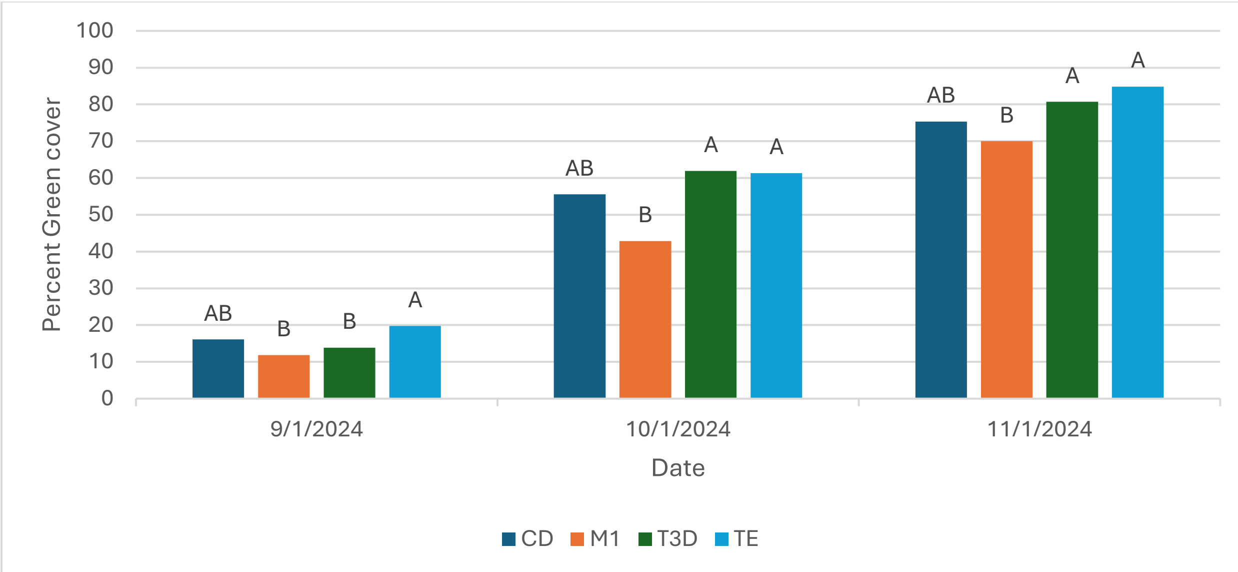


Figure 5. Bermudagrass cultivars percent green cover during establishment. Means followed by the same letter within each rating date are not significantly different from one another according to Fisher's unprotected least significant difference ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

Figure 6. Bermudagrass cultivar establishment comparison on October 29, 2024. Left to right: Celebration Dwarf, Mach 1, Tif3D, and TifEagle.

Title: Evaluation of gypsum and fertilizer products for enhanced bermudagrass performance under salinity conditions in sandy soils

Project Leader: Marco Schiavon, Alejandra Sierra
Affiliation: Fort Lauderdale Research and Education Center UF-IFAS

Start Date: 2024
Project Duration: One year
Total Funding: $14,500

OBJECTIVE:

1. Evaluate the effect of two fertilizers (ammonium sulphate and calcium nitrate) used in combination with gypsum or by themselves, to counteract the effect of Na hazard and bicarbonates in Florida sandy soils.

TREATMENTS:

Trt No.	Treatment Code	Product Description
1	CAMS	
2	CCaNO3	
3	SAMS	
4	SCaNO3	
5	GAMS	
6	GCaNO3	
7	SGAMS	
8	SGCaNO3	

MATERIALS AND METHODS:

The experiment was conducted on a mature stand of 'Celebration' bermudagrass located at the University of Florida's Fort Lauderdale Research and Education Center (26.0840° N, 80.2372° W). Table salt (NaCl) was dissolved in water and applied at a rate of 5 lb NaCl/1000 ft^2 and fertilizers were applied at a rate of 0.5 lb N/1000 ft^2 for a total of 3 lb N/1000 ft^2. Salt and fertilizer were applied every two weeks, alternating between each other, for a total of seven applications each during (December 4, 2023, to March 14, 2024). Initial salt treatment was applied on December 6, 2023, while fertilizer treatments were initially applied on December 13, 2023. Gypsum was applied at a rate of 230 lb gypsum/1000 ft^2 and divided in two applications (December 27, 2023, and January 24, 2024). Area was irrigated after each treatment application. Four replications of 5' x 5' plots in a split-split-split design were used for the trial, with salt serving as a main plot, gypsum as a sub-plot and fertilizer treatment as a sub-sub-plot (Figure 1). Turf was mowed two times per week at 0.58 in. with clippings returned. Area was irrigated daily to prevent drought stress. Weather data was retrieved from FAWN weather station locate 1000 ft away from the experiment.

Data was collected weekly. Turf quality was measured on a 1-9 scale with 9=dark green dense turf, 1=dead/brown turf, and 6=minimally acceptable turf. Normalized difference vegetation index was assessed using a handheld sensor. Percent green cover and DGCI were assessed through digital image analysis from one image taken per plot. Turf injury was measured on a scale from 0 to 100% where 0% = nonvisible, 100% = dead plant, volumetric water content and electrical conductivity (EC) data were collected starting after the first salt and fertilizer applications and were measured at a 3-in depth using a time domain reflectance sensor and were analyzed as an average of three readings per plot. Soil cores were collected prior to trial initiation, upon completion of the first phase (January 31, 2024) and at end of the experiment (after a high rainfall event). Clippings were collected at the end of the experiment to evaluate Na concentration in plant tissue. Data were subject to statistical analysis using SAS to determine treatment effect at $P<0.05$.

Main plot	Salt	No Salt
	No Salt	Salt
	No Salt	Salt
	Salt	No Salt

Sub-plot	Gypsum	No Gypsum	Gypsum	No Gypsum
	Gypsum	No Gypsum	No Gypsum	Gypsum
	No Gypsum	Gypsum	Gypsum	No Gypsum
	No Gypsum	Gypsum	Gypsum	No Gypsum

Sub-sub-plot	CaNO3	AMS	AMS	CaNO3	AMS	CaNO3	CaNO3	AMS
	AMS	CaNO3	CaNO3	AMS	CaNO3	AMS	CaNO3	AMS
	CaNO3	AMS	CaNO3	AMS	AMS	CaNO3	AMS	CaNO3
	AMS	CaNO3	AMS	CaNO3	CaNO3	AMS	AMS	CaNO3

Figure 1. Treatment distribution.

METEOROLOGICAL:

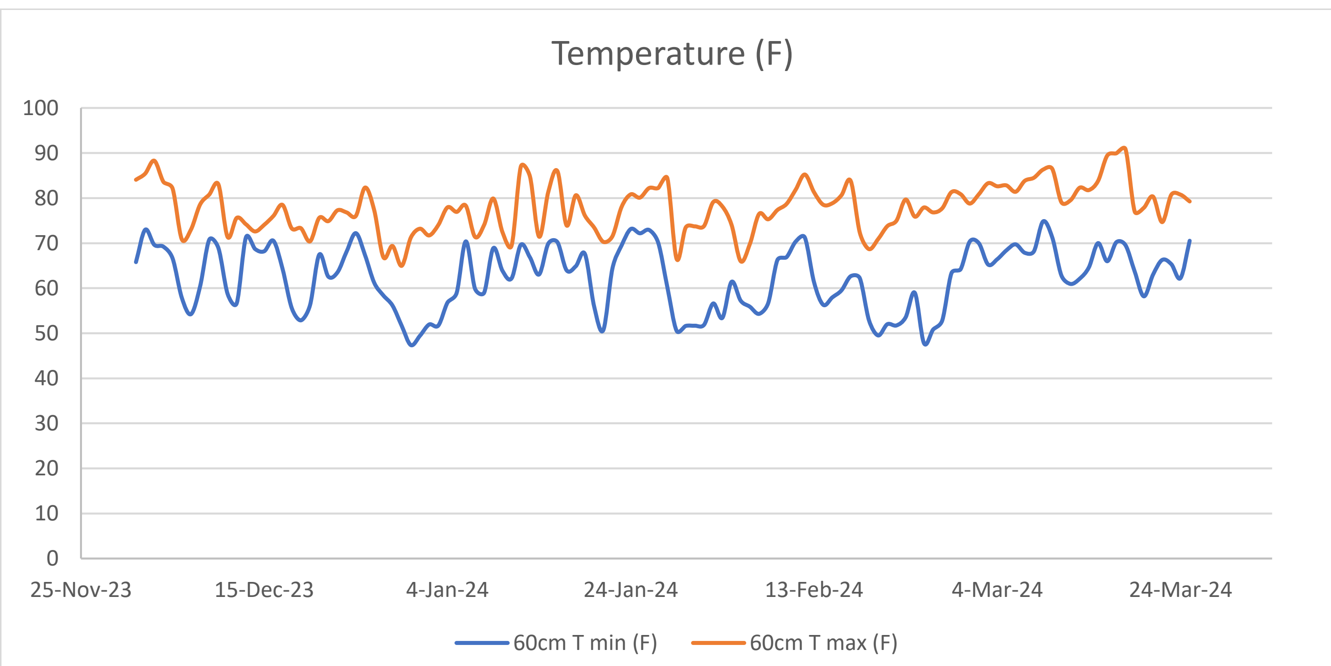


Figure 2. Minimum and maximum temperature during reported trial period.

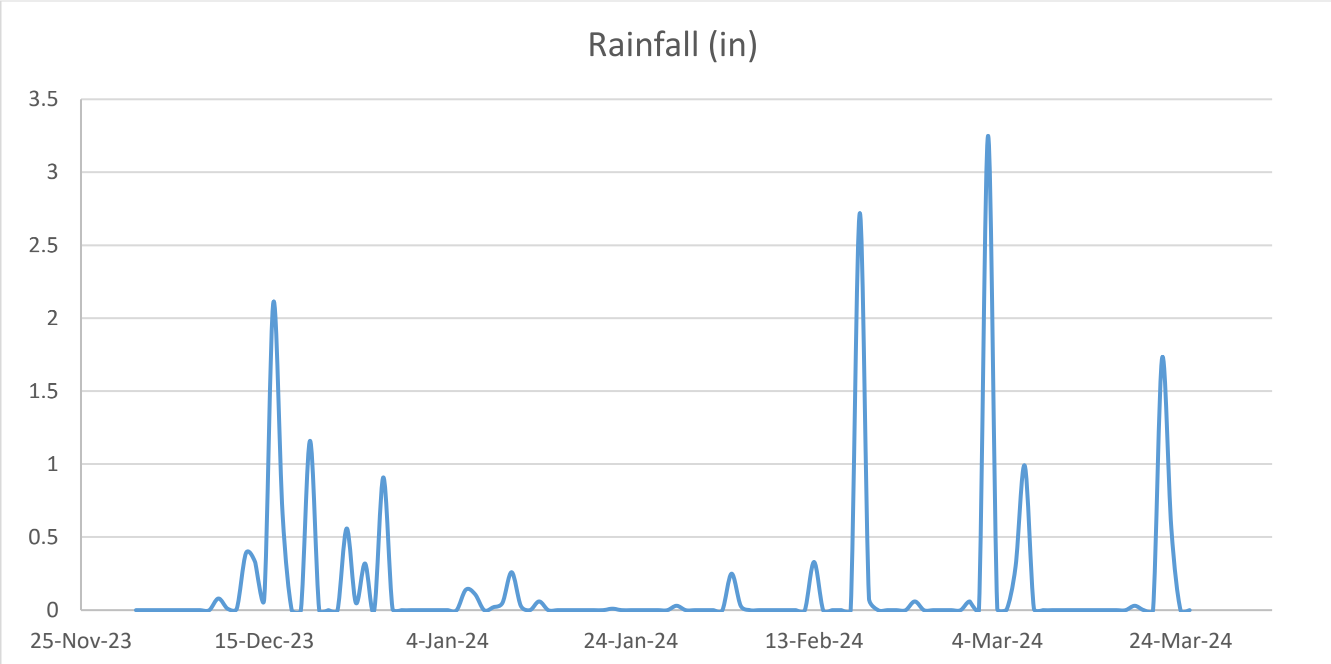


Figure 3. Precipitation during reported trial period.

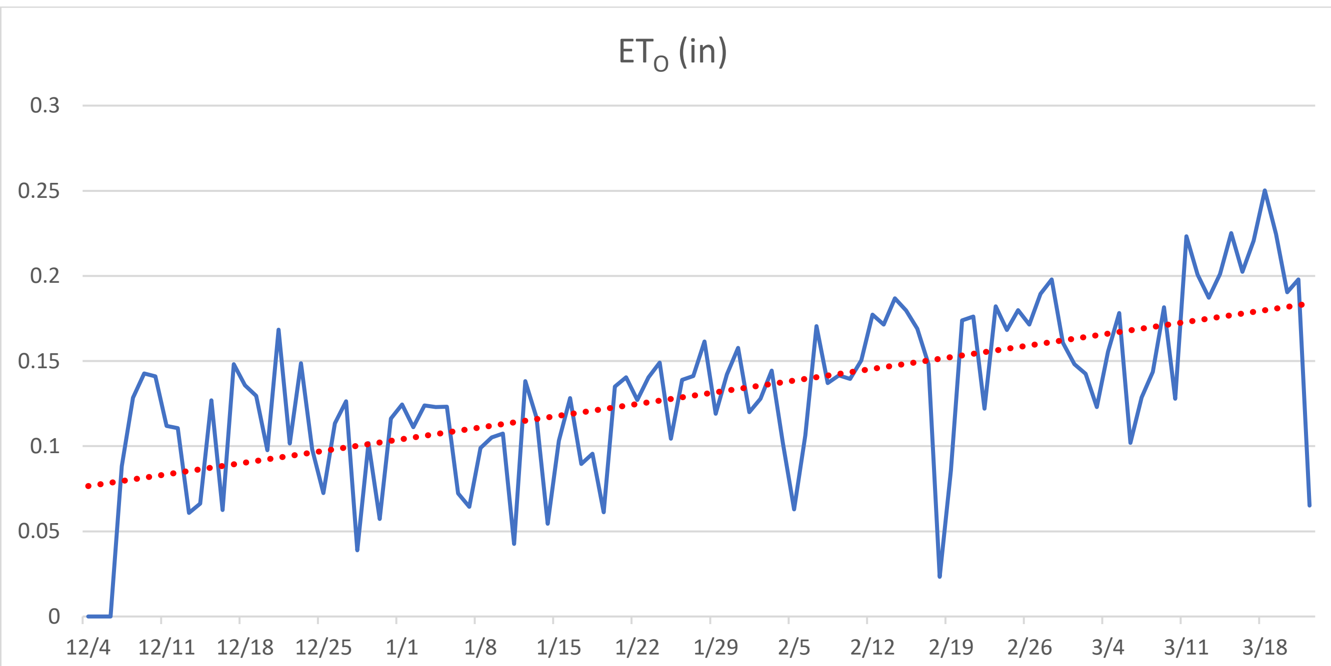


Figure 4. Daily evapotranspiration (in) during reported trial period.

