

2025 PROGRESS REPORTS

Mike Davis Program for Advancing
Golf Course Management



2025 USGA Davis Program Progress Reports

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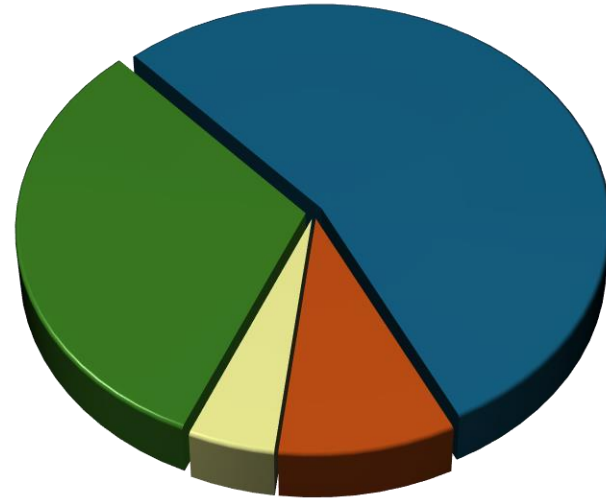
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2025 FINANCIAL OVERVIEW

- Davis Program 2025 Investment \$1,461,977
 - 32% Genetics & Breeding
 - 54% Integrated Turfgrass Management
 - 5% Environment
 - 9% Regional Grants



INTEGRATED TURFGRASS MANAGEMENT
\$796,615

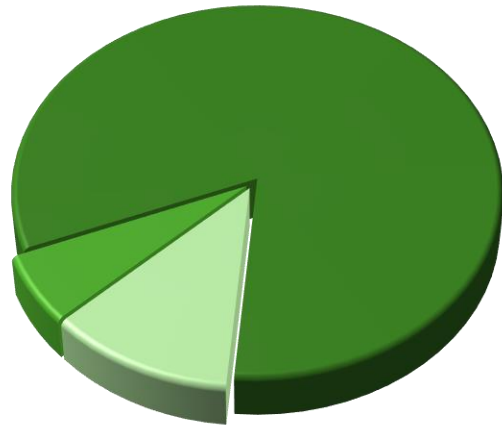
GENETICS & BREEDING
\$461,838

ENVIRONMENT
\$67,036

OUTREACH & REGIONAL GRANTS
\$136,489



GENETICS & BREEDING

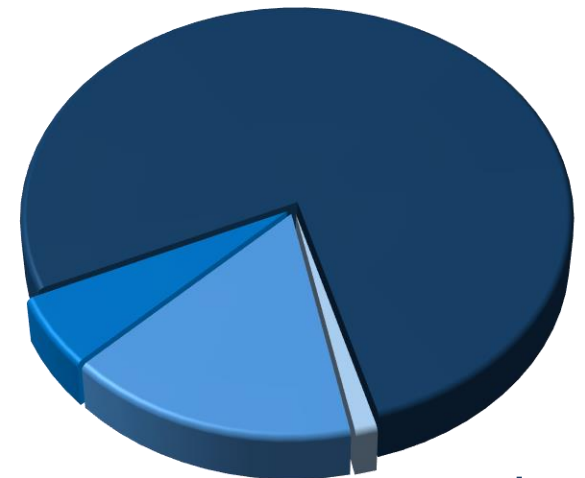


Warm-Season Grasses
\$380,686

Cool-Season Grasses
\$27,456

Bioinformatics
\$53,696

INTEGRATED TURFGRASS MANAGEMENT



Ecophysiology
\$614,792

Weed Science
\$43,691

Pathology
\$128,272

Entomology
\$9,860

USGA ID#: 2024-04-814

Project Leader: Jinyoung Barnaby, Scott Warnke

Affiliations: USDA-ARS, U.S. National Arboretum, Floral and Nursery Plants Unit

Title: Understanding Thatch Accumulation in Creeping and Colonial Bentgrass, and Its Association with Dollar Spot Disease Progression

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 Year: 2024

Project Duration: 3

Total Funding: \$90,640

Summary Points:

- The 277-line interspecific bentgrass population exhibited broad genetic variation for dollar spot severity.
- Spatially adjusted BLUP and Δ BLUP values revealed strong genetic control and transgressive segregation.
- Early progression patterns (Δ BLUP) differentiated stable, improving, and worsening genotypes.
- qPCR validation confirmed the accuracy of visual and BLUP-derived disease groups.
- Moderate-to-high heritability ($H^2 = 0.44\text{--}0.50$) demonstrated strong genetic contributions to disease severity.
- These high-resolution phenotypes provide a robust foundation for QTL mapping, parent selection, and future marker-assisted breeding.
- With completed genome assemblies and GBS data, the population is fully positioned for high-resolution QTL mapping in 2026.

RATIONALE:

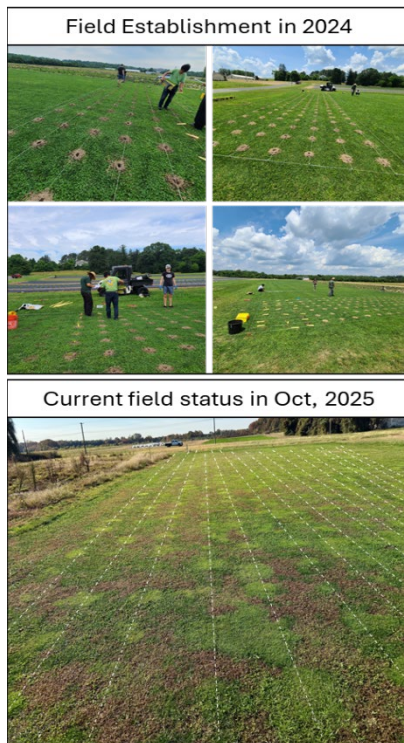
Dollar spot continues to be the most persistent and economically important disease in cool-season grasses. Breeding turfgrass with reduced disease severity and lower management needs is strengthened by understanding how structural traits such as rhizome and stolon development shape long-term performance and how these traits relate to disease progression and thatch accumulation. Although the phenotypic characteristics of creeping and colonial bentgrass are well documented, the genomic relationships connecting vegetative architecture, thatch accumulation, and disease tolerance are still not fully resolved. This project addresses that gap by integrating multi-year phenotyping with genomic resources to dissect the genetic basis of rhizome/stolon development, dollar spot tolerance, and thatch formation.

In Year 1, the full 277-line creeping \times colonial bentgrass population was established in the field, and greenhouse assessments of rhizomes and stolons were completed. In Year 2, we expanded vegetative assessments to the field and executed a population-wide, controlled dollar spot inoculation to generate the core disease phenotypes needed for resistance classification and future QTL mapping. A second

disease trial will be conducted to strengthen multi-year repeatability and improve precision in estimating resistance loci. Completion of both parental genome assemblies and GBS data generation provides the genomic foundation for trait mapping.

In the final project year, we will quantify thatch accumulation across the entire population and evaluate its relationship with the vegetative traits from Year 1 and the disease responses documented this year. Integrating rhizome/stolon growth, two years of disease phenotyping, and thatch measurements will enable a unified multi-trait QTL analysis. This effort will deliver genetic insights needed to develop low-input *Agrostis* germplasm with reduced dollar spot damage and lower thatch production.

MATERIALS AND METHODS:



Plant Materials and Clonal Replication. An interspecific bentgrass mapping population of 277 hybrid lines was generated from a cross between the susceptible creeping bentgrass cultivar ‘Providence’ and the tolerant colonial bentgrass cultivar ‘BCD’. Each hybrid was clonally propagated into six ramets, and each parent into 30 ramets, to provide genetically identical replicates. Ramets were grown under uniform conditions and then established in a randomized field grid defined by row–column coordinates.

Dollar Spot Inoculation. Dollar spot was initiated using a standardized inoculation protocol. On June 3, 2025, three oat grains colonized by *Clarireedia* spp. were placed at the center of each plant. Every hybrid and each parental check received identical inoculum to standardize pathogen exposure. No fungicides were applied, and field moisture was maintained to favor infection.

qPCR Quantification of *Clarireedia* spp. To validate phenotypic groupings, nine genotypes representing tolerant (T), intermediate (I), and susceptible (S) classes were sampled two weeks after inoculation. DNA was extracted, and pathogen load was quantified by qPCR. Ct values were transformed using 2^{-Ct} , and group differences were tested using one-way ANOVA.

Image Collection and Disease Severity Scoring. Top-view images were collected at Week 2 (June 17) and Week 3 (June 27). Visual disease severity was assigned to five categories: **1**, No visible symptoms; **2**, <33% symptomatic; **3**, 33–66% symptomatic; **4**, 66% symptomatic; **5**, Missing/dead (excluded). Categories 1–4 were converted to proportional scores (0, 0.33, 0.66, 1.0).

Spatial Mapping. To assess spatial heterogeneity in disease pressure, categorical scores were mapped to the field grid and visualized as green-to-red heatmaps. These raw maps were used to evaluate micro-environmental effects prior to mixed-model adjustment.

Data Processing. Week 2 and Week 3 data were merged into a long-format table containing genotype, ramet, sampling week, spatial (row/column) coordinates, and proportional scores. Ramet IDs were retained for data tracking but treated as part of the residual error structure rather than explicit model terms.

Mixed Model and Spatial Adjustment. BLUP (Best Linear Unbiased Prediction) is widely used in quantitative agriculture and plant breeding to summarize genotype performance in field trials. Because field trials inevitably contain spatial variation such as row, column, and other micro-environmental effects,

BLUP helps adjust for these influences and generate estimates that better represent each genotype's underlying response. This approach improves the reliability of genotype comparisons and provides a consistent basis for downstream analyses, including group evaluation and QTL mapping. BLUP values were obtained from a linear mixed model fitted in JMP Pro using Restricted Maximum Likelihood (REML; a statistical method to estimate variance components in mixed models). Week was treated as a fixed effect. And genotype, row, and column were modeled as random effects to capture genetic variation and spatial heterogeneity: $y_{gijt} = \mu + W_t + G_g + R_i + C_j + \epsilon_{gijt}$. Genotype BLUPs were extracted from the Random Effect Predictions output and used as spatially and temporally adjusted estimates of disease severity.

Temporal Trajectory Classification. To characterize week-to-week disease responses, week-2 BLUP values were plotted against Δ BLUP (Week 3 – Week 2). Dotted reference lines at ± 0.05 on each axis were added to create four interpretive trajectory regions. Genotypes with low $BLUP_{WK2}$ (< -0.05) and negative Δ BLUP (< -0.05) were classified as avoidance-like, reflecting low initial disease and limited progression. Lines with high $BLUP_{WK2}$ (> 0.05) but negative Δ BLUP were classified as tolerance-like, indicating recovery or stabilization following early infection. Genotypes with low $BLUP_{WK2}$ but positive Δ BLUP (> 0.05) were categorized as delayed susceptible, while those with high $BLUP_{WK2}$ and positive Δ BLUP represented fully susceptible trajectories. Genotypes within the ± 0.05 band on either axis were considered intermediate. This framework allowed temporal resistance patterns to be quantified across the hybrid population.

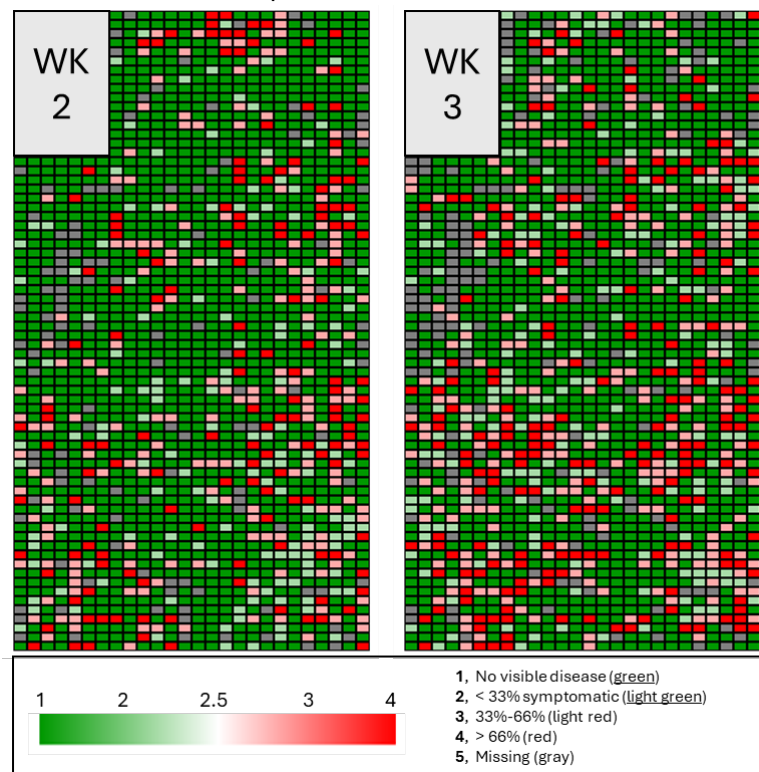
Heritability Estimation. Broad-sense heritability (H^2) of dollar spot severity was estimated for each rating date using a mixed linear model implemented in JMP Pro v17 (SAS Institute Inc., Cary, NC). Each genotype was represented by six independent clonal field plots, which were treated as the experimental units. To account for spatial heterogeneity across the trial area, Row and Column were included as random positional effects, with Genotype modeled as a random genetic effect: $Y_{ijt} = \mu + G_i + Row_j + Column_k + \epsilon_{ijt}$, where G_i represents genotypic variance and Row and Column capture field-level microenvironmental variation. Variance components were obtained from the Random Effects Covariance Parameter Estimates table in JMP. Broad-sense heritability on a line-mean basis was calculated as: $H^2 = \sigma^2_G / (\sigma^2_G + \sigma^2_e/r)$, where σ^2_G is the estimated genetic variance, σ^2_e is the residual variance, and $r = 6$ is the number of clonal plots per genotype.

RESULTS:

Spatial Variation Demonstrates the Need for Mixed-Model Adjustment.

Despite uniform inoculation, the Week 2 and Week 3 heatmaps displayed non-genetic spatial structure across the field plot (Figure 1).

Figure 1. Spatial distribution of dollar spot severity at Week 2 and Week 3 following uniform individual inoculation. Each tile represents one of 277 hybrid lines or the tw



o parental checks. Disease severity was scored on a 1–4 categorical scale (1 = no visible disease; 2 = <30% symptomatic; 3 = 30–66% symptomatic; 4 = >66% symptomatic; 5 = missing). Despite identical inoculation, micro-environmental variability produced clear spatial structure across the field. Week 2 exhibited mostly low severity with localized hotspots, whereas Week 3 showed broader, continuous areas of high severity, reflecting epidemic intensification. These raw maps highlight the need for spatial mixed-model adjustment to accurately estimate genotype effects.

Week 2 scores were mostly in the 1–2 range, with scattered pockets of higher severity (categories 3–4). These localized early hotspots indicate that subtle differences in moisture retention, airflow, shading, or drainage influenced disease expression even under standardized pathogen application. By Week 3, disease pressure increased across much of the field plot, and several zones showed clear upward shifts in severity category. Symptomatic plots became more numerous and more continuous across multiple rows and columns, demonstrating rapid epidemic progression under conducive environmental conditions. At the same time, clusters of consistently healthy plots remained, reflecting inherent genetic resistance independent of spatial effects. The presence of these spatial gradients—arising even after equal inoculation—demonstrates the necessity of using a spatial mixed model. Incorporating row and column effects is essential to remove micro-environmental bias and produce reliable BLUP-adjusted phenotypes used in all downstream analyses.

Adjusted Phenotypes and Genetic Variation for Dollar Spot Severity. BLUP-adjusted severity spanned –0.15 to 0.35, forming a broad unimodal distribution across the interspecific population (Figures 2–3). The tolerant parent ‘BCD’ ranked among the most resistant ~12% of lines, whereas ‘Providence’ ranked near the population midpoint (~51%). Several hybrids exceeded the tolerant parent, demonstrating transgressive segregation and confirming that both parents contributed favorable alleles. The ranked BLUP curve (Figure 3) highlights the wide phenotypic spread and underscores the strong genetic variability available for selecting superior lines and for downstream QTL discovery.

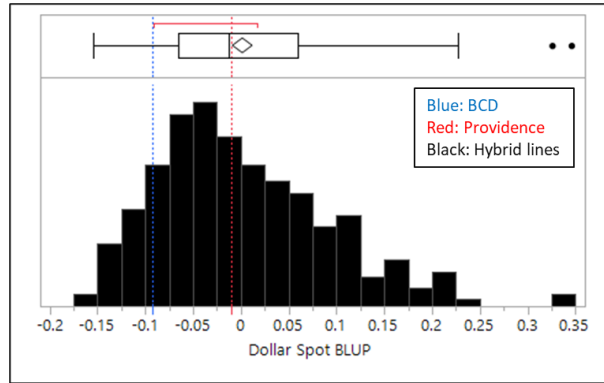


Figure 2. Histogram and boxplot of BLUP-adjusted dollar spot severity across the interspecific bentgrass population. Vertical lines show parental BLUP values (‘BCD’ in blue; ‘Providence’ in red). BLUPs represent spatially and temporally adjusted mixed-model estimates of disease severity.

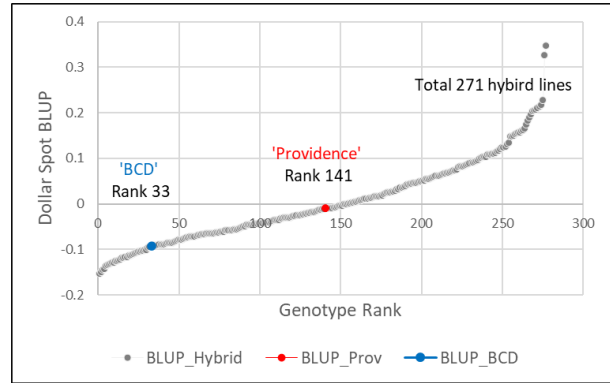


Figure 3. Ranked BLUP plot from most tolerant (left) to most susceptible (right). Each point represents a genotype’s adjusted disease severity score. ‘BCD’ (blue) ranks among the most resistant; ‘Providence’ (red) ranks near the population midpoint. Several hybrids outperform ‘BCD’, illustrating transgressive segregation for dollar spot tolerance.

Temporal Disease Progression. Week-specific BLUPs revealed substantial variation in dollar spot trajectories from week 2 to week 3 across the hybrid population (Figures 4–5). Δ BLUP values spanned a wide range—from noticeable improvement (below –0.15) to clear symptom escalation (above 0.30)—indicating that genotypes differ not only in initial disease levels but also in how they respond once infection is underway. Plotting Δ BLUP relative to week-2 severity (Figure 4) separated the population into interpretable response patterns. Genotypes with low week-2 BLUP values and minimal progression formed an avoidance-like region, consistent with limited early infection or slower pathogen establishment.

In contrast, several lines that began with moderate disease still showed negative Δ BLUP values, reflecting recovery or maintenance of green tissue despite ongoing disease pressure—a tolerance-like behavior. A subset of genotypes maintained low disease initially but then worsened between weeks 2 and 3, representing delayed susceptibility. Lines in the fully susceptible region exhibited both higher initial severity and continued decline. Population-level patterns supported these trajectory groupings. The Δ BLUP distribution was nearly symmetrical (**Figure 5**), with approximately one-third of genotypes improving or recovering, one-third remaining stable, and one-third worsening. The parental checks aligned with these trends: ‘BCD’ fell within the improved/recovered group, whereas ‘Providence’ clustered with worsening trajectories, providing practical biological anchors for interpreting hybrid responses. Together, these data demonstrate that the population segregates for multiple components of dollar spot response. Early-stage avoidance and later-stage stability or recovery are both detectable and quantifiable in this framework, offering a clearer path toward distinguishing tolerance from avoidance mechanisms. While the underlying physiological basis remains to be validated, the presence of distinct temporal trajectories suggests that combining genotypes exhibiting both early suppression and post-infection recovery could strengthen long-term disease performance in bentgrass.

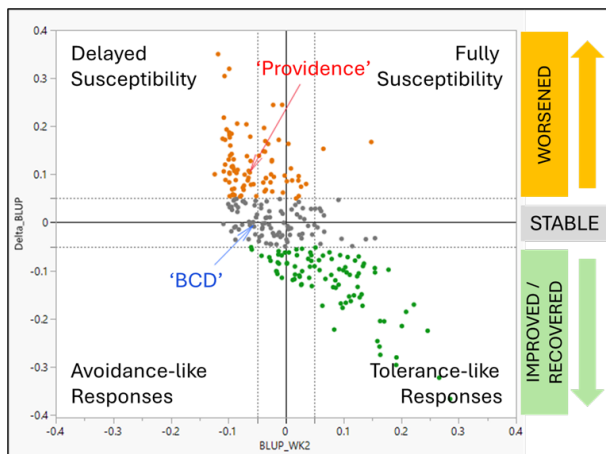


Figure 4. Figure 4. Dollar spot progression relative to initial disease severity. Progression was quantified as the change in BLUP values from week 2 to week 3 (Δ BLUP = BLUP_WK3 – BLUP_WK2) and plotted against week-2 BLUP values. Each point represents an individual genotype. Two horizontal reference lines at Δ BLUP –0.05 and Δ BLUP 0.05 delineate thresholds used to classify temporal response categories: Improved/Recovered (green; Δ BLUP < –0.05), No Change (grey; $-0.05 \leq \Delta$ BLUP ≤ 0.05), and Worsened (orange; Δ BLUP > 0.05). Vertical dotted reference lines at week-2 BLUP –0.05 and 0.05 further divide the plot into four trajectory regions. Genotypes with low week-2 BLUP and negative Δ BLUP (lower-left quadrant) exhibit avoidance-like responses, showing low initial disease and little progression. Genotypes with higher week-2 BLUP but negative Δ BLUP (lower-right quadrant) display tolerance-like responses, beginning with more disease but recovering or stabilizing. The upper-left quadrant reflects delayed

susceptibility, where low initial disease is followed by rapid worsening. The upper-right quadrant represents fully susceptible trajectories, characterized by high initial disease and continued decline. Parental cultivars ‘BCD’ (tolerant) and ‘Providence’ (susceptible) are highlighted to anchor temporal responses relative to the hybrid population.

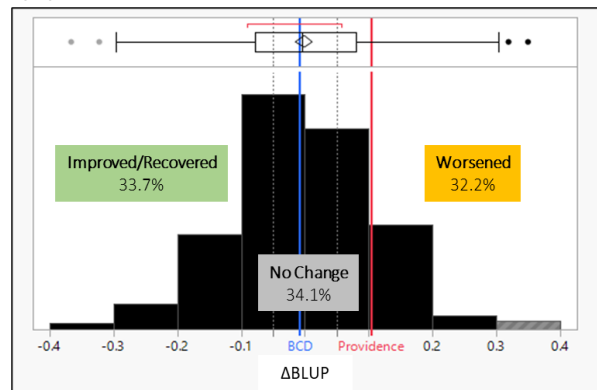


Figure 5. Distribution Δ BLUP values across the population. Histogram shows population-wide changes in disease severity between Week 2 and Week 3, with Δ BLUP values grouped into three classes: Improved/Recovered (green; Δ BLUP < –0.05), No Change (grey; $-0.05 \leq \Delta$ BLUP ≤ 0.05), and Worsened (orange; Δ BLUP > 0.05). Percentages indicate the proportion of genotypes within each category. Vertical reference lines mark Improved/Recovered (green; Δ BLUP < –0.05), No Change (grey; $-0.05 \leq \Delta$ BLUP ≤ 0.05), and Worsened (orange; Δ BLUP > 0.05). Δ BLUP values for parental cultivars ‘BCD’ (tolerant) and ‘Providence’ (susceptible) illustrate their progression relative to the broader hybrid population.

Heritability Confirms Genetic Control. Mixed-model analysis revealed significant genotypic variation for dollar spot severity at both Week 2 and Week 3 (Wald $p < 0.0001$). After adjusting for spatial variation using row and column effects, broad-sense heritability values were moderate to moderately high, ranging from 0.44 to 0.50 (**Table 1**). Heritability was highest at Week 2 ($H^2 = 0.50$), demonstrating that early-stage

lesion development was strongly influenced by inherent genetic resistance. By Week 3, heritability decreased slightly ($H^2 = 0.44$), reflecting greater environmental influence as disease intensity increased across the field. These results indicate that early disease ratings capture intrinsic resistance differences most effectively, while Week 3 ratings still maintain sufficient genetic signal for detecting major resistance loci. The combination of moderate-to-high heritability and spatially adjusted mixed models supports the use of these phenotypes for high-resolution QTL mapping, parent selection, and evaluation of resistance levels within the interspecific hybrid population.

Table 1. Variance components and broad-sense heritability (H^2) estimates for dollar spot severity at Week 2 and Week 3. Variance components were obtained from mixed models including genotype and spatial row–column effects as random factors. Heritability was calculated on a line-mean basis using six clonal plots per genotype.

Component	Week 2	Week 3	Description
Genotype variance (σ^2G)	0.0149707	0.0146567	Genetic variation among bentgrass hybrids
Residual variance (σ^2e)	0.0895039	0.1121381	Microenvironmental and unexplained variance
Replicates (r)	6	6	Clonal plots per genotype
H^2 (line-mean)	0.50	0.44	Broad-sense heritability

Molecular Validation of Disease-Response Groups. qPCR analysis of nine representative genotypes confirmed that molecular pathogen levels were consistent with visual and BLUP-based classifications (**Figure 6**). Susceptible genotypes had the highest pathogen loads, intermediate lines displayed moderate levels, and tolerant lines exhibited minimal detectable pathogen presence (ANOVA $p = 0.00011$). Field images of the same plants mirrored these molecular patterns. This independent validation strengthens confidence in the resistance classifications.

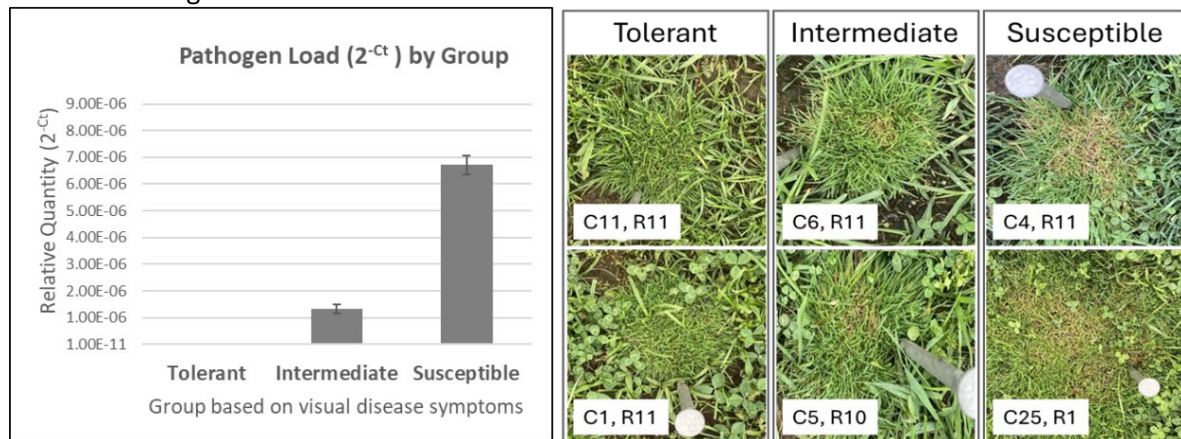


Figure 6. Molecular and visual validation of tolerant, intermediate, and susceptible groups. Left: Relative *Clariireedia* load (2^{-Ct}) measured from nine genotypes selected to represent the tolerant (T), intermediate (I), and susceptible (S) classes defined in Figures 1–4. Bars show group means \pm SEM. Susceptible genotypes exhibited substantially higher pathogen accumulation compared with intermediate and tolerant lines (ANOVA, $p = 0.00011$). Right: Representative field images of the same genotypes used for qPCR analysis. Visual symptom severity closely matched the molecular pathogen load, with tolerant lines showing minimal blighting, intermediate lines showing patchy early decline, and susceptible lines displaying pronounced necrotic centers.

FUTURE EXPECTATIONS:

The upcoming project year will complete the multi-trait framework. Thatch accumulation will be quantified across all hybrids and integrated with the vegetative traits evaluated in Years 1–2 and the disease phenotypes from this year. A second controlled disease trial will increase multi-year stability and enhance QTL resolution. Chromosome-scale genome assemblies for creeping and colonial bentgrass are now complete. The creeping bentgrass genome manuscript has been accepted (minor revisions) in Scientific

Data, and the colonial bentgrass manuscript is in preparation. GBS data for all 277 hybrids have been generated. With structural trait data, two years of disease phenotypes, finalized reference genomes, and dense genotyping, the Year 3 dataset will enable comprehensive QTL mapping. These outcomes will support development of next-generation bentgrass germplasm with reduced inputs, improved stress resilience, and enhanced long-term turf performance.

Impact and Overall Summary:

This year's work established the full phenotypic foundation needed to dissect the genetic basis of turf architecture, disease tolerance, and management-relevant traits. The interspecific population displayed wide and exploitable genetic variation for rhizome/stolon development, dollar spot severity, and temporal resistance dynamics. Spatially adjusted BLUPs, Δ BLUP progression metrics, and qPCR validation produced a high-resolution, biologically consistent classification of resistant, intermediate, and susceptible groups. Several hybrids outperformed the tolerant parent, demonstrating strong breeding potential. Together, these datasets position the population as a powerful resource for multi-trait QTL mapping in Year 3. The project is now fully prepared to deliver genetic markers and mechanistic insights that support breeding of low-input, resilient *Agrostis* cultivars.

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:

- A field nursery established with 147 selected progenies was evaluated for spring greenup, turfgrass quality under drought stress, and fall color retention using drone images and visual ratings.
- Five genotypes were selected based on a comprehensive analysis combining information on spring green-up, turfgrass quality under drought stress, establishment vigor, and fall color retention.

Summary Text:

Bermudagrass is the most extensively used turfgrass in the U.S. transition zone, covering approximately 45% of the turf acreage on golf courses (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-type bermudagrass cold hardiness since the 1980s. 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, ‘OKC3920’ in 2022, and ‘OSU1337’ in 2025. However, none of these cultivars has a drought resistance level comparable to some drought-resistant cultivars used in the South. Accordingly, our long-term goal is to breed, test, and develop interspecific hybrid cultivars improved in drought resistance, cold hardiness, and high turfgrass quality.

The major objective of this project is to develop common bermudagrass germplasm that combines cold hardiness, drought resistance, and turfgrass quality traits. Eight reciprocal single crosses between cold-hardy and drought-resistant common bermudagrass parents were made in

2023. From these and previous crosses, we developed 1,514 progenies. Of the progenies, 147 genotypes were selected for further testing after examinations with DNA markers and investigations on root traits of plants grown in a greenhouse. These plants were established with a randomized complete block design with 3 replicates, along with two parents (A12400 and A10202) in a field nursery in 2024. In 2025, irrigation was halted in the summer months to provide for on-field drought conditions. Spring green-up, turfgrass quality with and without drought stress, and fall color retention were visually rated (Figure 1). Drone images were taken for high-throughput evaluation (Figures 2 and 3). Additional data was collected through digital images. Statistical analyses were performed to identify top-performing entries.



Figure 1. Mr. Anit Poudel, an MS graduate student visually rated turfgrass quality of the replicated plots on the Agronomy Farm of Oklahoma State University, Stillwater, OK in summer 2025.

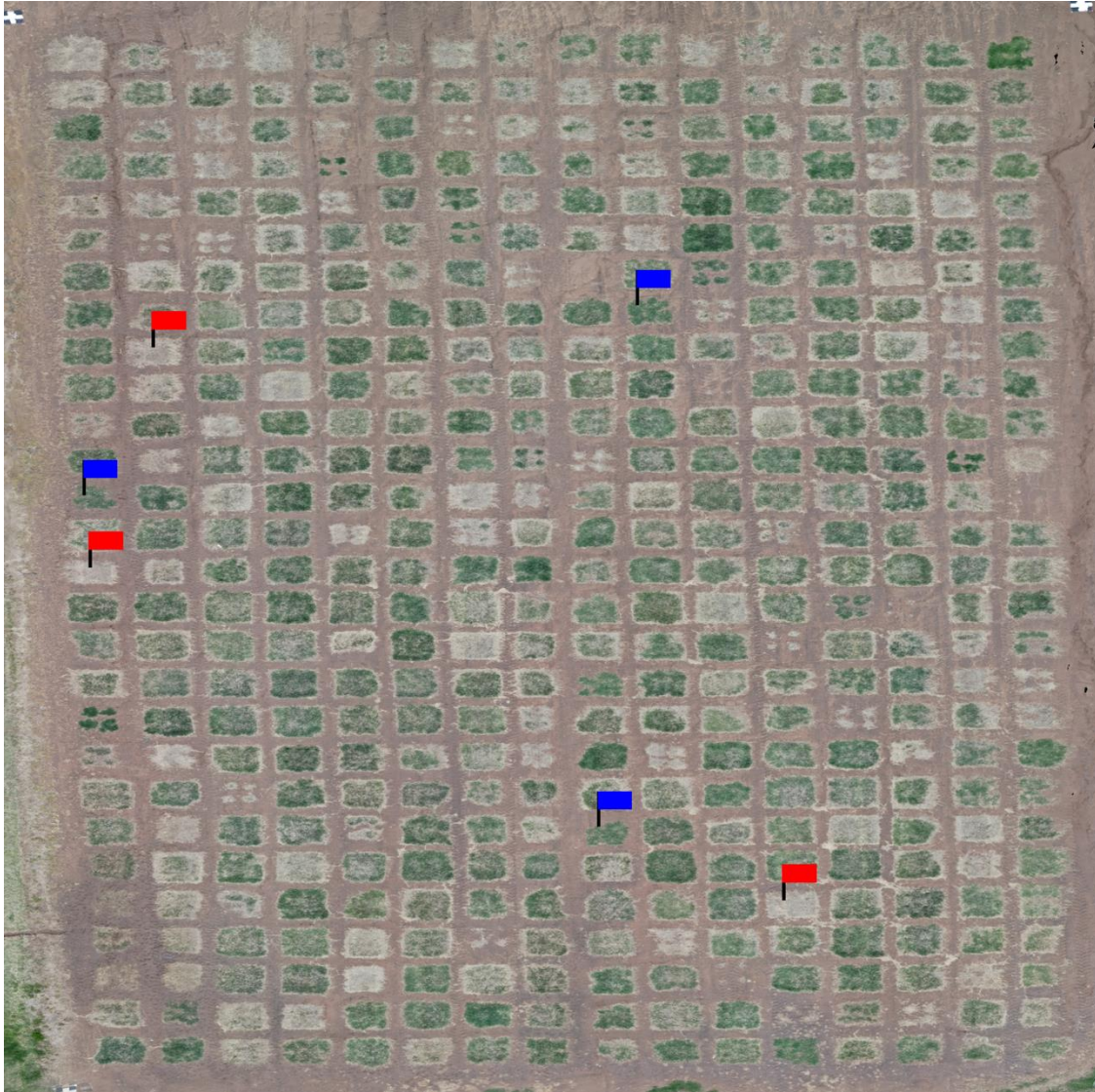


Figure 2. Drone imagery was collected to evaluate spring green-up on April 7, 2025. Blue flags were labeled for three plots of A12400, a cold-hardy parent, while red flags were labeled for plots of A10202, a drought-resistant parent.

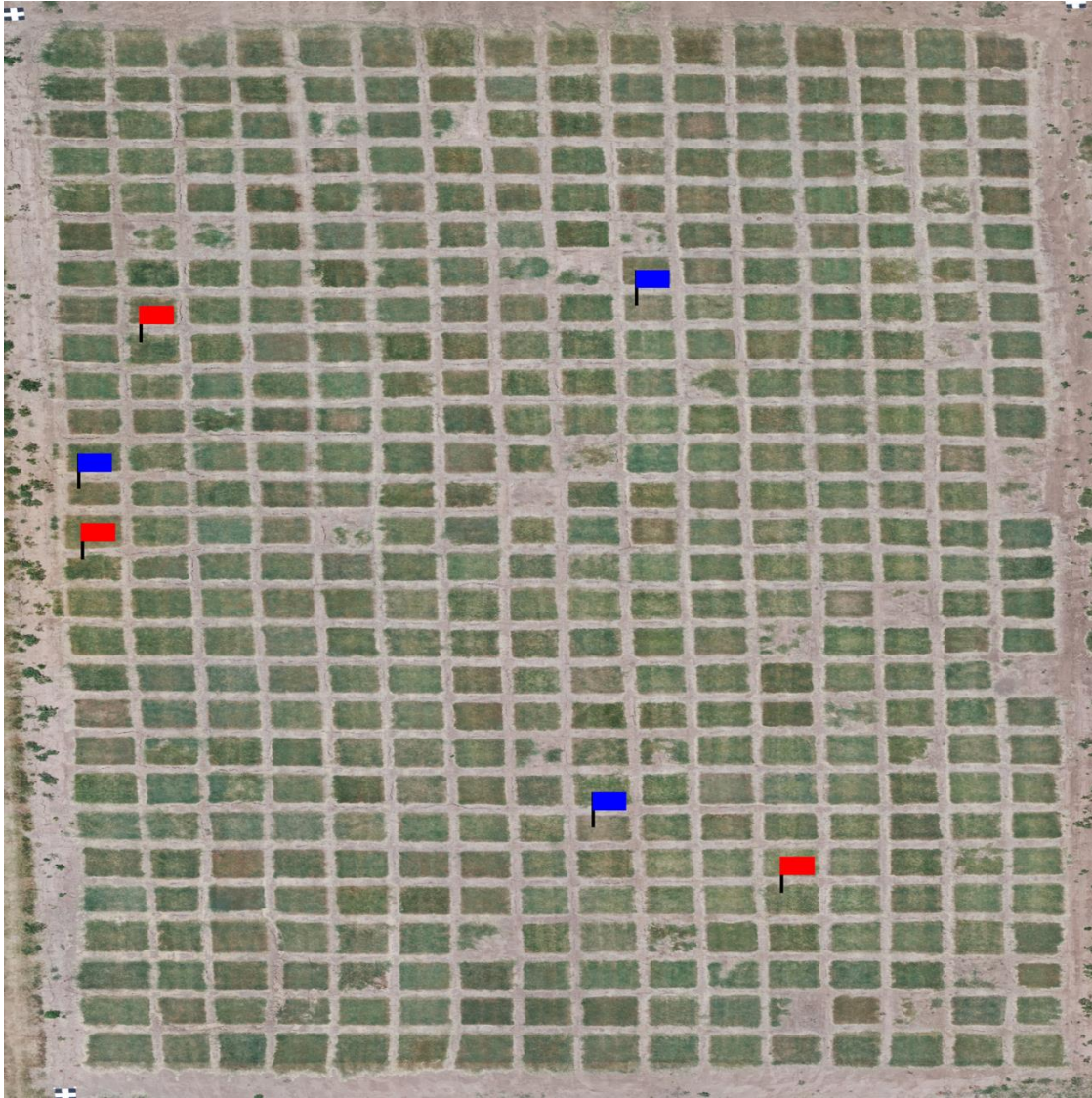


Figure 3. A Drone image taken on August 20, 2025, under drought conditions showed various responses of 147 progenies. Red flags indicate three plots of A10202, a drought-resistant parent, while blue flags for three plots of A12400, a cold-hardy parent.

Statistical analysis was done using analysis of variance (R version 4.5.1), where significant differences were found between the genotypes for all traits evaluated. For selection of top-performing genotypes, drought resistance related traits such as turfgrass quality under drought stress (TQD), green leaf index under drought stress (GLI_DS), and normalized difference vegetative index under drought stress (NDVI_DS) and cold hardiness related traits such as spring green up (SGU), GLI under spring green (GLI_SG), NDVI under spring green (NDVI_SG) along with other important traits such as turfgrass quality (TQ), fall color retention (FCR), and establishment rate (EST) were normalized, averaged, and ranked. The top 100 genotypes were plotted against the trait vectors using the Principal Coordinate Analysis Genotype-by-Trait biplot. The first two components explained 72.68% of the variability in the datasets, indicating a reliable 2D representation (Figure 4). In the biplot, traits are represented as vectors and

genotypes as points, allowing simultaneous visualization of genotype performance across traits. Genotypes projecting further in the direction of a trait vector represent better performance for that trait. The genotypes #420, #382, #595, #193, and #209 that performed well across all evaluated traits were selected as top-performing lines.

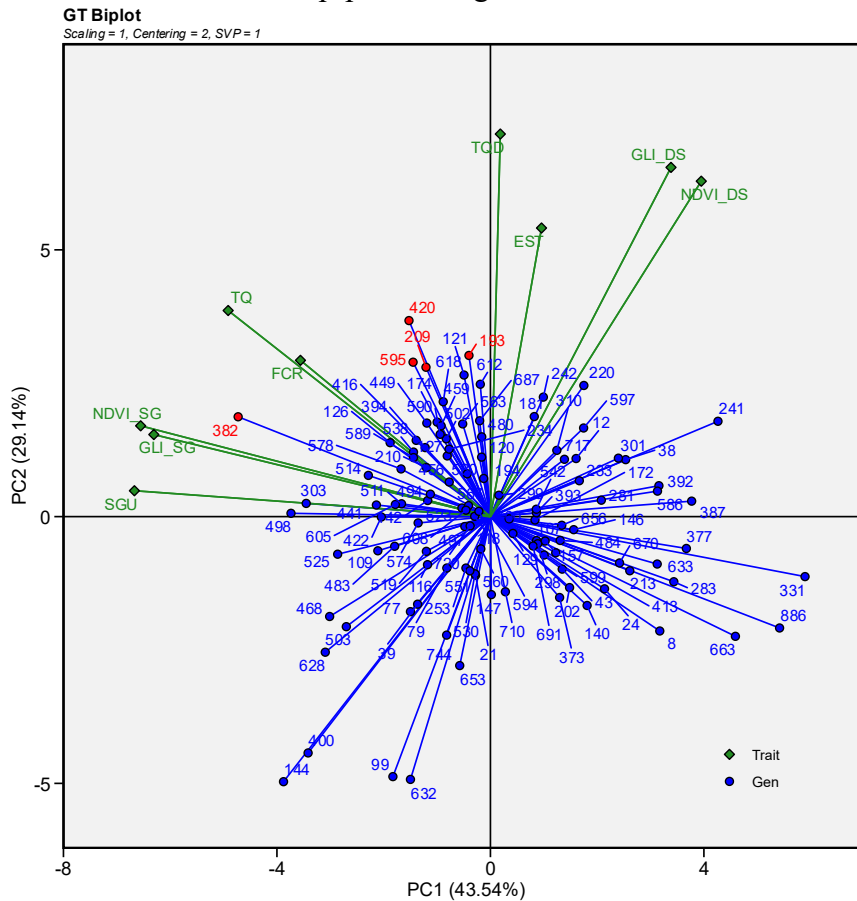


Figure 4. A 2-D graph of a principal coordinate analysis indicates top performers in red color, including #420, #382, #595, #193, and #209.

This field-based trial will continue in 2026. Further analysis will be conducted to select elite progenies, which combine cold hardiness, drought resistance, and turfgrass quality traits. The selected genotypes will be employed to cross with elite African bermudagrass in breeding new F₁ interspecific hybrids.

References Cited

1. Shaddox, T. W., Unruh J. B., Johnson M. E., Brown C. D., and Stacey G. (2023). Turfgrass use on US golf courses. *HortTechnology*. 33(4): 367-377. <https://doi.org/10.21273/HORTTECH05238-23>.

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:

- ‘OSU1337’ bermudagrass was released as a new cultivar in 2025.
- A genome-wide association study (GWAS) indicated that 48 unique SNPs were associated with common bermudagrass seed germination traits, of which six were consistent over two years.
- Two OSU experimental entries, developed with USGA funding, were advanced to the 2025 NTEP Warm Season Putting Green Trial for testing across several environments/geographic locations in the US.

Summary Text:

Common bermudagrass [*Cynodon dactylon* (L.) Pers.] is an economically and ecologically important warm-season perennial species widely used for turf, forage, and soil conservation and remediation. Seeding offers economic and practical advantages over vegetative propagation for establishing common bermudagrass. However, the adoption of seeded cultivars is limited by slow germination speed and low germination rates. The genetic basis behind these traits in common bermudagrass remains elusive. One study was conducted to evaluate genetic and phenotypic variation and identify genetic loci associated with seed germination-related traits in common bermudagrass. A diverse panel of 216 genotypes was formed for a genome-wide association study (GWAS). Seeds for each genotype of the panel were collected over two years and germinated separately in a randomized complete block design (RCBD) with 3 replications (100 seeds per replicate). The germination process was phenotyped by counting germinated seeds every three days from the beginning to determine the germination rate and estimate total

germination percentage over a 21-day period. The panel was sequenced, and 21,810 high-quality single-nucleotide polymorphisms (SNPs) were retained for GWAS analysis. GWAS indicated that 48 unique SNPs were associated with the seed germination traits, of which six were consistent over the two years (Figure 1). Twenty candidate genes linked to the consistent SNPs were identified to be involved in seed germination. These findings add valuable information on genetic mechanisms for seed germination and its rapidness and provide a foundation for developing breeder friendly markers to improve seed germination in the species.

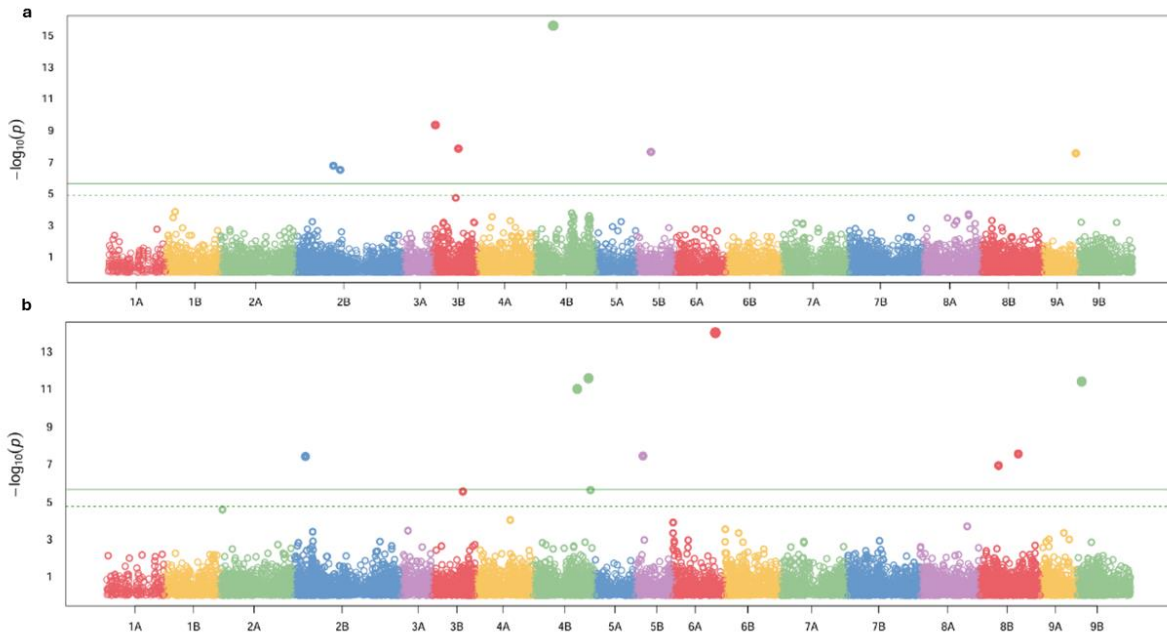


Figure 1. Manhattan plots showing significant SNP marker-germination trait associations identified by BLINK model in a common bermudagrass panel of 216 genotypes, seeds collected in (a) 2023 (a), and 2024 (b).

The turfgrass breeding program at Oklahoma State University released ‘OSU1337’ as a new cultivar for commercial production in 2025. OSU1337 is a vegetatively propagated, interspecific F₁ hybrid derived from a cross between *C. dactylon* var. *dactylon* accession A12268 ($2n = 4x = 36$) and *C. transvaalensis* Oklahoma State University (OSU) selection ‘2747’ ($2n = 2x = 18$). This grass was created in 2010 from a small crossing plot established in 2006. From multiple tests from 2010 to 2025, OSU1337 has exhibited a significantly improved freeze tolerance as good as Tahoma 31 (tested as OKC 1131, Wu et al., 2020), the most cold-hardy turf bermudagrass cultivar available on the market. OSU1337 does not produce frequent seedheads, which is better than some popular drought-resistant varieties. It has demonstrated early spring green up, fine leaf texture, high density, dark green color, excellent establishment growth vigor, and sufficient traffic tolerance. It has exhibited excellent sod harvest strength for reliable, large-scale commercial production on farms.

A putting-green-type bermudagrass evaluation trial was established under the direction of Dr. Mingying Xiang at the Turfgrass Research Center (TRC) in 2022, testing 14 genotypes compared to Tahoma 31 and TifEagle. Plots were maintained at a 1/8” mowing height for two consecutive years to assess overall performance, turf quality, and ball roll distance. Across the growing seasons of 2023 and 2024, all entries were evaluated weekly for density, uniformity, color, texture, and performance. Based on two years of data, progeny 20x10 and 11x8 consistently emerged as the top-performing genotypes. During the winter of 2024-2025, the research plots remained uncovered to assess cold tolerance and winter survivability under natural conditions. 20x10 exhibited delayed spring green-up and slower recovery from winter dormancy in 2025 (Table 1). 11x8 demonstrated superior winter survivability and earlier, more uniform spring green-up.

Table 1. Spring green up visual ratings collected in 2025.

Genotype	Spring Green Up ⁱ	
	18-March	01-April
11×8	2.3	4.0
17×12	1.0	1.0
17×16	1.0	2.0
19-8×1	1.0	1.3
1×7	1.0	1.3
20-8×7	1.3	2.0
20-9×19	1.0	1.7
20×10	1.0	2.0
25×8	1.7	2.3
37×14	1.0	2.0
7×18	1.3	2.0
9×15	1.5	2.0
9×21	1.3	1.7
‘OKC3920’	2.0	2.5
‘Tahoma 31’	2.7	3.3
‘TifEagle’	1.0	1.0
LSD ⁱⁱ	0.89	1.2

ⁱTurfgrass spring green up was rated on a 1 to 9 scale, where 9 was dark green and 1 was considered to be straw brown.

ⁱⁱLSD = Least significant difference at the $p = 0.05$ level.

Based on the multi-year performance, winter response, and overall suitability for putting-green management, OKC2020 (15x9) and OKC2021 (11x8) were selected as OSU entries for the 2025 NTEP Warm Season Putting Green Test. The two selections represent strong candidates with promising agronomic and playability characteristics. In addition, the M.S. student Mujibur Khan was trained on this putting-green-type bermudagrass research successfully defended his thesis

and completed his degree in Summer 2025 and has since begun pursuing his Ph.D. in biology.

An OSU germplasm trial established in 2023 was 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. The experimental design for the test is an 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 and 2025. The trial is anticipated to continue in 2026. Large differences were again 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 again present among clonal entries with respect to late-season color retention in 2025 (Figure 2) as in 2024 and frost resistance. Sod tensile strength and handling quality assessment will occur on a subset of entries in this trial in 2026, as well as a continuation in collection of visual performance parameters.



Figure 2. Extraordinary differences in late-season color retention were again present during November 2025 among OSU entries in the 2023 – 2026 experimental bermudagrass evaluation at OSU-Stillwater, OK. Mowing height strips of 0.5 (simulated fairway) and 1.5 inches (simulated rough or lawn) are administered to the entries.

Reference Cited

Wu, Y.Q., Martin, D.L., Moss, J.Q., Walker, N.R., and Fontanier, C. 2020. Bermudagrass Plant Named ‘OKC 1131’. US PP31,695 P3.

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

- Data collection initiated in the 2024 bermudagrass fairway trial.
- FB1628 bermudagrass was expanded to 10,000 ft² and shared with Florida sod growers.
- One bermudagrass, FB2424, was entered in the 2025 NTEP Bermudagrass Trial.
- Selections for spring greenup and freeze tolerance were made from the 2024 bermudagrass space plant nurseries.
- FZ1440 zoysiagrass is being expanded for release
- Three zoysiagrass lines, FZ1357, FZ1704, and FZ2401, were entered in the 2025 NTEP Putting Green 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.
- Selections were made from the 2023 zoysiagrass spaced plant nursery

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

In July 2025 turfgrass quality (TQ) ratings were initiated and collected monthly from the 2024 bermudagrass fairway trial (planted in November 2024). The best performing commercial entries were TifTuf and Celebration Hybrid with four experimental lines, FB1628, FB2424, and FB2239 having comparable average TQ ratings with TifTuf (Figure 1). Seedhead ratings were also collected in 2025. Celebration Hybrid and TifTuf produced the fewest seedheads among commercial entries along with two experimental lines, FB2423 and FB2214 (Figure 2).

Because of its excellent performance in previous UF trials and the 2019 NTEP Bermudagrass Trial, FB1628 was expanded to 10,000 ft² and shared with several sod growers to learn more about its potential for production. Golf courses are being sought out for testing. FB2424 was entered in the new 2025 NTEP Bermudagrass Trial.

2024 Bermudagrass Spaced Plant Nursery

Space planted nurseries of bermudagrass were planted in 2024 with 2,500 new progenies planted on 1.5 m centers. These trials were established by fall 2024 and in the spring of 2025, selections were made for lines with good spring greenup. Two groups of lines were selected, 1) with few seedheads and potential as vegetative cultivars and 2) those with dense production of seedheads and turf quality to use for further breeding. 190 lines were subsequently clonally propagated and planted at two locations in Florida. Evaluations of these lines will begin in 2026. A subset of 7 lines was selected for dwarf growth habits and planted as border plots around the NTEP Putting Green Trial.

In November 2025, following an early freeze, 100 lines were selected from these same nurseries for their color retention and resistance to freeze damage. Both the spring greenup (with dense seedheads) and freeze tolerant materials will be planted in separate crossing blocks in 2026 to produce subsequent cycles of selection.

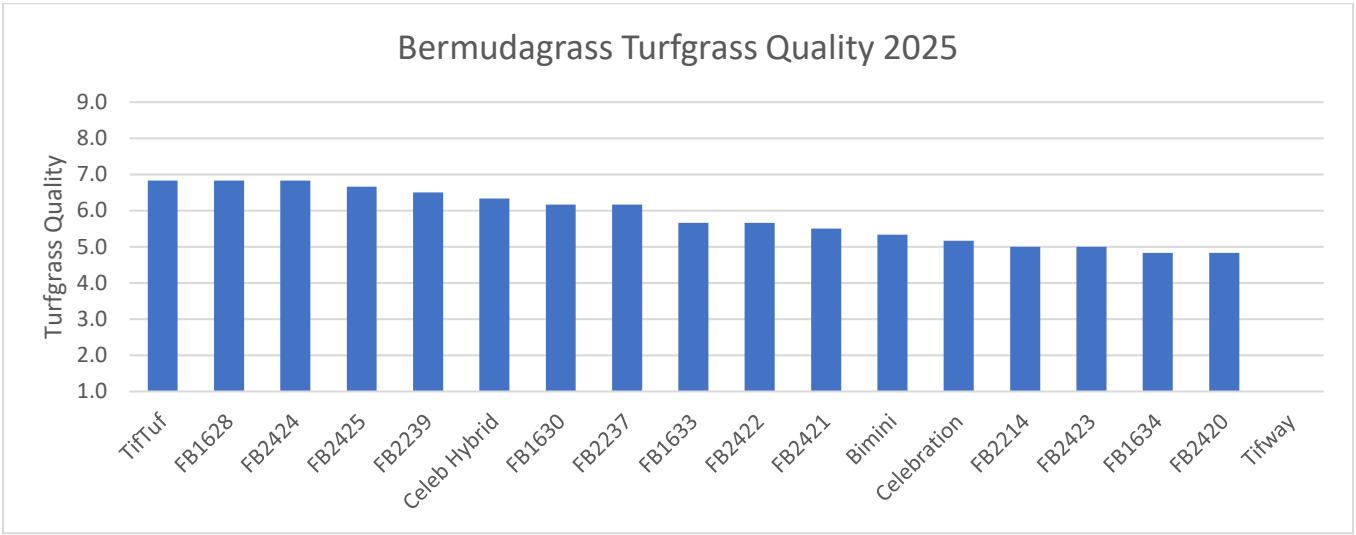


Figure 1. Average visual turfgrass quality ratings for bermudagrass entries from July through November 2025 at Citra, Florida. Turfgrass Quality was rated 1-9, where 9 is the best possible quality and six represents acceptable quality. Tifway was planted later than other entries. As a result, it is behind the other entries for establishment and wasn't rated.

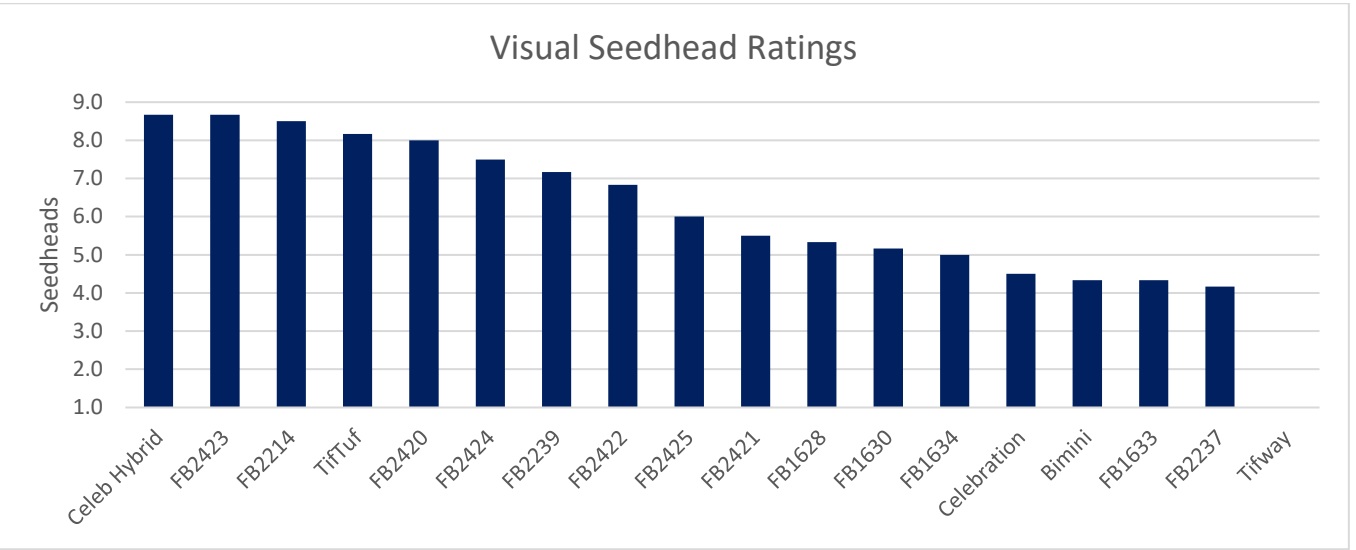


Figure 2. Average seedhead ratings for bermudagrass entries from July through November 2025 at Citra, Florida. Visual ratings were made using a 1-9 scale, where 9 equates to no seedheads present. Tifway was planted later than other entries. As a result, it is behind the other entries for establishment and wasn't rated.

Zoysiagrass

Information learned over the last decade from local trials and NTEP resulted in the selection and small expansion of 8 lines of *Zoysia matrella*. In the past year, based on golf course trials and a shade trial, the eight lines were narrowed to FZ1440. This line is favored by golf course superintendents. Additionally, it was advanced over other lines that exhibited better NTEP performance for its establishment and turfgrass quality when grown for two years under 60% shade (Figure 3). It's under expansion for further testing and is being considered for release.

2017 and 2021 Zoysiagrass Spaced Plant Nurseries

Selections of 185 lines from these two terminated nurseries were propagated in the greenhouse in 2024. The selections were based on winter color retention, spring greenup, and persistence across multiple seasons with minimum irrigation. In 2025, three trials of these selections were planted. One trial was planted under heavy tree shade in Citra, Florida and two trials were planted in the full sun (Citra, Florida and Immokalee, Florida). Data collection was initiated in late 2025 and will continue for several years.

2023 Zoysiagrass Spaced Plant Nursery

The 2023 zoysiagrass spaced plant nursery was planted with 2,000 plants. It was minimally irrigated and screened for persistence using diquat herbicide. In November 2025, 35 lines were selected based on good color retention, percent cover, growth habit, and turfgrass quality. These lines will be propagated in 2026 for further evaluations.

2025 Zoysiagrass Spaced Plant Nursery

In 2025 a new nursery of 1,000 zoysiagrass plants were established. The sources of this nursery were high seed yielding lines.

Putting Green Zoysiagrass Selections

FZ1710 exhibited good performance in the 2019 NTEP Warm Season Putting Green trial and is being expanded for further testing (Figure 4). FZ1704, FZ1357, and FZ2401 were entered in the 2025 NTEP putting green trial.

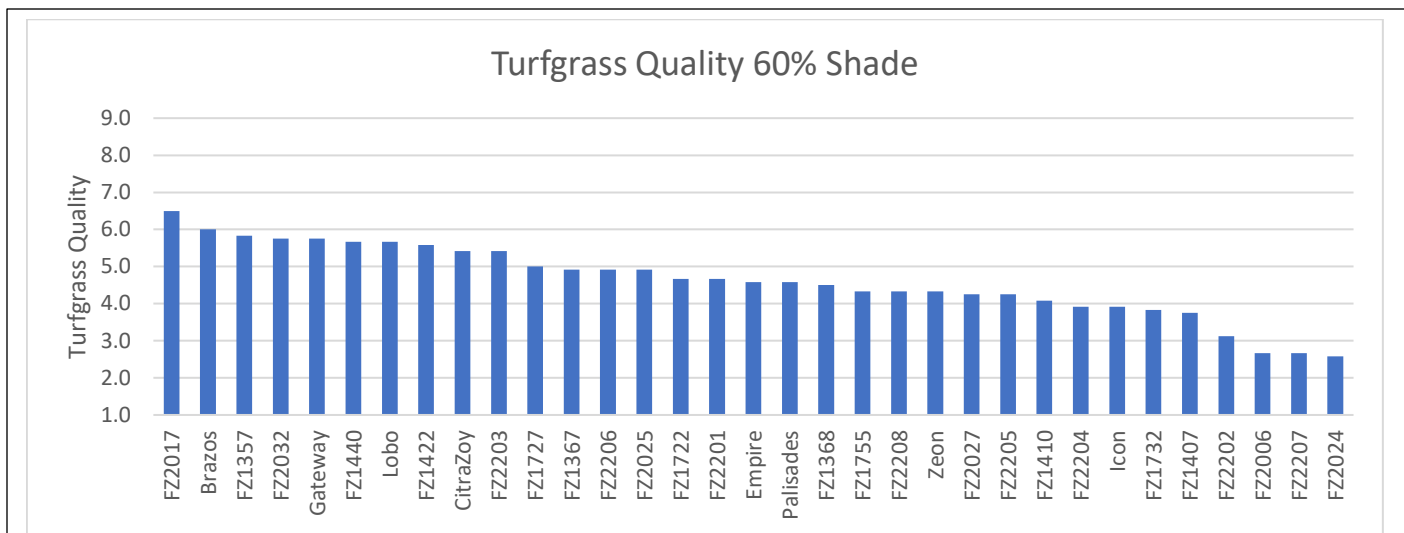


Figure 3. Two year (2024 and 2025) average visual turfgrass quality ratings for zoysiagrass entries grown under 60% shade at Citra, Florida. Turfgrass Quality was rated 1-9, where 9 is the best possible quality and six represents acceptable quality.



Figure 4. Expansion of FZ1710 zoysiagrass. The expansion will be used to supply golf courses for further testing.

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 (2nd cycle)

Total Funding: \$250,000

Summary Points

- Hybrid bermudagrass cv. Coachella (UCR TP6-3) was released and licensed in 2025; West Coast Turf is the exclusive licensee in the U.S. and Mexico; ca. 140 acres of sod are currently in production.
- The Farms GC in Rancho Santa Fe, CA was the first golf course to establish Coachella on tees, fairways, and rough (ca. 70 acres); the course reopened following renovation on October 1, 2025.
- Big Canyon CC in Newport Beach, CA is the second golf course to establish Coachella on ca. 60 acres of tees, fairway, and rough. Renovation began in November 2025.
- ‘Presidio’ hybrid bermudagrass (UCR 17-8) licensing is pending.
- Evaluation of bermudagrass suitable for roughs and lawns and replicated test plots of kikuyugrass selected for fairways/sports fields was concluded.
- Evaluation of the bermudagrass shade tolerance trial and bermudagrass hybrids selected for fairways/sports fields continued.
- Evaluation of multi-location trials in the Southwest for advanced bermudagrass hybrids established in the summer of 2024 continued.
- A trial was established to evaluate kikuyugrass hybrids with no or minimal anther extrusion in October 2025.
- A new kikuyugrass nursery was established
- Efforts to broaden genetic diversity of kikuyugrass continue with multiple collection trips to 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.

Since 2024, the person responsible for the general advancement and day-to-day operations of this project has been Dr. Christian Bowman.

Bermudagrass

Evaluation and selection in nurseries established in 2020 and 2022 continues. New bermudagrass hybrids are generated routinely; both detached tiller crosses and open-pollination have been used to produce new hybrids that will be planted next spring in a new nursery. Four parents, which consistently generated hybrids with valuable traits, were planted in trays and used for crosses in the greenhouse.

Evaluation of bermudagrass hybrids suitable for roughs/lawns, planted in 2021, has concluded with selections made this year. Twenty-two hybrids were selected and planted at UCR in three replicates in 2021. 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 were 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. Over the course of the trial, the highest overall quality among the UCR hybrids was observed in UCRC180015, UCRC190311, UCRC190307, UCRC190108, UCRC190766, and UCRC180661. These hybrids performed similar to or better than the highest performing checks, UCR 17-8, ‘Coachella’, and ‘Celebration’. UCRC180661 had the best winter color retention, while UCRC180015 and UCRC190307 had the fastest spring greenup, comparable to that of UCR 17-8, ‘Coachella’, and ‘Santa Ana’. Selections made from this trial will be harvested and expanded, and multi-location trials are expected to be established in 2026.

A low light conditions trial was started in July 2021 and continues today. It includes 35 UCR experimental bermudagrass accessions, two recently patented UCR accessions: ‘Coachella’ (UCR TP 6-3) and UCR 17-8, and four checks (‘Latitude 36’, ‘Santa Ana’, ‘TifTuf’, ‘Tifway’). The trial was planted in three replicates at UCR, Riverside, CA. Plots were maintained under shade cloth (60% shade) and evaluated for turfgrass quality (1-9; 9=best), spring greenup (1-9; 9=fastest), and genetic color (1-9; 9=darkest). UCRC190640, UCRC190127, UCRC180617, UCRC180211, and UCRC180217 were the top performers in terms of overall turf quality. ‘TifTuf’ and UCR 17-8 performed similarly, and were among the top performers in both turf quality and visual color. UCRC190640, UCRC190127, UCRC180127, UCRC180176, and UCRC180211 had the best spring greenup. Select top performers in this trial were also included in the multi-location advanced trials established in 2024.

Evaluations continue for 57 UCR accessions for fairway/sports field suitability. UCR 17-8 and five commercial cultivars (‘Latitude 36’, ‘Santa Ana’, ‘Tahoma 31’, ‘TifTuf’, ‘Tifway’) were used

as checks. ‘Coachella’ (UCR TP6-3) had to be removed due to a mix-up of entries. Plots were maintained under fairway mowing height (0.5 in) and evaluated for 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). The accessions with the overall best turf quality include UCRC180617, ‘Santa Ana’, ‘TifTuf’, UCR 17-8, and UCRC180174. The accessions with the overall best winter color retention/spring greenup include UCRC190691, UCRC190640, UCRC190750, UCRC180581, and ‘TifTuf’.

Results from the dry-down trial conducted in 2020-2022 have been published. Plots were subjected to repeated periods of long-term 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. Results from this study suggest the presence of a ‘stress memory’: individual responses to drought may change when subjected to consecutive periods of drought stress, depending on the genotype. These responses can be categorized as ‘susceptible’, ‘resistant’, or ‘neutral’, and should be considered in future attempts to improve drought tolerance in breeding programs. This study was published in March 2025 in the International Turfgrass Society Research Journal (DOI: 10.1002/its2.70034) and was presented at the 2025 International Turfgrass Research Conference.

After an almost 10-year long evaluation process, two bermudagrass hybrids, UCR TP6-3 and UCR 17-8, have been patented. UCR TP6-3 is registered under US PP35,441 P2 and is available under the name ‘Coachella’. UCR 17-8 is registered under US PP35,357 P2. ‘Coachella’ was licensed to West Coast Turf and currently 140 acres of sod is in production in Southern California and Arizona. A trial was initiated at UCR to determine the best management practices for ‘Coachella’ including mowing heights, fertility, and PGRs.

After years of observation at the UCR turf facility, eight new bermudagrass hybrids were 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) and planted in the summer of 2024. These hybrids were selected based on their strong performance in multiple trials at UCR. 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 a randomized complete block design with two replicates. The trial experienced a few disruptions, and drought trials were postponed for all locations except Riverside, CA. In Colorado and New Mexico, winter conditions were colder than expected, resulting in the loss of most entries in Colorado and all entries in New Mexico. ‘Tahoma 31’, ‘TifTuf’, ‘Coachella’, and UCR 17-8 survived in Denver, with ‘Tahoma 31’ and ‘TifTuf’ demonstrating a full recovery by the spring. The trials were reestablished in Colorado and New Mexico at the end of June 2025.

In Stockton, CA, a complete loss of one experimental replication occurred due to unintentional soil disturbance from field maintenance in an adjacent area in October 2024. Replacement of these replicates was not possible. Hence, seven of the 14 entries will only have one replicate going forward.

Despite setbacks at external locations, a drought trial was performed at the UCR field site. Complete drought (0% ET_{os} replacement) was imposed on August 1, 2025, and irrigation was restored on September 1, 2025. Plots were evaluated weekly for turf quality (1-9; 9 = best), visual color (1-9; 9 = dark green), flowering/seedhead production (1-9; 9 = no visible seedheads), and injury (1-9; 9 = no visible injury). Each plot was also split into two different mowing heights (0.5 in. or 2.0 in.). Under drought and at the mowing height of 2 inches, UCRC180557 had the best turf

quality, followed by UCR 17-8 and UCRC180118. At the mowing height of 0.5 inches, UCRC180060, ‘TifTuf’, UCRC180557, and BH 10-9 had the best turf quality under drought, though differences among entries at 0.5 inches were not as pronounced as those observed at 2 inches. UCR 17-8 had slightly better drought tolerance than ‘Coachella’ and performed on par with ‘TifTuf’.

A total of 733 bermudagrass hybrids developed in 2023 were planted as a nursery in June 2024. Of these, 272 are being evaluated under a split family augmented design with five checks (two parents involved in the production of the hybrids, UCR 17-8, ‘Coachella’, and ‘TifTuf’) replicated eight times. Evaluating them in this way should enable better resolution of the heritability of certain traits and direct comparison with standard entries.

Kikuyugrass

Evaluations have concluded for the replicated trials of kikuyugrass hybrids established in the spring of 2022. Forty experimental accessions and cv. Whittet as a check were evaluated for establishment, turfgrass quality, winter color retention, genetic color, texture and anther production. Top performers from this trial were selected and will be used as parents in future crosses. One entry in particular, UCRK190336, was selected for its reduced anther extrusion and has been entered into in multi-location advanced trials.

Anther extrusion is one of the more bothersome aspects of kikuyugrass as turf. 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 were established in Winchester, CA and Riverside, CA. Plots were mowed once per week at 1.5 inches, and evaluated for turfgrass quality (1-9; 9=best), anther extrusion (1-9; 9=no anthers), and scalping/mechanical injury from mowing (1-9; 9=no visible injury). UCRK220003 had the highest overall turf quality at both locations, followed by UCRK220070. At the Winchester location, little to no anthers were produced among the six entries, but ‘Whittet’ produced anthers at a moderate level. In Riverside, anther extrusion was moderate in ‘Whittet’ and UCRK220070, less than average in UCRK000090 and UCRK190336, and minimal in UCRK000095, UCRK000025, and UCRK220003. ‘Whittet’ and UCRK220070 were the most susceptible to scalping injury from mowing at both locations.

While other facets of our program focus on improving the genetics of kikuyugrass, we must also consider the management aspects for it. The development of a male-sterile cultivar requires successful post- and preemergence control of existing kikuyugrass able to produce viable seed. Herbicides that can eradicate kikuyugrass turf and also prevent seedling establishment will be important for existing kikuyugrass-to-improved kikuyugrass conversion strategies. Two studies were conducted at UCR in August 2025.

The first study evaluated the efficacy of 13 preemergence herbicides in controlling kikuyugrass seedlings sown on bare soil. Preemergence herbicides from this study were effective at preventing emergence of kikuyugrass seed on bare soil (Barricade, Pendulum, Tower, Ronstar, Specticle, Dimension, Pennant), had reduced efficacy (Kerb, Sencor, Princep, SureGuard), or no effect on germination when compared to the control (Tenacity, Dismiss CA).

The second study evaluated the injury caused by the same 13 preemergence herbicides when applied at different rates to a monostand of established kikuyugrass turf. Injury was apparent from certain herbicides in the form of foliar burning (Sencor, Ronstar, SureGuard, Dismiss CA) or foliar bleaching (Tenacity).

Evaluation of the kikuyugrass nursery with 112 hybrids continues. A new nursery of 134 hybrids was planted in June 2025. The ongoing effort to evaluate hybrids for less aggressive traits and reduced anther exertion continues, though limitations exist with the genetic diversity available.

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 involved 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 was the testing site for the overall performance, as well as drought and salinity tolerance. 2023 was the last year of evaluation in all trials of this project. 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 and a manuscript for this study is under review for publication.

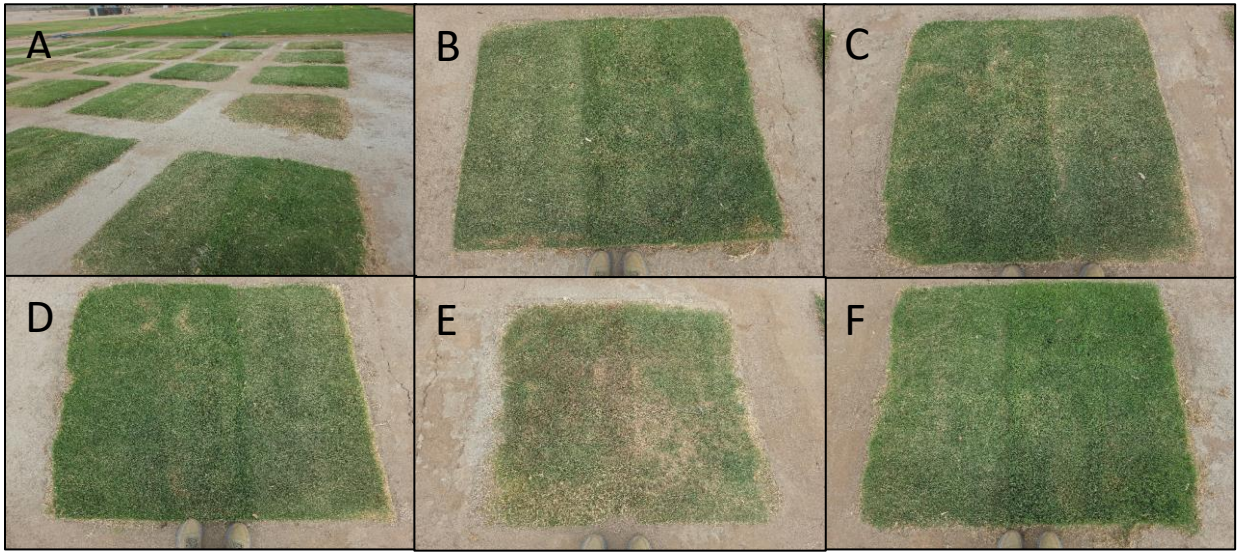


Figure 1. Bermudagrass entries in a drought trial for advanced bermudagrass hybrids after ca. 30 days without irrigation at UCR Agricultural Operations field in Riverside, CA. Photo taken on September 2, 2025. (A) Overview of the plots, (B) UCR 17-8, (C) ‘Coachella’ (UCR TP6-3), (D) ‘TifTuf’, (E) ‘Tahoma 31’, (F) UCRC180557.

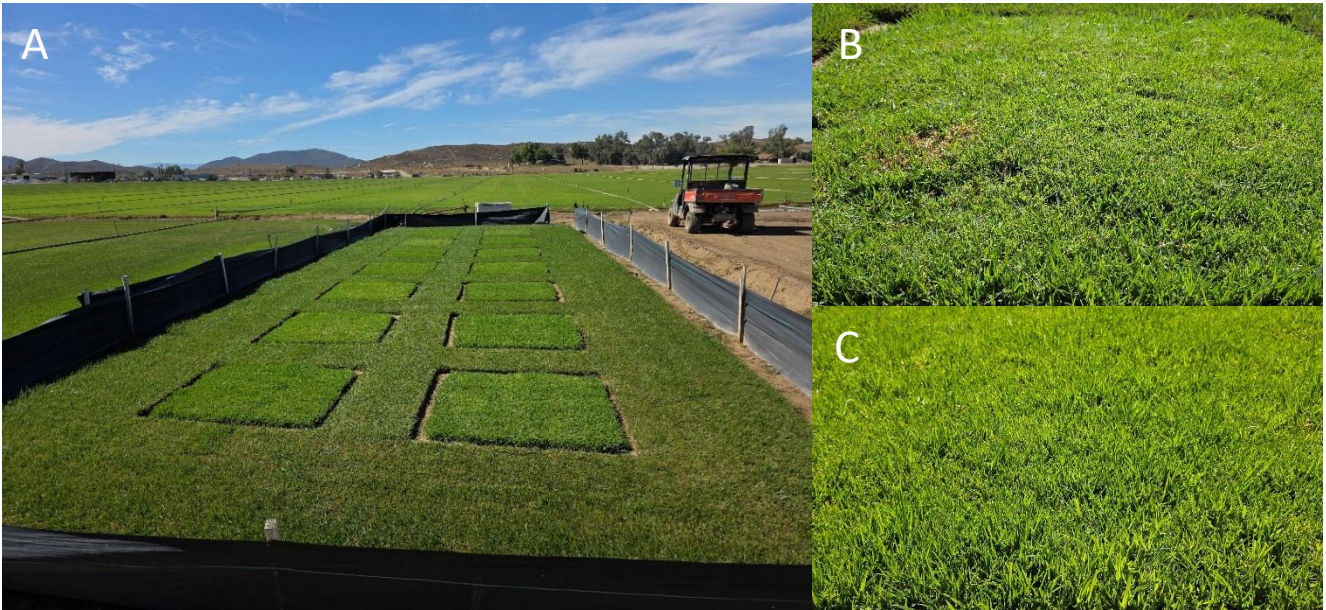


Figure 2. Advanced trial to evaluate select kikuyugrass accessions with minimal or no anther extrusion in Winchester, CA at West Coast Turf. Photo taken on July 24, 2025. (A) Overview of the plots, (B) moderate anther exertion in cv. ‘Whittet’, (C) no anther exertion in UCRK220003.



Figure 3. Spring greenup of bermudagrass accessions selected for suitability on roughs/lawns at UCR Agricultural Operations field in Riverside, CA. Photo taken on March 1, 2025.

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 (TAMAR-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.

Summary Points:

- Seed harvested from (1) early (two parent) and (2) late synthetic (three parent) varieties in collaboration with a Seed Company in Oklahoma (SC-OK) has produced over 8 lbs. of breeder's seed. Seed was scarified, germination tested and entered as two experimental seeded varieties in the 2025 Zoysia NTEP identified as DALSZ 2501 and DALSZ 2502.
- Our collaboration with a Seed Company located in Oregon (SC-OR) resulted in the planting of 546 seeded zoysia experimentals at two locations in OR in the spring of 2024. Data was collected during the 2025 growing season and has resulted in the selection of 30 plants with high numbers of flowers and tall reproductive stems. The 30 plants will be divided into four parts and planted into a replicated polycross nursery in 2026.
- 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 tested for percent germination were found to be low in 2025. Seed quality was an issue. New synthetics are being designed both at SC-AL and TAMAR-Dallas for development and testing.
- Vegetative material from nine selections made by TAMAR-Dallas from the 2021 Seeded Zoysia Spaced Plant Nursery (SPN) were used as parental lines for pairwise crossing in the 2024 winter greenhouse. Hybrid seed lots resulting from crosses with the nine parental lines were divided into two portions. One set was germinated for testing in the 2025 Zoysia SPN as vegetative types and the second set of remnant seed was set aside for germination to populate a 2026 Seeded SPN at TAMAR-Dallas.
- The 2023 Seeded Zoysia SPN grown at TAMAR-Dallas consisted of 1152 hybrid progeny (emphasizing Meyer and cold tolerant zoysiagrass germplasm like DALZ 1701 and KSUZ 0806 as parental lines) was planted July 2023. Seed collected from 11 red seeded types and 6 yellow seeded types in 2024 was scarified and planted in the field in a seed increase block (7/1/25). Another round of selections were made from the 2023 SPN in 2025 with the identification of 21 seeded types, 40 vegetative types and 3 seeded/vegetative types (10/24/25).

Project updates:

- **Collaboration with a Seed Company in Oklahoma (SC-OK)** – Using 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 by SC-OK. Note, TAES 6596-05 is a common parent in both synthetic blocks. Seed was harvested from both the early and late synthetics during 2023 and 2024 growing seasons. Over 8 lbs. were harvested from each of the two synthetics. Seed was chemically scarified using sodium hydroxide, germination tested and found to be of good quality. The early synthetic was coded as DALSZ 2501 and the late synthetic was coded as DALSZ 2502 entered in the 2025 NTEP (Figure 1).



Figure 1. DALSZ 2502; Left: NTEP test plot at Purdue University (August 19, 2025), Right: NTEP test plot at TAMAR-Dallas 36 days after seeding on August 7, 2025.

- a) Scarification with 30% NaOH was accomplished using 3 lb samples of each of the two DALSZ experimentals. Half pound subsamples were contained in pantyhose toes and then soaked in the NaOH solution for 35 min before washing. Scarified seed was held in the cold at 40°F for 3 weeks before drying in a laminar flow hood.

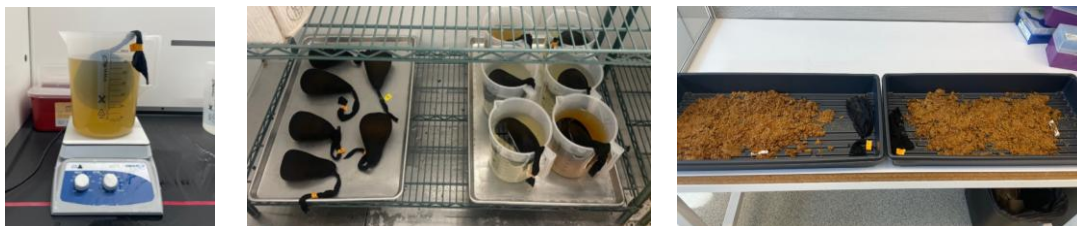


Figure 2. Seed scarification process: Left: Soaked in 30% NaOH for 35 min; Middle: Cold stratification for 3 weeks at 40°F; Right: Dry down in laminar flow hood.

- b) Seed germination testing was accomplished both in house as well as by an independent seed laboratory. Percent germination was determined to be 64% for DALSZ 2501 and 58% for DALSZ 2502.
- c) Seed increase blocks (400 sq.ft. each) were planted (7/1/25) in Dallas at a rate of 1.5 lbs/1000 sq.ft. with scarified seed of both DALSZ 2501 and DALZ 2502 (Figure 3).



Figure 3. Seed increase plot of DALSZ 2501 (left) and DALSZ 2502 (right) on 11/12/25 at TAMAR-Dallas; Plots were planted on 7/1/25.

- d) Seed of DALSZ 2501 and DALZ 2502 were germinated in sod trays in the greenhouse during the winter/spring of 2024/25. The resulting sod was used to create sprigs to plant test plots (7/1/25) of DALSZ 2501 and DALSZ 2502 (Figure 4) in a replicated trail with Zenith and Compadre as checks in order to compare turf performance traits.



Figure 4. Sprigged test plots of DALZ 2501 and 2502 (left) were planted (7/1/25) in order to evaluate performance traits with Zenith and Compadre as checks; trial photo taken 11/12/2025 (right).

- ***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 three promising seeded parental lines (6609-47, 6618-37 and 7327).
 - a) They are being planted either as two clone or three clone synthetics:
 Synthetic Block 1 (6609-47 and 6618-37), Synthetic Block 2 (6609-47 and 7327), Synthetic Block 3 (6618-37 and 7327) and Synthetic Block 4 (6609-47, 6618-37 and 7327) at SC-AL.
 - b) An additional two clone synthetic was planted at TAMAR-Dallas (8/18/25) using one of the lines identified by SC-AL (6618-37) and DALZ 1701.
 - c) A two rep Replicated Field Trial (RFT) mow study planted as 4” plugs on 4’ centers (planted 7/18/25) is being conducted at TAMAR-Dallas with the 21 seeded lines being evaluated by SC-AL.

- ***Collaboration with a Seed Company in Oregon (SC-OR)*** – In the late spring of 2024, a total of 546 experimental varieties were planted by the SC-OR at two locations, Albany and Madras, OR. Most of the plants survived the winter at both locations.
 - a) Data was collected for fall color (11/2/24), genetic color (1/28/25), dormant color (4/7/25), spring green up (4/7/25), plant size (6/4/25), family average anthesis date (day of the year) and % of plants in a family that produced seed.
 - b) Genotypes with the best seed yield characteristics such as high number of flowers and tall reproductive stems were the same individuals at both Albany and Madras.
 - c) Thirty genotypes that exhibited good seed yield potential in both nurseries were selected from 10 of 22 families and sod planted in a 5 gallon pot for each. The remainder of the two nurseries were eliminated.
 - d) In 2026, SC-OR will split the 30 selected individuals into four parts and plant in a replicated polycross nursery.

- ***Selections were made by TAMAR-Dallas from the 2021 Seeded SPN and used as parental lines to produce the 2025/26 SPN's (both vegetative and seeded)*** – 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 in the 2021 Seeded SPN. Plots were rated for establishment, quality, spring greenup, and seedhead development in the spring and summer of 2022 and 2023. A total of nine lines were selected (8/23/23) from the 2021 SPN comprised of 663 experimental entries representing five cycles of phenotypic selection. The nine advanced lines were used as parental lines during the Fall of 2024 as a part of our breeding program. Pairwise crosses made with the nine lines have produced hybrid seed lots where a portion was germinated and those progeny are being evaluated in our 2025 Zoysia SPN (vegetative type) while the remaining seed will be germinated in 2026 for evaluation in a seeded type zoysia SPN.

- ***2023 Seeded SPN at TAMAR-Dallas*** - 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 July of 2023. Our first cycle of selection (2024) lead to seed being collected from 11 red seeded types and 6 yellow seeded types. Seed was scarified and planted at a rate of 1 lb./1000 sq. ft. (7/1/25) as experimentals identified as TAES 8836 (red) and 8837 (yellow). The 2023 SPN was severely impacted by winter kill in 2024 so additional selections were made during the summer of 2025. These selections were made 10/24/25 with the identification of 21 new seeded types, 40 vegetative types and 3 seeded/vegetative types based on field notes (Table 1.). The remainder of the nursery will be eliminated.

Family	Spread (1-9)				Spring Greenup (1-9)		Winterkill (%)	Turfgrass Quality (1-9)			Leaf Spot (1-4)	Seedhead Density (1-4)				
	10/23	03/24	04/24	06/24	03/24	04/25	04/24	11/23	08/24	08/25		A P R	M A Y	J U N	A U G	N O V
8215	2.5	3.0	3.2	6.4	6.2	3.0	1.2	5.4	6.2	6.4	2.9	3.3	3.1	3.2	3.7	3.3
8217	2.9	3.9	4.0	7.1	6.2	3.0	0.0	4.9	6.0	5.6	1.9	3.3	3.1	2.9	3.7	3.9
8224	2.8	4.1	4.0	7.2	6.1	1.9	6.3	5.3	6.6	5.4	2.5	2.5	3.1	1.9	3.6	2.8
8226	2.7	3.7	3.9	7.2	6.3	2.5	0.2	4.8	6.6	5.7	2.5	3.0	2.8	2.2	3.3	3.2
8227	2.2	2.4	2.5	5.6	5.1	4.8	0.2	4.1	5.3	6.9	1.9	3.1	2.0	2.4	2.6	3.5
8229	2.7	2.9	3.3	6.5	5.8	3.8	1.3	4.5	4.7	5.7	2.1	2.0	2.3	1.8	3.1	2.8
8232	2.4	3.1	3.3	5.9	5.5	3.2	2.1	4.7	5.2	4.6	2.3	2.6	2.8	2.7	3.9	3.4
Compadre	2.5	2.8	3.2	6.5	5.0	2.7	0.0	4.3	4.7	3.3	1.8	3.2	2.5	3.2	3.7	4.0
Zenith	2.6	2.6	3.0	6.2	4.0	3.4	0.0	4.0	5.2	5.0	1.8	3.4	2.6	3.0	3.8	4.0
DALZ 1701	3.0	4.3	4.3	8.3	7.0	2.7	0.0	5.3	7.0	4.7	2.0	2.7	3.0	3.0	4.0	2.3
KSUZ 0806	2.0	2.0	2.3	5.3	5.0	3.0	0.0	5.0	5.7	5.7	2.3	1.0	2.7	2.0	4.0	3.5

Table 1. Field notes taken during the 2024 and 2025 growing season for the 2023 Seeded Zoysia Spaced Plant Nursery (SPN). Green color cell indicates better performance for that trait column and yellow color cell indicates lower performance for that trait.