RESULTS:

During the trial period, gypsum did not significantly impact most turfgrass performance parameters. However, it did exhibit a higher percent green cover (71%) compared to plots where gypsum was not applied (68%) across all dates (data not shown). Plots fertilized with AMS showed a higher quality than plots fertilized with calcium nitrate within two weeks after initial fertilization. This higher quality was sustained for four weeks; however, no differences were observed thereafter, except for Feb. 15 (Figure 5). Salt had a negative effect on turfgrass quality, reducing it below minimal acceptable threshold (6) until Jan. 9. Additionally, when salt was applied to bermudagrass, its quality consistently remained lower (Figure 6). A similar trend was observed for NDVI, were plots with salt application yielded lower NDVI than plots without salt application (Figure 7). After the second salt application (Dec. 19), percent cover of plots that received no salt was consistently higher than plots applied with salt (Figure 8). As temperature increased, percent cover increased for both treatments and no differences were observed during that period (Figure 8). Treatments had no effect on DGCI. Salt caused turfgrass injury, especially after the first and second application, however, it seems that turfgrass adapted to salinity conditions as turfgrass injury from salt declined in the second half of the experiment (Figure 9). Volumetric water content (VWC) and electrical conductivity (EC) was affected by the interaction between salt and gypsum applications (Figure 10 and 11). Throughout the experiment, plots that received salt and no gypsum had a similar VWC and EC to plots that received no salt nor gypsum. However, towards the end of the initial phase and at the end of the experiment, salt-treated plots, regardless of gypsum application showed an increase in VWC and EC, whereas salt-free plots maintained or had a decrease in VWC and EC (Figure 10 and 11). The increase in VWC could be attributed to the potential salt induced damage to bermudagrass roots, thereby reducing water absorption (Figure 10). More research is needed to substantiate physiological changes occurring in bermudagrass in field conditions when salt is applied to the turf, and their effect of soil VWC.

No Treatments had any effect on soil P and Ca concentration (Table 1). Gypsum application influenced K and Mg concentrations, soil pH, EC, bicarbonates, and Sodium Absorption Ratio (SAR) (Figure 12). Following the rain event, plots treated with gypsum presented lower K (Figure 12A), Mg (Figure 12B) and SAR (Figure 12F) compared to those without gypsum. A similar trend was observed for soil pH and bicarbonates at mid trial and following the rain event (Figure 12C and 12E). Conversely, EC was higher in plots treated with gypsum compared to those without gypsum (Figure 12D). Lower Mg and K may be because of Ca in gypsum that bounds to soil colloidal, displacing the first elements that are subsequently leached. Despite lower Mg and K level, gypsum application seemed beneficial after repeated salt application. In fact, while rain was able to get rid of excessive EC, Na was left to dominate after additional application during the winter and SAR increased in plots that received no gypsum even after the rain (Figure 12). Soil pH was also affected by fertilizer source with plots fertilized with AMS showing a lower pH compared to plot fertilized with $CaNO_3$ (Table 2). At mid trial, salt application resulted in a higher K and SAR than plots without salt (Figure 13A and 13B). The interaction between salt and fertilizer affected Na concentration at mid trial (Table 3). Plots receiving both salt and AMS had the highest Na concentration, followed plots where salt and $CaNO_3$ were applied. No differences were found among fertilizer treatments that received no salt. Following the rain event, Na concentration was affected by the interaction between salt and gypsum (Table 4). Plots treated with salt but no gypsum, exhibited the highest Na concentration followed by those subjected to both salt and gypsum. However, no differences were observed among the gypsum treatments not receiving salt. Furthermore, salt application also impacted Na concentration in plant tissue. Bermudagrass treated with salt exhibited a doubled Na concentration (0.12%) in comparison to those without salt (0.06%) (data not shown).

Soil salinity levels remained under dangerous threshold for bermudagrass growth, hence turfgrass injury was caused by direct application of salt to the leaves. Initial results (mid-trial) suggested that gypsum application in sandy soils brought little to no benefits to turfgrass and soil, and fertilization alone could help bermudagrass withstand salt injury. However, following the rain event the addition of gypsum aided in maintaining lower SAR levels, indicating a potential delayed effect of gypsum when salt keeps being applied to the soil. More research is needed to investigate long term effects of salt application on bermudagrass fairway to simulate worst case scenarios, and to assess if application of gypsum could be beneficial and economically viable in the long run, or similar effects in sandy soils could be obtained by fertilization with calcium nitrate. Pictures of experiment progression are attached at the end of this report.

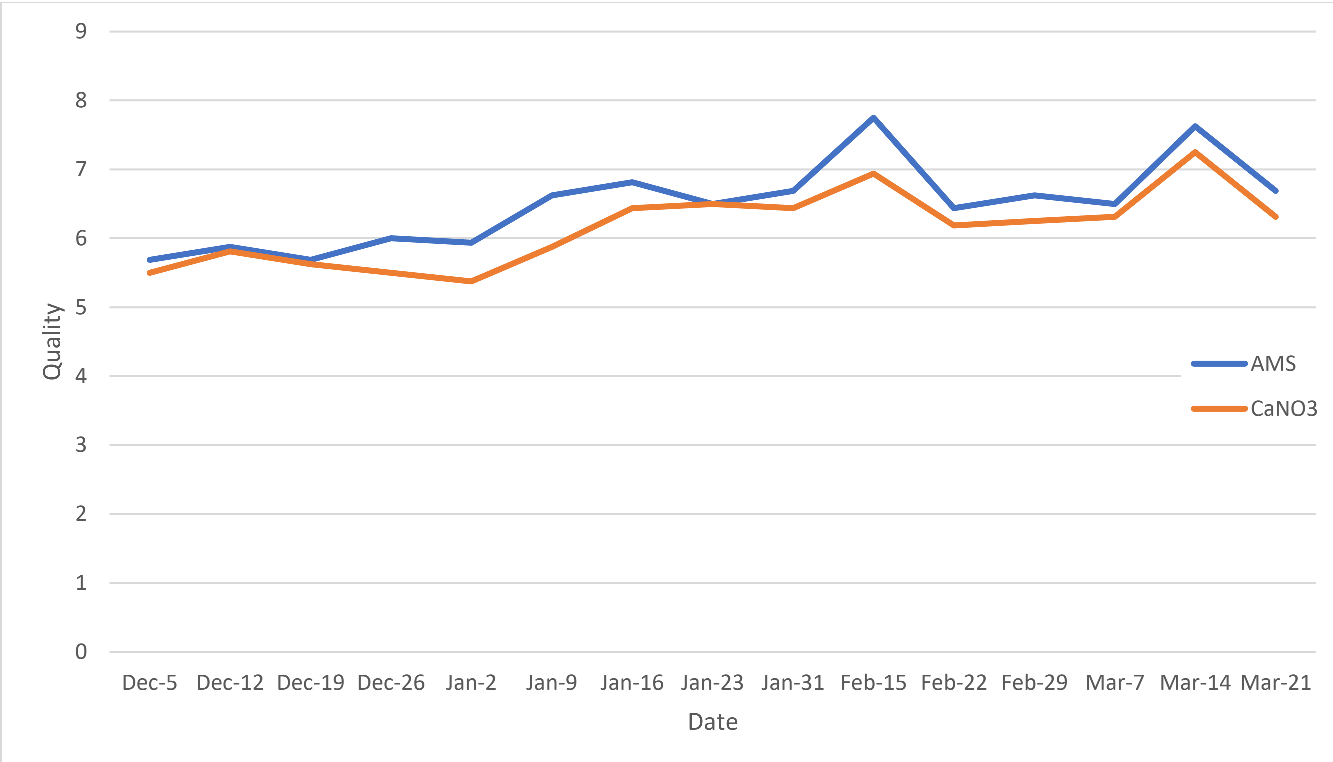


Figure 5. Effect of fertilizer on turfgrass quality.

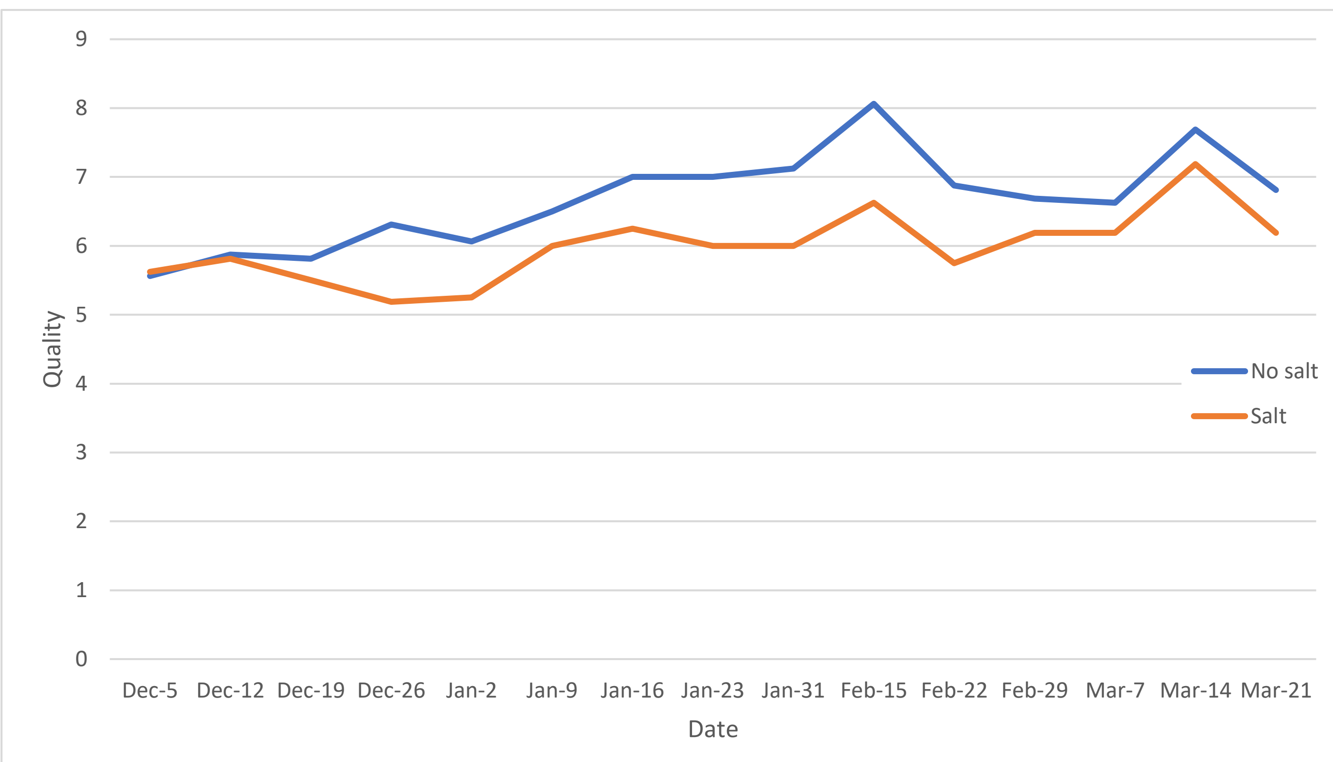


Figure 6. Effect of salt on turfgrass quality.

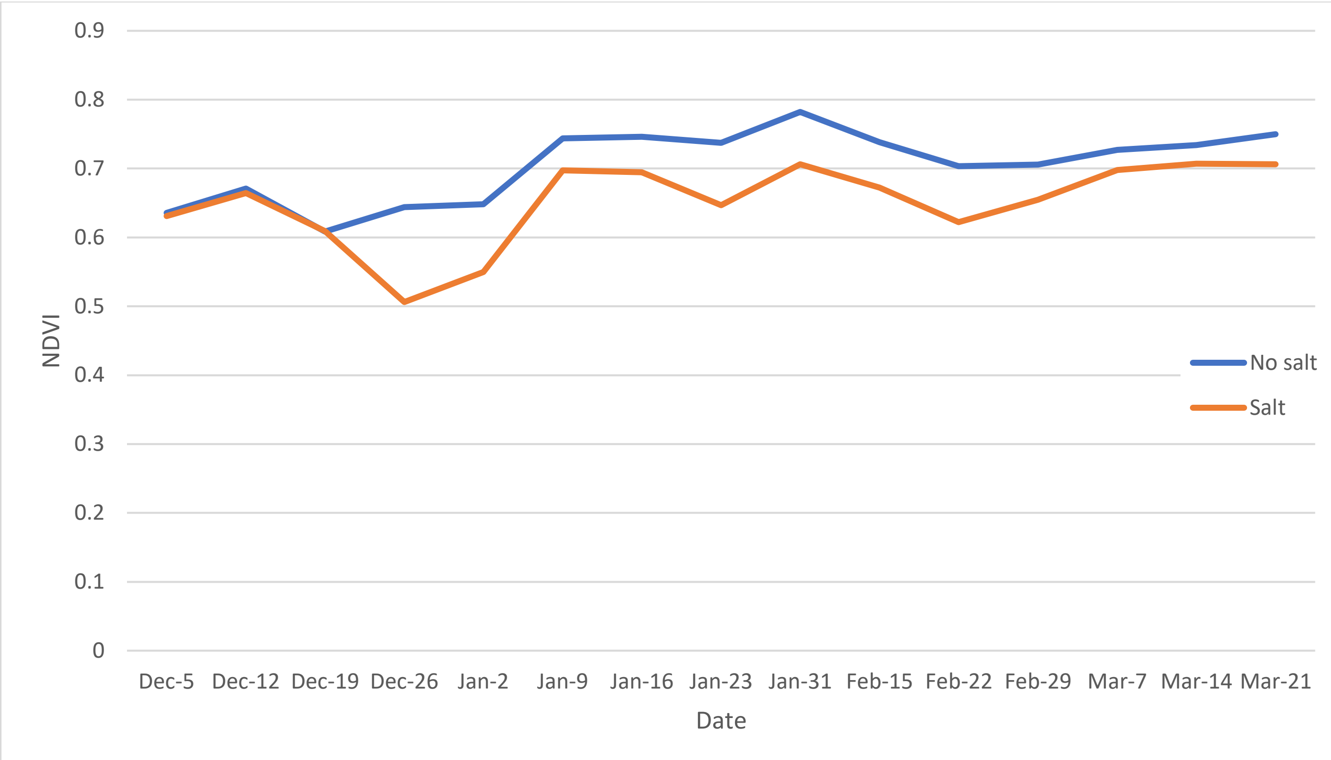


Figure 7. Effect of salt on turfgrass NDVI.

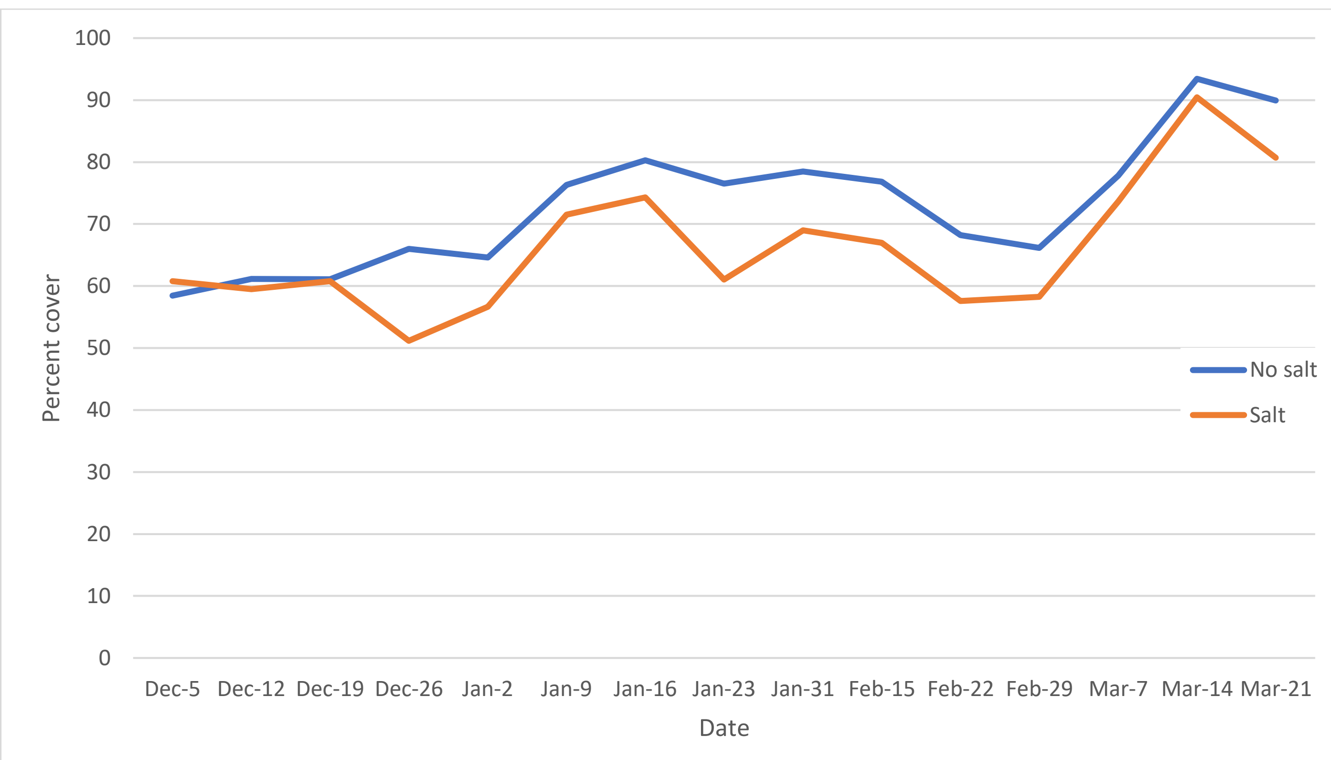


Figure 8. Effect of salt on percent green cover.

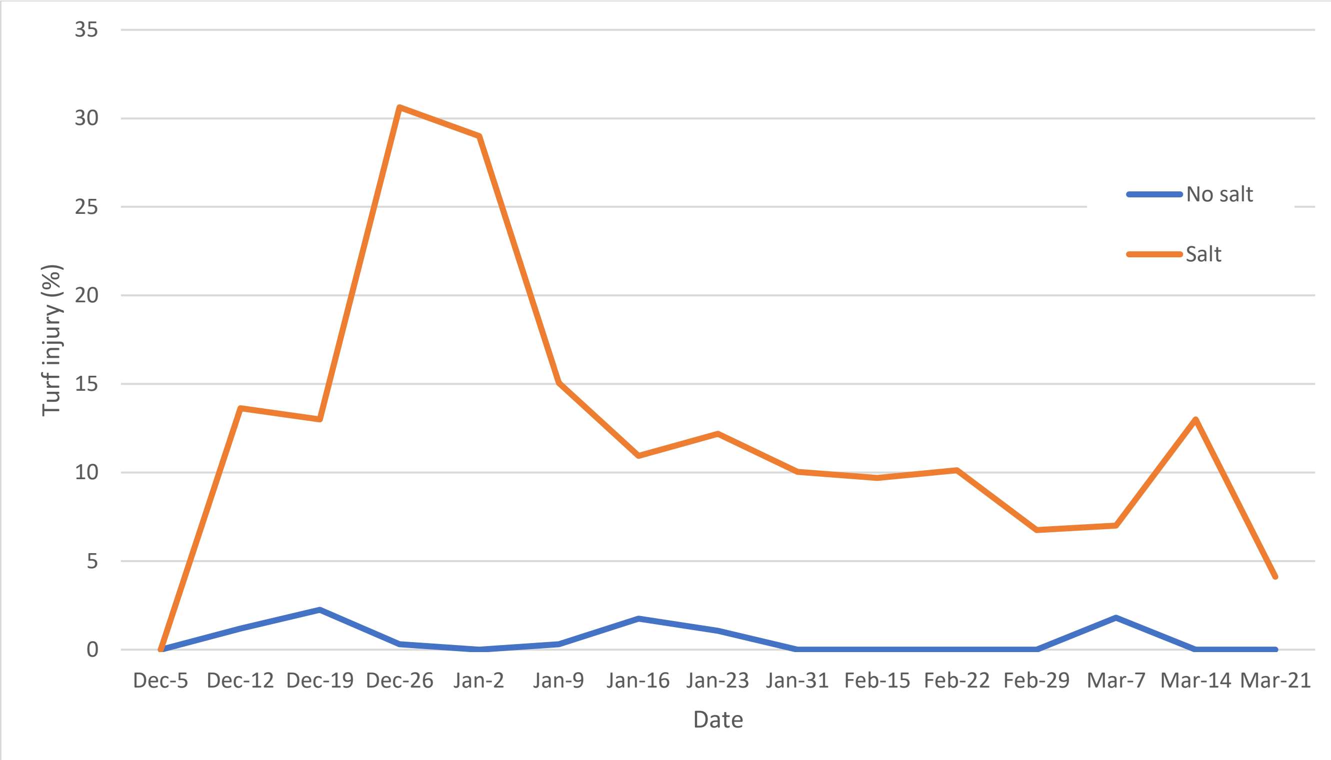


Figure 9. Effect of salt on turfgrass injury.

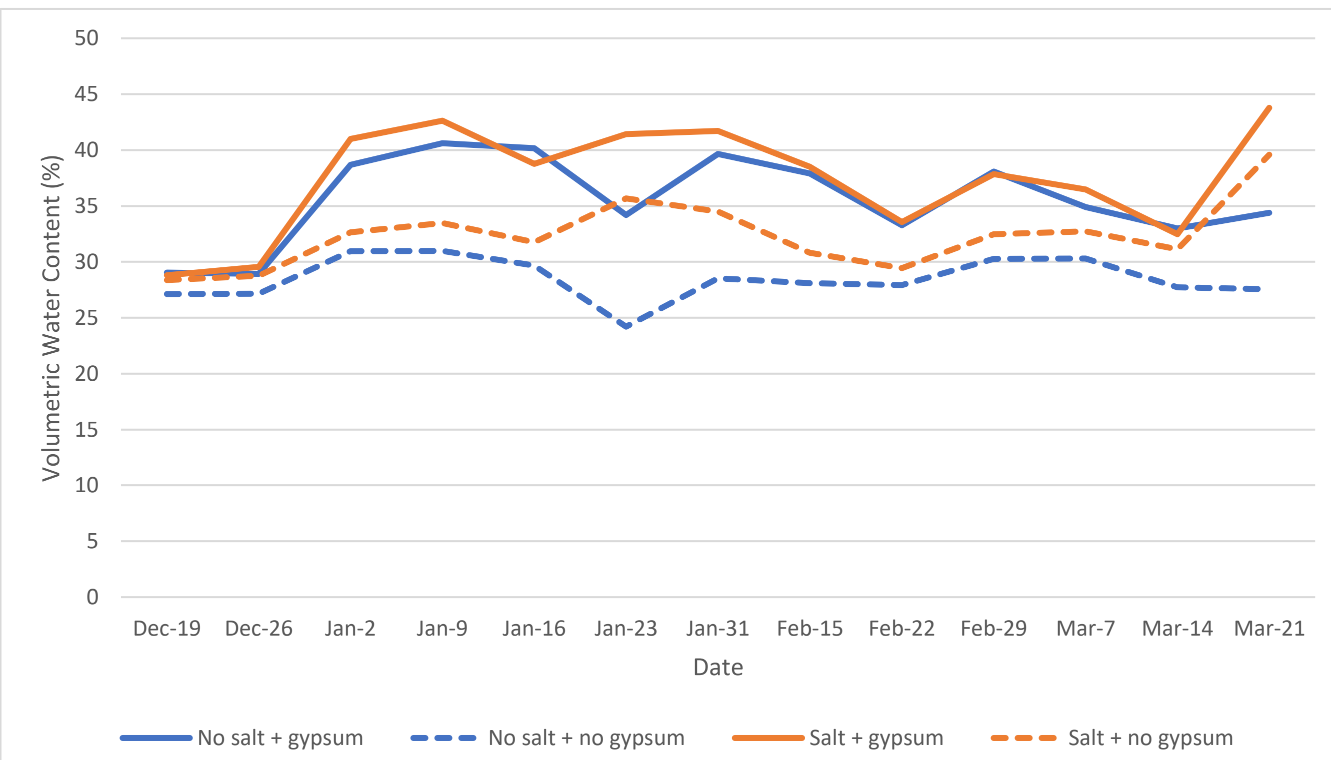


Figure 10. Effect of salt and gypsum on soil volumetric water content.

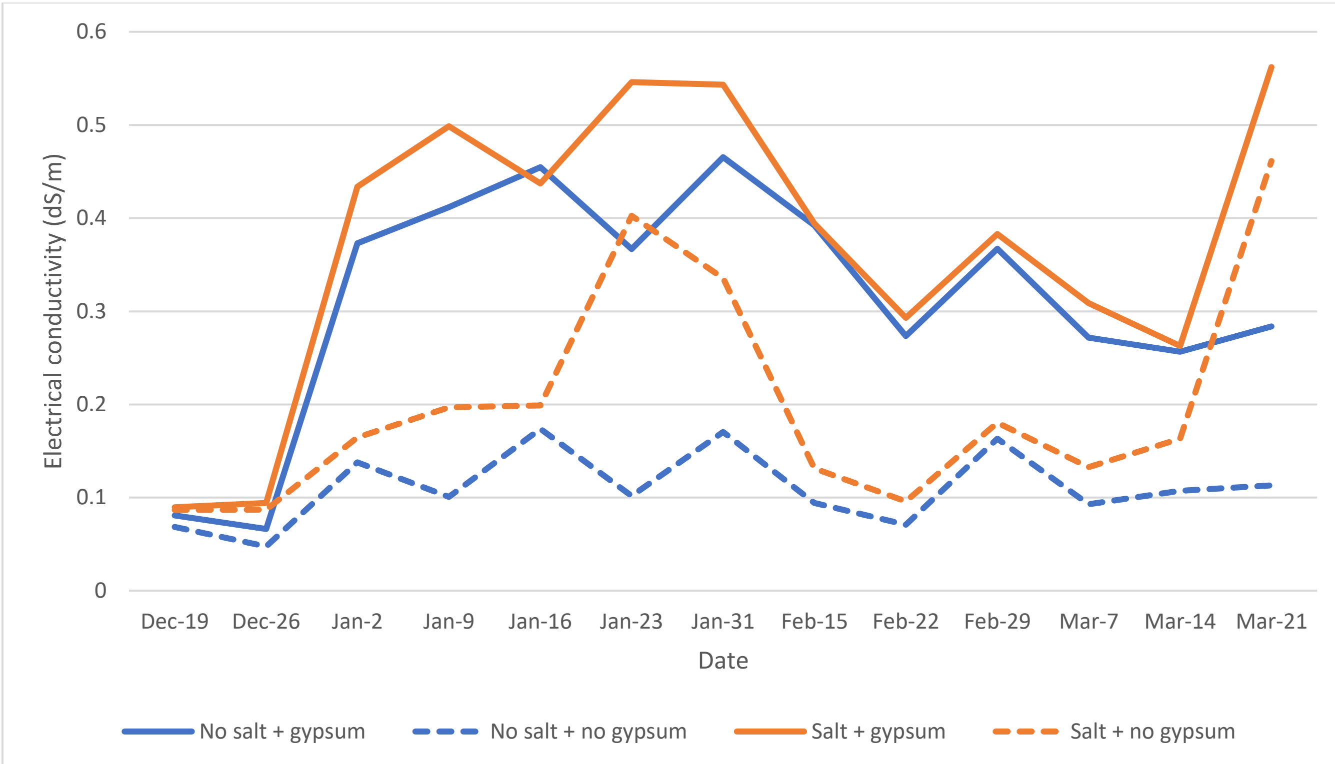


Figure 11. Effect of salt and gypsum on soil electrical conductivity.

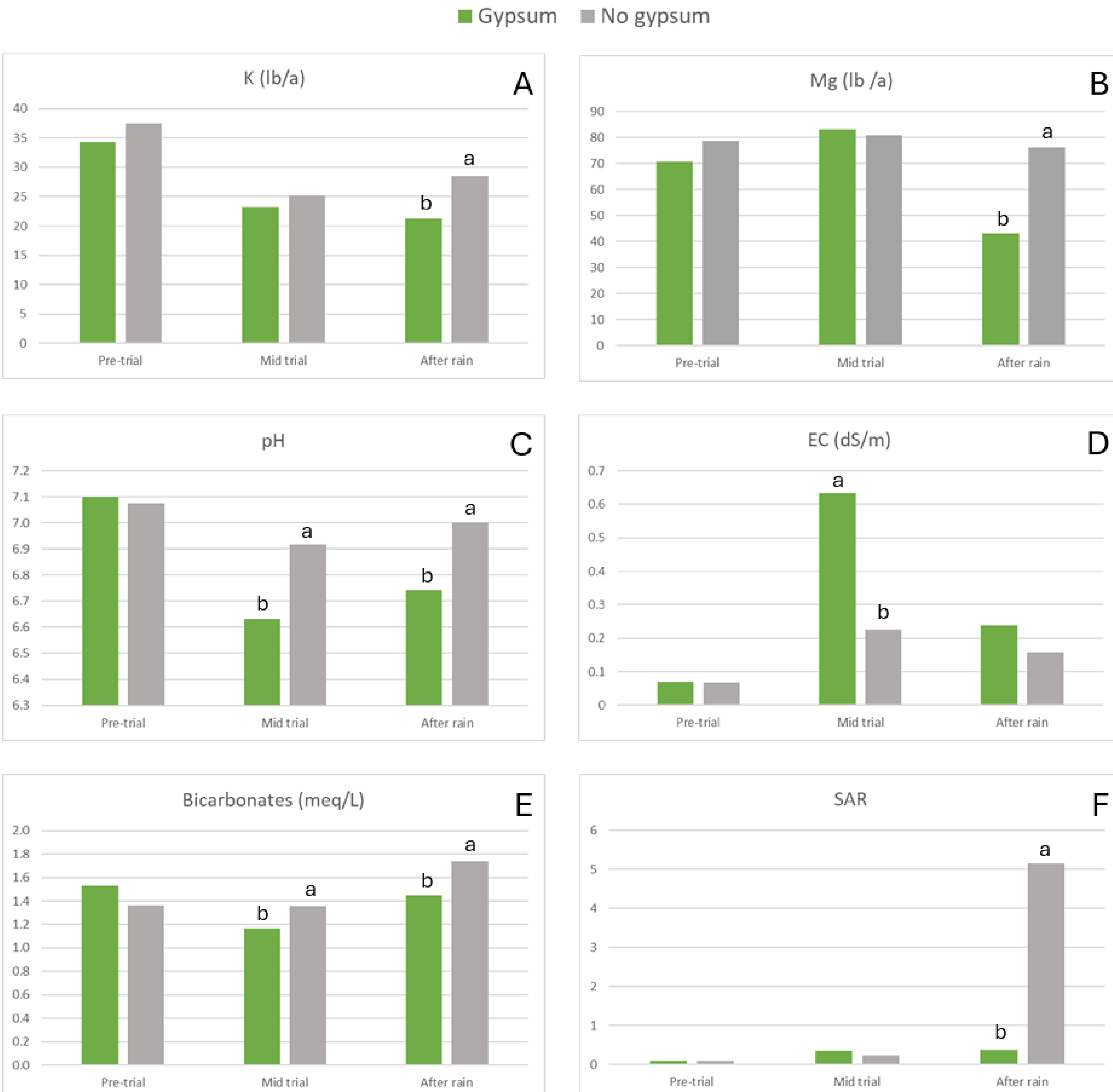


Figure 12. Effect of gypsum on (A) K concentration (lb/a), (B) Mg concentrations (lb/a), (C) soil pH, (D) electrical conductivity (dS/m), (E) bicarbonates (meq/L) and (F) Sodium Absorption Ratio (SAR).