Goals for 2026:

- Evaluate seeded plots of DALSZ 2501 and DALSZ 2502 in the 2025 Zoysiagrass NTEP to determine how they are performing. Also evaluate turf performance of sprigs plots of DALSZ 2501 and 2502 planted at TAMAR-Dallas.
- Check the establishment of DALSZ 2501 and 2502 planted in Dallas for seed increase.
- Evaluate experimental synthetics planted at TAMAR-Dallas, (1) three clone synthetic (7013-01, 7006-01 and DALZ 1701) using new parental lines identified by SC-OK and (2) two clone synthetic (6618-37 and DALZ 1701) using a parental line identified by SC-AL and one of our elite vegetative types.
- Track the status of the new two and three clone synthetics planted by SC-AL.
- In collaboration with SC-OR, continue to evaluate seed production traits and establish polycross nurseries with plants selected from the families with the best seed yield potential.
- Plant sod in 2026 of the 21 new seeded selections made 10/24/25 from the 2023 SPN in a 2 Rep RFT and continue to take notes on their performance in order to identify the ones with the best potential as seeded parental types in future synthetics.

USGA ID#: 2018-01-651

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

Project Co-Leaders: Ambika Chandra¹, Ross Braun², Aaron Patton³, Meghyn Meeks¹, Dennis Genovesi¹

Affiliations: Texas A&M AgriLife Research-Dallas¹, Kansas State University², Purdue University³

Objectives:

- 1) **Phase I (year 1): Completed** - Generate cold tolerant, large patch resistant, finer-textured hybrid zoysiagrass for the transition zone and plant progeny in Dallas, TX, Olathe, KS, and West Lafayette, IN
- 2) **Phase II (years 2 and 3): Completed** - Evaluate progeny in non-replicated spaced plant nurseries (SPNs) and identify those with superior cold tolerance and quality.
- 3) **Phase III (years 4-6): Completed** – Test superior hybrids in multilocation replicated trials across the United States and evaluate environmental and consumer-like stress tolerances

Start Date: 2018

Project Duration: 8 years

Summary Points:

- The project objectives were completed in 2024-2025, and 16 genotypes were identified (Table 1) with seven hybrids selected due to their superior performance in the transition zone or southern region (making a total of 14), and two hybrids were selected due to their superior performance in both the transition and the southern regions
- All 16 were additionally planted in replicated trials in West Lafayette, IN and Dallas, TX under USGA project ID#: 2025-06-837b.
- Five of these hybrids (Table 2) were advanced to the 2025 National Zoysiagrass Test (NTEP).

Summary Text:

In Phase I (2016-2017), crossing work was conducted at Texas A&M AgriLife-Dallas utilizing parental lines expressing cold tolerance and large patch resistance. Progeny from this effort was divided for Phase II testing across three test locations in Dallas, TX, Olathe, KS, and West Lafayette, IN from 2018 to 2020. At the conclusion of this phase, collaborators used data to select 65 superior hybrids which were then propagated in the winter of 2020/2021 and distributed to eight replicated trial locations as part of Phase III. These trials were conducted from 2021 to 2024 and placed greater emphasis on a wider range of environmental tolerances including cold, drought, and shade as well as tolerance to consumer-use such as mowing height, divot recovery,

and traffic tolerance. This collaborative effort identified a total of 16 hybrids with superior performance in one or both regions (transition and southern) upon completion of this project.

Table 1. Top zoysiagrass hybrid selections from this project.

Southern U.S.		Transition Zone	
Entry ID	Lineage	Entry ID	Lineage
6782-75^a	[(Zj × Zp)/Zj] × Zp]	6782-75	[(Zj × Zp)/Zj] × Zp]
6782-104^{ab}	[(Zj × Zp)/Zj] × Zp]	6782-79	[(Zj × Zp)/Zj] × Zp]
6785-19 ^b	([(Zj × Zp)/Zj] × Zp)	6782-104	[(Zj × Zp)/Zj] × Zp]
6789-23 ^b	([(Zj × Zp)/Zj] × Zp)	6829-36	[(Zj × Zp)/Zj] × Zm)
6789-40 ^b	([(Zj × Zp)/Zj] × Zp)	6844-36	[Zm × Zj] × [(Zj × Zp)/Zj])
6792-44 ^b	([(Zj × Zp)/Zj] × Zp)	6844-74	[Zm × Zj] × [(Zj × Zp)/Zj])
6829-69	[(Zj × Zp)/Zj] × Zm)	6844-104	[Zm × Zj] × [(Zj × Zp)/Zj])
6941-36	(Zj × Zm)	6844-150	[Zm × Zj] × [(Zj × Zp)/Zj])
6942-22	(Zj × Zp)	6844-202	[Zm × Zj] × [(Zj × Zp)/Zj])

^a The two bolded entries were top performers across both climatic regions and included in both selections.

^b These five entries are golf course putting greens candidates due to performance and leaf texture data.

^c Lineage abbreviations: Zj = *Zoysia japonica*, Zm = *Zoysia matrella*, Zp = *Zoysia pacifica*.

Five of the 16 hybrids (Table 2) were propagated as entries in the 2025 National Zoysiagrass Test conducted by the National Turfgrass Evaluation Program (NTEP) which will further evaluate these hybrids across 10 standard locations and five ancillary locations. Five of the standard locations are in the transition zone (College Park, MD; West Lafayette, IN; Blacksburg, VA; Manhattan, KS; and Knoxville, TN), four are in the southern region (College Station, TX; Starkville, MS; Davie, FL; and Maricopa, AZ), and one in Logan, UT. The ancillary locations will test for drought (Dallas, TX), traffic tolerance (Raleigh, NC), large patch resistance (Jay, FL), and tolerance to overseeding (Maricopa, AZ and Starkville, MS).

Concurrently, material for each of the 16 hybrids as well as six commercial cultivars were propagated and sprigged into replicated trials in West Lafayette, IN and Dallas, TX under USGA ID#: 2025-06-837b (Figures 1 and 2). The Dallas location also included five elite experimental lines for a total of 27 entries. These trials will evaluate establishment, sod harvestability, and regrowth as it pertains to sod production as well as fall color and spring greenup related to cold-hardiness.

Table 2. Five advanced experimental lines in the 2025 NTEP trials.

TAES Number	Advanced DALZ number
6941-36	2510
6782-75*	2513
6782-104*	2514
6942-22	2516
6844-104	2521

*Indicates hybrids which performed best across regions.



Figure 1. Sprigging the 2025 replicated trial in Dallas, TX on June 25, 2025.



Figure 2. Establishment of the 2025 replicated trial in Dallas, TX on November 7, 2025.

USGA ID: 2025-06-837a (KSU), 2025-06-837b (TAMU), 2025-06-837c (Purdue)

Title: Evaluation Of Advanced Zoysiagrass Hybrids For Golf Course Tees To Greens Use

Project Leader: Ross C. Braun, Ambika Chandra, Aaron J. Patton,

Affiliation: Kansas State University, Texas A&M AgriLife Research - Dallas, Purdue University

Objectives:

1. **In-Depth Evaluation of Top Hybrids at Research Stations - Phase IV (years 1-3, 2025-2027):** The objective of Phase IV experiments is to conduct rigorous testing of the elite hybrids to evaluate establishment rates, divot recovery, management influence on thatch accumulation, and additional traits that include morphological differences, drought tolerance, freeze tolerance, sod tensile strength, mowing quality, rooting depth characteristics, herbicide tolerance, as well as turf performance using NTEP protocols.
2. **Field Demonstration Sites of Top Choices at Golf Courses and Sod Farms - Phase V (years 4 and 5, 2028-2029):** The objectives of Phase V are to select and plant the top two or three elite hybrids at golf courses and sod farms within each state to provide on-course evaluation, demonstration, and golf course superintendent or sod producer feedback.

Start Date: 2025

Project Duration: 5 years

Total Funding: \$370,834 (\$122,912 - KSU, \$122,395 - TAMU, \$125,527 - Purdue)

Summary Points:

- In 2025, all three sites planted field experiments by sprigging top zoysiagrass entries and standard checks (Table 1). A consistent methodology was followed at all three sites to have each 5 x 7 ft plot sprigged at a rate of 0.31 ft³ using a “customized bushel box” designed to be 1.24 ft³ (Figure 1). After sprigging, plots were topdressed with ~0.5 inch of soil and tamped. The study area received Ronstar (Oxadiazon) at a rate of ~150 lb product/A and a starter fertilizer at a rate of 1 lb P₂O₅//1000 ft² and 0.75 lb N/1000 ft².
- These field plots were planted on 5 June 2025 (KSU), 2 July 2025 (Purdue), 25 June 2025 (TAMU) (Figures 1, 2, 3, and 4). The plots were fertilized at 1, 2, and 3 months after planting at a rate of 0.75 lb N/1000 ft² with Urea (46-0-0) for a total annual N rate of 3 lb N/1000 ft²/yr (including starter fertilizer).
- Data was collected at all three sites to quantify the establishment speed of entries. Visual turf cover (0-100%) and visual turf quality (1-9 scale) were rated at

least monthly or more often at all three sites, and digital images with a light box were collected at least two of the sites. Additional data on other turf characteristics were collected as well.

- A slight trend toward faster sprig establishment was observed in entries with more *Zoysia japonica* or *Zoysia matrella* in their lineage than *Zoysia pacifica* in Kansas, but this was not consistent across all entries (Table 2).
- In Indiana entry 6844-202 was the slowest to establish compared to other entries (Table 2).
- Some of the newer entries, such as 6941-36 (DALZ 2510), 6829-69, 6829-36, 6844-202, 6942-22 (DALZ 2516) as some examples exhibited faster visual establishment than other experimental entries and standard checks, at times at earlier evaluation dates (Table 3, Figure 4).
- Researchers met at the CANVAS 2025 Conference in Salt Lake City, UT, to discuss current activity and future project timeline (Table 4).

Table 1. Top zoysiagrass hybrid selections and standard comparisons planted in 2025 at the three sites (Phase IV).

Southern U.S. (Dallas)			Transition Zone (Kansas & Indiana) ^d		
Entry ID	Lineage ^c	Leaf Texture	Entry ID	Lineage	Leaf Texture
6782-75^a (DALZ 2513)	[(Zj × Zp)/Zj] × Zp	Very fine	6782-75 (DALZ 2513)	[(Zj × Zp)/Zj] × Zp	Very fine
6782-104^{ab} (DALZ 2514)	[(Zj × Zp)/Zj] × Zp	Very fine	6782-104 (DALZ 2514)	[(Zj × Zp)/Zj] × Zp	Very fine
6782-79	[(Zj × Zp)/Zj] × Zp	Very fine	6782-79	[(Zj × Zp)/Zj] × Zp	Very fine
6785-19 ^b	[(Zj × Zp)/Zj] × Zp	Very fine	–		
6789-23 ^b	[(Zj × Zp)/Zj] × Zp	Very fine	–		
6789-40 ^b	[(Zj × Zp)/Zj] × Zp	Very fine	–		
6792-44 ^b	[(Zj × Zp)/Zj] × Zp	Very fine	–		
6829-36	[(Zj × Zp)/Zj × Zm)	Fine-medium	6829-36	[(Zj × Zp)/Zj × Zm)	Fine-medium
6829-69	[(Zj × Zp)/Zj × Zm)	Fine-medium	–		
6844-104	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium	6844-104 DALZ 2521)	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium
6844-150	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine	6844-150	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine
6844-202	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium	6844-202	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium
6844-36	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium	6844-36	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium
6844-74	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium	6844-74	[Zm × Zj] × [(Zj × Zp)/Zj]	Fine-medium
6941-36 (DALZ 2510)	(Zj × Zm)	medium-coarse	6941-36 (DALZ 2510)	(Zj × Zm)	medium-coarse
6942-22 (DALZ 2516)	(Zj × Zp)	Fine-medium	6942-22 DALZ 2516)	(Zj × Zp)	Fine-medium
Standard checks					
Palisades	Zj	Coarse	Meyer	Zj	Medium-coarse
Lobo	Zj × Zm	Fine-medium	Innovation	Zj × Zm	Fine-medium
DALZ 1701	[(Zm × Zj) × Zj]	Medium-coarse	DALZ 1701	[(Zm × Zj) × Zj]	Medium-coarse
Brazos	Zj	Medium-coarse	DALZ 0101	Zj	Medium-coarse
Emerald	Zj × Zp	Fine	–		
Stadium	Zm	Fine	–		
Zeon	Zm	Fine	–		
DALZ 1311	Zj	Coarse	–		

^a The two bolded entries were top performers across both climatic regions and included in both selections in Phase III (Replicated field trials in 2021 to 2023).

^b These five entries are golf course putting greens candidates due to performance and leaf texture data.

^c Lineage abbreviations: Zj = *Zoysia japonica*, Zm = *Zoysia matrella*, Zp = *Zoysia pacifica*.

^d Eleven entries were planted at KS and IN sites because of their past history of good winter hardiness, while all sixteen entries were planted in Dallas, TX.

Table 2. Visual cover of entries at two dates in Kansas and Indiana.

Treatment	Entry ID	Kansas		Indiana	
		9/25/25 16 WAP ^a	10/25/25 20 WAP	8/28/2025 8 WAP	10/23/2025 16 WAP
		Visual zoysiagrass cover (%)			
1	6782-75 (DALZ 2513)	88 d	92 c	53 abcd	77 abc
2	6782-104 (DALZ 2514)	92 cd	100 a	33 bcde	63 c
3	6782-79	73 e	82 d	60 ab	88 a
4	6829-36	99 ab	100 a	58 abc	83 ab
5	6844-104 (DALZ 2521)	97 abc	100 a	30 de	68 bc
6	6844-150	93 bcd	97 ab	55 abcd	73 abc
7	6844-202	97 abc	99 a	7 e	33 d
8	6844-36	95 abc	98 a	32 cde	63 c
9	6844-74	92 cd	93 bc	60 ab	73 abc
10	6941-36 (DALZ 2510)	100 a	100 a	70 a	83 ab
11	6942-22 (DALZ 2516)	97 abc	100 a	78 a	87 ab
12	Meyer	97 abc	99 a	60 ab	83 ab
13	Innovation	100 a	100 a	60 ab	80 abc
14	DALZ 1701	100 a	100 a	55 abcd	85 ab
15	DALZ 0101	97 abc	100 a	38 bcd	75 abc
<i>p-value</i>		<0.0001	<0.0001	0.0012	0.0007

^aWAP = weeks after planting (sprigging).

Note. Means within a column with a common letter are not significantly different according to Fisher's protected LSD ($\alpha = .05$).

Table 3. Visual cover of entries at two dates in Dallas, TX.

Treatment	Entry ID	Texas	
		10/17/25 17 WAP ^a	11/19/25 22 WAP
		Visual zoysiagrass cover (%)	
1	DALZ 1311	95 ab	100 a
2	Palisades	100 a	100 a
3	6941-36 (DALZ 2510)	75 defg	92 abcde
4	Brazos	92 abc	100 a
5	DALZ 1701	92 abc	100 a
6	Lobo	88 abcd	98 ab
7	6829-69	93 abc	100 a
8	6829-36	67 efghi	86 cdef
9	6844-104 (DALZ 2521)	67 efghi	88 abcdef
10	6844-202	75 defg	91 abcde
11	6844-36	73 defg	88 abcdef
12	6844-74	53 ij	69 gh
13	6942-22 (DALZ 2516)	80 bcdef	97 abc
14	6844-150	62 ghij	78 fg
15	Emerald	82 bcde	94 abcd
16	Stadium	78 cdef	96 abc
17	Zeon	72 efgh	95 abcd
18	6782-104 (DALZ 2514)	47 j	63 h
19	6782-75 (DALZ 2513)	52 ij	77 fg
20	6782-79	60 ghij	83 def
21	6785-19	60 ghij	87 bcdef
22	6789-23	65 fghi	91 abcde
23	6789-40	57 hij	82 ef
24	6792-44	62 ghij	81 efg
<i>p-value</i>		<0.0001	<0.0001

^aWAP = weeks after planting (sprigging).

Note. Means within a column with a common letter are not significantly different according to Fisher's protected LSD ($\alpha = .05$).

Table 4. Project Timeline Summary.

Sub-objectives	Year 1 (2025)				Year 2 (2026)				Year 3 (2027)				Year 4 (2028)				Year 5 (2029)			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Propagation and shipment of hybrids (greenhouse)	AC																			
Sprigging establishment rate (field)	ALL																			
Evaluate the performance of replicated field trials according to NTEP protocols (field)	ALL																			
Freeze tolerance (controlled environment)					AP				AP											
Divot recovery (field)						RB				RB										
Mgmt practices (fertilization/mowing height) influence on thatch accumulation (field)					RB				RB											
Sod tensile strength (field)					AP				AP											
					RB															
					AC															
Mowing quality (field)					AP				AP											
Drought tolerance (field)					AC				AC											
Morphological assessment (greenhouse)								AC												
Rooting depth measurements (greenhouse)						RB				RB										
Herbicide screening (field)									AP				AP							
Transplant sod for on-site demonstrations and feedback (golf courses/sod farms)													ALL							
Semi-annual project meetings (virtual/ CSSA)	ALL																			

Legend of Partners




	Texas A&M AgriLife-Dallas		Purdue University
	Kansas State University		All partners participating
L	Lead (bolded) or co-investigator initials on sub-objective/effort		



Figure 1. Creating sprigs in the greenhouse (a) and planting in the field in Manhattan, KS, on 5 June 2025 (b). Collecting data on zoysiagrass establishment speed on 30 June 2025 (c), and plots on 29 September 2025 (~116 days after sprigging) in Kansas.



Figure 2. Sprigs planted in the field in West Lafayette, IN on 2 July 2025 (left) and plots on 15 August 2025 (44 days after sprigging) in Indiana (right).



Figure 3. Sprigs planted in the field in Dallas, TX on 25 June 2025.



Figure 4. Plot establishment on 5 November 2025 in Dallas, TX, which corresponded to 20 weeks after planting.

USGA ID# 2021-16-740

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

Project Leaders: Susana Milla-Lewis¹, Aaron Patton², and Brian Schwartz³

Affiliation: ¹North Carolina State University, ²Purdue University, ³University 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, and 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

- Experimental zoysiagrass genotypes were planted in golf courses in NC and GA and in demonstration plots in IN. Feedback from golf course superintendents, producers and golfers was collected on their potential for golf course roughs.
- Genomic regions associated with large patch resistance were identified in a Meyer x PI 231146 mapping population.
- Preliminary evaluation of new zoysiagrass hybrids identified promising lines in terms of turf quality, establishment rate, and stress tolerance over a large geographical area.
- Results from this project might help increase adoption of zoysiagrass cultivars in golf courses, which would decrease management inputs and increase sustainability.

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.

Objective 1: Expand evaluation of zoysiagrass genotypes

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 at golf courses in NC and GA and we continue to receive feedback on overall appearance, persistence and management inputs from these locations. Additionally, in August 2025, we hosted a Zoysiagrass Field Day at Purdue University to share our project findings to date and to continue to gather feedback on the use of zoysiagrass in golf course roughs at different cutting heights (**Figures 1 and 2**). We surveyed the golf course superintendents in attendance to learn more about their zoysiagrass research needs and to gather their opinions and those shared by golfers at their courses on the performance of zoysiagrass. Those survey results are summarized here:

Management Advantages. All the Midwestern superintendents in attendance rated zoysiagrass as having superior turf quality compared to other grass species, and the majority reported that it requires substantially lower maintenance inputs. Specifically, 77% found that zoysiagrass needs less fertilizer and irrigation than alternative turfgrass species, while all noted fewer weed problems. Additionally, superintendents reported fewer disease issues and about half reported reduced insect problems, making zoysiagrass an attractive option from a resource management perspective.

Golfer Perceptions. From a playability standpoint, golfers have overwhelmingly positive impressions of zoysiagrass surfaces. Among the golfers surveyed, seven out of eighteen rated playability as "excellent," with additional respondents providing ratings of "very good" or "great." Golfers consistently praised the grass for providing forgiving, good ball lies, noting that balls stay exposed and visible rather than becoming lost in the turf (Figure 1). The fine texture and dense, uniform playing surface create consistent conditions that enhance the golfing experience. However, mowing height does matter for playability—some golfers found that three-inch heights can be too challenging as balls get "swallowed," while two-inch heights provide better playability.

Critical Limitations. Despite these advantages, zoysiagrass faces significant limitations that restrict its wider adoption on golf courses. The most critical issue identified was winterkill susceptibility, with almost half the superintendents identifying cold stress as their biggest abiotic concern. The grass also exhibits slow spring recovery, taking considerable time to green up and recover from winter dormancy. Establishment challenges present another major barrier, as zoysiagrass is consistently noted for slow establishment rates and high initial costs. Other superintendents also expressed the need for improved shade tolerance, which would be particularly beneficial for tree-lined fairways common on many golf courses.

Maintenance Considerations. Regarding maintenance ease, 80% of superintendents found zoysiagrass fairways easier to maintain than other turfgrasses, while others commented similarly about rough maintenance. The primary pest management concerns include large patch disease (see Obj. 2), which was identified by 77% of superintendents as the most common disease issue, and billbugs, noted by over half the superintendents as the most problematic insect pest. Crabgrass and goosegrass remain the most common weed challenges, though weed pressure overall is significantly lower than with other turfgrass species.

Research Priorities. For turfgrass scientists, golf course superintendents noted that research priorities should focus first on developing cultivars with improved winter hardiness, as this represents the primary barrier to expanded use. Equally important is research into accelerating establishment and spring recovery speed. Additional research priorities suggested include breeding for enhanced shade tolerance, developing integrated pest management strategies specifically for large patch disease and billbugs in zoysiagrass systems, and conducting economic feasibility studies to demonstrate cost-benefit analyses of zoysiagrass fairway and rough conversion.

As climate change has increased the occurrence and intensity of drought stress, there is a need to capitalize on the reduced irrigation needs of warm-season grasses in a larger portion of the country. Zoysiagrass is uniquely poised to fill that niche because of its higher levels of cold tolerance. Therefore, our work to increase adoption of zoysiagrass in golf courses will ultimately help increase the sustainability of the golf industry.

Objective 2: Develop materials with improved large patch tolerance

Two hundred and twenty-nine 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 (DI-API), 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 (Figure 3). 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. Details on this research can be found at <https://doi.org/10.1094/PHYTO-10-24-0311-R>

Objective 3: Evaluate the performance of new experimental lines

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. The resulting top 26 lines were propagated over winter. In spring 2025, twenty-four plugs from each line were planted in 5 x 5 ft plots with 1.5 ft alleys in a randomized complete block design with three replications in NC, GA, FL, TN, IN, CA and AZ. Six commercial cultivar checks (Meyer, Zeon, Lobo, Palisades, Brazos, and Australis) were included for comparison. Data collected in year 1 included: turf quality, genetic color, dollar spot incidence, percent green cover, green leaf area index, texture, density, and fall color.

Preliminary data analysis identified lines with superior performance for turf quality and establishment rate across locations (**Figure 3**). Evaluation of these trails will continue through 2028 and will include data collection on overall performance, winter survival, tolerance to prevalent insect and fungal pests, as well as drought tolerance and color retention in the western locations (CA and AZ), where the need for zoysiagrass cultivars with reduced irrigation needs is especially critical. Additionally, ancillary trials for evaluation of shade tolerance and sod strength will be planted in 2026. In Spring 2028, data will be analyzed across traits, locations and years to select breeding lines with potential for commercial release for expansion.

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. Zoysiagrass maintained at different golf course rough cutting heights.



Figure 2. Superintendents, sod growers, and educators interacting at the Zoysiagrass Field Day at Purdue University and assessing the performance and ball lie of different zoysiagrass germplasm maintained at rough heights.



Figure 3. Meyer x PI 231146 advanced trial showing differences in A. fall color at Sandhills (NC), B. fall color at Tifton (GA), C. establishment rate at Vero Beach (FL), and D. turf quality at West Lafayette (IN).

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 replications.
- Deficit irrigation treatment of 80, 60, and 40 % ET replacement started on May 1st, 2025.
- Genotypic variation among saltgrass accessions for establishment, density, and color was observed among the accessions.
- Evaluation for chilling tolerance continue for the next one year using visual assessment and proximal sensing devices that collect spectral and image data.

Summary Text:

Rationale and Methodology

Recent megadroughts and substantial high temperatures in southwestern USA (Williams et al., 2022) have strained the availability of fresh water for turfgrass irrigation. Research has shown that switching from naturalized turfgrass to low-input native grass alternatives and ground covers on non-play areas of golf courses in the low desert can minimize water usage and improve turf management (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. 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). However, research on identification and use of adaptable native grasses that are

accepted for their aesthetic value, ecosystem services, and drought tolerance is limited in the Desert Southwestern USA.

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 2.25m² (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.

The deficit irrigation treatment started May 1st, 2025 and the plots are being evaluated monthly for color and quality. Also, active spectral and RGB image data are being collected for objective evaluation of the accession in different irrigation regimes.

Results and Future Expectations

Percent threshold analysis using ortho-mosaics of RGB-image data revealed noticeable differences among the plots for percentage area coverage (Fig. 1). In this mosaic image taken on August 20, 2025, few genotypes with good percentage of ground cover, density, and greenness were identified.

Similarly, winter color retention of the accession under different reduced irrigation in a mild Arizona winter is being evaluated (Fig. 2). There is a notable variation in green color retention among genotypes. Monthly data on visual rating scales (1-9 scale; 1 = brown, 9 = dark green) and digital image data are being collected. In addition, field observation of spring green-up and winter survival will be collected and analyzed.

This study highlights the genotypic variation among accessions for establishment, density, greenness, winter color, and overall turfgrass characteristics. These results suggest that saltgrass can serve as an alternative native turfgrass in the desert environment for non-play areas of golf courses, recreational areas, parks, and home lawns providing substantial ecosystem services. The naturally adapted native grass studied is expected to also offer significant benefit in reducing irrigation water requirements and other external inputs. The data will be analyzed for genotype-by-irrigation treatment interaction and stress tolerance. This study implies significance of native grasses for turfgrass characteristics in drought-stress landscapes.

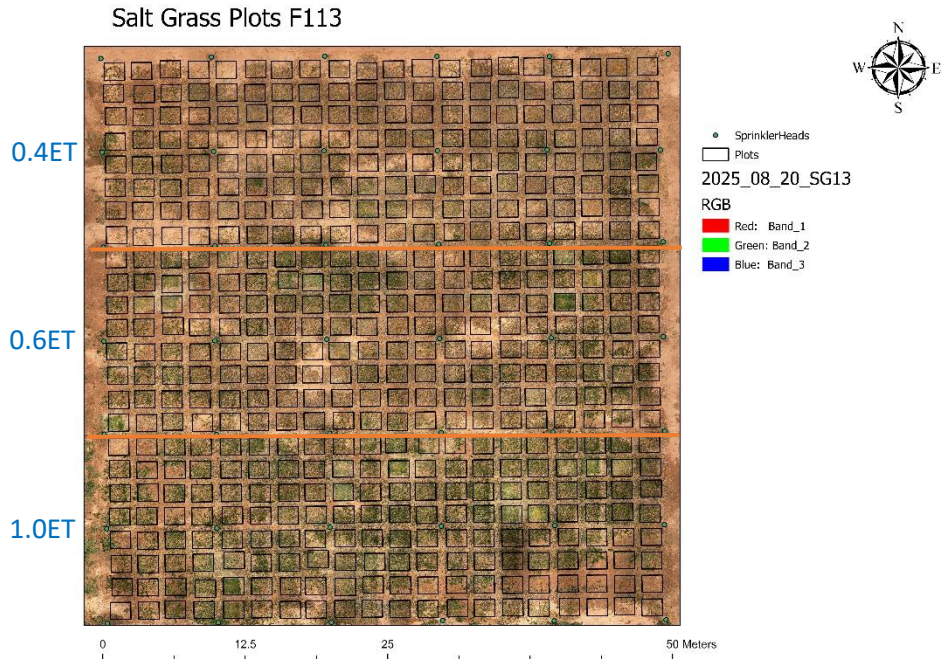


Fig. 1: RGB image of saltgrass accessions evaluated under different evapotranspiration replacement irrigation along with bermudagrass and zoysiagrass checks during 2025 in Maricopa, AZ.



Fig. 2: Winter color retention variation among saltgrass accessions in Maricopa, AZ (Picture taken on Dec. 02, 2025).

USGA ID#: 2021-04-728

Title: Buffalograss breeding and development

Project Leader: Keenan Amundsen

Affiliation: University of Nebraska-Lincoln

Objectives: The primary objectives of this study 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:

Buffalograss spring green-up was modeled showing a 4% increase in greenness per degree C after April 28th, 2025.

Dramatic differences in timing of winter dormancy onset and color retention were observed among elite breeding lines.

Initiated a long-term trial to evaluate species under minimal management.

Summary Text: Buffalograss (*Bouteloua dactyloides*) is an important warm-season turfgrass species, widely recognized for its exceptional heat and drought tolerance, making it highly suitable for low-input environments. Buffalograss thrives under minimal management, which aligns with sustainability goals and water conservation efforts. Our buffalograss breeding program is focused on improving traits that increase adoption by turf managers while supporting economic return on production. Among these traits, timing of winter dormancy onset and spring green-up is a primary concern. Straw-colored dormant buffalograss is not desirable when grown adjacent to green cool-season turfgrasses in early spring or late fall.

To address this issue, preliminary data was collected to begin modeling the timing of breaking winter dormancy in the spring. Selection for green-up is relatively easy since the aim is to distinguish green versus straw-colored buffalograss, but accurately quantifying differences and determining optimal selection timing is more challenging and necessary for genetic improvement. In this study, buffalograss plots were imaged and 3-inch soil temperatures recorded from March 26, 2025, when buffalograss was fully dormant, through June 2, when dormancy had completely broken (Figure 1). Initial analysis indicated a 2% increase in green color per degree Celsius. However, minimal changes in green-up occurred prior to April 28, so the model was adjusted to better align with the onset of green-up. This adjustment improved correlation ($R^2 = 0.71$) and revealed a 4.78% increase

in greenness per degree Celsius. Although preliminary, this model provides a foundation for predicting green-up timing and guiding breeding decisions.

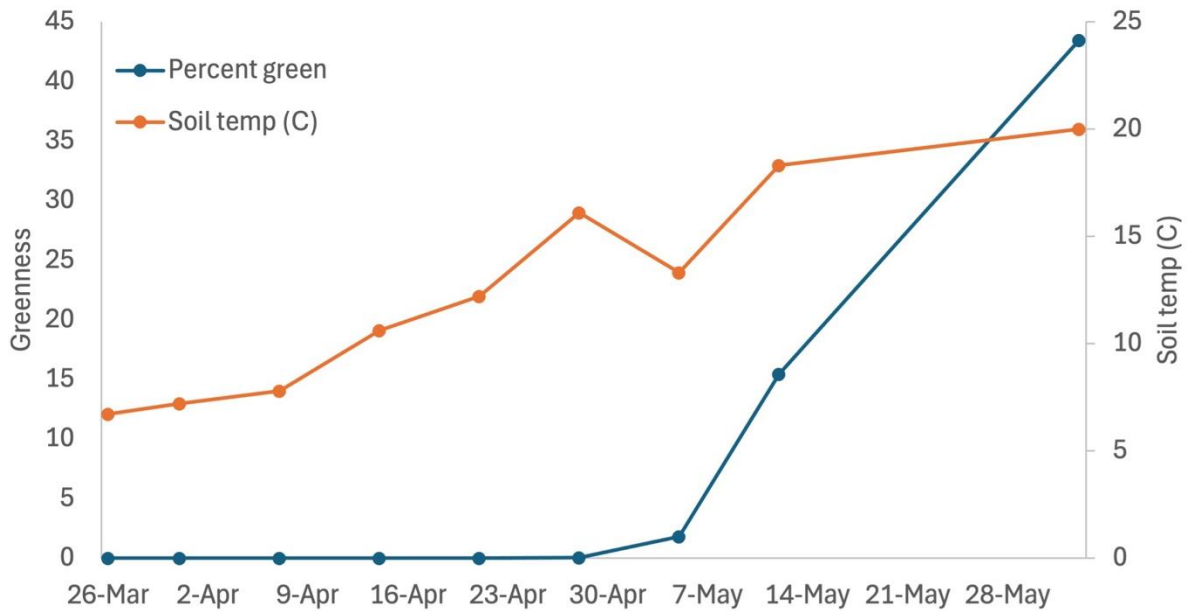


Figure 1 Buffalograss spring green-up vs 3-inch soil temperature

Timing of winter dormancy onset among elite vegetative lines was also visually rated in the fall. Substantial differences in timing and severity of early dormancy onset were observed (Figure 2). One experimental line (NE-BFG-15-3654) had significantly better color retention



Figure 2 Color differences among elite breeding lines during onset of winter dormancy, November 3rd, 2025

than Legacy on November 3, and 15 experimental lines outperformed Prestige. Four of the 15 experimental lines also have exceptional establishment rate, sod strength, and recovery based on prior evaluations. Extending the buffalograss growing season is complicated by the importance of winter dormancy for survival in northern climates; selecting against dormancy could increase winter injury risk so this breeding objective is advancing cautiously.

A low-input evaluation trial was established using a wheel-and-spoke design to assess long-term stand persistence under minimal management (Figure 3). The research was



Figure 3 Wheel and spoke layout of low-input turf species evaluation

inspired by a social media post highlighting better low input performance of improved cool season lawn species compared to native grasses. The side-by-side comparison of species under minimal and no supplement inputs beyond precipitation in this study will document clear winners under these harsh conditions. Persistence is critical because some buffalograss lines decline within three years after establishment. Our elite seeded breeding lines nearing the end of the cultivar development pipeline were initially selected for persistence, insect and disease resistance, turf quality, and seed yield. From an initial set of 14 lines, five have consistently demonstrated superior seed yield across multiple years. Successful lines will be advanced to regional trials for potential future release.

Our research is addressing key factors that influence breeding efficiency, production economics, and turf quality. The project supports the development of improved buffalograss cultivars suitable for use on golf courses and in other turf landscapes.

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:

There is a need for consistent and detailed experimental design meta data in sequencing projects.

Integrating data from multiple sequencing projects can improve condition-specific gene identification.

A minimal number of genes were conserved across 16 cool-season species drought RNA-seq studies.

Summary Text: High-throughput transcriptome sequencing has been widely applied to turfgrass species, often used to study specific conditions or genotypes, identify genes or mutations, characterize genotype performance differences, and develop molecular markers to accelerate plant breeding objectives. These studies generate substantial amounts of data, but the information is rarely used beyond the scope of the initial study. We are beginning to test if these datasets can be integrated to study broader patterns of gene expression to better understand turf systems.

As a test, nine drought-related projects were identified in the National Center for Biotechnology Information Sequence Read Archive (SRA) database. The nine projects included 16 separate genotypes (7 perennial ryegrass, 3 creeping bentgrass, 3 tall fescue, and 3 Kentucky bluegrass). More perennial ryegrass studies were included because at the time of the analysis, there was a sequenced genome of *Lolium perenne* cv. Kyuss available through the Ensembl Plants database (<https://plants.ensembl.org/>). The perennial ryegrass genome was used as a reference. Limited experimental details are provided for most of the projects used in this study, making it difficult to test how specific stress conditions are impacting turf performance. At a minimum, each project was selected because it contained replicated well-watered control and water-limited or drought-stressed

treatments. The water-limited condition descriptions varied by project and included deficit-based ET irrigation, low volumetric water content, reduced % field capacity, or labeled simply as drought stressed. Some of the tested genotypes were identified as resistant or susceptible to drought stress. Data for each of the 96 experimental units (16 projects x 2 water treatments x 3 replicates) were downloaded from the SRA and represented more than 506 billion sequenced nucleotides (Table 1). Perennial ryegrass

Table 1 Select drought related projects of turf species

Species	Genotype	BioProject	Raw data (G)
Perennial ryegrass	Citation IV	PRJNA1172787	39.27
	Falster	PRJEB9841	11.94
	LP2142	PRJNA1247987	29.84
	LP2951	PRJNA1247987	28.55
	LP2972	PRJNA1247987	25.89
	Manhattan	PRJNA1247987	30.91
	Veyo	PRJEB9841	14.74
Creeping bentgrass	Declaration	PRJNA1320721	27.94
	PennA4	PRJNA957937	12.52
	Penncross	PRJNA304034	15.41
Kentucky bluegrass	Brilliant	PRJNA1165320	41.57
	Midnight	PRJNA719097	23.91
	PI440603	PRJNA719097	33.11
Tall fescue	S279	PRJNA746971	21.8
	T400	PRJNA746971	19.1
	Unknown	PRJNA1259052	36.94

BioProject - accession numbers of samples tested

(<https://www.ncbi.nlm.nih.gov/bioproject/>). Raw data – billions of sequencing read base-pairs per project.

projects followed a reference-based assembly and differential gene expression workflow whereas Kentucky bluegrass, creeping bentgrass, and tall fescue followed a de novo differential gene expression workflow. Treatment-specific differentially expressed transcripts associated with drought were identified for each project, compared, and mapped to the perennial ryegrass reference.

Differential gene expression results from the seven perennial ryegrass projects were compared, and there were 96 genes that were consistently differentially expressed across all datasets. These genes were mapped to the perennial ryegrass reference genome and showed stable expression patterns across projects (Figure 1). Their consistent expression

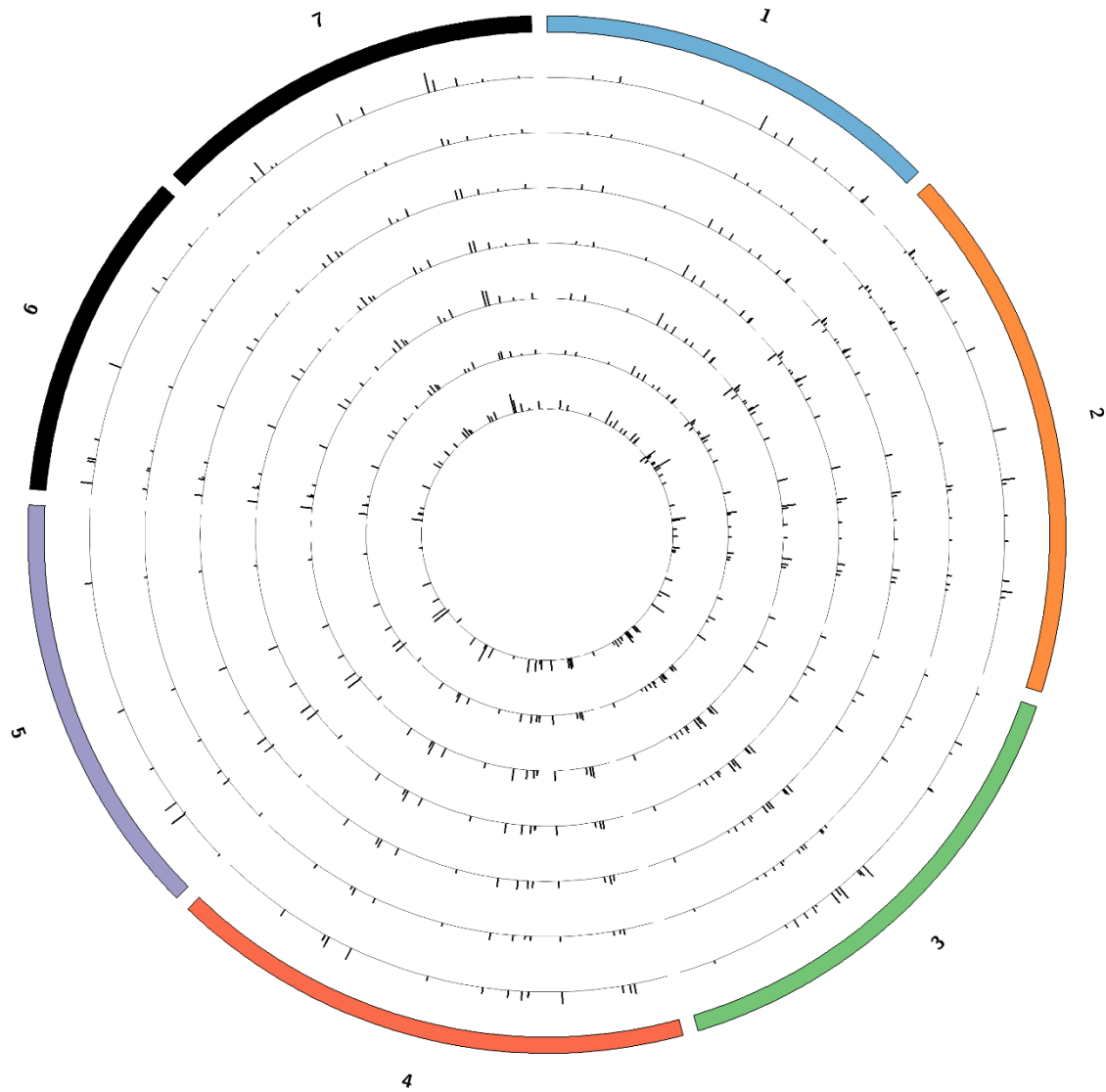


Figure 1 Drought responsive genes mapped to the perennial ryegrass genome

The numbers around the outside of the figure represent each of the perennial ryegrass chromosomes. The inner circles represent genotypes from individual studies and conserved differentially expressed genes are indicated. The genotypes Citation IV, Falster, LP2142, LP2951, LP2972, Manhattan, and Veyo are arranged from outer to inner in the interior circle maps. The location of each bar along an inner circles represents the genomic location and the magnitude of the bar represents expression levels (outward facing have higher expression in drought samples, inward facing have higher expression in control samples).

suggests they are highly conserved and likely play a central role in the species' drought response. While these genes may appear significant in individual differential expression

analyses, they are not ideal candidates for molecular marker development or breeding because of their conserved nature.

Seven genes were differentially expressed across all Kentucky bluegrass, creeping bentgrass, and tall fescue projects (Table 2). Except for an unknown protein, all the genes

Table 2 Log2 fold change in expression for highly conserved drought responsive genes

Species	Genotype	low temp induced	ABA-inducible	heat shock	LEA	U-box	heat shock	unknown
Kentucky bluegrass	Brilliant	3.74	2.14	3.73	2.95	7.57	4.27	5.90
	Midnight	5.08	6.40	5.06	3.75	6.77	3.68	3.10
	PI440603	1.98	3.68	1.03	3.14	5.90	1.64	3.15
Creeping bentgrass	Declaration	7.92	6.08	-2.85	4.25	7.29	6.45	1.82
	PennA4	0.43	-5.77	0.86	1.43	1.72	1.56	2.28
	Penncross	6.29	8.84	5.37	3.48	5.38	6.33	1.54
Tall fescue	S279	4.01	4.96	2.58	3.30	3.92	6.91	-0.94
	T400	5.62	1.54	3.29	1.83	4.89	5.52	-0.73
	Unknown	3.44	6.68	2.07	2.51	5.03	3.37	-6.20

Genotypes tested in drought studies are listed for each species. Log2 fold changes in gene expression are listed and positive numbers indicate higher expression of that gene in response to drought stress, whereas negative numbers indicate higher expression in the control samples in response to drought stress.

have been previously described as being associated with drought stress. It is worth noting that there was a substantial difference in numbers of differentially expressed transcripts among the projects which is expected due to differences in sequence identify conservation between species, sequencing depth, and experimental conditions. Identifying genes already described as associated with drought might not seem exciting, but it demonstrates that the workflow is successful and can be leveraged to tease apart conserved and unique conditional responses.

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, Ph.D. and Mark LaBarge, M.S.

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 and 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:

- Bermudagrass and zoysiagrass can be established from sprigs in the northern transition zone with widely varying establishment times
- DALZ 1701 and Lobo zoysiagrass were able to maintain high turf quality when being managed with a low maintenance fairway program
- Tiftuf bermudagrass required the least amount of irrigation to maintain 30% or less visual wilt stress
- Using improved bermudagrass and zoysiagrass can reduce irrigation and fungicide use on golf course fairways
- Creeping bentgrass fairways may require less herbicides than both zoysiagrass and bermudagrass
- Cold hardy bermudagrass and zoysiagrass offer alternative sustainable options for use on fairways in the northern transition zone.

Rationale

Climate change in the northern transition zone has expanded the use of warm-season turfgrasses, driving demand for improved cold hardy bermudagrass (*Cynodon* spp.) and zoysiagrass (*Zoysia* spp.). Improved bermudagrass and zoysiagrass have not been extensively evaluated for use on fairways in the northern transition zone. Detailed information on the agronomic performance, maintenance inputs required, and perception of golfers on bermudagrass and zoysiagrass is lacking for the region. This project includes a series of studies to provide detailed information on bermudagrass and zoysiagrass in the northern transition zone and determine the feasibility of utilizing either species for golf course fairways.

Study 1 Summary

Cold hardy bermudagrass and zoysiagrass were established via sprigs at a 500 US bushels/acre rate on June 30, 2022 in a randomized complete block design with three replications. Plot sizes for the trial were 9.3 m² and included 13 zoysiagrass and 16 bermudagrass entries. Results from this trial have been presented in previous reports (2023-2024 USGA progress reports) and were used to inform selections for continued evaluation of the top performers in fairway trials (study 2) and a water use trial (study 3). An additional trial was sprigged on July 18, 2025 using the same experimental design to acquire another year of data on establishment from sprigs. The same entries were included in the trial, but plot sizes are smaller at 2.3 m² instead of 9.3 m². Visual establishment data was statistically evaluated using non-linear regression with a sigmoid variable slope model (Karcher et al, 2008; Sandor et al, 2021) in GraphPad Prism Version 10.1 (GraphPad Software, Boston, MA) to model time required to reach 90% turfgrass coverage after sprigging (Figure 1). Similar trends were seen in both 2022 and 2025 with bermudagrass establishing quicker than zoysiagrass. Under ideal conditions, all bermudagrass entries can be expected to establish in 50 days or less. Six zoysiagrass entries can be expected to establish in 125 days or less. Overall, it was determined that it is feasible to establish zoysiagrass and bermudagrass from sprigs in the northern transition zone with time to establishment varying significantly between species and entries. Previous data from the 2022 trial proved that several entries were able to survive through the first winter after sprigging with limited winter kill. Additional data will be collected on winter kill following establishment in the spring of 2026.

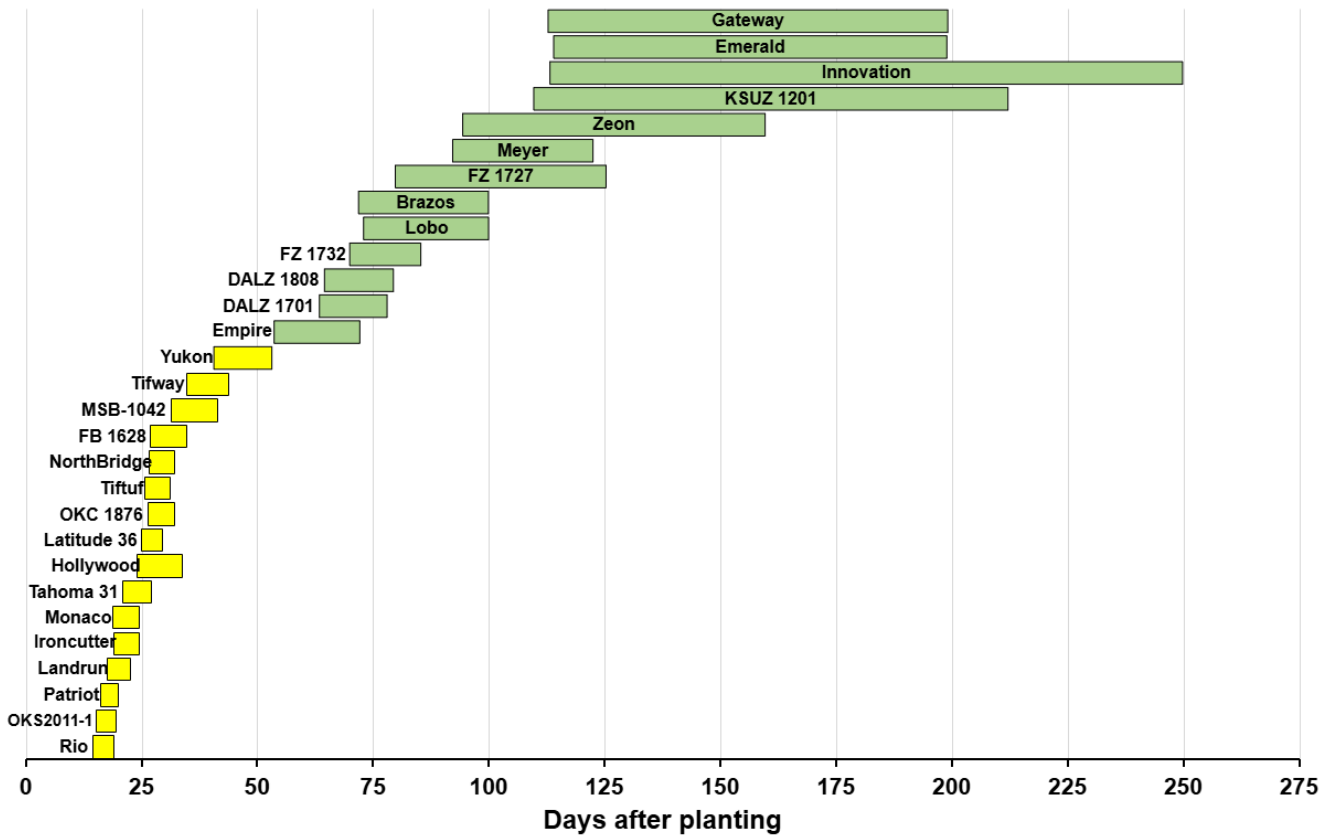


Figure 1. Visual establishment ratings from 2025 analyzed with non-linear regression showing days to reach 90% turfgrass coverage. Non-overlapping bars are significantly different. Bermudagrass entries are yellow and zoysiagrass entries are green.

Studies 2 and 3 Methodology

The results of study 1 provided valuable information to select the best performing entries of bermudagrass and zoysiagrass for the northern transition zone. Extensive evaluation of study 1 results and collaboration with turfgrass experts aided in determining the entries used for studies 2 and 3 (Table 1). Selected entries were established via sod on July 1, 2024 in two fairway trials (study 2) and a water use trial (study 3). Study 2 plots measure 1.2 m x 1.8 m and are arranged in a randomized complete block design nested by species. Study 3 plots measure 1.5 m x 1.5 m and are arranged in a randomized complete block design. Studies 2 and 3 can be seen in Figure 2.

Study 2 includes two fairway trials, a high maintenance trial and a low maintenance trial. Management plans (Table 2) for these trials were developed by reviewing best management practices for each species and extensive collaboration with turfgrass pathologists, weed scientists, and turfgrass management experts. The management plans were split into the following categories: Irrigation, fertilizer, herbicides, fungicides, insecticides, and cultural practices. Preventative management practices were calendarized and curative management practices were triggered with predetermined thresholds based on the maintenance level. Visual turf quality, spring green-up, fall color retention, and applicable disease ratings were recorded throughout the trial. Turf quality ratings were taken weekly from May 15 to November 10 and analyzed using a mixed model repeated measures (MMRM) ANOVA with a Bonferroni correction using R (v4.4.2; R Core Team, 2024). In addition, soil volumetric water content was measured using a TDR 350 soil moisture meter (Spectrum Technologies, Inc. Aurora, IL) and digital images were collected using a lightbox (data not shown).

Study 3 served as a water use trial specifically designed to determine the required irrigation amounts for each cultivar (from three different species). Plots were established under a rain out shelter to prevent any additional water from hitting the plots. Plots were mowed 2 to 3 times a week and maintained at a 1.27 cm mowing height. Fertilizer, herbicides and fungicides were applied as needed to prevent nutrient deficiency, unwanted weed encroachment, or disease. The

Table 1. List of selected entries for each species used in studies 2 and 3.

Species	Cultivar/Experimental Selection
<i>Zoysia</i> spp.	DALZ 1701
	Lobo
	Meyer (standard)
<i>Cynodon</i> spp.	Tiftuf
	Tahoma 31
	Ironcutter (standard)
<i>Agrostis</i>	Coho
<i>Stolonifera</i> L	Spectrum
	007 (standard)



Figure 2. Image A shows study 2 (low vs. high maintenance) and image B shows study 3 (water use trial).

Figure 3. Calibration of an irrigation square utilized for single plot irrigation in the water use trial (study 3).



Azusa, CA) on each corner (Figure 3). The squares were calibrated using a catch can test kit to apply 0.64 cm of irrigation evenly to a single plot. The amount of irrigation applied to each plot was recorded and statistically analyzed using SAS 9.4 software (SAS Institute Inc., Cary, NC) with a one-way ANOVA test.

Studies 2 and 3 Results and Discussion

Zoysiagrass required the least amount of management inputs under low maintenance (Table 3). Under low maintenance, an entry from each species was able to maintain acceptable turf quality (≥ 6) throughout the first year of the trial (Table 4). DALZ 1701 and Lobo zoysiagrass showed statistically significantly higher turf quality than all other entries under low maintenance. Under high maintenance, DALZ 1701 also exhibited statistically significantly higher turf quality than all other entries (Table 4). All entries (except Spectrum creeping bentgrass) of bermudagrass and creeping bentgrass showed improvement in turf quality when managed under high maintenance (Table 4). There was less variation in turf quality among entries under high maintenance with two entries from each species exhibiting acceptable turf quality. Each species had one entry that did not exhibit acceptable turf quality under high maintenance (Meyer, Ironcutter, and Spectrum). In study 3, turf quality was higher in all entries except for Tahoma 31 during the month of September (Table 5). Water use was higher in July for all entries (Figure 4). Tiftuf bermudagrass required the least amount of irrigation in both July and September (Figure 4) and was able to maintain statistically significantly higher turf quality than all other entries (Table 5).

The use of bermudagrass or zoysiagrass on fairways can decrease water use and increase turf quality during the summer. When looking at both fairway maintenance levels and the water use trial, it appears that bermudagrass requires the least amount of irrigation when compared to zoysiagrass or creeping bentgrass. Bermudagrass and zoysiagrass require less irrigation and fungicides when compared to creeping bentgrass. However, herbicide inputs are higher for bermudagrass and zoysiagrass when compared to creeping bentgrass. Cold hardy bermudagrass and zoysiagrass offer alternative sustainable options for use on fairways in the northern transition zone.

experiment was conducted for two separate months from July 2 to July 31, 2025 and from August 27 to September 25, 2025. During the experiment, plots were visually rated daily for wilt stress and volumetric water content was measured using a TDR 350 soil moisture meter. Digital image data was collected 2-3 times a week using a lightbox. Plots were individually irrigated when visual wilt stress was 30% or more. Irrigation squares measuring 1.5 m x 1.5 m were used for single plot irrigation. The squares were constructed of 1.27 cm PVC pipe with pressure regulated Rain Bird 1800 heads and a 5Q nozzle (Rain Bird Inc,

Table 2. Fairway management programs used for each species and maintenance level during fairway trials (study 2) at the Adelphia Plant Science Research Station.

	Low Maintenance			High Maintenance		
	Zoysiagrass	Bermudagrass	Creeping Bentgrass	Zoysiagrass	Bermudagrass	Creeping Bentgrass
Irrigation	Apply 1.27 cm of irrigation when wilt is visible in at least 40% of the plot			Apply 0.64 cm of irrigation when Soil Volumetric Water Content falls below 20%		
Fertility (lb N/year)	0.5	1	1	1	2	2
Preventative Herbicide	Fall Proflaminate		None	Fall Proflaminate Spring Oxadiazon		Spring Oxadiazon
Curative Herbicide	When weeds are visible in 40% of a plot			When weeds are visible in 10% of a plot		
Preventative Fungicide	None			High rate Posterity XT (2x @ 28-d fall + 1x spring @ half green-up)	High rate Posterity XT (2x @ 28-d fall)	High rate Maxtima Exteris stressgard Briskway Rotator (@ 21-d)
Curative Fungicide	When disease is visible in 40% of a plot			When disease is visible in 10% of a plot		
Mowing Height (cm)	1.27 – 1.52			0.95 – 1.52		0.95
Aeration	1 x/year			1-2x/year		

Table 3. Fairway maintenance inputs applied on fairway trials (study 2) at the Adelphia Plant Science Research Station from November 1, 2024 to November 1, 2025.

	Low Maintenance			High Maintenance		
	Zoysiagrass	Bermudagrass	Creeping Bentgrass	Zoysiagrass	Bermudagrass	Creeping Bentgrass
Irrigation (cm)	1.27	2.54	8.89	4.44	1.27	4.44
Fertility (lb N/1000 ft ²)	0.5	1	1.125	1	2	2.375
Herbicides (lb ai/acre) ¹	1 ²	1 ²	none	3 ^{2,3}	3 ^{2,3}	2 ³
Fungicides (lb ai/acre) ¹	none	none	4.5 ^{4,5,6}	10.6 ^{4,9,10}	7.1 ^{4,9,10}	14.7 ^{4,5,6,7,8,9,11}

¹Represents the sum of all active ingredients used to treat the species

²Proflaminate ³Oxadiazon ⁴Azoxystrobin ⁵Difenoconazole ⁶Fluazinam ⁷Fluopyram ⁸Mefentrifluconazole

⁹Propiconazole ¹⁰Pydiflumetofen ¹¹Trifloxystrobin

Table 4. Estimated marginal means of turf quality in low and high maintenance fairway trials (study 2) at the Adelpia Plant Science Research Station in 2025. Estimated means were determined by a mixed model repeated measures ANOVA with a Bonferroni correction for 36 tests ($\alpha = 0.0014$). Capital letters show significant differences between low maintenance entries. Lower-case letters show significant differences between high maintenance entries.

Species	Cultivar	Low Maintenance Turf Quality		High Maintenance Turf Quality	
<i>Zoysia</i> spp.	DALZ 1701	7.6	A	7.7	a
	Lobo	7.6	A	6.8	abc
	Meyer	5.2	BCD	3.5	d
<i>Cynodon</i> spp.	Tiftuf	5.4	BCD	7.1	ab
	Tahoma 31	5.8	BC	6.6	abc
	Ironcutter	4.2	D	5.5	bc
<i>Agrostis</i>	Coho	4.9	CD	6.9	abc
	Spectrum	5.7	BC	5.4	c
<i>Stolonifera</i> L	007	6.3	B	6.5	abc

Table 5. Estimated marginal means of turf quality in a water use trial (study 3) conducted under a rainout shelter at the Adelpia Plant Science Research Station in 2025. Estimated means were determined by a mixed model repeated measures ANOVA with a Bonferroni correction for 36 tests ($\alpha = 0.0014$). Capital letters show significant differences between entries in July. Lower-case letters show significant differences between entries in September.

Species	Cultivar	July Turf Quality		September Turf Quality	
<i>Zoysia</i> spp.	DALZ 1701	5.8	A	7.0	ab
	Lobo	6.0	A	7.1	ab
	Meyer	1.8	C	4.9	abc
<i>Cynodon</i> spp.	Tiftuf	5.8	A	7.5	a
	Tahoma 31	5.4	A	4.4	c
	Ironcutter	4.3	AB	4.2	c
<i>Agrostis</i>	Coho	5.4	A	5.9	abc
	Spectrum	4.8	AB	4.9	abc
<i>Stolonifera</i> L	007	2.6	AB	4.6	bc

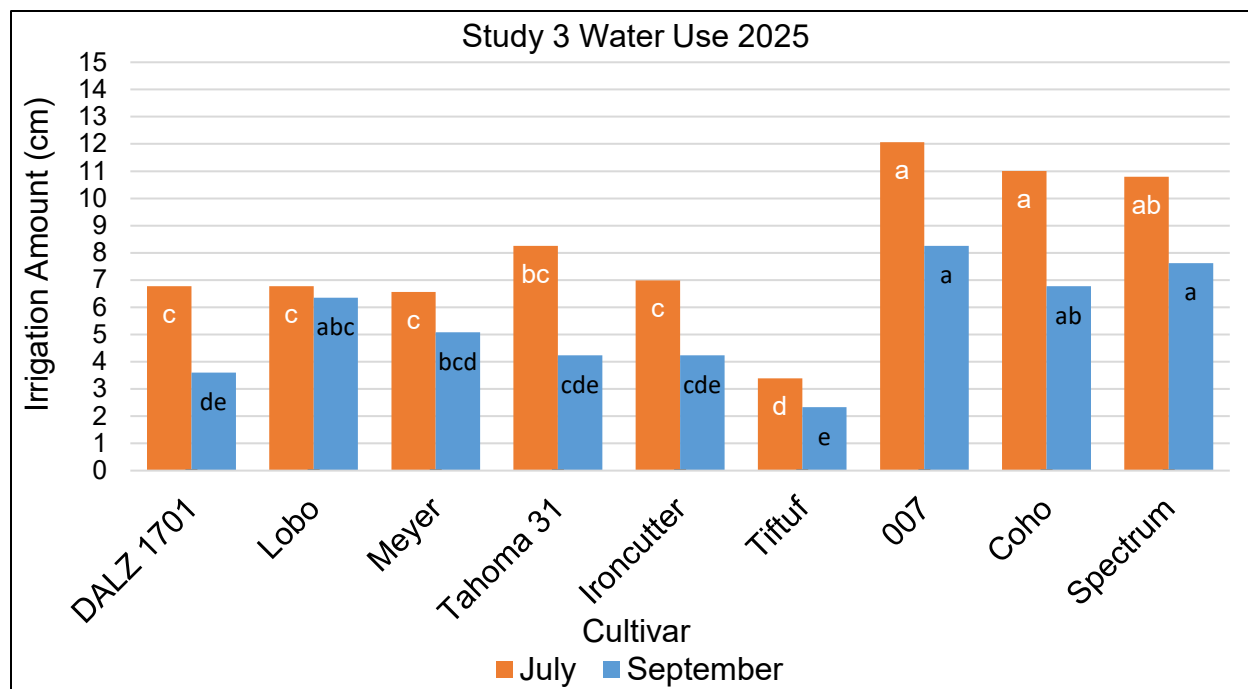


Figure 4. Estimated water use requirements from a fairway trial conducted under a rainout shelter at the Adelpia Plant Science Research Station in 2025. Bars represent the amount of water needed for each entry to maintain 30% or less visual wilt symptoms. Significant differences within months between entries are shown with white or black letters based on Tukey’s HSD ($\alpha = 0.05$).

Future Expectations (Studies 2-4)

Leveraging the information from the field trials, an economic model will be developed to predict the potential costs associated with both course renovations and management over time for each turfgrass species. The inputs required for each species will be drawn from the field trial results. Additionally, the model will incorporate information from structured interviews with golf course superintendents who are actively managing fairways in the northern transition zone. The economic model will be constructed in MS Excel and will use the current costs for pesticides, equipment, and labor. An environmental assessment will also be written to accompany the economic model. The environmental assessment will highlight potential areas where environmental impact can be lessened, and more sustainable practices can be incorporated. The assessment will draw information from the field trials, structured interviews, current environmental models, and the Environmental Impact Quotient (Kovach et al, 1992).

In order to provide a complete picture to golf courses who are considering using bermudagrass or zoysiagrass in the northern transition zone, it is important to consider the perceptions of golfers. We have designed a golfer preference survey to help determine the opinion and perception of golfers. Specifically, how golfers perceive the differences between warm-season and cool-season turfgrasses used on fairways. The survey was reviewed by the Institutional Review Board at Rutgers University and is being conducted through the Qualtrics survey software (Qualtrics, Provo, UT). Once completed, survey results will be reviewed and statistically analyzed for significance.

References

Karcher, D.E., Richardson, M.D., Hignight, K. and Rush, D. (2008), Drought Tolerance of Tall Fescue Populations Selected for High Root/Shoot Ratios and Summer Survival . *Crop Science*, 48: 771-777. <https://doi.org/10.2135/cropsci2007.05.0272>

Kovach, J., Petzoldt, C., Degni, J., & Tette, J. (1992). A method to measure the environmental impact of pesticides. *A Method to Measure the Environmental Impact of Pesticides* | New York State Integrated Pest Management.

Sandor, D, Carr, TQ, Karcher, D, & Richardson, M. Irrigation requirements for establishing seeded tall fescue and bermudagrass cultivars in the transition zone. *Crop, Forage & Turfgrass Mgmt.* 2021; 7:e20108. <https://doi.org/10.1002/cft2.20108>

USGA ID# 2025-01-832

Title: INTEGRATING PHOSPHORUS AND PH MANAGEMENT WITH A PLANT GROWTH REGULATOR FOR ANNUAL BLUEGRASS SUPPRESSION IN BENTGRASS

Project Leaders: Co PIs Matthew T. Elmore and James A. Murphy. Graduate student Emmanuel U. Nwachukwu.

Affiliation: Rutgers University

Objectives: To evaluate effects of mat layer pH and phosphorus, combined with chemical management (paclobutrazol) to better understand annual bluegrass and creeping bentgrass population dynamics for superintendents who desire creeping bentgrass or annual bluegrass. 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. It is being accomplished with two fields trials. Project 1 is evaluating ‘Oakley’ creeping bentgrass encroachment in a three-way factorial of acidic or near neutral pH mat layer, low or adequate phosphorus, and paclobutrazol or trinexapac-ethyl. Project 2 compares ‘Penncross’ vs. ‘Oakley’ creeping bentgrass encroachment across a five-level pH gradient that ranges from 4.8 to 7.0. From June 30 to July 3, 2025, creeping bentgrass plugs were planted into both field trials. Annual bluegrass turf quality and related variables were assessed in 2025. Creeping bentgrass encroachment was first measured in November 2025 and will continue in 2026.

Start Date: 2025

Project Duration: 3 years

Total Funding: \$139,213

Summary Points:

- For Project 1, the mat layer pH ranged averaged 6.7 in limed plots and 5.2 in gypsum plots (as of June 2025 sampling). The mat layer pH ranged from 4.8 to 7.0 in Project 2.
- Near-neutral mat layer pH (>6) resulted in highest turfgrass quality of annual bluegrass putting greens, especially in the summer for Project 2. Supplementing acidic plots in Project 2 with gypsum alone or gypsum + nitrogen partially ameliorated reductions in turfgrass quality of annual bluegrass attributed to an acidic mat layer (pH < 6).
- Bentgrass encroachment into annual bluegrass was reduced as lime rate increased in Project 2. Gypsum application also reduced bentgrass encroachment, which suggests which suggests calcium plays a major role in annual bluegrass competitiveness.
- No differences in bentgrass encroachment have been observed in Project 1 to date. All acidic plots in this experiment receive a gypsum supplement.

Summary Text:

Methods

Site management: The site was managed as described in the proposal. Minor summer patch disease was observed in plots with pH of 7.0, but no other disease was observed in 2025. The site for both projects was core-cultivated on 15 October 2025 using 1.8 cm-diameter solid tines on a 5 x 5 cm spacing and backfilled with sand.

Amendments: Lime (3664 kg ha⁻¹) was applied to the neutral pH plots on 24 November 2025, and gypsum (1265 kg ha⁻¹) was applied to the acidic pH plots on 21 June, 15 August, 21 September and 23 November 2025 for Project 1 (Figure 1). Lime was applied at 80, 230, 700, 2090, and 6280 kg ha⁻¹ on 21 November 2025 for Project 2. Gypsum was applied to gypsum treatments at 925 kg ha⁻¹ on 21 June, 15 August, 21 September and 21 November 2025 for Project 2. A slight adjustment from last year was made in Project 2, by changing high-rate gypsum treatment to gypsum (925 kg ha⁻¹) + supplemental nitrogen. Nitrogen was applied at 5 kg ha⁻¹ once monthly during the growing season to supply an additional 25 kg N ha⁻¹ annually.

Other treatment applications: For both projects, phosphorus (P₂O₅) was applied monthly to P treatments at a rate of 10 kg P₂O₅ ha⁻¹ beginning in July and at 20 kg ha⁻¹ for the November application. The nitrogen supplement was applied foliarly from ammonium sulfate at the same time for Project 2. Paclobutrazol was applied to PGR plots at a rate of 25 g ha⁻¹ in Project 1, beginning 1 August 2025 (to allow the bentgrass plugs to acclimate from transplant in early July), and continued on a 300 GDD interval. The paclobutrazol rate will likely increase to 50 g ha⁻¹ in 2026.

Plug Installation: From June 30 to July 1, 2025, creeping bentgrass plugs (5 cm diameter) were harvested from a putting green nursery and immediately planted to the plots (0.9 m by 2 m) in both projects (Figure 2). Originally, plots proposed to be 2 m by 2 m, but after concerns about not being able to publish a journal article from two years of evaluating the same plots, they were divided in half. The other half of each plot will be planted in 2026 to produce two runs of each project repeated in time. Four plugs of Penncross and Oakley cultivars each (totaling 320 plugs) were planted to each plot on 1 ft centers in Project 2, while eight plugs of Oakley (totaling 256 plugs) were planted to each plots in Project 1. Plugs were removed from the nursery with a plugger and cut to a 1 cm depth to be installed.

Data collection

Mat layer sampling occurred just prior to amendment applications on 10 June 2025 and again just prior to amendment application in November 2025 following Xu's (2023) methods described in the proposal. Turfgrass quality was evaluated visually on a 1 (poor) to 9 (excellent) scale monthly. NDVI and NDRE data were collected from weekly drone flights. Clipping yields were collected monthly. A grid count was conducted in November 2025 to determine the number of intersects containing bentgrass using a 0.9 m by 0.9 m grid with intersects on a 1.3 cm spacing

(Figure 3). November mat layer sampling data, most NDVI and NDRE data, and clipping yield data are not yet available. Data was analyzed using the Glimmix procedure in SAS (v 9.4).

Results

Project 1: The effect of pH treatment on mat layer pH was highly significant ($P < 0.001$) for the June 2025 sampling (Table 1). Turfgrass quality was affected by pH only on every rating date (Table 1, Figure 4). That only pH is having an effect is not surprising since phosphorus deficiencies are not apparent in the plots and PGR treatments are not designed to affect turfgrass quality. However, it is concerning that mean mat layer phosphorus across all the plots continued to increase (data not presented). Mat layer P averaged across all plots increased from 47 ppm in November 2024 to 53 ppm in June 2025 despite no phosphorus being applied to the site since May 2023.

For bentgrass cover, no statistical differences were observed for any factor or their interaction (Table 1). Since plugs were planted in early July we suspect differences will emerge in 2026. There are some non-significant trends of more bentgrass cover in the acidic and low phosphorus plots (data not presented).

Project 2: Mat layer sampling from June 2025 indicates a range of mat layer pH from 5.2 to 7.0 from the non-treated to highest lime rate (Table 2). Treatments also influenced mat layer calcium (Mehlich III) sampled in June 2025. Calcium increased with lime application rate. Gypsum application also increased calcium, although the difference was not statistically significant compared to the non-treated. Mat layer calcium data will be re-analyzed with a data transformation that we suspect will allow us to better separate means where there appears to be biologically significant differences.

There was also a substantial effect of lime treatment on turfgrass quality at every rating date. This effect was most apparent in July and August. Turf quality tended to increase with lime rate. Applying gypsum and gypsum + nitrogen increased turf quality compared to the non-treated in July, August and October, but quality of these plots was still lower than the three highest lime rates on most rating dates. NDVI and NDRE tended to increase with lime rate although differences are not as apparent as with turf quality data.

Treatments also affected bentgrass cover as determined by grid intersect counts. The non-treated, lowest lime rate, and nitrogen supplement were in the top statistical category for bentgrass cover. The three highest lime rates were in the lowest statistical category for cover. The bentgrass cover in these three highest lime rates was 72 to 79% of the non-treated control. Gypsum reduced bentgrass cover compared to the non-treated which suggests calcium plays a role in annual bluegrass competitiveness.

Plans for 2026: The other half of the plots will be planted with creeping bentgrass plugs in 2026 to establish a second run of this experiment. We will continue grid counts for plugs installed in 2025 for both projects. Tissue from clipping yield data will be analyzed for tissue nutrients for

both projects. Other data collected but not yet analyzed will be finished during the winter. We are considering rootzone sampling at two different depths (0-5 cm and 5-10 cm) for one of the samplings in 2026. We will assess the lack of phosphorus depletion in Project 1 and determine how to proceed with that factor before spring 2026.

Table 1. ANOVA for Project 1 in 2025. Mat layer pH was determined in June 2025, monthly turf quality, and bentgrass cover (number of intersects) are also presented.

Factor	Turf quality								Bentgrass cover (intersect #)
	pH	May	June	July	Aug	Sep	Oct	Nov	
Phosphorus (P)	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH	***	***	***	***	***	***	***	***	NS
PGR	NS	NS	NS	NS	NS	NS	NS	NS	NS
P * pH	NS	NS	NS	NS	NS	NS	NS	NS	NS
P * PGR	NS	NS	NS	NS	NS	NS	NS	NS	NS
pH * PGR	NS	NS	NS	NS	NS	NS	NS	NS	NS
P * pH * PGR	NS	NS	NS	NS	NS	NS	NS	NS	NS
<i>pH effect</i>		<i>Turf quality (1 to 9 scale)</i>							<i>#</i>
Acidic	5.2	5.6	5.5	6.3	6.4	6.1	7.1	5.8	189
Neutral	6.7	6.5	6.9	7.3	7.3	7.8	8.0	7.3	198

Abbreviations: ***, NS; P-value < 0.001 and not significant, respectively.

Table 2. Mat layer pH and calcium, turfgrass quality and NDVI and NDRE for selected dates, and bentgrass cover as affected by amendments for Project 2. Turfgrass quality values >7.0 are shaded in green and those <6.0 are shaded in red.

Amendment	pH ^a	Calcium (ppm)	Turfgrass quality (1 to 9)					NDVI		NDRE		Bentgrass cover	
			June	May	July	Aug	Oct	Nov	July	Oct	July	Oct	# ^b
Non-treated	5.2 e ^d	215 c	4.9 de	5.5 e	5.8 e	6.1 d	5.4 bc	0.600 d	0.725 c	0.196	0.163 d	154 a	100 a
Lime (80 kg ha ⁻¹)	5.5 d	316 c	5.5 bc	6.4 b	6.0 e	6.5 cd	5.0 cd	0.600 d	0.775 ab	0.194	0.168 d	137 abc	92 ab
Lime (230 kg ha ⁻¹)	5.6 d	398 c	5.6 b	6.4 bc	6.3 de	7.1 bc	5.8 bc	0.600 d	0.800 a	0.197	0.165 d	135 bc	89 abcd
Lime (700 kg ha ⁻¹)	6.2 c	515 c	6.4 a	7.4 a	7.4 ab	7.4 ab	6.0 b	0.600 d	0.800 a	0.203	0.175 cd	118 de	79 cde
Lime (2090 kg ha ⁻¹)	6.9 c	1660 b	6.6 a	7.5 a	7.3 ab	8.0 a	7.0 a	0.700 a	0.800 a	0.208	0.202 a	108 e	72 e
Lime (6280 kg ha ⁻¹)	7.0 a	7127 a	6.6 a	7.8 a	7.6 a	8.0 a	7.0 a	0.675 ab	0.800 a	0.201	0.201 ab	117 de	78 de
Phosphorus	5.1 ef	235 c	5.1 cd	5.6 de	5.8 e	6.0 d	5.8 bc	0.600 d	0.750 bc	0.191	0.166 d	124 cde	82 bcde
Nitrogen (N)	4.8 f	185 c	4.5 e	6.0 cd	6.3 de	6.1 d	4.4 d	0.625 cd	0.800 a	0.201	0.188 bc	143 ab	95 a
Gypsum	4.9 f	381 c	5.1 cd	6.0 cd	6.6 cd	7.1 bc	5.9 b	0.600	0.775 ab	0.196	0.171 d	125 cde	83 bcd
Gypsum + N	4.9 f	435 c	5.4 bc	6.5 b	6.9 bc	7.9 a	7.1 a	0.650 bc	0.800 a	0.201	0.198 ab	134 bcd	89 abc
P-value	***	***	***	***	***	***	***	***	*	NS	***	***	***

Abbreviations: *, ***, NS; P-value < 0.05, 0.001, and not significant, respectively.

^a pH and Mehlich III calcium of mat layer sampled in June 2025.

^b Number of intersects determined to be creeping bentgrass pooled across cultivars. A greater number of intersects indicates greater cover.

^c Bentgrass cover compared to the non-treated control, pooled across cultivars.

^d Means followed by the same letter are not significantly different according to Fisher's Protected LSD (0.05) test

Figure 1. Gypsum amendments applied to project 1 on November 21, 2025.



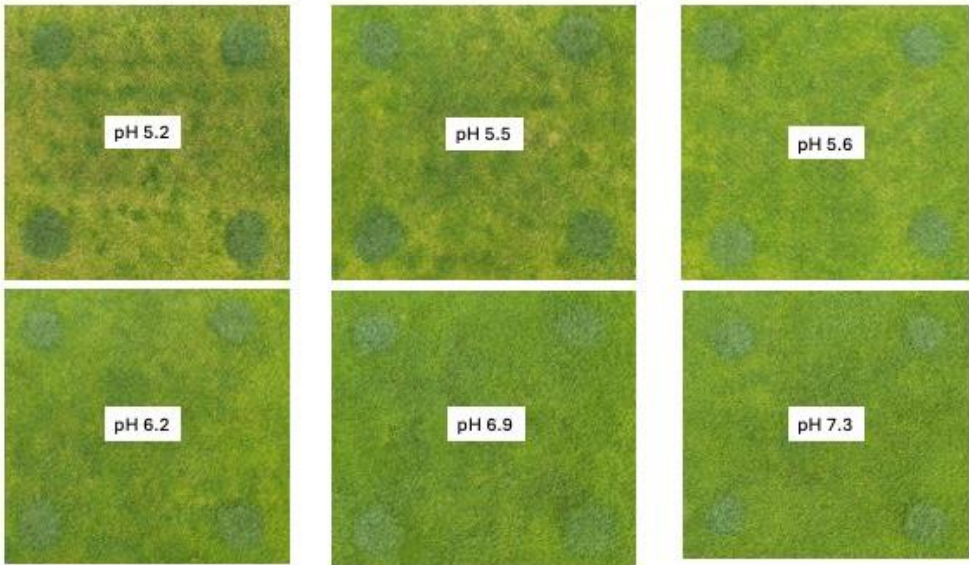
Figure 2. Installing bentgrass plugs.



Figure 3. Grid count of creeping bentgrass plugs encroaching into annual bluegrass



Figure 4. Plot differences on 24 September 2025 as affected by mat layer pH in Project 2. Notice the difference in annual bluegrass color as affected by pH, while the the four bentgrass plugs appears unaffected.



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) Miller¹; Krishna Ghimire¹; Paul Koch²; Scott Warnke³

Graduate Research Assistant: Justice Ruwona¹

Affiliations: ¹Purdue University; ²University of Wisconsin; ³USDA 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:

- Greenhouse experiments showed that dollar spot severity decreases as the ratio of the resistant cultivar in a stand increases.
- Cultivar performance and disease response varied by region.
- In the Wisconsin field trial, glyphosate-treated plots exhibited lower disease severity compared to interseeded plots without herbicide application. This difference along with overall dollar spot severity was lower in 2025 than 2024, providing phenotypic evidence of resistant cultivar incorporation in glyphosate treated plots.
- Disease severity declined across all treatments in 2025 in Wisconsin. Glyphosate-treated plots required the fewest fungicide applications.
- At Purdue, combining interseeding with a selective herbicide (methiozolin, bispyribac-sodium) or PGR (paclobutrazol) reduced *Poa annua* incidence in 2024. Annual bluegrass presence increased in 2025.

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). Consequently, eliminating a single application would amount to approximately eight 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 long term through reduction in fungicide expenditure. This information can justify the initial expense 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

Study 1 - Greenhouse experiments

Greenhouse experiments were conducted on cultivar blend ratios (0%, 10%, 25%, 50%, 75%, 90%, 100%) of dollar spot-resistant (Pure Select, 007XL, Coho) and susceptible (Penncross) bentgrass challenged with inoculation of two *Clariireedia jacksonii* isolates with differing fungicide sensitivities (SO84, SO88). Treatments were arranged in a split-plot design, with *Clariireedia* isolate used for inoculation as the main plot and cultivar and blend ratio organized as randomized subplots within the main plot. The experiment was conducted twice with each trial including four replications for each treatment combination. Inoculum was grown on rye grain for two weeks at 21°C, placed on pins in bentgrass canopies, and maintained under conditions providing 10–12 hours of leaf wetness daily (Fig. 1A). Disease severity was assessed over a 42-day period post inoculation using visual estimates and digital image analysis.

Study 2 – Interseeding field trials

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 in two directions. Plots were either untreated, treated with non-selective glyphosate, or treated with four herbicide/PGR treatments *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 a curative fungicide, Fluazinam (Secure – 0.5 fl oz/1000 sq ft), when a threshold of five-dollar spot infection centers was reached. Turfgrass quality, dollar spot severity, and percent *Poa annua* encroachment were assessed throughout the season both visually and with digital image analysis (light box). Leaf clippings of each plot were collected thrice (May, July, September) (Fig. 1B) and are being genetically analyzed to determine integration of the new cultivar into the plant population (conversion success).

Results

Greenhouse experiments: Dollar spot severity was significantly influenced by the *Clariireedia* isolate, with a fungicide-resistant isolate (SO88) being more aggressive and producing more disease than the sensitive one. Dollar spot severity was highest on Penncross alone, with no statistical differences observed among the resistant cultivar monostands. These results demonstrate that the three newer cultivars possess enhanced resistance to dollar spot when compared to the 1954-released Penncross, although none exhibit complete resistance. Mean disease severity of the blended cultivar ratios was divided into three statistically different

groups—low resistance (10% and 25%), medium resistance (50% and 75%), and high resistance (90% and 100%). Increasing resistant cultivar proportions led to a consistent decrease in dollar spot severity, with blends containing 90% resistant cultivar achieving up to 42% less disease (Fig 2). These findings indicate that no blend ratio provided complete resistance, but higher seeding rates of resistant cultivars offer greater disease reduction. This study was published in *International Turfgrass Research Journal* and presented at the 15th International Turfgrass Research Conference in Japan.

Interseeding field studies: Cultivar and herbicide/PGR program impact varied by location (Table 2). In Wisconsin, interseeded plots without herbicide had 198% higher disease severity than glyphosate-treated seeded plots in 2024, indicating poor resistant cultivar establishment without herbicide (Fig 3A). In 2025, Wisconsin plots seeded with glyphosate showed 58% lower disease severity than interseeded plots without herbicide. Disease declined overall in 2025, but fungicide applications were still required (Fig 3B). Glyphosate-treated plots required fewer fungicide applications in both years. Indiana plots showed only 9% and 12% disease differences between glyphosate and interseeded plots without herbicide in 2024 and 2025, with no difference in fungicide needs across years. No disease was observed in Pennsylvania in 2024 and no differences among treatments were observed in 2025. In 2024 at Indiana, glyphosate-treated plots had over three times more *Poa annua* than plots treated with methiozolin, paclobutrazol, and bispyribac-sodium (Fig 3C). *Poa* increased across all treatments in 2025.

Future expectations

Disease phenotype, *Poa* counts, and fungicide use data collection will be repeated in the 2026 growing season. Data generated will enable us to determine the return on investment for a complete renovation versus minimally disruptive interseeding programs (Objective 3). Current efforts to genetically analyze leaf clippings for cultivar quantification will allow us to better understand the composition of the grass stand over time as affected by treatments (Objective 2).

Table 1. Herbicide/PGR program

Herbicide/PGR	Trade name	Timing*	Rate
Amicarbazone	Xonerate	21 & 7 DBS	3 fl oz/A
Bispyribac sodium	Velocity	14 DBS & 30 DAS	1.5 fl oz/A 0.75 fl oz/A
Methiozolin	Poacure PM	45 DBS & 84 DAS	1.2 fl oz/1000 sq
Paclobutrazol	Trimmit	14 DBS & 42 DAS	16 oz/A
Glyphosate	Roundup Pro	14 & 7 DBS	48 oz/A
Untreated	Xonerate		

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

Table 2 Analysis of variance indicating significant sources of variation based on AUDPC¹

	<i>West Lafayette, IN</i>	<i>Madison, WI</i>
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Factor	Df	2024 ²	2025	2024	2025
Cultivar	2	0.024³	0.071	0.005	0.279
Herbicide/PGR	5	0.144	0.885	<0.0001	0.017
Cult x Herb/PGR	10	0.067	0.197	0.001	0.415

¹AUDPC (Area Under Disease Progress Curve) represents the total disease severity calculated over the assessment period with the trapezoidal rule,

²Location and Year significantly influenced AUDPC ($p < 0.001$), necessitating separate analyses for each location

³Significant main effects or interactions ($p < 0.05$)

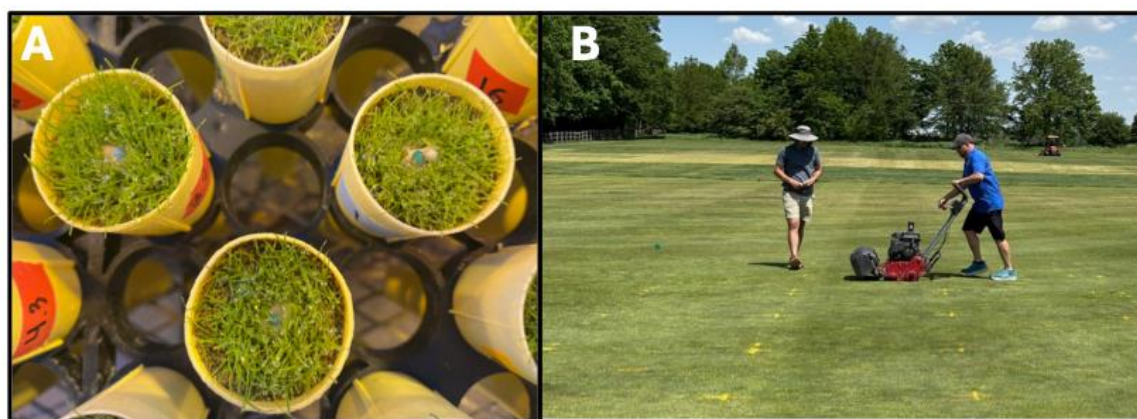


Fig 1. (A) Twenty-four hours post inoculation on ten-week-old creeping bent grass in greenhouse experiments (B) Collection of leaf clippings from interseeded plots for subsequent genetic analysis. Photo taken May 16th, 2025.

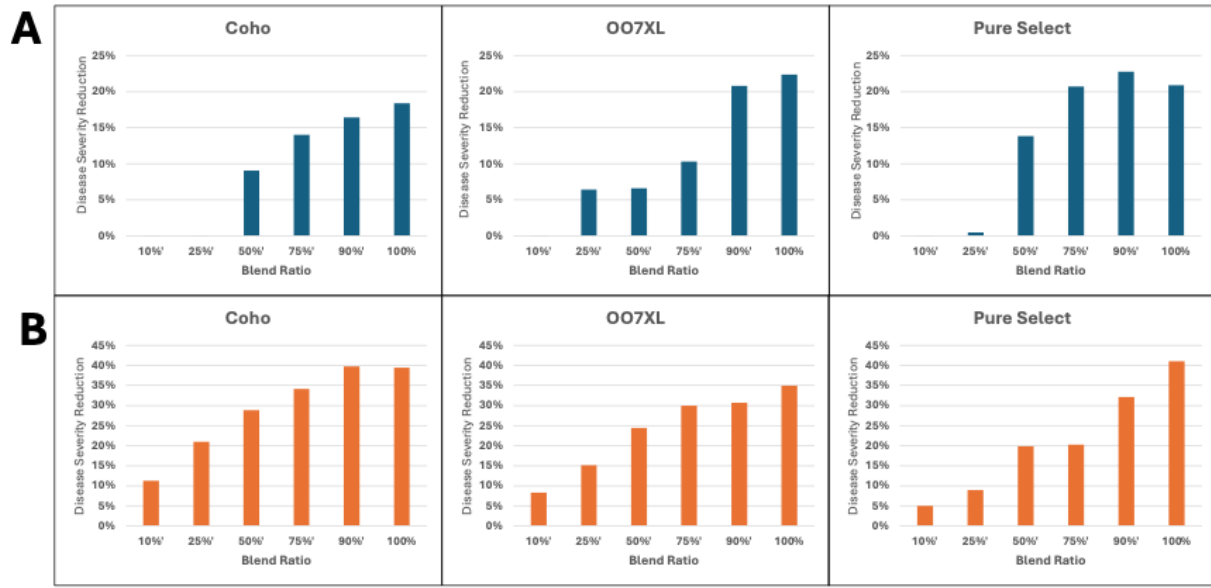


Fig 2. Disease severity reduction in Experiment 1 (A) and Experiment 2 (B) based on the area under the disease progress curve (AUDPC). Reduction represents the percentage reduction in resistant cultivar polystand compared to Penncross monostand. AUDPC represents the total disease severity calculated over a given time.

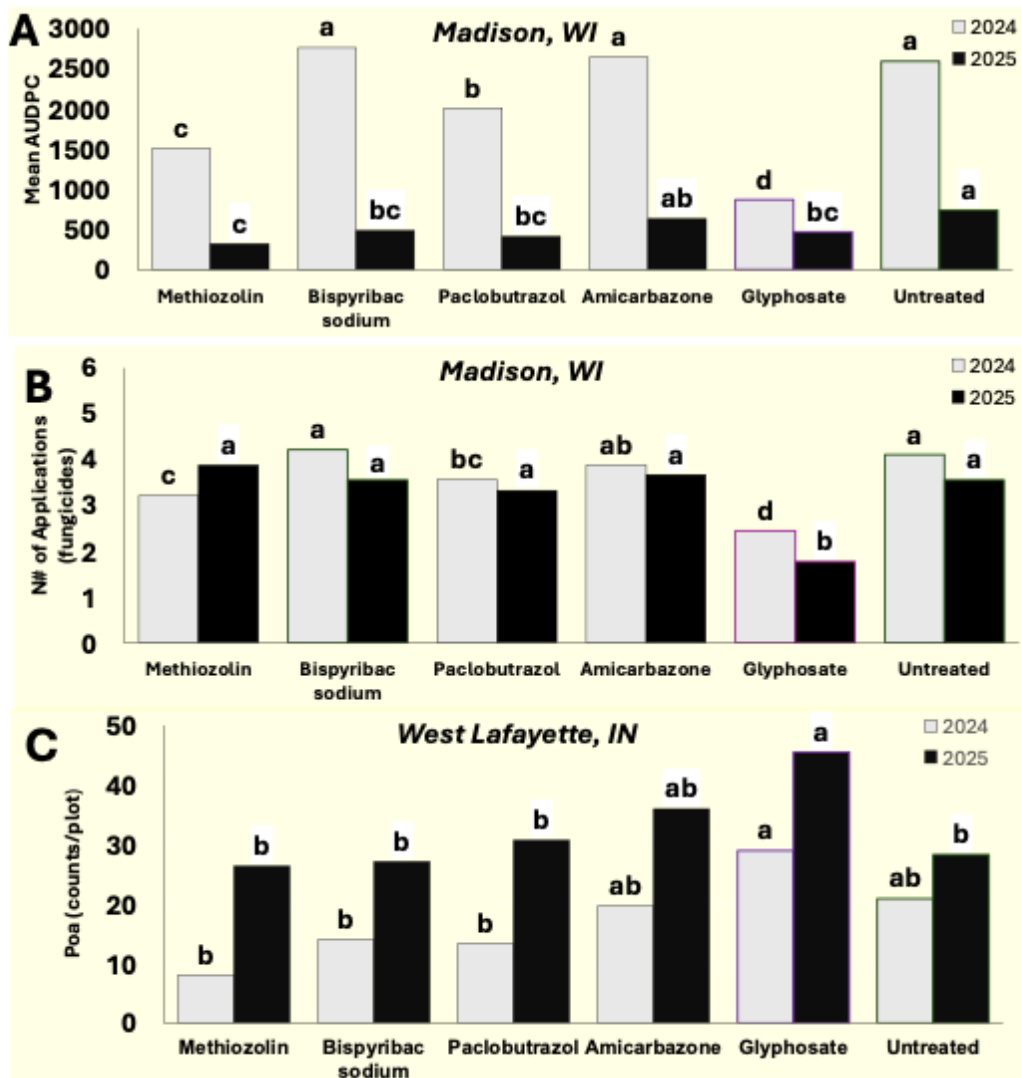


Fig 3. Herbicide/PGR effectiveness based on (A) the area under disease curve progress curve (AUDPC) based on dollar spot severity, (B) number of fungicide applications during the 2024 & 2025 season in Wisconsin and (C) *Poa* counts conducted during *Poa* seedhead flush (GDD22) on April 19th, 2024 and April 26th, 2025. Columns with the same letter are not significantly different according to Fisher's Protected LSD (P = 0.05).

USGA ID: 2025-10-841
Title: Effects of shade on cold tolerance and winter injury of warm-season grasses
Project leaders: Michael Richardson and Wendell Hutchens, University of Arkansas
Key Project Personnel: John McCalla and Will Green, University of Arkansas
Project Report Date: Dec. 5, 2025
Objectives: The overall goals of this project will be to test the effects of varying shade levels and trinexapac-ethyl on stem carbohydrate levels, LT₅₀ values, and field winterkill of an ultradwarf bermudagrass green and a *Zoysia matrella* fairway

Start Date: Spring 2025

Project Duration: Data collection will be completed in Spring 2027

Total Funding: \$86,659

Summary Points:

- Shade structures were deployed on both turfgrass sites in May 2025 and remained on the sites until leaf drop (mid-November)
- Both grasses experienced some decline in overall turfgrass quality under increasing shade through the season, but both species maintained adequate coverage at all shade levels except the 50% level.
- Application of the PGR resulted in a slight improvement in turfgrass quality under shaded conditions in both species
- Significant data collection will begin in January 2026, as freeze chamber tests and tissue carbohydrate levels will be measured in early 2026 and field assessment of winterkill will be assessed in spring 2026.

Background: Warm-season grasses have been widely-used on golf courses in tropical and sub-tropical regions of the United States and the world for over 100 years, but their use in transition zone environments has significantly increased over the last 20 years. Much of this northerly spread has been a result of the development of more cold-tolerant varieties, especially with bermudagrass (*Cynodon* spp.) (Gopinath et al., 2021; Xiang et al., 2022). However, warm-season grasses have weaknesses, most notably their sensitivity to shade and potential for winter injury (Hutchens et al., 2024; Carr et al., 2025).

Bermudagrasses are used on every playing surface on a golf course, including putting greens, tees, fairways, approaches, collars, and rough. Ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers. x *Cynodon transvaalensis* Burt Davy) has been the primary choice for golf greens in the warm climatic zones of the United States and there has been an increased use in more northern environments in the transition zone, from central Oklahoma across to Virginia (Richardson and Booth, 2023). Bermudagrass is noted for its aggressive growth rate, ability to withstand and recover from traffic, and ability to survive severe drought conditions. Zoysiagrass (*Zoysia* spp.) is also widely-used on golf courses, but is primarily used on fairways, tees, approaches and collars (Patton et al., 2017). Zoysiagrass has many positive traits such as reduced fertilizer needs, enhanced cold tolerance, and moderate shade tolerance (Patton et al., 2017). It is also widely-regarded as a better fairway and tee playing surface in comparison to bermudagrass because of its high shoot density and uniformity and good ball lie characteristics (Trappe et al., 2011).

As warm-season grasses have been planted in more northern locations, there has been an increase in the incidence of winterkill on both bermudagrass and zoysiagrass turf (Hutchens et al., 2024; Carr et al., 2025). There is ample, anecdotal evidence that shaded areas on golf courses, in sports stadiums, and in landscapes are more likely to experience winterkill, as extension articles, research articles and textbooks often discuss the compounding effects of shade on winter injury (Frank, 2016; McCarty and Miller, 2018; Richardson et al., 2014; Richardson and Booth, 2023). However, we are not aware of any studies that have attempted to document the amount of shade that might contribute to increased winterkill.

Project Objectives:

- Determine the effect of shade levels and trinexapac-ethyl on stem carbohydrate levels and LT₅₀ values of an ultradwarf bermudagrass green and a *Zoysia matrella* fairway
- Determine the effect of shade levels and trinexapac-ethyl on field winterkill of an ultradwarf bermudagrass green and a *Zoysia matrella* fairway

Research Methodology:

Field trials – Two field trials were conducted at the Milo J. Shult Agricultural Research & Extension Center in Fayetteville AR during 2025. One trial was conducted on a 3-yr old ‘Tif3D’ bermudagrass putting green (0.125 inch HOC) and the other on a ‘Cavalier’ zoysiagrass fairway (0.5 inch HOC). Both sites were managed according to practices typical for these grasses in this region.

From May through October, shade structures were deployed on the plots to create five light level treatments including 0, 20, 30, 40, and 50% shade (Richardson et al., 2019), which will produce daily light integral conditions ranging from approximately 22-44 mol m⁻² day⁻¹. The total dimensions of each shade structure was 6.1 x 9.1 m and the structure was divided into five randomized shade treatments, each measuring 6.1 x 1.8 m. The various shade cloths (Bulk Shade Cloth, International Greenhouse Co., Danville IL) were custom-cut to fit inside each of five sections on the structures. The frame was mounted on six pneumatic wheels that allow easy movement of the structure on and off the plots for maintenance and data collection. For two of the replicate structures in the trial, PAR sensors (SQ-100X-SS Quantum Sensor, Apogee Instruments) were mounted approximately 10 cm under each of the shade cloth treatments and connected to a datalogger such that PAR light was continuously measured during the trial. The PAR light measurements will eventually be integrated to calculate the total irradiance load reaching the plots each day (mol m⁻² day⁻¹).

Two plant growth regulator treatments were randomly applied in a split-plot design across the various shade treatments and included the label rate of Primo Maxx (trinexapac-ethyl) applied every 7 or 14 days (depending on turfgrass species), and an untreated control.

Example replicate of the shade x PGR treatment structure

0% shade	20% shade	30% shade	40% shade	50% shade
PGR +	PGR -	PGR -	PGR +	PGR -
PGR -	PGR +	PGR +	PGR -	PGR +

Plots were evaluated regularly throughout the growing season for standard performance traits, including visual quality ratings and digital image analysis (green turf coverage and dark green color index). Turfgrass quality data are reported as the performance metric in this report. Once additional data on winter performance is collected, non-linear regression will be used to determine the DLI required to produce acceptable turf and the DLI that can lead to enhanced winterkill (Russell et al., 2019). Soil temperature sensors are installed in the plots to continuously monitor exposure temperatures for rhizomes and stolons. All other environmental data (air temperature, wind, relative humidity, etc.) will be monitored using an onsite weather station.

Freeze tests - Methods regarding freeze tests are modelled after previously-published work (Gopinath et al. 2021; Xiang et al., 2023) with a few exceptions. The previously-cited work used greenhouse-grown plant material in

conetainers. In our studies, we will remove intact plugs from the field plots in February using a 6.0 cm diameter x 6.3 cm depth plugger. Plugs will immediately be moved into the freeze chamber which will be set at an initial temperature of 2 °C and the plugs will be maintained at that temperature for 24 hours. After the initial acclimation period, the temperature will be dropped to -4 °C, followed by a gradual linear decline of 1 °C/h. At the target temperatures of -4 to -11 °C, three plugs of each treatment will be taken out of the chamber, thawed overnight at 2 °C, and then placed in a greenhose to monitor recovery. Plug survival and recovery (% green coverage) will be monitored using digital image analysis. Appropriate regression analysis will be used to estimate the LT₅₀ values for each shade x PGR level.

A preliminary test run was conducted in early 2025 to evaluate the protocol and we got expected results from those trials. In early 2026, additional samples will be taken for each shade x PGR plot and analyzed for carbohydrates using methods described by Patton et al. (2007).

Results

Turfgrass quality was significantly affected by Shade, PGRs, and duration of the shade (Date) and there were interactions of Shade x Date on both species and PGR x Date on zoysiagrass (Table 1).

Table 1. Summary analysis of variance for turfgrass quality using a repeated measures analysis, testing the whole plot (shade) and split plot (PGR) factors and date and their interactions. Cells that are shaded with green are significant at the P<0.05 level.

Effect	DF	Tif3D bermudagrass		Cavalier zoysiagrass	
		F Value	Pr > F	F Value	Pr > F
Shade	4	117.29	<.0001	51.37	<.0001
PGR	1	12.22	0.0006	23.37	<.0001
Date	4	6.18	0.0001	3.35	0.0113
Shade * Date	16	2.53	0.0016	2.20	0.0067
Shade * PGR	4	1.56	0.1867	0.42	0.7972
PGR * Date	4	1.46	0.2162	6.61	<.0001
Shade * PGR * Date	16	0.55	0.9179	0.89	0.5863

Both grasses experienced some decline in overall turfgrass quality under increasing shade through the season (Fig. 1), but both species maintained adequate coverage (data not shown) and quality (Fig. 1) at all shade levels except the 50% level. This is what we were hoping to see, in that we are expecting to identify a shade level that will not affect summer performance of the turf, but will predispose the turf to additional winter injury. Although the 50% level had a negative effect on the summer performance of both species, this is at least confirmation that we are exposing the grasses to adequate stress to generate some valuable numbers.

The most important and informative data from this trial will be collected in early 2026 and reported in the 2026 report.

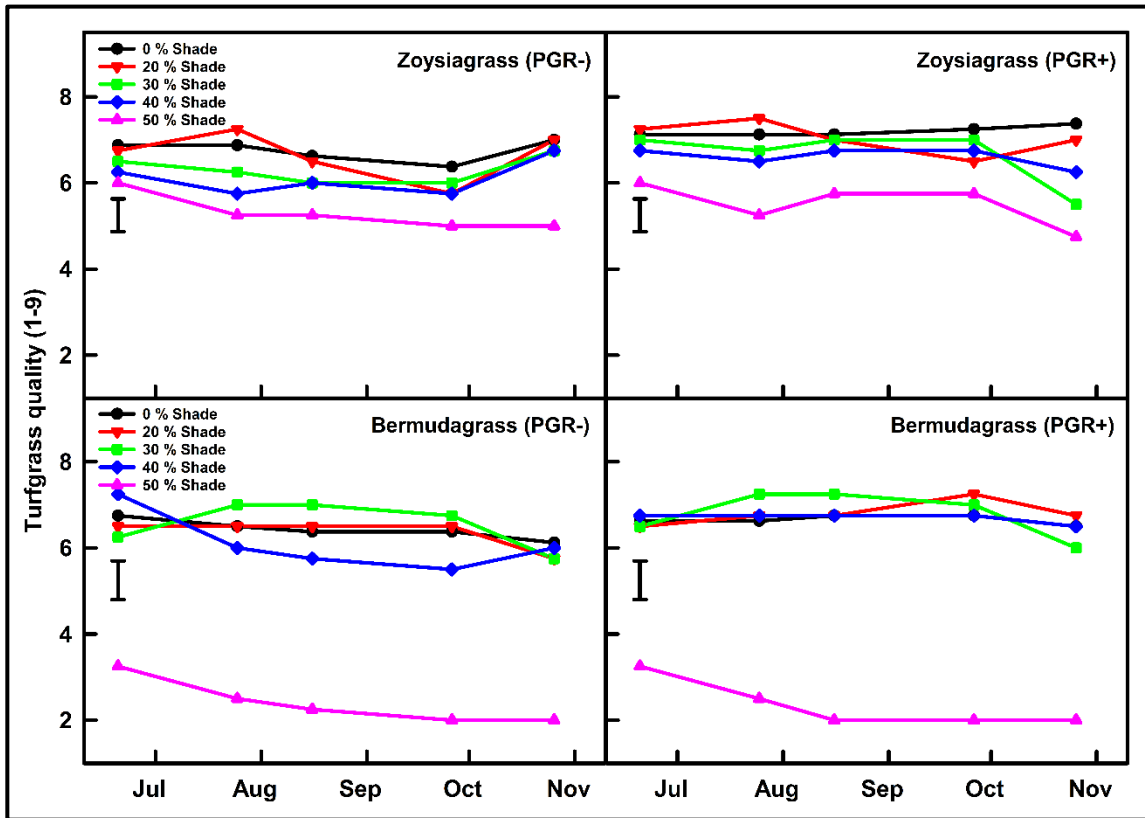


Figure 1. Turfgrass quality of ‘Tif3D’ bermudagrass (HOC = 0.125 inch) and ‘Cavalier’ zoysiagrass (HOC = 0.5 inch) over the 2025 season in Fayetteville AR, as affected by shade levels and application of the plant growth regulator (PRG), trinexapac-ethyl. Error bars represent the least significant difference ($P < 0.05$) values for comparing treatments and dates within each species.

Updated Timeline

Item	1 st Qrt 2025	2 nd Qrt 2025	3 rd Qrt 2025	4 th Qrt 2025	1 st Qrt 2026	2 nd Qrt 2026	3 rd Qrt 2026	4 th Qrt 2026	1 st Qrt 2027	2 nd Qrt 2027
Field trials										
Freeze / carbohydrate tests										
Data analysis and writing										
Planned										
Completed										

PI & Co-PI Bios

Dr. Michael Richardson received a B.S. Degree from Louisiana Tech University, a MS from Louisiana State University and PhD from the University of Georgia. Prior to joining the faculty at the University of Arkansas in 1998, he was a member of the faculty at Rutgers University and was also the director of research at Turf Merchants, Inc., an Oregon-based turfgrass seed company. Dr. Richardson’s research has focused on cultural practices that impact cool- and warm-season turfgrass production in the transition zone.

Dr. Wendell J. Hutchens received his BS and MS degrees from North Carolina State University and his PhD from Virginia Tech. His PhD research was on the biology, epidemiology, and management of spring dead spot of bermudagrass. He also conducted research during his MS on developing plant growth regulator growing degree

day application models for ultradwarf bermudagrass putting greens as well as research during both his MS and PhD on DMI fungicide physicochemical properties and efficacy against root diseases. He has served as an Assistant Professor of Turfgrass Science at the University of Arkansas with an extension, research, and teaching appointment since August 2022.

Literature Cited

- Carr, T.Q., W.J. Hutchens, A.J. Patton, R.C. Braun, D. McFadden, & M.D. Richardson. 2025. Management strategies for preventing and recovering from zoysiagrass winterkill. *Crop, Forage & Turfgrass Management*, 11, e70050. <https://doi.org/10.1002/cft2.70050>.
- Frank, K. 2016. The war on winter: Preparing your turfgrass for the snowy, icy, frigid months. *GreenMaster*. 51(6):p. 22-23.
- Gopinath, L., J. Q. Moss, and Y. Wu. 2021. Evaluating the freeze tolerance of bermudagrass genotypes. *Agrosyst. Geosci. Environ.* 4:20170 <https://access.onlinelibrary.wiley.com/doi/10.1002/agg2.20170>.
- Hutchens, W., Carr, T., Patton, A., Bigelow, C., DeBoer, E., Goatley, M., Martin, D, McCall, D, Miller, G., Powlen, J., Richardson, M., Xiang, M. 2024. Management strategies for preventing and recovering from bermudagrass winterkill. *Crop Forage and Turfgrass Management Crop Forage & Turfgrass Mgmt.* 10:e20302 <https://doi.org/10.1002/cft2.20302>.
- McCarty, B., and G. Miller. 2018. Turfgrass winter-kill recovery strategies. *Carolinas Green*. p. 30-31.
- Patton, A. J., B. M. Schwartz, and K. E. Kenworthy. 2017. Zoysiagrass (*Zoysia spp.*) history, utilization, and improvement in the United States: A review. *Crop Sci.* 57: S-37-S-72.
- Patton,A.J., S.M. Cunningham, J.J. Volenec, and Z.J. Reicher. 2007. Differences in freeze tolerance of Zoysiagrasses:II. Carbohydrate and proline accumulation. *Crop Sci.* 47:2170–2181, doi: 10.2135/cropsci2006.12.0784
- Richardson, M.D., J.T. Brosnan, and D.E. Karcher. 2014. Turfgrass winterkill observations from the transition zone. *Applied Turfgrass Science* DOI 10.2134/ATS-2014-0049-BR.
- Richardson, M.D., G. Mattina, M. Sarno, J.H., McCalla, and D.E. Karcher. 2019. Shade effects on overseeded bermudagrass athletic fields: I. Turfgrass quality, coverage, and growth rate. *Crop Sci.* 59:2845–2855, doi: 10.2135/cropsci2019.05.0310
- Richardson, M., and J. Booth. 2023. Best management practices for preventing winter injury on ultradwarf bermudagrass putting greens. *USGA Green Sec. Rec.* 61(2):p. [1-14].
- Russell, T.W., D.E. Karcher, and M.D. Richardson. 2019. Daily light integral requirement of a creeping bentgrass putting green as affected by shade, trinexpac-ethyl, and a plant colorant. *Crop Science* 59:1768–1778. doi: 10.2135/cropsci2018.08.0501
- Trappe, J. M., D. E. Karcher, M. D. Richardson, and A. J. Patton. 2011. Bermudagrass and zoysiagrass cultivar selection: Part 1, clipping yield, scalping tendency, and golf ball lie. *Appl. Turfgrass Sci.* p. [1-12].
- Xiang, M., J. Fry, and Y. Wu. 2022. Winter survival of experimental bermudagrasses in the upper transition zone of the U.S.. *Int. Turfgrass Soc. Res. J.* 14(1):p. 708-712.

USGA ID#: 2023-12-779

Title: Mitigating Bentgrass Summer Decline Utilizing Endophytic Plant Growth-Promoting Bacteria

Project Leader: Bingru Huang, Ning Zhang, and William Errickson

Affiliation: Rutgers University

Objectives:

- 1.) Determine efficacy of plant growth promoting bacteria (PGPB) inoculants on improving heat stress tolerance in creeping bentgrass under field conditions
- 2.) Optimize dosage or concentration of inoculants for most effective heat stress mitigation in creeping bentgrass

Start Date: 2023

Project Duration: 2 years

Total Funding: \$95,120

This report presents the results of the second-year field trial conducted in 2024, addressing objectives 1 and 2; to investigate the effects of PGPB inoculants on the summer performance of creeping bentgrass under field conditions.

Summary Points:

- Inoculation with two novel strains of PGPB resulted in improved reflectance indices, and enhanced root growth of creeping bentgrass under heat stress conditions
- Combining two strains of PGPB was more effective at improving heat stress tolerance of creeping bentgrass than either strain individually.
- Increasing the application rate relative to greenhouse and growth chamber trials was more effective at improving heat stress tolerance in field conditions.

Methodology:

This project was carried out in sand-based putting green plots established with creeping bentgrass (cv. 007) at the Rutgers University turfgrass research farm. The turf plots were managed following typical practices of fertility and pest management for putting greens in the northeast region during the growing season. The field experiment was performed during the months of June through September 2023 and 2024. This annual report summarizes the findings from 2024.

Bacteria inoculation and application

Two novel strains of growth promoting *Paraburkholderia aspalathi* ‘WSF23’ and ‘WSF14’, and a commercially available microbial product, Quantum Growth (Green Earth Ag and Turf LLC), containing *Bacillus* spp. were applied to the plots every two weeks at varying concentrations

listed below. A 0.01% humic acid solution was also added to the *P. aspalathi* and non-inoculated control treatments. All treatments were applied using a backpack sprayer in a carrier volume of 2 gallons /1000 ft² and were watered in with 0.25” of water to saturate the root zone immediately following application.

Experimental design

The experiment was set up as a complete randomized design. Each treatment was repeated in four 3 x 4 ft plots.

Bacteria inoculant treatments:

- 1) Non-inoculant Control
- 2) Quantum Growth
- 3) ‘WSF23’ (1.0 x 10⁷ cfu/mL)
- 4) ‘WSF23’ (1.5 x 10⁷ cfu/mL)
- 5) ‘WSF23’ (2.0 x 10⁷ cfu/mL)
- 6) ‘WSF14’ (1.0 x 10⁷ cfu/mL)
- 7) ‘WSF14’ (1.5 x 10⁷ cfu/mL)
- 8) ‘WSF14’ (2.0 x 10⁷ cfu/mL)
- 9) ‘WSF23 +WSF14’ (1.0 x 10⁷ cfu/mL)
- 10) ‘WSF23 +WSF14’ (1.5 x 10⁷ cfu/mL)
- 11) ‘WSF23 +WSF14’ (2.0 x 10⁷ cfu/mL)

Evaluation of turfgrass heat tolerance and bacteria colonization

Turf performance and physiological health were evaluated weekly during the hottest months of July-September or peak heat season in NJ. Turf performance was visually rated on a scale of 1 to 9. Thermal images of turf plots were also taken to evaluate canopy temperature using an infrared thermal imaging camera. An unmanned aerial vehicle (UAV) outfitted with a multispectral imaging camera that measures canopy reflectance in the range of 400 to 1000 nm wavelengths and a handheld ground-based multispectral radiometer were used to collect reflectance data to analyze various vegetation and physiological indices, including photochemical reflectance index (PRI) = (R531 – R570)/(R531 + R570), plant senescence reflectance index (PSRI) = (R680 – R500)/R750, normalized difference red edge (NDRE) = (R750 – R705)/(R750 + R705), and normalized difference vegetation index (NDVI) = (R800 – R680)/(R800 + R680). Roots were collected and washed free of soil to quantify rooting characteristics (length, surface area, and biomass). Bacteria were also isolated from roots to quantify the colonization level and stability using qPCR analysis.

Summary of Results:

Turf quality

Though fluctuations in turf quality were observed throughout the season, there were no significant differences detected in turf quality for any of the treatments in 2024 (Figure 1).

Canopy temperature

Canopy temperature was also significantly affected by any of the treatments in 2024.

Multispectral image analysis

PRI was significantly greater in plots inoculated with WSF23+14 at the 2.0x concentration on 5 dates during the growing season (7/22, 7/29, 8/19, 8/26, and 9/9) (Figure 3). Other reflectance indices did not show improvements with inoculation during the 2024 season.

Root characteristics

Inoculation with the combination of strains (WSF23+14) enhanced root growth of creeping bentgrass during summer stress in both the July and September sampling dates. Plants inoculated with WSF23+14 at the 1.0x, 1.5x, and 2.0x concentrations demonstrated greater root length (Figure 4), root surface area (Figure 5), and root volume (Figure 6), compared to non-inoculated plants in July. Root biomass was not significantly affected in July (Figure 7). The WSF23+14 inoculation at the 2.0x concentration also resulted in increased root length (Figure 8), root surface area (Figure 9), and root volume (Figure 10) in September. Root biomass was not significantly affected in September (Figure 11).

Confirmation of inoculation

Confirmation of inoculation was conducted using qPCR analysis during the July and September root sampling periods. Positive inoculation was observed for all WSF23+14 treatments at all rates of concentration (Figures 12, 13).

Conclusions

Heat stress tolerance of creeping bentgrass was improved by inoculation with a combination of two novel strains of plant growth promoting bacteria in field conditions. The consortium of *P. aspalathi* WSF23 and WSF14 was most effective at improving heat tolerance when the highest application rate was used (2.0×10^7 cfu/mL). Inoculation resulted in the enhancement of turf quality, as indicated by improved PRI and greater root development evident in root length, surface area, and volume. The *P. aspalathi* treatments performed comparably or better than the commercial Quantum Growth inoculant for the parameters that were measured. Based on these encouraging results, *P. aspalathi* WSF23 and WSF14 have potential for further research and development into commercially viable inoculants to improve summer performance of cool season turfgrass.

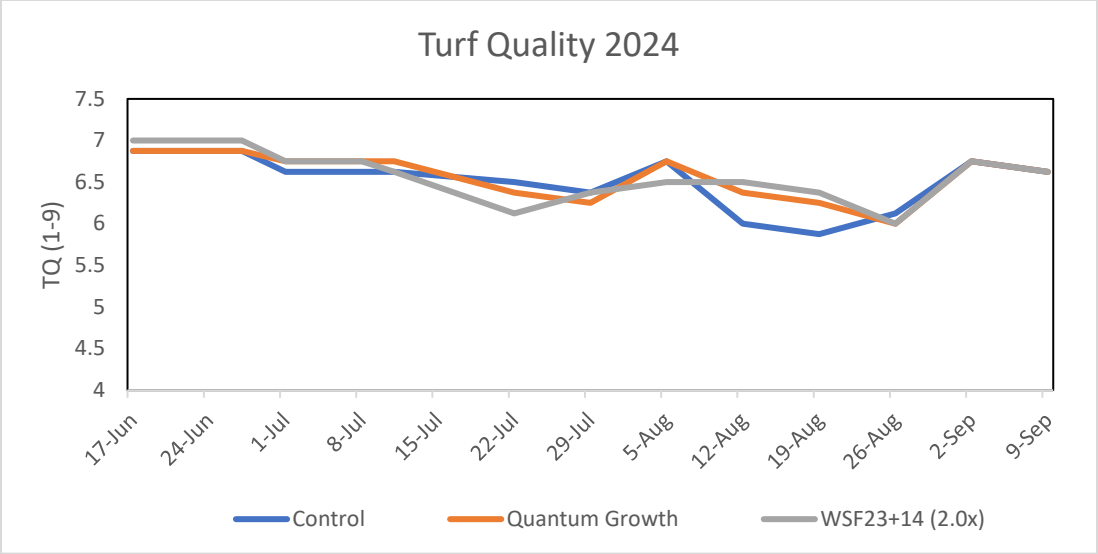


Figure 1: Turf quality of creeping bentgrass with inoculation treatments under summer heat stress conditions.

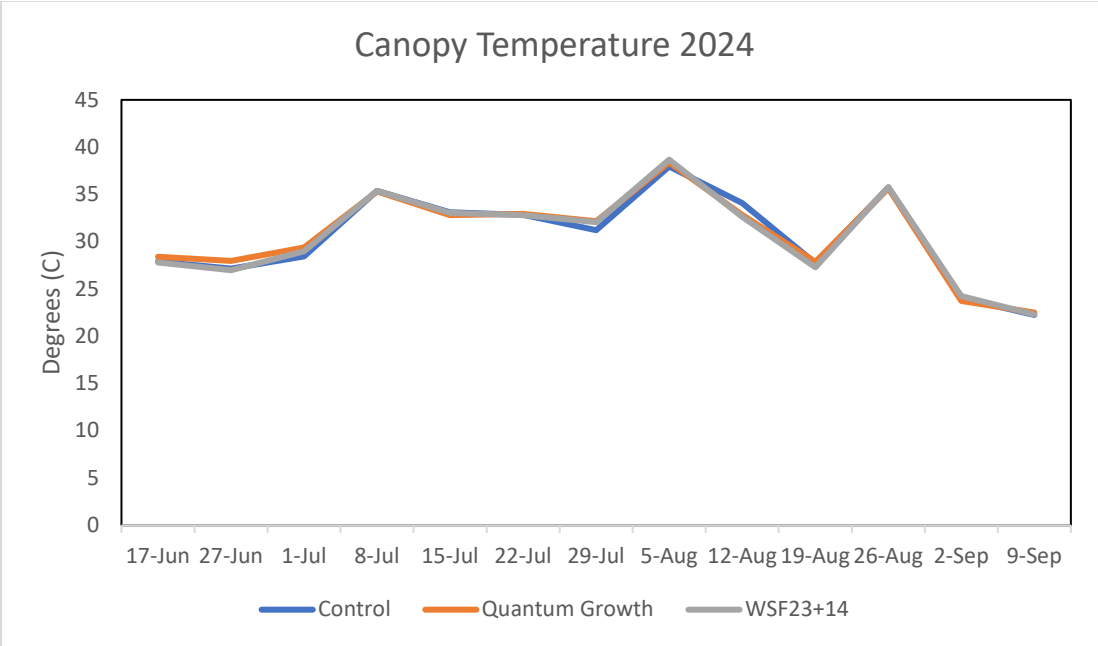


Figure 2: Canopy temperature of creeping bentgrass with inoculation treatments under summer heat stress conditions.

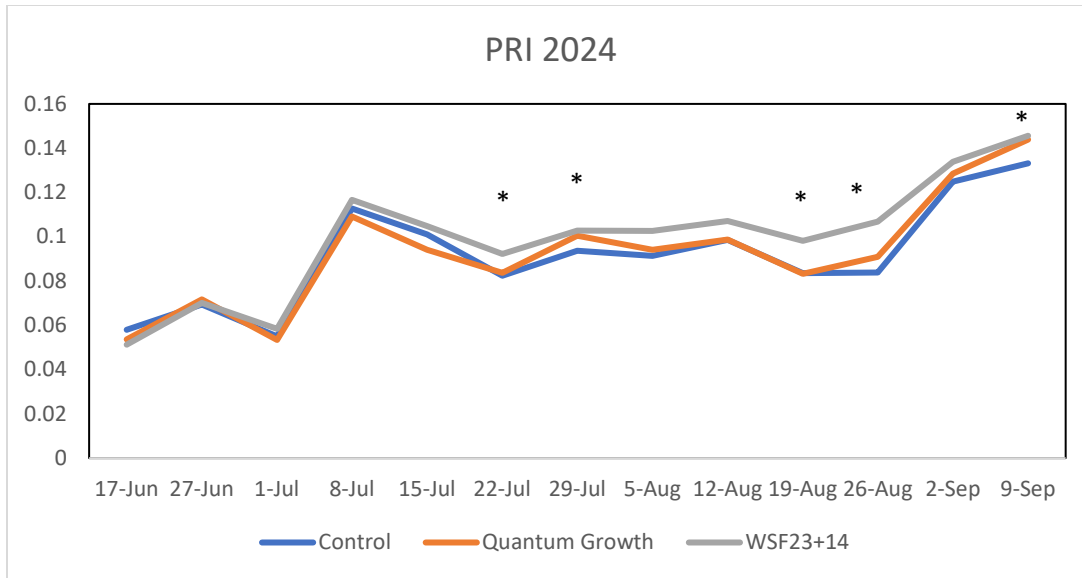


Figure 3: Photochemical reflectance index (PRI) of creeping bentgrass with inoculation treatments under summer heat stress conditions. Greater PRI indicates higher stress tolerance.

* Indicates significance at $p \leq 0.05$.

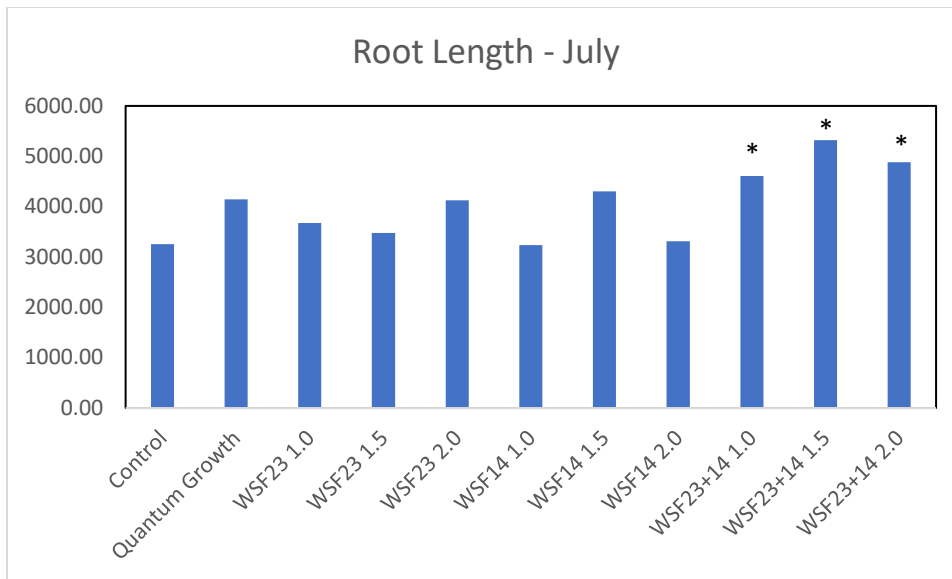


Figure 4: Root length of creeping bentgrass during July sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$ for that date.

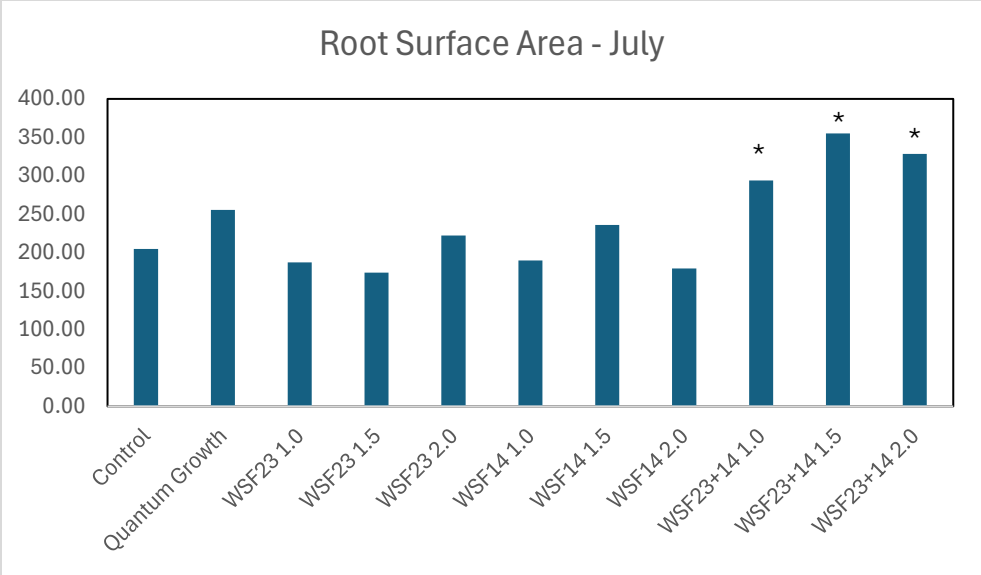


Figure 5: Root surface area of creeping bentgrass during July sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$ for that date.

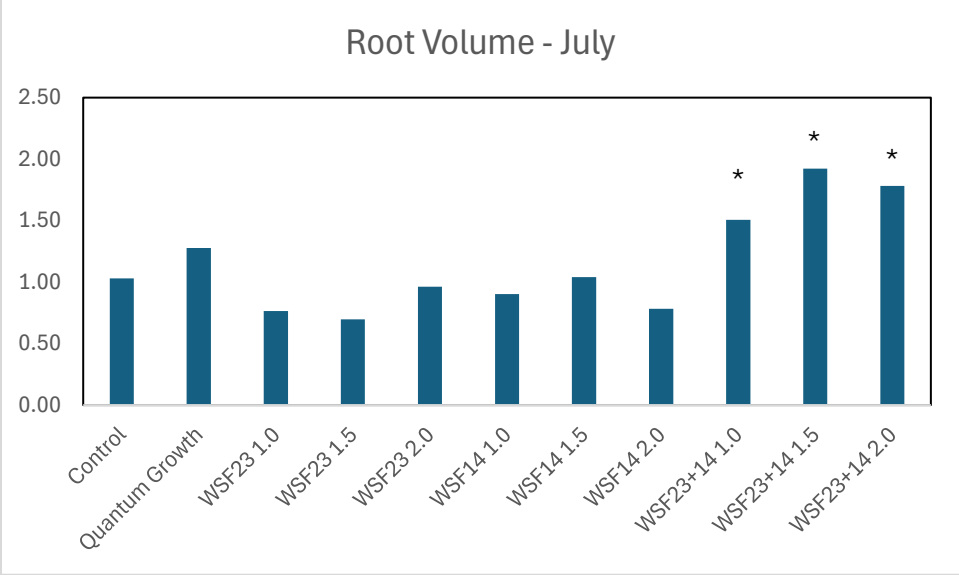


Figure 6: Root volume of creeping bentgrass during July sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$.

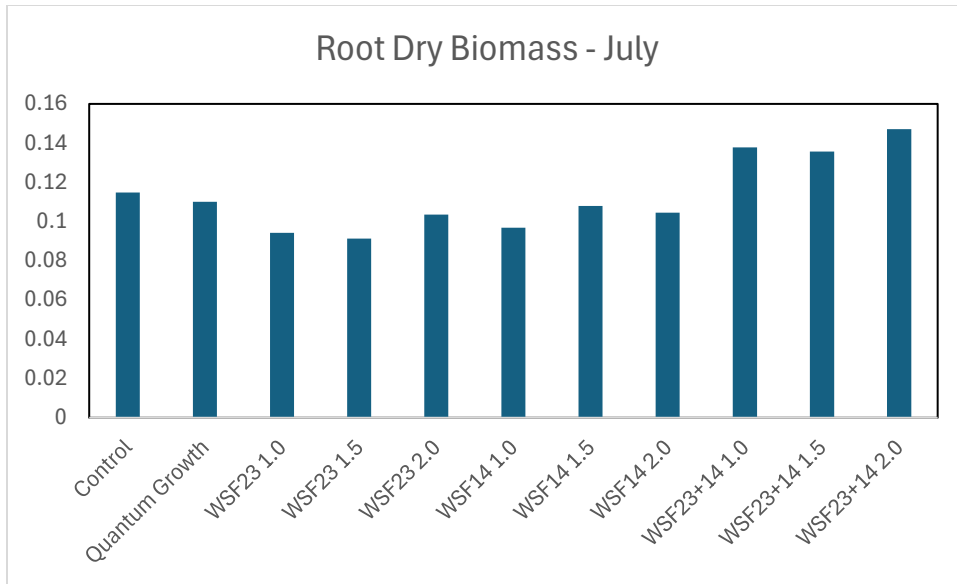


Figure 7: Root dry weight of creeping bentgrass during July sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$.

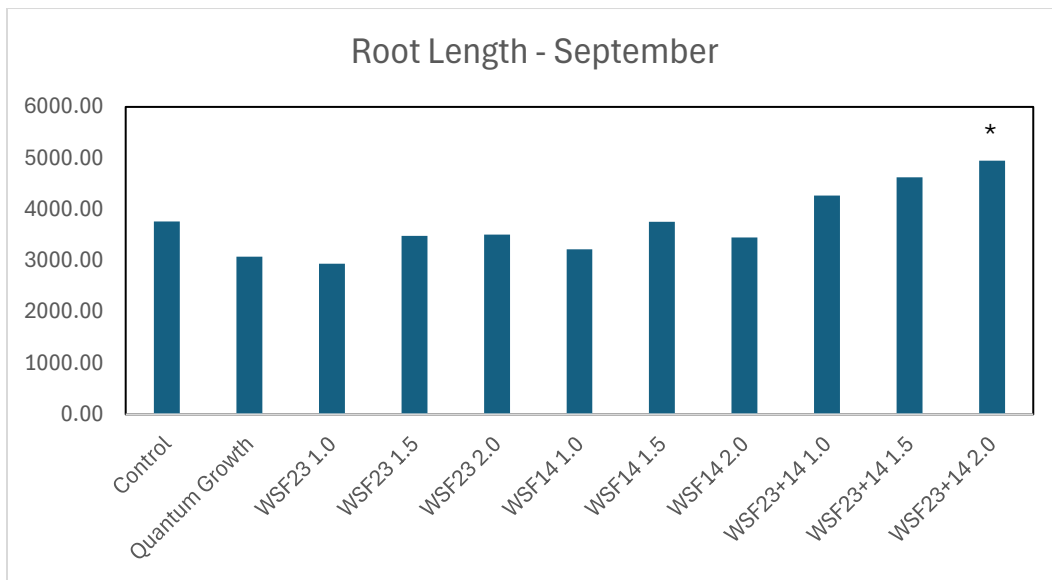


Figure 8: Root length of creeping bentgrass during September sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$ for that date.

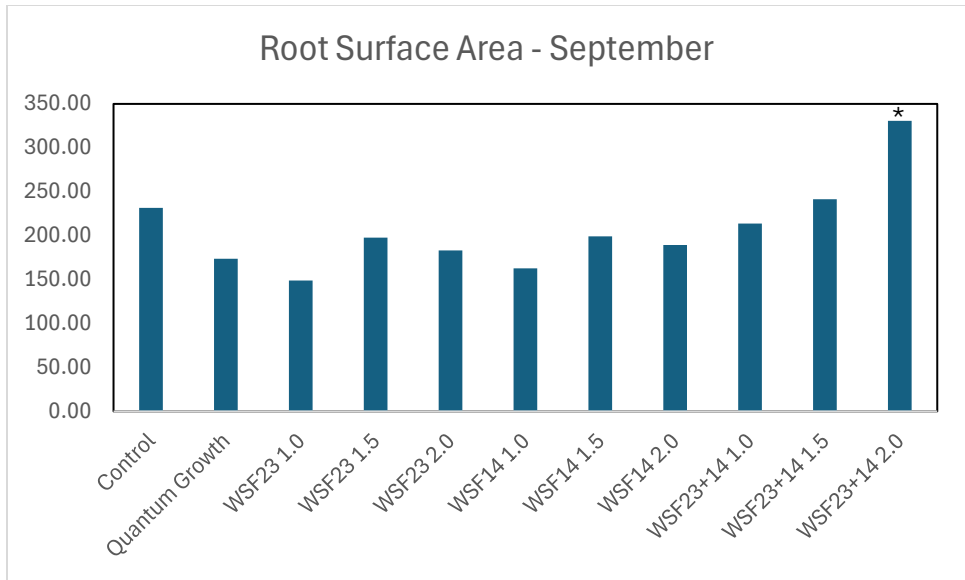


Figure 9: Root surface area of creeping bentgrass during September sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$ for that date.

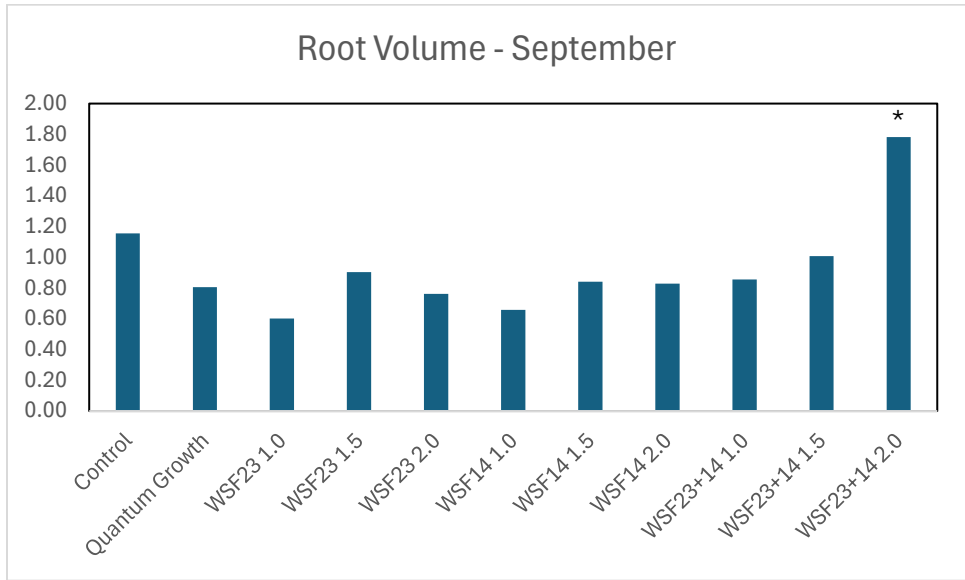


Figure 10: Root volume of creeping bentgrass during September sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$.

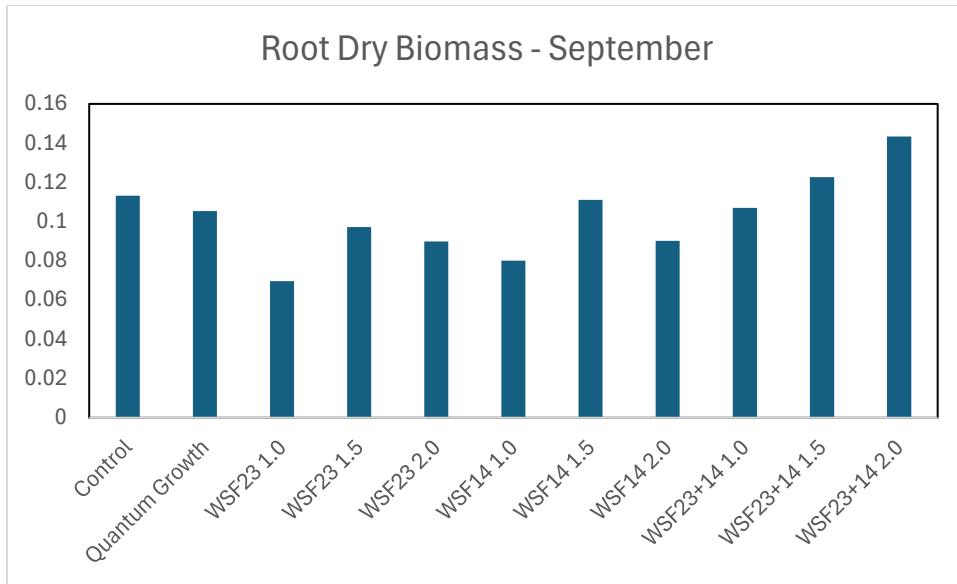


Figure 11: Root dry weight of creeping bentgrass during July sampling with inoculation treatments under summer heat stress conditions. * Indicates significant difference at $p \leq 0.05$.

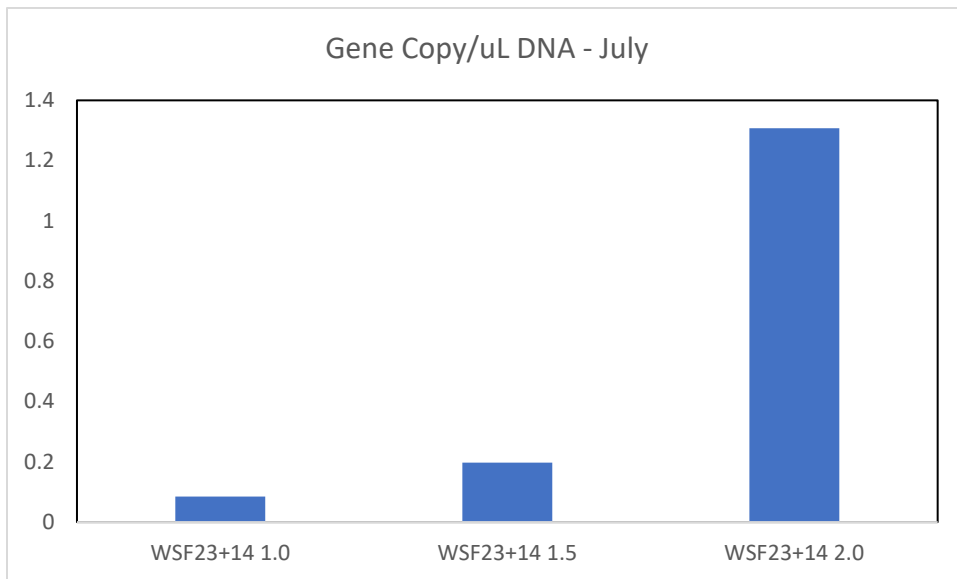


Figure 12: Inoculation confirmation during July sampling using qPCR analysis for roots treated with WSF23+14.

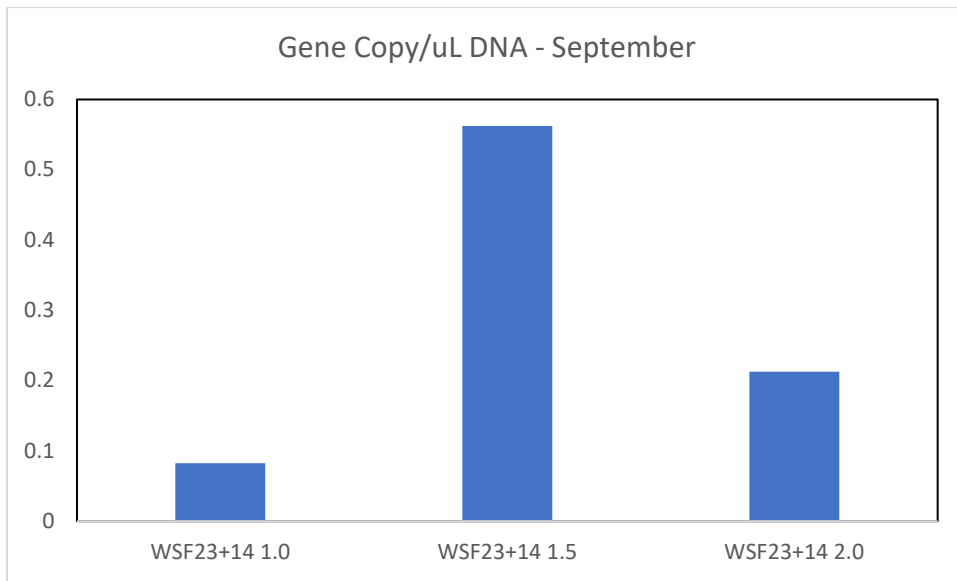


Figure 13: Inoculation confirmation during September sampling using qPCR analysis for roots treated with WSF23+14.

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 3 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 (PH) 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* Burt-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 1000ft² or prohexadione-Ca (PH; Anuew, Nufarm) at 0.05 fl oz 1000ft², and N rate, either 0.075 or 0.15 lb N 1,000 ft² 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; June 18, July 11, August 15 2024; June 24, July 16, August 14 2025 to plots with no previous PGR application that year. 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 ft²). Plant growth regulator treatments were applied with a CO₂-pressurized backpack sprayer using a carrier volume of 2.0 gal 1,000 ft².

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].

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

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.

RESULTS

All combinations of PGRs (TE and PH) and N rate (0.075 and 0.15 lb N 1,000 ft² wk⁻¹), compared across months (June, July, and August) and years (2023, 2024, and 2025), indicated a significant relationship between relative clipping yield and GDD using a sine wave regression model with R² values ranging from 0.497 to 0.686 (Figure 1). Peak growth suppression for TE was observed at 230 and 175 GDD for the low and high rate of N, respectively, with predicted reapplication intervals of 299 and 228 GDD. Reapplication interval for TE in combination with high rates of N (228 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 ft²), the reapplication interval is higher (299 GDD) than previous recommendations. Differences in peak suppression and reapplication interval between N rates (low and high) for PH treatments were 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 183 GDD and a reapplication interval of 238 GDD (Figure 1). These results indicate that the reapplication interval for PH on annual bluegrass is less than recommendations for creeping bentgrass putting greens (280 GDD; Kreuser, 2016). In general, PH applications resulted in a greater peak suppression in growth compared to TE, with PH reducing growth by 45 and 44% for the high and low rates of N, respectively. Compared to TE treatments, which reduce ABG growth by 33 and 28% for the high and low N rates, respectively.

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, subtle differences in peak suppression or reapplication interval were observed between low and high rates of N for both TE or PH, with low rates of N resulting greater reapplication intervals (Figure 2). During July, a substantial difference in reapplication intervals was 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 215 to 235 GDD for all treatment combinations (Figure 4). These results indicate that when the turfgrass is exposed to high levels of abiotic stress (i.e. during late summer; July applications), and low N fertilization, reapplication intervals are extended by > 135 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.

REFERENCES

- Hempfling, J.A. C.J. Schmid, R. Wang, B.B. Clarke, and J.A. Murphy. 2017. Best management practices effect on anthracnose disease of annual bluegrass. *Crop Sci.* 57:1-9
- Inguagiato, J.C., J.A. Murphy, and B.B. Clarke. 2008. Anthracnose severity on annual bluegrass influenced by nitrogen fertilization, growth regulators, and verticutting. *Crop Sci.* 48:1595–1607.
- Kreuser, W.C. 2016. The perils of PGR over-regulation. *Golfdom.* April. 72(4):30-33.
- Kreuser, W.C., and D.J. Soldat. 2011. A growing degree day model to schedule trinexapac-ethyl applications on *Agrostis stolonifera* golf greens. *Crop Sci.* 51:2228-2236.
- Kreuser, W.C., J.R. Young, and M.D. Richardson. 2017. Modeling Performance of Plant Growth Regulators. *Agric. Environ. Lett.* 2:170001.

- Kreuser, W.C., G.R. Obear, D.J. Michael, and D.J. Soldat. 2018. Growing Degree-Day models predict the performance of Paclobutrazol on bentgrass golf putting greens. *Crop. Sci.* 58:1402–1408.
- McMaster, G.S., and W.W. Wilhelm. 1997. Growing degree-days: One equation, two interpretations. *Agric. For. Meteorol.* 87:291-300.
- Reasor, E.H., J.T. Brosnan, J.P. Kerns, W.J. Huchens, D.R. Taylor, J.D. McCurdy, D.J. Soldat, and W.C. Kreuser. 2018. Growing degree day models for plant growth regulator applications on ultradwarf hybrid bermudagrass putting greens. *Crop Sci.* 58:1801–1807.
- Schmid, C.J., B.B. Clarke, and J.A. Murphy. 2017. Anthracnose severity as influenced by nitrogen source. *Crop Sci.* 57:1-8
- USGA. 2018. USGA recommendations for a method of putting green construction. US Golf Assoc., Far Hills, NJ.

Figure 1. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon averaged across June, July, and August treatments during 2023, 2024 and 2025, 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 ft² (low N; top) or 0.15 lb N/1,000ft² (high N; bottom). Equation and R² values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

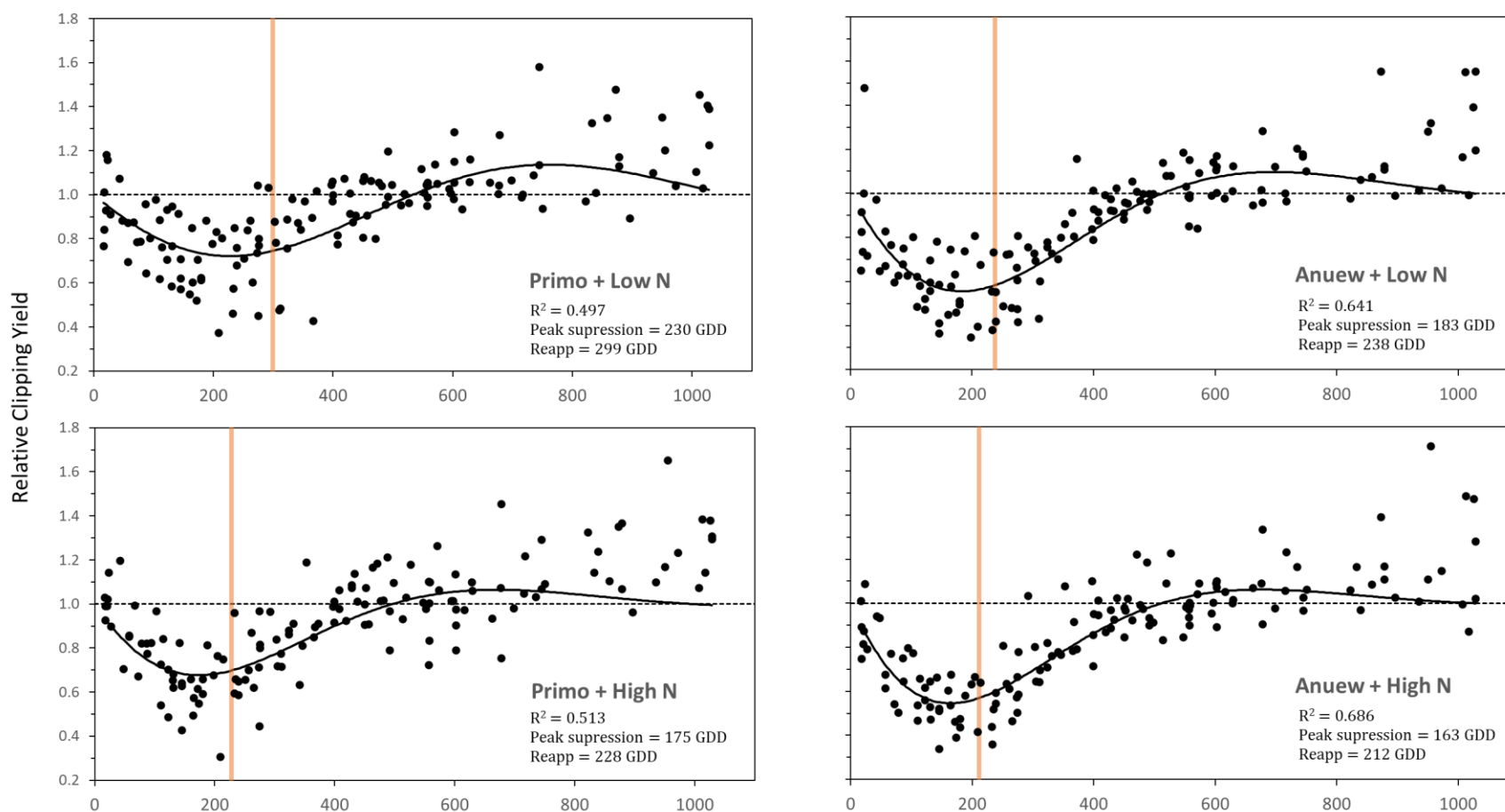


Figure 2. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon during June of 2023, 2024, and 2025 (averaged across years), after a single application of trinexapac-ethyl (left) or prohexadione-Ca (right) combined with weekly applications of nitrogen at 0.075 lb N/1,000 ft² (low N; top) or 0.15 lb N/1,000ft² (high N; bottom). Equation and R² values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

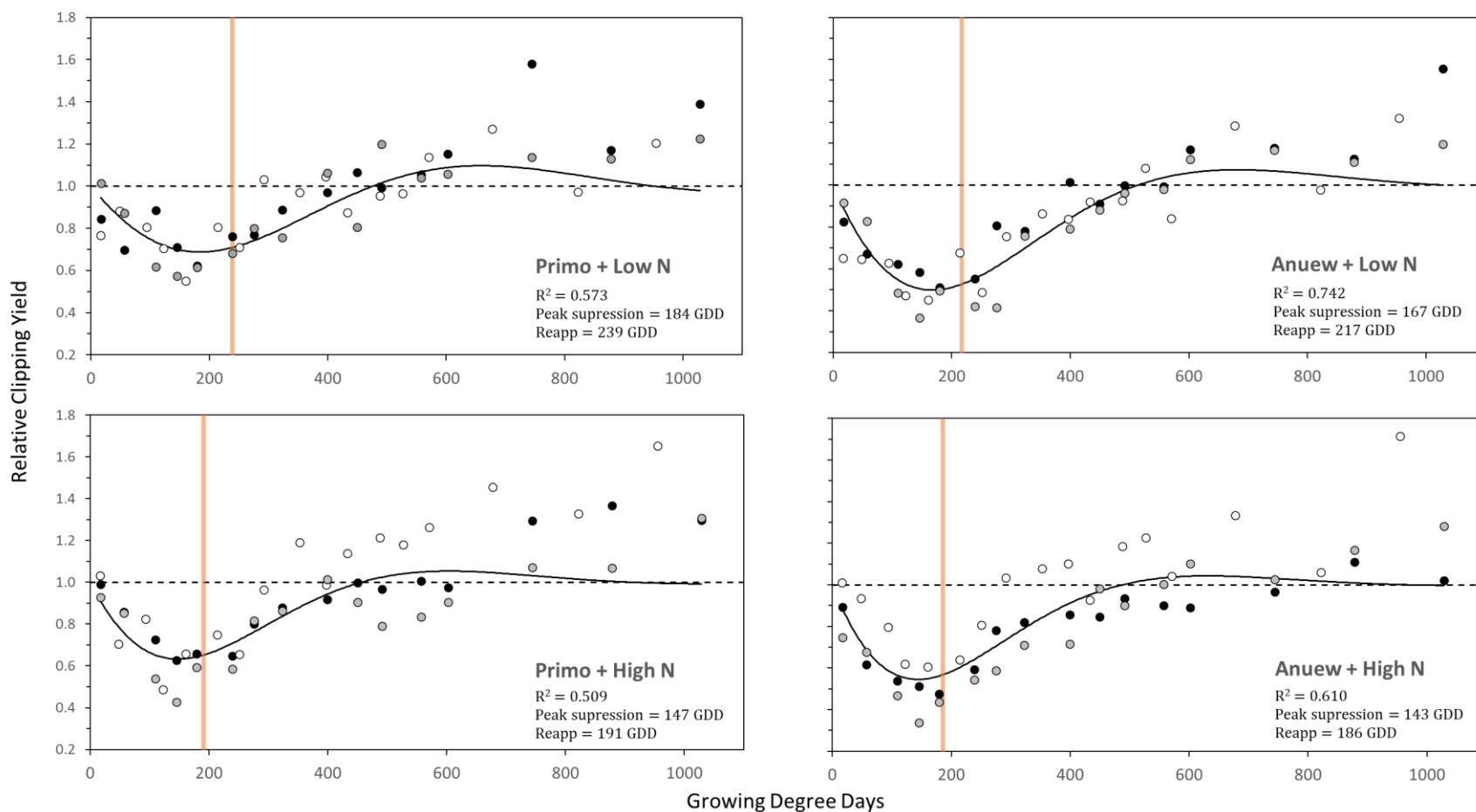


Figure 3. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon during July of 2023, 2024, and 2025 (averaged across years), after a single application of trinexapac-ethyl (left) or prohexadione-Ca (right) combined with weekly applications of nitrogen at 0.075 lb N/1,000 ft² (low N; top) or 0.15 lb N/1,000ft² (high N; bottom). Equation and R² values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

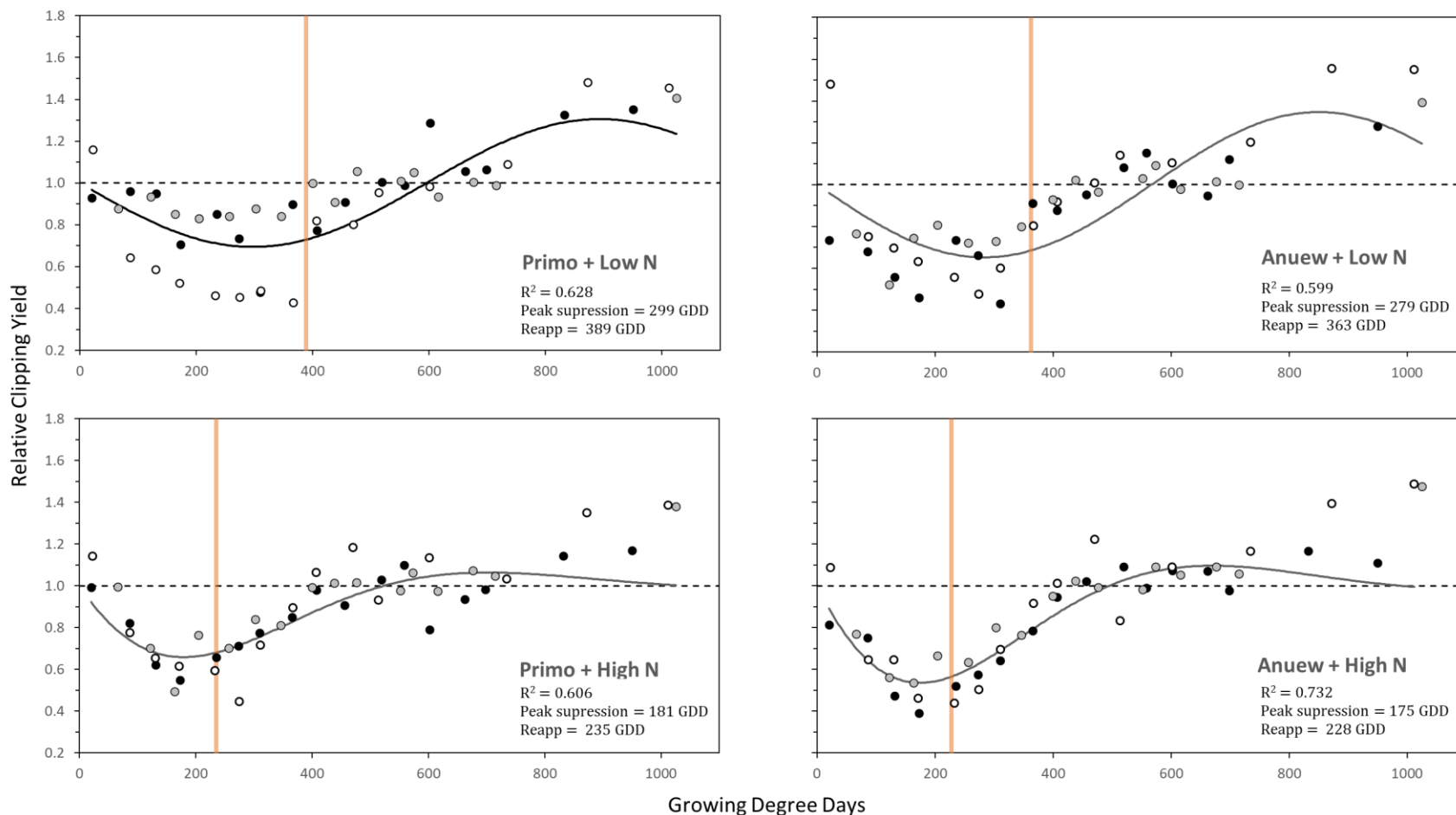


Figure 4. Normalized relative clipping yield of annual bluegrass putting green turf in Corvallis Oregon during August of 2023, 2024, and 2025 (averaged across years), after a single application of trinexapac-ethyl (left) or prohexadione-Ca (right) combined with weekly applications of nitrogen at 0.075 lb N/1,000 ft² (low N; top) or 0.15 lb N/1,000ft² (high N; bottom). Equation and R² values are from the sinewave model used to calculate relative growth suppression. Vertical line indicates reapplication interval.

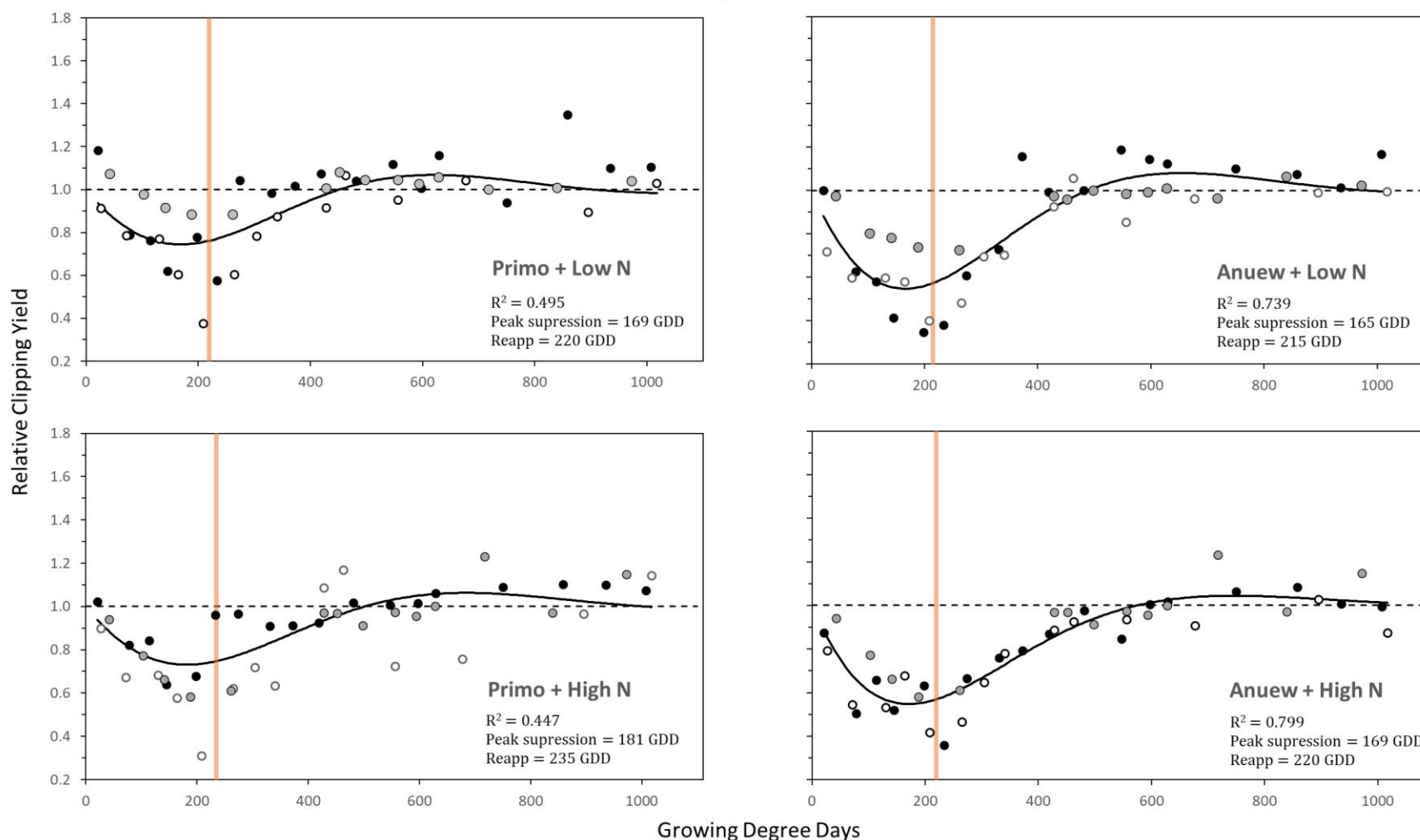




Image 1. Clipping collection from PGR and nitrogen treatments using a Toro eFlex 2120 greens mower equipped with a custom clipping collection bucket.



Image 2. Drone photo of PGR and nitrogen treated plots; collected on 11 Aug 2025.

USGA ID#: 2023-05-772

Title: EFFECTS OF EQUIPMENT TRAFFIC ON TURFGRASS DURING FROST CONDITIONS

Project Leader: Alec Kowalewski and Chas Schmid

Affiliation: Oregon State University

Objectives: Evaluate the effects of daily winter cart, foot and roller traffic applied to a creeping bentgrass, annual bluegrass, and perennial ryegrass fairway.

Start Date: 1 January 2023

Project Duration: 3 years (1 January 2023 to 27 March 2025)

Total Funding: \$30,000

Summary Points: Include 3-6 bullet points summarizing key findings to date

- Despite varying trends in surface and soil temperature, repeated winter roller and cart traffic regularly reduced green and fairway health quality.
- Winter morning roller and cart traffic typically produced greater reduction in turfgrass health than the afternoon traffic.
- Winter foot traffic reduced perennial ryegrass fairway health in one year (2025) only, with morning foot traffic producing the greatest reduction in turfgrass health.
- Winter foot traffic did not reduce creeping bentgrass fairways health.
- Meaningful correlations between traffic damage, and surface/soil temperatures could not be identified.

Introduction

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, which are often early in the morning prior to golfer arrival, translate to significant reductions in revenue and valuable maintenance time.

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. Additionally, 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 a creeping bentgrass and perennial ryegrass fairway was added. In 2025, an ancillary trail evaluating the effects of cart traffic applied to a perennial ryegrass rough will also be added.

Results (2023 to 2025)

Roller and cart traffic regularly reduced all putting green and fairway NDVI values in comparison to the nontreated control particularly in the later part of the data collection period from February to early March 2023, 2024, and 2025 (Image 1, 2, 3 and 4; Table 1; Figure 1, 3, 5, 7 and 9). The morning roller and cart traffic typically produced greater reduction in turfgrass NDVI than the afternoon traffic. Foot traffic reduced NDVI values of a perennial ryegrass fairway in 2025 only (Table 2), with the morning foot traffic producing a greater reduction in NDVI values than the afternoon foot traffic. Creeping bentgrass fairways were not affected by foot traffic in 2023, 2024 or 2025.

In 2023, freezing morning soil and surface conditions were regularly recorded (Image 1; Figure 2, 4, 6 and 8), while afternoon temperatures were above freezing. In 2024, freezing morning surface conditions were infrequent and freezing morning and afternoon soil temperatures were not observed. In 2025, freezing morning surface temperatures were regularly observed, while freezing morning soil conditions were not observed (Figure 2, 4, 6, 8 and 10), and afternoon freezing conditions were observed on one day only. In multiple instances, four or more days of consecutive freezing surface temperatures, and sometimes soil temperatures, were followed by significant reductions in turfgrass NDVI values caused by roller or cart traffic.

In 2023, 2024 and 2025 afternoon soil and surface temperatures, with the exception of one day in 2025, were above freezing.

Despite the different trends in morning soil and surface temperatures observed in 2023, 2024 and 2025, roller and cart traffic morning and afternoon generally reduced turfgrass NDVI values when repeatedly applied in the winter months, and morning traffic produced greater reductions in NDVI values than afternoon traffic particularly in February and March.



Image 1: Roller traffic being applied to an annual bluegrass putting green during freezing surface conditions in February 2023.



Image 2: Effects of morning roller traffic (left) compared to no rolling (right) on an annual bluegrass putting green in Corvallis OR in February 2023.



Image 3: Winter cart traffic being applied to an annual bluegrass fairway in Corvallis, OR in February 2023.



Image 4: Effects of morning cart traffic (left) compared to no cart traffic (right) on a creeping bentgrass fairway in Corvallis OR in February 2023.

Table 1: Analysis of variance for normalized difference vegetation index (NDVI) data as affected by date and time of rolling and cart traffic, and main effects for time of cart traffic when interaction between date and time of traffic (8:00 am or 1:00 pm) were not significant. Data were collected in Corvallis, OR from 2 January to 27 February 2023, 2 January to 8 March 2024, and 6 January to 26 February 2025.

	Rolling on annual bluegrass sand-based green			Cart traffic on creeping bentgrass native soil fairway			Cart traffic on perennial ryegrass sand-based fairway			Cart traffic on annual bluegrass native soil fairway			Cart traffic on native soil perennial ryegrass rough
	2023	2024	2025	2023	2024	2025	2023	2024	2025	2023	2024	2025	2025
Source of variation	Pr > F												
Date (D)	***	***	***	***	***	***	***	***	***	***	***	***	***
time of traffic (T)	***	***	***	***	***	ns	***	***	***	***	***	*	***
D x T	***	***	***	***	***	ns	***	***	ns	*	ns	***	**

	2025 cart traffic on perennial ryegrass sand-based fairway				2024 cart traffic on annual bluegrass native soil fairway			
Time of traffic	NDVI		Mean temperature (F) at the time of traffic		NDVI		Mean temperature (F) at the time of traffic	
			Soil	Surface			Soil	Surface
8:00 AM	79.6	b [†]	39.5	24.9	73.8	c	44.4	38.2
1:00 PM	82.5	a	39.8	42.6	74.7	b	44.7	50.2
control	82.7	a			76.5	a		

*** Significant as at 0.001 level of probability; **Significant at 0.01 level of probability; *Significant at 0.05 level of probability; ns = not significantly different at a 0.05 probability level.

[†]Means followed by the same letter are not statistically different according to Fisher’s least protected significant difference test at P≤ 0.05.

Table 2: Analysis of variance for normalized difference vegetation index (NDVI) data as affected by date and time of foot traffic. Data were collected in Corvallis, OR from 2 January to 8 March 2024, and 6 January to 26 February 2025.

	Foot traffic on creeping bentgrass native soil fairway		Foot traffic on perennial ryegrass sand-based fairway	
	2024	2025	2024	2025
Source of variation	Pr > F			
date	ns	***	ns	***
time of traffic	ns	ns	ns	***
date*time of traffic	ns	ns	ns	ns

*** Significant as at 0.001 level of probability; ns = not significantly different at a 0.05 probability level.

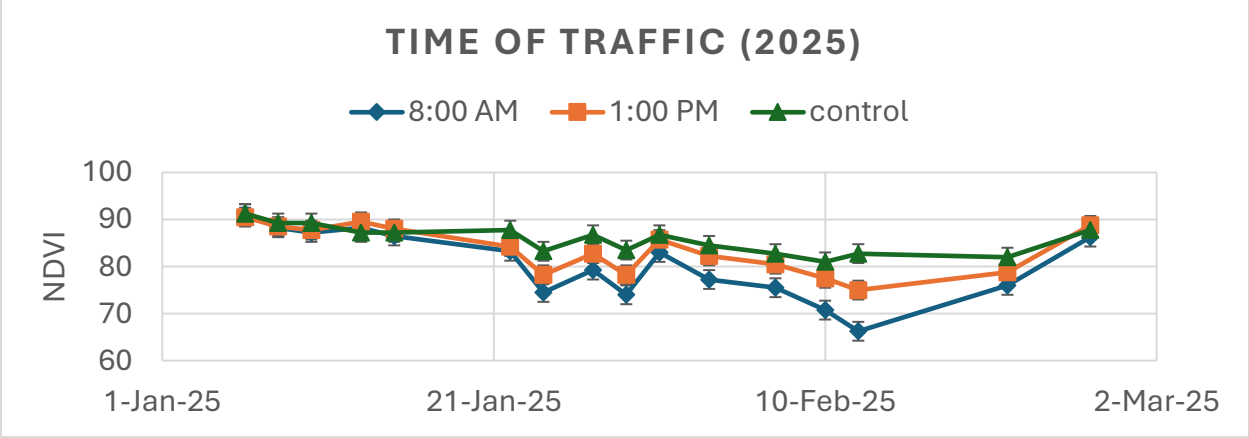
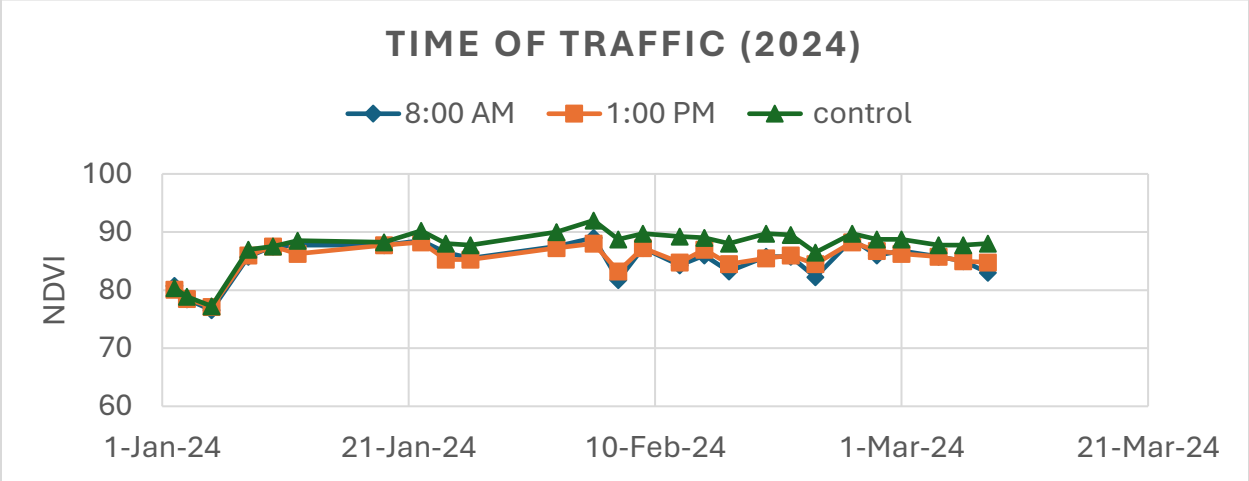
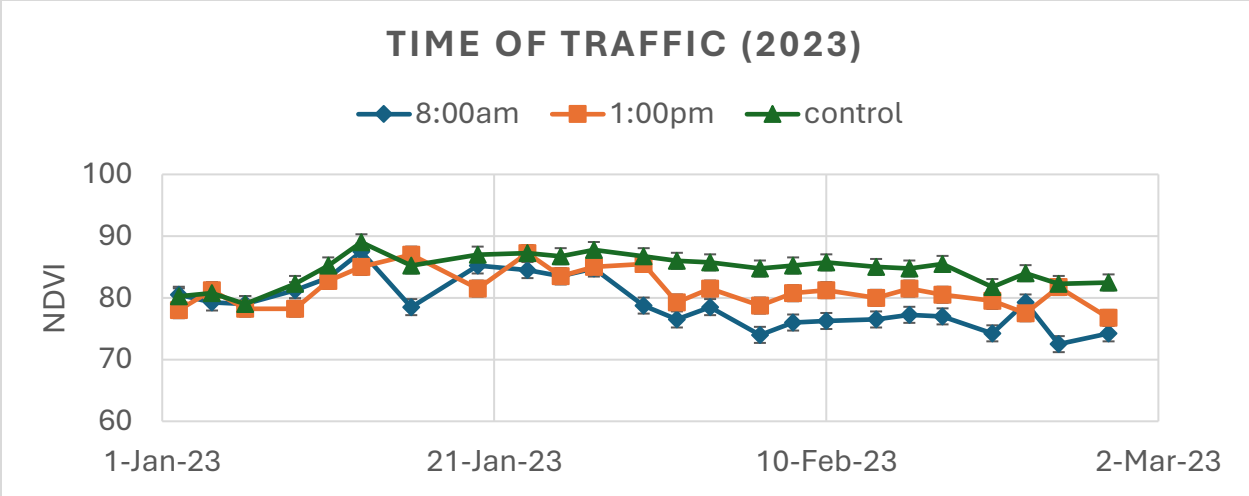


Figure 1: Effects of a greens roller applied 5 days per week during the winter on the normalized difference vegetation index (NDVI) values of a sand-based annual bluegrass putting green in Corvallis, OR, 2023, 2024, and 2025 [LSD (0.05) = 1.3, 0.01 and 2.0, respectively]. Error bars represent significant differences at a 0.05 level of probability using Fisher's LSD.

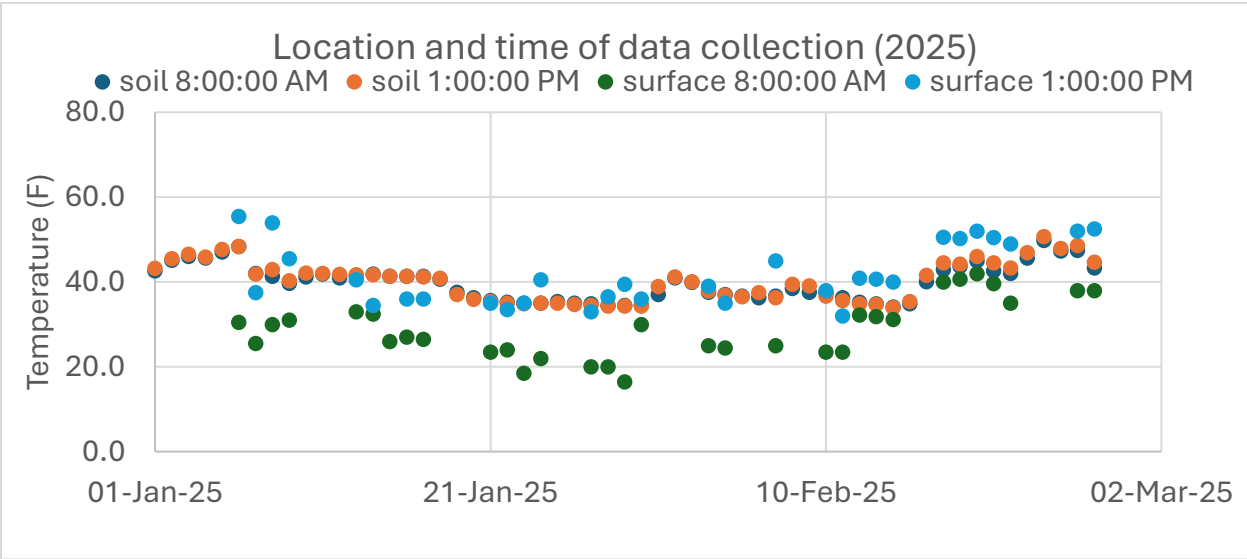
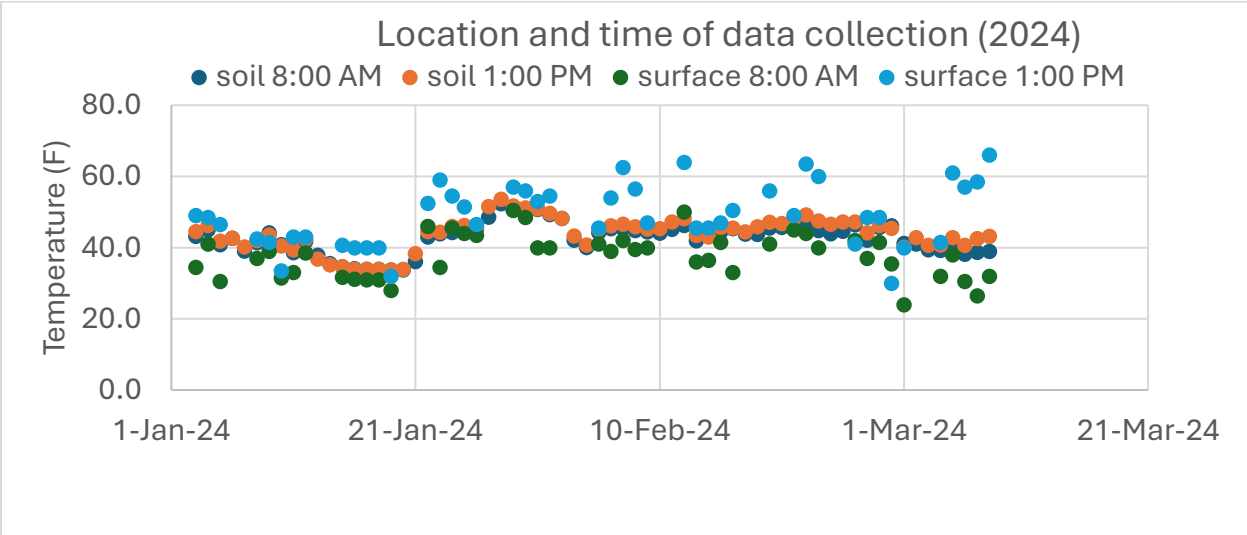
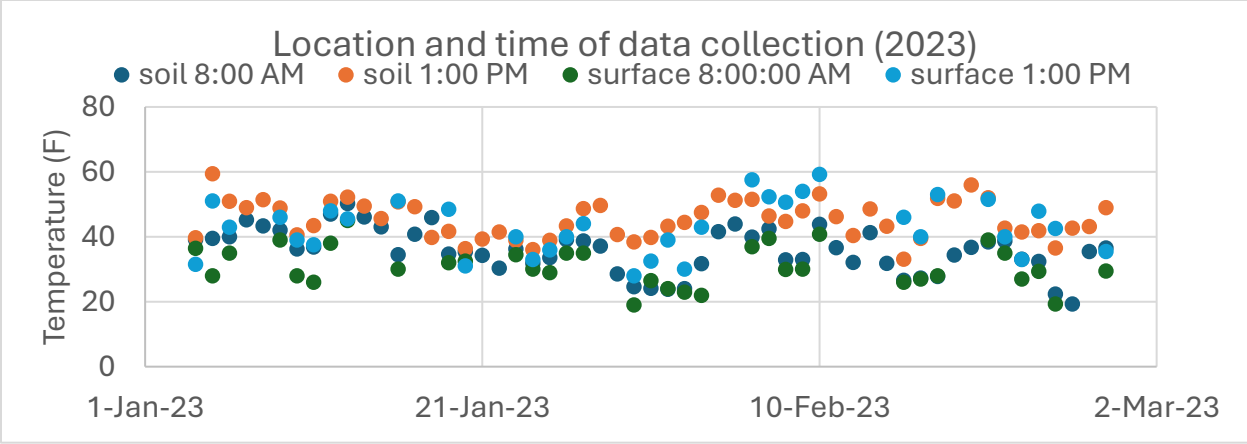


Figure 2: Surface and soil temperature collected from a sand-based annual bluegrass putting green in the winter in Corvallis, OR, 2023, 2024, and 2025.