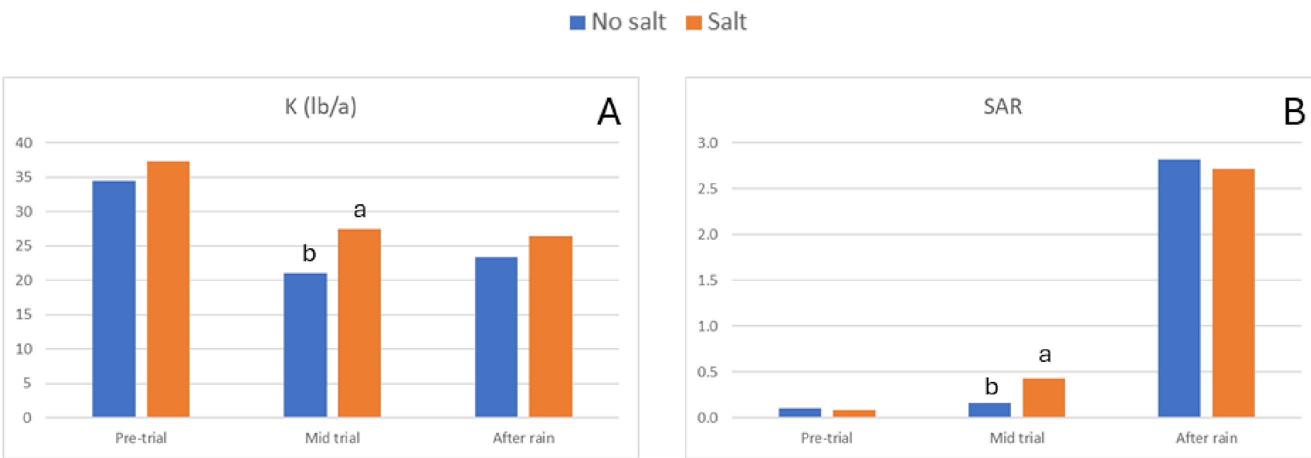


Figure 13. Effect of salt on (A) K concentration (lb/a) and (B) Sodium Absorption Ratio (SAR).

Table 1. Average concentration of soil P, and Ca (lb/a) before treatment application, at the end of the first phase (January 31, 2024) and after rain event (March 25, 2024).

Treatment	**P (lb/a)**			**Ca (lb/a)**		
	Pre-trial	Mid-trial	After rain	Pre-trial	Mid-trial	After rain
AMS	199	215	195	4368	4411	4098
CaNO3	218	247	206	4004	4554	4168
Gypsum + AMS	208	216	206	4083	4692	4653
Gypsum + $CaNO_3$	237	260	238	3949	4485	4479
Salt + AMS	244	267	224	4103	4385	4105
Salt + CaNO3	227	225	218	4455	4636	4582
Salt + Gypsum + AMS	246	259	220	4111	4629	4169
Salt + Gypsum + CaNO3	194	203	191	3912	4547	4305

Table 2. Effect of fertilizers on soil pH and electrical conductivity.

Treatment	**pH**		
	Pre-trial	Mid-trial	After rain
AMS	7.1	6.7 b	6.8 b
CaNO3	7.1	6.9 a	6.9 a
Significance	**N/A**	**	**

Table 3. Effect of salt and fertilizer treatments on Na concentration before treatment application and at the end of the first phase (January 31, 2024).

Treatment	**Na (lb/a)**	
	Pre-trial	Mid-trial
No salt		
AMS	34	34 c
CaNO3	30	35 c
Salt		
AMS	31	198 a
CaNO3	32	174 b
Significance	**N/A**	**

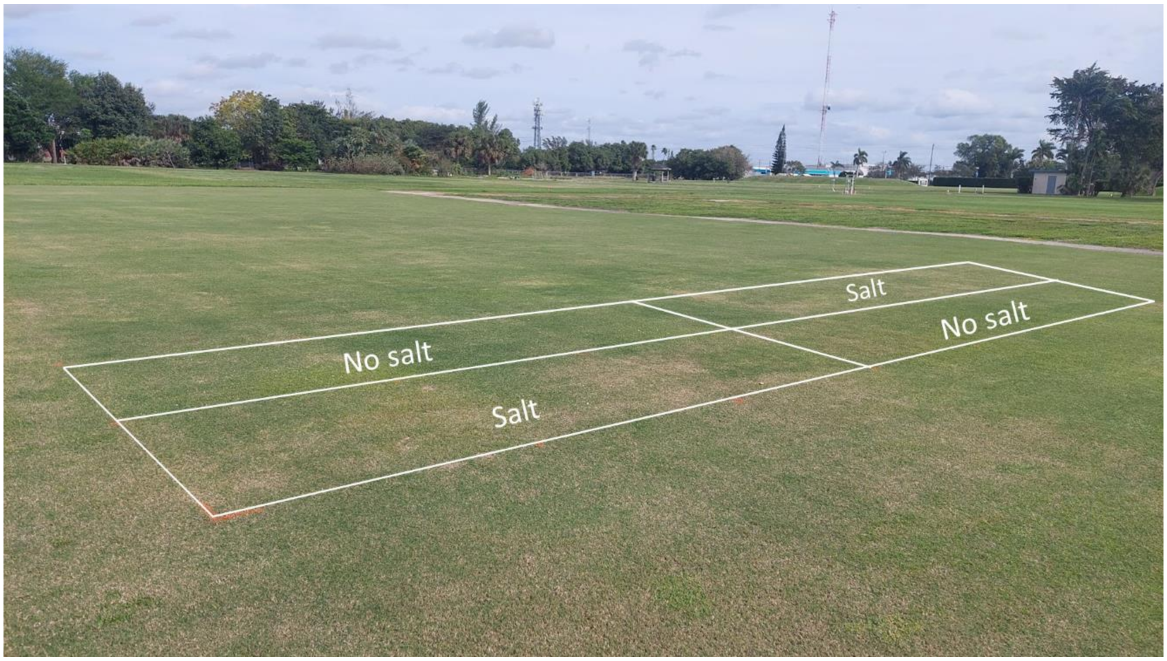
Table 4. Effect of salt and gypsum treatments on Na concentration before treatment application and after rain event (March 20, 2024).

Treatment	Na (lb/a)	
	Pre-trial	After rain
No salt		
Gypsum	30	29 c
No gypsum	35	33 c
Salt		
Gypsum	28	60 b
No gypsum	36	141 a
Significance	**N/A**	***

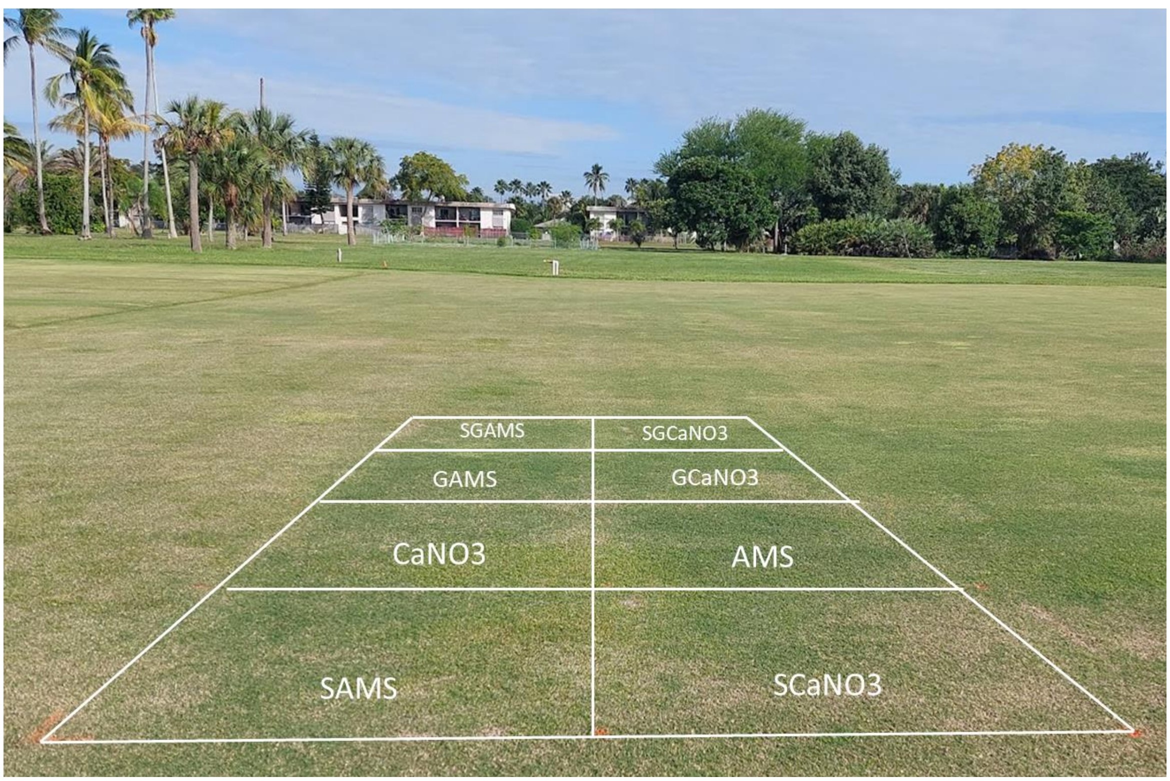
PICTURES OF PROGRESS

November 29, 2023 (Pretrial)

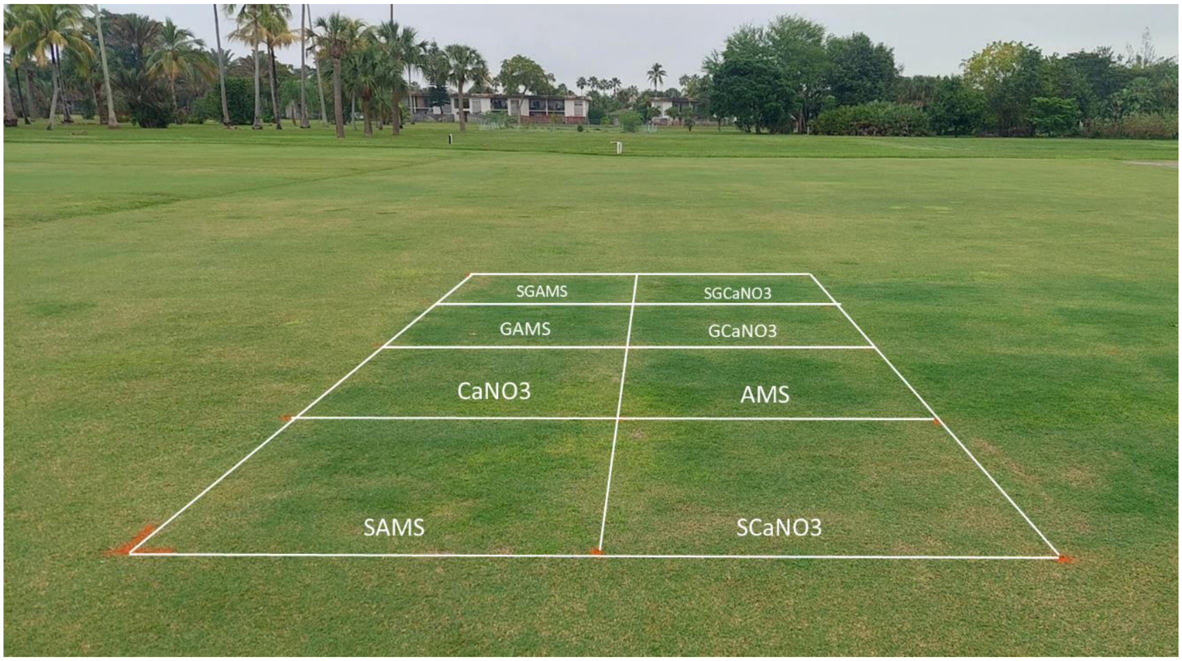
December 26,2023 (before gypsum application)



January 4, 2024 (after gypsum application)

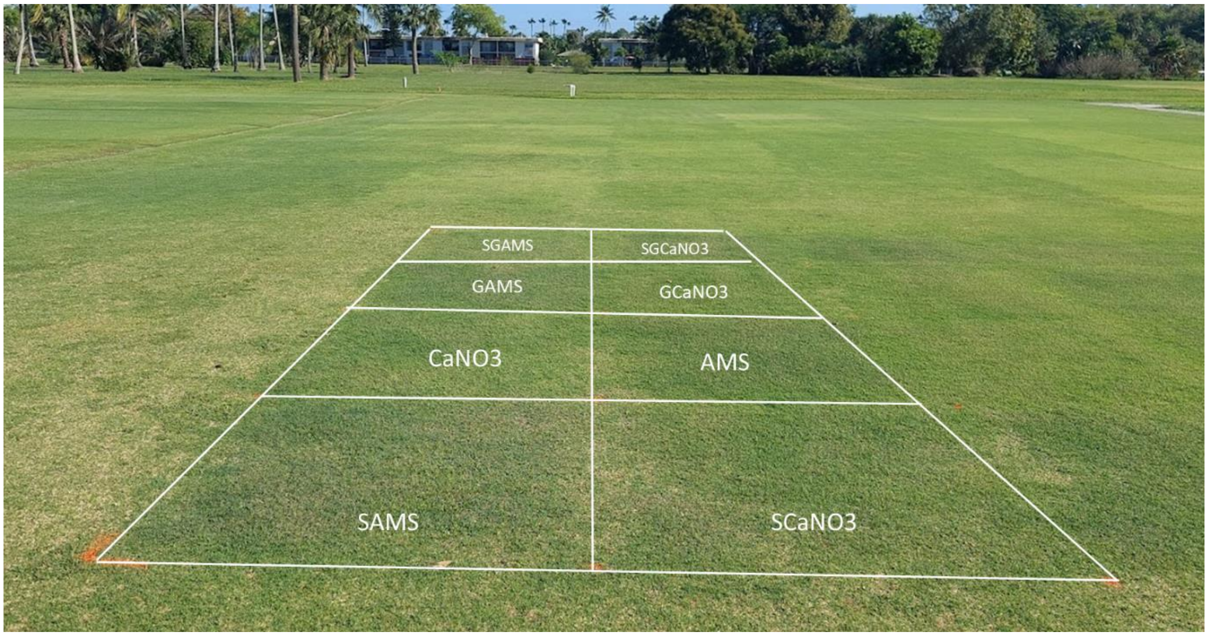


January 11, 2024



February 2, 2024

March 19, 2024



USGA ID# 2023-39-806

Title: Does the Right Divot Pattern Actually Increase Recovery?

Project Leaders: Aaron Patton and Naba Amgain
Affiliation: Purdue University

Objective: Quantify the impact of three common divot patterns on available tee space, divot mix needs, and divot recovery.

Start date: 7/1/2023
Project duration: 2 years (01/01/2023-12/31/2024)
Total funding: $10,000

Summary points

- Divot pattern impacts available tee space, divoted turf percent, and divot recovery.
- Although scattered pattern had a higher area of impact and a higher percentage of divoted turf, this divot type was fastest to recover. This pattern would work well when sufficient driving range tee space is available.
- Concentrated divots had a lower area of impact but required the most time to recover.
- The linear divot pattern appears to be the best divot pattern option as it had a lower area of impact and divoted turf than scattered pattern and a higher recovery rate than concentrated pattern. This pattern would work best when driving range tee space is limited which is likely the case for most.

Summary Text:

Golfers warm-up and practice on driving range tees by hitting various clubs causing severe damage through the creation of multiple divots. Golf course superintendents shift hitting positions on the range tee to provide a fresh surface for the golfers while simultaneously allowing the recovery of the damaged portion of the tee. Divots can be of different shapes and sizes depending on the club used and the divot pattern used by the golfer. Golf courses commonly post signage related to the preferred divot pattern (Figure 1, Table 1). The linear divot pattern is preferred and recommended by the USGA because it “removes the least amount of turf” and “promotes quick recovery.” However, neither a removal of less turf or a faster recovery has been documented beyond anecdotal accounts. Faster divot recovery is very important for golf courses to use driving range tee space efficiently.

Table 1. Description of divot patterns shown in Figure 1.

Divot pattern	Description
scattered	A scattered divot pattern removes the most amount of turf because a full divot is removed with every swing. Scattering divots results in the most turf loss and uses up the largest area of a tee stall. This forces the golf facility to rotate tee stalls most frequently and often results in an inefficient use of the tee.
concentrated	A concentrated divot pattern removes all turf in a given area. While this approach does not necessarily result in a full-sized divot removed with every swing, by creating a large void in the turf canopy there is little opportunity for timely turf recovery.

linear	The linear divot pattern involves placing each shot directly behind the previous divot. In so doing, a linear pattern is created and only a small amount of turf is removed with each swing. This can usually be done for 15 to 20 shots before moving sideways to create a new line of divots. So long as a minimum of 4 inches of live turf is preserved between strips of divots, the turf will recover quickly. Because this divot pattern removes the least amount of turf and promotes quick recovery, it is the preferred method.

Descriptions from McClellan, 2014.

We conducted an experiment in 2023 and 2024 at the W.H. Daniel Turfgrass Research and Diagnostic Center in West Lafayette, IN on a 'Penncross' creeping bentgrass fairway mown at 0.5". The site was established in 2012 and received 2 lbs N/1000 sq. ft (applied over three applications annually). The site was also treated with fungicide to ensure 100% green turf to quantify divot injury and recovery using digital image analysis.

Three divot patterns were created by four single digit handicap golfers. Each golfer struck 10 full shots with a sand wedge (54-56 degrees). The treatments were arranged in randomized complete block design with three replications of each divot pattern. In total, there were 39 plots [3 blocks × (4 golfers x 3 divot patterns, plus a nontreated plot)] (Figure 2). Each plot was randomly assigned a golfer and pattern. Golfers were instructed to hit 10 shots from each plot per the prescribed pattern. Each golfer hit 90 total sand wedges (3 reps, 3 patterns, 10 golf balls for each plot) on August 2, 2023 to initiate the experiment. We repeated the experiment on June 20, 2024.

Concentrated divots	Scattered divots	Linear divots

Figure 1. Divot pattern treatments produced by golfers in this experiment.

Divots were filled with sand after the golfer shots, and the volume of sand required to fill the divots was recorded. The total area of divots was quantified with digital image analysis on Day 0. Following day 0, digital images of each plot were collected with a light box twice per week to quantify recovery. The light box captured an image with a surface area of 40 by 55 cm. Images were taken before mowing to avoid interference from fresh grass clippings. Data collections were continued until each divot pattern was filled in or the end of the growing season.

Each block contained a non-treated check plot with no divots. A check plot was used to determine the maximum green coverage potential of a plot (accounts for plot injury that is not a divot, i.e., disease or scalping).

The percentage of each plot divoted (turf removed via divots) was calculated as

$$\% \text{ divoted turf} = 100 \times \frac{(check - divot)}{check} \quad \text{Eq.1}$$

Where check is the % green cover in the non-treated plot and divot is the % green cover in the plot with divots.

Divot recovery was calculated as:

$$\% \text{ recovery} = 100 \times \frac{(d_0 - d_\mathrm{i})}{d_0} \qquad \text{Eq.2}$$

where d_0 is the percent of turf in the image removed by divots (divoted) on day 0 and d_i is the percent of turf in the image removed by divots (divoted) on day i (i^{th} observation). Digital image analysis was done with Turf Analyzer.

The total teeing area made unavailable for other golfers was calculated for each divot pattern in each plot. This was done on day 0 immediately after shots by using a rectangle frame around each area of divots, allowing for a 2” border of green grass. A 2-inch border was chosen based on half the distance recommended between linear divot patterns. The “area made unavailable” was used as a proxy to determine how much tee space would be occupied or created by each pattern. All data were analyzed with SAS version 9.4 (SAS Institute Inc.) utilizing GLIMMIX procedure.

Figure 2. A photo of golfers in the study during treatment initiation.

Day 0 results: The results revealed that a linear divot pattern had the lowest percentage of divoted turf compared to scattered pattern and concentrated pattern. A scattered divot pattern resulted in less teeing area being available compared to linear and concentrated divot patterns (Table 1). The amount of sand required to fill divots was not significantly different, but the concentrated divot patterns had numerically higher sand requirements compared to scattered and linear divot patterns.

Table 1. Effect of divot patterns on percentage of divoted turf, area impacted, and divot mix needed immediately after treatment (Day 0).

Divot Pattern	% Divoted turf	Area impacted (cm^2)	Divot mix needed (cm^3)
Concentrated	35 a	1914 b	723.3 a
Linear	27 b	2128 b	608.3 a
Scattered	34 a	2736 a	625.5 a

Recovery: In both years, the recovery rate of individual plots was higher for scattered divot patterns followed by linear and concentrated patters (Figure 1 and 2). Due to faster recovery, divoted turf from the scattered pattern decreased over time and was fully recovered faster than linear and concentrated divot patterns. In year 1, 50% of scattered divots recovered in 19 DAT, linear divots recovered in 27 ADT, and concentrated divots recovered in 34 DAT, respectively. In year 2, 50% of scattered, linear, and concentrated divots recovered in 20, 25, and 33 DAT, respectively. In year 1, 90% of scattered divots recovered in 44 DAT, linear divots recovered in 50 DAT, and concentrated divots recovered in 54. In year 2, 90 % of scattered, linear, and concentrated divots recovered in 57, 82, and 92 DAT, respectively. The slow recovery of divots observed in year 2 may be attributed to the slow growth of cool season bentgrass during summer. In year 1, divots were created on August 2, whereas in year 2, divots were created on June 20. We conducted this experiment without adding seed to our divot sand in order to assess the effects of divot pattern. Adding seed and organic matter to the divot mixture would help encourage faster recovery of tee boxes.

Divot pattern impacts available tee space, divoted turf percent, and divot recovery. Although the scattered pattern had a higher area of impact and a higher percentage of divoted turf, this divot type was the fastest to recover. This pattern would work well when sufficient driving range tee space is available. Concentrated divots had a lower area of impact and percentage of divoted turf but required the most time to recover. The linear divot pattern appears to be the best option as it had a lower area of impact and divoted turf than the scattered pattern and a higher recovery rate than the concentrated pattern. This pattern would work best when driving range tee space is limited, which is likely the case for most.

The USGA plans on conducting similar work on bermudagrass in the future to determine how recovery may or may not be different between divot types on driving range tees with rhizomatous species compared to the stoloniferous grass tested in this study.

References:

1. McClellan, T.A. (2014). Does Your Divot Pattern Help Or Hurt The Golf Course? Available at: https://www.usga.org/course-care/2014/09/does-your-divot-pattern-help-or-hurt-the-golf-course-21474873114.html

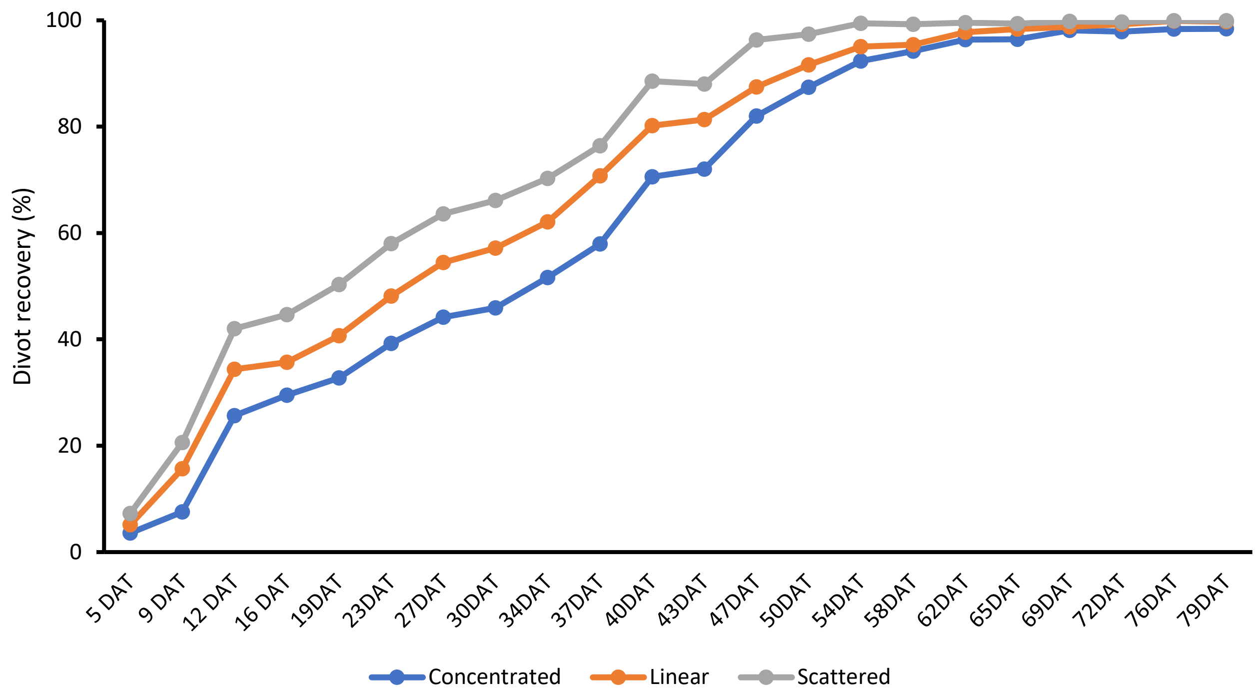


Figure 2. Effect of divot patterns on divot recovery in year 1.Divots were created on August 2, 2023.

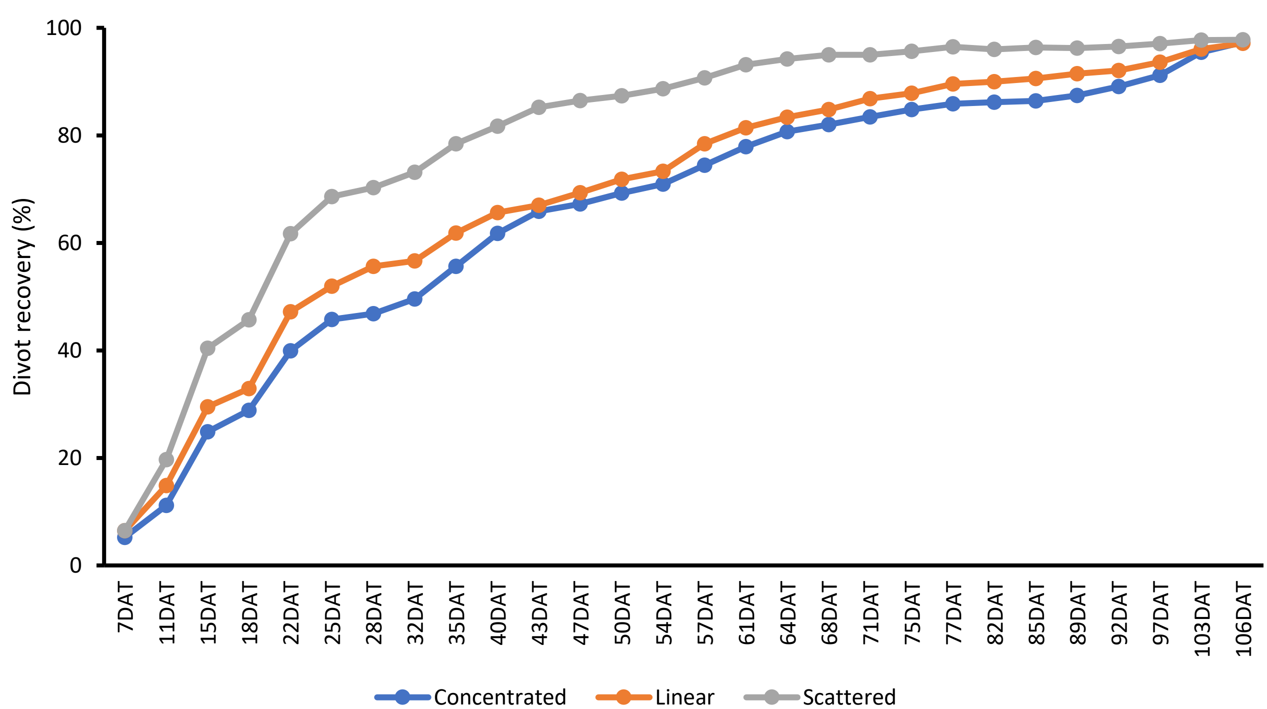


Figure 3. Effect of divot patterns on divot recovery in year 2. Divots were created on June 20, 2024.

USGA ID#: 2024-01-811

Title: Identifying and developing turfgrass research opportunities in the U.S. federal government and allied non-profit organizations

Project Leader: Kevin Morris
Affiliation: National Turfgrass Federation

Objectives: The objective of this proposal is to expand on our recent successes in significantly increasing federal and NGO funding for turfgrass research. The funding requested in this proposal will be allocated primarily to our policy consultant, Mr. Jonathan Moore, who interacts with Congress and the Administration on a regular basis on behalf of the turfgrass industry and its research needs. Mr. Moore's efforts and expertise are the primary reasons for our successes since 2016.

Start Date: 2024
Project Duration: Three years
Total Funding: $118,125

SUMMARY POINTS

- Advocacy efforts are supporting National Turfgrass Survey language and $2,000,000 in authorization funding for inclusion in the new Farm Bill
- A $20,000,000 Congressional authorization of the first turfgrass-specific competitive federal grant program has been requested for inclusion in the new Farm Bill
- A new effort of ecosystem services research is expanding within the USDA-ARS Turfgrass Consortium, a group of fifteen federal turfgrass scientists conducting genetics, genomics and water conservation research.
- Congressional language was passed encouraging the National Park Service to utilize lower-input turfgrasses, train personnel in sustainable turf management and connect with university turf research programs.