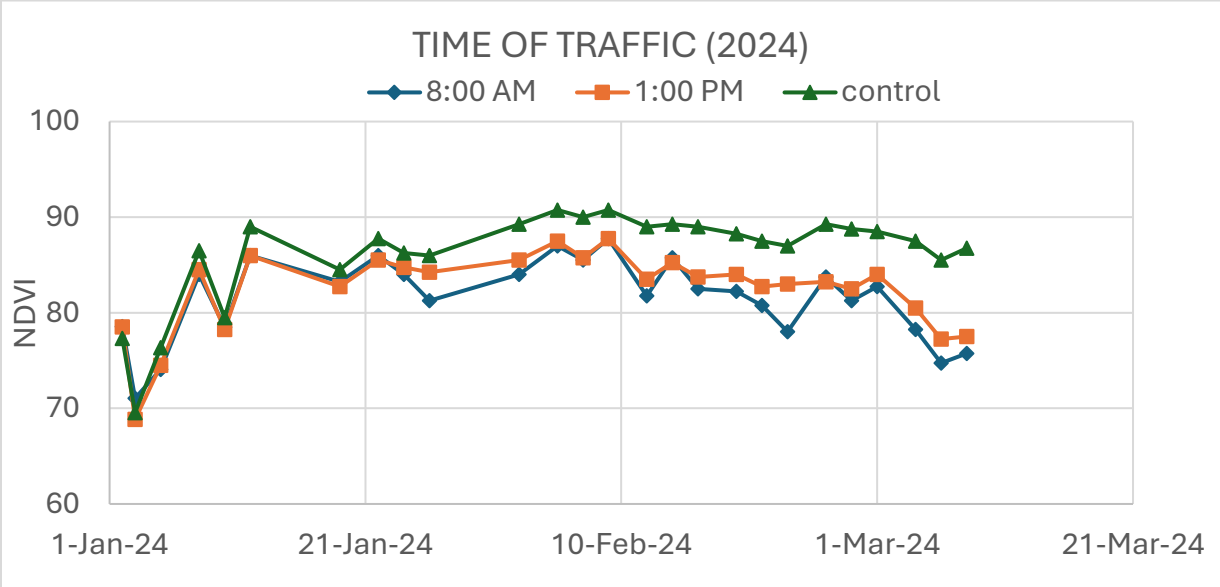
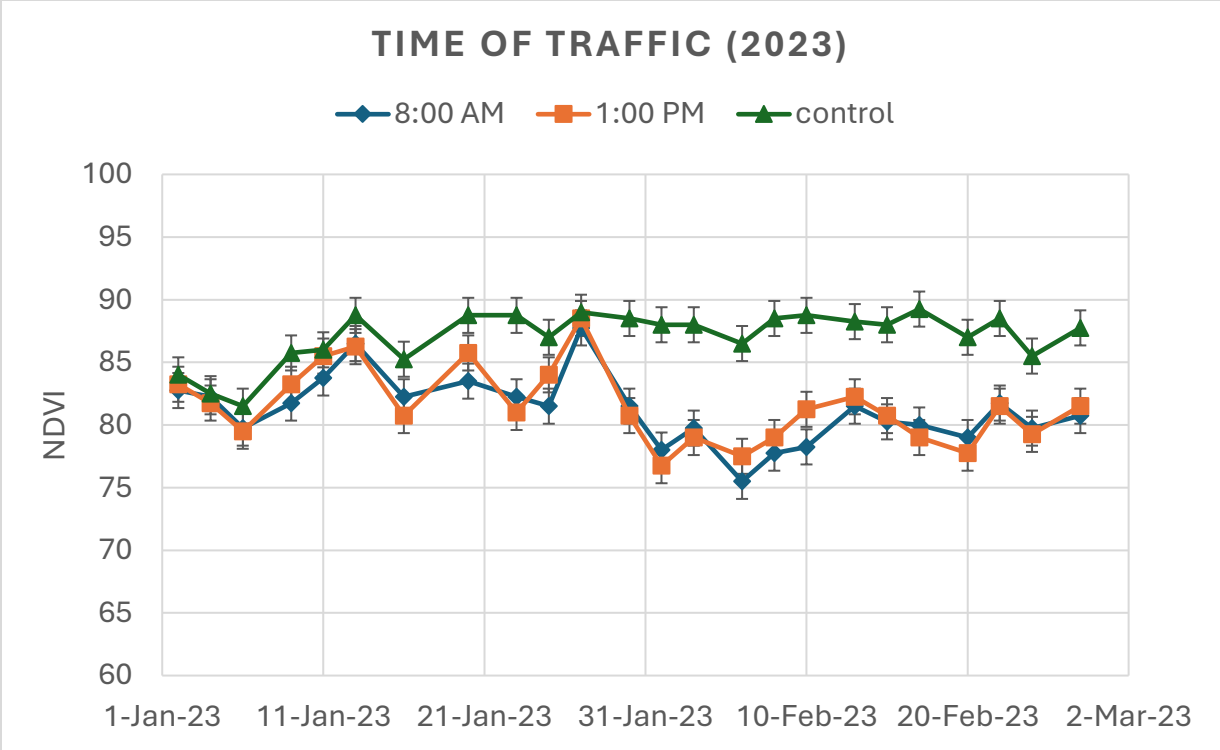


Figure 3: Effects of cart traffic applied 5 days per week during the winter on the normalized difference vegetation index values of a native soil bentgrass fairway in Corvallis, OR, 2023, and 2024 [LSD (0.05) = 1.4 and 0.02, respectively] (2025 interactions were not significant and not shown). Error bars represent significant differences at a 0.05 level of probability using Fisher’s LSD.

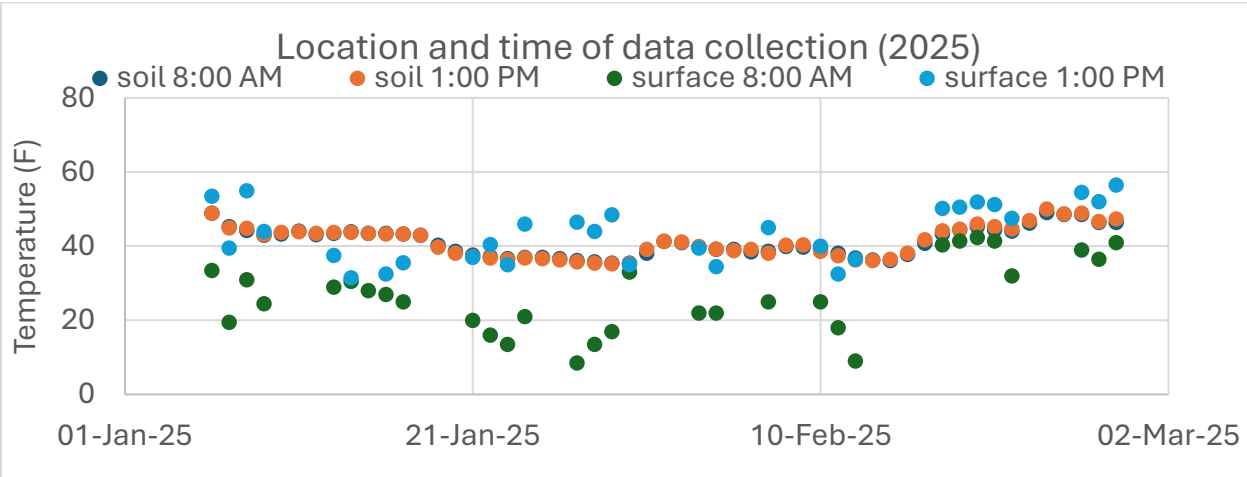
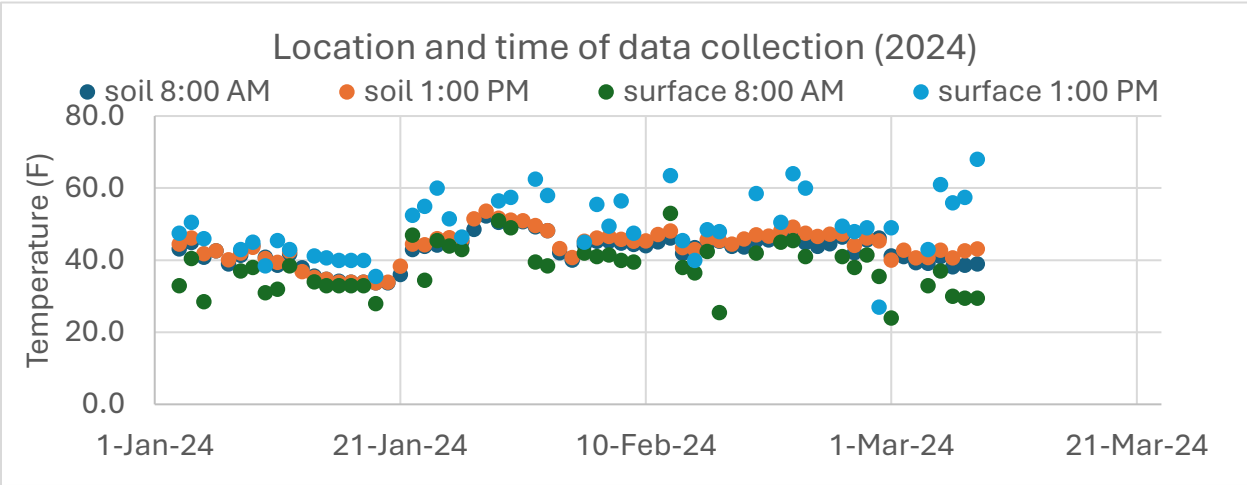
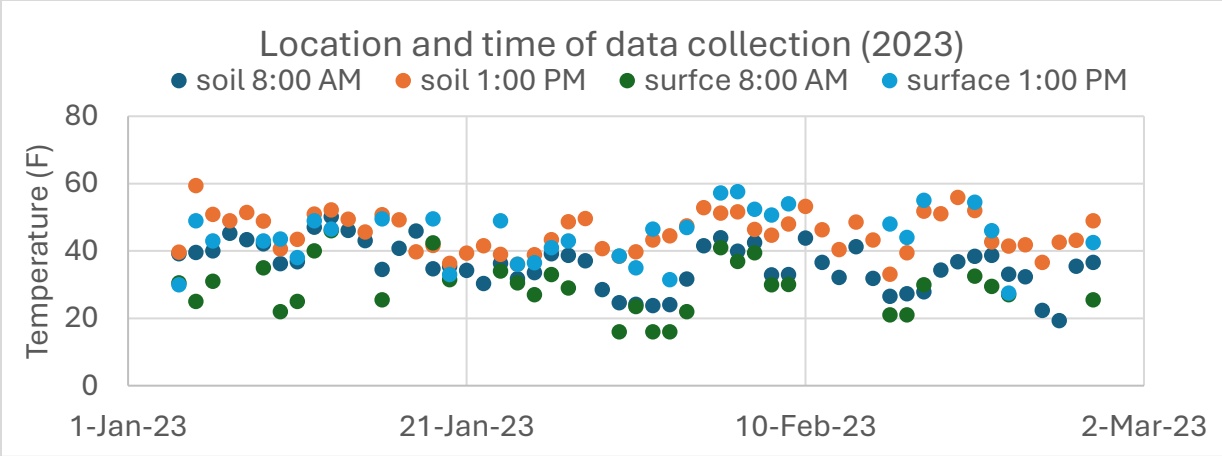


Figure 4: Surface and soil temperature collected from a native soil creeping bentgrass fairway in the winter in Corvallis, OR, 2023, 2024 and 2025.

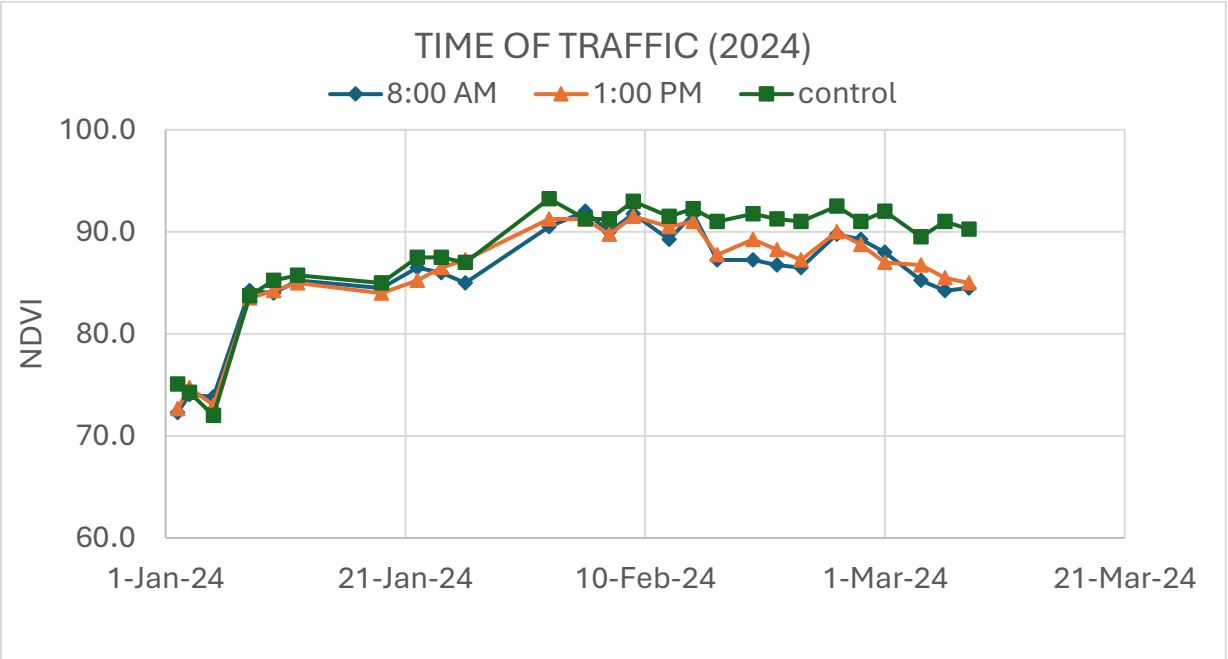
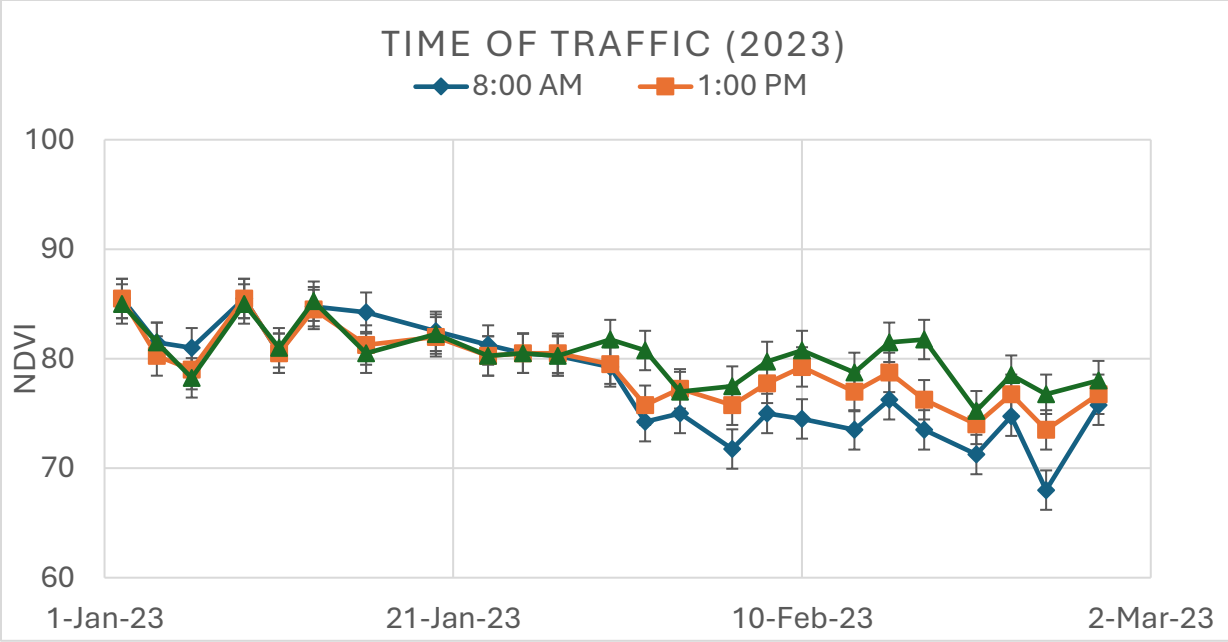


Figure 5: Effects of cart traffic applied 5 days per week during the winter on the normalized difference vegetation index values of a sand-based perennial ryegrass fairway in Corvallis, OR, 2023, and 2024 [LSD (0.05) = 1.8, and 0.01, respectively]. Error bars represent significant differences at a 0.05 level of probability using Fisher’s LSD.

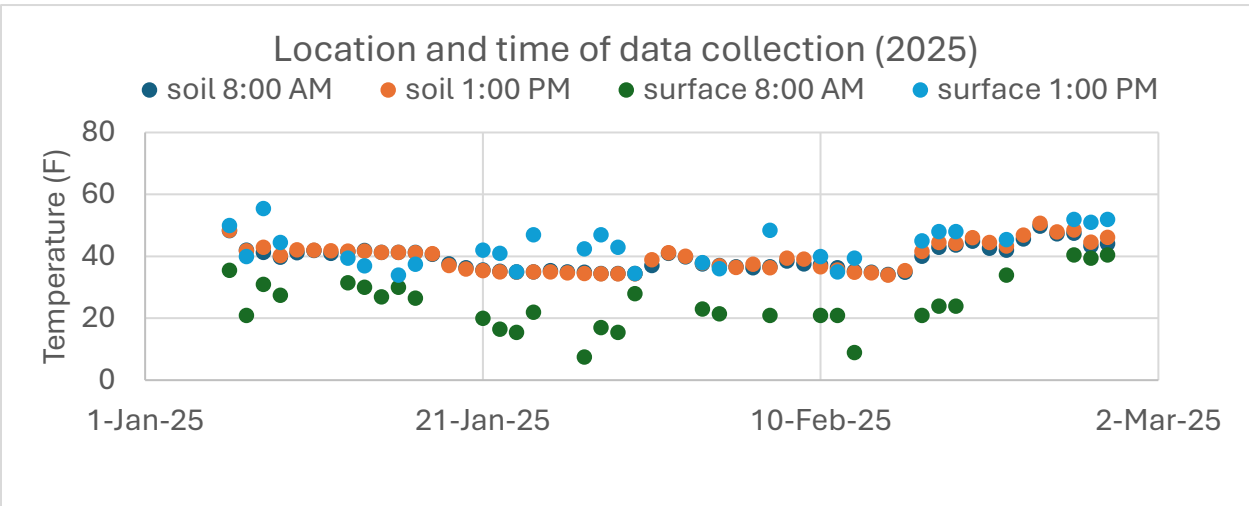
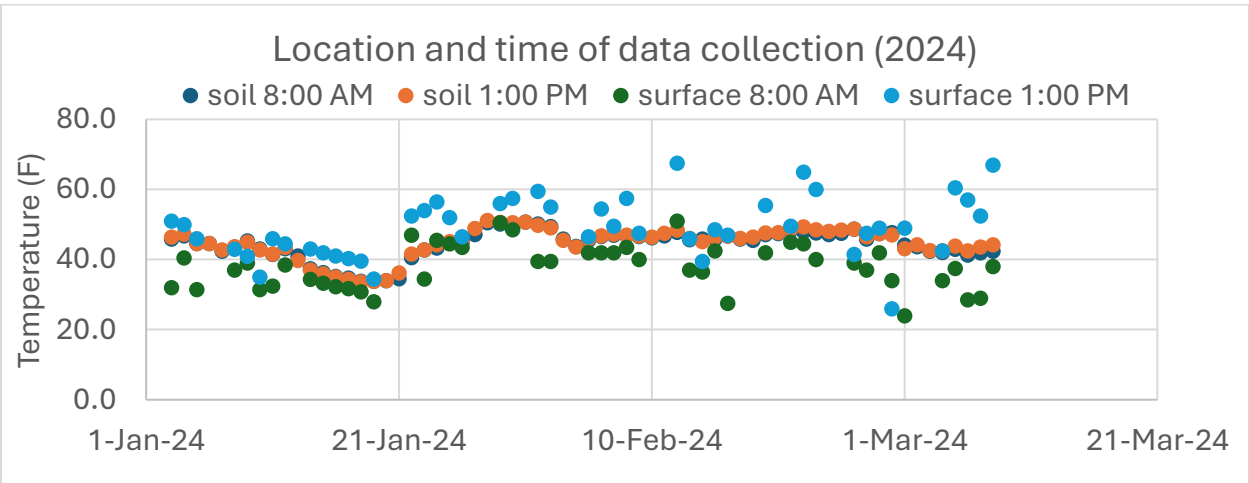
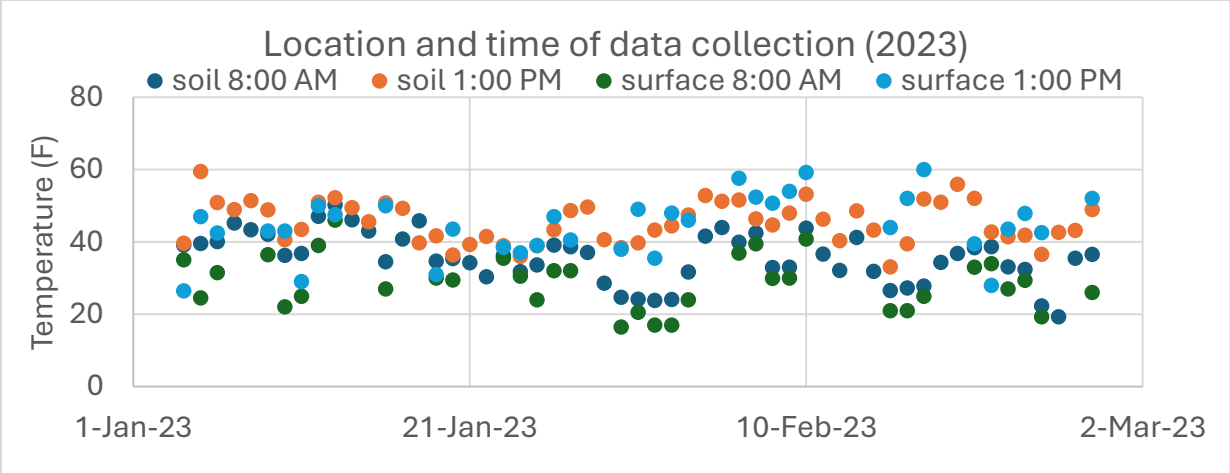


Figure 6: Surface and soil temperature collected from a sand-based perennial ryegrass fairway in the winter in Corvallis, OR, 2023, 2024, and 2024.

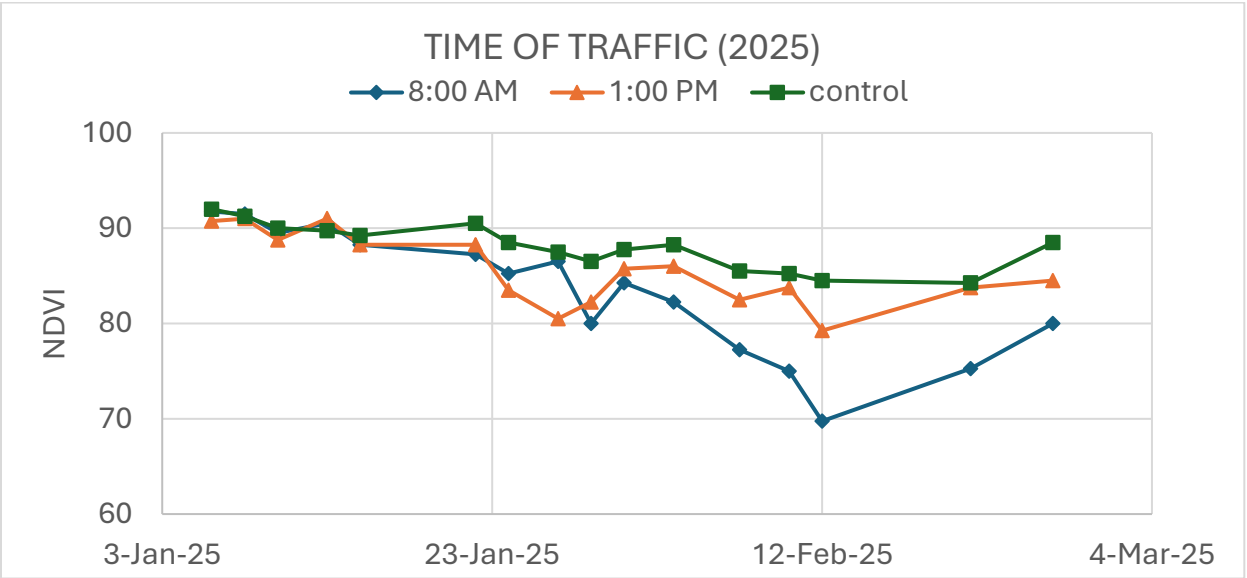
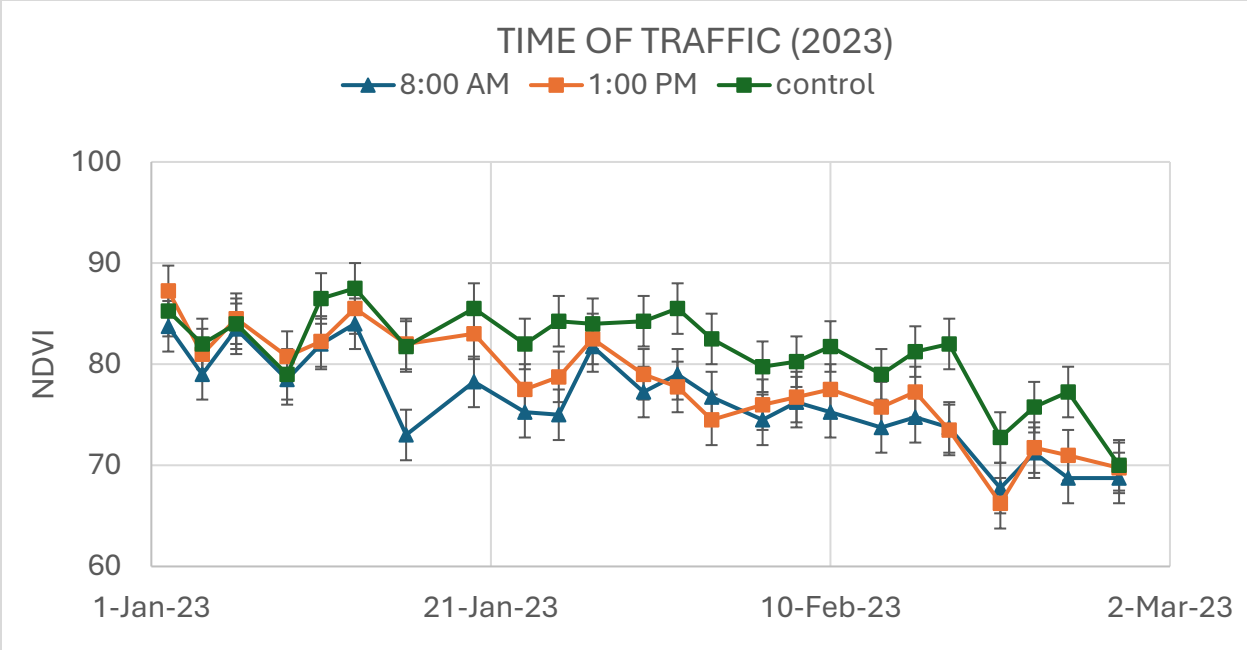


Figure 7: Effects of cart traffic applied 5 days per week during the winter on the normalized difference vegetation index values of a native soil annual bluegrass fairway in Corvallis, OR, 2023, and 2025 [LSD (0.05) = 2.5, and 0.5, respectively] (2024 interactions were not significant and not shown). Error bars represent significant differences at a 0.05 level of probability using Fisher’s LSD.

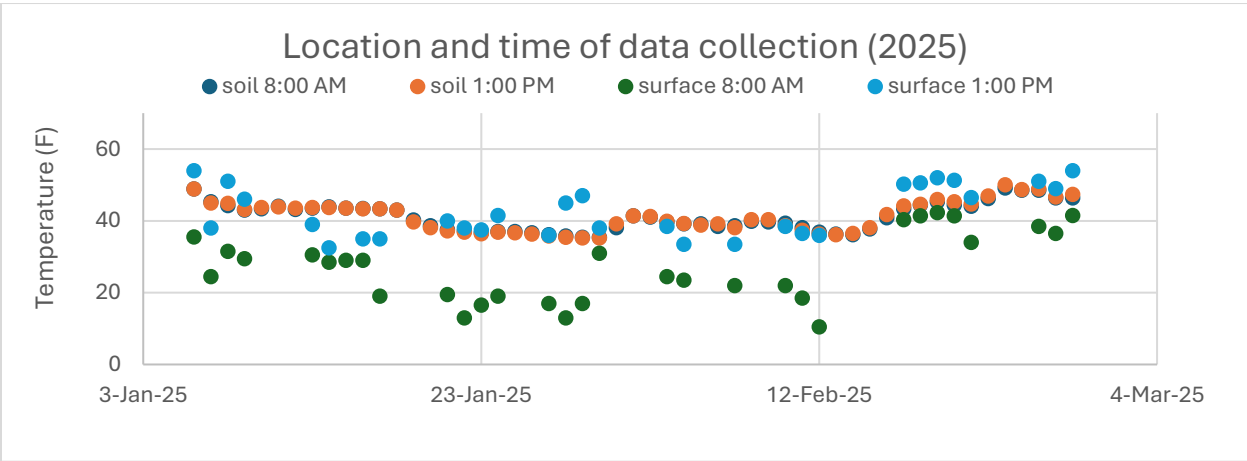
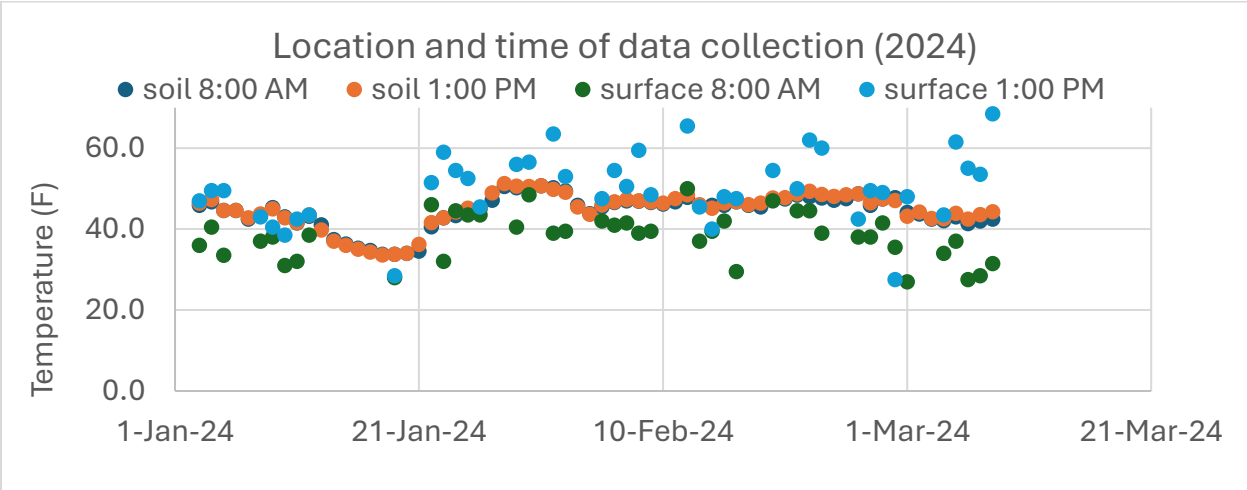
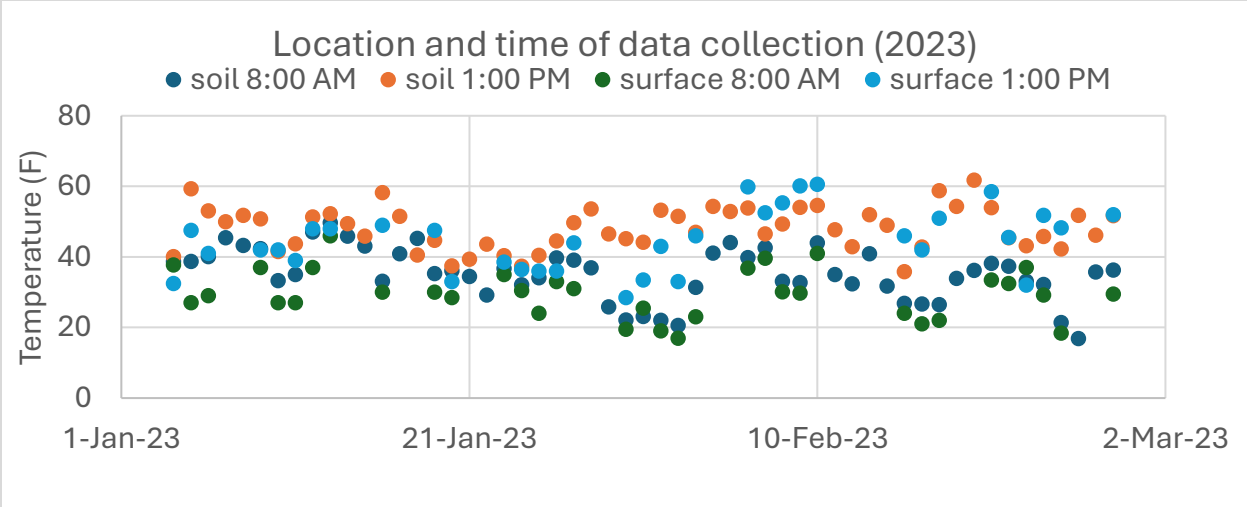


Figure 8: Surface and soil temperature collected from a native soil annual bluegrass fairway in the winter in Corvallis, OR, 2023, 2024, and 2025.

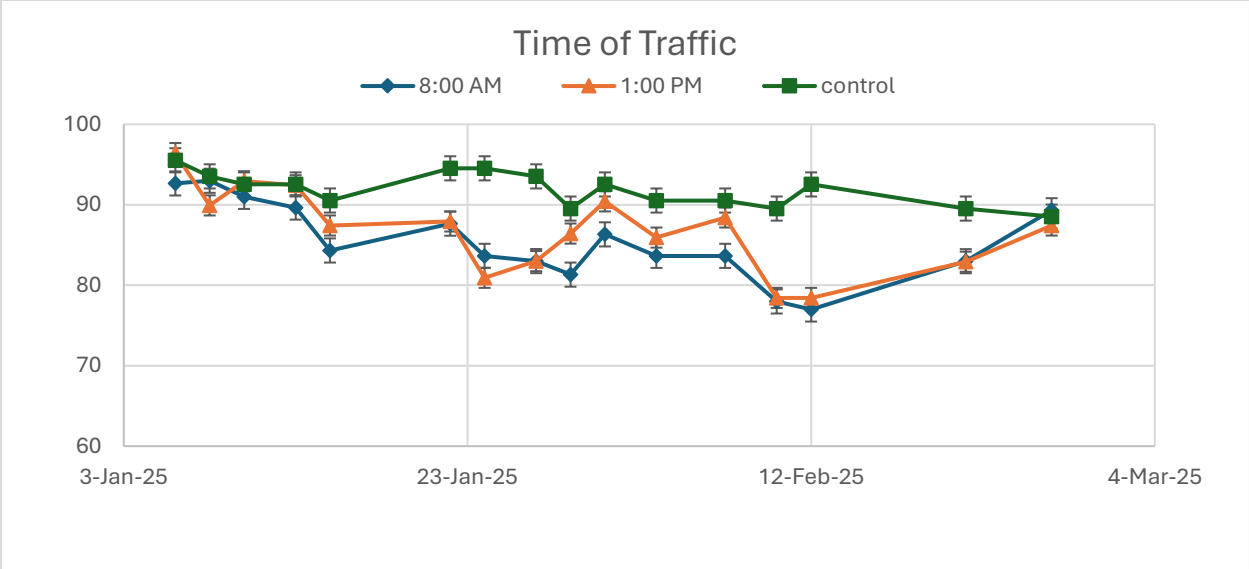


Figure 9: Effects of cart traffic applied 5 days per week during the winter on the normalized difference vegetation index values of a native soil perennial ryegrass rough in Corvallis, OR, 2025 [LSD (0.05) = 3.0]. Error bars represent significant differences at a 0.05 level of probability using Fisher’s LSD.

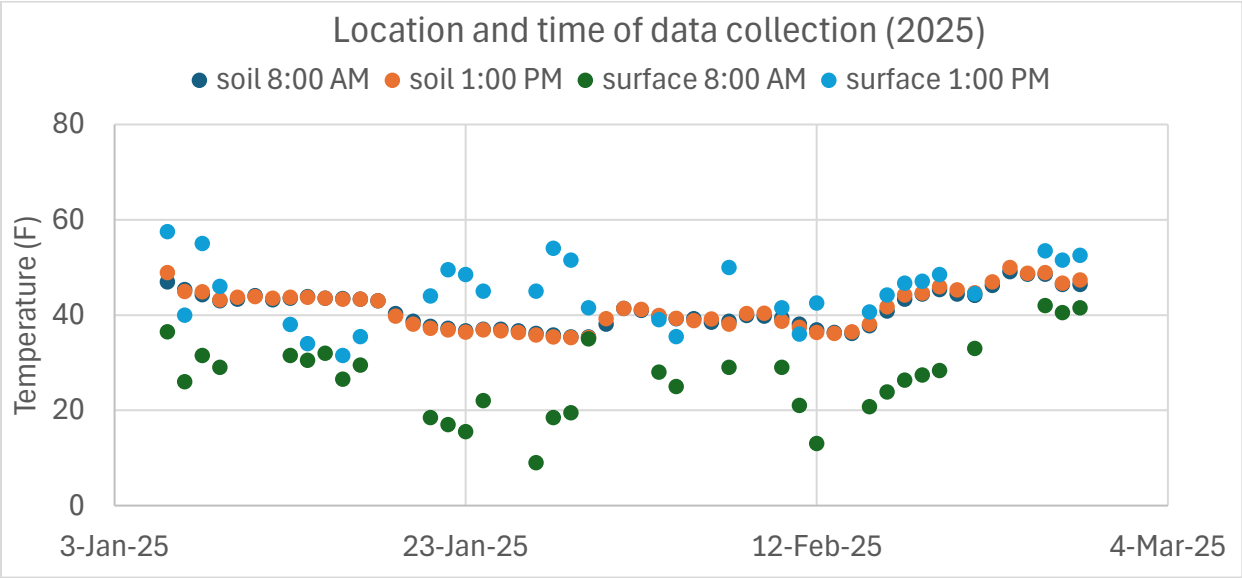


Figure 10: Surface and soil temperature collected from a native soil perennial ryegrass rough in the winter in Corvallis, OR, 2025.

2025 Report

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:

- The fourteen topdressing and cultivation programs were continued for a tenth growing season during 2025. Treatment combinations included 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. Additionally, treatment combinations included two levels of cultivation: non-cultivated or a ProCore® 648 setup with mini tine heads (staggered 5 tines per plate) and equipped with 3/8-inch diameter solid tines to apply the fifth and sixth solid tine cultivation events during this grant period.
- Data collection during 2025 included visual quality ratings, volumetric water content, bulk density with Troxler nuclear gage, in situ saturated conductivity (SATURO), soil hardness, and playability measures with the USGA GS3 devices (green speed, smoothness, trueness, and firmness). Analysis of data is ongoing.
- All factors (sand size, topdressing rate, and cultivation) impacted surface hardness (Clegg) and firmness (GS3) during 2025. Many responses are similar to those previously reported (Chen et al., 2025). However, there are some notable changes in responses. For example, a harder surface occurred on plots topdressed with the medium-coarse and medium-fine sand, but this was often observed only at the 50 lb (dusting) topdressing rate. At the 100 lb rate, topdressing with either medium-fine or fine-medium sand resulted in a harder surface than topdressing with medium-coarse sand. It is noteworthy that this increase in hardness occurred despite the medium-fine and fine-medium surfaces being wetter than the medium-coarse plots; typically, a wetter surface will reduce hardness. This suggests that a structural difference exists in the mat layers created by medium-fine and fine-medium sand topdressing at 100 lb, which offsets the greater wetness to improve surface hardness.
- A peer-review manuscript summarizing treatment responses over the first seven years of this trial was published in *Agronomy Journal*.
 - Hui Chen, James W. Hempfling, Charles J. Schmid, Zhongqi Xu, Hiranthi Samaranayake, James A. Murphy. 2025. Finer topdressing sand affects creeping bentgrass quality and surface characteristics. *Agronomy Journal*, 117, e70039. <https://doi.org/10.1002/agj2.70039>
- A second publication reporting the physical properties within the mat layer during the first seven years of this trial is planned for submission to the *Agronomy Journal* in 2026.

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 \leq 0.5-mm) has diluted and modified thatch accumulation much like that of a coarser topdressing sand (particles \leq 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 the initiation of 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 in terms of their 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.

Table 1 summarizes the factorial treatment combination that included two topdressing factors: sand size (medium-coarse, medium-fine, fine-medium) and quantity of summer topdressing (50- or 100-lb per 1,000 sq ft, applied every 10 to 14 days, resulting in ten applications from June through early October). The third factor was cultivation, either non-cultivated or cultivation twice a year with solid tines ($\frac{5}{8}$ -inch diameter) applied in April or May and October. Two controls (no summer topdressing) were included at each cultivation level for comparison, resulting in a total of 14 treatments (Table 1). Six solid-tine cultivation events have been performed since the initiation of this grant: 18 May and 23 October 2023, 15 April and 15 October 2024, 29 April and 15 October 2025.

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 exceeds 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, achieving an annual total of 2.4 lb N per 1,000 sq ft. Irrigation was applied at 50 to 80% ET_o. To delay the use of overhead irrigation and avoid over-watering plots with greater water retention, light (<0.1-inch) irrigation was applied to individual plots using a handheld hose, based on volumetric water contents predictive of incipient wilt stress. Overhead irrigation was used once the water content of the wettest plots had declined below 30%. Pests were preventively managed with pesticides.

Data collection during 2025 included visual ratings of turf quality, normalized difference vegetation index (NDVI), volumetric water content (VWC) of the surface 0- to 3-inch depth zone; *in situ* saturated hydraulic conductivity (SATURO), playability assessments with the Clegg soil impact tester (hardness) and the USGA GS3 device (green speed, smoothness, trueness, and penetration depth).

Complementary Cultivation Tine 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 June 30, 2023, applied four treatments: non-cultivated control, ½-inch i.d. hollow tine cultivation, ½-inch diameter solid tine cultivation, and ⅝-inch diameter solid tine cultivation. All treatments were replicated four times in a randomized complete block design. All treatments were reapplied on 11 October 2023, 5 April and 24 September 2024, and 17 April and 1 October 2025 (six cultivation events 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, and 24 April and 9 October 2025 (five cultivation events since the initiation of the trial).

All cultivated treatments were applied using 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 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 2025 included visual ratings of turf quality, healing of tine holes, residual sand after topdressing, normalized difference vegetation index (NDVI), volumetric water content of the surface 0- to 3-inch depth zone, and playability assessments with the Clegg soil impact tester (hardness) and USGA GS3 device (green speed, smoothness, trueness, and penetration depth). Additionally, dual-head infiltrometers were used to measure field-saturated hydraulic conductivity. Statistical analyses of 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 Number	Sand size ^a	Topdressing rate during mid-season ^b lb/1,000 sq ft/application	Cultivation ^c	Annual quantity of sand applied lb/1,000 sq ft
1	medium-coarse	50	none	1,300
2	medium-coarse	50	Solid tine + backfill	1,700
3	medium-coarse	100	none	1,800
4	medium-coarse	100	Solid tine + backfill	2,200
5	medium-fine	50	none	1,300
6	medium-fine	50	Solid tine + backfill	1,700
7	medium-fine	100	none	1,800
8	medium-fine	100	Solid tine + backfill	2,200
9	fine-medium	50	none	1,300
10	fine-medium	50	Solid tine + backfill	1,700
11	fine-medium	100	none	1,800
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 5/8-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.

Results

Topdressing Trial

Surface Hardness (Clegg)

The topdressing rate and cultivation main effects affected surface hardness on 11 of 12 measurement dates in 2025 (Table 2). Plot surfaces were harder when summer topdressing was applied at 100 lb per 1,000 sq ft compared to 50 lb (dusting). Except for the dates immediately after cultivation in May, plots that were cultivated with solid tines were harder than non-cultivated plots.

A sand size impact on surface hardness (G_{max}) was evident as a main effect and/or an interaction on 10 of 12 dates. Surface hardness was greatest for plots topdressed during the summer with the medium-fine sand on 8 dates out of 12 (main effect, Table 2), despite the corresponding volumetric water content (VWC) indicating that the plots topdressed with medium-fine sand had an intermediate wetness (not the driest) (Table 3). On five dates, the effect of sand size on surface hardness depended on the summer topdressing rate, which indicated that plots topdressed at 50 lb per 1,000 sq ft with either medium-fine or medium-coarse sands had similar hardness and were harder than plots topdressed with fine-medium sand (Table 4). Conversely, the plots topdressed during the summer at 100 lb per 1,000 sq ft with either medium-fine or fine-medium sand had similar hardness and were harder than plots topdressed with medium-coarse sand. The similarity in surface hardness between plots topdressed at 100 lb per 1000 sq ft with either medium-fine or fine-medium sand occurred despite the fine-medium plots being wetter than the plots topdressed with coarser sand (medium-fine and medium-coarse; Table 3).

On six dates, the effect of sand size on surface hardness depended on cultivation. Non-cultivated plots topdressed with medium-fine sand were firmer than the other sands except for one date when the medium-fine sand was only firmer than the fine-medium plots (Table 4). Surface hardness on the solid-tine cultivated plots was similar regardless of the sand size of topdressing, except for one date when the medium-coarse sand had a lower firmness than plots topdressed with medium-fine or fine-medium sand. The greater hardness of plots topdressed with medium-fine sand on non-cultivated plots occurred despite the medium-fine plots having an intermediate wetness (not the driest) except on one date (June 18) when wetness was similarly dry between medium-fine and medium-coarse plots (Table 3). Similarly, the surface hardness among plots topdressed with the three sand sizes and receiving solid-tine cultivation was similar, despite the fine-medium plots being wetter than the plots topdressed with coarser sand (medium-fine and medium-coarse).

Firmness (GS3 Penetration Depth)

The topdressing rate and cultivation factors had a greater impact on the penetration depth of the GS3 than the sand size factor. Plots topdressed at 100 lb per 1,000 sq ft during the summer had lower penetration depth than plots topdressed with 50 lb of sand on 10 of 12 dates and were drier than the 50 lb plots on all dates. Except for the date immediately after solid tine cultivation in May, the penetration depth of the GS3 was shallower on plots cultivated with solid tines twice a year than on plots that were not cultivated on 11 of 12 dates. Plots cultivated with solid tines were drier than non-cultivated plots on all dates.

The GS3 penetration depth was affected by sand size as a main and/or interaction effect on 5 out of 12 dates. The main effect indicated that plots topdressed with the medium-fine and fine-medium sand had the shallowest penetration depth of the GS3, except for one date (July 9) when the shallowest depth occurred only on the medium-fine plots (Table 5). These results occurred despite the corresponding volumetric water content (VWC), indicating that plots topdressed with the fine-medium sand had the greatest wetness, and plots with medium-fine sand had similar or greater wetness than

the plots topdressed with coarse-medium sand (Table 2). Thus, despite greater wetness, the fine-medium and medium-fine topdressed plots were firmer than the plots topdressed with coarser sand. Additionally, the penetration depth response to sand size depended on the topdressing rate on 4 of 12 dates in 2025, indicating that topdressing at 100 lb per 1,000 sq ft with medium-fine and fine-medium produced firmer plot surfaces than topdressing with medium-coarse sand, despite surface wetness of medium-fine and fine-medium plots being similar or wetter than the medium-coarse plots.

An interaction of topdressing rate and cultivation was observed on five dates, indicating that plots topdressed with 100 lb of sand had a lower penetration depth than plots topdressed with 50 lb of sand when plots were not cultivated. This response was likely due to plots topdressed with 50 lb of sand being wetter than plots topdressed with 100 lb of sand, especially under non-cultivated conditions.

Discussion

All factors (sand size, topdressing rate, and cultivation) impacted surface hardness (Clegg) and firmness (GS3) during 2025. Topdressing at 100 lb per 1,000 sq ft (compared to 50 lb) and solid tine cultivation (compared to no cultivation) increased surface hardness on most dates, corroborating our previous report (Chen et al., 2025). The surface firmness (GS3) response to topdressing rate and cultivation mimicked the surface hardness (Clegg) response; topdressing at 100 lb per 1,000 sq ft and solid tine cultivation increased surface firmness on most dates.

Surface hardness (Clegg) was influenced by the sand size factor on 10 dates, while surface firmness (GS3) was only influenced by sand size on 5 dates. The nature of the surface hardness response to sand size was different from that previously reported (Chen et al., 2025). In the current study, a harder surface occurred on plots topdressed with the medium-coarse and medium-fine sand – as reported by Chen et al (2025) – but this was often observed only at the 50 lb (dusting) topdressing rate. However, at the 100 lb rate, topdressing with either medium-fine or fine-medium sand resulted in a harder surface than topdressing with medium-coarse sand. It is noteworthy that this increase in hardness occurred despite the medium-fine and fine-medium surfaces being wetter than the medium-coarse plots; typically, a wetter surface will reduce hardness. This suggests that a structural difference exists in the mat layers created by medium-fine and fine-medium sand topdressing at 100 lb, which offsets the greater wetness to improve surface hardness.

Additionally, the effect of cultivation on the response of surface hardness (Clegg) to sand size was different from our previous report (Chen et al., 2025). In the current study, topdressing with medium-fine sand during the summer produced harder surfaces than medium-coarse and fine-medium sands under non-cultivated conditions. In contrast, Chen et al. (2025) reported that surface hardness was greatest for medium-coarse and medium-fine sands than fine-medium sand under non-cultivated conditions. Moreover, in the current study, the greater hardness of medium-fine sand topdressing occurred despite the greater wetness of those plots compared to the medium-coarse plots, again, suggesting that a structural characteristic may exist in the medium-fine plots that enables a harder surface to develop despite an increase in water retention. Unlike the surface hardness response, the GS3 penetration depth response to sand size did not depend on the cultivation factor, which may indicate that the two devices are sensing different depth zones of the mat layer.

Table 2. Sand size, topdressing rate, and cultivation effects on surface hardness of plots measured on 12 dates during 2025 on a ‘Shark’ creeping bentgrass maintained as a putting green in North Brunswick, NJ.

ANOVA Source	25-Apr	7-May	15-May	23-May	29-May	4-Jun	12-Jun	18-Jun	9-Jul	15-Aug	14-Oct	3-Nov
----- F test -----												
Sand Size	0.0355	0.0591	0.171	0.0171	0.0121	0.0023	0.0258	0.3852	0.0942	0.0070	0.0028	0.0008
Topdress Rate (TR)	0.0002	<.0001	<.0001	<.0001	0.0004	<.0001	0.0009	0.0019	0.1652	<.0001	<.0001	<.0001
Sand Size*Rate	0.001	0.0008	0.0622	0.0285	0.0689	0.1577	0.0597	0.5843	0.0826	0.0413	0.0617	0.0056
Solid Tine Cultivation (STC)	<.0001	<.0001	0.0582	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Sand Size*STC	0.0119	0.0889	0.1087	0.0491	0.0243	<.0001	0.5091	0.0079	0.3490	0.0061	0.6369	0.0811
TR*STC	0.0002	0.1139	0.0582	0.0025	0.0077	0.0327	0.0979	0.8270	0.4534	0.0033	0.0182	0.0007
Sand Size*TR*STC	0.9895	0.0421	0.8272	0.8254	0.2760	0.6850	0.0101	0.4373	0.1102	0.2974	0.6128	0.1946
CV(%)	2.2	2.5	2.8	2.7	2.7	2.6	3.2	3.8	3.2	3.1	2.7	2.3
----- G _{max} -----												
Sand Size main effect												
Medium-coarse (310)	74.3 b	66.3 b	66.2	67.1 b	68.5 b	73.5 ab	75.5 b	71.3	70.4	70.9 b	68.1 b	70.8 b
Medium-fine (330)	75.6 a	67.8 a	66.9	68.7 a	70.5 a	74.9 a	77.4 a	72.1	72.1	73.5 a	70.4 a	73.0 a
Fine-medium (65)	74.1 b	67.1 ab	65.7	66.9 b	68.8 b	72.3 b	75.2 b	70.8	70.6	71.5 b	68.5 b	70.9 b
LSD(5%)	1.2	ns1.2	ns1.3	1.3	1.4	1.4	1.7	ns2	ns1.7	1.6	1.3	1.2
Topdress Rate main effect												
50 lb/1000 sq ft	73.7	65.7	64.9	66.2	68.2	72.3	74.8	70.1	70.6	70.4	66.8	69.5
100 lb/1000 sq ft	75.6	68.4	67.6	69	70.4	74.9	77.3	72.7	71.5	73.5	71.2	73.6
LSD(5%)	1	1	1.1	1.1	1.1	1.1	1.4	1.6	ns1.4	1.3	1.1	1
Solid Tine Cultivation main effect												
None	69.7	68.7	66.7	66.4	68.1	71.5	73.8	67.2	67.4	67.0	63.9	69.5
Twice a year	79.6	65.5	65.8	68.8	70.5	75.7	78.3	75.6	74.7	77.0	74.1	73.7
LSD(5%)	1	1	1.1	1.1	1.1	1.1	1.4	1.6	1.4	1.3	1.1	1

Table 3. Sand size, topdressing rate, and cultivation effects on volumetric water content at the 0- to 3-inch depth of plots measured on 12 dates during 2025 on a 'Shark' creeping bentgrass maintained as a putting green in North Brunswick, NJ.

ANOVA Source	25-Apr	28 Apr	7-May	15-May	23-May	29-May	4-Jun	12-Jun	18-Jun	9-Jul	15-Aug	14-Oct	3-Nov
	----- F test -----												
Sand Size	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Topdress Rate (TR)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Sand Size*Rate	0.1927	0.1927	0.3790	0.7205	0.4899	0.2534	0.5262	0.8297	0.1864	0.1948	0.2206	0.7898	0.2832
Solid Tine Cultivation (STC)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Sand Size*STC	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0002	<.0001	0.0148	<.0001	0.0016
TR*STC	0.6103	0.6103	0.2860	0.2475	0.0822	0.1585	0.0682	0.0184	0.0860	0.033	0.0089	0.0303	0.2567
Sand Size*TR*STC	0.1766	0.1766	0.0927	0.5376	0.7882	0.1918	0.0535	0.0179	0.3745	0.1113	0.0728	0.2455	0.0842
CV(%)	5.9	5.9	5.4	5.1	6.7	5.9	7.4	8.6	6.7	7.8	8.9	6.5	9.9
Sand Size main effect	----- Volumetric Water Content (%) -----												
Medium-coarse (310)	23.8 c	23.8 c	26.4 c	30.0 c	29.4 c	26.9 c	23.8 c	21.1 c	27.7 b	23.2 b	23.4 b	26.9 c	22.6 b
Medium-fine (330)	25.4 b	25.4 b	27.5 b	31.6 b	31.2 b	28.3 b	25.5 b	22.9 b	28.8 b	24.1 b	24.5 b	28.8 b	24.3 b
Fine-medium (65)	31.1 a	31.1 a	32.5 a	36.8 a	35.9 a	33.9 a	31.0 a	27.6 a	34.2 a	28.4 a	29.4 a	33.4 a	29.3 a
LSD(5%)	1.1	1.1	1.1	1.2	1.5	1.3	1.4	1.5	1.5	1.4	1.6	1.4	1.8
Topdress Rate main effect													
50 lb/1000 sq ft	28.1	28.1	30.4	34.3	34.1	31.5	28.4	25.5	31.9	26.8	28.2	31	27.1
100 lb/1000 sq ft	25.5	25.5	27.2	31.3	30.3	27.9	25.1	22.2	28.6	23.7	23.4	28.4	23.7
LSD(5%)	0.9	0.9	0.9	1	1.3	1	1.2	1.2	1.2	1.2	1.3	1.1	1.5
STC main effect													
None	30.6	30.6	33.0	37.7	37.5	34.3	31.1	27.8	35.1	29.4	29.0	33.6	29.3
Twice a year	23	23	24.6	28	26.9	25.1	22.4	19.9	25.4	21.1	22.5	25.8	21.5
LSD(5%)	0.9	0.9	0.9	1	1.3	1	1.2	1.2	1.2	1.2	1.3	1.1	1.5

Table 4. Surface hardness (G_{max}) response to sand size as influenced by topdressing rate or cultivation during 2025 on a 'Shark' creeping bentgrass maintained as a putting green in North Brunswick, NJ.

Interactions		25-Apr	7-May	15-May	23-May	29-May	4-Jun	12-Jun	18-Jun	9-Jul	15-Aug	14-Oct	3-Nov
<u>Sand Size</u>	<u>Topdressing Rate</u>	----- G_{max} -----											
Medium-coarse (310)	50-lb	74.3	66	65.6	66.4	68.3	72.9	75.4	70.5	70.8	70.5	66.7	69.9
Medium-fine (330)	50-lb	74.9	66.7	65.7	67.6	69.4	73.5	76	70.5	71.9	71.7	68.3	70.7
Fine-medium (65)	50-lb	71.8	64.4	63.5	64.5	67	70.5	73	69.2	69.0	69.1	65.4	68
Medium-coarse (310)	100-lb	74.2	66.6	66.8	67.8	68.8	74.1	75.6	72	70.1	71.3	69.6	71.8
Medium-fine (330)	100-lb	76.2	68.8	68.1	69.8	71.7	76.2	78.9	73.8	72.3	75.2	72.5	75.4
Fine-medium (65)	100-lb	76.4	69.9	67.9	69.4	70.7	74.2	77.4	72.4	72.1	74	71.5	73.8
LSD(5%)		1.7	1.7	NS	1.8	NS	NS	NS	NS	NS	2.2	NS	1.7
<u>Sand Size</u>	<u>Cultivation</u>												
Medium-coarse (310)	None	69.5	68	66.7	66	67.7	71.3	73.8	68	66.8	66.8	62.7	69
Medium-fine (330)	None	71.4	70	68.2	68.3	70.0	74.6	75.1	68.8	69.1	69.2	65.4	71.4
Fine-medium (65)	None	68.2	68	65.5	64.9	66.5	68.6	72.5	64.7	66.3	65	63.6	68
Medium-coarse (310)	Twice	79.1	64.7	65.7	68.1	69.4	75.7	77.3	74.5	74.1	75.1	73.6	72.7
Medium-fine (330)	Twice	79.7	65.6	65.7	69.1	71.0	75.2	79.8	75.5	75.1	77.7	75.4	74.6
Fine-medium (65)	Twice	80.1	66.3	65.9	69	71.1	76.1	78	76.9	74.8	78.1	73.3	73.8
LSD(5%)		1.7	NS	NS	1.8	1.9	1.9	NS	2.8	NS	2.2	NS	NS

Table 5. Sand size, topdressing rate, and cultivation effects on the penetration depth of GS3 drop measured on 12 dates during 2025 on a ‘Shark’ creeping bentgrass maintained as a putting green in North Brunswick, NJ.

ANOVA Source	28-Apr	7-May	15-May	23-May	29-May	4-Jun	12-Jun	18-Jun	9-Jul	15-Aug	14-Oct	3-Nov
	----- F test -----											
Sand Size	0.0984	0.4036	0.0066	0.0664	0.1015	0.1044	0.0833	0.1140	0.0001	0.5802	0.0042	<.0001
Topdress Rate (TR)	<.0001	0.0008	<.0001	0.1422	0.0007	0.4713	0.0397	0.0034	0.0004	0.0486	0.0012	<.0001
Sand Size*Rate	0.0349	0.1425	0.0178	0.3281	0.7058	0.4710	0.8679	0.1213	0.0010	0.1971	0.4324	0.0095
Solid Tine Cultivation (STC)	<.0001	0.9371	0.0027	0.0008	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Sand Size*STC	0.1561	0.5968	0.7676	0.2539	0.5207	0.0819	0.6987	0.9834	0.9632	0.4796	0.8120	0.4807
TR*STC	0.0057	0.1936	0.3373	0.5101	0.1429	0.0018	0.0030	0.1013	0.0229	0.5699	0.1022	0.0007
Sand Size*TR*STC	0.6485	0.4574	0.3474	0.3897	0.7006	0.6535	0.8191	0.1578	0.0244	0.3800	0.4468	0.1222
CV(%)	1.9	2	1.9	3.1	2	2	2.3	2.4	1.5	2.4	2.8	1.7
Sand Size main effect	----- GS3 penetration depth (cm) -----											
Medium-coarse (310)	0.458	0.473	0.464	0.463	0.453	0.453	0.447	0.465	0.461	0.458	0.463	0.447
Medium-fine (330)	0.450	0.468	0.455	0.451	0.448	0.448	0.439	0.457	0.449	0.454	0.450	0.433
Fine-medium (65)	0.451	0.469	0.457	0.455	0.447	0.455	0.440	0.459	0.457	0.457	0.448	0.437
LSD(5%)	NS	NS	0.006	NS	NS	NS	NS	NS	0.005	NS	0.009	0.005
Topdress Rate main effect												
50 lb/1000 sq ft	0.458	0.475	0.465	0.459	0.454	0.453	0.445	0.465	0.459	0.460	0.460	0.445
100 lb/1000 sq ft	0.447	0.465	0.452	0.453	0.444	0.451	0.439	0.455	0.451	0.453	0.447	0.432
LSD(5%)	0.005	0.006	0.005	ns0.009	0.005	ns0.005	0.006	0.007	0.004	0.006	0.007	0.004
STC main effect												
None	0.467	0.47	0.463	0.464	0.458	0.463	0.452	0.47	0.467	0.472	0.469	0.446
Twice a year	0.437	0.47	0.455	0.448	0.441	0.441	0.432	0.45	0.444	0.442	0.438	0.431
LSD(5%)	0.005	ns0.006	0.005	0.009	0.005	0.005	0.006	0.007	0.004	0.006	0.007	0.004

Table 6. The GS3 penetration depth responses to the sand size interaction with topdressing rate and topdressing rate with cultivation during 2025 on a 'Shark' creeping bentgrass maintained as a putting green in North Brunswick, NJ.

Interactions		28-Apr	7-May	15-May	23-May	29-May	4-Jun	12-Jun	18-Jun	9-Jul	15-Aug	14-Oct	3-Nov
Sand Size	Topdressing Rate	----- GS3 penetration depth (cm) -----											
Medium-coarse (310)	50-lb	0.458	0.479	0.466	0.464	0.456	0.452	0.451	0.465	0.459	0.459	0.466	0.448
Medium-fine (330)	50-lb	0.460	0.470	0.462	0.451	0.453	0.448	0.441	0.463	0.453	0.455	0.457	0.44
Fine-medium (65)	50-lb	0.456	0.477	0.467	0.462	0.452	0.458	0.443	0.467	0.466	0.464	0.457	0.447
Medium-coarse (310)	100-lb	0.455	0.466	0.463	0.461	0.45	0.453	0.442	0.464	0.462	0.457	0.459	0.445
Medium-fine (330)	100-lb	0.441	0.467	0.447	0.45	0.442	0.448	0.437	0.45	0.444	0.453	0.444	0.426
Fine-medium (65)	100-lb	0.446	0.461	0.446	0.447	0.441	0.452	0.437	0.45	0.448	0.449	0.438	0.426
LSD(5%)		0.009	NS	0.009	NS	NS	NS	NS	NS	0.007	NS	NS	0.008
Topdressing Rate	Cultivation												
50-lb	None	0.477	0.477	0.470	0.468	0.464	0.468	0.460	0.478	0.473	0.478	0.478	0.457
100-lb	None	0.459	0.463	0.455	0.459	0.451	0.457	0.444	0.462	0.460	0.467	0.459	0.436
50-lb	Twice	0.438	0.474	0.460	0.450	0.444	0.438	0.430	0.452	0.445	0.444	0.442	0.434
100-lb	Twice	0.435	0.467	0.449	0.447	0.438	0.445	0.433	0.448	0.442	0.439	0.435	0.429
LSD(5%)		0.007	NS	NS	NS	NS	0.008	0.008	NS	0.006	NS	NS	0.006

2026 Plan of Work

- We will collect undisturbed cores of the mat layers to assess bulk density, porosity, and sand size distribution in spring 2026 (after 10 years of treatments). These data will be compared to the same measurements made in April 2023 (after 7 years of hollow-tine cultivation).
- A peer-review publication on the physical properties during the first seven years of this trial is being drafted for submission to Agronomy Journal.
- We will continue applying topdressing and solid-tine cultivation treatments as well as 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); dual head infiltrometers (SATURO) to assess water infiltration during 2026.
- In the spring of 2026, we will conduct a preliminary study of golf shoe traffic effects on GS3 green speed, smoothness, and trueness to determine the timeframe of recovery of these playability measures after golf shoe traffic. This will inform us on how to structure the time frame for applying golf shoe traffic and subsequent playability measurements after traffic on the topdressing trial. The objectives of this work are to determine whether sand size, topdressing, or cultivation affects i) playability of surfaces trafficked by golf shoes and ii) recovery of playability with time after traffic.

USGA ID#: 2025-02-833

Title: Long term effects of topdressing and cultivation on an annual bluegrass putting green; years 6-8

Project Leader: Chas Schmid

Collaborators: Robert Starchvick, Emily Braithwaite, and Brian McDonald

Affiliation: Department of Horticulture, Oregon State University

Objectives:

1. Determine whether continuous solid tine cultivation treatments reduce soil infiltration to an unacceptable level rate long term.
2. Determine if two hollow tine cultivations per year are required to maintain acceptable soil infiltration levels compared to a single cultivation event.
3. Understand the interaction between sand topdressing and cultivation with respect to turfgrass quality, surface firmness, total organic matter (OM), and infiltration rate.

Start Date:

May 2025

Project Duration:

3 years, Jan 2025 to Dec 2027 (year 1 report)

Total Funding:

\$90,000 (\$30,000 per year)

Summary Points:

- Hollow tine cultivation results in higher infiltration rate compared to solid tine cultivation after 6 years of treatments
- Sand topdressing had the greatest influence on total OM content in the 0-4 cm depth, with topdressing at 100 lb/1,000 ft² every 14-d reducing total OM content compared to lower rates.
- Cultivation in both spring and fall reduced total OM content in the 0-6cm depth compared to spring or fall alone

Introduction:

Hollow tine aerification and sand topdressing have been used on golf course putting greens for decades. These cultural practices are used to mitigate organic matter accumulation, provide rapid infiltration, and maintain firm playing conditions (Green et al., 2001; Stier and Hollman, 2003). In more recent years, superintendents and researchers have been exploring solid tine aerification and topdressing without aerification (Hempfling et al., 2014; Inguagiato et al., 2012; Wang et al., 2018). These practices are less intensive and minimize surface disruption, a

frequent golfer complaint. Despite these recent trends, aerification and topdressing research on annual bluegrass putting greens in the Pacific Northwest, where 12 months of annual bluegrass growth can be expected, and long-term research on putting greens is minimal.

Materials and Methods:

This field trial was initiated in May 2020 at the OSU Lewis-Brown Horticulture Farm in Corvallis, OR. Research was conducted on a putting green that was built in 2009 by placing 12" of USGA spec sand over a silty clay loam soil with flat drainage. Turfgrass was established using sand-based annual bluegrass (*Poa annua*) sod (Bos Sod, Canada).

Experimental design for the trial is a randomized complete block design with four replications. Treatments are arranged in a 2 x 2 x 3 factorial, with two sand topdressing rates (50 and 100 lbs/1000ft²), two tine types (hollow and solid tine), and three cultivation timings (spring, fall, and both spring and fall). A non-treated control (no cultivation, no sand topdressing) and two non-cultivated plots that received either 50 or 100 lb/1,000 ft² sand topdressing were also included in the analysis. Spring cultivation treatments were applied on 3 Jun 2025 and fall cultivation treatments were applied 30 Oct 2025. Sand topdressing treatments were applied every 2-wks during the summer from June through end of October.

Fungicides were applied year-round to prevent diseases including anthracnose (*Colletotrichum cereale*), yellow patch (*Rhizoctonia cerealis*), and Microdochium patch (*Microdochium nivale*). The plots were fertilized every 2 weeks during the growing season (spring, summer, and fall) at 0.2 lbs N/1000 ft², and at the same rate monthly during the winter. The plots were mowed no higher than 0.110 inches during the growing season and 0.140 inches during the winter.

Response Variables:

Surface firmness was measured routinely during the summer using the USGA GS3, with 3 measurements collected within each plot. Percent volumetric water content was measured at the same time and location as surface firmness to determine if surface firmness differences were a result of a treatment response or soil moisture differences. Soil infiltration rates for each plot were collected on Oct 7, 2025 using a double ring (6" inner ring, 12" outer ring) falling head method similar to the methods described by Wander and Bollero (1999). One linear inch of water (450ml) was added to the inner ring on each plot and the time required to infiltrate 1 in. was recorded. This procedure was repeated for the second inch of infiltration. Soil samples for total organic matter were collected using methods described by Lockyer (2008) on 2 June 2025 prior to spring cultivation treatment in 2025; where soil samples are divided into depth increments of 0-0.8, 0.8-1.6, 1.6-2.4 in. (0-2, 2-4, and 4-6cm) and the verdure is not removed from the sample. Three soil samples were collected per plot using a 1.25" soil probe. Total organic matter was determined using loss on ignition (LOI) method described by Gaussoin et al. (2024); where intact samples are ignited at 440°C for two hours.

Findings:

Statistical differences in soil infiltration rate were detected between treatments in 2025. The non-treated control and topdressing alone (both rates) resulted in significantly lower soil infiltration rates compared to all combinations of cultivation and topdressing, except fall solid tine treatments at both rates of sand topdressing (Figure 1). The treatment that produced the greatest infiltration rate was the combination of hollow tine cultivation in spring and fall, and sand topdressing at 100 lb/1,000 ft². Cultivation tine type was the only main effect to influence infiltration rates in 2025. After 6 years of treatments, hollow tine cultivation had higher infiltration rates compared to solid tine cultivation, increasing infiltration rate on average by 43% (Figure 2). These results suggest that long-term, hollow tine cultivation is more effective at maintaining/increasing infiltration rate on annual bluegrass putting greens

Total organic matter content, collected June 2025, indicated that plots receiving no cultivation or topdressing treatments have almost twice as much total OM content in the 0-2 cm depth compared to all other treatments (Figure 3). A factorial analysis indicated that the main effects of both topdressing rate and cultivation timing influenced total OM content in the 0-2 and 2-4cm depth (Table 1). Cultivation timing also had an effect total OM content at 4-6cm depth. Sand topdressing had the greatest influence on total OM in the 0-2 and 2-4cm depths; with sand applied at 100 lb/1,000 ft² every 14-d during the summer resulting in lower total OM content compared to 50lb/1,000 ft² applied at the same interval. Cultivation timing also affected total OM at all soil depths measured. Cultivation treatments in both spring and fall resulted in lower total OM compared to either season alone (Table 1). Additionally, fall cultivation treatments had statistically lower total OM levels in the 0-2cm depth compared to spring cultivation. It is unclear whether this result is an artifact of soil sample timing or if vigorous growth after spring cultivation results in higher total OM. An additional sample collection will be conducted in the fall of 2026 to determine the impact of soil sample timing. Interestingly, data from 2025 suggests that tine type (hollow vs solid) had no effect on total organic matter content at any depth. This result indicates that greater infiltration rates observed in hollow tine treatments are not a result of reduced total OM when compared to solid tine treatments.

References:

- Gaussoin, R., D. Linde, J. Murphy, D. Soldat, and B. Whitlark. 2024. A standard method for measuring green surface organic matter. *USGA Green Sec. Rec.* 62(2): p. [1-6]
- Green, R., L. Wu and G.J. Klein. 2001. Summer Cultivation Increases Field Infiltration Rates of Water and Reduces Soil Electrical Conductivity on Annual Bluegrass Golf Greens. *HortScience.* 36(4):776-779.
- Hempfling, J.W., B.B. Clarke and J.A. Murphy. 2014. Anthracnose Disease on Annual Bluegrass as Influenced by Spring and Summer Topdressing. *Crop Science.* 55(1):437-443.
- Inguagiato, J.C., J.A. Murphy and B.B. Clarke. 2012. Sand Topdressing Rate and Interval Effects on Anthracnose Severity of an Annual Bluegrass Putting Green. *Crop Science.* 52(3):1406-1415.

- Lockyer, J. 2008. STRI – Testing for organic matter. Turfgrass Bulletin. Oct 2008. Issue 242.
- Stier, J.C. and A.B. Hollman. 2003. Cultivation and Topdressing Requirements for Thatch Management in A and G Bentgrasses and Creeping Bluegrass. HortScience. 38(6):1227-1231.
- Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63:961-971.
- Wang, R., J.W. Hempfling, B.B. Clarke and J.A. Murphy. 2018. Seasonal and Annual Topdressing Effects on Anthracnose of Annual Bluegrass. Agronomy Journal. 110(6):2130-2135.
- USGA. 2018. USGA recommendations for a method of putting green construction. United States Golf Association, Liberty Corner, N.J.
(<http://archive.lib.msu.edu/tic/usgamisc/monos/2018recommendationsmethodputtinggreen.pdf>)
Accessed Nov 21, 2022.

Table 1. Analysis of variance of total organic matter content of an annual bluegrass putting green in response to topdressing rate, tine type, and cultivation timing; collected on the 2 Jun 2025.

Main effects	Sampling depth		
	0-2 cm	2-4 cm	4-6 cm
	%		
Topdressing Rate (T) [†]			
50 lbs/M	36.0	8.5	8.5
100 lbs/M	29.2	7.3	7.3
Tine Type (TT)			
Hollow tine	32.3	7.6	4.3
Solid tine	32.9	8.1	4.3
Cultivation Timing (CT)			
Spring	36.2	8.6	4.4
Fall	32.2	8.3	4.4
Spring & Fall	29.4	6.8	4.0
LSD _(0.05)	2.7	0.7	0.3
<hr/>			
Source of variation			
T	***	***	ns
TT	ns	ns	ns
T x TT	ns	ns	ns
CT	***	***	**
T x CT	ns	ns	*
TT x CT	ns	ns	ns
T x TT x CT	ns	ns	ns

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability level; ns = not significant.

[†] Topdressing treatments applied every 14-day from June through September

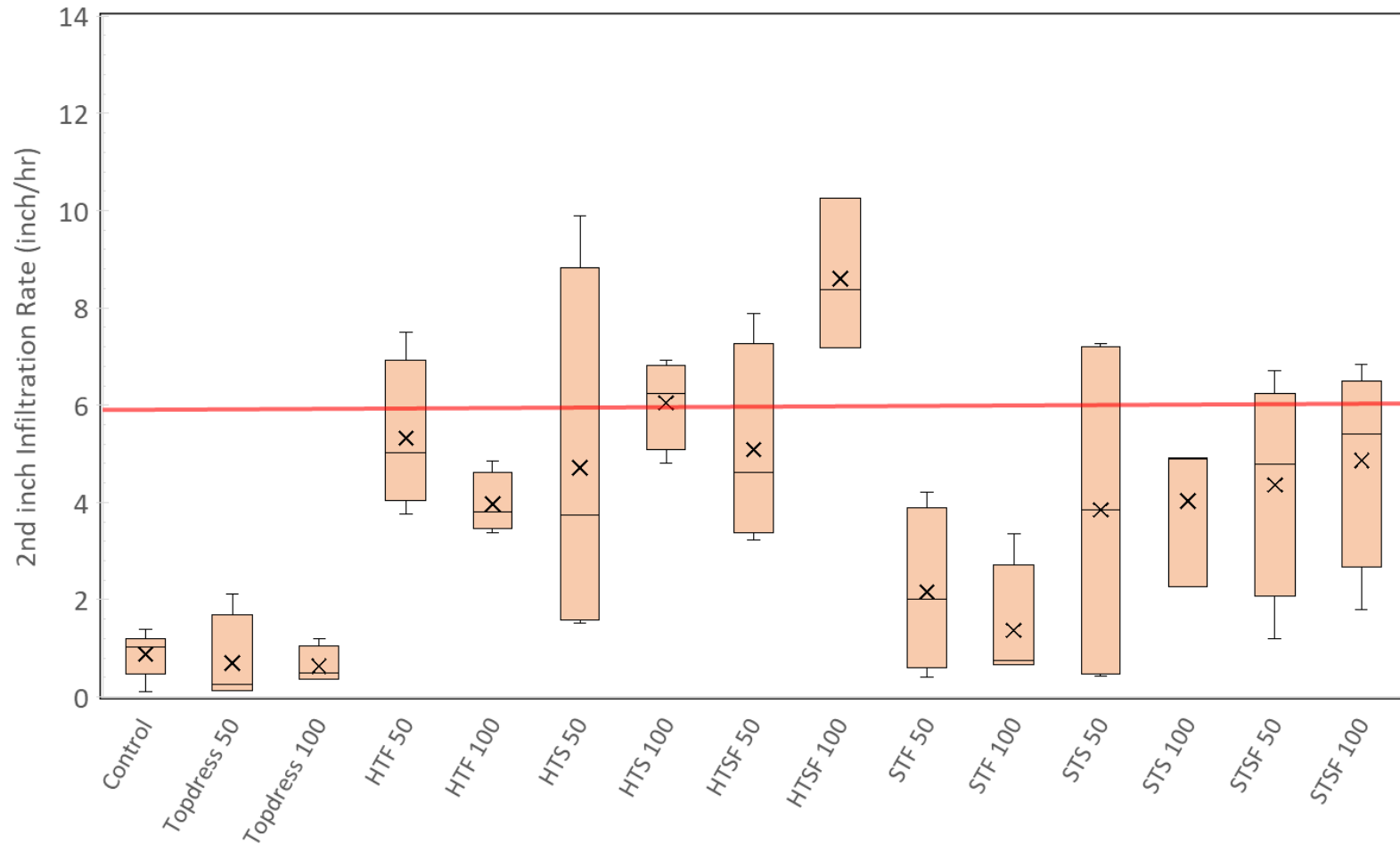


Figure 1. Box plot of cultivation and topdressing treatments effect on 2nd inch infiltration rate on an annual bluegrass putting green, collected 7 Oct 2025. HT= hollow tine, ST= solid tine; spring and/or fall refers to the timing of cultivation treatments; 50 or 100 at the end of treatment label refers to the summer topdressing rate in lbs /1,000 ft² applied every 14-d. Horizontal red line indicates the minimum infiltration rate (Ksat) for new putting green construction (6 in/hr; USGA staff 2018)

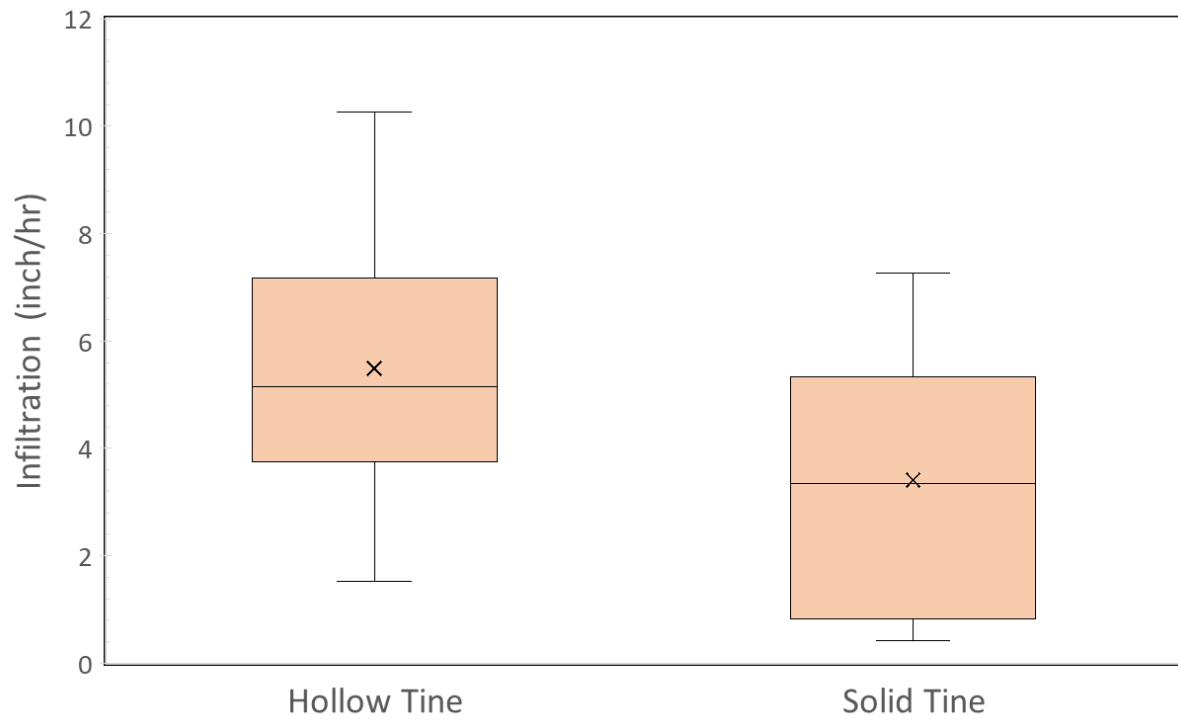


Figure 2. Box plot of cultivation tine type main effect influence on 2nd inch infiltration rate on an annual bluegrass putting green, collected 7 Oct 2025.

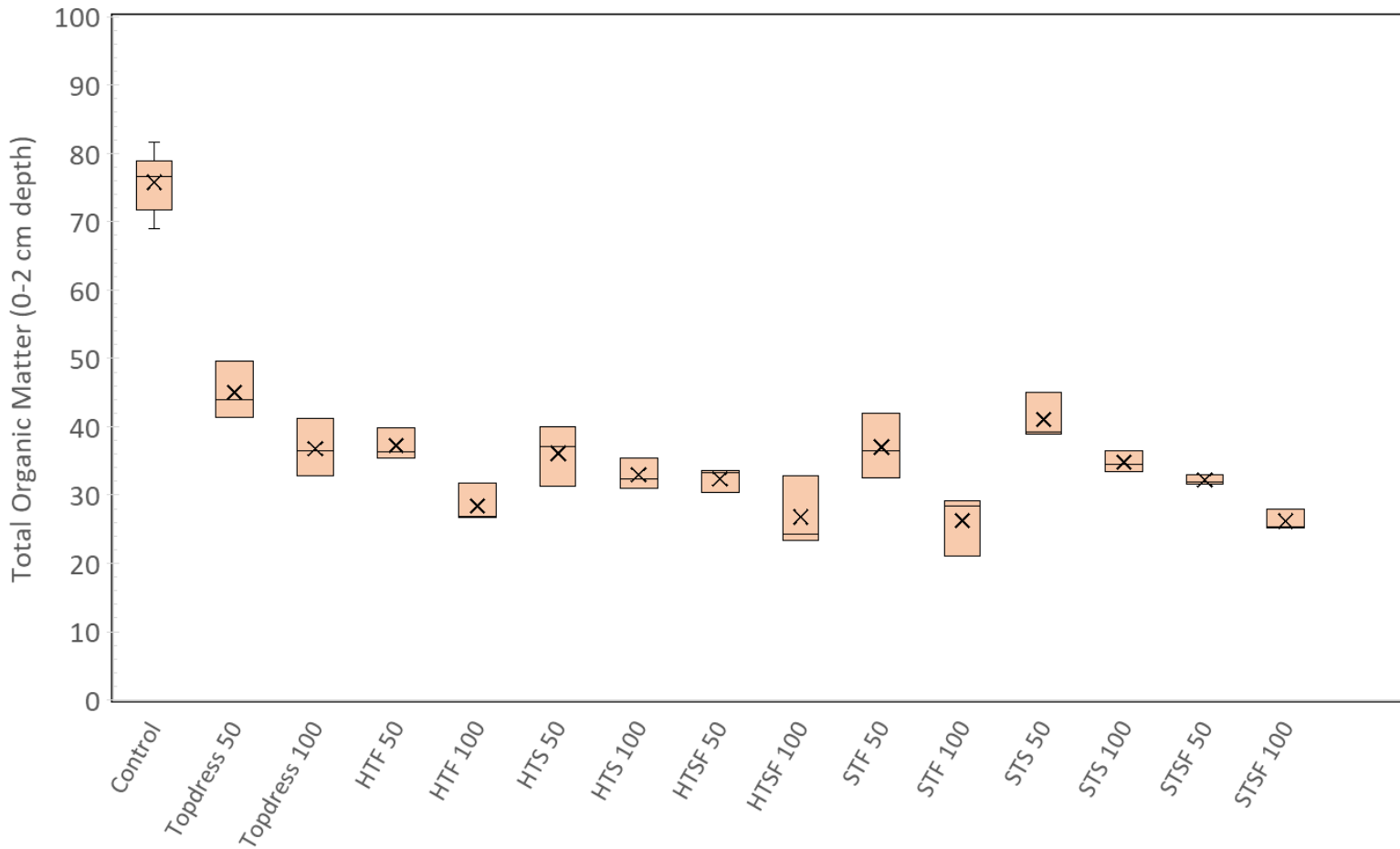


Figure 3. Box plot of cultivation and topdressing treatments effect on total organic matter content of an annual bluegrass putting green, collected 2 June 2025. HT= hollow tine, ST= solid tine; Spring and/or Fall refers to the timing of cultivation treatments; 50 or 100 at the end of treatment label refers to the summer topdressing rate in lbs /1,000 ft² applied every 14-d.



Image 1. Backfilling hollow and solid tine treatments with kiln dried sand using push brooms; Oct 30th 2025.



Image 2. Field measurement of infiltration rates on the cultivation and topdressing trial at Lewis-Brown Horticultural Farm in Corvallis, OR; Oct 7th 2025.

USGA ID#: 2025-03-834

Title: Evaluating cultivation timing effects on annual bluegrass recovery and playability

Project Leader: Chas Schmid

Collaborators: Robert Starchvick, Emily Braithwaite, Sadie Duffy, and Brian McDonald

Affiliation: Department of Horticulture, Oregon State University

Objectives:

- 1) Determine the effect of cultivation timing, both spring and fall, on annual bluegrass recovery time.
- 2) Evaluate the effect of cultivation timing on the playability (i.e ball roll distance and surface firmness) of annual bluegrass putting green turf during cultivation recovery.

Start Date:

March 2025

Project Duration:

2 years, March 2025 to Dec 2026 (year 1 report)

Total Funding:

\$20,000 (\$10,000 per year)

Summary Points:

- Cultivation tine type had the greatest influence on recovery times, with hollow tine treatments resulting in the longest recovery times
- Cultivation timing influenced recovery time, with March treatments recovering the slowest, followed by April treatments, and the May treatments recovering the quickest.
- Cultivation treatments had the greatest impact on putting green smoothness and trueness, with hollow tine treatments impacting these metrics much longer than solid tine treatments.
- Both tine types initially reduce green speed, but eventually resulted in greater ball roll distance
- Cultivation treatments had little effect on surface firmness after one cultivation event.

Introduction:

Mitigating organic matter (OM) accumulation is a critical component of golf course putting green management. Cultivation with solid or hollow tines has been used to manage OM accumulation, however it is one of the most disliked and misunderstood management practices performed to putting greens (Maloy, 2002). Traditionally, cultivation of putting greens is done in the spring and fall on actively growing cool-season turfgrasses to minimize recovery time (Beard, 1973); however, in the Pacific Northwest turfgrass managers have been pressured by owners and

general managers to cultivate putting greens earlier in the spring, and later in the fall to maximize golf revenue during peak season. These weather conditions are not conducive for recovery. Moreover, frequent rain during these periods can make it difficult to pull a core with hollow tines and can cause sand bridging in cultivation holes, reducing the effectiveness of the treatment and overall playability. It is possible that cultivation recovery time is prolonged and playing conditions are reduced for an extended period when cultivation is done either too early in the spring or too late in the fall.

Materials and Methods:

A field trial was initiated in March 2025 on a sand-based annual bluegrass research green constructed using the United States Golf Association rootzone specifications (USGA, 2018). Experimental design for this trial is a randomized complete block design with four replications. Treatments are arranged in a 2 x 3 factorial, with two tine types (hollow and solid tine), and three cultivation timings (Spring: March 15th, April 15th, and May 15th; Fall: Sept 1st, Oct 1st, and Nov 1st). A non-treated control (no cultivation) will be included as a comparison for playability measures (ball roll and surface firmness). Plot size for the trial is 4' x 15' (60 ft²), to accommodate for ball roll measurements. The cultivation treatments (hollow and solid tine) were applied with a Toro Procore 648, with an outside tine diameter of 0.6' set at a 2 x 2" tine spacing. A complete fertilizer (Anderson's 28-5-18) was applied 2-d prior to cultivation events at a rate of 0.25 lbs N/1000 ft².

The putting green was mowed Monday through Friday at 0.125 inches with a Toro 3150 greens mower. Irrigation was applied when needed to provide moderately moist soil to encourage recovery from cultivation treatments. 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 weather data (soil/air temperature, relative humidity, wind speed, etc.).

Digital photos were taken at the same location within each plot, three times per week during the recovery period, using a lightbox. Digital images were analyzed using ImageJ to determine percent recovery over time. The USGA GS3 was used twice per week during the recovery period to measure playability (surface firmness and ball roll distance) on treated. Data was compared to non-cultivated plots as an additional metric to determine when plots recovered completely.

Preliminary Findings:

The spring of 2025 had mild environmental conditions compared to historical norms, but differences in temperature and moisture were observed between cultivation timings (Figure 1). During the March cultivation timing, average temperatures were 52°F, which was lower than the average temperature observed in the April and May timings of 58 and 61°F, respectively. Additionally, much more rain was observed in March 2025 compared to April and May, with 2.85" of precipitation in the March treatments compared to 0.92 and 0.61" of precipitation in the April and May treatments, respectively.

During the spring of 2025, both cultivation tine type and cultivation timing influenced cultivation recovery time. Hollow tine cultivation had longer recovery times compared to solid tine cultivation, regardless of timing (Figure 2). Hollow tine treatments resulted in an 82% greater recovery time compared to the solid tine treatments. Cultivation timing also had an effect on recovery time during the spring, with March treatments resulting in the longest recovery time, followed by April treatments, and then May treatments with the fastest recovery time. May cultivation treatments recovered just over 9 days quicker than March treatments.

As of writing this report, the November cultivation treatments are still recovering and are not included in this analysis. Results from September and October cultivation treatments showed a similar trend with respect to the effect of tine type on cultivation recovery, with hollow tine treatments having a 65% longer recovery time compared to solid tine treatments (data not shown). No difference in recovery time was observed between September and October cultivation treatments.

In general, the playability data (green speed, smoothness, trueness, and firmness) varied by month in the spring, but the trends were consistent across months. For brevity, only the playability data from May cultivation timing is presented. Cultivation treatments appeared to have the greatest impact on putting green smoothness (Table 1). Solid tine treatments had limited impact on green smoothness, only reducing smoothness compared to the non-treated control on 3 and 6 days after treatments. Hollow tine treatments had a much greater impact on smoothness, reducing it for up to 31 days after treatments. Similarly, solid tine treatments had a minimal effect on green trueness, but hollow tine treatments appeared to have a large effect on trueness. Both hollow and solid tine treatments reduced ball speed initially compared to the control, but 20 days after cultivations ball speeds increased. Few differences in surface firmness were detected between the non-treated control and cultivation treatments. This result suggests that golfer's perception that cultivation treatments reduce surface firmness is likely due to increased soil moisture used to aid recovery, rather than cultivation treatments impacting firmness.

References:

Beard, J.B. 1973. Turfgrass science and culture. Prentice Hall, Englewood Cliffs, NJ.

Maloy, B. 2002. What are golfers thinking?: The top ten questions frequently asked of the USGA Green Section. USGA Green Sec. Rec. 40:13-16.