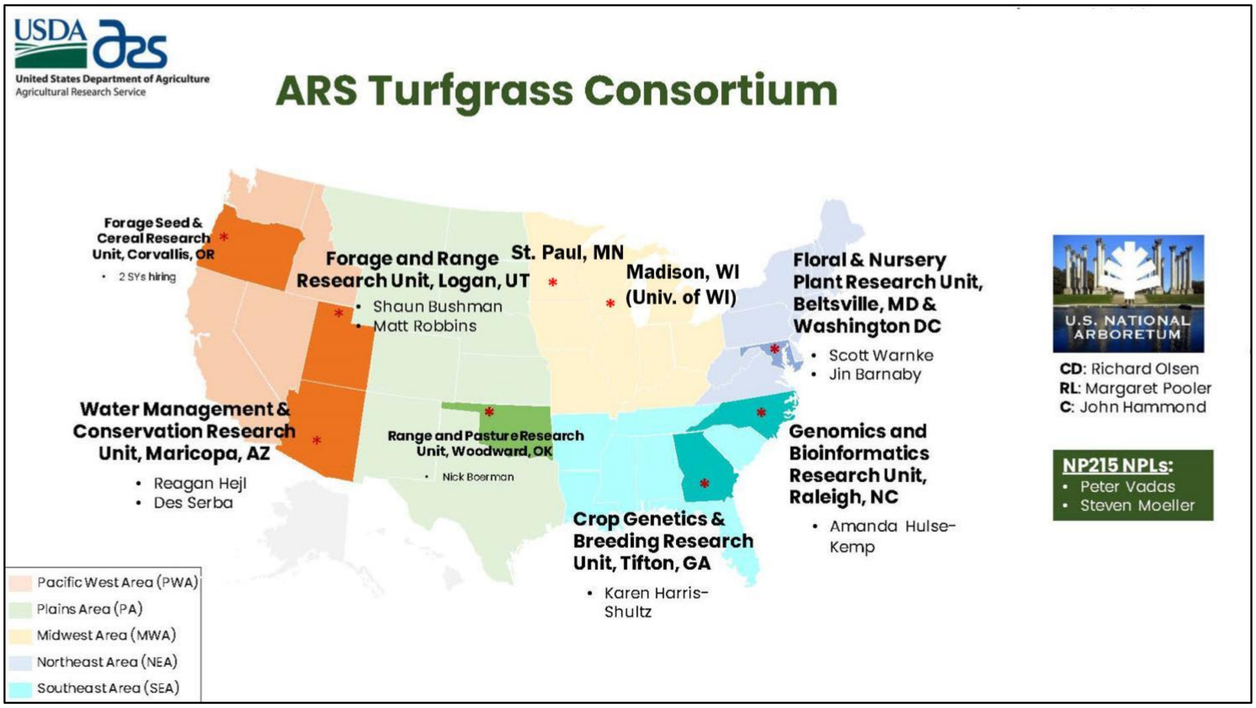
SUMMARY TEXT

Turfgrass is an estimated $60 billion, 60-million-acre industry in the U.S., making turfgrass the third largest agricultural crop in the U.S. by acreage. With tens of millions of home lawns, millions of miles of turfgrass on roadsides, a million or more athletic fields, thousands of parks, golf courses, institutional grounds and other sites, turfgrass is a ubiquitous crop in the U.S., but often taken for granted as to its importance and value.

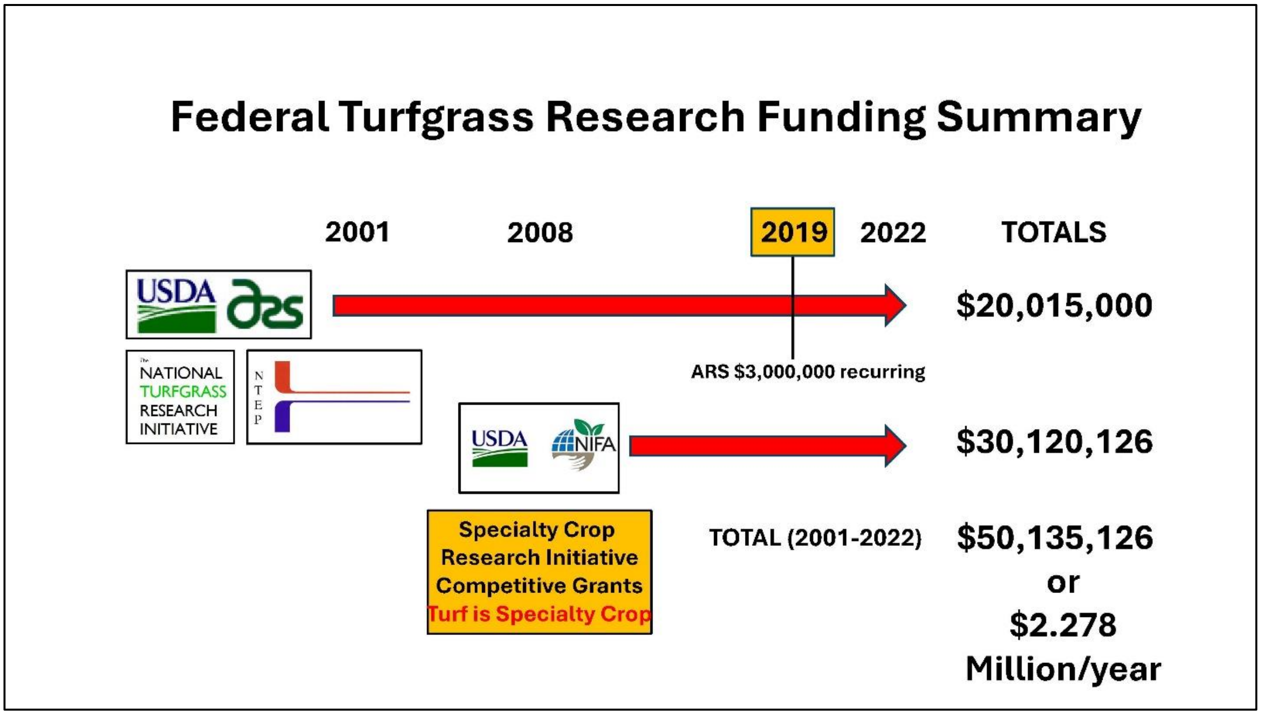
From 2000-2022, the National Turfgrass Federation (NTF) advocated for increased federal funding for turfgrass research. In 2004, as a part of this effort to increase research funding, NTF partnered with the turfgrass industry, USDA-Agricultural Research Service (ARS) and stakeholders to develop a National Turfgrass Research Initiative (NTRI) (http://www.turfresearch.org/initiative.htm).

Initially, Congress responded by providing new funding for USDA-ARS labs in Beltsville, MD and Logan, UT to work on lower input and water saving turfgrass germplasm. In 2019, with advocacy from NTF and National Golf Day participants, an additional $3,000,000 in *recurring* funds were allocated to

USDA-ARS. Four new research positions were created and funding was increased in several locations. As a result, ARS formed the Turfgrass Consortium, with turfgrass research added via several new locations by ARS.

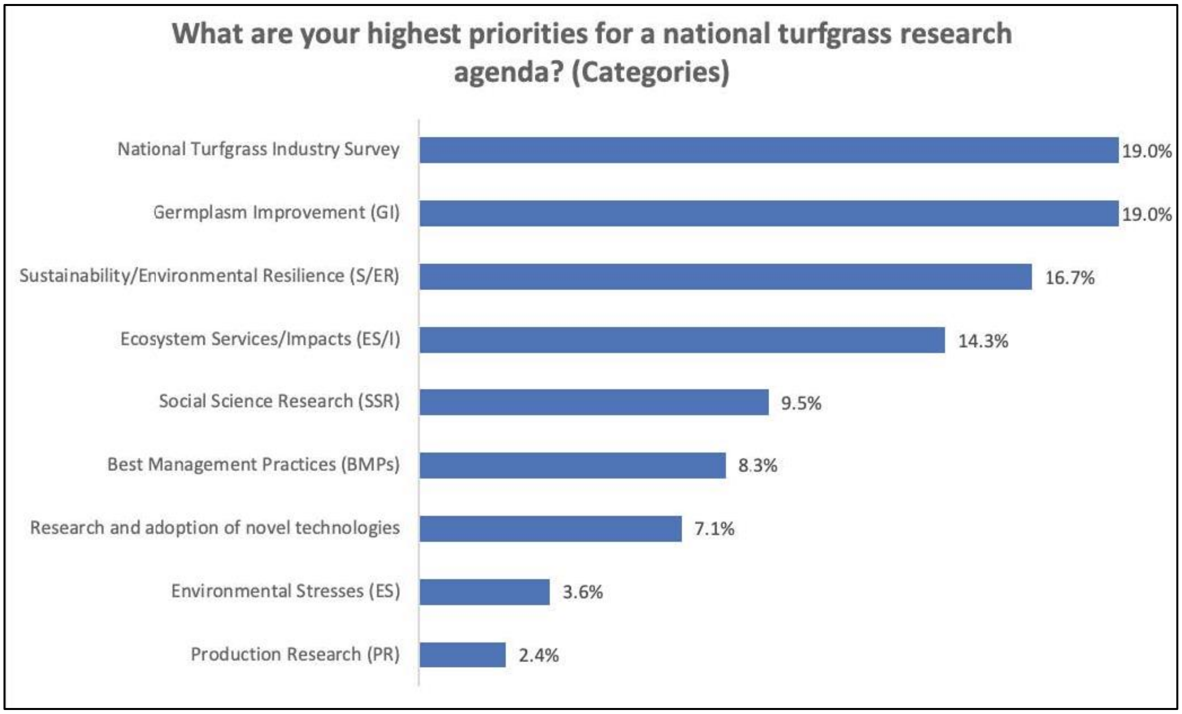


NTF successfully advocated for inclusion of language in the 2008 Farm Bill that documents the need for turfgrass research and the importance of NTRI. In addition, NTF, along with the Turfgrass Producers International advocated successfully for turfgrass to be listed as a specialty crop, such that turfgrass scientists and growers would be eligible to compete for the newly created Specialty Crop Research Initiative (SCRI) and Specialty Crop Block grant programs. To date, several turfgrass research grants have been selected for funding through SCRI (see graphic below), and a few projects through the Block Grant program. (https://nifa.usda.gov/funding-opportunity/specialty-crop-research-initiative-scri)



Even with these increases, federal government turfgrass research funding, including SCRI grants and USDA-ARS recurring dollars falls far below research funding for other comparably sized agricultural industries. To better address industry challenges, in September 2017, about fifty industry leaders participated in a turfgrass stakeholder summit, professionally facilitated and hosted by the National Turfgrass Federation (NTF) to discuss turfgrass research needs, priorities and funding strategies. Attendees included representatives from golf, parks, seed and sod, lawn and landscape, irrigation, equipment and the plant protection/enhancement industries, as well as university research, non-profits and the federal government.

At Turfgrass Stakeholder Summit II, held in 2020 and co-sponsored by NTF and the non-profit Foundation for Food and Agriculture Research (FFAR), forty industry leaders reviewed NTRI and provided current research needs. Information on the event found here: https://www.nationalturfgrassresearchinitiative.info/conference-outputs.html



Input from participants resulted in an updated National Turfgrass Research Initiative, which will soon be available on the web. The nine highest rated research needs are listed above. Note the top research needs include: 1) a national turfgrass survey, 2) germplasm improvement (including genomic studies to identify genes that infer drought, disease, cold and other tolerances in turfgrasses) and 3) studies to improve sustainability and environmental resistance. The summit also served as a 'Convening Event' for FFAR, developing innovative research programs that can be funded utilizing a 1:1 match of dollars from FFAR and industry.

The number one priority item determined by Stakeholder Summit II participants was the need for a National Turfgrass Survey, which will document acreage, scope and economic value as well as justify the need for increased federal research funding. On two separate occasions, we have applied but been unsuccessful in receiving a $1,000,000 USDA, Agricultural Marketing Service (AMS), Specialty Crop Multi State grant to conduct a turfgrass survey that will cover the U.S. not only nationally, but regionally and by state as well.

Using the current priorities, in 2023, we requested the following: 1) turfgrass survey language in the upcoming Farm Bill as well as $2,000,000 for the USDA, National Agricultural Statistics Service to conduct the survey, 2) a national turfgrass research initiative funded at $20,000,000 annually and 3) $5,000,000 annual funding for the National Park Service (NPS) turfgrass management and improvement strategy. We submitted our plan for a new NPS initiative, but our funding was not included in 2023 appropriations.

Progress in 2024

A new Farm Bill has yet to be passed by Congress. The current Farm Bill was extended through September 2024, but that extension expired. We are hopeful Congress will pass the new Farm Bill by early 2025. We will continue our advocacy efforts through 2025 as we watch the process.

NTRI funding through the Farm Bill is critical as turfgrass research is severely underfunded at the federal level. And a national turfgrass survey is important to explaining and justifying our need for research dollars to Congress and the Administration. Understanding the size (acreage), scope (number of athletic fields, parks, lawns, golf courses, miles of roadsides, etc.) and value of turfgrass are key metrics when discussing research funding requests and the impact on our industry. In addition, having these numbers is important to researchers applying for federal, state or local grants. Additionally, due to the cost, many turf associations have never conducted surveys of the industry in their state. Therefore, this project will also provide critical information for state and local advocacy. We are also continuing our efforts to identify competitive grant funding opportunities through other USDA-National Institute of Food and Agriculture (NIFA) programs.

Regarding the National Park Service initiative, the following favorable 'report' language was included in the FY24 appropriations bill, which gives NPS justification to request turfgrass management funding in their FY25 budget request.

Turfgrass Maintenance and Research.—*The Committee supports use of grasses and ornamental plants requiring less water, fertilizer, and other inputs for landscapes for the National Park Service and national historic sites, and encourages the National Park Service to utilize applied research from land grant university specialists; train personnel in establishing and maintaining sustainable landscapes; cooperate with Federal and State university researchers to identify drought, heat, and pest resistance grasses for national parks, maximize the amount of carbon captured by turfgrass systems and reduce carbon output through enhanced maintenance systems; and, enhance ornamental turfgrass contributions for the appearance of national parks, monuments, and historic sites.*

Based on this report language we secured in the FY24 appropriations bill, we requested funding for six demonstration projects in the FY25 budget. These projects focus on turf maintenance at historic sites from Montana to Georgia. Given the current congressional stalemate over FY25 appropriations, this initiative also remains in limbo.

In addition to the recently initiated organization of the Turfgrass Consortium, ARS genomic studies have continued as several turfgrass species have been sequenced or will likely have their genomes sequenced within the next 12-18 months. Much like the potential of genome sequencing to develop new treatment strategies for human health issues, this funding will contribute foundational information to aid the development of improved stress tolerant grasses.

NTF has helped organize stakeholders to provide input to USDA-ARS on a new program investigating ecosystem services provided by turfgrass (the fourth ranked priority above). ARS is working to develop a research plan that includes scientists from seven of their locations. This effort has potential to document and elevate the benefits of turf and hopefully lead to an increase in sustainability on golf courses and other turf sites.

USGA ID#: 2023-18-785

Title: Indexing the Soil Nutrient Status of Turfgrass Systems in Delaware and Comparing the Results to MLSN (Minimal Levels of Sustainable Nutrition) Guidelines

Project Leader: John Emerson
Graduate Committee: Erik Ervin, Amy Shober, Micah Woods

Affiliation: University of Delaware

Objectives: Analyze soil samples from good performing turfgrass throughout the state of Delaware and ensuingly compare the results with the Minimal Levels of Sustainable Nutrition (MLSN) guideline. The basis of the project is to evaluate the validity of the MLSN as a standard soil test interpretation method and to identify state-specific nutrient guidelines.