USGA. 2018. USGA recommendations for a method of putting green construction. US Golf Assoc., Far Hills, NJ.

Table 1. Putting green playability response to cultivation timing; treatments applied 16 May 2025

Response Variables	Days after cultivation						
	3	6	11	13	18	20	31
Speed							
Hollow tine	9.16	10.55	10.44	9.42	10.22	12.12	9.65
Solid tine	8.90	11.12	9.93	10.05	10.48	12.40	9.36
None	9.06	11.26	11.19	10.55	10.53	11.72	9.35
LSD _{0.05}	---	0.42	0.87	0.47	---	0.34	0.21
Smoothness							
Hollow tine	6.03	8.31	7.30	5.74	6.53	6.94	4.65
Solid tine	5.94	8.43	5.71	5.09	4.52	5.76	3.95
None	5.51	5.92	5.66	5.08	5.14	5.71	4.03
LSD _{0.05}	0.32	0.76	0.86	0.52	0.85	---	0.58
Trueness							
Hollow tine	1.02	1.29	1.09	1.00	0.93	1.05	0.87
Solid tine	0.99	1.19	0.78	0.86	0.83	1.00	0.72
None	0.94	1.04	0.85	0.83	0.79	0.90	0.70
LSD _{0.05}	0.05	---	0.18	0.10	---	---	0.12
Firmness							
Hollow tine	0.54	0.53	0.53	0.54	0.55	0.53	0.53
Solid tine	0.54	0.52	0.53	0.56	0.52	0.54	0.53
None	0.53	0.51	0.53	0.52	0.54	0.54	0.53
LSD _{0.05}	---	---	---	---	---	---	---

* No LSD value indicates that no statistical difference was observed on that rating date

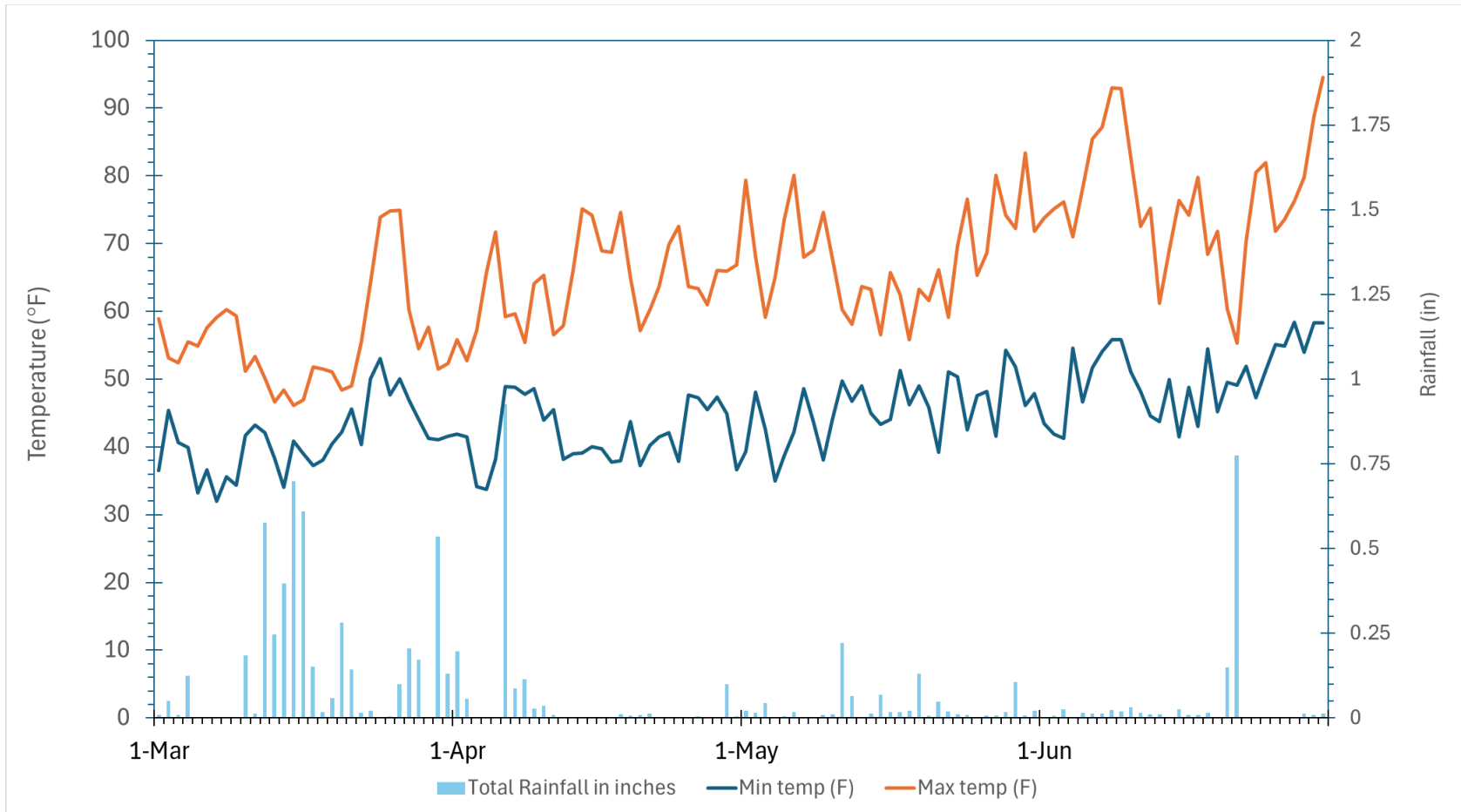


Figure 1. Weather data (daily min temperature, max temperature, and rainfall) for the spring cultivation timing treatment period during 2025.

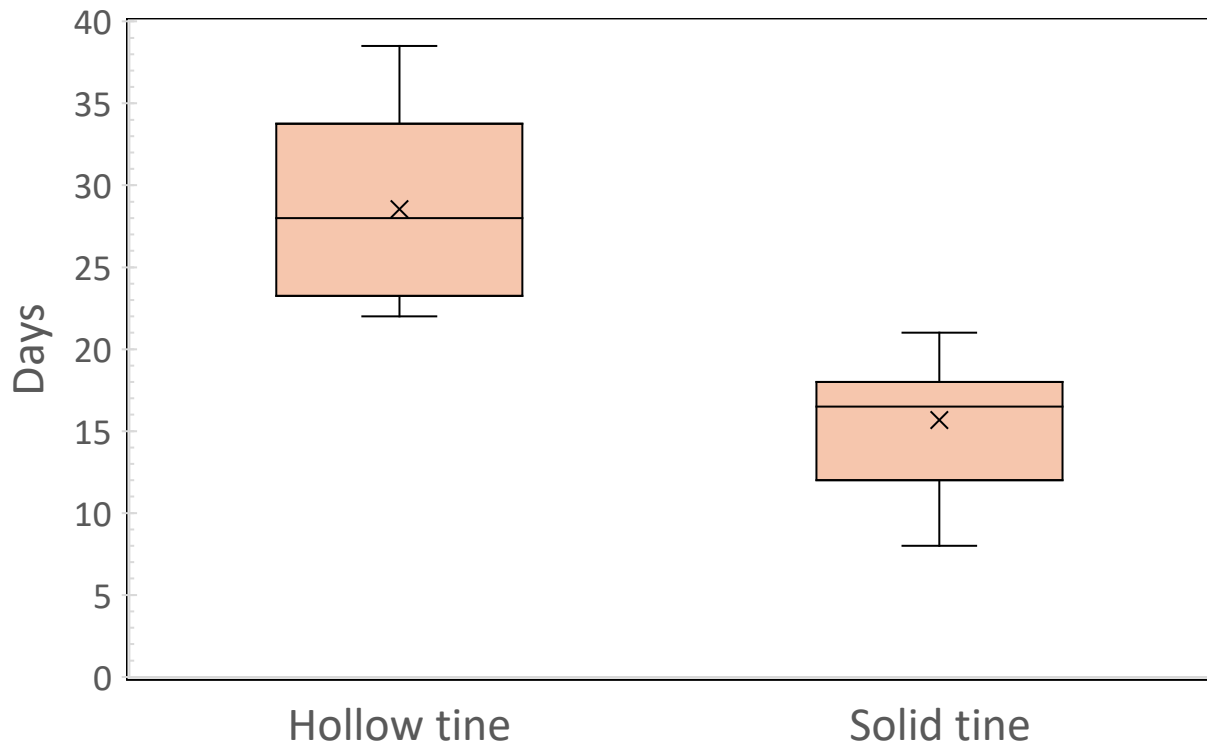


Figure 2. Box plot of cultivation tine type main effect influence on total days to recover from a cultivation event on an annual bluegrass putting green, during the spring of 2025.

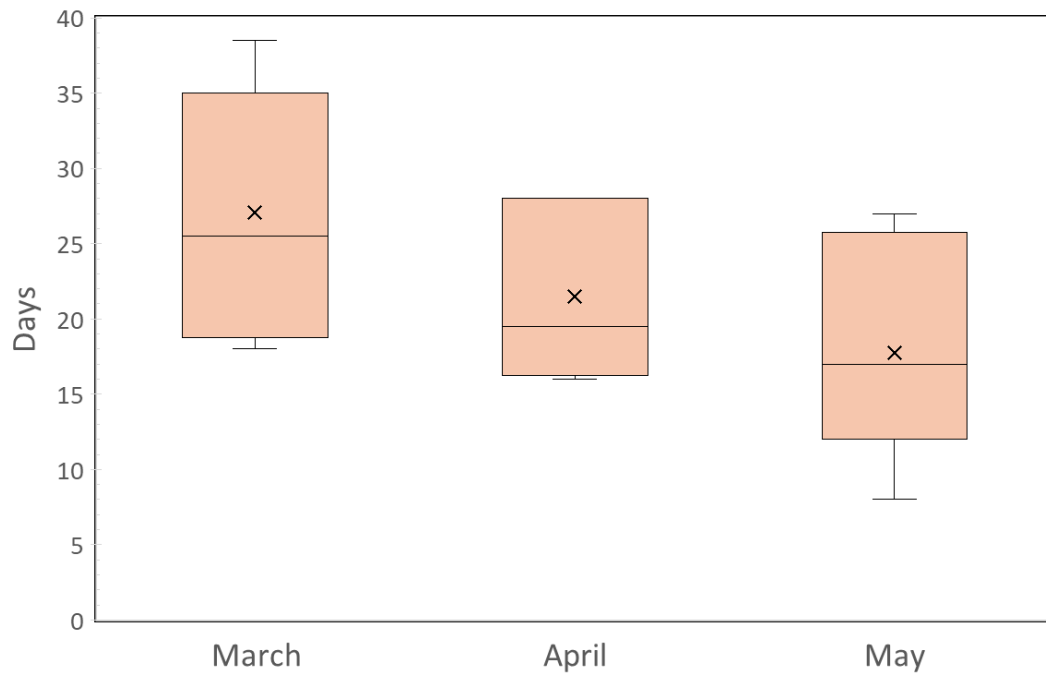


Figure 3. Box plot of the timing effect on total days to recover from a cultivation event (hollow and solid combined) of an annual bluegrass putting green during the spring of 2025.



Image 1. Hollow tine treatments being applied to an annual bluegrass putting green; March 25th 2025.



Image 2. Collecting ball roll distance (green speed), smoothness, and trueness with the USGA GS3 ball; Oct 2025.

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 (2022-13-756) and turfRad experiments

Project Leader: Ben Wherley, 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. Develop variable-rate prescription maps for precision N 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 economic efficiency.

Start Date: 2022

Project Duration: 4-years (2022-2025)

Total Funding: \$90,000 (2022-13-756) and \$20,000 (2024-18-828)

Summary Points:

- Spatial datasets from three golf courses were evaluated using the Precision Sense 6000 (PS6000), unmanned aerial vehicle (UAV) imagery, and soil electrical conductivity (EC_a) to characterize within-fairway variability and guide experimental site selection (Objectives 1–3).
- At Carlton Woods, EC_a showed strong relationships with volumetric water content and penetration resistance, whereas normalized difference vegetation index (NDVI) was a weak predictor of N status in sand-capped fairways (Objective 1).
- On Bearkat Course, UAV-based NDVI and PS6000 measurements supported variable-rate zone delineation, but zone classifications shifted over time, indicating that prescriptions cannot be static and require periodic re-evaluation (Objective 2).
- Spring and fall 2024 field trials showed that variable-rate N (VRN) applications maintained turfgrass performance comparable to uniform N treatments when assessed using visual turfgrass quality and clipping yield (Objective 3).
- NDVI-guided VRN treatments reduced total N inputs by up to 37 percent without negative effects on turfgrass quality, demonstrating improved nutrient efficiency under operational fairway conditions (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 targeted nutrient delivery, reducing over-application and minimizing environmental risks like nutrient runoff.

Despite the availability of these technologies, adoption in the golf course management industry has been limited due to unclear benefits and a lack of direct comparisons with conventional uniform application programs. This research aims to evaluate three fertilization treatments, conventional, NDVI-based, and model-based variable rate, across multiple seasons under operational fairway conditions. By developing prescription maps that integrate soil and turfgrass variables, the study seeks to improve fertilizer use efficiency, maintain or enhance turfgrass quality, and reduce environmental impacts, supporting sustainable turfgrass management practices on golf courses.

Methodology

Objective 1: Data were collected on April 12, 2021, at The Club at Carlton Woods in The Woodlands, TX, on two sand-capped hybrid bermudagrass and two sand-capped zoysiagrass fairways. This objective included two sub-objectives:

1. to compare the spatial relationship of EC_a to other turfgrass and soil characteristics, and
2. to compare the spatial relationship of turfgrass tissue N content to other turfgrass and soil characteristics.

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

A sampling grid of 62–137 points (depending on fairway size) was established and loaded into a handheld GNSS unit to guide further data collection. At each grid point, VWC and soil EC_a at a depth of 12.2 cm were measured using a FieldScout TDR 350 (Spectrum Technologies, Aurora, IL, USA). Additional measurements included elevation from the GNSS unit, a single soil core to determine organic layer depth, and three soil cores per location for clipping tissue N analysis. Soil samples were analyzed for particle size distribution, organic carbon, and root mass.

Aerial imagery was captured at 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). Images were processed in Pix4D to generate orthomosaics and raster maps for four VIs: NDVI, green NDVI (GNDVI), normalized difference red edge (NDRE), and enhanced vegetation index (EVI). Ground-based measurements for both sub-objectives were interpolated using ordinary kriging. The sampling grid coordinates were then used to extract raster pixel values from each map, and spatial correlations were assessed to evaluate relationships between variables ($\alpha=0.05$).

Objective 2: This phase was conducted at The Bearkat Course in Huntsville, TX, on ‘Tifway 419’ hybrid bermudagrass fairways with sandy loam soil. Four surveys were collected in May, July, September, and October 2022 using the PS6000 to measure VWC, PR, and NDVI across hundreds of georeferenced points per fairway. Data were interpolated using ordinary kriging to generate raster maps for each variable.

UAV multispectral imagery was collected during each survey period using a Dragonfly Commander 2 UAV with a MicaSense Altum-PT camera flown at 120 m. Pix4D processing produced NDVI orthomosaics and digital elevation models, which were used to derive slope. UAV-derived NDVI formed the foundation for zone classification.

Management zone delineation was implemented on Fairways 1 and 5 (F1 and F5). Each was subdivided into management polygons (91 and 65, respectively), sized to match the effective spreader width of the Texas A&M GNSS-equipped applicator (12.2 x 11.5 m)

- In the NDVI-based approach, management zones were defined using UAV NDVI values: low (0–0.38), medium (0.39–0.58), and high (0.59–1.00). Thresholds were derived from historical NDVI collected in October 2021.
- In the model-based approach, slope, VWC, and PR were integrated with NDVI using a K-means clustering approach. This approach incorporated site conditions beyond canopy vigor to generate zones reflecting environmental and soil variability. Historical October 2021 data were used to validate zone consistency.

Objective 3: This phase was conducted at The Bearkat Course in Huntsville, Texas, on ‘Tifway 419’ hybrid bermudagrass (*Cynodon dactylon* L. Pers. × *C. transvaalensis* Burt-Davy) grown on sandy clay loam soils. A randomized complete block design was used to compare three N management strategies:

1. conventional uniform fertilization (F7, F10, F13),
2. NDVI-based variable rate (NDVI-VR; F2, F5, F18), and
3. model-based variable rate (Model-VR; F1, F3, F12).

NDVI-VR prescriptions were derived from UAV NDVI maps, assigning N rates based on turfgrass vigor. Model-VR prescriptions incorporated NDVI along with VWC, PR and slope, and zones were generated using K-means clustering (Figure 4).

Prescription maps were loaded into a Ninja GPS guided spreader (Frost Inc., Saint Croix Falls, WI) mounted on a Toro Heavy Duty Workman (The Toro Company, Bloomington, MN) equipped with a Turfco 1550 topdresser (Turfco, Blaine, MN). Fertilization used Polyon Mini 30–0–0 (80:20 polymer-coated urea blend) applied in spring and fall 2024. Low, moderate, and high application rates were set at 24.4, 48.8, and 73.2 kg N ha⁻¹, respectively, with a standard uniform rate of 48.8 kg N ha⁻¹ for the conventional treatment. Spreader calibration was performed prior to each application using the catch-pan method.

Turfgrass response was monitored at 1, 2, 4, and 8 weeks after treatment using UAV-derived NDVI, visual quality ratings (1–9 scale), clipping yield (g m⁻²), tissue N concentration (%), soil N content, and standardized lightbox imaging to assess density, dark green color index, and percentage turfgrass cover. Measurements were collected from six georeferenced points per fairway. Economic analysis was based on an N price of \$8.82 per kg N (Harrell’s LLC, Lakeland, FL).

Statistical analysis was conducted in RStudio version 4.3.2 (Posit, Boston, MA) using a linear mixed-effects model. Treatment, season, and week were treated as fixed effects, replication as a random effect, and week as a repeated measure. Mean separation was performed

using least-squares means with 95% confidence intervals. Only clipping yield, visual turfgrass quality, N applied (kg N ha⁻¹), and cost savings are reported here.

Results to Date

Objective 1: The first sub-objective examined the spatial relationships between EC_a and other turfgrass and soil characteristics in sand-capped fairways at The Club at Carlton Woods. Across three of the four surveyed fairways, EM-38 EC_a showed positive and statistically significant correlations with VWC measured using both the PS6000 ($r = 0.13$ – 0.63) and the TDR 350 ($r = 0.20$ – 0.62). PR exhibited negative correlations with EM-38 EC_a, indicating that wetter areas tended to be less compact. Weak and non-significant positive correlations were observed between EM-38 EC_a and organic matter depth.

Relationships between VIs and soil EC_a were turfgrass-dependent. In zoysiagrass fairways, NDVI showed significant positive correlations with EM-38 soil EC_a, while bermudagrass fairways showed mixed responses. Elevation was negatively correlated with soil EC_a in three of the four fairways. Spatial raster maps showed that variability in soil EC_a aligned with turfgrass and soil properties across sand-capped fairways, although the strength and direction of these relationships differed both within and between courses (Figure 1). These results have been published in *Agrosystems, Geosciences & Environment* as “Using electromagnetic induction to inform precision turfgrass management strategies in sand-capped golf course fairways” (DOI: 10.1002/agg2.70020).

The second sub-objective evaluated the spatial relationship between turfgrass tissue nitrogen (N) and multiple VIs (NDVI, GNDVI, and NDRE). Nearly all VIs (NDVI_{UAV/Ground}, GNDVI_{UAV}, and NDRE_{UAV}) were significantly and positively correlated with one another, indicating strong internal agreement among spectral indices. In contrast, VIs showed consistently weak and non-significant correlations with tissue N across all fairways.

Tissue N content also did not correlate with VWC or PR at any site, suggesting that tissue N was not directly governed by underlying spatial gradients in soil physical status. By comparison, VIs showed significant positive relationships with VWC and generally negative (but mostly non-significant) relationships with PR, except for one zoysiagrass fairway. These findings indicate that VIs are highly interrelated and are more sensitive to moisture-driven canopy conditions than to tissue N status at the time of sampling (Figure 2). A standalone manuscript titled “Spatial relationship of turfgrass tissue nitrogen content and several vegetation indices on sand-capped golf course fairways” is currently under revision in *Agrosystems, Geosciences & Environment*.

Objective 2: Both the NDVI-based and model-based prescription maps showed clear seasonal changes across the management polygons on F1 and F5 (Figure 3). Early in the season (May–June), most zones were classified as green or yellow, indicating generally healthy turfgrass. By mid-summer, particularly in July and August, a noticeable increase in red-classified areas emerged, reflecting turfgrass stress. These shifts illustrated that variability was not constant through time and that zone designations responded to dynamic seasonal conditions.

The seasonal patterns underscored several stress drivers. Areas that transitioned from green or yellow into red tended to coincide with zones where moisture availability declined, penetration resistance increased, or local topography restricted water retention. These same areas

often returned to more favorable conditions by October, when NDVI values rebounded with cooler weather and reduced physiological stress.

Although both approaches reflected this temporal variability, the NDVI-based maps tended to track canopy status more directly, highlighting areas of visual decline during peak stress periods. In contrast, the model-based maps were more conservative, maintaining zone assignments based on underlying soil and environmental conditions. This reduced unnecessary expansion of “high input” areas and limited fertilizer delivery to locations where turfgrass stress was likely driven by subsurface constraints rather than temporary color changes.

Collectively, these findings demonstrate that variable-rate fertilizer prescriptions cannot be static. Management units must be updated with each fertilizer application, as seasonal shifts in turfgrass vigor, moisture dynamics, and compaction meaningfully altered where fertilizer was needed and where it was wasteful.

Objective 3: Across the spring and fall 2024 application cycles, clipping yield and visual turfgrass quality were statistically similar among the conventional, NDVI-VR, and Model-VR nitrogen treatments (Figure 5). Mean clipping yield ranged from approximately 2.4 to 2.7 g m⁻², and visual quality scores ranged from 5.6 to 8.0, indicating that both VR approaches sustained turfgrass performance comparable to the uniform treatment under operational fairway conditions.

Quality trends improved consistently over time following N applications. Ratings generally increased beginning 2–4 weeks after fertilization and continued through weeks 4–6, reflecting recovery and canopy response across all treatments. Neither VR strategy produced declines in turf appearance, density, or overall play readiness relative to the uniform rate.

N inputs differed substantially among treatments. The NDVI-VR approach reduced fertilizer input by approximately 12% in spring and 37% in fall relative to the uniform program (Figure 6). Reductions were most pronounced during the fall application period, when spatial differences in canopy vigor were more distinct. Model-VR generated smaller reductions, reflecting its more conservative zone design that incorporates VWC, PR, and slope.

Reduced N inputs translated directly into cost savings. Under the same N price assumption, NDVI-VR produced approximately \$51 ha⁻¹ in fertilizer savings during spring and \$181 ha⁻¹ in fall (Figure 6). These savings occurred without compromising turfgrass quality or surface performance indicators.

Taken together, the results demonstrate that both VR strategies improved N use efficiency while maintaining acceptable turfgrass performance. NDVI-VR provided the strongest reduction in fertilizer use and the most responsive targeting of canopy vigor, while Model-VR offered a more stable, soil-aware application approach. Both represent viable operational options, but NDVI-VR delivered the greatest return on N savings.

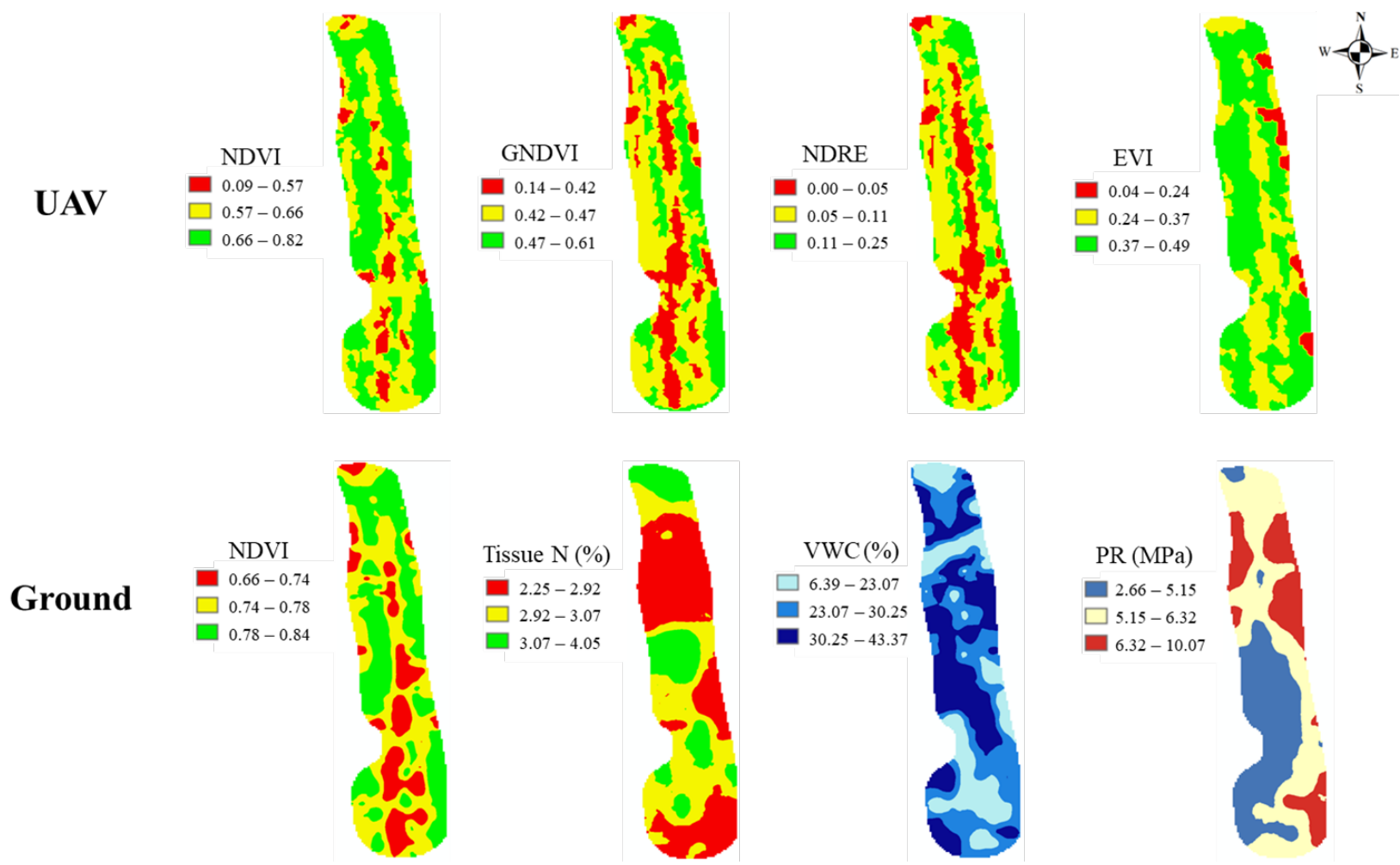


Figure 1. Spatial maps of variables collected from bermudagrass fairway 2 at The Club at Carlton Woods, The Woodland, TX.

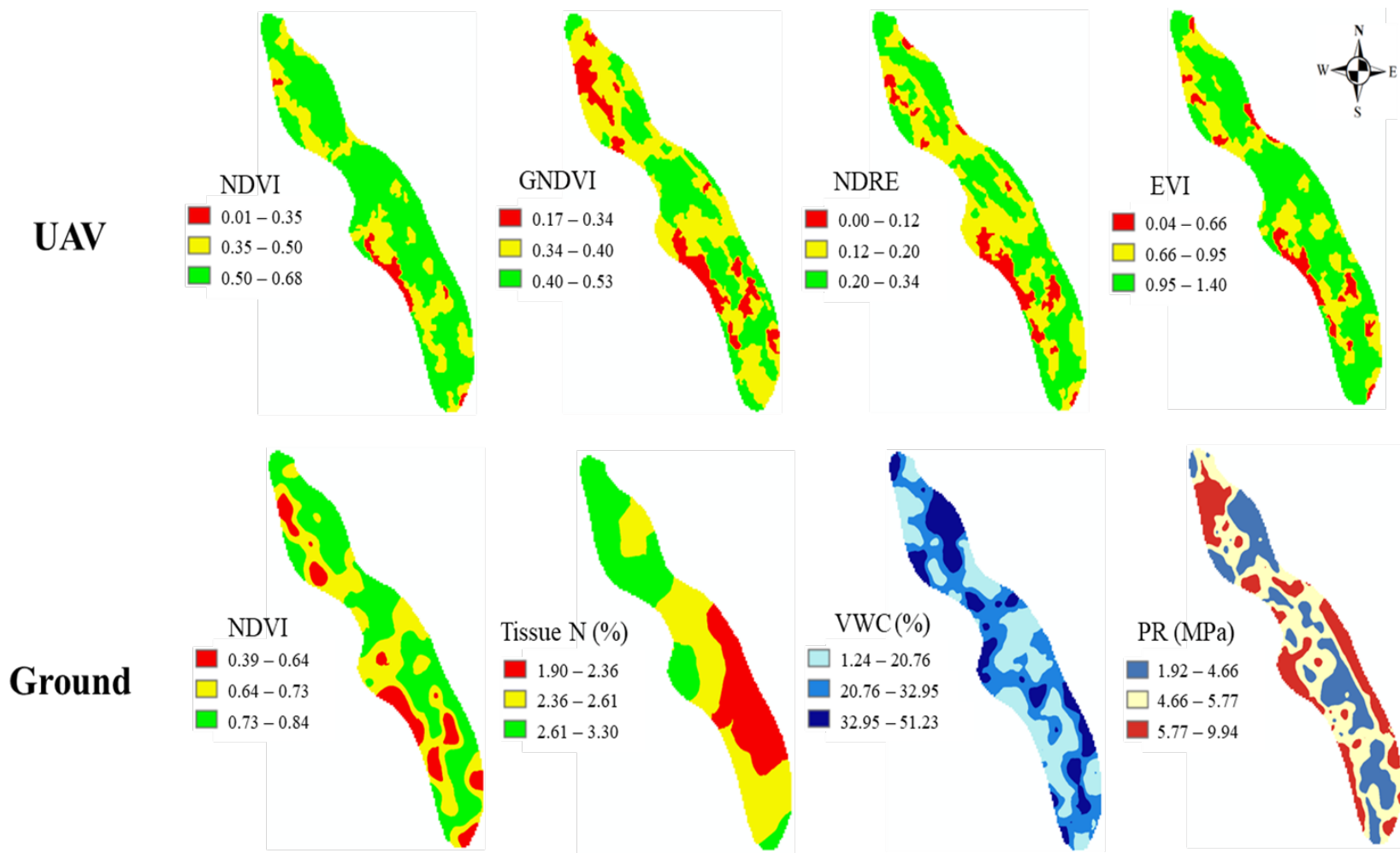


Figure 2. Spatial maps of variables collected from zoysiagrass fairway 8 at The Club at Carlton Woods, The Woodlands, TX.

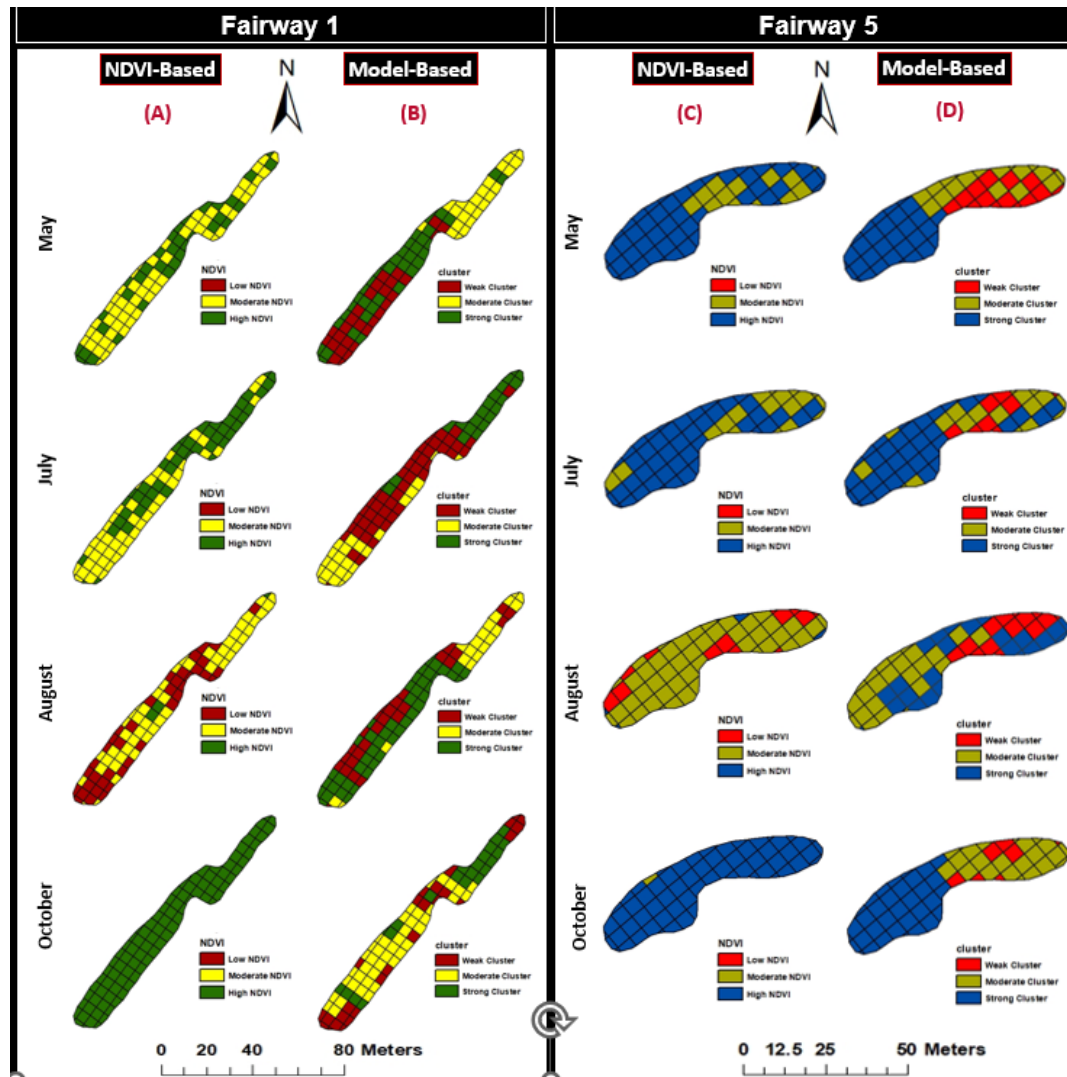


Figure 3. Spatiotemporal variation of SSMUs on golf course fairways (May–October 2022). (A, C) NDVI-based seasonal variation in fairways 1 and 5, categorized as low, medium, and high NDVI. (B, D) Cluster-based variation categorized as weak, medium, and strong.

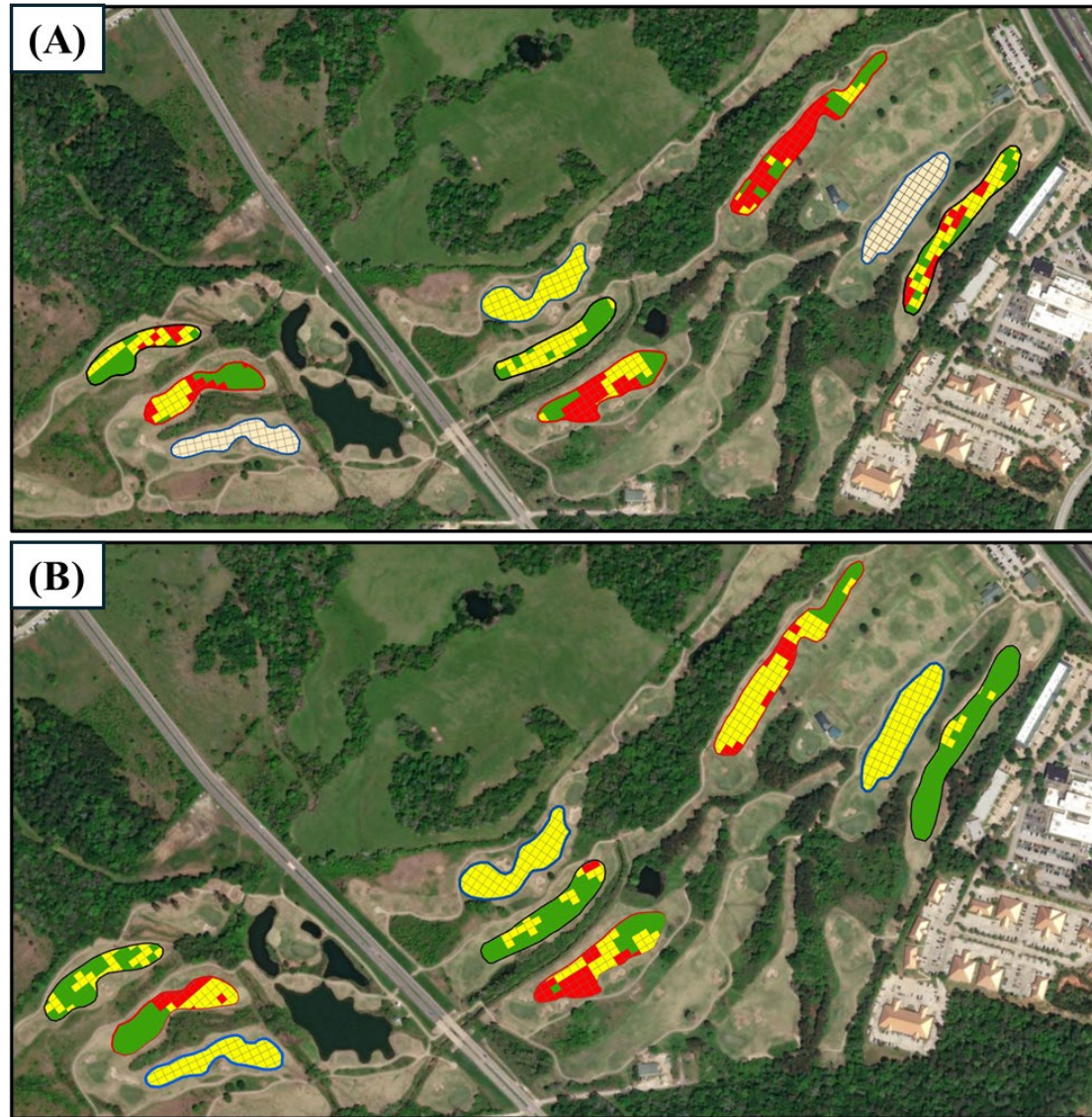


Figure 4. Nine fairways selected for fertilizer application: three each for conventional (blue outline), NDVI-based (blue outline), and model-based (red outline) approaches. (A) Spring variable-rate prescription maps; (B) Fall application maps.

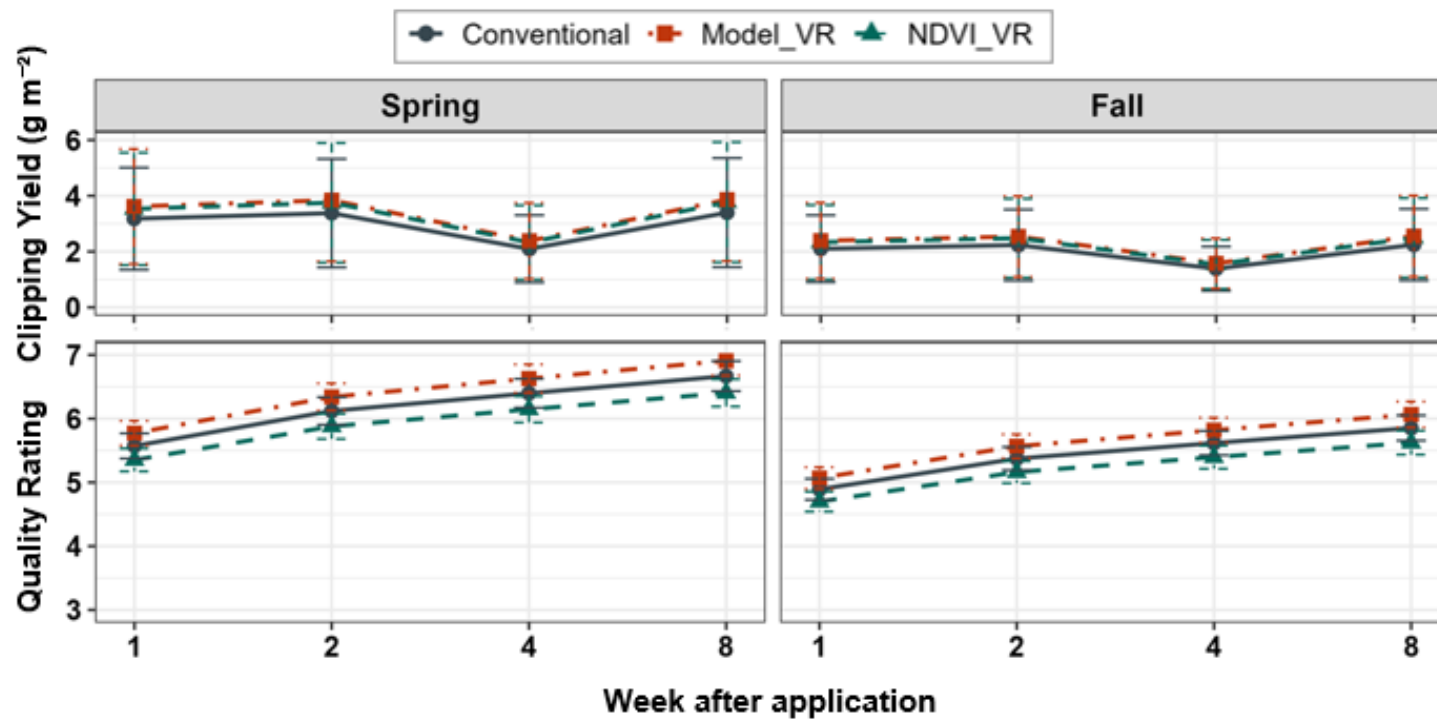


Figure 5. Time-series of clipping yield and visual quality rating (LS-means \pm 95% CI) under three nitrogen management approaches across spring and fall 2024.

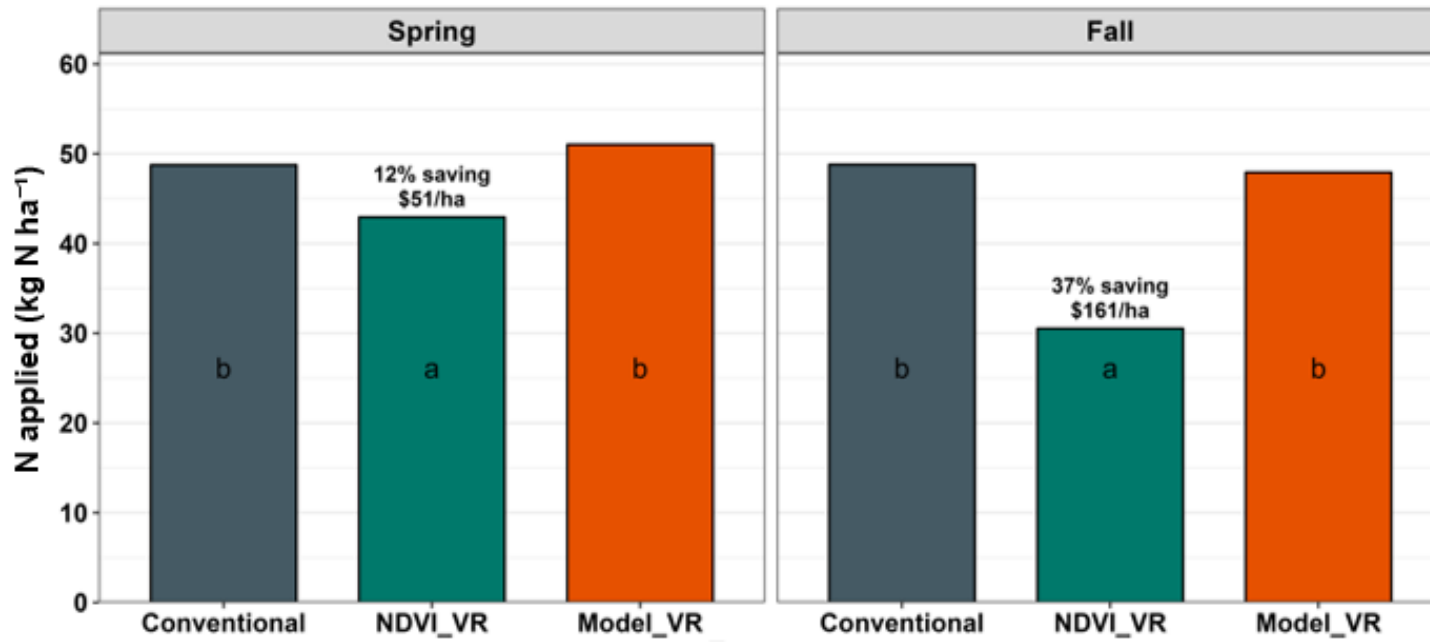


Figure 6. Mean nitrogen (N) applied (kg N ha⁻¹) under different fertilization approaches across spring and fall 2024

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: Will Green, Sam Kreinberg (currently at VaTech), and John McCalla, Univ. of Arkansas

Project Report Date: Dec. 5, 2025

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 aeration 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 and smoothness measurements were highly correlated to each other across a range of putting green surface 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. While providing some value, it is difficult to reproduce reliable data on a regular basis.

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.

Within the present project, we have collected a wide range of data over a range of turfgrass species and experimental treatments. Some of the data we have collected includes ball roll distance with the Stimpmeter and GS3, trueness and smoothness using the GS3, visual bobble tests, dispersion tests, surface firmness with the GS3 and Clegg impact tester, shear strength, and soil volumetric water content. Only a small subset of that data will be discussed in the present report.

Study 1 – Comparison of GS3 to other performance metrics

Materials & Methods: Data were collected every other week over a three-month period (June-August) on Pure Eclipse creeping bentgrass, TifEagle ultradwarf bermudagrass, and Lazer zoysiagrass. Each species was mown at either 0.125 or 0.100 inches and individual mowing plots measured 3 x 15 feet. Data collected included: Stimpmeter ball roll distance, GS3 roll test (ball roll distance, trueness and smoothness), visual bobble test, dispersion length width and area, 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. For this report, only ball roll metrics are discussed.

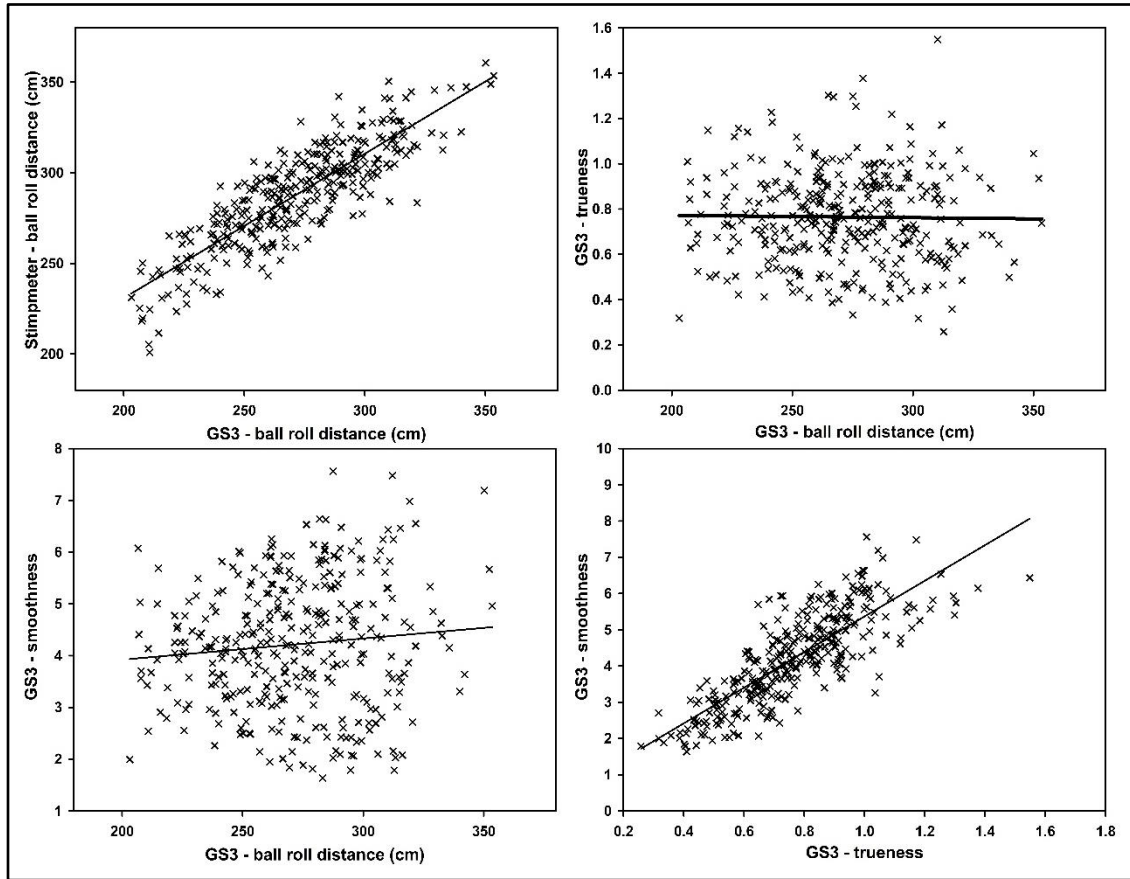


Figure 1. Comparison of various performance metrics used to assess putting green quality across 3 putting green species (bermudagrass, bentgrass, and zoysiagrass). For each graph, linear regression was used to determine the significance of the relationship ($P > F$), the intercept (Y_0) and slope of the line, and the coefficient of determination of the model (r^2). Model parameters are as follows:

Figure	$P > F$	Y_0	Slope	r^2
GS3_BRD vs Stimpmeter_BRD (upper left)	<0.0001	71.450	0.970	0.730
GS3_BRD vs GS3_TRUENESS (upper right)	0.762	0.790	0.001	0.0002
GS3_BRD vs GS3_SMOOTHNESS (lower left)	0.069	3.090	4.100	0.0099
GS3_TRUENESS vs GS3_SMOOTHNESS (lower right)	<0.0001	0.440	4.910	0.650

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 distance (BRD) test was well-correlated with the BRD produced by the Stimpmeter, with a P-value of <0.0001 and a coefficient of determination (r^2) of 0.73. The GS3 BRD was not well-correlated with either the GS3_Trueeness ($P=0.762$) or GS3_Smoothness ($P=0.069$) measurements (Fig. 1). One interesting comparison in this dataset that continued to be evident into the second season was the highly significant relationship ($P<0.0001$) between the GS3_Trueeness and GS3_smoothness variables (Fig. 1). These metrics were well-correlated ($r^2=0.65$), which suggests that a single “deviation” measurement might be more appropriate to simplify the results to the end-user.

Study 2 – GS3 metrics in response to foot traffic

Materials and 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 and repeated on both species in the 2024 and 2025 seasons. For the duration of the study, irrigation was not applied unless wilting was observed. The putting green height of cut was 0.125 inches and treatments included foot trafficked and non-foot trafficked plots (plot size = 4 x 15 feet). To simulate foot traffic, plastic spike golf shoes (Footjoy Superlites and Footjoy Freestyle) 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 BRD, GS3 ball roll test, dispersion test, GS3 drop test, and volumetric water content at 0.5, 1.5, and 3.0 inches. 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). For brevity, only data on smoothness and trueeness are reported.

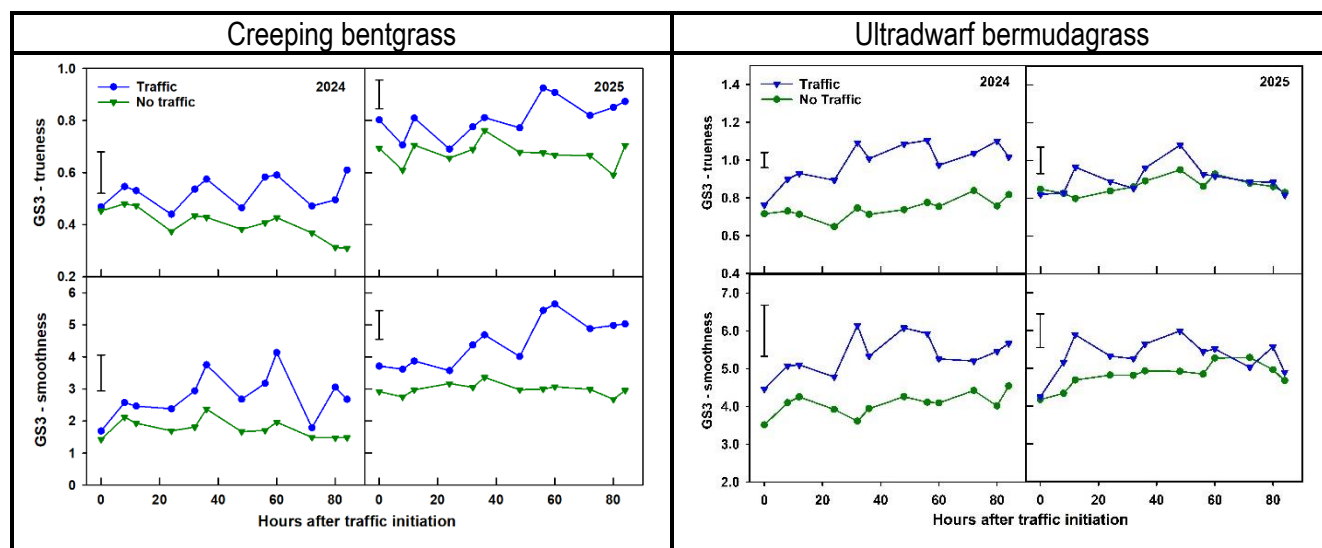


Figure 2. Response of GS3 Trueness and smoothness metrics to foot traffic over a 4-day period. For each graph, error bars (LSD, $P<0.05$) can be used to compare traffic effects or the effects of increased rounds of traffic (hours after traffic initiation).

Results: The GS3 was able to pick up subtle changes in surface characteristics over the course of a 4-day traffic period on both creeping bentgrass and bermudagrass putting greens (Fig. 2). With both smoothness and trueness, values increased following the initiation of traffic and continued to increase slightly as more rounds of traffic were applied to the plots. There were also significant differences in smoothness and trueness measurements between trafficked and non-trafficked plots in both species. One interesting observation in this experiment was that daily maintenance practices (mowing only in this study) tended to improve smoothness and trueness values, and in some cases, returned those values to pre-trafficked levels (Fig. 2). This suggests that more aggressive management practices, such as daily double-cutting or rolling, might affect changes in

smoothness and trueness that are occurring over a multi-day event. Overall, it was apparent from these studies that the GS3 has the ability to more closely monitor subtle changes in surface characteristics during a multi-day tournament compared to other metrics such as ball roll distance.

Study 3 – GS3 metrics in response to hollow-tine cultivation

Materials and Methods: This study was performed on both a ‘Pure Eclipse’ creeping bentgrass and ‘TifEagle’ bermudagrass putting green managed at a 0.125 inch height of cut. The study was repeated in both the 2024 and 2025 seasons. Hollow-tine aeration was conducted using a Toro 648 equipped with 3-inch deep, 5/8-inch diameter hollow tines on a 2.0 x 2.0 inch spacing. Topdressing sand was applied immediately after cultivation to fill holes and topdress the surface to ~0.125 inches, which equated to ~2.0 lb sand / ft². Individual aeration plots were 3 x 15 feet and data were collected before aeration (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. For brevity, only data on ball roll distance, smoothness and trueness are reported.

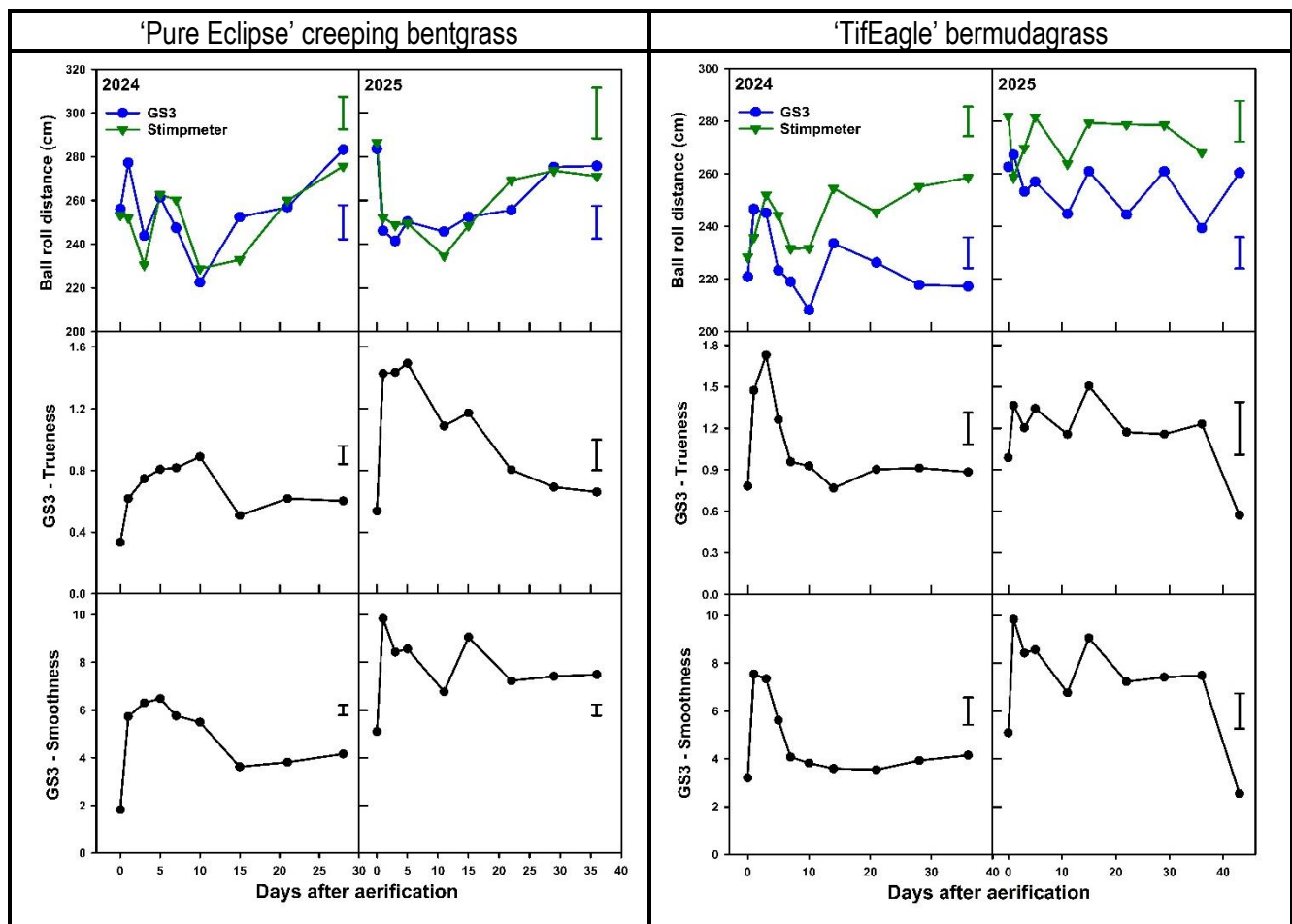


Figure 3. Response of surface metrics during recovery from core-aerification over a 40-day period on creeping bentgrass (left) and ultradwarf bermudagrass (right). Within each graph, error bars (LSD, P<0.05) can be used to compare days after aerification.

Results: Ball roll distance in response to core aeration was inconsistent on a day to day basis, but the overall trend was for BRD to decrease slightly after aeration and then trend upward once recovery began (Fig. 3). In the most striking results, BRD decreased by as much as 40 cm (~16 inches) post-aeration. GS3 trueness

and smoothness values both increased significantly immediately following core aerification and peaked at day 3-5 after core aerification (Fig. 3). Trueness and smoothness values began to decline at 5-7 days following aerification, indicating recovery of the surface and values returned to levels that were observed before aerification at 7-10 days after cultivation (Fig. 3). This was especially true on the bermudagrass putting green, while values on the creeping bentgrass surface rarely returned to pre-aerification levels, even after 30+ days. While the overall trends in these metrics were not surprising, it is noteworthy that a golf course superintendent could use these metrics to better monitor recovery and possibly use other practices to return surfaces to pre-cultivation levels. It should also be noted that recovery appeared to be complete (based on visual observations) while trueness and smoothness measurements indicated that they were not completely healed even after 30 days.

Overall conclusions:

After two seasons of data collection, we have made some initial observations that are noteworthy, but more data analysis needs to be conducted to more fully 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 known 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 findings confirm that the GS3 is able to monitor changes in surface characteristics that effect vertical or horizontal movement of the golf ball, even when those changes are not apparent to an observer.

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 (data not shown). When looking at the 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 also suggests 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#: 2023-03-770

Title: Remote Soil Sensing of Fairways for Irrigation Water Conservation

Project Leader: Bernd Leinauer^{1,3}, Tatiana Kardashina⁴, Tom Egelhoff⁵, and Ciro Velasco-Cruz^{2,3}

Affiliation: ¹Department of Extension Plant Sciences, ²Department of Agricultural Economics and Agricultural Business, ³New Mexico State University, Las Cruces, NM ⁴Mechanical Engineering and Materials Science, Washington University, St. Louis, MO, and ⁵The 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
3) Compare irrigation water use between standard ET-based scheduling and ET-based scheduling adjusted using soil moisture measurements

Start Date: 2023

Project Duration: The project is expected to run until end of 2026

Total Funding: \$208,102

Summary Points:

- 1) Measurements taken with the USGA CDX show a significant and strong correlation with volumetric soil moisture (θ_v) determined either with a TDR 350 or by loss of weight.
- 2) Similar to 2023 and 2024, the relationship between turfRad and TDR 350 is weak, although it improves if a deep learning model is applied to estimate soil moisture.
- 3) Although turfRad measurements showed inconsistent and weak agreement with TDR, the use of turfRad-based adjustments resulted in lower water use, suggesting that even imperfect soil moisture feedback can contribute to meaningful water savings.

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 four-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

One fairway, #16 (76,829 ft²) (Figure 1), was selected from the Sunset golf course at The Club at Las Campanas in Santa Fe, NM. The fairway is divided by an arroyo, effectively separating the fairway into two distinct playing areas. The left portion (looking at it from the tee box) of the fairway measures approximately 30,200 ft², while the right portion covers approximately 46,700 ft². From a playability perspective, the left fairway presents a greater challenge to golfers, requiring longer and more accurate tee shots to successfully reach the landing area. In contrast, the right fairway is more easily accessible due to shorter required carry distances. The fairway is par 4 and was established in 1999 with ‘Penn Trio’ creeping bentgrass. The fairway is mowed at 0.4” (10 mm) between twice and three times per week with clippings returned. It is aerated once per year in April and de-thatched with a verti-cutter Model VC60 (First Products Inc., Tifton, GA) in September. The fairway received approximately 10 g N/m² (2 lbs N/1000 ft²) annually. The surfactant ‘Revolution’ and plant growth regulators ‘Primo’ (ai Trinexapac-ethyl) and ‘Legacy’ (ai 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). The fairway is irrigated predominately from Toro DT34 and DT35 heads installed within the center and from RainBird 750 heads around the perimeter.



Figure 1: Fairway #16 from championship tee box (left) and from green (right) (courtesy of Tom Egelhoff).




Irrigation was scheduled by a Rainbird central controller CirrusPRO™. Sprinkler run times are generally based on evapotranspiration rates for the area adjusted for the different micro-climates on the course. During July, irrigation management on #16 differed between the two sections. The right portion of the fairway received three to four turfRad passes per week, with irrigation run times adjusted after each pass based on the soil moisture measurements. The left portion was managed using standard controller settings with no soil moisture–based adjustments, thereby providing a conventional irrigation management reference.

Soil Moisture Equipment

Data collection started on 7 April 2025 and ended on 28 October 2025. Soil moisture sensing equipment during the 2025 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). On April 7, the turfRad sensor was calibrated according to the manufacturer's recommendations using ten TDR measurements near ten randomly selected sprinkler heads on the fairway. In addition, soil cores were collected to determine volumetric soil moisture θ_v (kg kg^{-1}) by loss of weight. Starting on September 1, the handheld USGA soil moisture meter (CDX) was used as well. A GEODE™ GNS3S (Juniper Systems, Logan, UT) was used to determine exact GPS coordinates of the location of each TDR measurement. 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	turfRad	TDR 350 / GEODE™ GNS3S	USGA moisture meter (CDX)
Sensor Type	Capacitance	Passive reflectance	Frequency Domain Reflectometer with GNS3S receiver	Modified Frequency Domain Reflectometer
Wave-length		L-Band (21 cm)		
Soil depth	10 cm	Approx. 5 cm [†]	7.5 cm	7.5 cm

[†]Information provided by manufacturer

Data Collection and Analysis

Twenty soil samples were collected on September 1. Cores were taken randomly and measured 5 cm in diameter and 7.5 cm in depth. They were weighed, dried for 24 hours at 105 °C, weighed again and volumetric soil moisture was calculated. TDR 350 and CDX readings were taken at the same locations. Subsequently, θ_v (kg kg^{-1}), TDR 350 and CDX values were compared to one another. A GEODE™ GNS3S (Juniper Systems, Logan, UT) (Table 1) was used to determine exact Global Positioning System (GPS) coordinates of all measurement locations, a needed procedure to make fair comparisons of the soil moisture readings of the different methods. According to the unit's manual, the GNS3S determines locations with an accuracy of 10 cm or less.

Soil volumetric water content was measured on Fairway #16 using multiple sensing technologies. Measurements were collected with a turfRad sensor mounted either on a Utility Vehicle or on a fairway mower (Figures 2 and 3) on 7 April, 8 April, 12 May, 16 June, 11 August, 1 September, and 27 October. Concurrent soil moisture measurements were also taken using a handheld TDR 350 sensor. Beginning on 1 September, additional soil moisture data were collected using a CDX sensor. Measurements with the handheld units were taken on a grid of approximately 5m by 5m. Locations of turfRad readings did not align with measurements taken by the TDR 350. Consequently, we implemented the Nearest Neighbor Gaussian Process with an isotropic spatial correlation with exponential covariogram model (Datta et al, 2016) to predict turfRad values at the TDR 350 locations. The number of nearest neighbors is 10. The statistical analysis was performed using the R software (version 4.3.0) with a user defined function coded in C++ 17. As an assessment of simple association, the corresponding coefficient of

determination values (R^2), 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 sensor mounted on a Utility Vehicle



Figure 3. turfRad sensor scanning #16 with a Utility Vehicle (left) and with a fairway mower (right).

To evaluate whether alternative modeling approaches could improve turfRad-based soil moisture estimation, Random Forest and Deep Learning models were implemented. Both models were trained to estimate soil volumetric water content by learning the statistical relationship between measured soil moisture and corresponding turfRad-derived inputs, including soil temperature (K) and vertically and horizontally polarized microwave emission signals.

The Deep Learning model consisted of four hidden layers with 100 neurons per layer and employed linear activation functions. Model training minimized prediction error using Mean Absolute Error as the loss function, while model performance was evaluated using Mean Squared Error. In parallel, a Random Forest model was developed using an ensemble of 100 decision trees to capture nonlinear relationships between the input variables and measured soil moisture. These modeling approaches were used to compare predicted soil moisture values against observed measurements and assess potential improvements in estimation accuracy relative to existing methods.

Results

1. Comparing TDR 350 and USGA's CDX

Soil moisture measurements taken with TDR 350 and with USGA's CDX show a significant and strong correlation with θ_v (kg kg^{-1}) determined by loss of weight (Figure 4). A similar very good relationship was shown between the TDR 350 and the CDX. Data were collected on three sampling days (Figure 5). Unfortunately, saving and downloading values from the CDX for further analysis and processing turned out to be cumbersome and impractical in field use. We decided to keep using the TDR 350 as a reference or the standard against which turfRad is compared.

2. Accuracy of turfRad Soil Moisture Values

Prior to initiating the study, the turfRad sensor was calibrated according to the manufacturer's recommendations using field measurements collected on the fairway. Soil moisture values calculated before and after calibration showed no noticeable differences. Regression analysis indicated similar coefficients of determination (R^2) and root mean square error (RMSE) for both calibrated and uncalibrated data (Figure 6). These results suggest that the manufacturer-recommended calibration did not substantially improve turfRad moisture estimates under the conditions evaluated in this study.

Left column of figures 7, 8, and 9 shows boxplots of soil moisture values recorded on 7 sampling dates during 2025. Across these sampling dates, moisture values measured by turfRad showed different agreements with the TDR 350. Generally, box plot comparisons indicated similar moisture estimates on three dates (April 7, June 16, October 27), while turfRad values were lower than TDR on two dates (April 8, and September 1) and higher on two other dates (May 12 and August 11). This inconsistent pattern suggests no systematic bias in turfRad measurements relative to TDR 350. Instead, deviations between the two technologies appeared to be date-specific, with no clear or consistent direction of error across the study period.

Three modeling approaches were evaluated to estimate soil moisture of the turfRad: the manufacturer's proprietary model, a random forest model, and a deep learning model. Sampling date affected relationship between TDR 350 and TurfRad estimations in 2025 for all three models. Observed (TDR 350) versus predicted (turfRad) soil moisture values show that turfRad estimates are significantly correlated with ground-truth measurements, although the relationship remains generally weak. Coefficients of determination range from 0.108 (September 1) to 0.379 (June 16) using the manufacturer's model to determine soil moisture. The accuracy of the turfRad improves somewhat if the deep learning model is applied with regression coefficients ranging from 0.256 (September 1) to 0.416 (June 16).

Regression analysis using coefficients of determination (R^2) and root mean square error (RMSE) indicated the weakest agreement between TDR measurements and the manufacturer's model, and the strongest agreement between TDR and the deep learning model, with the random forest model showing intermediate performance. Despite these relative differences, none of the modeling approaches demonstrated a strong relationship with TDR measurements, as all R^2 values were below 0.5. These results indicate limited predictive accuracy across all models under the conditions of this study.

3. Irrigation Water Use

Irrigation water use differed between the two fairway areas. Reference evapotranspiration during the study period reached 7.6 inches. The conventionally managed fairway section (ET-based control) applied 5.86 inches of irrigation or 77% of ET), whereas the soil moisture–based turfRad-managed section applied only 3.92 inches or 52% of ET). This corresponded to average daily irrigation of 0.19 inches day⁻¹ for the ET-based approach compared with 0.13 inches day⁻¹ when soil moisture was used to adjust run times. Although turfRad measurements showed inconsistent and weak agreement with TDR in this study, the use of turfRad-guided adjustments nevertheless resulted in lower irrigation inputs, suggesting that even imperfect soil moisture feedback can contribute to meaningful water savings.

Table 2. Irrigation amounts during July 2025 on different parts of fairway #16 irrigated based on ET only (standard) or based on ET but adjusted for soil moisture.

	ET-based (standard)	turfRad adjusted
ET (inches)	7.6	7.6
Rainfall (inches)		
Area (ft ²)	30175	46654
Irrigation (gal)	110255	114013
Irrigation		
inches	5.86	3.92
inches/day	0.19	0.13
%ET	77%	52%

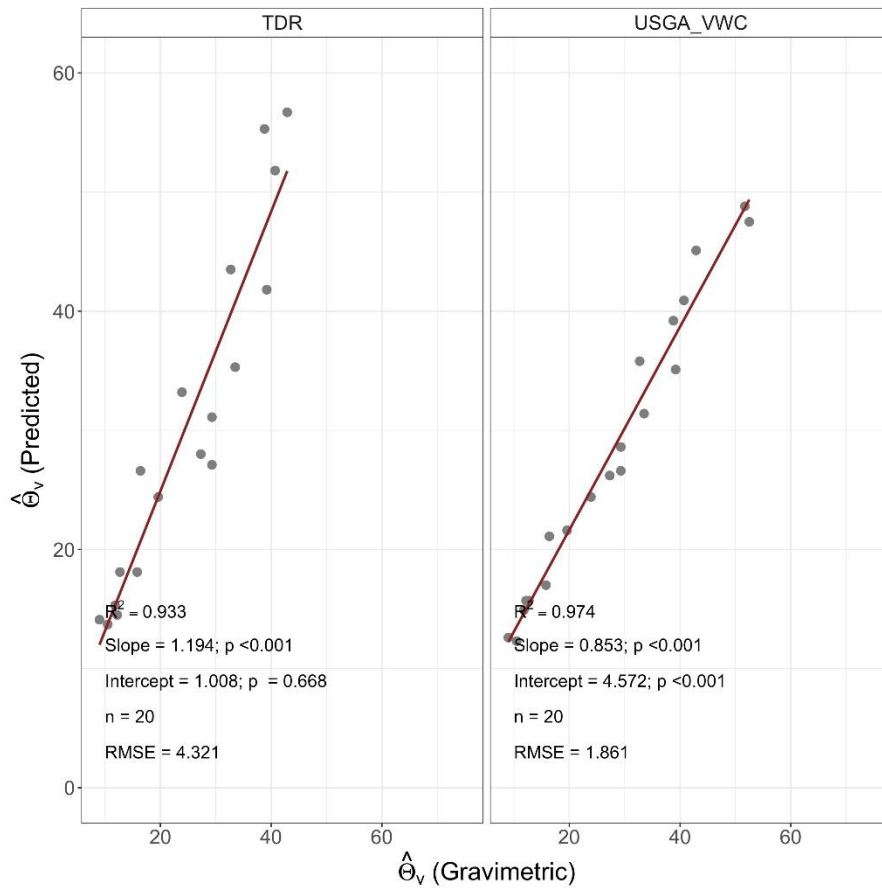


Figure 4. Relationship between volumetric soil moisture determined gravimetrically (θ_v , kg kg^{-1}) and TDR 350 values (left) and the USGA moisture meter (right).

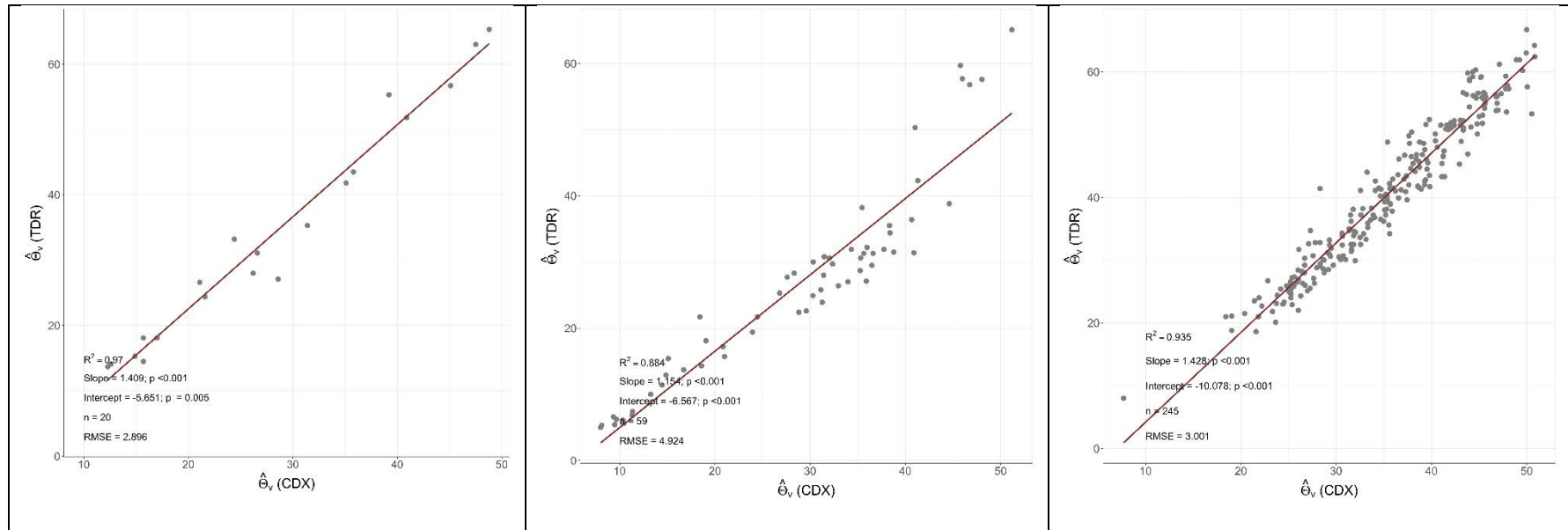


Figure 5. Relationship between volumetric soil moisture determined with a TDR 350 and the USGA moisture meter (CDX). Data were collected on September 1 (left), September 3 (center) and on October 27 (right).

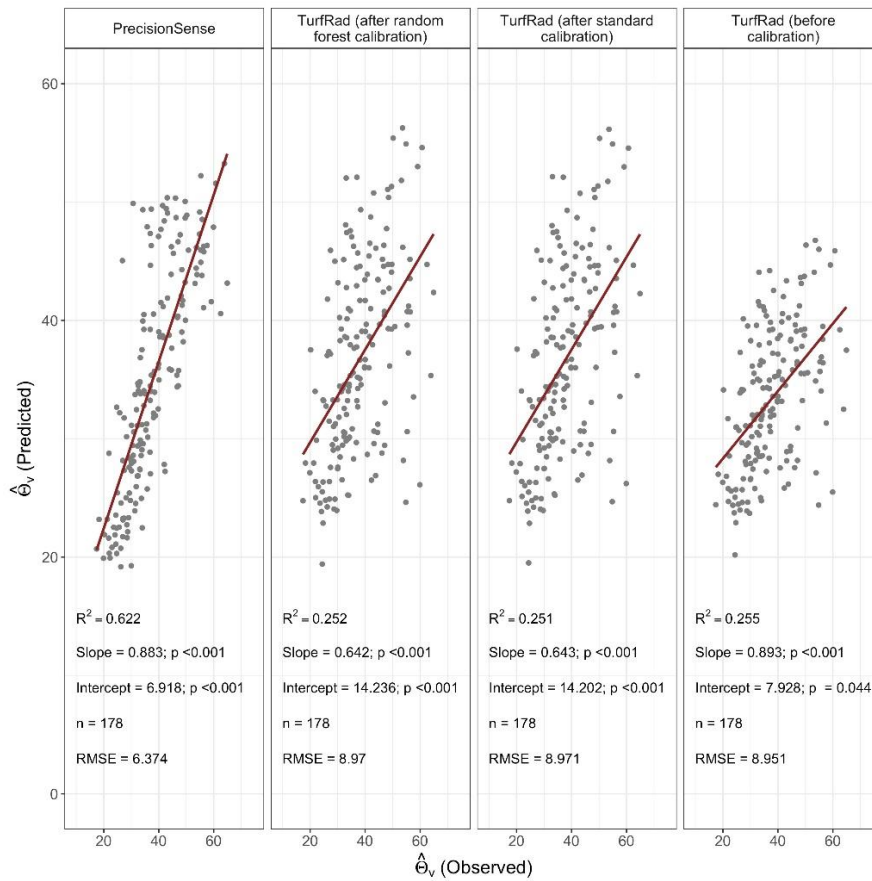


Figure 6. Volumetric soil moisture relationship between turfRad-derived soil moisture estimates and ground-based TDR 350 measurements using uncalibrated data (right), data adjusted using manufacturer's recommended calibration (second from right) and data adjusted using random forest calibration (second from left).

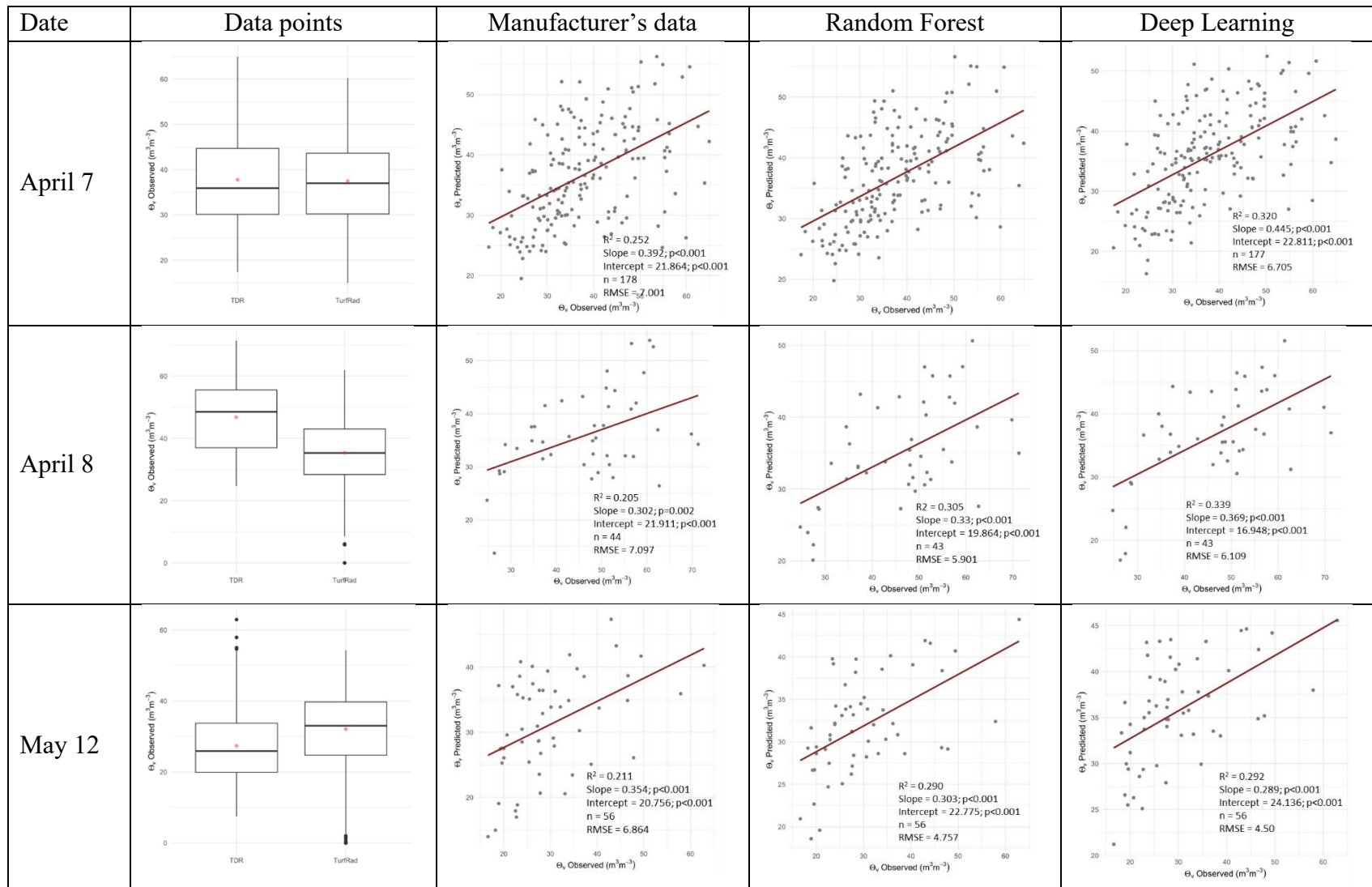


Figure 7. Volumetric soil moisture distribution and relationships between turfRad-derived soil moisture estimates and ground-based TDR 350 measurements at varying dates during the 2025 research period. Measurements were taken on Fairway #16 with a mobile portable radiometer (turfRad) installed on a utility vehicle and a handheld TDR device (TDR 350). The second column shows results obtained using the standard manufacturer model. The third and fourth columns present regressions using Random Forest and Deep Learning models, respectively.

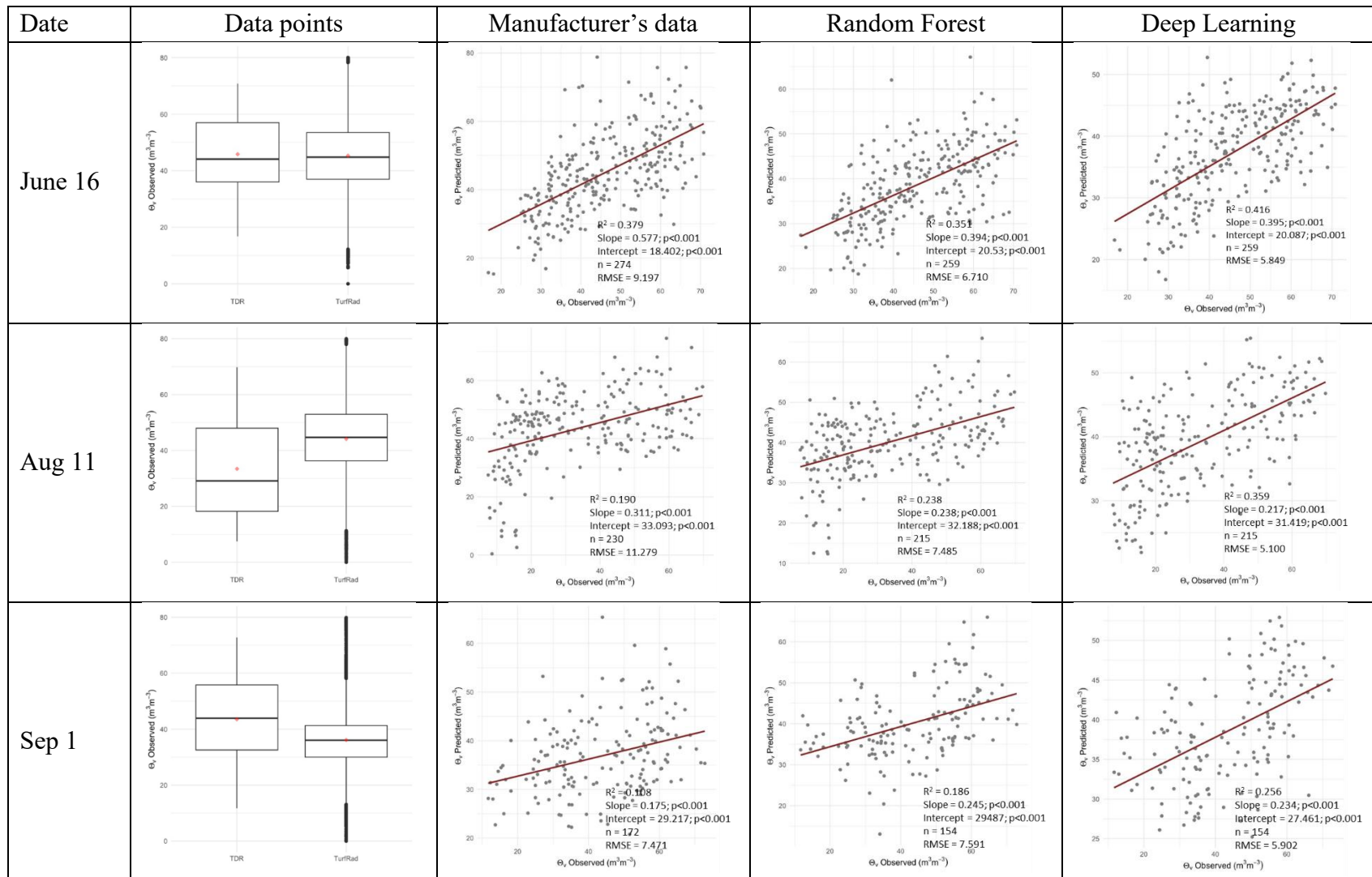


Figure 8. Volumetric soil moisture distribution and relationships between turfRad-derived soil moisture estimates and ground-based TDR 350 measurements at varying dates during the 2025 research period. Measurements were taken on Fairway #16 with a mobile portable radiometer (turfRad) installed on a utility vehicle and a handheld TDR device (TDR 350). The second column shows θ_v results obtained using the standard manufacturer model. The third and fourth columns present regressions using Random Forest and Deep Learning models, respectively.

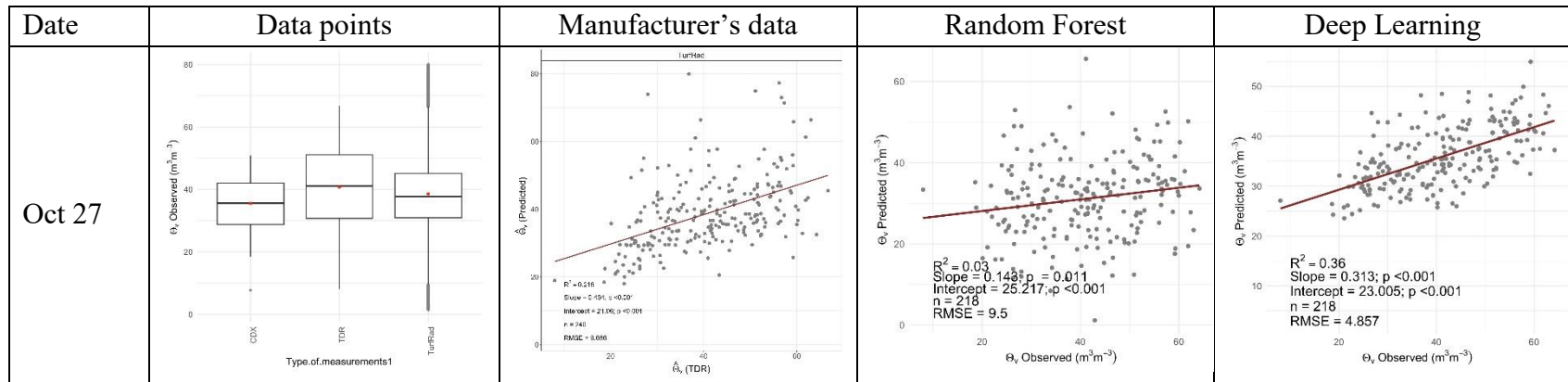


Figure 9. Volumetric soil moisture distribution and relationships between turfRad-derived soil moisture estimates and ground-based TDR 350 measurements on October 27, 2025. Measurements were taken on Fairway #16 with a mobile portable radiometer (turfRad) installed on a utility vehicle and a handheld TDR device (TDR 350). The second column shows results obtained using the standard manufacturer model. The third and fourth columns present regressions using Random Forest and Deep Learning models, respectively.

Conclusions and Future Expectations

When turfRad measurements were compared with TDR 350, coefficients of determination were statistically significant but consistently low. Similar patterns were observed in 2023 and 2024; however, coefficients of determination generally improved in 2025 relative to the previous years. In 2023 and 2024, soil moisture conditions were relatively uniform and predominantly wet, limiting variability and likely constraining the strength of statistical relationships. In contrast, during 2025 we achieved a wider range of soil moisture conditions on #16, from wet to dry, which may have contributed to the observed improvement in turfRad accuracy.

Overall, the accuracy of soil moisture estimates was influenced by the underlying modeling approach used to estimate moisture from sensor data. Differences observed among the manufacturer's model, random forest, and deep learning approaches indicate that model type plays a critical role in determining agreement with reference TDR measurements. These findings suggest that meaningful improvements in soil moisture estimation may be achieved through the development or adoption of alternative modeling frameworks better suited to site-specific conditions. Continued refinement of modeling approaches therefore represents a key opportunity for enhancing the performance of sensor-based irrigation decision support tools.

Our third objective in this study was to use sensor data to schedule irrigation. During July, Tom Egelhoff used the turfRad maps and adjusted sprinkler run times based on the soil moisture around sprinkler heads. Surprisingly and despite its low accuracy, the use of turfRad-guided adjustments resulted in meaningful water savings. This is a promising outcome of our study and hopefully we can apply this approach to a greater area and over a longer period of time.

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). 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 or if different technologies are useful on turf areas. During 2026 we plan to add the METOS TSM (Top Soil Mapper) unit to our investigations and compare it against the TDR and the turfRad.

References

Datta, A., Banerjee, S., Finley, A. O., & Gelfand, A. E. (2016). Hierarchical Nearest-Neighbor Gaussian Process Models for Large Geostatistical Datasets. *Journal of the American Statistical Association*, 111(514), 800–812. <https://doi.org/10.1080/01621459.2015.1044091>

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: Ben Wherley, Chase Straw, Madan Sapkota, and Weston Floyd

Affiliation: Texas A&M University

Objectives:

1. Investigate the factors affecting the sensitivity of microwave radiometry for enhanced soil moisture measurements in golf course fairways.
2. Develop a rapid approach to calibrate raw microwave radiometry measurements to in-situ soil moisture across diverse locations.

Start Date: 2024

Project Duration: 2-years (2024-2025)

Total Funding: \$75,188 (2024-07-817) and \$20,000 (2024-18-828)

Summary Points:

- Soil moisture data were collected from three golf courses in Texas and one in Virginia across 17 survey events, resulting in 598 paired PoLRa and TDR measurements (Objective 1 & 2).
- PoLRa performance showed a strong depth dependency. Calibration accuracy was highest at 1.5 inches and declined at 3.0 and 4.8 inches, indicating the sensor is most sensitive to near-surface soil moisture (Objective 1).
- Models using both vertical brightness temperature (TBV) and horizontal brightness temperature (TBH) consistently produced the best prediction accuracy across courses and depths. Additional variables including polarization ratio (PR), thermal infrared temperature (TIR), soil organic matter (SOM), and soil type contributed little to overall model performance (Objective 1).
- The off-the-shelf PoLRa calibration provided only moderate accuracy ($R^2 \approx 0.40$), indicating the need for improved calibration to support irrigation decision making (Objective 1).
- A site-independent machine-learning calibration (SVR) improved accuracy when trained on pooled data, but did not transfer well to new fairways, courses, or survey periods. This indicates that fully universal “one-size-fits-all” calibrations are unreliable in practice (Objective 2).
- Both global and regional analysis of covariance (ANCOVA) approaches produced high and stable calibration accuracy across locations. The global ANCOVA model worked well because it used a shared radiometric–soil moisture slope while accounting for site-

level baseline differences, providing the best balance of accuracy, scalability, and ease of calibration (Objective 2).

- The minimal ground-truth calibration analysis showed that only five to six sampling points per fairway were needed to achieve reliable calibration accuracy, reducing labor and improving operational practicality (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 technologies that can provide 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).

Given these constraints, this project aims to identify the key environmental, canopy, and soil factors that affect PoLRa sensitivity in sand-capped golf course fairways and to develop a rapid, transferable calibration approach that links raw L-band radiometer output to in-situ soil moisture measurements across diverse sites. Establishing a reliable calibration framework will improve the accuracy and operational utility of the PoLRa system for large-scale soil moisture mapping. Validating this approach across multiple locations in Texas and Virginia will support the integration of radiometry-based sensing into precision irrigation programs, enabling more accurate water-use assessments and ultimately improving irrigation efficiency on golf course fairways.

Methodology

Objective 1: Data for this project were collected from three golf courses in Texas, including the Jackrabbit Course at Champions Golf Club in Houston, Austin Country Club in Austin, and Fields Ranch East in Frisco, and one course in Virginia, Independence Golf Club in Midlothian. Two survey periods per course were used in the analysis, and each fairway included twelve ground-truth sampling locations.

PoLRa measurements included polarization variables (TBV and TBH), along with TIR. The PR was calculated using these two polarization values $(TBV - TBH) / (TBV + TBH)$. Ground-truth volumetric water content (VWC) was recorded at 1.5, 3.0, and 4.8 inches using a time-domain reflectometry (TDR) probe immediately following PoLRa measurements. Soil samples were collected for SOM, which was also included in the model as a predictor.

All datasets were merged into a single database with standardized variable names. PoLRa variables were treated as continuous predictors and course and fairway were treated as categorical

factors. Two complementary modeling approaches were used to evaluate how PoLRa relates to in-situ soil moisture.

Linear mixed-effects models were used first to evaluate how PoLRa measurements predict soil moisture at each depth. Separate models were developed for the three depths to determine which depth best reflects the sensor's effective sensing layer (1.5, 3.0, and 4.8 inches). These models included TBV, TBH, PR, TIR, and SOM when available, with random intercepts for course and fairway. Model performance was assessed using R^2 , RMSE, and MAE, and stepwise selection was used to identify the strongest predictors.

SVR was used to test whether nonlinear relationships improved prediction accuracy across depths and locations. The same predictors were used and models were trained using repeated cross-validation with automated parameter tuning. Prediction performance was evaluated using R^2 and RMSE. All analyses were conducted in R version 4.4.1.

Objective 2: Data collection for this objective was conducted at the same four golf courses used in Objective 1, resulting in 17 surveys across all locations. Each survey included three sampled fairways with twelve ground-truth locations per fairway, producing a total of 598 paired PoLRa–TDR measurements.

Soil moisture data were collected using the mower-mounted PoLRa system. The sensor was operated along preplanned transects at approximately 1.5 to 2 meters above the surface to record TBH and TBV polarization variables, along with TIR. Immediately after each PoLRa pass, VWC was measured at 1.5, 3.0, and 4.8 inches at all sampling locations using handheld TDR probes.

PoLRa and TDR datasets were synchronized using timestamps recorded as the radiometer passed each flagged location. Records with missing or invalid values were removed, and course, fairway, and sampling event were treated as categorical factors.

Three calibration approaches were evaluated. The factory PoLRa output (i.e., off-the-shelf) served as the baseline to determine whether calibration was necessary. A site-independent SVR model was then trained on pooled multisite data to test whether a single universal calibration could be applied across locations. The SVR model used TBV, TBH, and TIR as predictors and was evaluated using multiple cross-validation schemes to assess generalizability.

Because soil and environmental conditions vary by course, two site-dependent approaches were also tested. The global ANCOVA model used pooled data from all locations and included TBV as a continuous predictor, with course as a categorical factor to allow intercepts to vary by site. The regional ANCOVA approach developed separate calibration models for each course and incorporated a fairway-time factor to account for within-course spatial and temporal variability.

Model performance was evaluated using R^2 , RMSE, and MAE. To determine the minimum ground-truth requirement for practical field use, a subsampling experiment was conducted. For each fairway, calibration subsets ranging from two to nine TDR sampling points were randomly selected, while three remaining points were used for independent testing. This process was repeated hundreds of times to examine stability in calibration accuracy.

Calibration performance was compared against established benchmarks, where RMSE values below $0.06 \text{ m}^3 \text{ m}^{-3}$ were considered acceptable and values below $0.02 \text{ m}^3 \text{ m}^{-3}$ were considered very good.

Results to Date

Objective 1: Linear mixed-effects models were fit separately for the three TDR measurement depths (1.5, 3.0, and 4.8 inches) to assess how strongly PoLRa measurements relate to soil moisture. Across all depths, the model using both brightness temperature polarizations (TBV + TBH; Model M1) consistently produced the best performance, as indicated by the lowest AIC values (Table 1). Models that included additional variables such as TIR, PR, SOM, or soil type did not improve performance and, in most cases, substantially increased AIC. These results confirm that TBV and TBH provide the majority of useful radiometric information for predicting VWC.

Calibration strength decreased consistently with depth (Table 2). The PoLRa–VWC relationship was strongest at 1.5 inches ($R^2 = 0.54$; $RMSE = 0.06 \text{ m}^3 \text{ m}^{-3}$), weaker at 3.0 inches ($R^2 = 0.41$; $RMSE = 0.07 \text{ m}^3 \text{ m}^{-3}$), and further reduced at 4.8 inches ($R^2 = 0.32$; $RMSE = 0.09 \text{ m}^3 \text{ m}^{-3}$). These results indicate that PoLRa is most sensitive to near-surface soil moisture conditions, with reduced ability to capture moisture signals deeper in the profile.

The leave-one-variable-out (LOVO) analysis further confirmed the dominant role of TBV and TBH (Table 3). Removing TBV produced the largest declines in performance at 1.5 and 3.0 inches ($\Delta AIC = 28.55$ and 11.26 , respectively), while TBH consistently ranked second in influence. By comparison, removing PR, TIR, SOM, or soil type resulted in minimal or negative changes in performance, showing that these variables added little predictive value under the golf course fairway conditions tested. Together, these findings show that PoLRa calibration is driven primarily by brightness temperature components, with measurement sensitivity strongest at shallow depths and diminishing as depth increases.

Objective 2: Across all courses and survey periods, the off-the-shelf PoLRa calibration showed a moderate relationship with measured soil moisture ($R^2 = 0.40$), with relatively high errors ($RMSE = 0.081 \text{ m}^3 \text{ m}^{-3}$; $MAE = 0.062 \text{ m}^3 \text{ m}^{-3}$) (Figure 1). This indicates that PoLRa output is insufficient for operational irrigation decision-making without calibration against ground-truth measurements.

The site-independent SVR model improved overall accuracy using the pooled dataset ($R^2 = 0.572$ under random 70/30 splitting; Table 4). However, when tested using independent validation schemes designed to represent real-world deployment (LOFO, LODO, and LOCO), performance declined sharply. R^2 values dropped to 0.326, 0.196, and 0.283, respectively, with similar or worse errors. These results show that a fully universal “one-size-fits-all” calibration does not transfer across courses or survey periods because moisture dynamics, surface conditions, and management practices vary.

Both global and regional ANCOVA calibration approaches produced a strong and stable soil moisture relationship ($R^2 = 0.802$ and 0.807 , respectively; Table 5). Each achieved identical error levels ($RMSE = 0.046 \text{ m}^3 \text{ m}^{-3}$; $MAE = 0.035 \text{ m}^3 \text{ m}^{-3}$). Unlike SVR, the global ANCOVA model does not assume that all sites are identical. It applies a common radiometric–soil moisture slope while allowing course-specific intercepts, which captures consistent physical relationships in the sensor while accounting for baseline differences among fairways. Although the regional approach produced a slightly higher R^2 , implementing it in practice is prohibitively demanding because it requires collecting a full set of ground-truth TDR samples for every course and survey period in order to build separate calibrations for each site. This substantially increases the amount of field time, labor, and sampling effort needed, making the method impractical for

routine use by golf course managers. The global ANCOVA therefore provides a single transferable model that remains robust across locations and survey periods, without requiring separate calibrations for each course. Avoiding course-specific recalibration reduces workload and prevents model fragmentation at the superintendent level.

A minimal-ground-truth calibration assessment showed that accuracy stabilized at approximately five to six sampling locations per fairway (Figure 2). Beyond this point, improvements in R^2 and MAE were small, indicating diminishing returns from additional sampling. This finding demonstrates that reliable deployment can be achieved with limited calibration effort, supporting practical implementation at scale.

Table 1. Linear mixed-effects model selection results for PoLRa calibration at three soil moisture depths. Models using both TBV and TBH consistently outperformed models with additional predictors. Adding TIR, PR, SOM, or soil type increased AIC and reduced performance, confirming that polarization variables drive PoLRa sensitivity.

Depth (inches)	Model	Predictors	AIC	Δ AIC
1.5	M0	TBV	-749.16	73.62
	M1	TBV + TBH	-822.77	0
	M2	TBV + TBH + TIR	-813.82	8.95
	M3	TBV + TBH + TIR + PR	-814.62	8.15
	M4	TBV + TBH + TIR + PR + SOM	-559.31	263.46
	M5	TBV + TBH + TIR + PR + SOM + Soil	-551.24	271.53
3.0	M0	TBV	-706.53	31.46
	M1	TBV + TBH	-737.99	0
	M2	TBV + TBH + TIR	-730.57	7.43
	M3	TBV + TBH + TIR + PR	-727.75	10.25
	M4	TBV + TBH + TIR + PR + SOM	-558.17	179.83
	M5	TBV + TBH + TIR + PR + SOM + Soil	-548.51	189.48
4.8	M0	TBV	-537.35	35.63
	M1	TBV + TBH	-572.98	0
	M2	TBV + TBH + TIR	-565.01	7.97
	M3	TBV + TBH + TIR + PR	-565.70	7.28
	M4	TBV + TBH + TIR + PR + SOM	-413.22	159.76
	M5	TBV + TBH + TIR + PR + SOM + Soil	-400.23	172.75

Table 2. Calibration performance of the best-performing linear mixed-effects model across soil moisture depths. PoLRa accuracy was highest at 1.5 inches and decreased at deeper layers, showing strong near-surface sensitivity and diminished responsiveness to deeper moisture.

Depth (inches)	R ²	RMSE (m ³ m ⁻³)	MAE (m ³ m ⁻³)
1.5	0.54	0.06	0.048
3.0	0.41	0.07	0.055
4.8	0.32	0.09	0.071

Table 3. Leave-one-variable-out (LOVO) analysis showing the effect of removing individual predictors. Removing TBV and TBH caused the largest performance declines, while removing PR, TIR, SOM, or soil type produced minimal changes. These results confirm that brightness temperature variables dominate PoLRa soil moisture sensitivity.

Depth (inches)	Predictor Removed	ΔAIC	ΔRMSE	Rank
1.5	TBV	28.55	0.057	1
	TBH	5.04	0.054	2
	Soil	5.65	0.053	3
	SOM	-1.04	0.054	4
	PR	-1.18	0.054	5
	TIR	-1.60	0.053	6
3	TBV	11.26	0.056	1
	TBH	7.30	0.055	2
	SOM	4.43	0.054	3
	Soil	3.61	0.054	4
	PR	-1.91	0.054	5
	TIR	-1.94	0.054	6
4.8	SOM	10.17	0.07987	1
	TBV	3.18	0.07970	2
	TBH	0.98	0.07930	3
	PR	-0.50	0.07948	4
	TIR	-1.72	0.07842	5
	Soil	-3.86	0.07848	6

Table 4. Accuracy of the site-independent support vector regression (SVR) model using four validation schemes. Performance dropped substantially under course-, fairway-, and time-based validation, indicating that PoLRa calibration does not reliably transfer across locations or survey periods.

Validation Scheme	R ²	RMSE (m ³ m ⁻³)	MAE (m ³ m ⁻³)
Random 70/30 split	0.572	0.070	0.056
LOFO	0.326	0.074	0.060
LODO	0.196	0.074	0.061
LOCO	0.283	0.077	0.064

Table 5. Calibration results for global and regional analysis of covariance (ANCOVA) approaches. Both models produced high accuracy, but the global approach performed equivalently while using a single transferable calibration, making it more practical for course-level implementation.

Model type	R ²	RMSE (m ³ m ⁻³)	MAE (m ³ m ⁻³)
Global ANCOVA	0.802	0.046	0.035
Regional ANCOVA	0.807	0.046	0.035

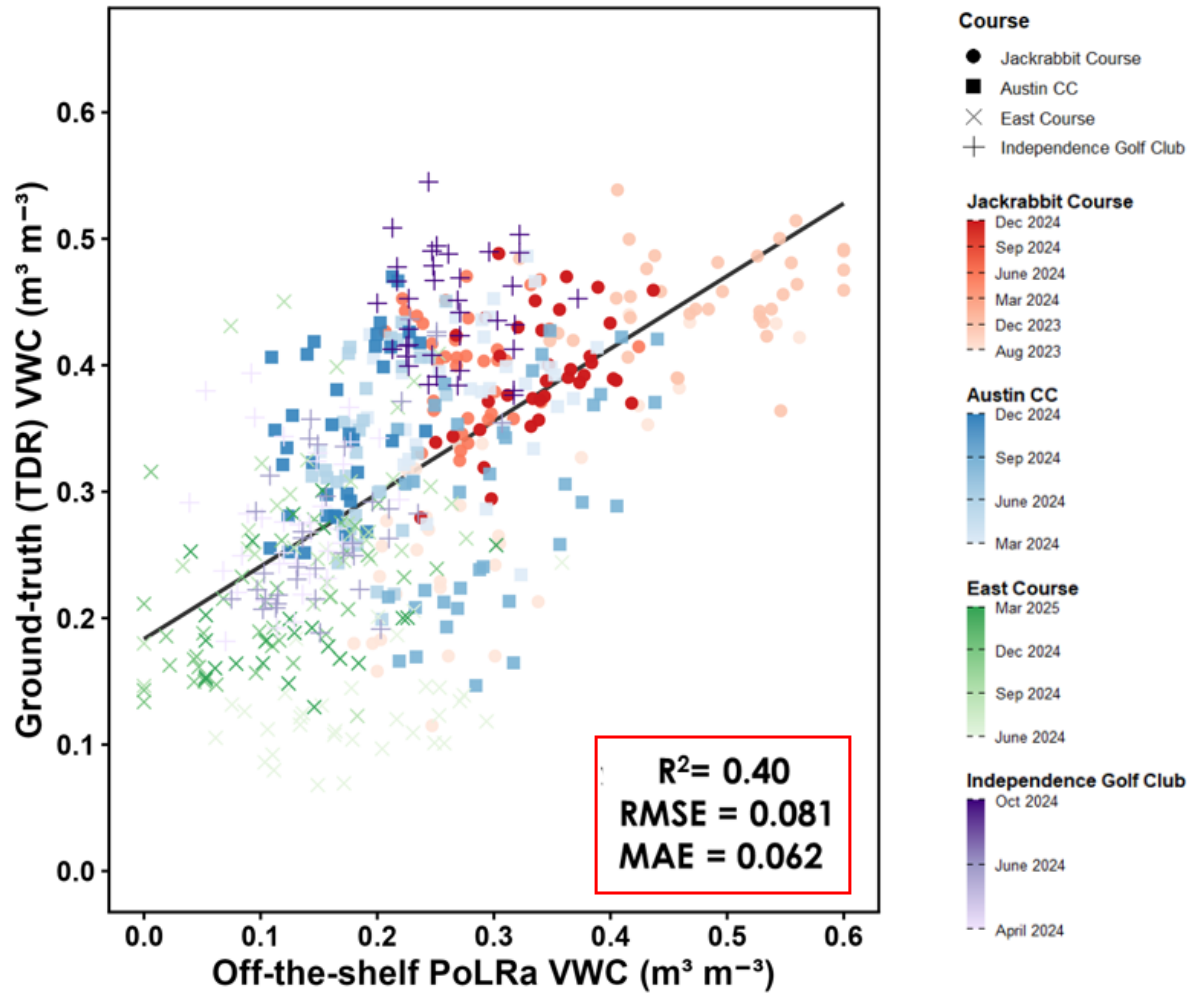


Figure 1. Relationship between off-the-shelf Portable L-band Radiometer (PoLRa) volumetric water content (VWC) estimates and ground-truth TDR VWC across four golf courses and multiple survey periods. The weak fit and broad error spread demonstrate that the factory calibration is not suitable for irrigation decision-making without site calibration.

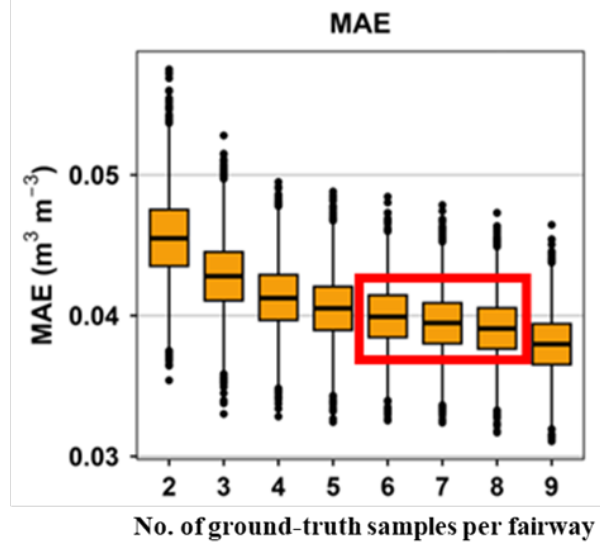
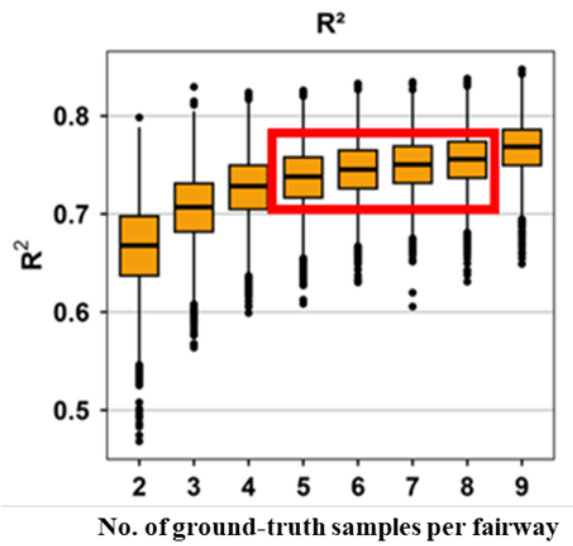


Figure 2. Model performance stability at different ground-truth sample sizes. Calibration accuracy plateaued when approximately five to six sampling locations per fairway were used, with minimal gains in R^2 and MAE from additional samples. This indicates that reliable calibration can be achieved with limited ground-truth effort.

USGA ID#: 2025-05-836

Title: LEVERAGING REMOTE SENSING FOR HIGH-RESOLUTION SOIL MOISTURE ESTIMATION IN GOLF COURSES FOR PRECISION IRRIGATION

Project Leader: Nan Li

Co-Investigators: Elia Scudiero and Jim Baird, University of California, Riverside

Collaborators: Bernd Leinauer (New Mexico State University) and Chase Straw (Penn State University)

Affiliation: University of California, Riverside

Objectives:

1. Expand the UCR Digital Agriculture Lab remote sensing of soil moisture machine learning model to golf courses based on ground truth collected in NM (Bernd Leinauer - collaborator), TX (Chase Straw - collaborator), and CA (Jim Baird - coPI).
2. Use daily PlanetScope 8-band imagery to downscale the VWC forecasts to the 3-m scale.
3. Use weather forecast data to provide short-term (1-day) future soil moisture predictions.

Objective added post award: Evaluate the surface soil moisture product commercially available from Planet Labs using ground truth soil moisture data from golf courses

Start Date: February 1, 2025

Project Duration: 2 years

Total Funding: \$74,003.00

Summary Points:

- Ground measurements of soil moisture data were collected from collaborators using TDR from 10 different golf courses and using PS6000 from 6 different golf courses (Objective 1).
- Download remote sensing images and extracted data from SMAP, Sentinel-1, Sentinel-2, GRIDMET, extracted land surface parameters from NASA SRTM digital elevation model and soil properties from POLARIS (Objective 1).
- Preliminary analysis indicates that the transferability of UCR machine learning soil moisture model was acceptable ($R^2=0.56$) by including a small number of local training datasets (10%) into the model (Objective 1).
- The transferability of the empirical model can be improved by including more local training datasets into the model (Objective 1).
- Compared Planet Lab Soil Water Content Product with the ground measurements of soil moisture data from TDR and PS6000 (Objective 2).
- Future research will include data collection from all locations to downscale the VWC to the 3-m scale (Objective 2) and provide short-term (1-day) future soil moisture predictions (Objective 3).

Summary Text:

Rationale: Soil moisture sensors-based irrigation decision-making has the potential to reduce water use across tropical to arid climate zones (Dukes, 2012; Serena et al., 2020). However, point-based nature limits their ability to represent the soil moisture conditions across larger scale like fairways. The cost of deploying sensors across large areas as well as the time-intensive data collection and technical expertise required further constrains their scalability. Remote sensing has evolved as an effective tool to overcome limitations by providing synoptic, independent, and timely information on biogeophysical variables directly or indirectly related to irrigation, thereby delivering optimal course conditions while conserving and protecting water resources (USGA Strategic Initiatives 1). By covering large areas with fewer resources compared to ground-based sensors, remote sensing reduces the labor and maintenance costs associated with traditional methods. Remote sensing is easily scalable to different sizes and types of golf courses, making it a versatile solution for diverse geographic regions and climates. This technology could improve resource efficiency and optimize maintenance efficiency by reducing both golf course disruption and reliance on resources (USGA Strategic Initiatives 2).

This project aims to provide accurate soil moisture estimation by leveraging remote sensing and machine learning models to provide accurate and high-resolution soil moisture information on golf course fairways. The project will 1) transform the UCR Digital Agronomy Lab's remote sensing model to estimate golf courses soil moisture by utilizing ground truth data collected with either hand-held Time Domain Reflectometry (TDR) or the Toro Precision Sense 6000 sensor; 2) downscale the soil moisture estimate to a 3-m resolution use high-resolution PlanetScope 8-band imagery; and 3) provide short-term (e.g., 1-day) soil moisture forecast using the FRET weather forecast data.

Methodology:

Objective 1: Soil moisture measurements, recorded as volumetric water content (VWC) for this project were obtained using the hand-held Time Domain Reflectometry (TDR) and the Toro Precision Sense 6000 (PS6000) sensor mobile platform over the past five years. TDR instruments were used to collect soil moisture from 11 courses in Arizona, Colorado, Florida, Kansas, Minnesota, New Hampshire, New Mexico, and Texas. For each course, data were collected from 3 to 14 fairways, with a total number of 17,481 data were collected. In addition, soil moisture data at 5 courses in Texas and 1 course in Minnesota were collected using the PS6000 sensor that mounted on a utility vehicle.

In terms of the remote sensing data, the Synthetic Aperture Radar (SAR) will be preprocessed using the Sentinel-1 Toolbox within the Google Earth Engine platform. Sentinel-2 satellite images will be used to calculate vegetation indices, including the Normalized Difference Vegetation Index (NDVI), and others. In addition to remote sensing datasets, terrain parameters that characterize topography will be used to model soil moisture indirectly. This project will use the 30-m Shuttle Radar Topography Mission Digital Elevation Model to calculate terrain parameters, i.e., elevation, slope, aspect, and surface roughness factor. Soil physical and chemical properties will be extracted from the POLARIS, a 30-m probabilistic soil series map of the contiguous United States, and include clay and sand content, bulk density, and soil organic carbon content.

The satellite-based data and ground measurements are incorporated into machine learning models (Quantile Random-Forest Model - QRF) which combine multiple inputs to predict a single value of soil moisture content. In the training phase, ground-based measurements are needed to calibrate the

models. Based on the input, the models predict target values provided by ground-based systems (i.e. TDR, PS6000). The error in predicting soil moisture is propagated back through the ML model and incrementally changes the parameters inside the model to reduce the error for the next prediction. This process is iterated across all data points set aside for training. After training, the performance of the model is evaluated on data to select a model with a parameter that generalizes well on previously unknown data points. To evaluate the transferability of the empirical model, from regional to field scale, a “spiking” method was employed. This method has been adopted in many other fields such as the soil spectroscopy libraries established using datasets collected from different countries or instruments (Guerrero et al., 2010; Viscarra Rossel et al., 2016).

Objective 2&3: These objectives will be accomplished in year 2 of the project. Once the empirical machine learning model is evaluated, the PlanetScope 8-band imagery will be used to downscale the VWC forecasts to the 3-m scale. Specifically, we will evaluate the performance of this downscaling approach compared to a coarse resolution remotely sensed product, explore potential relationships between soil moisture estimates and local vegetation indices, and identify limitations and areas of poor downscaling performance to target future downscaling efforts. The model developed in Objectives 1 and 2 will then be applied with meteorological forecasts to provide short-term (e.g., 1-day) soil moisture prediction. The forecast reference crop evapotranspiration for 24 hours will be obtained from the FRET model within the Google Earth Engine platform. The forecast weather data and the most current remote sensing data are used by the latest model to predict soil moisture for the short-term (1-day) future.

Additional Objective: Evaluate the Planet Labs soil moisture product. Through the imagery access license that co-PI Scudiero is providing for the UCR Campus (<https://insideucr.ucr.edu/stories/2021/06/07/earth-spanning-satellite-images-now-available-anyone-ucr>), the soil moisture product offered by Planet Labs (<https://docs.planet.com/data/planetary-variables/soil-water-content/>) was downloaded and compared to the soil moisture measured using PS6000 and TDR at available locations.

For all the evaluation, the coefficient of determination (R^2) and root mean squared error (RMSE, accuracy) were calculated.

Results to Date

While data from all locations are still being analyzed, TDR soil moisture data has been used to evaluate the transferability of the machine learning QRF models. Figure 1 shows the relationship between estimated and measured ground truth soil moisture readings. It indicates that the UCR empirical soil moisture model was not transferable from the regional scale to field scale without local calibration data (Figure 1a). The spatial variations (spread) of soil moisture were smoothed without the use of any “spiking” datasets compared to measured soil moisture. Figure 1a shows that when the QRF soil moisture model was applied to the field without using any local training dataset, it failed to delineate the variations of soil moisture across the field. This suggested the transferability of the empirical model was poor from the regional scale to field scale without local calibration data. After a small number of local training data (10%) were added, the bias values of the models significantly reduced with RMSE of 0.094 cm³/cm³ (Figure 1b). In addition, the transferability of the empirical model can be further improved by including more local training datasets (Figure 1c and 1d). As shown in Figure 2, the spatial variations of soil moisture were smoothed without the use of any “spiking” datasets compared to use 10% of the “spiking” datasets.

To evaluate the accuracy and reliability of Planet Lab's soil water content products (SWC) reported in Fig. 3 for PS6000 and Fig. 4 for TDR. From Figure 3, we can see a moderate to strong positive correlation ($r = 0.14-0.78$) between Planet SWC and PS6000 measurements. Figure 4 shows that the coefficients between Planet SWC and TDR measurements range from 0.03 to 0.67. RMSE values range from 0.02 to $0.15 \text{ cm}^3/\text{cm}^3$, with the strongest agreement observed in AZ and TX fields. In addition, from the figures we can see that the Planet SWC values tend to have lower values than the ground-based measurements. The temporal comparison in Figure 5 shows that the temporal variation from Planet SWC closely follows the PS6000 measurements, effectively capturing the broad wetting and drying cycles. The factors that influence the differences can contribute to that (1) frequency of observations: the passive microwave and the Sentinel-2 satellites used might not coincide and the measurement dates in the files belong to the passive microwave satellite pass. If there are no cloud-free Sentinel-2 images available, the spatial distribution of the data is relying on "old data". (2) depth: passive microwave satellite only measures the first 5 cm of soil depth. (3) soil type: Planet SWC relies on a global database of soil type to calculate volumetric soil water content. This data might not correspond to the properties found in turf places where topsoil is usually replaced. (4) pixel level vs point level comparisons: any in the ground sensor is measuring a point which might not represent the data even at the pixel level ($20 \text{ m} \times 20 \text{ m} = 400\text{m}^2$).

Year 2 planned activities:

- Evaluate the performance of the empirical machine learning for delineating the temporal variation of soil moisture.
- Develop a methodology for downscaling the 10-m scale soil moisture estimation to a 3-m spatial resolution using the daily PlanetScope 3-m 8-band imagery.
- Provide short-term (e.g., 1-day) soil moisture prediction using the model developed in Objectives 1 and 2 with the real-time meteorological forecasts (FRET).

Figures:

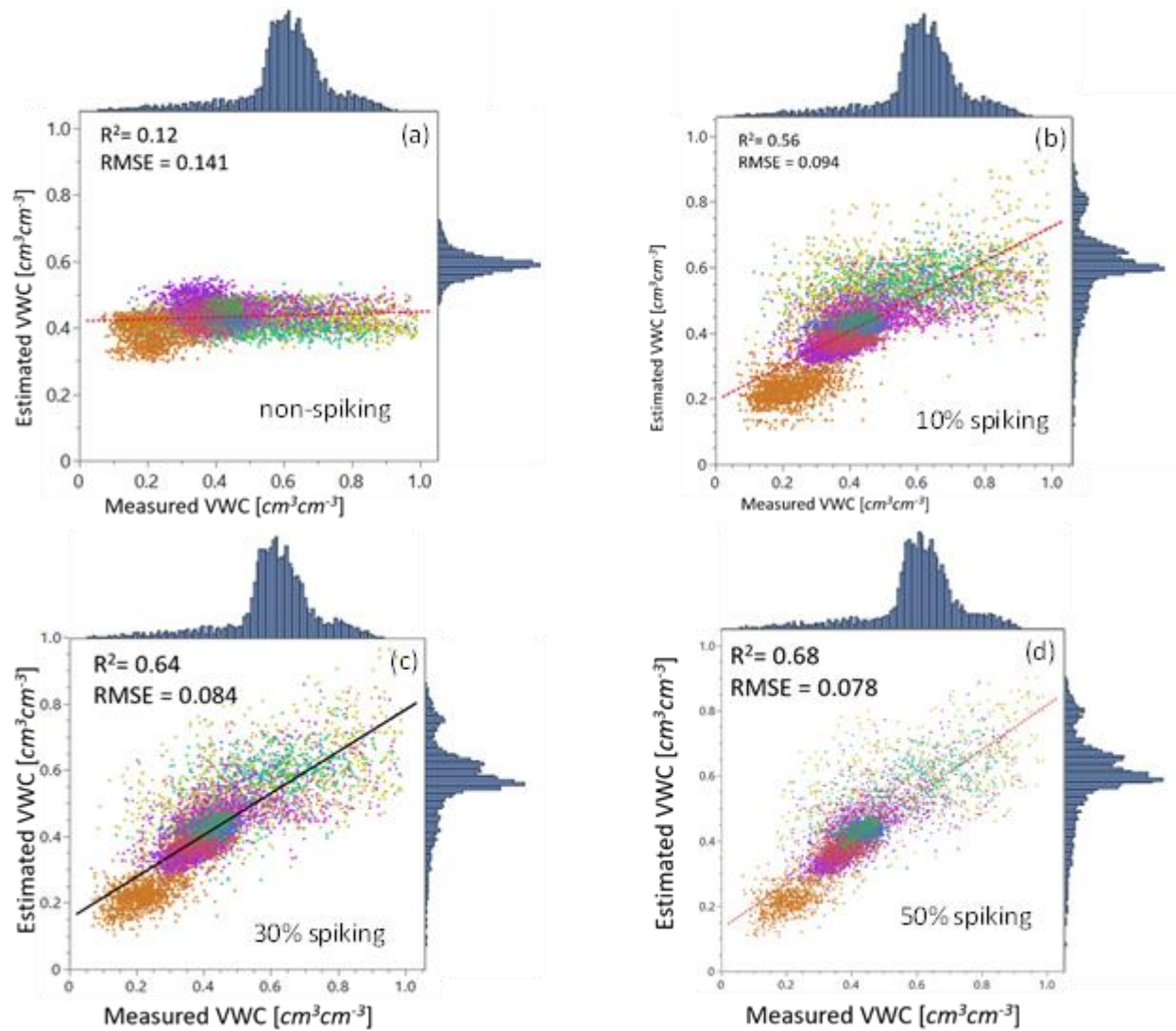


Figure 1. Relationship between estimated and measured soil moisture using remote sensing and quantile random forest (QRF) machine learning model. The QRF models were established without (non-spiking) and with (spiking) local training datasets. Data from different golf courses were highlighted in different colors.

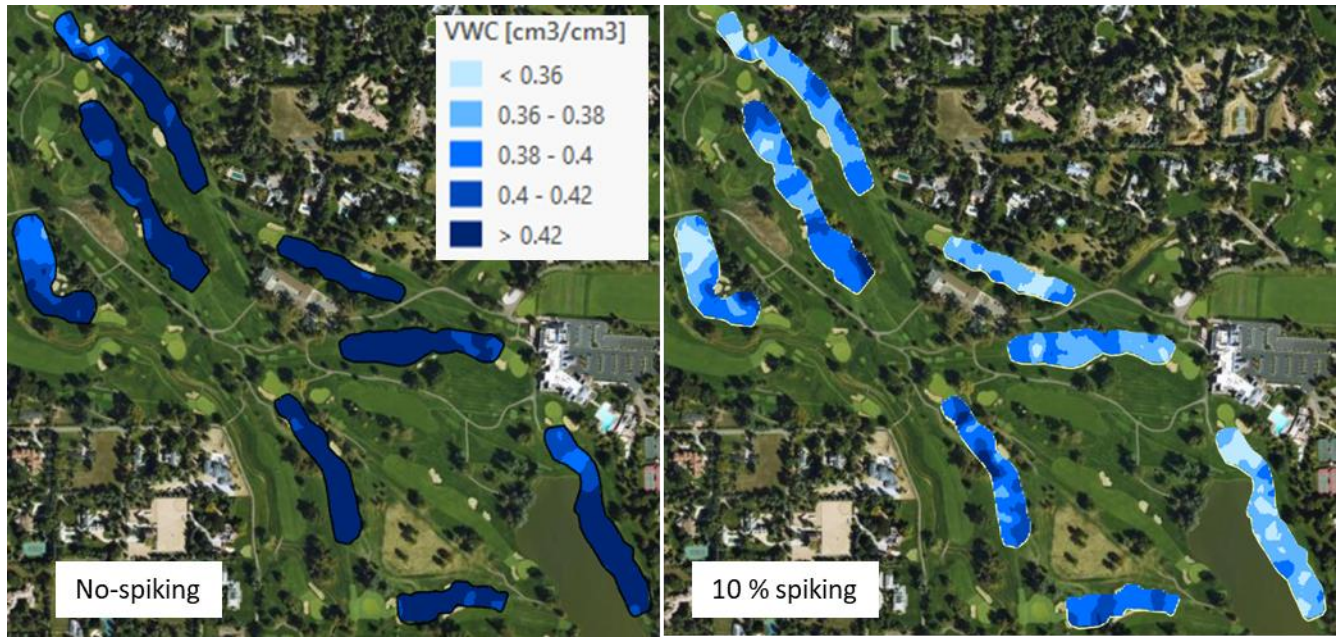


Figure 2. Maps of estimated soil moisture using remote sensing and quantile random forest (QRF) machine learning model established without (non-spiking) and with (spiking) local training datasets.

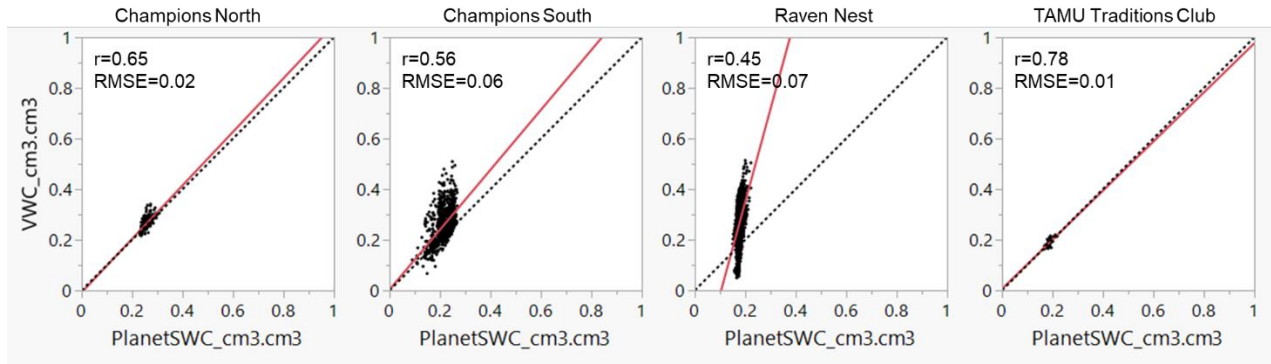


Figure 3. Comparison between Planet Lab soil water content products with the PS6000 measured soil moisture.

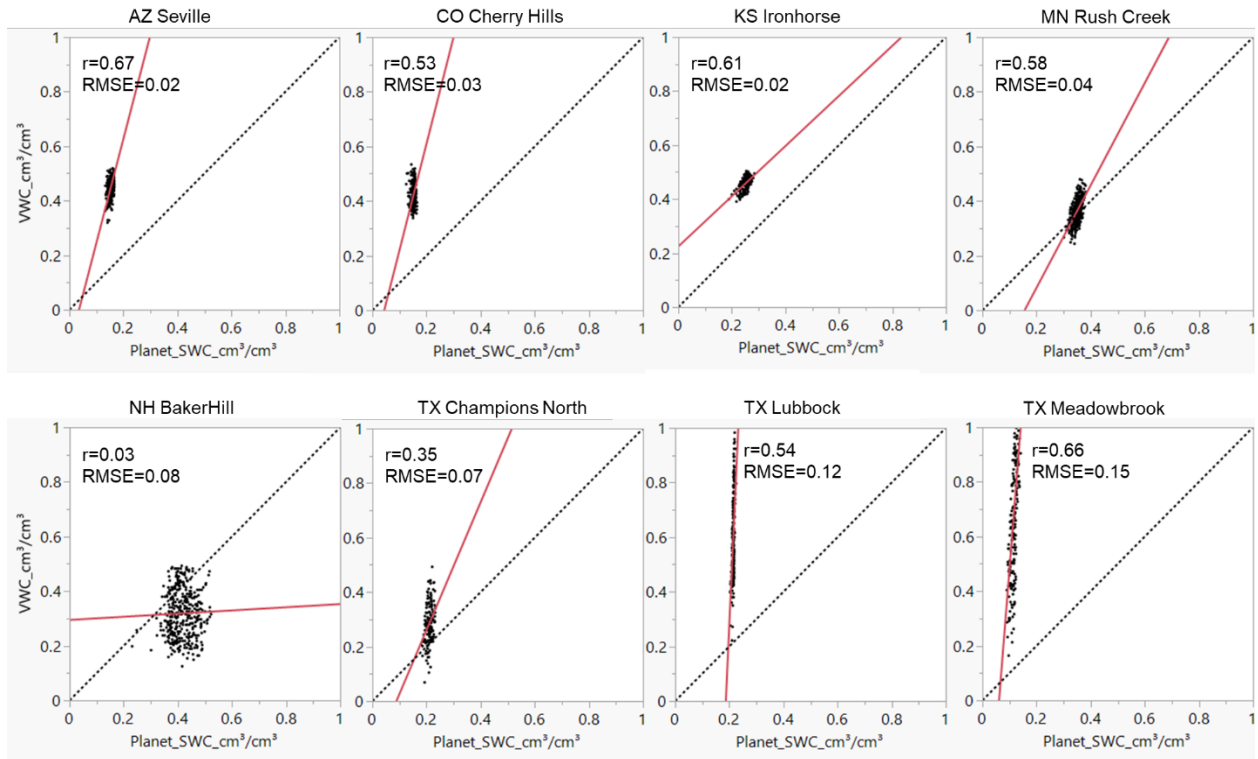


Figure 4. Comparison between Planet Lab soil water content products with the TDR measured soil moisture.

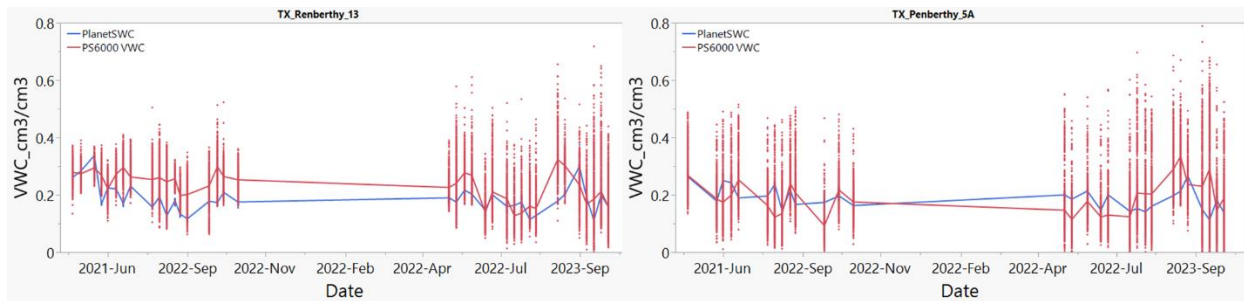


Figure 5. Comparison of the time-series soil water content from Planet Lab and the PS6000 sensor. Points are single PS6000 measurements within the Planet Lab pixel, the red line is the average PS6000 soil moisture for the pixel.

Reference

Dukes, M. D. (2012). Water Conservation Potential of Landscape Irrigation Smart Controllers.

Serena et al., (2020). Irrigation scheduling technologies reduce water use and maintain turfgrass quality. *Agronomy Journal*, 112(5), 3456–3469. <https://doi.org/10.1002/agj2.20246>

Guerrero, C., Zornoza, R., Gómez, I., and Mataix-Beneyto, J. (2010). Spiking of NIR regional models using samples from target sites: effect of model size on prediction accuracy. *Geoderma* 158, 66–77. doi: 10.1016/j.geoderma.2009.12.021

Viscarra Rossel, R., Behrens, T., Ben-Dor, E., Brown, D. J., Demattê, J. A. M., Shepherd, K. D., et al. (2016). A global spectral library to characterize the world's soil. *Earth-Sci. Rev.* 155, 198–230. doi: 10.1016/j.earscirev.2016.01.012

USGA ID#: 2025-16-847a

Title: Advancing precision irrigation on golf courses with regional demonstrations of best scheduling practices

Project Leader: Chase Straw¹, Brad Jakubowski¹, Jay McCurdy², and Kyle Foreman²

Affiliation: ¹Penn State University; ²Mississippi State University

Objectives:

1. Demonstrate irrigation practices that use technologies that are efficient, easy to use, and effective.
2. Quantify changes in water consumption and turfgrass quality between technological, data-driven approaches (precision irrigation) and conventional irrigation scheduling methods across different regions of the United States.

Start Date: 2025

Project Duration: 3 years (2025-2028)

Total Funding: \$245,555

Summary Points:

- Five golf courses began project onboarding in Fall 2025: Monterey Country Club in California, Frankfort Country Club in Kentucky, TPC Summerlin in Nevada, Toftrees Golf Resort in Pennsylvania, and Cimarron Hills Golf & Country Club in Texas.
- All sites were visited in person, during which all par 4 and par 5 fairway sprinkler locations and fairway boundaries were georeferenced.
- CDX handheld soil moisture sensors, ATMOS 41 weather stations, turfRads (portable L-band radiometers; PoLRa), and rX turf health sensors [vegetation index (VI) sensors] and aX dataloggers were delivered to each course and either installed, in use, or scheduled for installation by the end of 2025; the Second Sun satellite-based evapotranspiration platform (ET platform) was set up in Pennsylvania and will be set up in Nevada, and Soil Scout in-ground soil moisture sensors will be shipped to courses in California, Kentucky, and Texas.
- Fairway soil particle size analysis and maintenance documentation were completed at each course.
- Handheld soil moisture measurements and PoLRa scans were collected to group fairways with similar soil moisture behavior, enabling assignment of irrigation-scheduling treatments to fairways within comparable soil moisture response groups. Groupings are complete in Kentucky, Nevada, and Pennsylvania, and the remaining sites in California and Texas will be finished by the end of 2025.

Summary Text:

Rationale

Precision irrigation is becoming increasingly important as golf courses look for practical ways to reduce water use while maintaining high quality turfgrass surfaces. Although superintendents now have access to soil moisture sensors, weather stations, remote sensing tools,

modern irrigation controllers, and decision support software, these technologies are often underused or applied inconsistently. As a result, irrigation decisions still rely heavily on visual assessment and experience. This approach can overlook substantial spatial variability in soil and turfgrass conditions, particularly on fairways, which represent the largest irrigated area on a golf course and account for a significant share of total water use.

Previous research by the project team has shown that data-driven irrigation approaches can reduce water use in some climates, while showing smaller effects in others. These differences reflect the influence of climate, soils, management styles, and irrigation system design on overall efficiency. They also highlight the need to evaluate precision irrigation approaches across multiple climates and golf course environments. Fairways are especially well suited for this work because they exhibit strong spatial and temporal variability and provide an opportunity for meaningful water savings when managed more precisely.

This project aims to demonstrate practical and accessible precision irrigation strategies on fairways using technologies that superintendents can reasonably adopt. The integrated approach includes soil moisture sensing, radiometry, VI sensing, weather-station measurements, satellite-based ET, and in-ground soil moisture sensing. Applying these tools together across multiple golf courses allows the project team to compare irrigation-scheduling methods, quantify how they influence water use and turfgrass performance, and identify which approaches are most effective and practical under different environmental and management conditions.

Methodology

Research sites were selected across five states to represent a range of climates, soils, turfgrass species, and irrigation system designs. At each course, nine fairways will be selected for use in the study. These fairways will be chosen from all par 4 and par 5 holes judged appropriate for the study based on superintendent feedback and on-site observations, including the removal of holes that are too small, too large, or differ significantly in layout or topography from the others. Selected fairways will be grouped into three blocks (replications) based on similarities in soil moisture patterns derived from two handheld soil moisture data collections and two PoLRa scans. The resulting groups will serve as the basis for assigning the three irrigation-scheduling treatments.

Each course will receive three irrigation-scheduling treatments, although the specific configuration will vary by location. All sites will include a superintendent-driven approach that reflects typical day-to-day irrigation practices at the course. This approach generally relies on visual assessment, feel, and recent weather conditions. Nevada uses a more structured ET replacement system within its superintendent practice.

A PoLRa-based precision irrigation approach will also be implemented at every course. Under this treatment, soil moisture maps from the PoLRa scans will be used to determine when and where irrigation should be triggered. Thresholds for activation will be established by the superintendent, and replacement amounts will be based on ET from the on-site weather station.

The third treatment will differ by course. At California, Kentucky, and Texas, this approach will use hydrozones informed by handheld and in-ground soil moisture sensors to trigger irrigation at the zone level. Thresholds will be superintendent-defined, and replacement amounts will be based on ET. Nevada and Pennsylvania will use a spatial ET-based scheduling approach informed by satellite-derived ET. Pennsylvania and Texas will also include a fourth

treatment that follows a traditional ET approach, where on-site weather-station data guide superintendent adjustments to individual sprinkler runtimes.

Before treatments can begin, each course must complete several preparatory steps to ensure consistent implementation across locations. These steps include georeferencing fairway boundaries and sprinkler locations, installing weather stations, dataloggers, and in-ground soil moisture sensors, configuring the satellite-based ET platform at participating sites, and collecting the baseline soil moisture and radiometry data needed for creating fairway groups. Each course will also document general fairway management practices and complete soil particle size analysis.

Once fairway groupings are finalized and all equipment is fully operational, with most sites expected to be ready by the end of 2025 and the remaining sites by early 2026, irrigation programs for each treatment will be created in collaboration with course staff and irrigation technicians. Water use will be monitored at the fairway level throughout the project to quantify the effects of each scheduling approach on irrigation inputs and to assess how the treatments influence turfgrass performance, soil moisture variability, and overall playability. Superintendents will also provide feedback on the practicality of each approach throughout the study.

Results to Date

Fall 2025 focused on onboarding each participating golf course and completing the preparatory steps required before irrigation treatments begin in 2026 (Table 1). Site visits were conducted at all five locations, during which par 4 and par 5 fairways were evaluated with course staff to identify holes suitable for inclusion in the study. Fairway boundaries and sprinkler locations were georeferenced during these visits (Figure 1).



Figure 1. Georeferencing sprinkler locations at Monterey Country Club in Palm Desert, California (left), and mapped sprinkler heads and fairway boundaries at TPC Summerlin in Las Vegas, Nevada (right).

Handheld soil moisture sensors, weather stations, PoLRa units, and VI sensors and dataloggers were delivered to all courses, and data collection and installation are either complete or scheduled for completion by the end of 2025 (Figure 2; Table 1). Satellite-based ET platforms

were configured in Pennsylvania and are scheduled for Nevada. In-ground soil moisture sensors will be shipped to California, Kentucky, and Texas. General baseline information was collected at each course, including superintendent descriptions of current irrigation practices and fairway management considerations.



Figure 2. Handheld soil moisture sensor data collection on fairways at Frankfort Country Club in Kentucky (left), and mower-mounted PoLRa and VI sensors used for fairway scanning at Toftrees Golf Resort in Pennsylvania (right).

Baseline handheld soil moisture sensor data collections and PoLRa scans are nearly complete at all locations (Table 1). These data are being used to develop fairway groupings for treatment assignments. Fairway groupings have been created in Kentucky, Nevada, and Pennsylvania, and treatment assignments have been made within each grouping at those sites. Grouping development in California and Texas will be completed once the remaining scheduled baseline data collections and scans are finished. Course staff will review all grouping assignments to ensure they are operationally reasonable.

A small number of items will be completed by late 2025 or early 2026, depending on the course. These include installation or activation of weather stations, in-ground soil moisture sensors, VI sensors and dataloggers, and the satellite-based ET platform where applicable, as well as the remaining handheld soil moisture sensor data collections and PoLRa scans at California and Texas (Table 1).

Overall, progress to date has established most of the infrastructure and baseline datasets needed for treatment implementation. Completion of the remaining tasks in early 2026 will enable full deployment of irrigation-scheduling treatments during the 2026 growing season across all participating courses.

Table 1. Summary of golf course setup progress (Fall 2025).

Golf Course	Weather Station	PoLRa Status	In-Ground Sensors	VI Sensor Status	ET Platform	Handheld Data Collections	PoLRa Scans	Fairway Groups
Monterey CC (CA)	Installed	Active	To be shipped	Not installed	N/A	One needed	Completed	Not ready
Frankfort CC (KY)	Not installed	Active	To be shipped	Not installed	N/A	Completed	Completed	Completed
TPC Summerlin (NV)	Installed	Active	N/A	Not installed	To be activated	Completed	Completed	Completed
Toftrees (PA)	Installed	Active	N/A	Active	Active	Completed	Completed	Completed
Cimarron Hills (TX)	Not installed	Active	To be shipped	Active	N/A	One needed	Two needed	Not ready

Notes: Handheld soil moisture sensors (CDX) were delivered to all courses. All courses completed fairway maintenance documentation and soil particle size analysis. Fairway boundaries and sprinkler locations were georeferenced during site visits.

Future Expectations

Early 2026 will focus on completing remaining baseline collections, finalizing fairway groups, and verifying that all sensing and data platforms are operational before treatment implementation (Figure 3). Once all equipment is operational, irrigation programs for each treatment will be developed with course staff and irrigation industry support so that implementation can begin during the 2026 growing season.



Figure 3. Example of hydrozone delineations on two golf course fairways based on volumetric water content (% VWC). The left fairway (Kentucky) uses individual-head control, resulting in smaller and more discrete hydrozones, whereas the right fairway (California) uses block-based irrigation, leading to larger grouped hydrozones. An in-ground soil moisture sensor will be installed within each hydrozone to monitor conditions and trigger irrigation at the zone level.

During the 2026 season, water use will be monitored at the fairway level to compare the irrigation-scheduling approaches and quantify differences in irrigation inputs among treatments. Turfgrass performance and soil moisture variability will be evaluated regularly to document how each method affects surface conditions. Superintendents will also provide feedback on the practicality and usability of each approach to help identify strategies that are both effective and realistic for day-to-day irrigation management.

The remainder of the project will focus on collecting full-season treatment data across all locations, interpreting multi-site patterns, and developing recommendations that account for differences in climate, soils, and management styles. These results will support the development of practical guidance for superintendents who are interested in integrating data-driven or precision irrigation approaches into everyday irrigation scheduling.

USGA ID#: 2025-07-838

Title: DETERMINATION OF WATER POTENTIALS LIMITING TURFGRASS WATER UPTAKE TO DEVELOP CRITICAL THRESHOLDS FOR IRRIGATION EVENTS.

Project Leader: David Jespersen

Affiliation: University of Georgia

Objectives:

- 1) Determine if soil water potential sensors can more accurately and consistently identify when a critical threshold has been reached in contrasting soil textures compared to TDR sensors.
- 2) Compare a modern drought tolerant cultivar (TifTuf) to an older standard (Tifway) to understand if the ability to extract water is one of the traits improved by recent breeding efforts.
- 3) Compare the placement of shallow and deep sensors to determine if a given sensor depth provides more valuable information, or if the critical depth changes as seasonal growth progresses.

Start Date: 2025

Project Duration: 3-years (2025-2027)

Total Funding: \$59,508

Summary Points: Include 3-6 bullet points summarizing key findings to date

- Weighing lysimeters were established with embedded soil water potential and time domain reflectometry soil moisture content sensors
- Soil water potential sensors demonstrated little changes in signal when the soil was moist, but a relatively greater response as it dried.
- Differences in sensor data between cultivars may indicate differences in distribution of water uptake.

Summary Text:

Rationale: Conservation of water is a critical goal for golf course superintendents. However, determining when plants require water can be difficult to fully understand, with irrigation requirements being dependent on weather conditions, soil characteristics, and other management factors (e.g. cultivar used, mowing height). Soil water potential sensors promise to accurately quantify the water potential of the soil and estimate when water is still available for plant uptake, regardless of soil type. Therefore, it may be possible to leverage the use of these sensors to more accurately time irrigation events for when plants require supplemental water.

Methodology: Sod from mature fields was harvested and transplanted into weighing lysimeters and allowed to establish in greenhouse conditions prior to being moved at trial initiation (Figure 1). Lysimeters are approximately 30 cm in diameter and 50 cm deep. Three rootzone mixtures

were used: a Cecil sandy clay loam, more typical of piedmont soils sourced from Griffin, GA, a Tifton loamy sand more typical of coastal plain soils in South Georgia, as well as a calcined clay (Turface) rootzone to allow for comparison to previous literature on evapotranspiration rates that frequently utilize a calcined clay rootzone. The tested cultivars included ‘TifTuf’ and ‘Tifway’ hybrid bermudagrass (*Cynodon dactylon* x *Cynodon transvaalensis*). Within the two soil types, Teros 21 soil water potential sensors (Meter group) were installed at 15 cm and 7.5 cm depth. Additionally, a TDR-310 soil moisture sensor (Acclima) was also installed at a depth of 7.5 cm. Sensors were connected to a datalogger (DT80; CAS dataloggers) that collects readings hourly over the course of the study. Lysimeters were positioned on custom load-cell platforms to capture weights and to gravimetrically calculate total water loss from the system (Figure 2). All lysimeters were brought to field capacity at the initiation of the trial, and received no further irrigation for the remainder of the trial, with the exception of the calcined clay rootzone that was brought to field capacity every 5-days to serve as a well-watered control and did not have the buried suite of sensors. In addition to automatically logged sensor data, every 7-days leaf relative water content, digital images for percent green cover, and canopy reflectance data were collected.

Results to date: Over the course of the study, lysimeters lost water at a fairly consistent rate, and there was little difference between cultivars in the rate of total water lost. Interestingly, the deeper soil water potential sensor showed a difference between the two cultivars, perhaps indicating a spatial difference in how the two cultivars are extracting water from the soil profile (Figure 3). As expected, the two different sensor types (soil water potential, and soil water content estimated via TDR), had contrasting response curves as the soil dried (Figure 4). Under the moist conditions in the first 10-days of the trial, there was little response in the Teros 21 soil water potential sensor when soil moisture was readily available. This is in contrast to the relatively larger changes in volumetric water content observed with the TDR sensor. As the soil continued to dry, this relationship changes with the soil water potential displaying relatively greater changes in signal compared to the estimated volumetric water content. Ultimately an end-user would need to make a decision about the importance of the data while a field is moist and relatively well-watered, compared to the information gained under drought conditions when selecting sensors. However, as data is too preliminary to make any strong recommendations, and additional years data will build on current results.

Future expectations: Data from the first year’s experiment will continue to be analyzed. Additional trials will be conducted in the upcoming years. This will allow for building a more robust data set to identify water potential thresholds for bermudagrass, and understand potential differences between cultivars, and the effects of environmental variables (e.g. soil type, rate of soil dry down).

Images:



Figure 1: Establishment of weighing lysimeters in greenhouse conditions, prior to the beginning of the trial

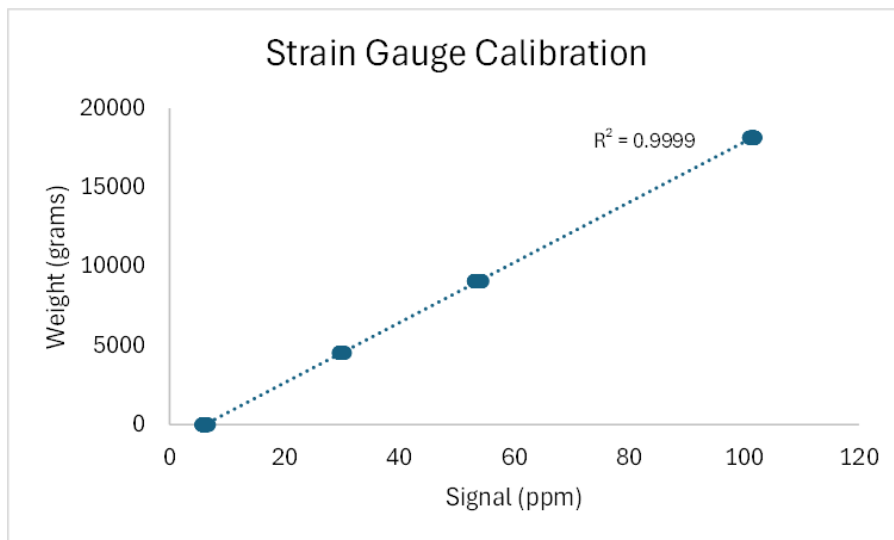


Figure 2: Calibration curve of load cell platforms to estimate water loss from weighing lysimeters.

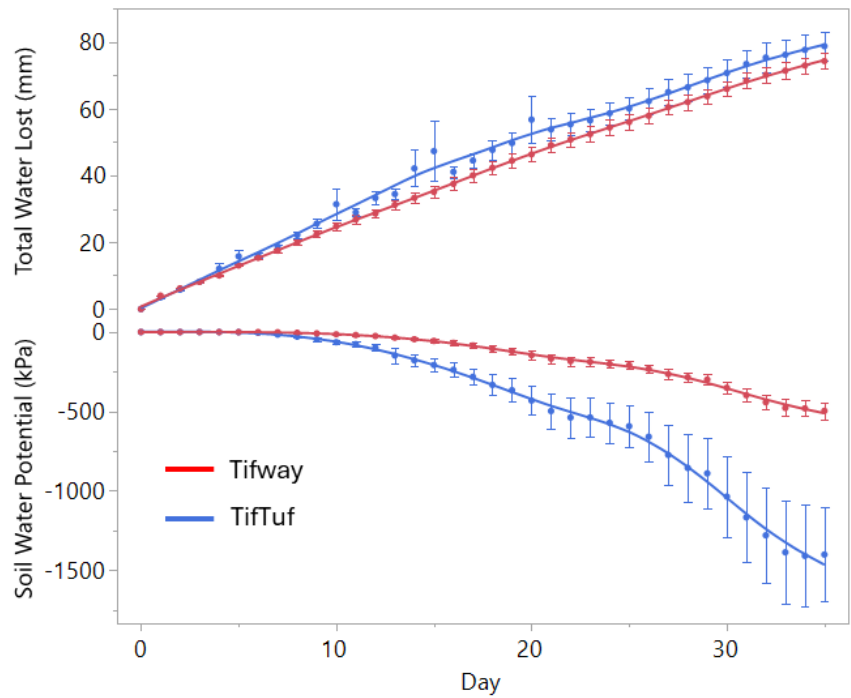


Figure 3: Comparisons in changes in total water loss, with soil water potential sensors in TifTuf and Tifway hybrid bermudagrasses.

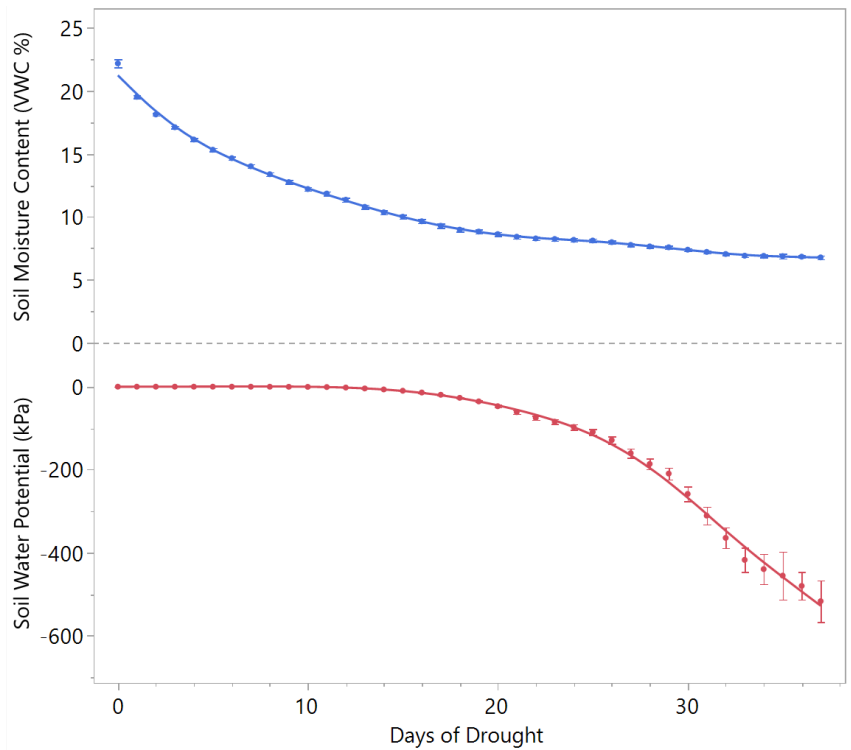


Figure 4: Comparisons between water potential sensors and TDR soil moisture sensors as water content decreases in a Cecil sandy clay loam.

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 the project are to evaluate the longer-term effects of both conventional and emerging cultivation strategies in combination with gypsum applications for 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:

- Linear decompaction + hollow tine aerification treatment causes a temporary decline in turfgrass quality and cover directly following cultivation but does not differ from the untreated plots within two weeks.
- Linear decompaction treatments provide similar levels of surface hardness reduction compared to traditional aerification methods.
- Linear decompaction treatments are showing improved turfgrass quality ratings over the control plots.

Summary:

As the quality of water available for golf course irrigation continues to decline, improved knowledge of cultural strategies to mitigate these deleterious are needed. 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 combat this problem; however it is extremely costly for a full 18-hole facility. Gypsum applications have been the traditional recommendation for counteracting sodic soils but may only have marginal effects. Although traditional solid and hollow tine aerification is 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 to fracture the upper soil profile to help relieve this hard pan layer. Literature on the linear decompaction unit is limited to one publication where it was tested on a native soil sports field. 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 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 and hollow tine and deep solid tine aerification. Briarcrest Golf Course is a public course with over 40,000 rounds per year with 'Tifway' bermudagrass on native clay loam soil.

Arranged as a randomized complete block design, treatments were implemented as 1) solid tine aerification, 2) hollow tine aerification, 3) deep solid tine, 4) linear decompaction (shockwave) perpendicular to slope, 5) shockwave parallel to slope, 6) shockwave different direction each event, 7) shockwave + hollow tine, 8) control (no cultivation). All treatments except the control were implemented with and without topdressing following cultivation. Gypsum was applied at 3,660 kg ha⁻¹ yr⁻¹ in one application in August and cultivation treatments were conducted in July and October. To assess treatment differences, turfgrass quality, NDVI, lightbox images, soil moisture (0-5cm), and surface firmness were measured biweekly. Soil bulk density cores were taken the first week of December to determine changes in physical properties. At the conclusion of the study, soil samples were obtained to determine changes in soil chemical properties. All data was subjected to the GLIMMIX procedure in SAS (v9.4). Means were separated using Fisher's LSD ($P \leq 0.05$).

To date it has been observed that the shockwave + hollow tine as well as the hollow tine only treatment is the most damaging treatment compared to solid and deep solid tine aerification. While initially, there is a significant loss of density from these treatments, four weeks after treatment the canopy density increases. After the fall 2024 treatments recovered, it was found that the shockwave (perpendicular) and the solid tine treatments were in the top statistical group for turfgrass color and density.

Across the first year, a cultivation method by sand topdressing interaction was observed for soil moisture (VWC), electrical conductivity (EC), surface firmness, percent green cover, and turfgrass quality. Plots that were cultivated with traditional solid tine, deep solid tine, and shockwave (different direction each event) were found to have lower soil moisture content when topdressed with sand. Only the shockwave treatment parallel to the slope was found to have higher VWC when topdressed with sand. All cultivation methods, except for traditional hollow tine aerification, reduced surface firmness over the untreated control when not topdressed with sand. Topdressing reduced surface firmness in plots cultivated with hollow tine and shockwave (perpendicular), and increased surface firmness in shockwave (both directions) treated plots. It was observed that sand topdressing increased percent green cover in shockwave (perpendicular), hollow tine, and shockwave + hollow tine treated plots. A reduction in % green cover after topdressing was noticed in plots cultivated with traditional solid tine aerification. Unacceptable turfgrass quality was measured from plots receiving hollow tine and shockwave (parallel) when not topdressed with sand. When sand topdressing was performed, the shockwave and shockwave + hollow tine treatments were found to have unacceptable turfgrass quality.

Field Lab Study:

A parallel field study is being conducted at the Texas A&M University Turfgrass Research Center. Arranged as a split plot design with cultivation method as the whole main plot and sand topdressing as the sub plot, the aforementioned treatments 1-8 (from the golf course study) were implemented in addition to a no cultivation + gypsum treatment to compare cultivation treatments to gypsum applications. Starting July 2024, native soil was brought in to renovate an existing plot and to construct a turtleback with a 4% slope on each side simulating a sloping golf course fairway. The first 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, there has been a significant cultivation method main effect for soil moisture, surface firmness, and turfgrass quality. Only the gypsum treatment was found to have higher soil moisture content than the control. The treatments receiving deep solid tine aerification were found to have lower soil moisture content than the control, shockwave + hollow tine, and the gypsum plots. The shockwave + hollow tine aerification

treatment was the only treatment found to reduce surface firmness compared to the control. All treatments, including the control, were found to produce acceptable turfgrass quality. The lowest TQ was measured in the shockwave (both directions) treatment. Although not different from the control, the highest TQ was measured in the gypsum, shockwave + hollow tine, shockwave (parallel) and the hollow tine treatments. Directly following the summer (8/29/25) cultivation event it was found that the shockwave + hollow tine and the shockwave (both directions) treatments were more damaging than the deep solid tine treatment and reduced turfgrass density. However, the shockwave + hollow tine and shockwave (both directions) were not significantly more damaging than the other treatments. Sand topdressing, pooled across all treatments, was found to increase turfgrass quality from an unacceptable 5.8 to an acceptable 6.7 turfgrass quality score. It was also found that sand topdressing significantly lowered the measured soil electrical conductivity.

Na-Degraded Soil Characterization and Establishment Study:

To better understand and reestablish sodic soils, a series of soil samples were collected and a plugging trial was conducted at Texas A&M University's campus as well as at Pebble Creek Country Club, College Station, TX. The objective of this multilocation field study was 1) to characterize chemical and physical soil conditions within and adjacent to historically sodium degraded areas and 2) determine establishment success of plugs of various turfgrass species.

Soil samples were collected from four sodium degraded areas at each location by taking a sample from the middle of the bald spot, the healthy turf/bald spot interface, and from a full turfgrass stand adjacent to the bald spot. The bulk density of each sample was calculated before submitting to the Texas A&M AgriLife Extension Soil, Water, and Forage Testing Lab for salinity analysis. Saturated hydraulic conductivity was measured using double ring infiltrometers and collected in the same areas as soil samples were taken. After characterization of soil properties, an establishment study was conducted in the same sodium degraded soil at each location. Washed plugs (25cm²) of 'Tahoma 31' and 'TifTuf' bermudagrass (*Cynodon dactylon* (L.) pers. x *C. transvaensis* Burt-Davy), 'Zeon' zoysiagrass (*Zoysia matrella* (L.) Merr.), and 'Platinum TE' seashore paspalum (*Paspalum vaginatum* Swartz.) were planted in bare soil or bare soil capped with 2.5 cm layer of either Field and Fairway Emerald (Profile, Buffalo Grove, IL) or an 80:20 (v:v) sand:compost mixture (Comand Turf, Life Soils, Winter Garden, FL). The TAMU Campus location was planted June 10th and the PCCC location planted July 14th, 2025. After planting, plug diameter and lightbox pictures were taken weekly to quantify lateral spread for 12-weeks. Average diameter was measured by taking two perpendicular measurements with the first being the largest diameter of the plug. Plugs were fertilized with 49 kg N ha⁻¹ (17-17-17) four and eight weeks after planting. At the end of the 12-week period, all aboveground biomass was collected along with a 5 cm X 15 cm plug from each plot to quantify root biomass. Root and shoots tissue were dried at 65°C for 72 hours before being weighed. Data were analyzed using ANOVA in PROC GLIMMIX (SAS v9.4, Cary, NC). Where significant differences were detected, mean separation was performed using Fishers LSD ($P \leq 0.05$).

All soil samples taken from TAMU were classified as sodic soils (EC < 4, pH > 8.5, and SAR > 12). Degraded areas at PCCC were classified as saline-sodic (EC > 4, pH < 8.5, and SAR > 12). The transition and full turf areas at PCCC were not saline, sodic, or saline-sodic. In all areas tested, soil bulk density was at or above the critical bulk density range for a sandy loam soil (1.5-1.7 g/cm³), likely contributing to the low hydraulic conductivity and poor turf coverage in these areas.

Pooled across all cultivars and capping methods, there was a significant location main effect for aboveground biomass and average plug diameter. At the TAMU location, plugs averaged 16.8 cm in diameter and 17.3 g of biomass compared to the 5.2 cm diameter and 0.4 g biomass collected from PCCC. Pooled across location, there was a cultivar by week interaction in which TifTuf had the greatest lateral spread during the study but did not differ from Tahoma 31 on the initial 10 of 12 dates. Zeon zoysiagrass showed the slowest establishment of all cultivars. Platinum TE seashore paspalum was intermediate and did not differ from Tahoma 31. A cultivar by capping material interaction was observed and showed that the sand + compost mixture increased plant growth in all cultivars (except Zeon) relative to bare soil at TAMU. At PCCC, only TifTuf grown in sand + compost or Profile was different from the bare soil treatments. Based on these results, planting TifTuf bermudagrass into a sand + compost capping mix appears to provide the highest success in reestablishment of sodium-degraded areas.

Figures:

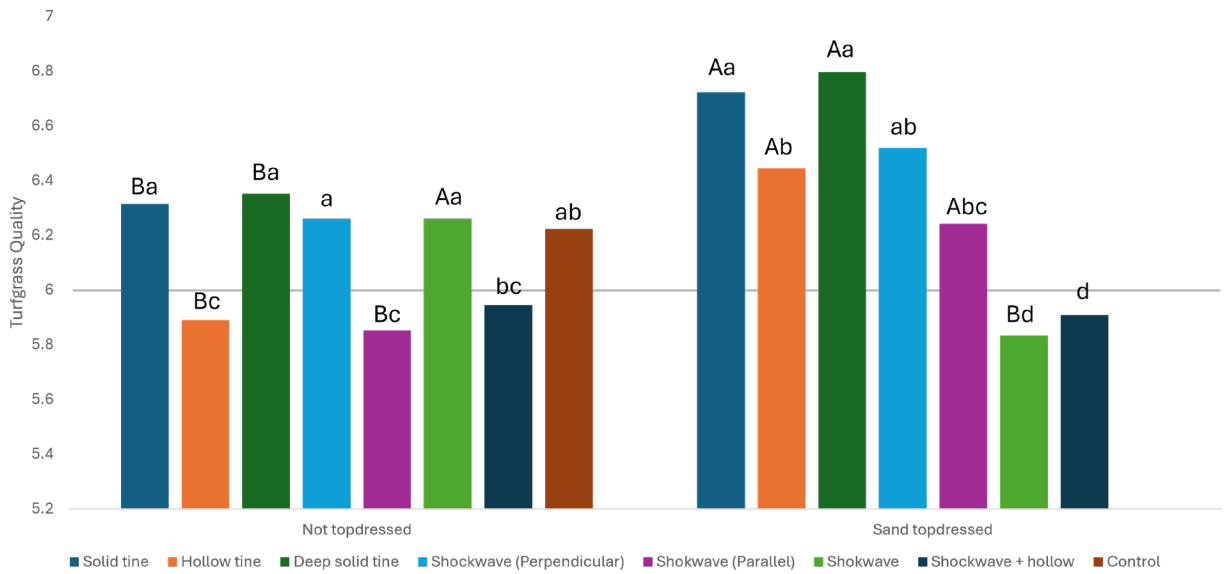


Figure 1. Cultivation method by sand topdressing interaction for turfgrass quality from the Briarcrest Golf Course location. Lower case letters indicate significance within each topdressing treatment. Upper case letters indicate significance between cultivation treatments across topdressing treatment.

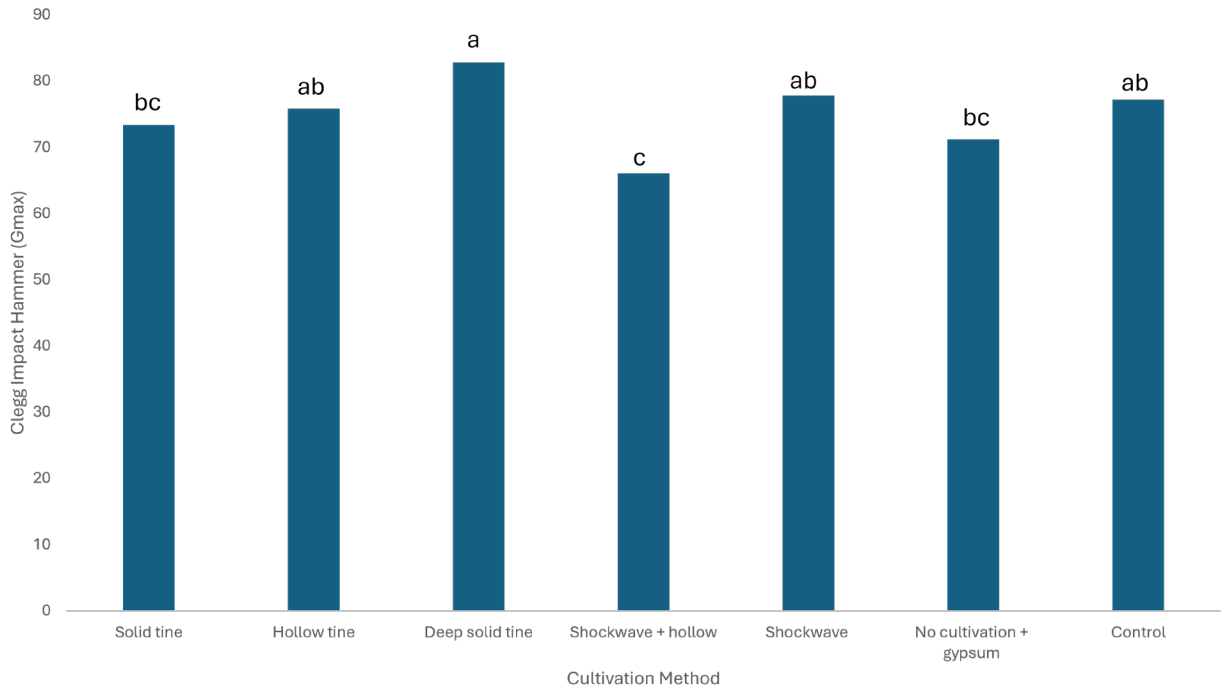


Figure 2. Treatment main effect of surface firmness at the TAMU field lab location for plots not receiving sand topdressing. Means that share the same letter are not significantly different from each other.



Figure 3. Image of linear decompaction scars on turfgrass canopy. Horizontal lines are from a treatment implemented the same day the picture was taken; vertical lines are from a treatment implemented three months before the picture was taken. Image taken October 3, 2024.



Figure 4. Comparison turf quality in no sand topdressing plots (left) vs. those receiving sand topdressing (right) across all cultivation methods. These pictures were taken on 11/19/25. Cultivation treatments were imposed three weeks prior to photo being taken.



Figure 5. Image of a sodium degraded area selected for the re-establishment study at the TAMU location. The double ring infiltrometers show the approximate areas where the soil chemical/physical characterization samples were obtained.



Figure 6. Two replications of the plugging study conducted at TAMU showing differences in the rate of growth of the species and topdressing methods used. Image was taken 12-weeks after planting.

USGA ID#: 2024-06-816

Project Title: Effect of acidification on soil bicarbonate concentration, infiltration rate, and Kentucky bluegrass performance.

Project Leaders: Elena Sevostianova¹, Maria Bronnikova², and Bernd Leinauer¹

Affiliation: ¹New Mexico State University, ²Texas Tech University

Objectives:

1. Assess the effect of N-pH_{uric} acid and WaterSOLV™ Curative on bicarbonate concentrations and other chemical properties within the rootzone.
2. Evaluate the influence of gypsum applications on bicarbonate levels, additional soil chemical parameters, and Kentucky bluegrass quality.
3. Determine whether gypsum applications alter the accumulation of carbonates in the soil.

Start Date: 2021

Project Duration: 3 years (extended to 2024-2026)

Total Funding: \$116,580.00

Summary Points:

- Although bicarbonate levels increased during the fall sampling periods, no evidence of long-term bicarbonate accumulation in the soil was found as of 2025.
- Gypsum applications had strong, consistent effects on all measured soil chemical parameters.
- Gypsum significantly reduced HCO₃⁻ concentrations, bringing all water treatments to similarly low levels across soil depths.
- Gypsum and sampling month were the primary drivers of Kentucky bluegrass quality and altered several key tissue nutrients (e.g., total N, Mn, and S) but had no measurable impact on others.
- Basalt dust accumulated more carbonate than decalcified soil; however, carbonate accumulation did not differ among the irrigation treatments.

Summary Text

Background and Rationale

Irrigation of golf course turf with low-quality water presents several challenges due to the high variability of chemical constituents. Among these, elevated bicarbonate concentrations—and their purported impacts on soil infiltration, structure, and turfgrass performance—remain a topic of debate. Claims linking bicarbonates to poor turf performance often lack supporting measurements of soil chemistry or turfgrass nutrient status, limiting the reliability of such conclusions. Although acidification is a widely used and expensive strategy to reduce bicarbonates in irrigation water, little long-term research exists to demonstrate its effectiveness or its sustained impact on turfgrass performance.

To improve scientific understanding of these relationships, gypsum was included as an additional treatment because of its potential to precipitate calcium carbonate in the soil, alter soil chemical properties, and influence turfgrass quality. Incorporating gypsum enables a more comprehensive

evaluation of whether observed responses are attributable to bicarbonate concentrations specifically or to interactions among multiple chemical factors.

This study was therefore designed to investigate the interactions among irrigation water quality, soil chemistry, and Kentucky bluegrass tissue nutrient composition under field conditions at New Mexico State University.

Methods

A field experiment was established in 2020 at the NMSU's Turfgrass Research Center in Las Cruces, NM, using the Kentucky bluegrass cultivar 'Barserati'. The site consisted of Bluepoint sandy loam soil arranged in sixteen 2.7 m × 2.7 m plots in a completely randomized block design.

Beginning in 2021, four 1,890-L (500-gallon) tanks were used to prepare irrigation water treatments (Figure 1). Sodium and potassium bicarbonate were added as needed to achieve target concentrations of approximately 500 ppm. Plots were hand-irrigated five times per week at 80% of reference evapotranspiration. Treatments consisted of:

1. Control: Potable tap water (low bicarbonate, ~200 ppm).
2. High bicarbonate: Potable water with elevated bicarbonate (450–500 ppm).
3. N-pHuric: high-bicarbonate water adjusted to pH 6.5 using N-pHuric acid.
4. Curative: high-bicarbonate water amended with WaterSOLV™ Curative per label instructions.

Water chemistry for the four treatments is summarized in Table 1.



Figure 1. Four water tanks containing tap water (Control), water high in bicarbonate, water high in bicarbonate with N-pHuric, and water high in bicarbonate with WaterSOLV™ Curative (left to right).

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

Beginning July 2024, each irrigation plot was divided in half, and one half received granular gypsum at 244 g m (50 lbs per 1,000 ft²) every two weeks. All plots except those receiving N-pHuric were fertilized with urea to ensure uniform nitrogen inputs across treatments (~34 g N m⁻² or 7 lbs 1000ft⁻² per season). Soil samples were collected at 0–10, 10–20, and 20–30 cm depths before and after the growing season.

Containers filled with decarbonated soil or basalt dust were installed to monitor carbonate accumulation at 0–10 and 20–30 cm depths under various irrigation treatments and in non-irrigated soil. These containers served as an additional source of silicate-bound calcium to promote carbonate formation through Ca-silicate weathering and atmospheric CO₂ sequestration.

Baseline and first-year measurements of CaCO₃ content were completed in May 2025 and analyzed for CaCO₃ content using Model CM5018 CO₂ Coulometer (UIC, Inc., IL) (Figure 2).



Figure 2. The CM5018 CO₂ Coulometer used in this study.

Turf quality (1–9 scale) was recorded monthly from June to November. Tissue nutrient analyses were conducted on samples collected in June and September 2025. All treatments were replicated four times. Data were analyzed using ANOVA (SAS PROC GLIMMIX) with Fisher’s LSD used for mean separation at $\alpha = 0.05$. Soil chemical variables were log-transformed as needed to satisfy model assumptions.

Results

Soil Chemical Parameters

ANOVA results (Table 3) indicate that in fall 2025, both irrigation treatment and gypsum application significantly affected soil bicarbonate concentrations. In all irrigation treatments, gypsum application reduced soil HCO_3^- (Figure 3). Without gypsum, high-bicarbonate irrigation increased soil pH, whereas gypsum exerted a mild acidifying effect, eliminating pH differences among treatments at both 0–10 and 10–20 cm. Gypsum significantly increased Ca at all depths. Although water treatments influenced Ca accumulation, the effects were minor relative to gypsum, particularly at the soil surface.

For Na, depth was the only significant factor, with concentrations increasing progressively from 10 to 30 cm. For Mg (log-transformed), gypsum exerted a strong positive effect that differed by depth: Mg decreased slightly with depth in untreated soil but increased with depth in gypsum-treated soil.

Overall, no evidence of long-term bicarbonate accumulation in the soil was detected.

Table 3. P-values from ANOVA testing the effects of four water treatments (Control, high bicarbonate, high bicarbonate with N-pHuric, and high bicarbonate with WaterSOLV™ Curative), gypsum application (with or without), soil depth (0–10, 10–20, and 20–30 cm), and their interactions on soil chemical characteristics in fall 2025.

Effect	pH	EC	HCO_3^-	Na	Ca	Mg	SAR
Water treatment	<.0001	0.4457	<.0001	0.7543	0.0005	0.0229	0.0008
Gypsum	<.0001	<.0001	<.0001	0.769	<.0001	<.0001	<.0001
Water treatment*Gypsum	<.0001	0.8751	0.0001	0.7536	0.3528	0.6561	<.0001
Depth	<.0001	0.1016	<.0001	0.0051	<.0001	0.3177	<.0001
Water treatment*Depth	0.0308	0.64	0.2318	0.1775	0.4918	0.6792	0.0101
Gypsum*Depth	<.0001	0.1805	0.101	0.6453	0.003	<.0001	0.0098
Water treatment* Gypsum*Depth	0.0288	0.3335	0.3836	0.453	0.0642	0.3222	0.1366

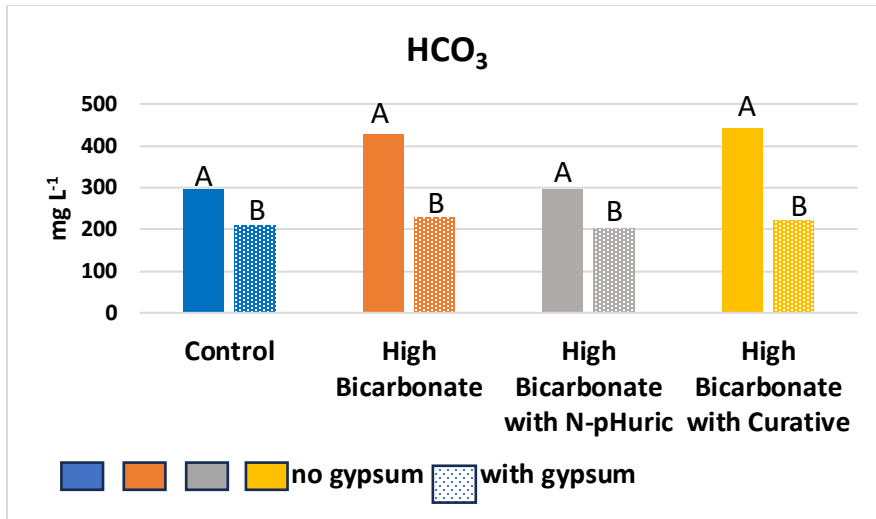


Figure 3. Bicarbonate concentrations (mg L⁻¹) in soil irrigated with four water treatments (Control, high bicarbonate, high bicarbonate with N-pHuric, and high bicarbonate with WaterSOLVTM Curative), gypsum application (with or without). Data are averaged over three depths (0-10, 10-20, and 20-30 cm) and four replications.

Carbonate Accumulation

Because carbonate formation is a relatively slow process, longer observation periods will be necessary to more accurately characterize carbonate accumulation dynamics. After one year, basalt dust accumulated significantly more carbonate than decalcified soil in irrigated plots ($p < 0.001$). In contrast, this difference was not statistically significant in native non-irrigated soil ($p = 0.0739$). Although calcium carbonate accumulation was consistently higher in irrigated plots than in their non-irrigated counterparts, the differences between water treatments were not statistically significant (Figure 4).