Start Date: May 2023

Project Duration: 1.5 years

Total Funding: $10,000

Summary:

1. Preliminary results indicate that the current MLSN guidelines are sufficient or even slightly more than necessary to safely support healthy turfgrass growth in the state of Delaware.
2. The University of Delaware's fertilizer recommendations for turfgrass systems may be significantly higher than what is required to produce good performing turf.
3. Traditional use of Sufficiency Levels of Sustainable Nutrients (SLAN) for turfgrass fertilizer recommendations is again proving to be illogical and wasteful.
4. More analytical work is needed to better understand and improve the quality of the data set with a special focus on how to address the issue of sample weighting.

Summary Text:

435 soil samples were collected throughout the state of Delaware (DE) in 2023 and 2024 (Figure 1). Golf course samples (greens, tees, fairways, and roughs) consisted of 87% of the data set. The remaining 13% came from athletic fields, residential and commercial lawns. 46% of the samples were from sand root zones, 17% from "push-up" root zones, and the remaining 37% came from native soils (Figure 2 and 3). Each sample, when possible, was assigned a turf quality (TQ) value rating of A, B, or C. Where A is exceptional TQ and is equivalent to a National Turfgrass Evaluation Program (NTEP) rating of an 8 or 9, B is 7 or 8, and C is 6 or 7. Where possible, Normalized Difference Vegetative Index (NDVI) scores were taken using a *GreenSeeker Handheld Crop Sensor*® (Trimble Agriculture). A plethora of metadata was collected for each site which included, location address of each sampling site, gps coordinates of the sampling site, soil type (sand, native, pushup), dominant soil series (WebSoilSurvey), dominant species of grass for each sample, and if clippings were collected or not (Y/N). Much of the metadata has yet to be statistically analyzed and work will continue with the aim to better understand the importance, relevance, and relationships of these points in the data set.

Of the metadata currently analyzed, the relationship between TQ and NDVI were poor at best (Figure 4). There could be a variety of reasons for the lack of interaction between the variables, but the most likely is that NDVI may not be a sufficient parameter to determine if a turf is performing well or not, with special regard to fine turf surfaces. NDVI may be useful for cultivar evaluation data, but for turf in the field it seems to provide little value, especially now that many turfgrass managers seem to be applying far less nitrogen than ever before.

To determine the Delaware Minimal Levels of Sustainable Nutrients (DEMLSN) we utilized the data analysis protocols from Woods et al (2016). The data set (n = 435) was filtered by pH (5.5 ≥ 8.5) and then by CEC (≤ 6.0 cmol/kg), cutting the data set to n = 288. The distribution of each element was then determined using the empirical cumulative distribution function (Figures 5 - 9). To create the DEMLSN guidelines, the nutrient concentration value which corresponds to the 10% probability on the distribution curve was chosen for each element (Table 1).

Even though the data set is generally strong there are a few glaring issues. Foremost are the potential problems in the number of samples per location. For example, there are locations with many samples and locations with only 1 or 2 samples. This lack of even representation may (or may not be) be hindering the clarity of the preliminary DEMLSN guidelines. For future analysis, Bayesian statistics will be used to model and evenly distribute the number of samples per location and then recalculate the DEMLSN guidelines.

Element	**MLSN (Mehlich 3 ppm)**	**DEMLSN (Mehlich 3 ppm)**
P	21	20
K	37	22
Mg	47	34
Ca	331	235
S	6	5

Table 1: DEMLSN Guidelines

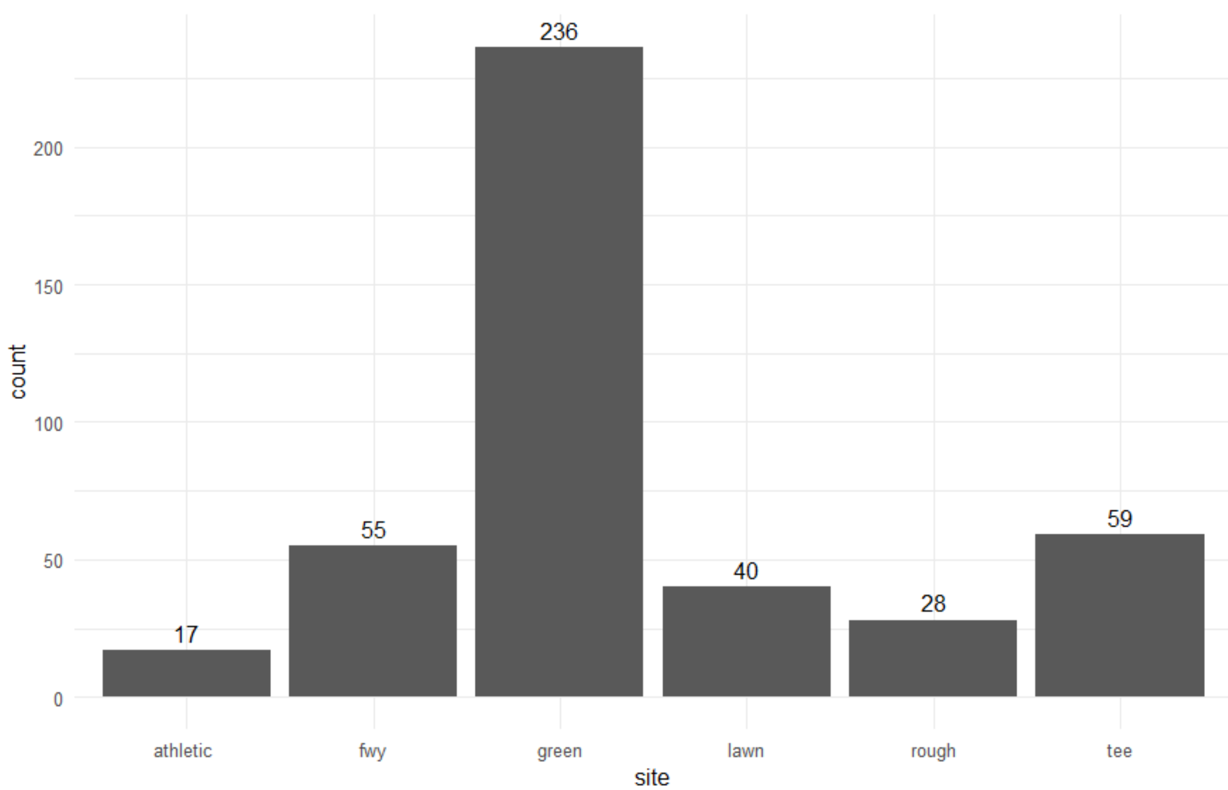


Figure 1: Sample counts by site use

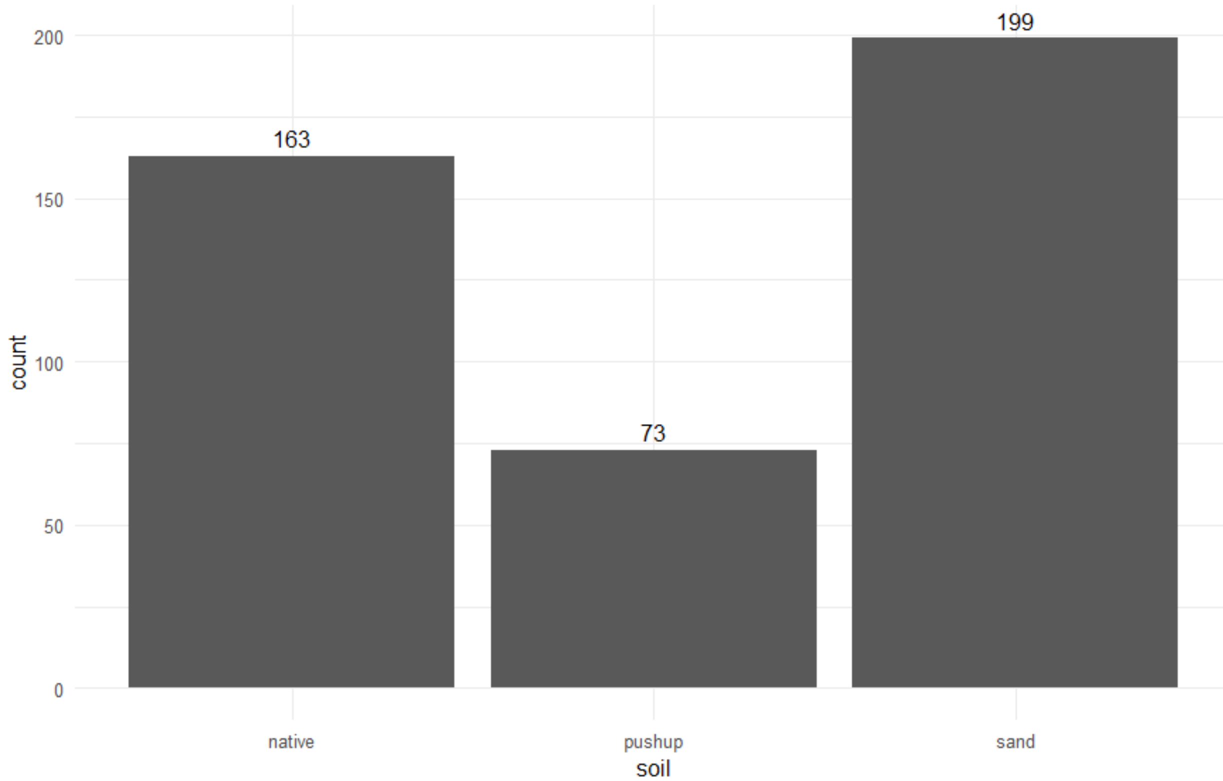


Figure 2: Sample counts by soil type

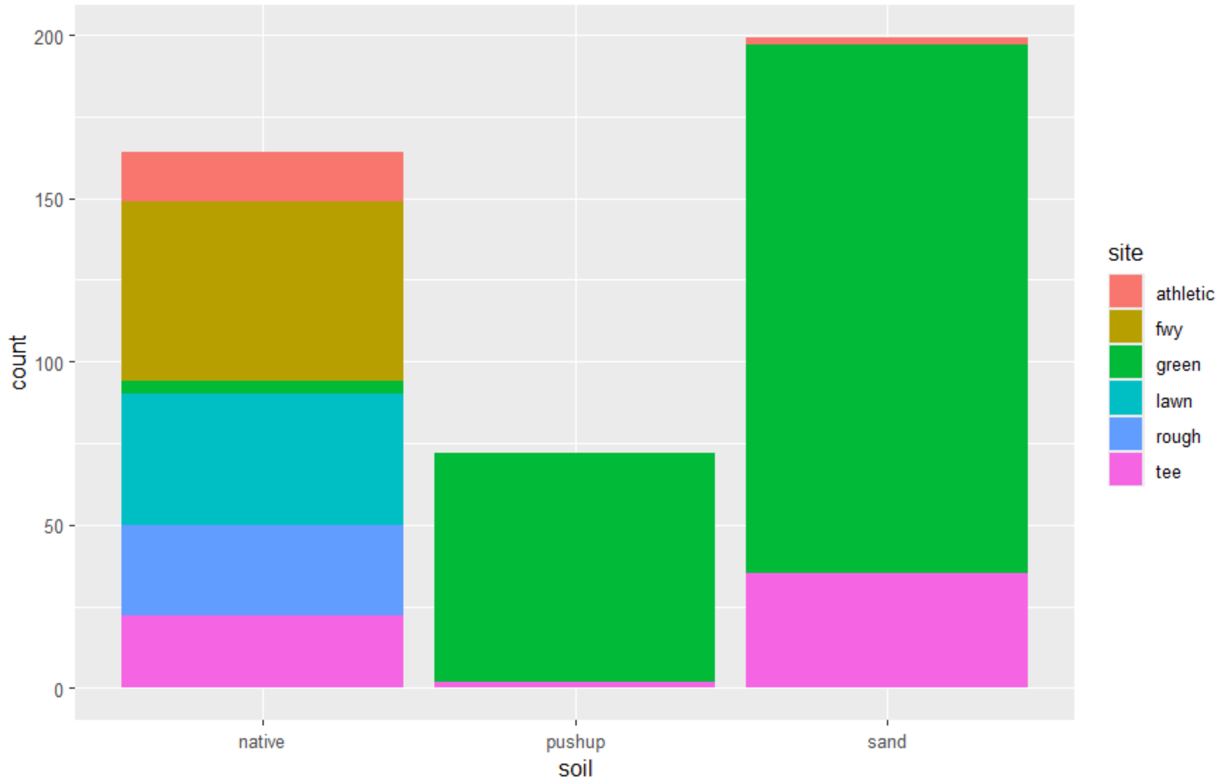
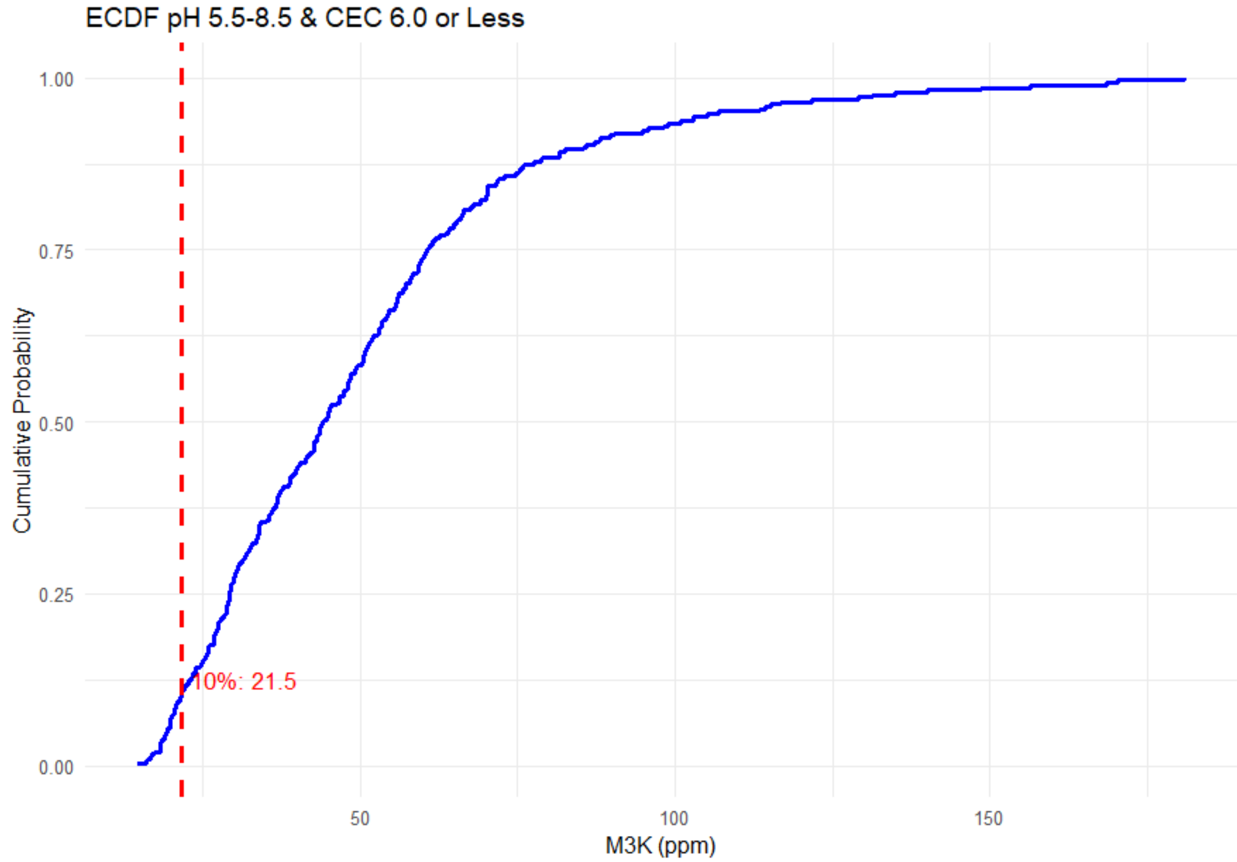
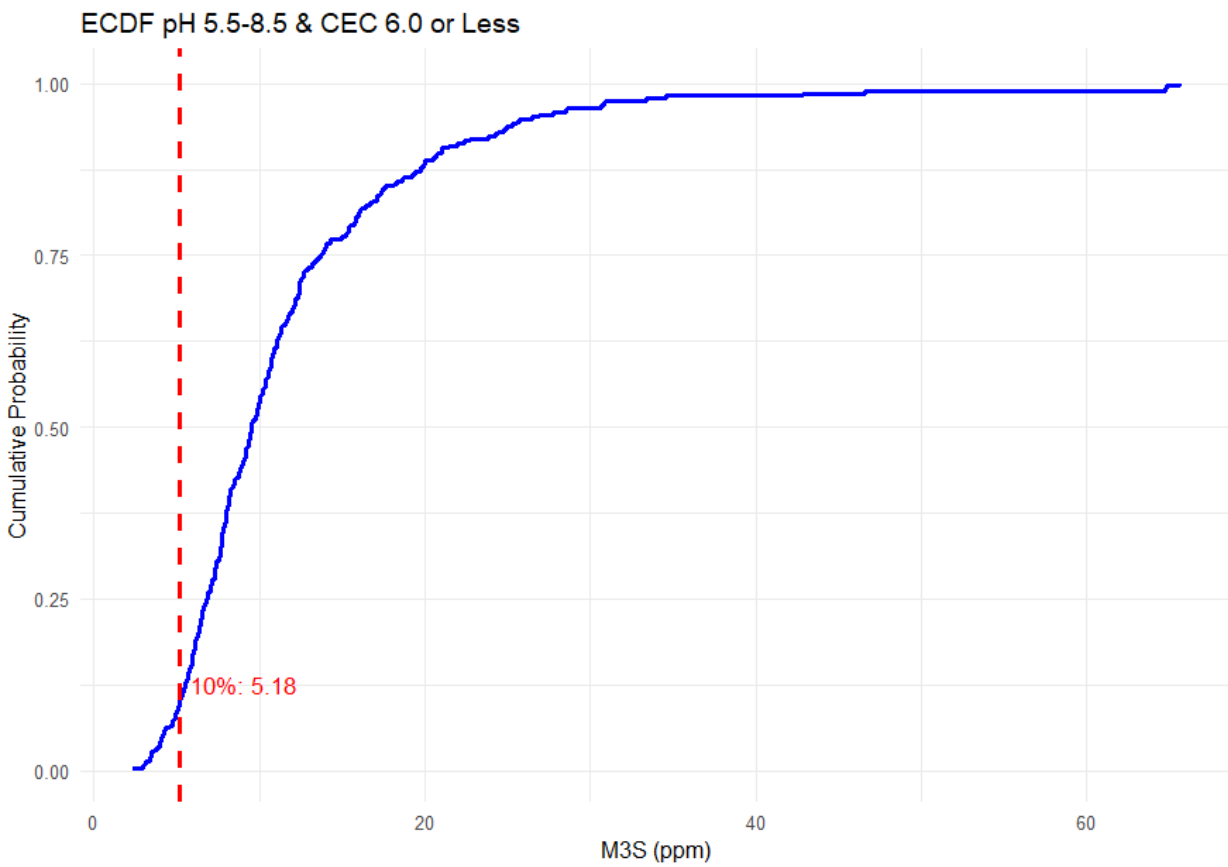