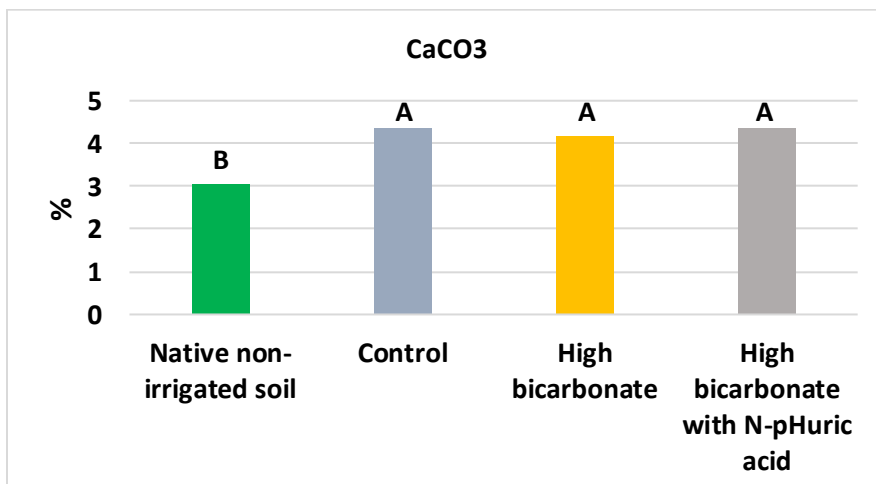


Figure 4. Accumulation of CaCO₃ (%) in native non-irrigated soil and irrigated with three water treatments (Control, high bicarbonate, high bicarbonate with N-pHuric). Data are averaged over two depths (0-10, and 20-30cm).

Turfgrass Visual Quality

Kentucky bluegrass irrigated with high-bicarbonate water with N-pHuric exhibited reduced visual quality relative to all other treatments. Quality declines were evident early in the season, became more pronounced by September, and have progressively intensified over the past four years.

After gypsum applications were initiated, ANOVA demonstrated that gypsum and sampling month were the primary determinants of turf quality, while irrigation treatment played a secondary role (Table 4). Gypsum improved turf quality throughout the season, with the strongest effects observed in September and October (Figure 5).

Treatment differences emerged largely in the late season, with N-pHuric performing the poorest. Overall, turf quality followed a seasonal pattern, with early-season peaks, mid-season declines, and gypsum-driven improvements later in the season (Figure 6).

Table 4. P-values from ANOVA testing the effect of four water treatments (Control, high bicarbonate, high bicarbonate with N-pHuric, and high bicarbonate with WaterSOLV™ Curative), gypsum application (with or without), and their interactions on visual quality of Kentucky bluegrass in 2025.

Effect	Visual quality
Water treatment	0.0034
Gypsum	<.0001
Water treatment*Gypsum	0.3794
Month	<.0001
Water treatment*Month	0.0575
Gypsum*Month	<.0001
Water treatment*Gypsum*Month	0.7903



Figure 5. Kentucky bluegrass irrigated with high-bicarbonate water, showing the gypsum-treated side (right) and untreated side (left) in August 2025.

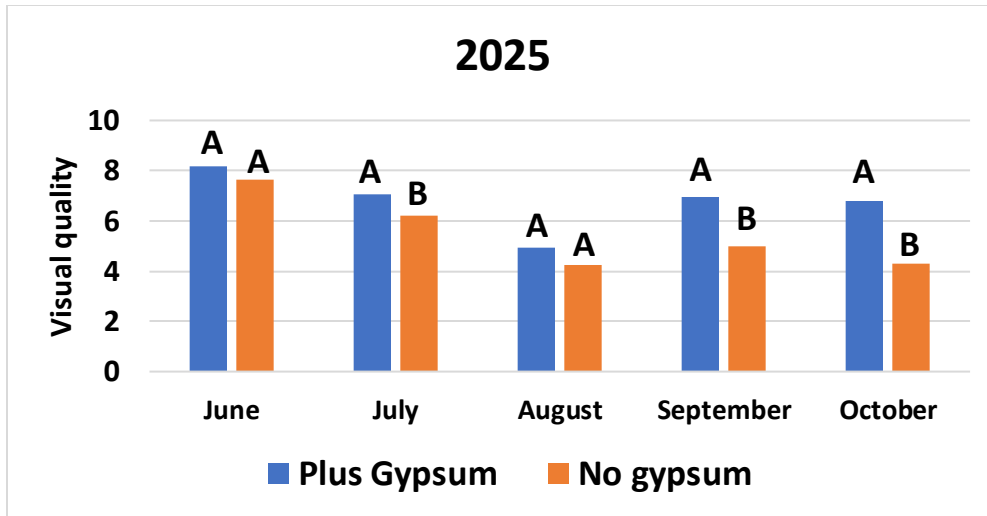


Figure 6. Quality (from 1=worst to 9=best) of Kentucky bluegrass with and without gypsum application in 2025. Data were averaged over four water treatments (Control, high bicarbonate, high bicarbonate with N-pHuric, and high bicarbonate with WaterSOLV™ Curative) and four replications.

Plant tissue

ANOVA P-values indicated a significant two-way interaction between water treatment and gypsum application on sulfur and sodium concentrations in Kentucky bluegrass tissue in fall 2025 (Table 5).

Table 5. P-values from ANOVA testing the effect of four water treatments (Control, high bicarbonate, high bicarbonate with N-pHuric, and high bicarbonate with WaterSOLV™ Curative) gypsum application (with or without) on nutrients in grass tissue in summer 2025.

Effect	N _{total}	Fe	S	Ca	Na	P	K	Zn	Mn
Water treatment	0.089	0.852	0.012	0.0003	0.000	<.0001	0.001	0.003	0.014
Gypsum	0.027	0.695	<.0001	<.0001	0.002	0.315	0.154	0.734	0.022
Water treatment* Gypsum	0.677	0.323	0.028	0.370	0.016	0.045	0.695	0.104	0.785

Gypsum reduced total nitrogen in Kentucky bluegrass tissue across all treatments. Neither irrigation treatment nor gypsum influenced tissue iron, and no chlorosis symptoms were observed. Gypsum substantially increased tissue sulfur across all irrigation treatments. Tissue calcium was highest under the Control and high-bicarbonate with N-pHuric treatments and lowest under the high-bicarbonate and Curative treatments, and gypsum significantly increased calcium across all irrigation treatments.

A significant treatment × gypsum interaction was observed for both sodium and phosphorus. For sodium, tissue concentrations without gypsum followed the pattern N-pHuric > High Bicarbonate ≈ Curative > Control. With gypsum, sodium declined sharply in both the Curative and high bicarbonate treatments but remained largely unchanged in the Control and N-pHuric treatments. For phosphorus, Control exhibited the highest tissue phosphorus and N-pHuric the lowest in the absence of gypsum. With

gypsum, phosphorus decreased only in the N-pH_{uric} treatment, while the other water treatments were unaffected.

Kentucky bluegrass irrigated with the Control and Curative treatments exhibited the highest tissue manganese concentrations, whereas the lowest concentrations occurred under the high-bicarbonate with N-pH_{uric} treatment. Gypsum application produced a uniform increase in tissue manganese across all irrigation treatments. Tissue zinc concentrations were highest in the Control and Curative treatments, intermediate under the high-bicarbonate treatment, and lowest under the N-pH_{uric} treatment; gypsum application had no effect on zinc levels.

Future expectations of the project

Continued gypsum applications will provide additional insight into the influence of bicarbonate, associated soil chemical parameters, and the temporal dynamics of carbonate formation.

Samples collected in 2025 after one year of exposure were submitted for thin-section preparation and will be examined by polarizing microscopy to characterize carbonate morphology, distribution, and pore-space associations. Subsamples of the substrates, along with soil and water samples, are undergoing stable isotope analysis to identify carbon sources for newly formed carbonates. The same analyses, including coulometric CaCO₃ measurements, micromorphology, and isotope studies, are planned for 2026 after two years of exposure.

Collectively, these efforts will improve our ability to characterize and predict bicarbonate- and carbonate-related processes in turfgrass irrigated with low-quality water.

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 compare 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 managed by a graduate student, with data collected during the growing season (May–November 2025) to evaluate the effectiveness of subsurface drip irrigation under fairway traffic stress conditions.
- Soil moisture sensors were installed in each plot to monitor root-zone volumetric water content and to guide irrigation scheduling for bermudagrass based on sensor readings.
- Subsurface drip irrigation (SDI) plots demonstrate notable reductions in the total volume of water applied while maintaining turfgrass health, with overall water use lower than that of sprinkler-irrigated plots during the study period.
- Turfgrass quality indicators, including color, density, and green cover, showed variability but remained within acceptable ranges under SDI-managed fairway conditions.

Summary

Subsurface drip irrigation (SDI) is one of the water-saving technologies that has been shown to reduce water usage and enhance turfgrass quality. It does this by minimizing surface water evaporation and lowering the risk of weed growth and disease. According to Rodríguez and Gil (2012), SDI can conserve 25% to 50% more water compared to surface irrigation methods. When compared with sprinkler systems, SDI also results in less runoff, reduced evaporation, and more even water distribution. Because the soil surface remains drier, SDI minimizes compaction from foot traffic, which helps maintain turfgrass health and quality (Ferguson, 1994). On golf courses,

SDI has proven capable of delivering turfgrass quality comparable to that achieved with overhead sprinklers (Thompson, 2019).

This research is being conducted at the Center for Turf, Irrigation, and Landscape Technology (CTILT) at California State Polytechnic University, Pomona. The study utilizes 10-by-10-ft. (3-by-3 meter) plots of Tahoma 31 hybrid bermudagrass, sodded in summer 2023. There are twelve plots in total, with three assigned to SDI treatments and one serving as a sprinkler-irrigated control. The experiment follows a randomized complete block design with three replications, and each plot is independently zoned and managed. The turf is grown on sandy clay loam soil. A graduate student is leading this study as part of their MS thesis.

The project compares subsurface drip irrigation systems, featuring emitter tubing from Hunter Industries, with conventional sprinkler systems programmed based on evapotranspiration (ET) data. Soil moisture sensors (SMS) are installed in each plot to monitor volumetric water content and help determine irrigation needs per treatment. Additionally, traffic stress is applied to half of the plots to simulate mechanical wear and evaluate its effect on turfgrass performance. Turf quality assessments, including visual evaluations of color and overall health, are being used to measure the impact of both irrigation type and stress. The data aims to determine whether SDI can match or surpass sprinklers in maintaining turf quality while optimizing water use under varying traffic conditions.

Before setting final control points on the sensor controllers, two wetting and drying cycles were conducted to verify accurate sensor performance. Based on the sandy clay loam soil analysis and standard reference tables, the field capacity is estimated at around 29% volumetric water content (compared to 32% for clay loam). Water application rates are recorded using hour meters connected to each plot's irrigation valve.

Tahoma 31 bermudagrass is maintained at a mowing height of 0.5 inches and mowed twice per week. Fertilization is applied at a rate of 0.4 pounds of nitrogen per 1000 ft² per growing month, divided into biweekly applications to maintain consistent shoot growth and avoid peaks and valleys (Foy, 2014).

During the study, SDI and control plots showed significant variation in turf quality. Fairway plots under traffic stress exhibited lower quality and color ratings than non-trafficked plots. Additionally, control plots required more irrigation than SDI plots. Further analysis will be required to fully interpret these trends and their implications.

In the second year, the study resumed between late April and early May, with data collection beginning in June 2025. Performance differences between sprinkler and SDI plots continued to be observed. Plots with SDI developed healthy turf patches aligned with drip line placement. Although traffic stress was applied to both treatment types, all plots demonstrated excellent recovery, and no substantial differences in performance were detected. Turfgrass density ratings averaged 4.5 in SDI plots, compared to 6.0 in sprinkler-irrigated plots.



Image 1: Twelve bermudagrass plots, CPP.



Image 2: Visit of USGA delegates at CTILT and observing the research 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#: 2024-08-818

Title: Environmental and economic comparison between Capillary Hydroponic System and Variable Depth Rootzone to promote sustainable putting green management

Project Leaders:

Thomas A Nikolai, Ph.D. Michigan State University, Michael Rabe Michigan State University

Collaborators:

Wei Zhang, Ph.D. Michigan State University, Kevin Frank Ph.D. Michigan State University, and Brian Horgan, Ph.D. Michigan State University

Objectives:

1. Determine differences in irrigation water used between 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: 2024

Project Duration: 2-years

Total Funding: \$29,876.56

Summary Points:

- CHS greens required 55% less irrigation than VDR greens while maintaining comparable turf quality, green speed, and clipping yield.
- Location within the greens had a measurable effect on firmness across all dates, and a significant interaction between treatment and location was observed on three of five dates, with the highest firmness consistently in low areas of CHS.
- SOM did not differ overall between CHS and VDR but showed a significant interaction with treatment and location, with low areas of CHS accumulating the most SOM, indicating emerging spatial variability as the CHS greens mature.

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 improved when adopting new water 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 (Figure

1). All six research greens were constructed with sand particles conforming to USGA specification.

Figure 1 Research site of CHS and VDR greens at Hancock Turfgrass research Center at Michigan State University, East Lansing, MI, 2025.



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 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 valve that controls an adjustable water table. The VDR greens diverges from USGA construction 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 once a week.

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. CHS greens

only received overhead irrigation following sand topdressing, fertility, and fungicide applications receiving the same volume of irrigation as VDR on those occasions.

Soil moisture has been monitored since 2023 at 7.5 cm, with a handheld TDR 350 across the greens surface in a 1.5 m x 1.5 m grid to map uniformity of moisture distribution. Surface firmness was measured with a USGA GS3 in a drop tester. Six readings were taken in the high areas and six in the low areas of each plot's surface. Additionally, the data collection method for surface firmness and surface organic matter accumulation was modified, adding a location factor within plots, surface organic matter (SOM) was measured following OM246 protocol (USGA, 2024) with three samples taken from high areas and three in the low areas of each plot's surface.

Other data collection included green speed measurements with a USGA Stimpmeter, soil testing, drainage water testing, clippings yield, and visual rating of pests and drought stress.

Results to Date

In 2025, CHS greens required 55% less irrigation water compared to VDR greens. In 2023 and 2024 moisture at a 7.5 cm depth in CHS was less uniform across the plot than VDR (Figure 2) and Surface firmness did not differ between treatment. In 2025 location affected surface firmness on all five data collection dates and there was a significant interaction between location and treatment on three of five dates (Table 1). Surface firmness resulted in greater penetration in the *LOW* areas of CHS followed by the *LOW* areas in VDR. SOM did not differ significantly between plots but there was significant interaction between treatment and location with the highest SOM measured in the *LOW* areas of CHS. SOM measurements did not differ significantly in other locations across treatments (Table 2).

Figure 2 Moisture map comparing VWC as taken with a TDR-350 in CHS and VDR greens at a depth of 7.5 cm, 2025.

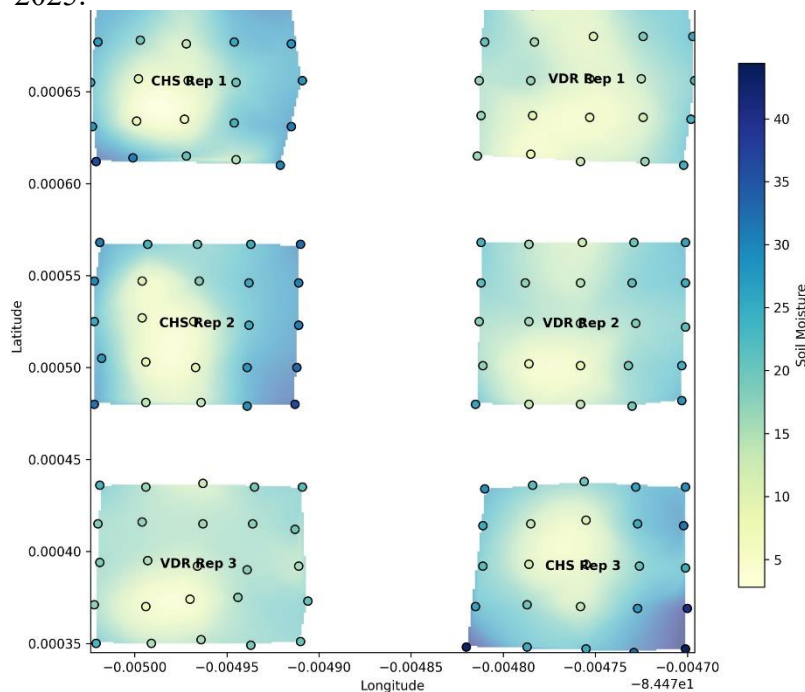


Table 1 Effect of location and treatment on surface firmness (inches) across dates as measured by a USGA GS3 in a drop fixture, 2025.

Date	1	2	3	4	5
Location	CHS				
<i>HIGH</i>	0.408 a [†]	0.417 a	0.422 a	0.415 a	0.412 a
<i>LOW</i>	0.500 d	0.475 c	0.491 c	0.459 b	0.498 d
	VDR				
<i>HIGH</i>	0.442 b	0.418 a	0.426 a	0.419 a	0.435 b
<i>LOW</i>	0.463 c	0.454 b	0.451 b	0.448 b	0.456 c

[†]Means followed by the same letter in the same column do not differ significantly ($\alpha \geq 0.05$)

Table 2 Effect of location and treatment on surface organic matter as measured by OM246 methods, 2025.

Treatment	<i>HIGH</i>	<i>LOW</i>
CHS	5.62 a [†]	9.96 b
VDR	5.93 a	7.31 a

[†]Means followed by the same letter do not differ significantly ($\alpha \geq 0.05$)

Future expectations

Across the first two years of the trial, the most consistent results showed that CHS greens required less irrigation, whereas VDR greens maintained higher moisture uniformity. Additionally, during the first two years of the trial there was no difference between treatments in regard to clipping yield, greens speed, or surface firmness. Into the third year of the trial (2025) this remains true for irrigation water applied, moisture uniformity, greens speed, and clipping yield. As the greens matured organic matter levels have increased resulting in noticeable differences between the high and low areas of the CHS greens. To date the greens have not been core cultivated as part of an organic matter control program. With SOM levels above 5% aggressive core cultivation may become necessary to return SOM to an acceptable range. The current irrigation schedule within the CHS greens is set to transfer the water every 4 hours, this is very frequent irrigation. Optimizing the frequency could lead to more uniform moisture retention, better SOM distribution and improved surface firmness.

AI Use Disclosure

OpenAI ChatGPT was used to help write Python code for processing and visualizing soil moisture data. The AI assistance was limited to programming support. All AI-generated code was reviewed, tested, and edited prior to use.

Literature Cited

Gelernter, W.D., Stowell, L.J., Johnson, M.E., Brown, C.D., & Beditz, J.F.(2015). Documenting Trends in Water Use and Conservation Practices on U.S. Golf Courses. *Crop, Forage & Turfgrass Management*, 1(1), cftm2015.0149. doi:<https://doi.org/10.2134/cftm2015.0149>

Scott, D., Rutty, M., & Peister, C. (2018). Climate variability and water use on golf courses: optimization opportunities for a warmer future. *Journal of Sustainable Tourism*, 26(8), 1453-1467. doi:10.1080/09669582.2018.1459629

Shaddox, T.W., Unruh, J.B., Johnson, M.E., Brown, C.D. & Stacey, G. 2022 Water use and management practices on U.S. golf courses *Crop Forage Turfgrass Manage.* 8 e20182 <https://doi.org/10.1002/cft2.20182>

United States Golf Association. (2024). *A standard method for measuring putting green surface organic matter*. USGA Green Section Record, 62(02). Retrieved from <https://www.usga.org/content/usga/home-page/course-care/green-section-record/62/issue-02/a-standard-method-for-measuring-putting-green-surface-organic-ma.html>

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C-3 Native Grass Herbicide Tolerance Field Trials

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Introduction

Native C-3 grasses are often slow to germinate and establish in primary and secondary rough areas. If grassy and broadleaf weeds are left unchecked during the early establishment period, aggressive weed competition can overwhelm native grass stands. Little information is currently available concerning the safe use of commercially available postemergent herbicides on C-3 native grasses. If selective postemergent herbicides that do not injure young, newly established C-3 native grasses can be identified, these active ingredients can be used as key agronomic tools in the successful establishment of native grasses used as secondary rough areas on golf courses, parkland areas, roadsides, and native grass restoration areas.

Objectives of this 2025 replicated field trial included the following:

- 1) to screen postemergent herbicide products on young C-3 native grasses in order to characterize and rank injury potential and safe use,
- 2) to identify those active ingredients that can be applied safely following the establishment of C-3 native grasses, and
- 3) to develop technically sound, research based agronomic programs from these data that can be applied safely to young native grasses, control weeds at a high level, and encourage rapid and successful establishment.

Materials & Methods

Five grassing blocks each measuring approximately 45' x 50' and located adjacent to the 14th fairway at the Links at Spanish Bay golf course in Pebble Beach, California, were seeded individually to the five C-3 native grass types presented below on September 15-17, 2024.

- 1) Pebble Beach fine fescue blend (Minimus hard fescue, Woodhall chewings fescue, Marvel creeping red fescue)
- 2) Tufted hairgrass (*Deschampsia cespitosa*), a native grass
- 3) Spike bentgrass (*Agrostis exarata*), a native grass
- 4) Nodding needlegrass (*Nassella cernua*), a native grass
- 5) Native fine fescue blend (Idaho hard fescue, Western chewings fescue, Molate creeping red fescue)

Superintendent Eric McAlister and the Pebble Beach Company graciously agreed to provide this off-rough area for these replicated field trials. Eric McAlister and his maintenance staff conducted a pre-plant soil nutritional test, deployed required nutrients in the top three inches of soil in preparation for seeding, seeded the specific grasses in each designated block site, and maintained the grasses throughout the trial period. Each grassing block was oriented among rough sprinklers to ensure uniform irrigation across each native grass type.

The field plots were located less than 0.5 miles from the Pacific Ocean. This area is characterized by a Mediterranean coastal climate featuring moderate summers and cool, moist winters. Summer temperatures may range from 55° to 70° F during the day to 44° to 54° F at night. Winter temperatures range from 42° to 62° F during the day to 34° to 42° F at night. This microclimate averages 16.5 inches of precipitation per year, with a very high percentage of rainfall occurring between November and March. Coastal fog and early morning ocean mist are common throughout the year in this location.

Treatment plots within each grass type measured 3' x 6', with the application plots located directly adjacent to 2' x 6' untreated in-plot checks (Photograph 2). Side-by-side in-plot checks allow for direct comparison of treated versus untreated areas. This is of critical importance when attempting to identify subtle treatment effects. Treatments were replicated three times for statistical analysis.

Photographs 1 & 2. The C-3 native grass herbicide tolerance field trial location adjacent to the 14th fairway at the Links at Spanish Bay golf course (left) and a 3' x 6' treatment plot adjacent to a 2' x 6' untreated, in-plot check (right).



After an eleven-month establishment period and several mowings, the grasses measured approximately 4" in height at the time of the first herbicide application.

All treatments were deployed with a CO₂-propelled small plot spray system pressurized to 20 psi and equipped with two TeeJet 11004 LP nozzles calibrated to deploy treatments at a spray volume of 1.5 gallons/1000 ft². A pacing watch was used for all applications to maintain proper walking speed and ensure accurate applications.

Identical treatment protocols as presented in Table 1 were deployed on each of the five grassing blocks.

Table 1. Treatment protocol for the C-3 native grass herbicide tolerance trial. The Links at Spanish Bay. Pebble Beach, CA. 2025.

<u>Treatments</u>	<u>Rate</u>	<u>Application Schedule</u>
1. Untreated Check	*	
2. Turflon 4E (triclopyr)	16 oz/A	8/19/25 & 9/16/25
3. SpeedZone Southern (2,4-D, 2,4-DP, dicamba, carfentrazone)	4 pt/A	8/19/25 & 9/16/25
4. Arkon (pyrimisulfan)	3.4 pt/A	8/19/25 & 9/16/25
5. Aethon (pyrimisulfan, penoxsulam)	3.4 pt/A	8/19/25 & 9/16/25
6. Drive XLR8 (quinclorac)	0.5 lb ai/A	8/19/25 & 9/16/25
7. Sapphire (penoxsulam)	6 oz/A	8/19/25 & 9/16/25
8. Tenacity (mesotrione)	5 oz/A	8/19/25 & 9/16/25
9. Fusilade (fluazifop-P-butyl)	16 oz/A	8/19/25 & 9/16/25
10. Prograss 1.5 EC (ethofumesate)	1 gal/A	8/19/25 & 9/16/25
11. Prograss + Turflon (ethofumesate, triclopyr)	1 gal + 32 oz/A	8/19/25 & 9/16/25
12. Dismiss (sulfentrazone)	4 oz/A	8/19/25 & 9/16/25
13. Manuscript (pinoxaden)	9.6 oz/A	8/19/25 & 9/16/25
14. Pylex (topramezone)	1 oz/A	8/19/25 & 9/16/25

Evaluations were conducted every two weeks throughout the trial period, extending from August 19, 2025 (day of application one: DOA1) to October 28, 2025 (28 days after application two: 28 DAA2). Turfgrass color was rated on a 0-10 scale with 0 representing no green color, 6 minimally acceptable green color, and 10 very dark green color. Turfgrass injury was rated on a 0-100 scale with 0 representing no injury, 30 a maximum level of acceptable injury, 60 an unacceptable level of injury with 50% necrosis, and 100 complete necrosis and death of the plant.

Photographs of key results were recorded. Data were summarized and statistically analyzed. Differences between means were determined via LSD (P=.05, Duncan's New Mean Separation).

Results and Discussion

◆ Pebble Beach Fine Fescue Blend

The Pebble Beach Fine Fescue Blend (PBFFB) consisted of Minimus hard fescue, Woodhall chewings fescue, and Marvel creeping red fescue. This fine fescue blend was the most herbicide-tolerant of the five native grasses evaluated, with a herbicide sensitivity total of 48.3 across 13 treatments on the final evaluation date. Grass type herbicide sensitivity is calculated as the sum of injury ratings (0-100 scale with 100 representing dead grass) for all 13 treatments during the final evaluation, 28 DAA2.

Table 2 shows PBFFB color data from five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- No statistically significant reductions in color of the Pebble Beach Fine Fescue Blend were observed as a result of two sequential applications of the products presented in Table 2.

Table 2. The influence of treatments on the color of the Pebble Beach fine fescue blend from September 2, 2025, to October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

<u>Treatments</u>	<u>Rate</u>	<u>Color¹ 8/19/25 DOA1²</u>	<u>Color 9/2/25 14DAA1³</u>	<u>Color 9/16/25 DOA2</u>	<u>Color 9/30/25 14DAA2</u>	<u>Color 10/14/25 28DAA2</u>
1) Check	*	7.0 a ⁴	7.0 a	7.0 a	6.7 a	6.3 a
2) Turflon 4E	16 oz/A	7.0 a	7.0 a	6.7 a	6.0 a	5.3 a
3) SpeedZone Southern	4 pt/A	7.0 a	7.0 a	7.0 a	6.0 a	5.7 a
4) Arkon	3.4 pt/A	7.0 a	6.3 a	7.0 a	6.3 a	6.0 a
5) Aethon	3.4 pt/A	7.0 a	6.3 a	6.7 a	6.3 a	6.0 a
6) Drive XLR8	42.6 oz/A	7.0 a	6.7 a	7.0 a	6.3 a	6.0 a
7) Sapphire	6 oz/A	7.0 a	7.0 a	7.0 a	6.7 a	6.7 a
8) Tenacity	5 oz/A	7.0 a	7.0 a	7.0 a	7.0 a	6.0 a
9) Fusilade	16 oz/A	7.0 a	6.0 a	6.7 a	6.3 a	6.0 a
10) Prograss 1.5 EC	1 gal/A	7.0 a	6.7 a	7.0 a	7.0 a	6.3 a
11) Prograss + Turflon	1 gal + 32 oz/A	7.0 a	7.0 a	6.3 a	5.7 a	5.3 a
12) Dismiss	4 oz/A	7.0 a	6.7 a	7.0 a	6.7 a	6.0 a
13) Manuscript	9.6 oz/A	7.0 a	7.0 a	7.0 a	6.7 a	6.0 a
14) Pylex	1 oz/A	7.0 a	6.7 a	6.7 a	6.7 a	5.7 a
LSD (P=.05)		0.00	0.65	0.75	1.07	0.95
Standard Deviation		0.00	0.39	0.45	0.64	5.59
CV		0.00	5.79	6.52	9.90	9.51
¹ Pebble Beach Fine Fescue Blend Color: 0-10 scale with 0 representing no color, 6 acceptable color, and 10 the darkest possible color. ² Day of application one. ³ 14 days after application one. ⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).						

Table 3 shows PBFFB injury data as generated over five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- When compared to the untreated check, no statistically significant differences in injury were observed as a result of two sequential applications of the products presented in Table 3.
- The injury data reveal that the PBFFB was either very tolerant or tolerant to all 13 herbicides evaluated 28 days after application two (28 DAA2).

Table 3. The influence of treatments on injury to the Pebble Beach fine fescue blend from September 2, 2025, to October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Injury ¹ 8/19/25 DOA1 ²	Injury 9/2/25 14DAA1 ³	Injury 9/16/25 DOA2	Injury 9/30/25 14DAA2	Injury 10/14/25 28DAA2
1) Check	*	0.0 a ⁴	0.0 b	0.0 a	0.0 a	0.0 a
2) Turflon 4E	16 oz/A	0.0 a	6.7 b	1.7 a	7.3 a	12.3 a ⁵
3) SpeedZone Southern	4 pt/A	0.0 a	0.0 b	0.0 a	3.3 a	2.7 a
4) Arkon	3.4 pt/A	0.0 a	3.3 b	0.0 a	0.0 a	3.3 a
5) Aethon	3.4 pt/A	0.0 a	3.7 b	1.7 a	0.7 a	0.7 a
6) Drive XLR8	42.6 oz/A	0.0 a	0.0 b	0.0 a	0.0 a	5.0 a
7) Sapphire	6 oz/A	0.0 a	0.0 b	0.0 a	0.0 a	0.0 a
8) Tenacity	5 oz/A	0.0 a	0.0 b	0.0 a	0.0 a	4.0 a
9) Fusilade	16 oz/A	0.0 a	16.7 a	3.3 a	0.0 a	0.0 a
10) Prograss 1.5 EC	1 gal/A	0.0 a	3.3 b	0.0 a	0.0 a	0.0 a
11) Prograss + Turflon	1 gal + 32 oz/A	0.0 a	0.0 b	5.0 a	8.3 a	11.7 a
12) Dismiss	4 oz/A	0.0 a	0.0 b	0.0 a	1.7 a	3.3 a
13) Manuscript	9.6 oz/A	0.0 a	0.0 b	0.0 a	0.0 a	0.0 a
14) Pylex	1 oz/A	0.0 a	0.0 b	0.0 a	0.0 a	3.3 a
LSD (P=.05)		0.00	0.60	5.92	8.37	9.39
Standard Deviation		0.00	0.36	3.52	4.99	5.59
CV		0.00	135.73	146.57	327.29	169.0

¹ Pebble Beach Fine Fescue Blend Injury: 0-100 scale with 0 representing no injury, 30 a maximum level of acceptable injury, 60 an unacceptable level of injury with 50% necrosis, and 100 complete necrosis and death of the plant.
² Day of application one.
³ 14 days after application one.
⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).
⁵ Red highlights indicate the highest injury levels.

Key Take-Home Messages as generated from these color and injury data:

- The PBFFB at 11 months of maturity is tolerant to two sequential applications of all herbicides tested at the rates presented.
- No dynamic visual discoloration or injury symptoms to the PBFFB were observed during the eight-week trial period.
- From these data, it would appear that the herbicides evaluated could be used safely on the PBFFB.

Photograph 3. The Pebble Beach Fine Fescue Blend field trial location. Note the uniform color and growth response. No discoloration or injury was observed following sequential applications of the herbicide treatments presented in Table 1. October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Photograph 4. No discoloration or injury to the Pebble Beach Fine Fescue Blend 28 days after receiving two sequential applications of Tenacity at 5 oz/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Photograph 5. No discoloration or injury to the Pebble Beach Fine Fescue Blend 28 days after receiving two sequential applications of Arkon at 3.4 pt/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Photograph 6. No discoloration or injury to the Pebble Beach Fine Fescue Blend 28 days after receiving two sequential applications of SpeedZone Southern at 4 pt/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



◆ **Tufted Hairgrass (*Deschampsia cespitosa*)**

Tufted Hairgrass (*Deschampsia cespitosa*) ranked number three of the five grasses evaluated, with a herbicide sensitivity total of 326.6 across 13 treatments on the final evaluation date

Table 4 shows Tufted Hairgrass color data from five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- Dynamic and highly unacceptable reductions in Tufted Hairgrass color were observed with Fusilade and Manuscript. Pylex and Tenacity also exhibited unacceptable color reduction. Differences were statistically significant when compared to the untreated check (red highlights in Table 4).

Table 4. The influence of treatments on Tufted Hairgrass color from September 2, 2025, to October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Color ¹ 8/19/25 DOA1 ²	Color 9/2/25 14DAA1 ³	Color 9/16/25 DOA2	Color 9/30/25 14DAA2	Color 10/14/25 28DAA2
1) Check	*	6.0 a ⁴	6.0 a	6.0 a	6.0 a	6.0 a
2) Turflon 4E	16 oz/A	6.0 a	6.0 a	6.0 a	5.7 ab	5.3 abc
3) SpeedZone Southern	4 pt/A	6.0 a	6.0 a	6.0 a	6.0 a	5.7 ab
4) Arkon	3.4 pt/A	6.0 a	5.0 bc	6.0 a	5.3 ab	4.7 bcd
5) Aethon	3.4 pt/A	6.0 a	5.3 ab	5.7 a	5.3 ab	5.3 abc
6) Drive XLR8	42.6 oz/A	6.0 a	6.0 a	6.0 a	6.0 a	5.7 ab
7) Sapphire	6 oz/A	6.0 a	6.0 a	6.0 a	5.7 ab	5.3 abc
8) Tenacity	5 oz/A	6.0 a	5.0 bc	4.7 a	4.0 c	4.0 d
9) Fusilade	16 oz/A	6.0 a	5.3 ab	5.0 a	3.0 d	2.3 e
10) Prograss 1.5 EC	1 gal/A	6.0 a	4.7 bc	5.7 a	5.0 ab	4.7 bcd
11) Prograss + Turflon	1 gal + 32 oz/A	6.0 a	6.0 a	5.7 a	5.0 ab	5.3 abc
12) Dismiss	4 oz/A	6.0 a	6.0 a	6.0 a	6.0 a	5.0 a-d
13) Manuscript	9.6 oz/A	6.0 a	3.7 d	3.7 b	2.7 d	1.7 e ⁵
14) Pylex	1 oz/A	6.0 a	4.3 c	5.3 a	4.7 bc	4.3 cd
LSD (P=0.05)		0.00	0.57	0.92	0.70	0.74
Standard Deviation		0.00	0.34	0.55	0.42	0.44
CV		0.00	6.31	9.88	8.30	9.40

¹ Tufted Hairgrass Color: 0-10 scale with 0 representing no color, 6 acceptable color, and 10 the darkest possible color.
² Day of application one.
³ 14 days after application one.
⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).
⁵ Red highlights indicate the lowest color ratings and statistically significant differences when compared to the untreated check.

Table 5 (Page 10) shows Tufted Hairgrass injury data as generated over five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- Injury trends followed trends in color reduction. Severe Tufted Hairgrass injury was observed following Manuscript and Fusilade applications. Tenacity showed unacceptable injury. Differences were statistically significant when compared to the untreated check (red highlights in Table 5).

Photograph 7. Discoloration and injury to Tufted Hairgrass 28 days after receiving two sequential applications of Manuscript at 9.6 oz/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Photograph 8. Discoloration and injury to Tufted Hairgrass 28 days after receiving two sequential applications of Fusilade at 16 oz/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Table 5. The influence of treatments on Tufted Hairgrass injury from September 2, 2025, to October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Injury ¹ 8/19/25 DOA1 ²	Injury 9/2/25 14DAA1 ³	Injury 9/16/25 DOA2	Injury 9/30/25 14DAA2	Injury 10/14/25 28DAA2
1) Check	*	0.0 a ⁴	0.0 c	0.0 b	0.0 c	0.0 a
2) Turflon 4E	16 oz/A	0.0 a	0.0 c	0.0 b	5.7 c	8.3 cd
3) SpeedZone Southern	4 pt/A	0.0 a	0.0 c	0.0 b	1.7 c	8.3 cd
4) Arkon	3.4 pt/A	0.0 a	26.7 b	0.0 b	5.0 c	13.3 cd
5) Aethon	3.4 pt/A	0.0 a	16.7 bc	1.7 b	6.7 c	16.7 cd
6) Drive XLR8	42.6 oz/A	0.0 a	0.0 c	0.0 b	1.7 c	8.3 cd
7) Sapphire	6 oz/A	0.0 a	6.7 bc	0.0 b	0.0 c	1.7 d
8) Tenacity	5 oz/A	0.0 a	13.3 bc	23.3 b	35.0 b	45.0 b
9) Fusilade	16 oz/A	0.0 a	10.0 bc	13.3 b	73.3 a	81.7 a
10) Prograss 1.5 EC	1 gal/A	0.0 a	23.3 b	3.3 b	13.3 c	23.3 c
11) Prograss + Turflon	1 gal + 32 oz/A	0.0 a	0.0 c	8.3 b	18.3 c	8.3 cd
12) Dismiss	4 oz/A	0.0 a	16.7 bc	0.0 a	0.0 c	0.0 d
13) Manuscript	9.6 oz/A	0.0 a	46.7 a	45.0 a	76.7 a	90.0 a⁵
14) Pylex	1 oz/A	0.0 a	26.7 b	3.3 b	20.0 c	21.7 c
LSD (P=.05)		0.00	13.11	17.06	12.28	11.10
Standard Deviation		0.00	7.81	10.16	7.32	6.61
CV		0.00	58.57	144.67	39.80	28.34

¹ Tufted Hairgrass Injury: 0-100 scale with 0 representing no injury, 30 a maximum level of acceptable injury, 60 an unacceptable level of injury with 50% necrosis, and 100 complete necrosis and death of the plant.
² Day of application one.
³ 14 days after application one.
⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).
⁵ **Red highlights** indicate the highest injury ratings and statistically significant differences when compared to the untreated check.

Key Take-Home Messages as generated from the Tufted Hairgrass color and injury data:

- Tufted Hairgrass at 11 months of maturity is tolerant to two sequential applications of the following herbicides:
 - Turflon
 - SpeedZone Southern
 - Arkon
 - Aethon
 - Drive XLR8
 - Sapphire
 - Prograss
 - Prograss + Turflon
 - Dismiss
 - Pylex
- Tenacity caused unacceptable injury to Tufted Hairgrass.
- Manuscript and Fusilade caused severe injury to Tufted Hairgrass.

◆ **Spike Bentgrass (*Agrostis exarata*)**

Spike Bentgrass (*Agrostis exarata*) ranked number four of the five grasses evaluated with a herbicide sensitivity total of 552.1 across 13 treatments on the final evaluation date.

Table 6 shows Spike Bentgrass color data from five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- Dynamic and highly unacceptable reductions in Spike Bentgrass color were observed with Tenacity, Fusilade, Manuscript, and Pylex. Prograss + Turflon and Drive XLR8 also showed color reduction. Differences were statistically significant when compared to the untreated check (**red highlights** in Table 6).

Table 6. The influence of treatments on Spike Bentgrass color from September 2, 2025, to October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Color ¹ 8/19/25 DOA1 ²	Color 9/2/25 14DAA1 ³	Color 9/16/25 DOA2	Color 9/30/25 14DAA2	Color 10/14/25 28DAA2
1) Check	*	6.0 a ⁴	6.0 a	6.0 a	5.7 a	5.7 a
2) Turflon 4E	16 oz/A	6.0 a	5.7 ab	5.0 a	5.0 a	4.7 ab
3) SpeedZone Southern	4 pt/A	6.0 a	4.7 c	5.0 a	4.7 a	4.3 ab
4) Arkon	3.4 pt/A	6.0 a	5.3 abc	5.7 a	5.0 a	5.0 ab
5) Aethon	3.4 pt/A	6.0 a	6.0 a	6.0 a	6.0 a	5.0 ab
6) Drive XLR8	42.6 oz/A	6.0 a	6.0 a	4.7 a	5.0 a	3.7 bc
7) Sapphire	6 oz/A	6.0 a	5.0 bc	6.0 a	5.0 a	5.0 ab
8) Tenacity	5 oz/A	6.0 a	1.0 e	0.0 c	0.0 b	0.0 d⁵
9) Fusilade	16 oz/A	6.0 a	2.0 d	0.7 c	0.0 b	0.0 d
10) Prograss 1.5 EC	1 gal/A	6.0 a	5.7 ab	6.0 a	5.3 a	5.0 ab
11) Prograss + Turflon	1 gal + 32 oz/A	6.0 a	5.0 bc	5.0 a	5.0 a	3.0 c
12) Dismiss	4 oz/A	6.0 a	5.0 bc	5.7 a	6.0 a	5.7 a
13) Manuscript	9.6 oz/A	6.0 a	2.7 d	2.0 b	0.7 b	0.3 d
14) Pylex	1 oz/A	6.0 a	2.0 d	2.0 b	0.7 b	0.3 d
LSD (P=.05)		0.00	0.59	0.97	0.88	1.04
Standard Deviation		0.00	0.35	0.58	0.53	0.62
CV		0.00	7.91	13.51	13.63	18.26

¹ Spike Bentgrass Color: 0-10 scale with 0 representing no color, 6 acceptable color, and 10 the darkest possible color.

² Day of application one.

³ 14 days after application one.

⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).

⁵ **Red highlights** indicate the lowest color ratings and statistically significant differences when compared to the untreated check.

Table 7 (Page 13) shows Spike Bentgrass injury data as generated over five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- Injury trends followed trends in color reduction. Extreme Spike Bentgrass injury was observed following Tenacity, Fusilade, Manuscript, and Pylex applications. Prograss + Turflon and Drive XLR8 showed unacceptable injury. Differences were statistically significant when compared to the untreated check (**red highlights** in Table 7).

Photograph 9. Discoloration and injury to Spike Bentgrass 28 days after receiving two sequential applications of Manuscript at 9.6 oz/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Photograph 10. Discoloration, injury, and death of Spike Bentgrass 28 days after receiving two sequential applications of Fusilade at 16 oz/A (left) versus the untreated check (center) versus Tenacity at 5 oz/A (right). October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Table 7. The influence of treatments on Spike Bentgrass injury from September 2, 2025, to October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Injury ¹ 8/19/25 DOA1 ²	Injury 9/2/25 14DAA1 ³	Injury 9/16/25 DOA2	Injury 9/30/25 14DAA2	Injury 10/14/25 28DAA2
1) Check	*	0.0 a ⁴	0.0 d	0.0 d	0.0 d	0.0 d
2) Turflon 4E	16 oz/A	0.0 a	6.7 d	13.3 c	11.7 bcd	21.7 cd
3) SpeedZone Southern	4 pt/A	0.0 a	33.3 c	13.3 c	23.3 b	25.0 cd
4) Arkon	3.4 pt/A	0.0 a	6.7 d	1.7 cd	5.0 cd	5.0 d
5) Aethon	3.4 pt/A	0.0 a	0.0 d	0.0 d	0.0 d	0.0 d
6) Drive XLR8	42.6 oz/A	0.0 a	0.0 d	6.7 cd	10.0 bcd	40.0 bc
7) Sapphire	6 oz/A	0.0 a	10.0 d	0.0 d	0.0 d	0.0 d
8) Tenacity	5 oz/A	0.0 a	86.7 a	99.3 a	100.0 a	100.0 a ⁵
9) Fusilade	16 oz/A	0.0 a	80.0 ab	98.3 a	100.0 a	100.0 a
10) Prograss 1.5 EC	1 gal/A	0.0 a	3.3 d	0.0 d	5.0 cd	6.7 a
11) Prograss + Turflon	1 gal + 32 oz/A	0.0 a	23.3 c	8.3 cd	18.3 bc	58.3 b
12) Dismiss	4 oz/A	0.0 a	30.0 c	8.3 cd	0.0 d	0.0 d
13) Manuscript	9.6 oz/A	0.0 a	70.0 b	85.0 b	95.0 a	96.7 a
14) Pylex	1 oz/A	0.0 a	80.0 ab	86.7 b	98.7 a	98.7 a
LSD (P=.05)		0.00	1.34	7.93	10.60	20.43
Standard Deviation		0.00	6.16	4.72	6.31	12.17
CV		0.00	20.05	15.71	18.93	30.87

¹ Spike Bentgrass Injury: 0-100 scale with 0 representing no injury, 30 a maximum level of acceptable injury, 60 an unacceptable level of injury with 50% necrosis, and 100 complete necrosis and death of the plant.
² Day of application one.
³ 14 days after application one.
⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).
⁵ Red highlights indicate the highest injury ratings and statistically significant differences when compared to the untreated check.

Key Take-Home Messages as generated from the Spike Bentgrass color and injury data:

- Spike Bentgrass at 11 months of maturity is tolerant to two sequential applications of the following herbicides:
 - Arkon
 - Aethon
 - Sapphire
 - Prograss
 - Dismiss
- Spike Bentgrass is marginally tolerant to two sequential applications of the following herbicides:
 - Turflon
 - SpeedZone Southern
- Drive XLR8 and Prograss + Turflon caused unacceptable injury to Spike Bentgrass.
- Tenacity, Fusilade, Manuscript, and Pylex caused severe injury (death) to Spike Bentgrass.

◆ ***Nodding Needlegrass (Nassella cernua)***

Nodding Needlegrass (*Nassella cernua*) ranked number five of the five grasses evaluated, with a herbicide sensitivity total of 638.0 across 13 treatments on the final evaluation date. Nodding Needlegrass was the least tolerant or most highly sensitive grass to the described herbicide treatments.

Table 8 shows Nodding Needlegrass color data from five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- Dynamic and highly unacceptable reductions in Nodding Needlegrass color were observed with Tenacity, Fusilade, Manuscript, and Pylex. Turflon, Drive XLR8, Prograss, and Prograss + Turflon also exhibited color reduction. Differences were statistically significant when compared to the untreated check (red highlights in Table 8).

Table 8. The influence of treatments on Nodding Needlegrass color from September 2, 2025, to October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Color ¹ 8/19/25 DOA1 ²	Color 9/2/25 14DAA1 ³	Color 9/16/25 DOA2	Color 9/30/25 14DAA2	Color 10/14/25 28DAA2
1) Check	*	6.0 a ⁴	6.0 a	6.0 a	6.0 a	6.0 a
2) Turflon 4E	16 oz/A	6.0 a	5.3 a	5.0 ab	4.3 c	3.0 c
3) SpeedZone Southern	4 pt/A	6.0 a	5.7 a	5.7 ab	6.0 a	5.0 a
4) Arkon	3.4 pt/A	6.0 a	6.0 a	6.0 a	5.7 ab	5.0 a
5) Aethon	3.4 pt/A	6.0 a	5.7 a	6.0 a	6.0 a	5.7 a
6) Drive XLR8	42.6 oz/A	6.0 a	5.3 a	5.0 ab	4.3 c	3.0 c
7) Sapphire	6 oz/A	6.0 a	6.0 a	6.0 a	6.0 a	4.7 ab
8) Tenacity	5 oz/A	6.0 a	3.0 cd	1.7 cd	0.7 e	0.0 e ⁵
9) Fusilade	16 oz/A	6.0 a	3.0 cd	1.0 d	0.0 e	0.0 e
10) Prograss 1.5 EC	1 gal/A	6.0 a	5.7 a	4.7 b	4.3 c	3.7 bc
11) Prograss + Turflon	1 gal + 32 oz/A	6.0 a	4.7 ab	5.3 ab	4.7 bc	3.3 c
12) Dismiss	4 oz/A	6.0 a	5.7 a	5.7 ab	5.7 ab	5.3 a
13) Manuscript	9.6 oz/A	6.0 a	3.7 bc	2.3 c	1.0 e	1.0 de
14) Pylex	1 oz/A	6.0 a	2.0 d	2.3 c	2.3 d	1.7 d
LSD (P=.05)		0.00	1.22	1.04	1.14	1.20
Standard Deviation		0.00	0.73	0.62	0.68	0.71
CV		0.00	15.03	13.89	16.72	21.11

¹ Nodding Needlegrass Color: 0-10 scale with 0 representing no color, 6 acceptable color, and 10 the darkest possible color.
² Day of application one.
³ 14 days after application one.
⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).
⁵ Red highlights indicate the lowest color ratings and statistically significant differences when compared to the untreated check.

Table 9 (Page 16) shows Nodding Needlegrass injury data as generated over five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- Injury trends followed trends in color reduction. Extreme Nodding Needlegrass injury was observed following Tenacity, Fusilade, Manuscript, and Pylex applications. Prograss + Turflon and Drive XLR8 showed unacceptable injury. Differences were statistically significant when compared to the untreated check (red highlights in Table 9).

Photograph 11. Discoloration and injury to Nodding Needlegrass 28 days after receiving two sequential applications of Fusilade 16 oz/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Photograph 12. Discoloration and injury to Nodding Needlegrass 28 days after receiving two sequential applications of Tenacity 5 oz/A (left) versus the untreated check (right). October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Table 9. The influence of treatments on Nodding Needlegrass injury from September 2, 2025, to October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Injury ¹ 8/19/25 DOA1 ²	Injury 9/2/25 14DAA1 ³	Injury 9/16/25 DOA2	Injury 9/30/25 14DAA2	Injury 10/14/25 28DAA2
1) Check	*	0.0 a ⁴	0.0 e	0.0 d	0.0 d	0.0 d
2) Turflon 4E	16 oz/A	0.0 a	23.3 cd	10.0 cd	28.3 c	70.bc
3) SpeedZone Southern	4 pt/A	0.0 a	16.7 de	3.3 cd	0.0 d	4.0 d
4) Arkon	3.4 pt/A	0.0 a	6.7 de	0.0 d	0.0 d	0.0 d
5) Aethon	3.4 pt/A	0.0 a	6.7 de	0.0 d	0.0 d	0.7 d
6) Drive XLR8	42.6 oz/A	0.0 a	10.0 de	8.3 cd	33.3 c	61.7 c
7) Sapphire	6 oz/A	0.0 a	0.0 e	0.0 d	0.0 d	13.3 d
8) Tenacity	5 oz/A	0.0 a	76.7 a	86.7 ab	99.3 a	99.7 a ⁵
9) Fusilade	16 oz/A	0.0 a	70.0 a	97.0 a	99.7 a	100.0 a
10) Prograss 1.5 EC	1 gal/A	0.0 a	6.7 de	21.7 c	25.0 c	50.0 c
11) Prograss + Turflon	1 gal + 32 oz/A	0.0 a	33.3 c	18.3 cd	18.3 cd	48.3 c
12) Dismiss	4 oz/A	0.0 a	13.3 de	3.3 cd	1.7 d	3.3 d
13) Manuscript	9.6 oz/A	0.0 a	50.0 b	83.3 ab	97.3 a	98.7 a
14) Pylex	1 oz/A	0.0 a	80.0 a	74.0 b	80.0 b	88.3 ab
LSD (P=.05)		0.00	14.67	17.02	16.94	23.05
Standard Deviation		0.00	8.74	10.14	10.09	13.73
CV		0.00	31.11	34.95	29.25	30.13

¹ Nodding Needlegrass Injury: 0-100 scale with 0 representing no injury, 30 a maximum level of acceptable injury, 60 an unacceptable level of injury with 50% necrosis, and 100 complete necrosis and death of the plant.
² Day of application one.
³ 14 days after application one.
⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).
⁵ Red highlights indicate the highest injury ratings and statistically significant differences when compared to the untreated check.

Key Take-Home Messages as generated from the Nodding Needlegrass color and injury data:

- Nodding Needlegrass at 11 months of maturity is tolerant to two sequential applications of the following herbicides:
 - SpeedZone Southern
 - Arkon
 - Aethon
 - Sapphire
 - Dismiss
- Turflon, Drive XLR8, Prograss, and Prograss + Turflon caused unacceptable injury to Nodding Needlegrass.
- Tenacity, Fusilade, Manuscript, and Pylex caused severe injury (death) to Nodding Needlegrass.

◆ **Native Fine Fescue Blend**

The Native Fine Fescue Blend (NFFB) consisted of Idaho hard fescue, Western chewings fescue, and Molate creeping red fescue. This NFFB was the second most herbicide-tolerant of the five native grasses evaluated, with a herbicide sensitivity total of 49.6 across 13 treatments on the final evaluation date. The NFFB mirrored the PBFFB (48.3) in very low herbicide sensitivity and exceptional herbicide tolerance. Grass type herbicide sensitivity is calculated as the sum of injury ratings (0-100 scale with 100 representing dead grass) for all 13 treatments during the final evaluation, 28 DAA2.

Table 10 shows NFFB color data from five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- Prograss + Turflon and Dismiss showed subtle reductions in the NFFB color. Differences were statistically significant when compared to the untreated check (red highlights in Table 10).
- No dynamic or statistically significant reductions in color of the NFFB were observed as a result of two sequential applications of the remaining products presented in Table 10.

Table 10. The influence of treatments on the color of the Native Fine Fescue Blend from September 2, 2025, to October 14, 2025. The Links at Spanish Bay. Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

<u>Treatments</u>	<u>Rate</u>	Color ¹ 8/19/25 <u>DOA1²</u>	Color 9/2/25 <u>14DAA1³</u>	Color 9/16/25 <u>DOA2</u>	Color 9/30/25 <u>14DAA2</u>	Color 10/14/25 <u>28DAA2</u>
1) Check	-	6.0 a ⁴	6.0 a	6.0 a	6.0 a	6.0 a
2) Turflon 4E	16 oz/A	6.0 a	6.0 a	6.0 a	6.0 a	6.0 a
3) SpeedZone Southern	4 pt/A	6.0 a	6.0 a	6.0 a	6.3 a	6.3 a
4) Arkon	3.4 pt/A	6.0 a	6.0 a	6.0 a	6.3 a	5.7 ab
5) Aethon	3.4 pt/A	6.0 a	6.0 a	6.0 a	6.3 a	6.3 a
6) Drive XLR8	42.6 oz/A	6.0 a	6.0 a	6.0 a	6.3 a	5.7 ab
7) Sapphire	6 oz/A	6.0 a	6.0 a	6.0 a	6.0 a	5.7 ab
8) Tenacity	5 oz/A	6.0 a	6.0 a	6.0 a	6.3 a	5.7 ab
9) Fusilade	16 oz/A	6.0 a	5.3 a	6.0 a	6.3 a	6.0 a
10) Prograss 1.5 EC	1 gal/A	6.0 a	6.0 a	6.0 a	6.3 a	5.7 ab
11) Prograss + Turflon	1 gal + 32 oz/A	6.0 a	6.0 a	6.0 a	6.3 a	5.0 b ⁵
12) Dismiss	4 oz/A	6.0 a	6.0 a	6.0 a	6.3 a	5.0 b
13) Manuscript	9.6 oz/A	6.0 a	6.0 a	6.0 a	6.3 a	6.0 a
14) Pylex	1 oz/A	6.0 a	6.0 a	6.0 a	6.0 a	6.0 a
LSD (P=.05)		0.00	0.52	0.00	0.48	0.70
Standard Deviation		0.00	0.31	0.00	0.29	0.42
CV		0.00	5.18	0.00	4.62	7.21

¹ Native Fine Fescue Blend Color: 0-10 scale with 0 representing no color, 6 acceptable color, and 10 the darkest possible color.

² Day of application one.

³ 14 days after application one.

⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).

⁵ Red highlights indicate the lowest color ratings and statistically significant differences when compared to the untreated check.

Table 11 shows NFFB injury data as generated over five evaluations during the eight-week field trial from August 19 to October 14, 2025.

- When compared to the untreated check, only Prograss + Turflon exhibited a statistically significant difference in injury as a result of two sequential applications of the products presented in Table 11. Although the injury generated by the Prograss + Turflon tank mixture was statistically significant compared to the untreated check, the injury level (20.0 a) fell within the marginally tolerant or acceptable injury level on the 0-100 injury scale.
- The injury data reveal that the NFFB was either very tolerant or tolerant to all 13 herbicides evaluated 28 days after application two.

Key Take-Home Messages as generated from these color and injury data:

- The NFFB at 11 months of maturity is tolerant to two sequential applications of all herbicides tested at the rates presented.
- No dynamic visual discoloration or injury symptoms to the NFFB were observed during the eight-week trial period.
- From these data, it would appear that the herbicides evaluated could be used safely on the NFFB.

Table 11. The influence of treatments on injury to the Native Fine Fescue Blend from September 2, 2025, to October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.

Treatments	Rate	Injury ¹ 8/19/25 DOA1 ²	Injury 9/2/25 14DAA1 ³	Injury 9/16/25 DOA2	Injury 9/30/25 14DAA2	Injury 10/14/25 28DAA2
1) Check	*	0.0 a ⁴	0.0 b	0.0 b	0.0 a	0.0 b
2) Turflon 4E	16 oz/A	0.0 a	20.0 a	11.7 a	0.0 a	0.0 b
3) SpeedZone Southern	4 pt/A	0.0 a	10.0 ab	0.0 b	0.0 a	0.0 b
4) Arkon	3.4 pt/A	0.0 a	10.0 ab	0.0 b	0.0 a	4.7 b
5) Aethon	3.4 pt/A	0.0 a	3.3 ab	0.0 b	0.0 a	0.0 b
6) Drive XLR8	42.6 oz/A	0.0 a	6.7 ab	0.0 b	0.0 a	6.7 b
7) Sapphire	6 oz/A	0.0 a	16.7 ab	0.0 b	0.0 a	3.3 b
8) Tenacity	5 oz/A	0.0 a	10.0 ab	0.0 b	0.0 a	3.3 b
9) Fusilade	16 oz/A	0.0 a	14.0 ab	0.0 b	0.0 a	0.0 b
10) Prograss 1.5 EC	1 gal/A	0.0 a	13.3 ab	3.3 b	0.0 a	3.3 b
11) Prograss + Turflon	1 gal + 32 oz/A	0.0 a	10.0 ab	0.0 b	0.0 a	20.0 a ⁵
12) Dismiss	4 oz/A	0.0 a	10.0 ab	0.0 b	0.0 a	8.3 b
13) Manuscript	9.6 oz/A	0.0 a	0.0 b	0.0 b	0.0 a	0.0 b
14) Pylex	1 oz/A	0.0 a	6.7 ab	0.0 b	0.0 a	0.0 b
LSD (P=.05)		0.00	9.94	4.14	0.00	7.50
Standard Deviation		0.00	5.92	2.47	0.00	4.47
CV		0.00	63.46	230.32	0.00	125.88

¹ Native Fine Fescue Blend Injury: 0-100 scale with 0 representing no injury, 30 a maximum level of acceptable injury, 60 an unacceptable level of injury with 50% necrosis, and 100 complete necrosis and death of the plant.

² Day of application one.

³ 14 days after application one.

⁴ Means followed by the same letter do not differ significantly (P=0.05, Duncan's New Mean Separation).

⁵ Red highlights indicate the highest injury ratings and statistically significant differences when compared to the untreated check.

Photograph 13. No discoloration or injury to the Native Fine Fescue Blend 28 days after receiving two sequential applications of Aethon 3.4 pt/A (right) versus the untreated check (left). October 14, 2025. The Links at Spanish Bay, Pebble Beach, CA. Mark M. Mahady & Associates, Inc.



Summary and Conclusions

From the data generated in this replicated field trial located at the Links at Spanish Bay golf course in the moderate coastal climate of Pebble Beach, California, the following conclusions are presented.

1. ***Pebble Beach Fine Fescue Blend:*** The color and injury data reveal that the PBFFB was either very tolerant or tolerant to all 13 herbicides evaluated 28 days after application two.
2. ***Tufted Hairgrass:*** Tufted Hairgrass was tolerant to two sequential applications of Turflon, SpeedZone Southern, Arkon, Aethon, Drive XLR8, Sapphire, Prograss, Prograss + Turflon, Dismiss, and Pylex. Tenacity caused unacceptable injury to Tufted Hairgrass, while Manuscript and Fusilade caused severe injury to Tufted Hairgrass.
3. ***Spike Bentgrass:*** Spike Bentgrass was tolerant to two sequential applications of Arkon, Aethon, Sapphire, Prograss, and Dismiss. Spike Bentgrass was marginally tolerant to Turflon and SpeedZone Southern. Drive XLR8 and Prograss + Turflon caused unacceptable injury to Spike Bentgrass. Tenacity, Fusilade, Manuscript, and Pylex caused severe injury (death) to Spike Bentgrass.

4. **Nodding Needlegrass:** Nodding Needlegrass was tolerant to two sequential applications of SpeedZone Southern, Arkon, Aethon, Sapphire, and Dismiss. Turflon, Drive XLR8, Prograss, and Prograss + Turflon caused unacceptable injury to Nodding Needlegrass, while Tenacity, Fusilade, Manuscript, and Pylex caused severe injury (death) to Spike Bentgrass.
5. **Native Fine Fescue Blend:** The color and injury data reveal that the NFFB was either very tolerant or tolerant to all 13 herbicides evaluated 28 days after application two.

Practical Perspectives

◆ Native Grass Herbicide Sensitivity Total and Herbicide Tolerance Ranking

When golf course agronomists and architects select native grasses for rough, secondary rough, and off-rough areas during golf course renovations and new construction projects, overall adaptation and growth performance in specific microclimates are the most critical considerations.

However, three questions that need to be answered in tandem with grassing decisions are as follows:

1. What are the most prevalent broadleaf and grassy weeds generally found in this specific microclimate?
2. What are the herbicides that are registered and most efficacious for control of these specific weeds?
3. Are the most efficacious weed control herbicides safe for use on the selected native grasses?

If the desirable grasses chosen are inundated with difficult-to-control weeds, and the herbicides best suited to control these weeds cause unacceptable and severe injury to the desirable grasses, then short and long-term surface quality issues will result.

Table 12 presents the comparative herbicide sensitivity totals and herbicide tolerance rankings for the five native grasses evaluated in this field trial.

Table 12. The herbicide sensitivity total and herbicide tolerance ranking for each native grass type. Links at Spanish Bay. October 14, 2025. Mark M. Mahady & Associates, Inc.

<u>Native Grass</u>	<u>Herbicide Sensitivity Total¹</u>	<u>Herbicide Tolerance Ranking²</u>
Pebble Beach Fine Fescue Blend	48.3	1
Native Fine Fescue Blend	49.6	2
Tufted Hairgrass	326.6	3
Spike Bentgrass	552.1	4
Nodding Needlegrass	638.0	5

¹ Calculated as the sum of injury ratings (0-100 scale with 100 representing dead grass) for all 13 treatments during the final evaluation, 28 DAA2.

² The lower the ranking, the higher the herbicide tolerance.

Table 13 presents a quick, practical, interpretive, color-coded spreadsheet summary of the results of the field trial in table form, showing the overall herbicide tolerance rating and herbicide injury average for each treatment and grass type.

Table 13. An interpretive summary of the herbicide tolerance rating (Very Tolerant, Tolerant, Marginally Tolerant, Injurious, Severely Injurious, and Death) and herbicide injury average (0-100 scale) for each herbicide and each native grass evaluated. For example, **T (12)** represents a Tolerant herbicide rating (T) with an average injury rating of 12 (0-100 scale, where 100 represents dead grass) for that herbicide and grass type. Links at Spanish Bay. October 14, 2025. Mark M. Mahady & Associates, Inc.

	Pebble Beach Fine Fescue Blend	Tufted Hairgrass	Spike Bentgrass	Nodding Needlegrass	Native Fine Fescue Blend
Turflon	T (12)²	T (8)	MT (22)	SEVINJ (70)	VT (0)
SpeedZone Soth	T (3)	T (8)	MT (25)	T (4)	VT (0)
Arkon	T (3)	T (13)	T (5)	VT (0)	T (5)
Aethon	T (1)	T (16)	VT (0)	VT (1)	VT (0)
Drive XLR8	T (5)	T (8)	INJ (40)	INJ (62)	T (7)
Sapphire	VT (0)¹	T (2)	VT (0)	T (13)	T (3)
Tenacity	T (4)	INJ (45)⁴	DEATH (100)⁶	DEATH (99)	T (3)
Fusilade	VT (0)	SEVINJ (82)⁵	DEATH (100)	DEATH (100)	VT (0)
Prograss	VT (0)	MT (23)³	T (7)	INJ (50)	T (3)
Prograss+Turflon	T (12)	T (8)	INJ (59)	INJ (48)	MT (20)
Dismiss	T (3)	VT (0)	VT (0)	T (3)	T (8)
Manuscript	VT (0)	SEVINJ (90)	DEATH (97)	DEATH (99)	VT (0)
Pylex	T (3)	MT(22)	DEATH (99)	SEVINJ (89)	VT (0)

¹ **VT = Very Tolerant: Injury rating 0-1** on a 0-100 scale with 0 representing no injury, 30 a maximum level of acceptable injury, 60 an unacceptable level of injury with 50% necrosis, and 100 complete necrosis and death of the plant.

² **T = Tolerant: Injury rating 2-20** on a 0-100 scale as described above. Minor color change.

³ **MT = Marginally Tolerant: Injury rating 21-30** on a 0-100 scale. Noticeable color change: borderline acceptable.

⁴ **INJ = Injurious: Injury rating 31-59** on a 0-100 scale. Unacceptable color change with some necrosis.

⁵ **SEVINJ = Severe injury: injury rating 60-89** on a 0-100 scale. Extreme loss of color with increasing necrosis.

⁶ **Death = Death: injury rating 90-100** on a 0-100 scale. No live plant material.

Acknowledgments

A special thanks to Eric McAlister, Superintendent at the Links at Spanish Bay, and his dedicated maintenance staff for their cooperation and conscientious efforts in establishing the five native grass plots and maintaining the replicated field research plot throughout the trial period.

Thanks to Pete Bachman, Director of Agronomy for the Pebble Beach Company, for permission to use this off-rough area at the Links at Spanish Bay for these replicated field trials.

Thanks to Jim Culley, owner of Seedking Enterprises LLC, for providing insights on the C-3 grasses to be evaluated and for donating the seed for the trial.

Thanks also to the United States Golf Association, PBI Gordon, ENVU, Syngenta, Seedking Enterprise LLC, and Mark M. Mahady & Associates, Inc. for providing products and funding to support the completion of these five field research trials.

Professional Ethics

Please note that *Mark M. Mahady & Associates, Inc.* does not receive monies, compensation, or benefits for recommending products, services, or equipment. We are an entirely independent research and consulting company. We only recommend those products, services, and equipment that we believe will bring quality and value to our clients.

* * *

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:

- Project 1 detailing soil moisture impacts on dollar spot severity and fungal/bacterial diversity in both fairway and putting green systems was continued for a second and final year. However, due to space constraints under the rain out shelter we could not accommodate conducting Project 2 this summer. Project 2 is investigating the impact of soil moisture on fungicide performance in dollar spot control and will begin with the summer of 2026. This will likely necessitate extending the project for a 4th year to allow for a second year of Project 2 to be conducted.
- The fairway plot (Figure 1) had high dollar spot pressure throughout the summer. The season-long area under the disease progress curve (AUDPC) results showed that the low (20%) soil moisture treatment had the least amount of dollar spot. The medium (30%) and the high (40%) soil moisture treatment had higher levels of dollar spot compared to the low treatment but were not statistically different from each other. This was consistent with the results obtained in Year 1. The full report for this project can be accessed online at: https://tdl.wisc.edu/wp-content/blogs.dir/42/files/Interactive%20Pages/2025_Summer/Reports/UWSoilMoistureFwy_2025.pdf
- The putting green plot (Figure 2) also had high dollar spot pressure throughout the summer. Much like the fairway plot the low soil moisture treatment had the least amount of dollar spot (using AUDPC) and there were no statistical differences in dollar spot between the medium and high moisture treatments. The full report for this project can be accessed online at: https://tdl.wisc.edu/wp-content/blogs.dir/42/files/Interactive%20Pages/2025_Summer/Reports/UWSoilMoistureGrn_2025.pdf
- Samples for microbiome analysis were again 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. Results from the samples collected in Year 1 showed that plant section (rhizosphere vs. phyllosphere) and soil type (putting green vs. fairway) were the primary drivers of microbial

community structure, with minimal influence from soil moisture treatments on overall diversity. Despite the limited influence of moisture on overall diversity, distinct taxonomic and functional shifts emerged under different moisture treatments.

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 in mid-May, 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: The dollar spot results were remarkably consistent between the soil-based putting green plot and the soil-based fairway plot. In both cases, dollar spot was markedly lower on the low soil moisture plots compared to the medium and high treatments (Figure 1 and 2). This was consistent with the results obtained in Year 1. No treatments were of acceptable turf quality during the course of the study due to damage from dollar spot. Microbiome results from the samples collected in Year 1 showed that plant section (rhizosphere vs. phyllosphere) and soil type (putting green vs. fairway) were the primary drivers of microbial community structure, with minimal influence from soil moisture treatments on overall diversity (Figure 3 and 4). For alpha diversity, both bacterial and fungal communities exhibited significantly higher richness and diversity in the rhizosphere and sand-based putting greens, whereas soil moisture showed no statistically significant effects. Similarly, beta diversity was strongly shaped by plant section and soil

type, collectively explaining 30-40% of community variation, while moisture treatments consistently showed no significant effect across all strata. Despite the limited influence of moisture on overall diversity, distinct taxonomic and functional shifts emerged under different moisture treatments. Fungal communities exhibited moisture-responsive patterns, with Ascomycota increasing and Basidiomycota decreasing with higher moisture, while Glomeromycota (arbuscular mycorrhizal fungi AMF) displayed positive moisture associations, particularly in the rhizosphere. Bacterial communities remained functionally stable overall, although Actinomycetota declined at the highest moisture levels. Although soil moisture did not drive overall microbial communities, it exerted an effect on the dollar spot pathogen, which displayed significantly lower abundance at the medium moisture levels (Figure 5). These findings suggest that moisture management may contribute to disease control not through broad shifts in microbial diversity, but through targeted taxonomic changes and enhanced symbiotic interactions.

Future plans: This was the second year of a 3-year study and the final year of Project 1. The microbiome samples we collected in 2025 will be processed and analyzed during the winter of 2025-2026. Project 2 focusing on fungicide performance in response to various soil moistures will begin in May of 2026 and will likely need a 2nd year to complete in the summer of 2027.

Figure 1. Photos from the first replication of soil moisture treatments from the fairway plot on August 5th, 2025.



Figure 2. Photos from the first replication of soil moisture treatments from the putting green plot on August 5th, 2025.



Figure 3. Principal Coordinate Analysis (PCoA) plot showing the ordination patterns of fungal communities. The distances between points represent Bray-Curtis dissimilarities. Samples are classified into plant section or moisture level, indicated by the shapes and colors.

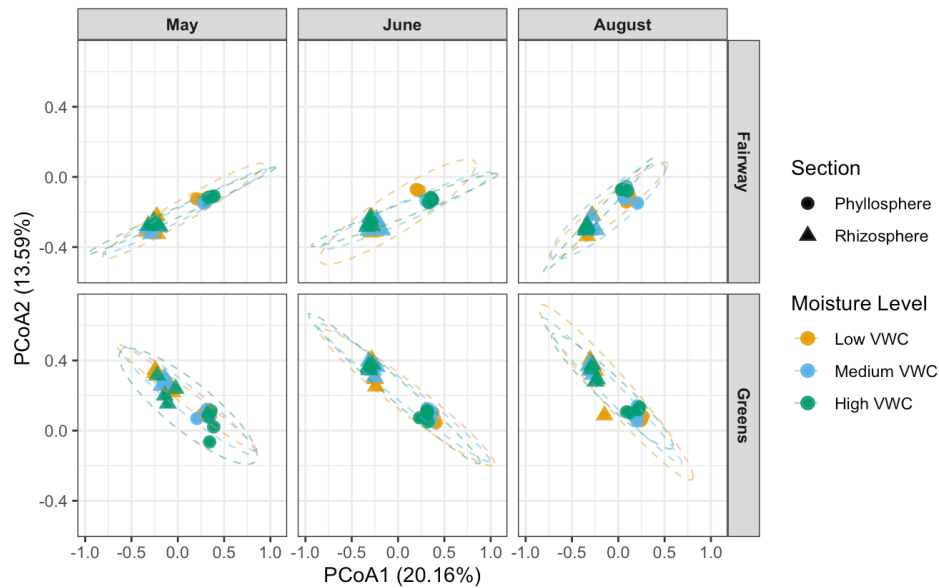


Figure 4. Bacterial beta Diversity (Bray-Curtis Dissimilarity) based on the soil type over time. A) Rhizosphere and B) phyllosphere, Collection date, and the type of soil had a significant effect on the beta diversity in the phyllosphere bacterial community. The soil type had a significant effect on the bacterial diversity in the rhizosphere community.

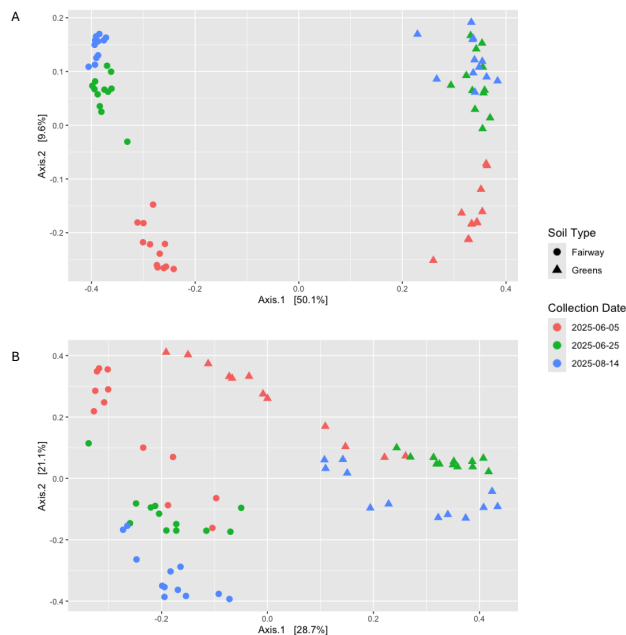
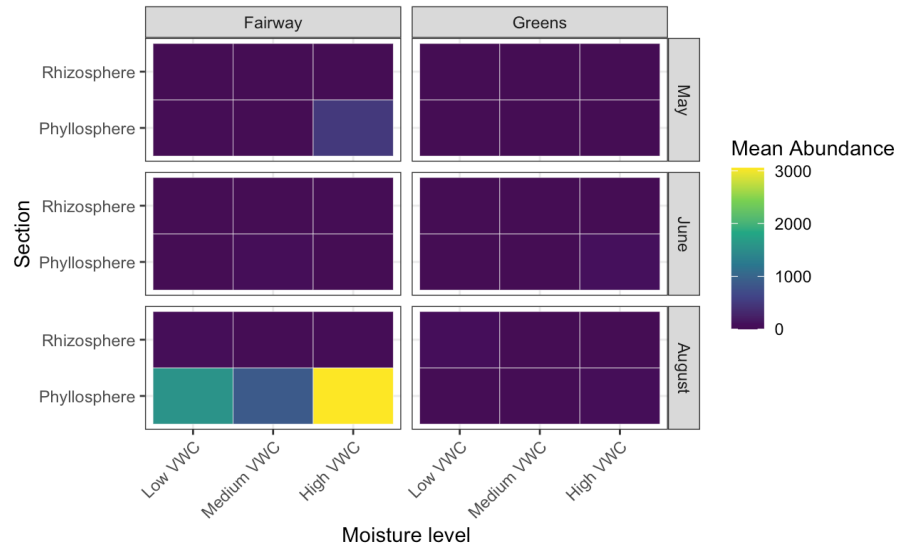


Figure 5. Heatmap showing the mean read abundance of *Clarithreedia jacksonii* ASVs across turfgrass sections, locations, moisture treatments, and sampling dates. Color scale represents average read counts per group.



USGA ID#: 2025-11-842

Development of a disease risk evaluation tool using digital PCR for consistent dollar spot quantification and fungicide resistant screening

Authors: Leandro Lopes de Silva, and Ming-Yi Chou
Department of Plant Biology, Rutgers University, New Brunswick, NJ 08901

Start: 2025
Duration: 3 years
Total funding: \$188,730

OBJECTIVES

This project is organized into three interconnected objectives that together aim to develop molecular tools for monitoring *Clariireedia* populations and SDHI resistance in turfgrass systems.

Objective 1 – Developing the multiplexed digital PCR-based *Clariireedia* quantification assay targeting multiple molecular markers and copy number variation (CNV) analysis

To develop a multiplex droplet digital PCR (dPCR) assay for accurate quantification of *Clariireedia* spp. in turfgrass samples. This includes selecting stable genomic targets, evaluating potential copy number variation (CNV), and establishing a robust panel of markers that reliably reflect total pathogen load.

Objective 2 – Survey of *Clariireedia jacksonii* isolates with varied level of fungicide resistance and their association with targeted SNPs to develop a multiplexed dPCR assay for fungicide resistance population detection and quantification

To survey a diverse collection of *C. jacksonii* isolates with different levels of SDHI fungicide resistance, identify and characterize resistance-associated SNPs in SDH and regulatory genes, and use this information to design SNP-specific (and ultimately multiplex) dPCR assays capable of detecting and quantifying resistant subpopulations.

Objective 3 – Validate the multiplexed dPCR-based pathogen quantification and SNP quantification assays for dollar spot using turf mowing clippings from research plots at Rutgers and golf courses across multiple states to determine the critical pathogen loads as disease risk, action thresholds, and fungicide resistant populations

To validate, under field conditions, the multiplex dPCR assays for both pathogen quantification (Objective 1) and resistance SNP detection (Objective 2) using DNA extracted directly from turfgrass mowing clippings. The aim is to relate pathogen load and resistance allele frequency to disease severity, define critical pathogen-load thresholds and action levels for fungicide use, and characterize the prevalence of SDHI-resistant populations across multiple locations.

INTRODUCTION

More than 70% of the fungicides applied on golf courses are used to control three major diseases: anthracnose caused by *Colletotrichum cereale*, brown patch caused by *Rhizoctonia solani*, and dollar spot caused by *Clarireedia* spp. (Bonos, 2006; Vargas, 2018). Among these, golf course superintendents apply more fungicides to control dollar spot than any other disease (Vargas, 2018). One consequence of this intensive fungicide use has been the development of fungicideresistant *Clarireedia* populations to several fungicide classes, including demethylation inhibitors (DMIs), benzimidazoles, and succinate dehydrogenase inhibitors (SDHIs) (Sapkota et al., 2022). In practice, disease control programs on many golf courses are still largely calendar-based, because superintendents lack precise information on pathogen load, disease risk, and the presence of fungicideresistant populations in the field.

Until recently, there were no practical methods to quantify *Clarireedia* populations in the field or to test the relationship between inoculum load and symptom development, making disease risk assessment difficult (Koch et al., 2017). A quantitative real-time PCR (qPCR) assay developed by our group can quantify *Clarireedia* spp. in asymptomatic and symptomatic leaf clippings (Groben et al., 2020), but qPCR is sensitive to PCR inhibitors in plant extracts, depends on standard curves for absolute quantification, and its accuracy can be affected by variation in amplification efficiency and standard quality. More recently, Ghimire et al. (2025)

developed a droplet digital PCR (ddPCR) assay to quantify *C. jacksonii* DNA in bentgrass clippings under field conditions, demonstrating high sensitivity and a strong correlation between pathogen load and dollar spot severity. However, both the qPCR and ddPCR assays target the ribosomal ITS region, which shows inter- and intra-specific variation in copy number (Kobayashi, 2011), and they focus on specieslevel detection without distinguishing between sensitive and resistant isolates.

Targeting housekeeping genes with more stable copy number should provide more reliable quantification across strains and species, but copy number variation (CNV) of potential markers has not yet been systematically studied in *Clariireedia* spp. Digital PCR (dPCR) is well suited for this purpose because it partitions each reaction into tens of thousands of independent micro-reactions, reducing the impact of inhibitors and allowing absolute quantification without a standard curve (Kuypers and Jerome, 2017). Our group has started to develop a dPCR assay using turfgrass samples collected from Rutgers University Hort Farm 2, and preliminary results indicate high sensitivity and efficiency for dollar spot detection using multiple candidate genetic markers.

Fungicide resistance in *Clariireedia* species has been attributed to single nucleotide polymorphisms (SNPs) in several genes. SDHI fungicides target the succinate dehydrogenase complex, and isolates with reduced sensitivity often carry SNPs in the genes encoding its subunits (Lee et al., 2021a, 2021b; Zhang et al., 2024). In addition, mutations in the transcription factor CjXDR1 have been shown to contribute to multidrug resistance, with some alleles associated with increased resistance to propiconazole, boscalid, and iprodione (Zhang et al., 2024). Digital PCR assays have been successfully used in other systems to quantify low-frequency resistance alleles in a predominantly wild-type background by using probes specific for wild-type and mutant nucleotides at the SNP site (Stevanato and Biscarini, 2016; Zulak et al., 2018; Baltrušis et al., 2018). Applying a similar strategy to *Clariireedia* would allow not only the quantification of total pathogen load but also detection and quantification of the key resistance alleles directly in field samples, without the need for lengthy and labor-intensive culture-dependent fungicide resistance diagnostic process.

Altogether, this project aims to bring more precision to dollar spot management by developing molecular assays that can both quantify pathogen load and detect fungicide resistance directly from turfgrass clippings. By moving from qPCR to dPCR, selecting stable genomic markers for more reliable *Clariireedia* load quantification, and designing SNP-specific assays that detect *C. jacksonii* and key SDHI resistance mutations in the same sample, we expect to generate tools that are useful for both researchers and the golf industry. These assays will help clarify plant–fungicide–*Clariireedia* interactions, support the definition of action thresholds based on pathogen load and resistance levels, and guide more informed fungicide choices at specific sites, with clear economic and environmental benefits.

MATERIALS AND METHODS

Acquisition and maintenance of isolates

A total of 116 isolates of *Clariireedia jacksonii* were obtained from the existing Rutgers collection and from collaborators at the University of Massachusetts, Purdue University, and Syngenta, representing isolates from 16 U.S. states and two from Japan. All isolates were routinely cultivated on potato dextrose agar (PDA) at room temperature for up to five days, after which they were cryopreserved as glycerol stocks at -80°C to ensure long-term viability. In addition, two isolates of *C. monteithiana*, one isolate of *C. bennettii*, and one isolate of *C. homoeocarpa* were maintained under the same culture conditions and were included as non-jacksonii controls for the validation of the species-specific and SNP-specific PCR assays.

***In vitro* assessment of fungicide sensitivity**

To evaluate phenotypic resistance profiles against SDHI fungicides, mycelial plugs derived from three-day-old PDA cultures were transferred to PDA plates amended with one of the following active ingredients: boscalid, penthiopyrad, fluxapyroxad, isofetamid, or pydiflumetofen, each at a discriminatory concentration of 1,000 $\mu\text{g}/\text{mL}$. Control plates consisted of unamended PDA. After incubation for 72 hours, colony diameters were measured and used to calculate relative mycelial growth (RMG), expressed as the ratio between the colony diameter on fungicide-amended medium and the diameter on control medium multiplied by 100.

The resulting RMG values for each isolate provided a quantitative measure of SDHI sensitivity.

Genomic DNA extraction

For DNA extraction, isolates were grown on PDA overlaid with sterile cellophane for five days. After this incubation period, the resulting mycelium was harvested from the plates, and genomic DNA was extracted using the Quick-DNA Fungal/Bacterial Miniprep Kit (Zymo Research), following the manufacturer's protocol. DNA concentration was measured fluorometrically using a Qubit instrument, and DNA purity was assessed by absorbance ratios. High-quality DNA preparations were subsequently used for both whole-genome sequencing and PCRbased validation assays.

Genome sequencing and data processing

For whole-genome sequencing, high-quality genomic DNA extracted from all the isolates were sequenced on an Illumina NovaSeq platform with paired-end 150 bp parameters, targeting approximately 10 Gb of raw sequence data per isolate. The resulting raw reads were first checked for quality using FastQC, and then adapters and low-quality bases were removed with Trimmomatic to obtain high-quality datasets for downstream analyses.

Reference gene sequences for the four succinate dehydrogenase subunits (SdhA, SdhB, SdhC, and SdhD) as well as the transcriptional regulator gene *CjXDR1* from *Clariireedia jacksonii* were used as mapping targets to extract homologous loci from each sequenced genome. Reference sequences were indexed using Bowtie, and each isolate's filtered reads were mapped against the indexed targets. Read alignments corresponding to each gene were recovered for all isolates. The mapped reads were subsequently assembled de novo using SPAdes, generating independent gene-level assemblies for each SDH subunit and for *CjXDR1* across the dataset. Following assembly, the resulting sequences were aligned using MEGA to identify polymorphic sites.

Target SNP PCR

Genomes from multiple *Clariireedia* species (9 *C. jacksonii*, 3 *C. monteithiana*,

3 *C. paspali*, 2 *C. hainanense*, and 3 *C. homoeocarpa*) were retrieved from GenBank, and the sequences corresponding to the succinate dehydrogenase subunits SdhB and SdhC were used as reference queries. These reference genes were used in local BLAST searches against each genome to recover homologous regions, and the resulting sequences were subsequently aligned in MEGA to identify species-specific variation and informative SNP sites suitable for marker development. Based on these alignments, informative SNP positions were selected as targets for primer development. Primer pairs for both species-specific and allelespecific amplification were designed using Primer3, enabling discrimination between wild-type and resistance-associated alleles.

For experimental validation, genomic DNA extracted from *C. jacksonii*, *C. monteithiana*, *C. homoeocarpa*, and *C. bennettii* was used as template in PCR assays employing the Platinum Hot Start Green PCR Master Mix (Invitrogen), following the manufacturer's recommendations. A touchdown PCR protocol was applied, beginning at 66°C and decreasing by 0.5°C per cycle until reaching 60°C, followed by standard amplification cycles to maximize specificity. Amplification products were resolved on 2% agarose gels stained with SYBR Safe and visualized under UV illumination to verify amplicon size and specificity.

RESULTS AND DISCUSSION

Relevance of geographic diversity in the isolate collection

To initiate this study, a total of 116 isolates of *Clariireedia jacksonii* were obtained, of which 114 originated from 16 different U.S. states, and two were collected from Hiroshima, Japan (Figure 1). This broad coverage is particularly significant because previous studies relied on small or regionally restricted isolate sets, which can narrow the observed range of genetic variation and lead to underestimation of the true genotypic diversity and mutational landscape of the species.

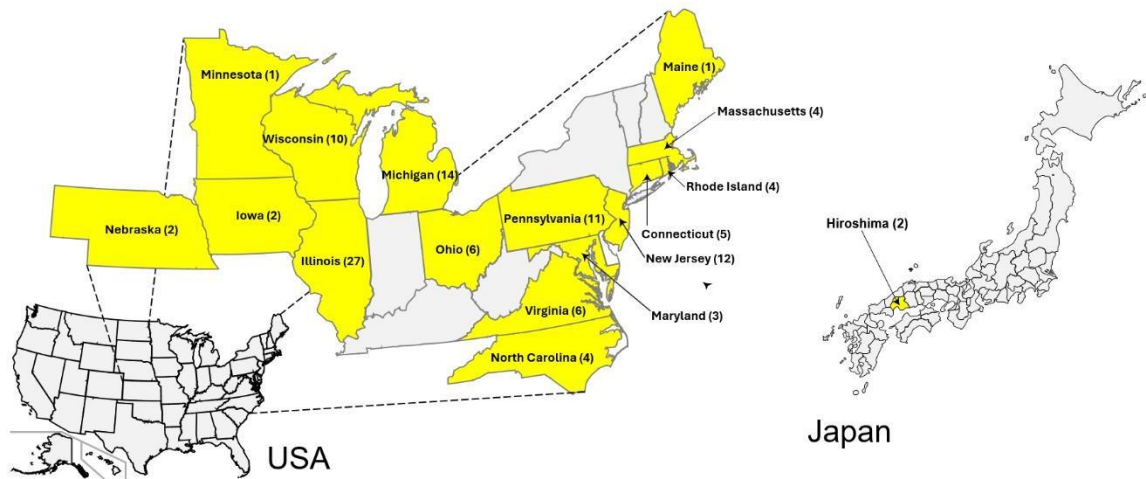


Figure 1. Geographic origin of the *C. jacksonii* isolates used in this study. States highlighted in yellow represent locations where isolates were collected, with the number of isolates from each state shown in parentheses.

The availability of such a large and geographically diverse isolate collection allows for a thorough and more accurate assessment for the spectrum of the mutation variability present in *C. jacksonii* population, including SNP variability across multiple genomic loci associated with fungicide resistance. This comprehensive sampling allow us to recover rare alleles, new variants, and regionspecific polymorphisms that could otherwise be missed in datasets derived from a small isolate collection. In addition, we included Japanese isolates because they were previously reported as SDHI-resistant in Popko et al. (2018). Inclusion of these isolates expands the geographic range of our collection and adds an important reference group of known resistant isolates.

We are continuing to expand this collection by adding isolates from more regions in the United States and from other countries. By increasing both the number of isolates and the geographic range of sampling, we will strengthen the power of our genetic analyses and improve the identification of resistance-associated alleles and evolutionary trends in this pathogen.

***In vitro* sensitivity to SDHI fungicides**

Among the isolates tested against the five SDHI active ingredients, we observed a wide range of relative mycelial growth (RMG%) values, indicating substantial diversity in fungicide sensitivity across the *C. jacksonii* population (Figure 2). Some SDHI fungicides, such as boscalid, fluxapyroxad, and penthiopyrad,

showed a similar overall distribution of RMG values. In contrast, isofetamid and pydiflumetofen displayed distinct resistance/sensitivity profiles, which may reflect differences in their binding affinity or inhibition of the succinate dehydrogenase enzyme complex.