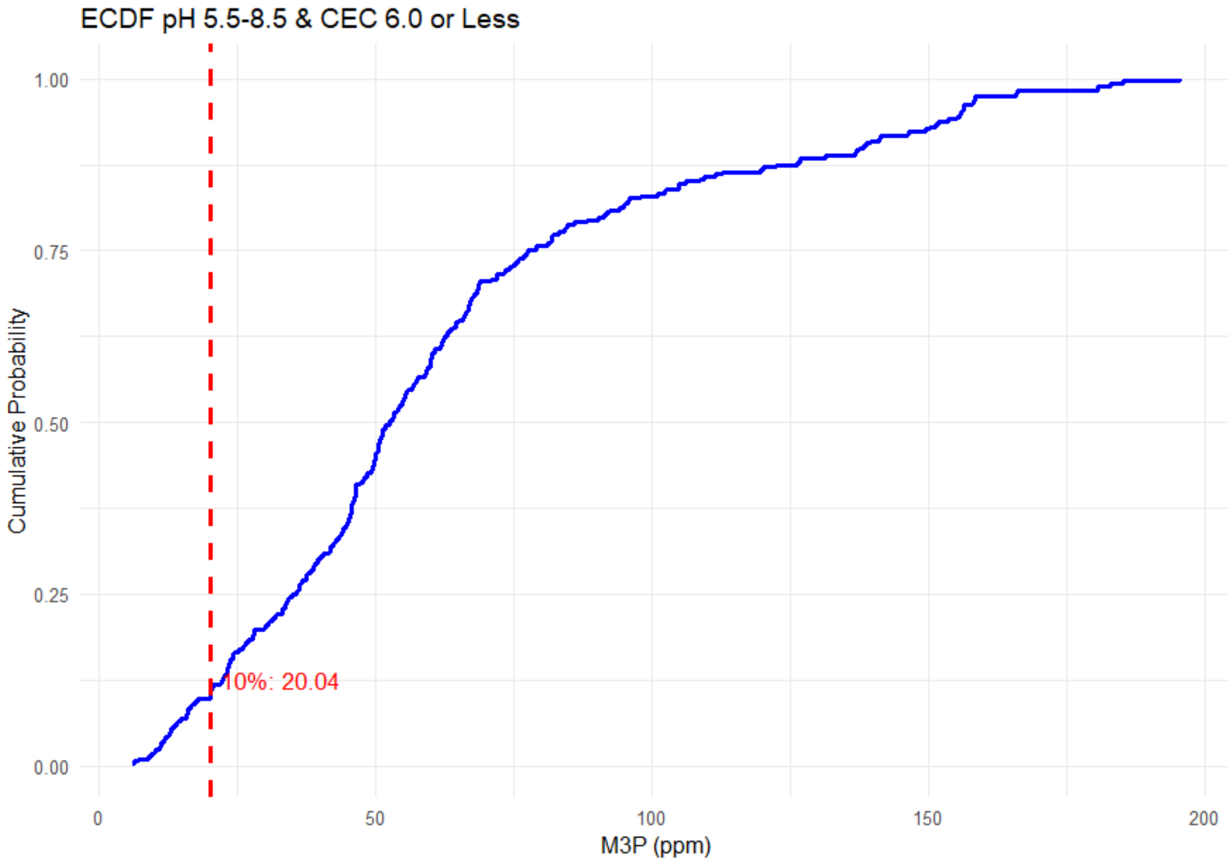
Figure 3: Site count by soil type

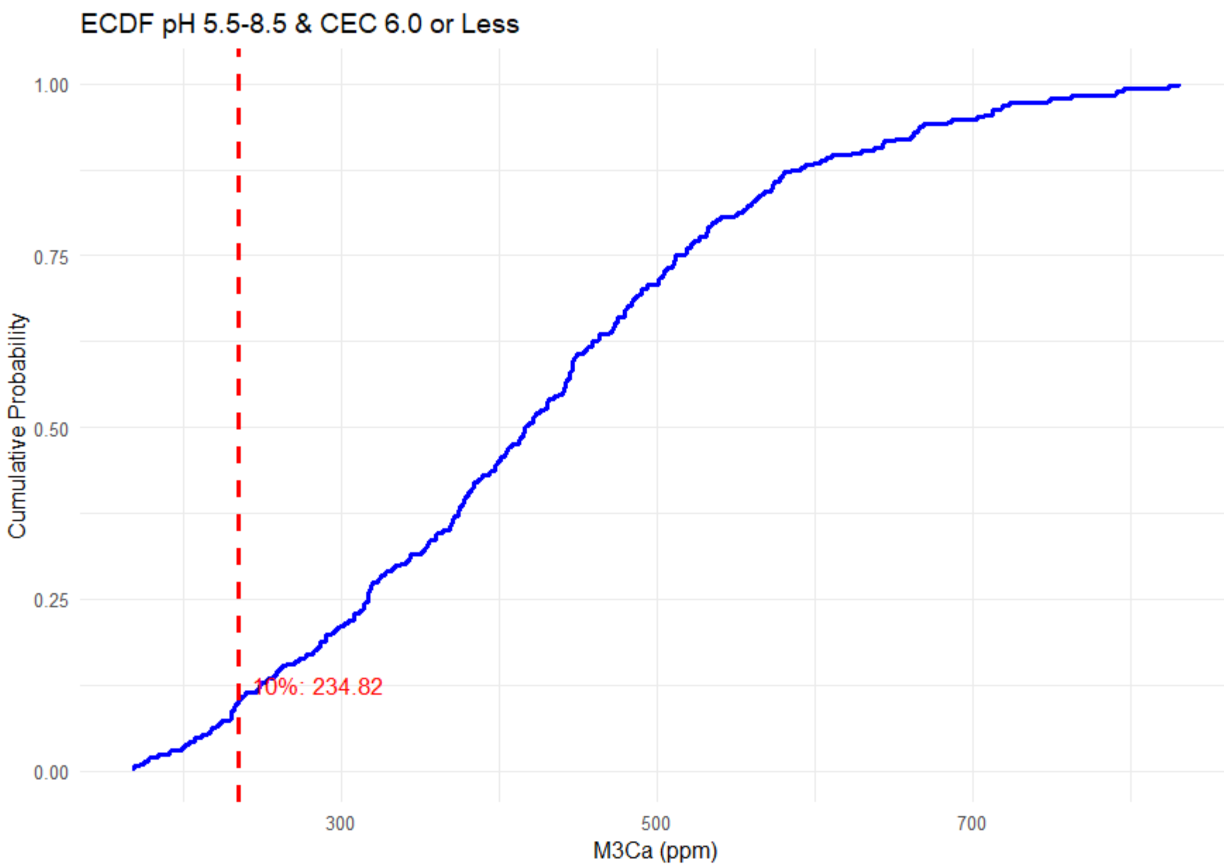
Figure 4: TQ vs NDVI

Figures 5, 6, 7, 8, and 9: Distribution of K, S, P, Ca, Mg

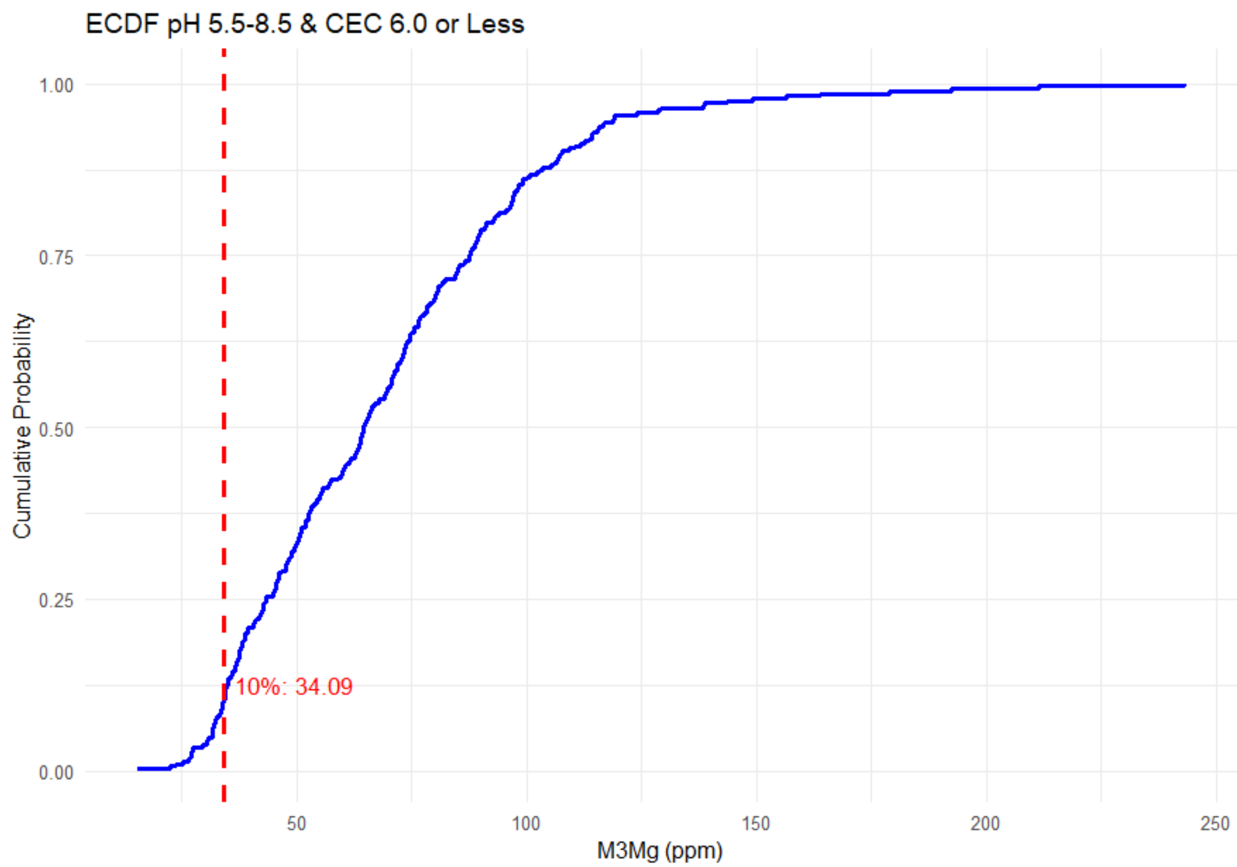



ECDF pH 5.5-8.5 & CEC 6.0 or Less
Cumulative Probability
1.00
0.75
0.50
0.25
0.00
10%: 5.18
0
20
40
60
M3S (ppm)


ECDF pH 5.5-8.5 & CEC 6.0 or Less
Cumulative Probability
1.00
0.75
0.50
0.25
0.00
10%: 20.04
0
50
100
150
200
M3P (ppm)



ECDF pH 5.5-8.5 & CEC 6.0 or Less
1.00
0.75
0.50
0.25
0.00
Cumulative Probability
10%: 234.82
300
500
700
M3Ca (ppm)



References

1. Woods MS, Stowell LJ, Gelernter WD. 2016. Minimum soil nutrient guidelines for turfgrass developed from Mehlich 3 soil test results. PeerJ Preprints 4:e2144v1 https://doi.org/10.7287/peerj.preprints.2144v1