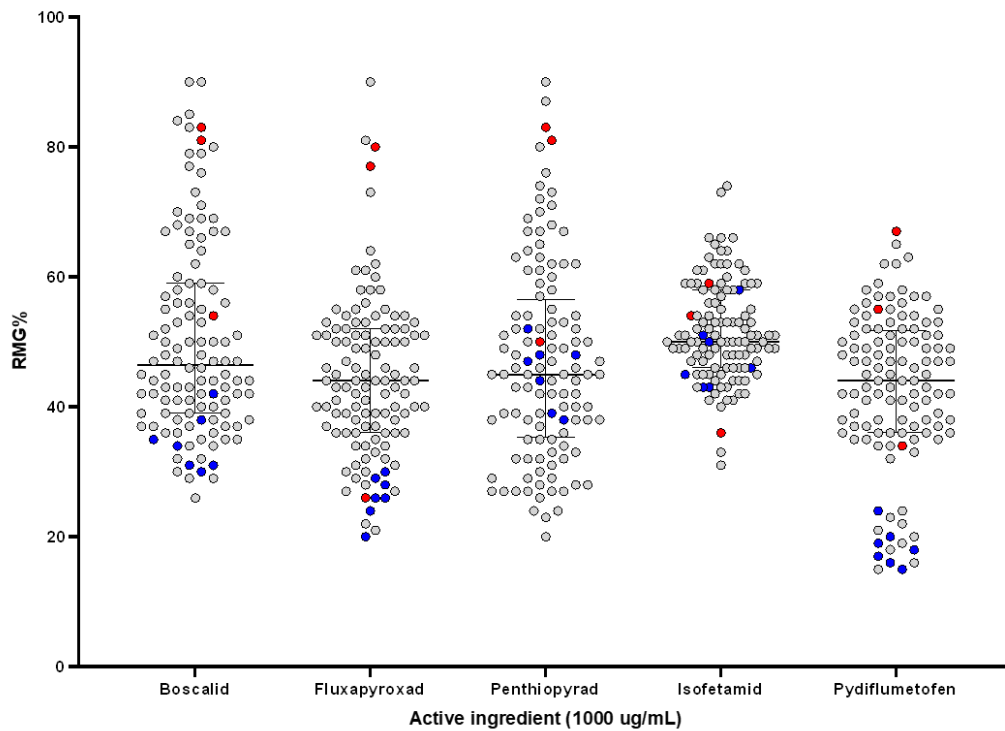


Figure 2. Relative mycelial growth (RMG%) of *Clariireedia jacksonii* isolates in response to five SDHI fungicides. Each point represents one isolate. Blue dots indicate baseline isolates, and red dots indicate isolates carrying previously proven SDH mutations that confer resistance.

The dataset also includes baseline isolates (shown in blue) that were collected between 1980s and 1990s, before the commercial introduction of SDHI fungicide (boscalid) for dollar spot control in turfgrass in the early 2000s. These historical isolates provide a reference for sensitivity and allow comparisons between pre-selection and post-selection genotypes. Isolates shown in red correspond to those from the United States (Rhode Island) and Japan, which were among the first reported to carry SDH mutations associated with SDHI resistance in *C. jacksonii* (Popko et al. 2018). These isolates show elevated RMG values for multiple SDHIs, confirming reduced sensitivity. However, some resistant isolates display high RMG for certain SDHIs but not for others, indicating that individual mutations may differentially affect the activity of specific SDHI molecules.

Most of the isolates (shown in gray), which represent the isolates collected post launching of boscalid, show a wide range of RMG values when challenged by SDHI fungicides, ranging from very low (highly sensitive) to very high (resistant). The RMG distribution of the tested isolates are mostly continuous (except for pydiflumetofen) rather than bimodal presented by sensitive and resistant groups. This pattern suggests that resistance in *C. jacksonii* is probably not controlled by a single major mutation, but instead results from different alleles at several resistance loci, producing a more gradual, quantitative type of resistance. These results highlight the importance of having a large and geographically diverse isolate collection to capture the full range of resistance phenotypes present in natural populations.

Cross-resistance among *C. jacksonii* isolates across SDHI fungicides

A simple inspection of the RMG values showed that the same isolates often appeared among the top 20–30 most resistant samples, regardless of which SDHI fungicide was tested. This pattern suggests that some isolates tend to be resistant to several SDHIs at the same time, rather than showing resistance to only one active ingredient.

Based on this observation, we evaluated cross-resistance by calculating pairwise correlations of RMG values across the five fungicides (Table 1). Strong positive correlations were found for several SDHI pairs, especially between boscalid and fluxapyroxad ($r = 0.83$), boscalid and penthiopyrad ($r = 0.77$), and fluxapyroxad and pydiflumetofen ($r = 0.74$). These results indicate that isolates that are less sensitive to one of these fungicides are often less sensitive to the others as well. In contrast, some combinations, particularly those involving pydiflumetofen with penthiopyrad or isofetamid, showed weaker correlations, suggesting that not all SDHIs are affected to the same extent by the same resistance mechanisms.

Table 1. Spearman correlation (r) of relative mycelial growth (RMG%) among the five SDHI fungicides.

Spearman r	Boscalid	Fluxapyroxad	Penthiopyrad	Isofetamid
Fluxapyroxad	0.83*			
Penthiopyrad	0.77*	0.61*		
Isofetamid	0.58*	0.67*	0.58*	
Pydiflumetofen	0.65*	0.74*	0.45*	0.36*

* p -value < 0.01

Mutation profile of SDH subunits

No mutation was identified in the *sdhA* subunit. Across the three SDH genes where variation was detected (*sdhB*, *sdhC*, and *sdhD*), we identified 12 different amino acid–changing mutations (Figure 3). Of these, two correspond to previously documented mutations whose role in SDHI resistance has been experimentally confirmed (Popko et al. 2018), and four other mutations had been reported in the literature but without genetic proof of their functional effect (Popko et al. 2018; Lee et al. 2021a,b; Hu et al. 2024). In our dataset, we also identified three new missense mutations in *sdhB*, one in *sdhC*, and two in *sdhD* genes, none of which had been previously described in *C. jacksonii*.

	<i>sdhB</i>				<i>sdhC</i>					<i>sdhD</i>		
Genes	N225T	H267Y	T268K	I269V	P80L/HN87S/KG91R		G150R	G159W		K6N	A16V	D143G
Mut	4	4	2	3	6	2	5	1	1	1	53	1

Figure 3. Observed mutation profile in the SDH genes of *Clarireedia jacksonii*. Red boxes indicate mutations with a proven effect on SDHI resistance, while yellow boxes indicate mutations previously reported in the literature without functional validation.

In addition to these amino acid substitutions, we detected a previously described synonymous (silent) mutation in *sdhB* in nearly half of all isolates. Because this mutation does not change the amino acid sequence and is also present in historical baseline isolates, we did not consider it as a candidate for resistance conferring mutation. Similarly, one of the newly detected amino acid substitutions in SDHD (A16V) occurred at high frequency in the population but was also found in baseline isolates collected before SDHI use. This pattern suggests that the mutation likely represents natural polymorphism rather than fungicide-driven selection, so it was also excluded as a causal resistance candidate.

Even after excluding the silent *sdhB* mutation and the common *sdhD* variant found in baseline isolates, the remaining SDH gene mutations still represent an important part of the population. In *sdhB*, the four missense variants each occur in two to four isolates, and in *sdhC* and *sdhD* the other mutations are also rare,

appearing in only one to six isolates each. Because, after removing the high-frequency *sdhD* variant, no isolate carries more than one of these low-frequency SDH mutations, the total number of affected isolates is simply the sum of their counts. In total, 30 of 116 isolates (25.9%) carry at least one of these SDH missense mutations, meaning that one quarter of the population has amino acid changes that may influence SDHI sensitivity.

Mutation profile of the *CjXDR1* regulatory gene

Analysis of *CjXDR1* sequences across all 116 isolates revealed a total of 11 different amino acid–changing mutations in this transcriptional regulator. Three of these variants had been reported before and were experimentally shown to affect SDHI resistance, while the other eight are newly detected substitutions that have not yet been tested functionally. One of these new variants (M5I) was also found in baseline isolates, so it was excluded as a strong resistance candidate. None of the isolates carried more than one *CjXDR1* mutation, indicating that these substitutions occur independently rather than in combination within the same genome. For the remaining new variants, their contribution to SDHI tolerance is still unknown, and further functional assays will be needed to determine whether they affect efflux regulation or other processes related to resistance.

CjXDR1 is not a direct target of SDHI fungicides, but it has been proposed as an important transcription factor that controls xenobiotic detoxification genes and can contribute to multidrug resistance in *C. jacksonii* (Sang et al. 2018). In that study, several point mutations in *CjXDR1* were linked to changes in SDHI sensitivity, and at least five different amino acid substitutions were described. In our population, we found three of these previously reported variants, as well as additional new changes. This supports the idea that different *CjXDR1* alleles can increase resistance to different degrees, often with a more additive and gradual effect. We also observed isolates that carry mutations both in SDH genes and in *CjXDR1*, suggesting that target-site changes and transcriptional regulation can act together to shape the resistance level. Until now, population studies of *CjXDR1* had been carried out mainly with Chinese isolates (Zhang et al. 2024). Our results extend this picture by showing the distribution of *CjXDR1* variants in a broad set of U.S., giving a wider view of how this regulator may contribute to SDHI resistance in field populations.

CjXDR1	M5I	G239R	V279F	N396V	T399S	M414I	G445D	K468T	S611F	V687I	M853T
Mut	1	2	1	8	1	1	2	2	4	1	1

Figure 4. Observed mutation profile in the *CjXDR1* gene of *Clarithreedia jacksonii*. Red boxes indicate mutations with a proven effect on SDHI resistance.

Association between *in vitro* sensitivity and mutations in SDH and CjXDR1 genes

When we compared the *in vitro* sensitivity data with the genotypes, we first saw that isolates with high RMG% values often carried at least one mutation in the *sdhB*, *sdhC*, or *sdhD* genes (Figure 5a). This pattern was most evident for boscalid, fluxapyroxad, and penthiopyrad, where the isolates with the highest RMG% usually had either known resistance mutations, previously reported mutations without functional proof, or new mutations identified in this study. For isofetamid and pydiflumetofen, the same general trend was present, but it was weaker.

When we looked at the transcriptional regulator CjXDR1, isolates carrying previously validated resistance-associated mutations usually showed an intermediate level of resistance, and only a few of them reached the highest RMG% values (Figure 5b). In contrast, several of the new CjXDR1 mutations were found in isolates with high resistance levels. However, these same new mutations also appeared in isolates with intermediate or even low RMG%, indicating that the effect of CjXDR1 variants on resistance is not consistent across all isolates and may depend on other genetic factors or compensatory mechanisms in the cell.

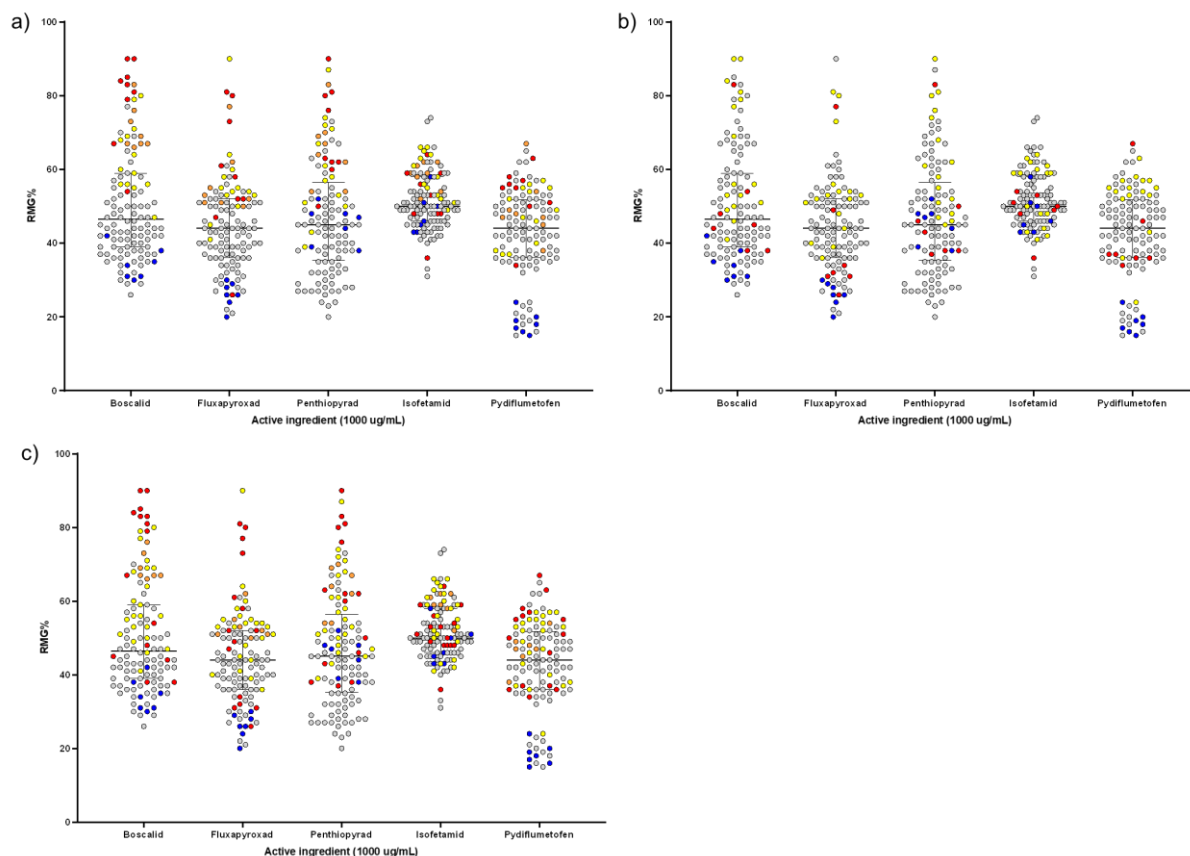


Figure 5. Distribution of relative mycelial growth (RMG%) across SDHI fungicides, colored by SDH and CjXDR1 mutation categories in *Clarireedia jacksonii* isolates. (a) colored by mutation in SDH genes (b) colored by mutation in CjXDR1 gene (c) colored by the mutation in SDH and CjXDR1 genes. Gray: isolates with no mutation; Red: mutations with a proven effect on SDHI resistance; Orange: mutations previously reported in the literature but not functionally validated. Yellow: identified mutations from this study; blue: baseline isolates.

Finally, when we combined the information from both the SDH genes and CjXDR1, we found a considerable number of isolates with high RMG% that did not have mutations in any of these known resistance-related loci. These isolates are phenotypically resistant but genetically “wild-type” for SDH and CjXDR1, which strongly suggests that other mechanisms also contribute to SDHI resistance in *C. jacksonii*. Possible explanations include epigenetic changes, physiological tolerance mechanisms, alternative efflux pump systems, metabolic detoxification pathways, or compensatory changes in the respiratory chain.

This pattern, in which some isolates are clearly resistant but do not carry target-site mutations, is not unique to *C. jacksonii*. Similar observations have been reported in other plant-pathogenic fungi. For example, in *Cercospora beticola* exposed to DMI fungicides, several resistant isolates do not have mutations in the

target gene, and resistance has been linked instead to mechanisms such as altered regulation, efflux transporters, and other genomic changes (Spanner et al. 2021). In those cases, additional candidate genes were discovered using broader approaches such as genome-wide association studies (GWAS) and transcriptomic analyses. These examples reinforce the idea that, beyond SDH and CjXDR1, other genes and pathways are likely involved in SDHI resistance in *C. jacksonii* and will need to be explored with similar genome-wide strategies.

SNP-specific PCR assay for detection of mutant *C. jacksonii*

In parallel with the genomic and *in vitro* sensitivity analyses, we began developing a SNP-specific PCR assay to detect *Clarithromycin* *jacksonii* isolates carrying SDHI resistance-associated mutations. As a starting point, three target SNPs previously described by Popko et al. (2018), one in *sdhB* and two in *sdhC*, were selected. To ensure that the assay would be both species-specific and mutation-specific, reference sequences of *sdhB* and *sdhC* from about 20 publicly available *Clarithromycin* genomes were aligned. This comparison revealed a few base substitutions that were fixed within species and could be used to distinguish *C. jacksonii* from other *Clarithromycin* species.

Primers were then designed with two complementary purposes. First, a pair of control primers was positioned in a conserved region unique to *C. jacksonii*, providing a species-specific amplification signal that does not depend on the presence of resistance mutations. Second, three additional primer pairs were designed to overlap the resistance-associated SNP sites in *sdhB* and *sdhC*, so that efficient amplification would occur only when the mutant allele is present. In this way, the assay was intended to distinguish (i) *C. jacksonii* from other *Clarithromycin* species and (ii) mutant *C. jacksonii* isolates from wild-type ones.

The first validation of this system was carried out using conventional PCR on a small panel of isolates representing four *Clarithromycin* species, including both wildtype and mutant *C. jacksonii* (Figure 6). The species-specific control primers produced amplicons only from *C. jacksonii*, confirming that the assay can discriminate this species from closely related taxa. In contrast, the SNP-targeted primer pairs produced visible bands only for *C. jacksonii* isolates known to carry the corresponding *sdh* mutations, and no amplification was detected for wild-type *C.*

jacksonii or for other *Clariireedia* species. These results show that the assay can selectively detect mutant *C. jacksonii* genotypes against a background of related species.

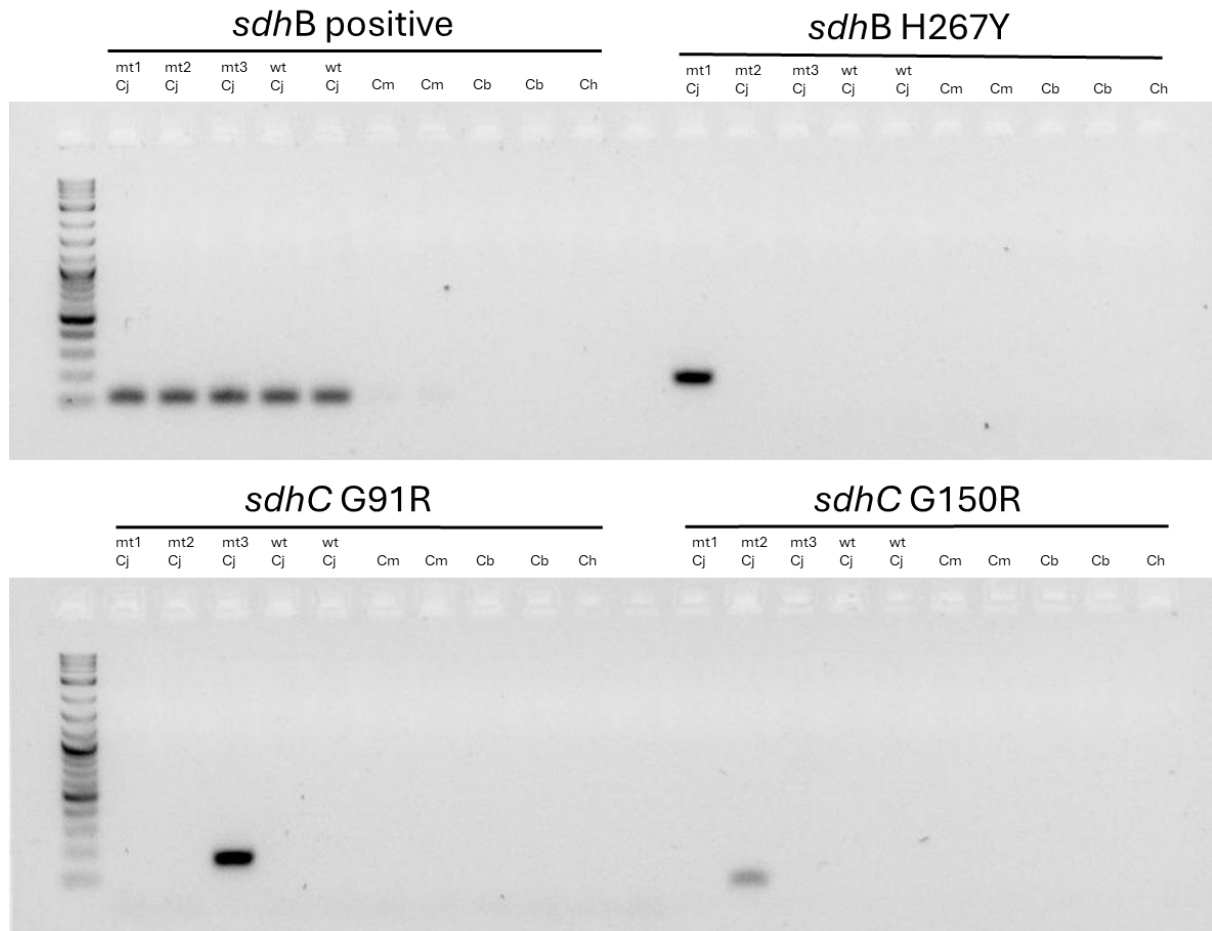


Figure 6. Conventional PCR validation of the SNP-specific assay for mutant *Clariireedia jacksonii*. Upper gel: amplification with the *C. jacksonii* species-specific control primers and SNP-specific primers targeting SDHI resistance-associated mutations in the *sdhB* gene. Lower gel: amplification with SNP-specific primers targeting SDHI resistance-associated mutations in the *sdhC* gene. Mt1, H267Y mutant; Mt2, G91R mutant; Mt3, G150R mutant; Wt, wildtype; Cj, *C. jacksonii*; Cm, *C. monteithiana*; Cb, *C. bennettii*; Ch, *C. homoeocarpa*.

At this stage, all tests were performed on DNA extracted from pure cultures and visualized only as presence/absence bands, which is sufficient as a proof of concept. A logical next step is to perform this assay on a more sensitive platform, such as digital PCR, and to apply it directly to DNA extracted from diseased turfgrass clippings. A recent study by Ghimire et al. (2025) showed that droplet digital PCR (ddPCR) can reliably detect and quantify *Clariireedia* DNA in field clipping samples and that pathogen load is strongly correlated with dollar spot severity. However, that

assay measures only the total amount of *Clarireedia* spp. and does not distinguish between sensitive and resistant isolates. Our goal is to go beyond simple species detection by combining species-specific and SNP-specific primers so that digital PCR can both detect *C. jacksonii* and identify key resistance alleles in the same clipping sample. This would allow rapid detection of SDHI-resistant subpopulations directly in field samples, without prior isolation and culturing, and would provide a practical diagnostic tool to support resistance monitoring and management decisions.

The SNP-specific PCR assay was first designed using a small set of resistance-associated mutations previously reported in SDH genes, and its development took place in parallel with the *in vitro* sensitivity tests and wholegenome sequencing of the isolate collection. After the sequencing and comparative analyses were completed, however, it became clear that the mutation pattern in *C. jacksonii* is much more complex than suggested by the originally described SDH variants. Several additional mutations were identified in both the SDH genes and CjXDR1, and many isolates with high RMG values carried one or more of these newly detected candidate SNPs.

These findings do not disapprove the original diagnostic assay; instead, they place it in a broader context and highlight new opportunities for improvement. Our findings suggest that some of the newly identified SNPs may also contribute to SDHI resistance and could be included as additional targets in future versions of the assay. At this stage, however, the functional role of these new mutations is still unknown, and systematic validation is required before they can be used as reliable diagnostic markers. Going forward, the SNP-specific assay will be updated and refined based on those SNPs that show the strongest and most consistent association with resistance in field populations. As additional variants are functionally validated, the most informative markers will be incorporated into future assay development, while we continue to test and optimize the current assay, so that it can ultimately be used as a robust tool for monitoring SDHI resistance in field samples.

Future directions

Although the work completed so far has focused mainly on Objective 2, it now provides a strong foundation to advance all three objectives of the project in a

connected and logical way. By assembling a large and geographically diverse collection of *C. jacksonii* isolates, characterizing their *in vitro* SDHI resistance profiles, sequencing their genomes, and profiling mutations in SDH genes and CjXDR1, we now have detailed information on SNP variation, candidate resistance loci, and resistance levels across the population. These datasets will directly guide the design of multiplex dPCR assays and the interpretation of pathogen and resistance quantification in field samples.

For Objective 1, the availability of high-quality genome sequences and a well-described SNP landscape allows us to select stable, non-variable genomic regions as targets for *Clariireedia* load quantification and to avoid loci under strong selection or with copy-number variation. In parallel, we have started long-read sequencing of the same isolate panel using Oxford Nanopore technology. These long-read assemblies will greatly improve genome contiguity and will be critical for accurate copy-number analysis, reducing the biases and limitations of PCR-based or shortread-only approaches.

For Objective 2, the discovery of multiple new SDH and CjXDR1 variants expands the scope of our initial diagnostic design, which was based only on previously reported mutations. The next step will be to test the association between each candidate SNP and the level of SDHI resistance. This will allow us to prioritize a subset of mutations that show the strongest and most consistent link to resistance. These high-confidence markers will then be incorporated into an expanded multiplex dPCR panel capable of detecting resistance alleles.

Looking ahead to Objective 3, the long-term goal is to move these tools from pure cultures to real turfgrass systems. Once the pathogen-load dPCR assay (Objective 1) and the resistance-SNP dPCR assay (Objective 2) are finalized, we will validate them using DNA extracted directly from clippings. This will allow us to quantify both total *Clariireedia* load and the proportion of resistant subpopulations in field samples, and to relate these measurements to observed disease severity. Over time, these data will help define critical pathogen-load thresholds for disease risk and action levels for fungicide use, and will also provide an early-warning system for the emergence and spread of SDHI-resistant *C. jacksonii* in managed turfgrass environments.

USGA ID#: 2023-07-774

Title: Understanding Pacific Northwest Turfgrass Plant-Parasitic Nematode Communities to Improve Management Efficiency

Project Leaders: Hannah Rivedal¹, Emily Braithwaite², Alec Kowalewski², Inga Zasada³
Affiliation: ¹USDA-ARS Forage Seed and Cereal Research Unit; ²Oregon State University Department of Horticulture; ³USDA-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.
- Metabarcoding sequencing was successful, though further data analysis is currently underway.

This research has led to the publication of three manuscripts, and 5 presentations to industry and scientific audiences in 2025.

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 were sampled through August of 2025, which allowed us to have 1 full year of data on 15-20 courses per state.

In each year, sampling was 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 were surveyed. Golf greens were walked in a zig-zag fashion, collecting 20 samples per green. Soil and plant samples were bulked by green before nematode extraction. Turfgrass damage was noted when it was visible. In conjunction with visual ratings, we collected 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 thresholds and management recommendations. Nematodes were extracted from samples using a Baermann funnel for 3 days. Extracted nematodes were 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. A set of 96 samples were selected for metabarcoding sequencing. These initial samples included known quantities of individual species (*Meloidogyne naasi*, *Globodera rostochiensis*, and *Anguina funesta*) to determine minimum number of PPN required for successful sequencing and to evaluate whether nematode abundance correlated to number of reads. An additional set of mixed population samples was included from seven surveyed courses. These contained varying proportions of free-living and plant-parasitic nematodes (ranging from 90% to 30% free-living). We ran sequencing on an Illumina MiSeq platform in collaboration with the USDA-ARS Beltsville, Maryland, Nematology laboratory.

Objective 3: Data collection is still under way for initial action threshold determinations and will continue into our USGA funded project in the next three years. 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 is 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 that is currently being confirmed with molecular and morphological 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.

We have collected metabarcoding sequences from our initial test and are working to process the data. Our samples had between 32,000 and 700,000 reads, with most falling between 150,000 and 400,000 reads. This indicates a successful round of sequencing, and indicates we had variability across our samples which may be due to the number of individual nematodes included in each sample. We will process samples with the assistance of bioinformatics tools and provide the updates on this project goal in the final report.

Deliverables: A manuscript describing the initial survey efforts at an Oregon golf facility supported by this proposal was accepted in *Plant Disease* (citation 1). A manuscript focused on the evaluation of *Meloidogyne* spp. in PNW turfgrass systems supported by this proposal was presented at the International Turfgrass Research Conference in Japan in 2025 and is published

in the *International Turfgrass Society Research Journal* (citation 2). This work has also led to a first report of *Anguina pacifica* in Washington state, published in the *Journal of Nematology* (citation 3). In total, 5 presentations about this work were presented in 2025 at regional industry events, national and international industry events, and scientific meetings.

Citations

1. Braithwaite, Emily, Robert J. Starchvick, Alec R. Kowalewski, Todd N. Temple, Hannah V. Baker, Megan Kitner, Amy B. Peetz, Inga A. Zasada, and Hannah M. Rivedal. 2025. A community analysis of plant-parasitic nematodes on coastal Oregon golf course putting greens. *Plant Disease* 109: <https://doi.org/10.1094/PDIS-02-25-0431-RE>.
2. Braithwaite, Emily, Robert J. Starchvick, Alec R. Kowalewski, Todd N. Temple, Inga A. Zasada, and Hannah M. Rivedal. 2025. Identification of *Meloidogyne* spp. from cool-season golf course putting greens in the Pacific Northwest. *International Turfgrass Society Research Journal*. 2025:1-3. <https://doi.org/10.1002/its2.190>.
3. Braithwaite Emily, Charles J. Schmid, Alec R. Kowalewski, Katherine Fleming, Amy B. Peetz, Inga A. Zasada, and Hannah M. Rivedal. 2025. First Report of *Anguina pacifica* Parasitizing Turfgrass in Washington. *Journal of Nematology*. 57(1):20250053. doi: 10.2478/jofnem-2025-0053.

Future Expectations: We will complete our initial metabarcoding efforts. With the support of the USGA, we have received additional funding to employ an action threshold and nanopore sequencing trial to help support decision making on golf courses. We will continue to share our results with the golf course industry.

Images:

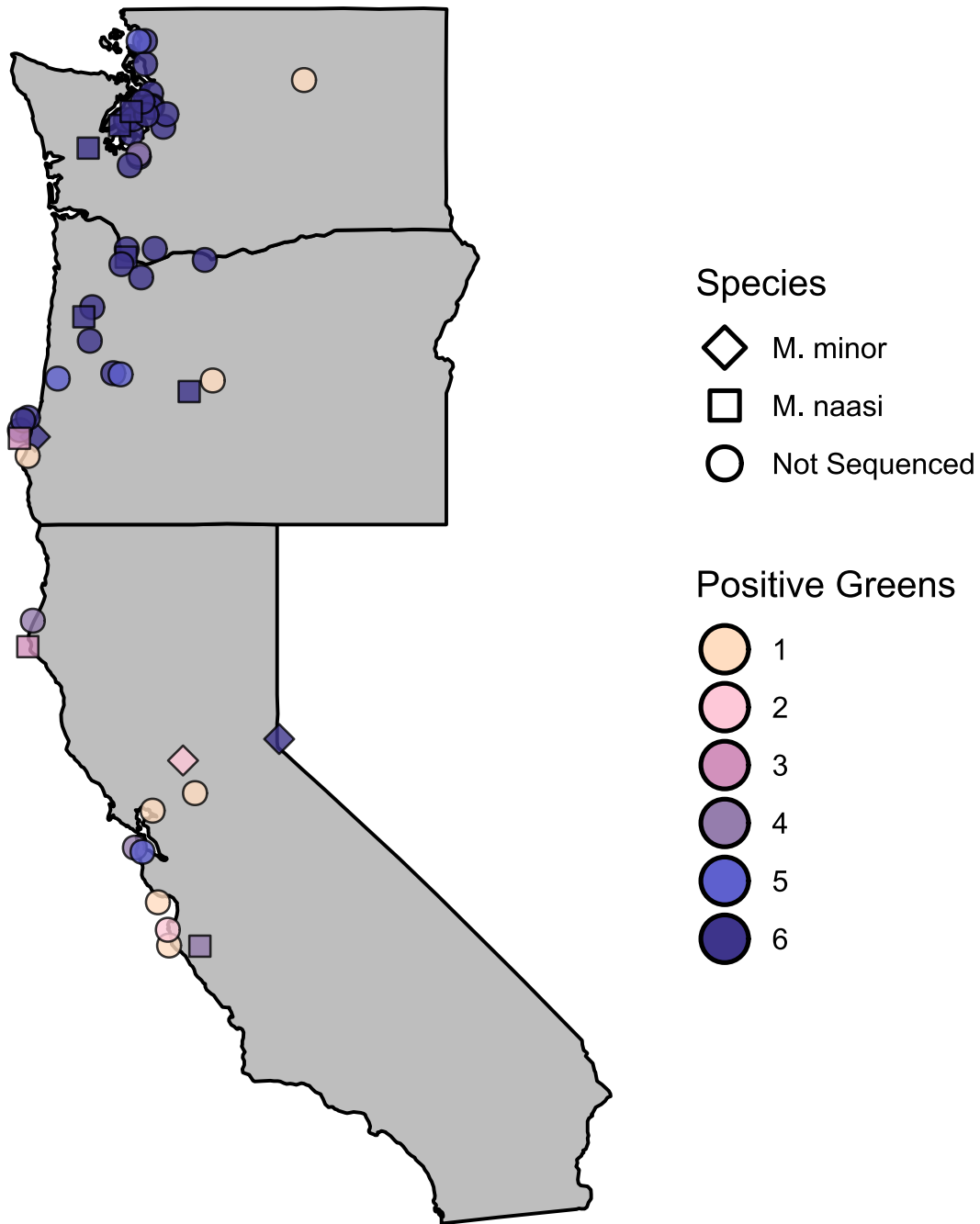


Figure 1. Geographic locations of golf courses sampled in Washington, Oregon, and California. A total of 44 courses were included in the analysis, with six putting greens sampled per course (n = 264). Point color indicates the number of greens that tested positive for *Meloidogyne* spp. (0–6 per course). Point shape denotes nematode identification: diamond = *M. minor*, square = *M. naasi*, circle = Not Sequenced..



Figure 2. Washington golf course with damage from *Anguina pacifica*. This is the first report of this species affecting golf courses outside California in the United States. It is also the first incidence of this nematode affecting tee boxes.

Seasonal Patterns of Nematode Species - Washington

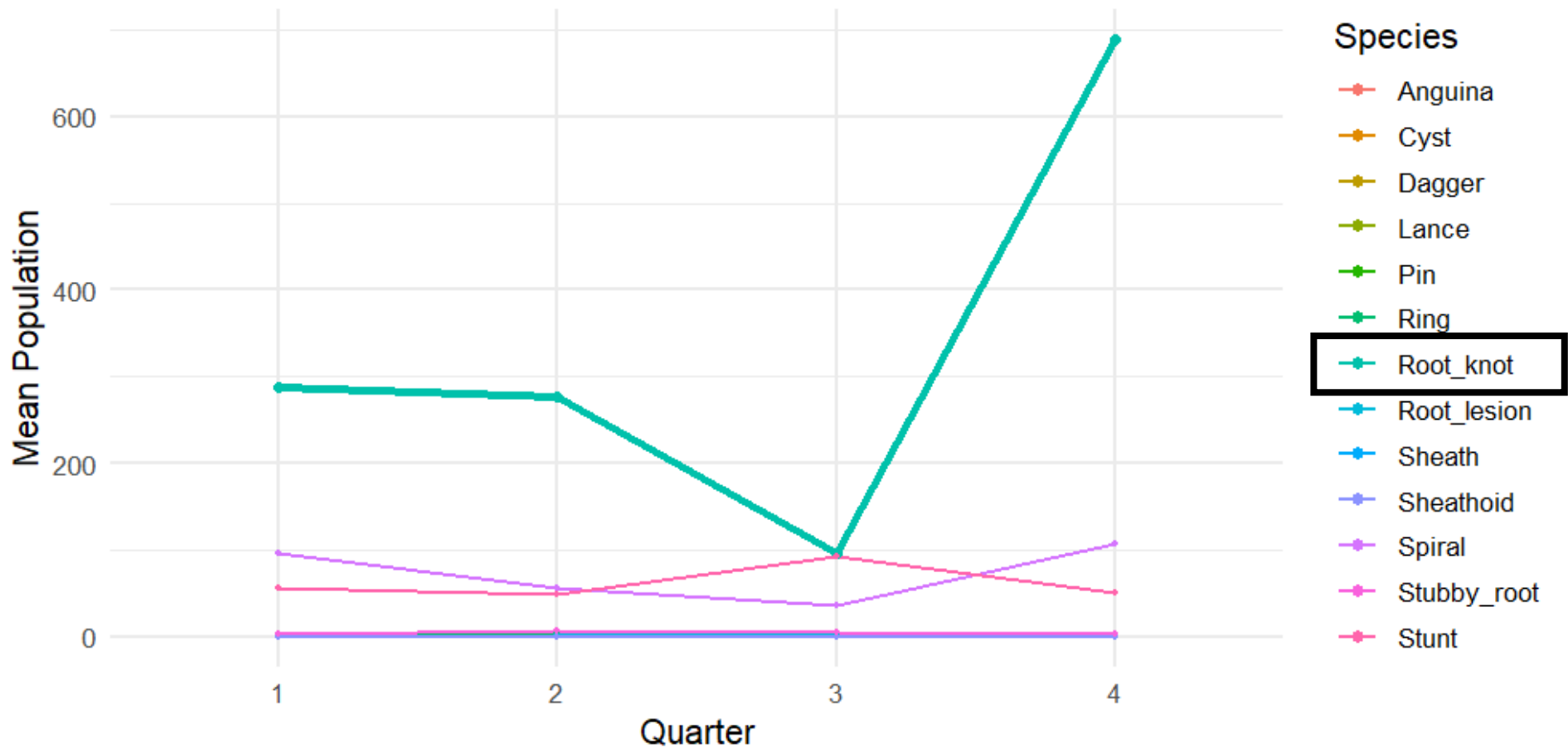


Figure 3: Seasonal patterns of nematode species recovered from Washington golf courses. Population densities represent averages across all 20 sampling locations, each consisting of six representative greens, including both healthy and symptomatic sites. Despite this broad averaging, root-knot nematodes remain consistently prominent, with densities peaking in November. This underscores their importance as a key species of concern going forward.

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 <i>Helicotylenchus sp.</i>	100%	100%	96%
Root-knot nematode <i>Meloidogyne sp.</i>	90%	91%	96%
Cyst nematode§ <i>Heterodera sp.</i> <i>Punctodera sp.</i>	8%	18%	9%
Ring nematode <i>Criconea sp.</i>	20%	36%	57%
Stunt nematode <i>Tylenchorhynchus sp.</i>	13%	45%	74%
Root-lesion nematode <i>Pratylenchus sp.</i>	0%	27%	0%
Sheathoid nematode <i>Hemicycliophora sp.</i>	0%	9%	0%
Stubby root nematode§ <i>Trichodorus sp.</i> <i>Paratrichodorus sp.</i>	46%	73%	48%
Pin nematode <i>Paratylenchus sp.</i>	0%	9%	4%
Pacific shoot-gall nematode <i>Anguina pacifica</i>	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 <i>Meloidogyne</i>	Average <i>Meloidogyne</i> spp. J2 per 100 cc on a single green	Max density of <i>Meloidogyne</i> spp. J2 per 100 cc on a single green	Sequence Identification
California	<i>Poa annua</i>	12	12	34	176	<i>Meloidogyne naasi</i>
	<i>Agrostis stolonifera</i>	18	16	24	48	<i>M. minor</i>
Oregon	<i>P. annua</i>	96	88	166	3,498	<i>M. naasi</i> <i>M. minor</i>
	<i>A. stolonifera</i>	12	12	184	660	<i>M. naasi</i>
	<i>Festuca rubra</i> ssp.	12	3	2	12	<i>M. naasi</i>
Washington	<i>P. annua</i>	120	113	748	10,244	<i>M. naasi</i>
	<i>A. stolonifera</i>	6	4	16	58	

USGA ID#: 2022-12-755

Title: USE OF ENDOPHYTIC MICROORGANISMS FROM A NEMATODE-TOLERANT BERMUDAGRASS CULTIVAR AS NEMATOCIDAL BIOCONTROL AGENTS

Project Leader: Marco Schiavon

Affiliation: University of Florida

Objectives: This study investigated the diversity of entomopathogenic nematodes (EPNs) in Floridian turfgrass systems and the effect of secondary metabolites of their symbiotic bacteria against grass root-knot (*Meloidogyne graminis*) nematodes

Start Date: 2022

Project Duration: Three years

Total Funding: \$116,655.69

Summary Points:

- Florida turfgrass soils harbor a high diversity of EPNs and associated bacteria
- Results suggest for the first time that *Xenorhabdus* and *Photorhabdus*-derived secondary metabolites offer a promising biocontrol approach for managing *M. graminis*.

Summary Text: Recent scientific advances have highlighted the potential of entomopathogenic nematodes (EPNs) and their symbiotic bacteria, *Xenorhabdus* and *Photorhabdus*, as sources of potent bioactive metabolites capable of disrupting plant-parasitic nematodes. While these bacterial metabolites have been studied in vegetable crops, their diversity in turfgrass ecosystems—and their potential activity against turfgrass-associated nematodes—remains unexplored. A total of 100 soil samples, randomly collected and submitted to the University of Florida Nematode Assay Lab for PPN analysis, were used to isolate EPNs. The samples were subjected to baiting using *Galleria mellonella* larvae to isolate any EPNs present. Emergent nematodes were identified first through morphological observation and then molecularly using 28S and ITS rDNA sequencing. Once identified, each nematode isolate's symbiotic bacteria were extracted by surface-sterilizing infective juveniles, homogenizing them, and streaking the homogenate on selective media. Bacterial colonies that exhibited characteristic *Xenorhabdus* or *Photorhabdus* morphology were further purified and identified by sequencing the 16S rRNA gene. The next stage involved extracting secondary metabolites from each bacterial isolate. Cultures were grown under controlled conditions, centrifuged, and filtered to produce cell-free supernatants; metabolites were extracted using ethyl acetate and concentrated by evaporation. These crude extracts were resuspended in sterile water and tested in

nematicidal assays. Second-stage juveniles of *M. graminis* and mixed-stage *B. longicaudatus* were exposed to the bacterial metabolites at concentrations of 25%, 50%, and 100% for 24, 48, and 72 hours. Mortality was quantified after verifying immobility via NaOH stimulation, and the resulting data were analyzed using multi-factor ANOVA and post hoc statistical comparisons.

The results demonstrated substantial diversity of both EPNs and their bacterial symbionts within Florida turfgrass soils. Twelve EPN isolates were recovered, representing *Heterorhabditis indica*, *Steinernema glaseri*, and *Steinernema diaprepesi*. These isolates came from northern, central, and southern Florida and were associated with several turfgrass species including zoysiagrass, St. Augustinegrass, and bermudagrass. Molecular analyses also revealed a surprisingly rich diversity of associated bacteria, including *Xenorhabdus poinarii*, *X. griffinae*, *X. indica*, *X. doucetiae*, *Photorhabdus akhurstii*, and *P. luminescens*. Several bacterial species were found in associations not previously reported, suggesting possible novel symbiotic relationships within turfgrass environments.

A comparison of means between concentrations revealed a statistically significant difference between each group (25%, 50% and 100%) ($P < 0.0001$). Similarly, statistical significance was observed between time groupings (24, 48 and 72 h) ($P < 0.0001$) and treatments (crude extracts) ($P < 0.0001$). The treatment \times concentration interaction was significant ($P < 0.0001$); however, the treatment \times time and the concentration \times time \times treatment interactions were not ($P = 0.0955$ and $P = 0.996$, respectively).

The bioassay data (Table 1) demonstrated that bacterial secondary metabolites at a 100% concentration significantly impacted *M. graminis* J2s mortality across different time exposures, regardless of treatment, compared to the untreated control. After only 24 h, a mortality of $>90\%$ was observed, with a 100% mortality rate seen after 72 h in eight of 12 isolates. Notably, the treatment *P. akhurstii* 1122 displayed consistently high levels of nematode mortality, ranging from 99.5% to 100%. Tukey's HSD test revealed no significant differences among the isolates, suggesting similar efficacy in nematode mortality across different bacterial secondary metabolites.

At 50% concentration, differing mortality patterns were observed at 24, 48 and 72 h, showing varying levels of *M. graminis* mortality over time. The highest mortality rates were seen in the treatments *X. poinarii* 733, *X. griffinae* 1050, *P. akhurstii* 752 and *P. akhurstii* 1122, which all maintained high mortality rates of $>90\%$ after 24 h to $>98\%$ after 72 h. At this concentration, the treatment *X. poinarii* FLREC exhibited the lowest mortality rates (9.9–42.6%) and statistically differed from other treatments (Table 1).

At 25% bacterial metabolite concentration, the *M. graminis* mortality rate varied across time exposures and treatments. The highest mortality rate was observed in the treatments *X. poinarii* 733 and *X. griffinae* 1050, which had a mortality rate of >87% at 24 h, progressing to >98% after 72 h. Treatments, *X. poinarii* FLREC, *X. indica* 1084, *X. doucetiae* 911, *P. akhurstii* 1122 and *P. akhurstii* 679 exhibited significantly lower mortality rates compared to *X. poinarii* 733 and *X. griffinae* 1050 at each time interval of exposure (Table 1).

The secondary metabolites at various concentrations induced small to large vacuoles in the body of >70% of *M. graminis* J2s, whereas water-treated nematodes showed no such vacuoles (Fig. 2).

Table 1. Effect of different concentrations (25, 50, and 100%) and exposure times (24, 48, and 72 hours) of secondary metabolites of symbiotic bacterial species on mortality of *Meloidogyne graminis*.

Bacterial isolates	100%			50%			25%		
	24h	48h	72h	24h	48h	72h	24h	48h	72h
<i>Xenorhabdus poinarii</i> _733	93.8±2.1a	98.3±1a	100.0±0.0a	92.5±0.3a	92.5±0.3ab	100.0±0.0a	84.8±2.8a	87.6±4.8ab	99.7±0.4a
<i>X. poinarii</i> _1086	91.0±3.5a	100.0±0a	100.0±0.0a	85.6±4.1abc	94.3±2.6a	100.0±0.0a	59.2±13.2a	62.1±7.6ab	76.7±2.3a
<i>X. poinarii</i> _FLREC	93.9±1.2a	97.7±1.4a	98.7±0.8a	9.9±4.3d	29.9±5.2c	42.6±2c	8.59±4.2cd	24.8±6def	41.5±8.7b
<i>X. griffiniae</i> _1050	92.3±1.5a	98.7±1.3a	100.0±0.0a	91.4±3a	96.1±2.7a	100.0±0.0a	90.2±4.2a	95.1±3.1a	99.6±0.3a
<i>X. indica</i> _1084	91.2±1.1a	100.0±0.0a	100.0±0.0a	71.7±8.2bc	77.1±5.8b	82.8±6.5b	8.3±4.2cd	8.3±4.2f	13.3±4.7b
<i>X. doucetiae</i> _911	94.8±2.2a	100.0±0.0a	100.0±0.0a	93.9±3.5a	98.4±1.6a	100.0±0.0a	5.2±3.4cd	17.8±4.3ef	29.4±10.7bc
<i>Photorhabdus luminescens</i> _1189	90.9±2.7a	98.7±1.3a	100.0±0.0a	66.4±6c	85.3±5ab	92.5±3ab	66.2±16.9a	68.5±12.9a	85.5±5.7a
<i>P. akhurstii</i> _679	93.5±3.2a	97.7±1.6a	100.0±0.0a	78.6±3.7abc	91.7±4ab	94.5±2.6a	65.9±8.3ab	82.3±2.3ab	85.7±3.4a
<i>P. akhurstii</i> _752	98.5±0.9a	100.0±0a	100.0±0.0a	94.6±0.6a	100.0±0.0a	100.0±0.0a	31.5±7.1bc	35.1±7.7cd	91.7±3.2a
<i>P. akhurstii</i> _846	95.2±3a	99±1a	99.0±1a	87.1±2.5ab	94.2±4.8a	95.3±1.8a	47.9±13.5a	49.6±1.7bc	83.5±6.9a
<i>P. akhurstii</i> _1122	99.5±0.5a	100.0±0a	100.0±0a	94±2.4a	100.0±0.0a	100.0±0.0a	67.8±15.4a	71.5±14.4a	76.8±10.6a
<i>P. akhurstii</i> _1129	93.9±1.5a	99.7±0.3a	100.0±0a	92.3±3.1a	96.8±1.9a	100.0±0.0a	46.7±7.2ab	86.7±5.4ab	93.3±3.8a
Control (water)	0.8±0.8b	1.5±0.9b	1.6±1.5b	0.0±0.0d	1.6±1.5d	4.8±1.7d	0.0±0.0d	5.4±2f	8.2±0.9c

Each value (± standard error) is the average of four replicates. Differences in means indicated by the same lower-case letters in the same column do not significantly differ according to Tukey's test at $P \leq 0.05$.

Images:

Figure 1. Map of Florida, USA, with positive entomopathogenic nematode locations marked with blue dots (●). Identified nematode species are listed with the isolate code. Spatial graphics were made with ArcGIS (ESRI, Redlands, CA).

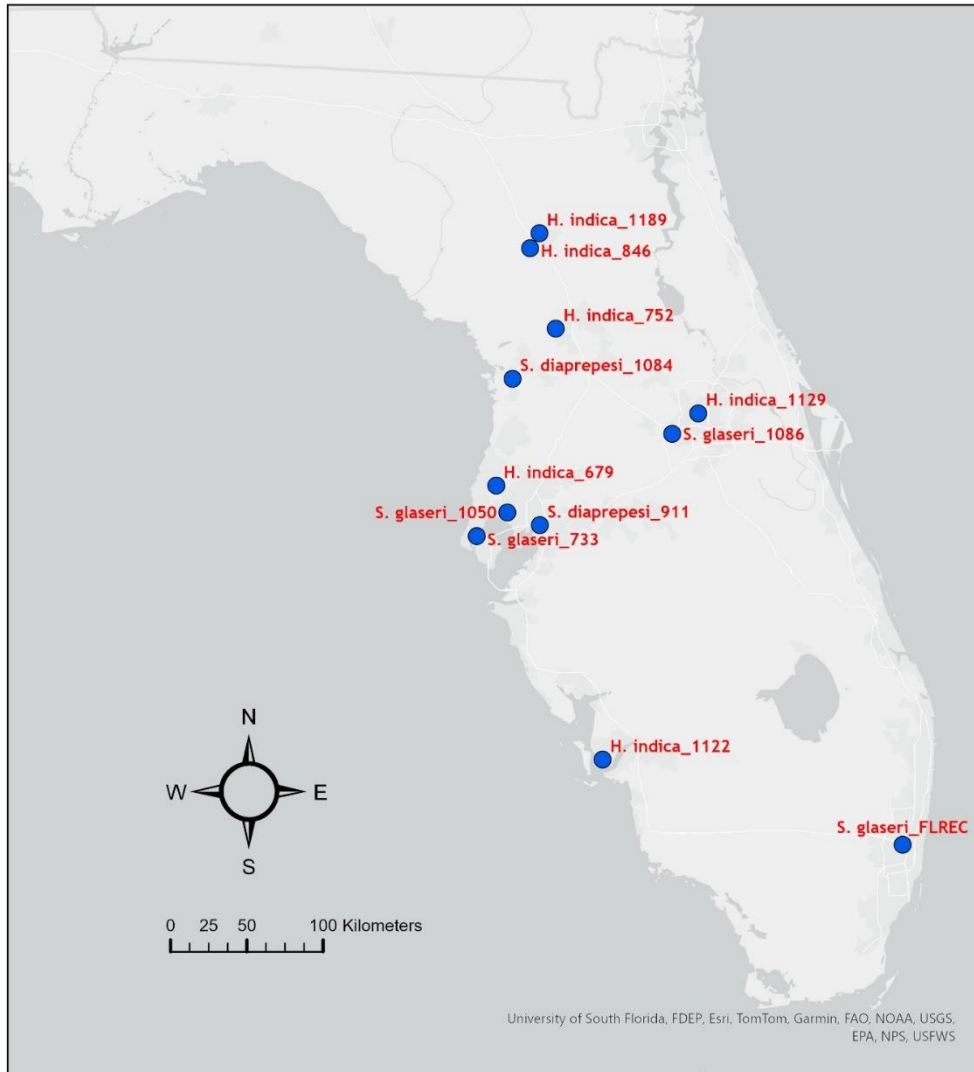


Figure 2. Representative photographs of live (A) and dead (B) second-stage juveniles of *Meloidogyne graminis* treated with water (control) and crude extract (secondary metabolites) of bacterial symbionts of entomopathogenic nematodes. Bacteria-treated nematodes showed vacuolar formations of variable size (arrowheads).



Project ID: 2023-16-783

Project Title: Effects of Moisture on Behavior, Fitness, and Management of *Listronotus maculicollis* Kirby

Principle Investigator: Ben McGraw, Ph.D.

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Objectives:

- (1) Determine the effect of soil/plant moisture on ABW female oviposition behavior in choice assays.
- (2) Assess ABW egg laying and egg survival through female no-choice assays.
- (3) Evaluate ABW life stage mortality in relation to soil moisture using a no-choice lifetable approach.

Start Date: 2023

Project Duration: 2023-2024 (*Two years with 1 year extension*)

Total Funding: \$76,762

Summary Points:

- (1) Soil moisture did not significantly affect oviposition preference in choice assays.
- (2) Early larval survival and recovery were influenced by soil moisture in no-choice assays.
- (3) Prolonged exposure to low soil moisture content may have adverse effects on ABW larval development.

Summary:

The choices that female insects make in selecting a host may have grave consequences for their developing offspring, including reduced growth and development, increased risk of predation, and reduced reproductive success (see review by Awmack & Leather, 2002). Given these potential outcomes, it is hypothesized that the selection pressure driving adult host-selection behavior should be strong toward selecting host plants that maximize offspring growth and development, especially for those herbivorous insects that produce relatively immobile offspring.

The annual bluegrass weevil (ABW) is a severely destructive insect pest that is most problematic on short-mown turfgrasses found on fairways, greens, tees, approaches, and collars in eastern North America (Vittum, 2020). Overwintering adult populations invade short mown turf areas on the golf course in spring, where females encounter multiple hosts in which they may oviposit. Little is known about ABW oviposition behavior, and much is surmised about egg laying decision making through spatial analyses of larval populations (McGraw & Koppenhöfer, 2009, 2010, 2015). Larval damage is most severe in patches of *Poa annua* L. within stands of *Agrostis stolonifera* L., though this association may weaken at finer spatial scales (McGraw and

Koppenhöfer, 2010). Areas where *P. annua* is the dominant turfgrass are often in soils with high volumetric water content (VWC).

The effects of plant moisture status on ABW oviposition behavior, fecundity, and larval survival remains an unexplored area. It stands to reason that ABW is attracted to and performs best in well-irrigated turfgrass stands. The genus *Listronotus* is a semi-aquatic group of weevils (Blatchley & Leng, 1916; O'Brien, 1981), and ABW is presumed to have transitioned to feeding on short-mown turfgrass relatively recently (Cameron and Johnson, 1971). The impact of plant water stress on herbivorous insects has been extensively studied (Waring and Cobb, 1992), with most insects responding negatively to plant water stress, though results may differ depending on insect feeding guild, plant nutritional status and quality, and plant type (Huberty and Denno, 2004). Not only is ABW oviposition and population densities greatest in spring when rainfall is ample and soil/plant moisture is high, but summer generations are most persistent in isolated well-irrigated areas. The relationship between turfgrass damage and moisture is also an area that warrants investigation. Although one would assume that crown feeding would cause noticeable damage under any moisture situation, it is not uncommon for first generation larvae (spring generations) to go unnoticed when rainfall is above normal and for damage to be severe during persistently dry conditions.

Objective 1: Determine the effect of soil/plant moisture on ABW female oviposition behavior in choice assays.

Materials and Methods:

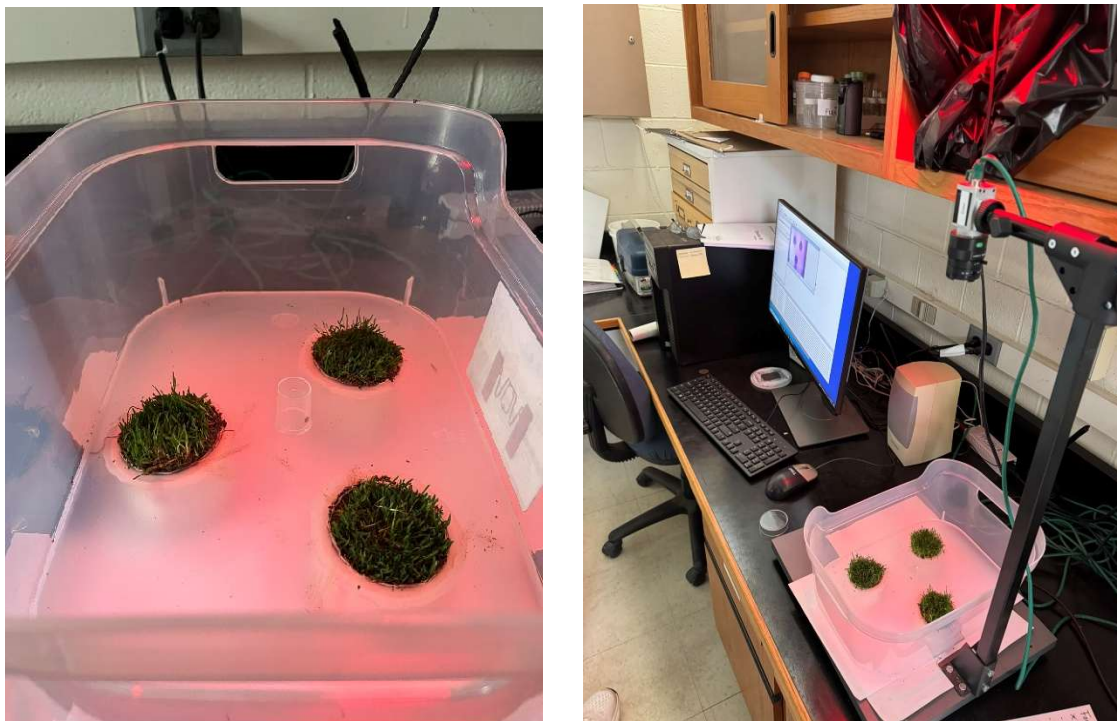
Turf-soil cores: *Poa annua* turf-soil cores (10.8 cm diameter × 10.0 cm depth) were extracted from a research putting green located at the Landscape Management Research Center (University Park, PA) on April 1, 2025. The putting green was maintained at a height of 3.8 mm (0.150"). Insecticides, plant growth regulators and herbicides were withheld from the area, though a fungicide mixture (fluoxastrobin (0.36 fl oz/M) + mefenoxam (1.0 fl oz/M)) was applied four hours prior to core extraction to prevent *Pythium* spp. and *Microdochium nivale* development in greenhouse conditions. Cores were removed using a standard golf course cup cutter and transported to a greenhouse in plastic pots (11.0 cm diameter × 10.5 cm depth). Soil moisture was measured in the greenhouse using a time-domain reflectometer (TDR) (Spectrum Technologies, Aurora, IL) fit with 3.8 cm rods. Three soil moisture treatments were established using supplemental irrigation, and each treatment replicated 20 times. Moisture levels were selected to represent a range of field realistic levels for the soil type (sand; 87.8% sand, 7.8% silt, 4.4% clay). Cores were maintained within a 5% VWC range within one of three soil moisture levels they were assigned. The moisture treatments were classified as "low" (10-15% VWC), "medium" (20-25%), or "high" (30-35%). Cores were assessed at least twice daily, and irrigation was applied or withheld as needed. If cores fell below their target soil moisture, they were irrigated and rechecked to confirm they were within range. Cores that measured above their target soil moisture were left to dry and were reassessed once moisture levels declined back into range. Each core was maintained within its assigned VWC range for one week prior to trials.

Insects: Overwintering adult ABW were vacuum-collected from *Poa annua* plots at the Joseph E. Valentine Turfgrass Research Center (University Park, PA) on April 4, 2025. Adults were sexed in the laboratory, males discarded, and females housed in 840 mL plastic containers with mesh lids. Containers were held overnight in an incubator at 10°C under a 14:10 light:dark cycle.

Prior to trials, females were acclimated to ambient room temperature (22°C) for at least 30 minutes. The experiment was replicated with first-generation females collected from the same site between 23 and 24 June 2025. These females were determined to be first-generation adults by the presence of fresh scales on their elytra.

Choice assays: Behavioral assays were conducted in an observational arena made of plastic containers (33.0 cm length × 24.1 cm width × 13.3 cm depth) with a single female at a time. The arena housed one core from each soil moisture treatment within a PVC well (5.2 cm diameter, 3.8 cm depth), with the foliage set flush with the bottom of the arena (Figure 1). Cores were positioned in a triangular fashion equidistant from the center of the arena and 12 cm apart from each other (on center). Core placement and arena orientation were randomized among six possible configurations. To begin an observational run, a female was containerized in the center of the arena using a clear plastic bottle cap. The female was held for five minutes to acclimate. Afterward, the cap was removed, allowing the insect to explore the arena until the 10-minute observation period ended or the individual remained within a single core for at least one minute. At the conclusion of the observational period, the female was placed in a freezer for < 24 hr then dissected to assess mating (presence of sperm in the spermatheca) and reproductive maturity. Following each observation, the arena and cap were thoroughly rinsed with mild soap and warm water, then dried with a clean towel to eliminate residual cues.

Figure 1: *A three-choice experimental arena with turfgrass cores (left). The EthoVision software captures the activity of insects within the arena from the mounted camera (right).*

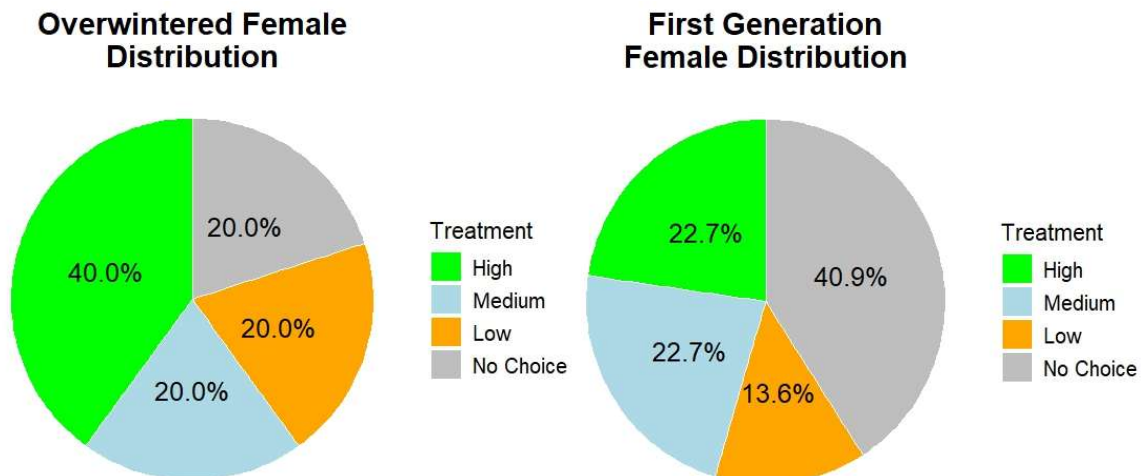


Results:

A total of 20 overwintered female ABW were tested in choice assays. Sixteen individuals (80%) made a choice within the 10-minute observation period, while four females did not make a selection. Among those that made a choice, four females selected the low (10–15% VWC), four selected the medium (20–25% VWC), and 8 selected the high moisture treatment (30–35% VWC)(Figure 2). A chi-square goodness-of-fit test revealed no significant deviation from an equal preference distribution ($\chi^2 = 2.0$, $df = 2$, $p = 0.37$), indicating that female ABW did not statistically prefer one soil moisture treatment over another under these conditions. Overwintered females made a choice at a median rate of 55 seconds per trial. Despite variation in reproductive status, none of the tested females were mated at the time of dissection, which may limit the interpretation of ovipositional preference.

Experiments conducted with first-generation adult females showed similar trends. Of the 22 individuals tested, 13 made a treatment choice, while 9 made no selection. Among the females that chose a treatment, three selected the low moisture treatment, five selected the medium treatment, and five selected the high treatment. A chi-square test revealed no significant preference among the soil moisture levels ($\chi^2 = 0.615$, $df = 2$, $p = 0.74$), consistent with the findings from the overwintered adult trial. First generation females made a choice at a median rate of 55 seconds per trial. As in the overwintered group, all dissected females were found to be unmated.

Figure 2 - Choice distributions of overwintered (left) and first-generation (right) female ABW among soil moisture treatments in greenhouse choice assays. Treatments included Low (10–15% VWC, orange), Medium (20–25% VWC, light blue), High moisture treatments (30–35% VWC, green), and No Choice (gray). Percentages represent the proportion of total individuals in each group ($n = 20$ for overwintered females, $n = 22$ for first-generation females).



Objective 2: Assess egg laying and egg survival through female no-choice assays.

Materials and Methods:

Turf-soil cores: *Poa annua* turfgrass cores (10.8 cm diameter × 10.0 cm depth) were extracted from a research putting green (height of cut = 3.8 mm) at the Landscape Management Research Center (University Park, PA), in the same manner as cores for the overwintered choice assays. The same moisture treatments as described in Objective 1 were established immediately after core collection. These ranges were maintained for one to two weeks prior to use in bioassay, with VWC monitored at least twice daily to guide irrigation. Cores were mown once a week with electric shears.

The cores were randomly assigned to the three moisture range treatments (24 cores per treatment) and split into two experimental runs of 36 cores each. Both runs were treated identically and began at the same time, but adult infestations were staggered to create temporal replication. Cores used for the second replicate received an additional fungicide mixture application (fluoxastrobin (0.36 fl oz/M) + mefenoxam (1.0 fl oz/M)) on April 14, 2025 (prior to adult infestation) to prolong disease prevention.

Insects: ABW adults were collected on April 4, 2025, sexed, and stored as described in Objective 1. Following the establishment of soil moisture treatments, one male and one female ABW were introduced to each *Poa annua* core and contained using a plastic lid with mesh ventilation. Adults were given seven days to mate and oviposit under greenhouse conditions. The first set of 36 cores was infested with adult ABW one week after moisture treatments were established and allowed seven days for oviposition. The second set was infested two weeks after treatment establishment, and were also allowed to oviposit for 7 days. After the oviposition period, cores were removed from their containers, placed onto modified Berlese funnels, and subjected to high heat extraction (40°C conditions) for 48 hours to collect larvae. Larval head capsule widths were measured to determine instar stage, and first-instar larvae were used to assess egg-laying success and egg survival.

Results:

Soil moisture treatments were successfully maintained within the target VWC ranges throughout both experimental runs. In Week 1, average VWC at the time of heat extraction was $14.14 \pm 0.29\%$ (Avg VWC \pm SE) in the Low treatment, $23.52 \pm 0.31\%$ in the Medium treatment, and $33.99 \pm 0.39\%$ in the High treatment (Table 1). In Week 2, VWC values at the time of heat extraction averaged $12.76 \pm 0.28\%$, $22.41 \pm 0.23\%$, and $32.83 \pm 0.38\%$ for the Low, Medium, and High treatments, respectively (Table 2).

First instar larval data for both weeks was normalized with square root transformations. A Shapiro-Wilks test confirmed the normality of the data. With assumptions met, an ANOVA model was used to test for significant differences and a Tukey's Honest Significance test was conducted to separate means. Significant differences in ABW first instar larval (L1) recovery were observed among soil moisture treatments in experiment 1 ($df = 2$, $F = 5.114$, $p = 0.012$). The highest number of L1s were found in Low moisture treatment (17.42 ± 4.33), followed by the Medium (8.92 ± 1.93), and the High VWC treatment (6.42 ± 2.32). Tukey's HSD test revealed that the Low treatment was significantly different from the High treatment, while the Medium treatment was intermediate and not significantly different from either (Table 1).

In contrast, no significant differences in L1 abundance were detected among soil moisture treatments in the second experiment ($df = 2$, $F = 2.418$, $p = 0.105$), despite similar target moisture levels being achieved. Average L1 counts were 6.00 ± 2.16 , 8.08 ± 1.81 , and 14.33 ± 3.50 for the Low, Medium, and High treatments, respectively, with all treatments sharing the same significance grouping (Table 2).

Table 1 - Average volumetric water content (VWC) and number of annual bluegrass weevil (ABW) first instars (L1) recovered from *Poa annua* cores one week after infestation (Week 1). Each treatment corresponds to a target soil moisture range maintained throughout infestation. VWC values are presented as means \pm standard error (SE). ANOVA was conducted on transformed data, and treatment means were separated using Tukey's HSD test ($\alpha = 0.05$). Different letters indicate significant differences among treatments.

Experiment 1		
Treatment	Avg VWC \pm SE(%)	Avg L1 \pm SE
Low	14.14 \pm 0.29	17.42 \pm 4.33 A
Medium	23.52 \pm 0.31	8.92 \pm 1.93 AB
High	33.99 \pm 0.39	6.42 \pm 2.32 B

Table 2 - Average volumetric water content (VWC) and number of annual bluegrass weevil (ABW) first instars (L1) recovered from *Poa annua* cores one week after infestation (Week 2). Each treatment corresponds to a target soil moisture range maintained throughout infestation. VWC values are presented as means \pm standard error (SE). An ANOVA was conducted on transformed data, and treatment means were separated using Tukey's HSD test ($\alpha = 0.05$). No significant differences were detected among treatments for L1 abundance.

Experiment 2		
Treatment	Avg VWC \pm SE	Avg L1 \pm SE
Low	12.76 \pm 0.28	6.00 \pm 2.16 A
Medium	22.41 \pm 0.23	8.08 \pm 1.81 A
High	32.83 \pm 0.38	14.33 \pm 3.50 A

Obj 3: Evaluate ABW life stage mortality in relation to soil moisture using a no-choice lifetable approach.

Materials and Methods:

Turf-soil cores: *Poa annua* turfgrass cores (10.8 cm diameter \times 10.8 cm depth) were extracted from a research putting green (height of cut = 3.8 mm) at the Landscape Management Research Center (University Park, PA) on April 1, 2025, following the same procedures as in Objective 1.

All cores were maintained within the VWC range of 15-20% to standardize egg laying conditions. This baseline was maintained throughout a seven-day ovipositional period following ABW adult infestation. Cores were briefly removed from the greenhouse on April 14, 2025 to receive a second application of the fungicide mixture (fluoxastrobin (0.36 fl oz/M) + mefenoxam (1.0 fl oz/M)) to prolong disease prevention.

Insects: ABW adults were collected on April 14, 2025, sexed, and stored in the same manner as in Objective 1. Two males and two females were placed onto each *Poa annua* core on April 16, 2025 at the baseline moisture treatment (15-20% VWC) and contained using a plastic lid with mesh ventilation. Adults were given seven days for oviposition before they were physically extracted over a three-day period.

Bioassay: After the removal of ABW adults, 24 cores were randomly assigned to three soil moisture treatments: Low (10–15% VWC), Medium (20–25% VWC), and High (30–35% VWC). Treatments were established 10 days post-infestation (DPI) using irrigation as needed and monitored twice daily for the remainder of the experiment using a TDR. Cores were mown once per week.

Larval development and survival were evaluated at three time points: 14, 19, and 24 DPI. At each time point, larvae from 8 randomly selected cores per treatment were heat extracted using modified Berlese funnels set at 40 °C. Developmental stages were determined via head capsule measurements to assess instar distribution. These data were used to evaluate the effects of post-oviposition soil moisture levels on ABW larval survivorship, development rate, and fitness.

Results:

Soil moisture level and time post infestation influenced the number of ABW larvae recovered from *Poa annua* turfgrass cores. At 14 DPI, there were no significant differences in larval recovery among soil moisture treatments (Kruskal–Wallis, $\chi^2 = 0.595$, $p = 0.743$) (Table 3). Mean larval recovery was highest in the High treatment (38.25 ± 12.27), followed by Low (35.75 ± 8.13) and Medium (31.75 ± 6.54), but all were statistically equivalent. At this time point, larvae across all treatments were approximately second instars, with average developmental stage values ranging from 2.69 to 2.96.

By 19 DPI, larval densities decreased across all treatments compared to 14 DPI, and no significant differences were observed among treatments (Kruskal–Wallis, $\chi^2 = 3.676$, $p = 0.159$). Larval recovery was highest in the Medium treatment (20.75 ± 3.75), followed closely by High (20.13 ± 6.13), with the fewest larvae recovered in the Low treatment (9.38 ± 3.07). The average larval developmental stage across treatments ranged from 3.76 to 4.05, indicating that most individuals had progressed to third or early fourth instar.

By 24 DPI, larval recovery further declined across all moisture levels. While no significant differences were detected among treatments at this time point (Kruskal–Wallis, $\chi^2 = 2.452$, $p = 0.294$), the Medium treatment again produced the highest average number of larvae (12.50 ± 3.57), followed by High (7.75 ± 1.83) and Low (6.75 ± 3.03). Larval age estimates were consistent with fourth instar development across all treatments (4.07–4.44).

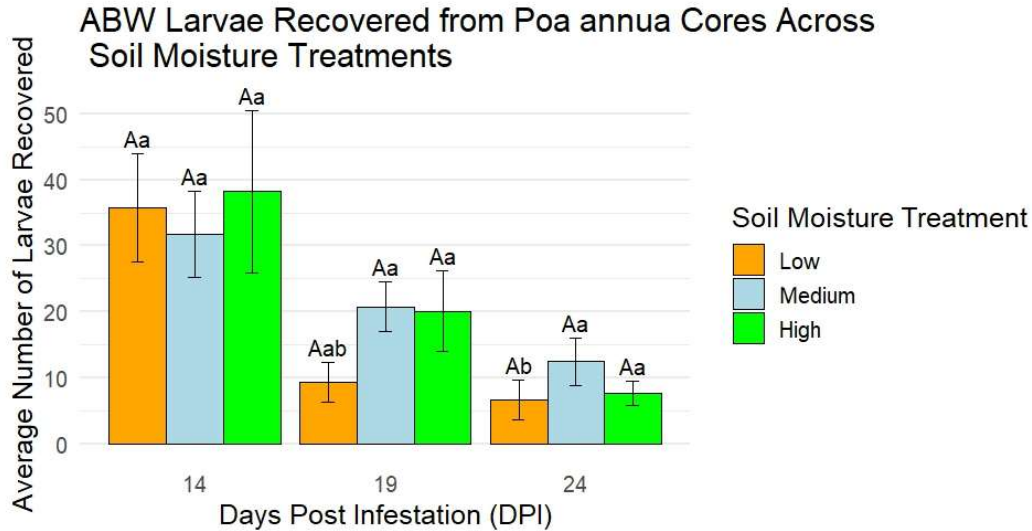
When comparing larval recovery across time points within the same moisture treatment, a significant reduction in larval density was observed between 14 and 24 DPI in the Low soil moisture group (Dunn’s test, $p = 0.040$). No other within-treatment comparisons across DPI

groups were significant. This distinct decline suggests a potential negative impact of sustained low soil moisture on ABW larval persistence or survivorship over time.

Table 3 - Mean (\pm SE) number and instar of annual bluegrass weevil (ABW) larvae recovered from *Poa annua* cores across three soil moisture treatments (Low: 10-15% VWC, Medium: 20-25% VWC, High: 30-35% VWC) and three sampling intervals (14, 19, and 24 DPI). Differences in larval recovery were analyzed using Kruskal–Wallis tests within and across time points. Uppercase letters indicate significant differences among treatments within a given DPI. Lowercase letters indicate significant differences across DPI time points within the same treatment. Treatments that do not share a letter are significantly different ($\alpha = 0.05$)

DPI	Treatment	Avg Larvae \pm SE	Avg Instar Reached
14	Low	35.75 \pm 8.13 Aa	2.69
	Medium	31.75 \pm 6.54 Aa	2.96
	High	38.25 \pm 12.27 Aa	2.92
19	Low	9.38 \pm 3.07 Aab	3.76
	Medium	20.75 \pm 3.75 Aa	3.77
	High	20.13 \pm 6.13 Aa	4.05
24	Low	6.75 \pm 3.03 Ab	4.07
	Medium	12.50 \pm 3.57 Aa	4.44
	High	7.75 \pm 1.83 Aa	4.42

Figure 3 - Mean number of annual bluegrass weevil (ABW) larvae recovered from *Poa annua* cores across soil moisture treatments at 14, 19, and 24 days post-infestation (DPI). Bars represent treatment means ($n = 8$) \pm standard error. Soil moisture treatments were classified as Low (orange, 10-15% VWC), Medium (blue, 20-25% VWC), and High (green, 30-35% VWC). Uppercase letters denote significant differences among treatments within a DPI group while lowercase letters denote significant differences for a given treatment across time points (Kruskal–Wallis test, Dunn’s post hoc, $\alpha = 0.05$).



Conclusion:

This study examined how soil moisture influences ABW oviposition behavior, egg laying success and survival, and larval development in *Poa annua*. While consistently strong patterns did not emerge across all three objectives, the results suggest that soil moisture may play a role in shaping certain aspects of ABW population dynamics and performance.

Choice assays did not reveal a statistically significant ovipositional preference among the three soil moisture treatments, though a slight tendency for females to chose higher moisture turf cores was observed among overwintered females. Notably, all tested females in both experimental runs were unmated, limiting the ability to draw firm conclusions about ovipositional behavior. It is likely that the females tested from both generations were collected too early in their respective seasonal development to allow sufficient time for feeding and reproductive maturation. These results underscore the importance of considering specimen collection timing and reproductive status in behavioral assays.

In no-choice trials, soil moisture had a measurable effect on egg survival and early larval development. During the first experimental run, significantly more first-instar larvae were recovered from low-moisture treatments than from high-moisture treatments. However, this pattern did not persist in the second experimental run in which more larvae were recovered from high moisture treatments than low or medium moisture treatments, although these results were not statistically significant. Notably, while all *Poa annua* cores and their respective moisture treatments were established at the same time, the two experimental runs differed in the timing of ABW infestation and oviposition. The first run began one week after treatment initiation, whereas the second run began two weeks following the establishment of VWC treatments. This temporal separation resulted in longer treatment duration for *Poa annua* cores used in the second experimental run, potentially altering plant or soil conditions in ways that affected egg laying, egg survival, or larval recovery. The differing outcomes between the two runs may reflect these

cumulative treatment effects over time, emphasizing the potential for prolonged environmental stress to modulate ABW reproductive success and egg survival.

Finally, life table assessments showed that larval recovery declined over time across all treatments. While no significant differences were detected among treatments at individual time points, larvae in the low-moisture treatment experienced a significant decline in abundance from 14 to 24 days post-infestation. This suggests that prolonged exposure to dry conditions may reduce larval survivorship over time, although additional data are needed to confirm this trend.

Collectively, these findings indicate that soil moisture can influence ABW fitness and development, particularly under prolonged low-moisture conditions. However, behavioral responses and early-stage survival appear context-dependent, warranting additional replication. To strengthen and validate these findings, all experiments will be repeated in the spring of 2026. Since the initial funding for this project, this work has also been extended into field trials investigating how increasing precipitation, one of the most important aspects of a changing climate, may affect the performance of larvicides commonly used in ABW control. While results from these trials are not presented here, they represent an important step in applying laboratory-based insights to field-scale, climate adaptive pest management strategies.

References

- Awmack, C. S., & Leather, S. R. (2002). Host plant quality and fecundity in herbivorous insects. *Annual review of entomology*, 47(1), 817-844.
- Blatchley, W. S., & Leng, C. W. (1916). *Rhynchophora or weevils of north eastern America*. Nature Publishing Company.
- Cameron, R. S., & Johnson, N. E. (1971). Biology of a species of *Hyperodes* (Coleoptera: Curculionidae) a pest of turfgrass.
- Huberty, A. F., & Denno, R. F. (2004). Plant water stress and its consequences for herbivorous insects: a new synthesis. *Ecology*, 85(5), 1383-1398.
- McGraw, B. A., & Koppenhöfer, A. M. (2009). Development of binomial sequential sampling plans for forecasting *Listronotus maculicollis* (Coleoptera: Curculionidae) larvae based on the relationship to adult counts and turfgrass damage. *Journal of economic entomology*, 102(3), 1325-1335.
- McGraw, B. A., & Koppenhöfer, A. M. (2010). Spatial distribution of colonizing *Listronotus maculicollis* populations: implications for targeted management and host preference. *Journal of Applied Entomology*, 134(4), 275-284.
- McGraw, B. A., & Koppenhöfer, A. M. (2015). Spatial analysis of *Listronotus maculicollis* immature stages demonstrates strong associations with conspecifics and turfgrass damage but not with optimal hosts on golf course fairways. *Entomologia Experimentalis et Applicata*, 157(3), 307-316.
- O'Brien, C. W. (1981). The Larger (mm.) *Listronotus* of America, North of Mexico (Cylindrorhininae, Curculionidae, Coleoptera). *Transactions of the American Entomological Society*, 69-123.

- Vittum, P. J. (2020). Turfgrass insects of the United States and Canada. In *Turfgrass Insects of the United States and Canada*. Cornell University Press.
- Waring, G. L., & Cobb, N. S. (2017). The impact of plant stress on herbivore population dynamics. In *Insect-Plant Interactions (1992)* (pp. 175-234). CRC Press.

USGA-ID: 2025-04-835

Title: Incorporating new insecticides into optimal management programs for annual bluegrass weevil populations with different insecticide resistance levels.

Project leaders: Albrecht M. Koppenhöfer, Tarikul Islam, Matthew S. Brown

Affiliation: Department of Entomology, Rutgers University, New Brunswick, NJ

Objectives: The overall goal is to develop a better understanding of the degree and scope of insecticide resistance in ABW to new(er) insecticide chemistry, specifically to: Compare field efficacy of recently developed insecticides used against ABW adults and larvae against ABW populations representing the full scope of insecticide resistance levels observed to date.

Start date: 2025-1-1

Project duration: 2 years

Total funding: \$19,720

The annual bluegrass weevil (ABW), *Listronotus maculicollis*, is a difficult-to-control pest with 2–3 generations/year, multiple life stages present simultaneously and increasing asynchrony in their stages during the growing season. It can cause serious injury to short-mown, often high profile turfgrass areas on golf courses (Fig. 1). Golf course superintendents have relied primarily on synthetic insecticides for ABW management, but excessive insecticide use has led to widespread insecticide resistance. Against highly resistant ABW populations, adulticides (pyrethroids, chlorpyrifos) provide no significant control, and several larvicides (e.g., chlorantraniliprole, clothianidin, indoxacarb, trichlorfon) are also affected by resistance. The reason for the broad spectrum of resistance is that enhanced enzymatic detoxification plays a major role in the resistance.

The advent of several new insecticides over the last decade has alleviated problems in managing ABW. We previously extensively studied the effect of different levels of pyrethroid resistance on the efficacy of some of earlier arrivals in these new chemistries, and our observations were incorporated in recommendations. While two of these chemistries, cyantraniliprole and spinosad, were not significantly affected by resistance, excessive use of any remaining effective insecticide is likely to lead to some level of resistance.

More recently two new insecticides have become available: the diamide tetraniliprole and benzoylurea insect growth regulator novaluron. In addition, the isoxazoline isocycloseram (or plinazolin) is expected to become available late in 2025. Information on the effect of pyrethroid resistance on these new insecticides is limited. Yet, such information is crucial for effective ABW management.

We selected four ABW populations for field studies based on previous observations on pyrethroid resistance levels in laboratory studies with technical grade active ingredients and product, and greenhouse and field studies with product. The most susceptible population was the one from Rutgers Horticultural Farm No. 2. Compared to this population, resistance ratios

(RR₅₀) based on topical tests in the lab with technical grade bifenthrin were 55x (i.e., LD₅₀ 55x higher) for Preakness Hills CC, 75x for Ridgewood CC, and 343x for Nassau CC. Laboratory assays with product confirmed that these populations still had similar RR₅₀s.

To keep the size of experiments manageable, insecticide applications targeting adults were tested in separate experiments from those targeting larvae. Adulticides (Table 1) were applied at the optimal timing to control overwintered adults, i.e., when most adults have moved onto the short-mown areas in spring but before females start laying eggs. Timing was determined by vacuum sampling of adults, degree day accumulation (base 50 °F) (150 GDD₅₀), and indicator plant phenology (forsythias half gold : half green). Larvicides (Table 1) were applied to target young larvae around late bloom of flowering dogwood (200 GDD₅₀) and mid-size larvae around full bloom of hybrid Catawba rhododendron, 400 GDD₅₀). Treatments were evaluated at around 700 GDD₅₀ when most developmental stages were around 5th instar (Fig. 2).

Table 1. Insecticides tested against adults (Ad) and young (L1-2) and older (L3-4) ABW larvae.

Insecticide class (IRAC)	Active ingredient	Trade name	Rate (lb ai/ac)	Targets
Pyrethroid (3A)	Bifenthrin	Talstar	0.100	Ad
IGR/benzoylurea (15)	Novaluron	Suprado	0.900	Ad, L1-2, L3-4
isoxazoline (30)	Plinazolin	Atexzo	0.134	Ad, L1-2, L3-4
Anthranilic diamide (28)	Cyantraniliprole	Ference	0.156	L1-2, L3-4
“	Tetraniliprole	Tetrino	0.090	L1-2, L3-4
Spinosyn (5)	Spinosad	MatchPoint	0.400	L3-4

Unfortunately, in 2025 ABW populations at the Ridgewood CC sites were too low for meaningful interpretation of data for both field experiments, targeting adults and targeting larvae. Hence, our observations were limited to the 1x, 55x and 343x populations. For the adulticides, we observed no interaction between resistance level and insecticides. Control at 1x was higher than at 343x with 55x not different from the other populations. All insecticides caused significant control but novaluron and plinazolin were more effective than bifenthrin. Novaluron was not affected by resistance (92-96% control at all sites), plinazolin was significantly less effective at 343x (58%) than at 55x and 1x (90-95%), and Talstar was significantly less effective at 55x and 343x (36-43%) than at 1x (71%) (Fig. 3, left).

For the larvicides, we observed no interaction between resistance level and insecticides. Control at 1x and 55x was higher than at 343x. All treatments caused significant control. Novaluron was significantly more effective at both timings than tetraniliprole and cyantraniliprole with the other treatments being intermediate. None of the treatments were significantly affected by resistance level. However, at 1x and 55x there were no significant differences between any treatments, whereas at 343x novaluron was significantly more effective than tetraniliprole and cyantraniliprole which only provided 60-67% control (Fig. 3, right). However, due to the high data variability especially at the 343x sites, experiments will be repeated in 2026 to allow for confident recommendations regarding the use of the new product at different pyrethroid resistance levels.

- At adulticide timing, novaluron efficacy is not affected by pyrethroid resistance level (1x, 55x, 343x) whereas efficacy of plinazolin is significantly reduced at 343x and efficacy of bifenthrin at 55x and 343x.
- At early and late larvicide timing, none of the products were significantly affected by resistance level.
- At 1x and 55x, there were no significant differences among the larvicide even though novaluron and plinazolin consistently provided 10-20% higher control than tetraniliprole and cyantraniliprole.
- At 343x targeting young and older larvae, novaluron provided significantly higher control than tetraniliprole and cyantraniliprole.



Fig. 1. Damage caused by ABW larvae in a fairway in early June.



Fig. 2. Evaluation of a field experiment testing insecticides on a fairway.

USGA ID#: 2022-09-752

Title: Engineering Turfgrass Rhizobacteria For Selective Control Of Fall Armyworm

FINAL REPORT

A peer reviewed summary of this work is published as a subcomponent in the following paper:

[Fast screening libraries of plant growth promoting rhizobacteria \(PGPRs\) for insecticidal activity | Journal of Applied Microbiology | Oxford Academic](#)

Overall Final Take homes: The research led to the discovery of at least one natural (non-engineered) strain (JM362) that shows moderate killing effects against fall armyworm with efficacy comparable to insecticides in initial trials. The strain also killed *Drosophila melanogaster* and thus showed off target effects. Our conclusion is that the potentially novel insecticide is a broad spectrum insect killer. Efforts to transform and manipulate the genetics of this bacterial strain were unsuccessful. From the funds of this grant, a masters student (Janiyah Cotton) was supported, graduated, and was placed with a job at a local biotech company in Alabama. After Janiyah's graduation, with the small amount of remaining funds we requested a no-cost extension and trained an undergraduate researcher (Alex Schamban) to sequence the genome of this interesting strain JM362. Alex is working on dissecting the genetic mechanism of the insect killing which could lead to a novel insecticide. We would be interested to propose another grant and continue this work on identifying this novel insecticide – if the USGA feels our work is of continued value.

Project Leader:

PI: John F. Beckmann

Co-PI: David Held

GRA: Janiyah Cotton (*graduated 2024)

Undergraduate Researcher: Alex Schamban

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 sequenced genomes of pertinent strains and are working to dissect the mechanism of the insect toxin.
- We tested the strains for off-target effects and found that they also kill *D. melanogaster*.

Objective 2)

- We have successfully synthesized and cloned the putative Lepidopteran killing gene cry1F into a shuttle vector plasmid for downstream bacterial transformations, but have been unable to transform the construct into the pertinent strains. They seem recalcitrant to transformation.

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 37°C, 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 27°C 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 27°C 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.

Genome Sequencing and Bioinformatic Analysis: Bacterial samples are sent to SeqCenter for whole genome sequencing using Illumina short-read technology. Next, the raw reads are preprocessed and trimmed using falco, and then assembled using metaSPades. We used Prokka to extract a list of all the protein sequences from the assembled genome, then used OrthoFinder for protein ortholog analysis. In ortholog analysis, a set of proteins from different organisms are analyzed, compared, and grouped together based on similarity and function. All of the proteins derived from insecticidal bacteria of a given species (ingroup) are compared against the proteins derived from a non-insecticidal bacteria (outgroup). Proteins that are shared between every killer but not shared with the outgroup are noted as possible candidates for cause of the insecticidal behavior. This small list of proteins is annotated with EGGNOG to predict their function. Proteins that were found to be functionally similar to known insecticides, like CRY/VIP toxins, or chitinases, are identified as possible insecticidal agents.

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. **Figure 7** shows survivorship data of *D. Melanogaster* larvae when exposed to JM-362, and suggests that JM-362 is killing not specific to FAW. **Figure 8** shows an annotated genome for JM-362, with possible insecticidal genes highlighted.

Murphy et. al. 2025 exhaustively investigated PGPR libraries for killing phenotypes, and this study informed which strains should be sequenced and used in for the orthogroup analysis. Strain 188 was annotated as *Serratia* in the JM database did not show any

killing behavior, so its genome was sequenced to serve as an outgroup. Strains 362 and 910 both showed killing behavior in FAW and *D. melanogaster*, so their genomes were sequenced to serve as ingroups. Over 900 genes were found to be unique to the killing strains, so a conclusive identification of the killing gene(s) was not possible. After sequencing, we determined that strain 188 was mislabeled in the database and was not *Serratia*. Because of this, 188 is not useful as an outgroup and future work will focus on finding a closely related bacteria that does not kill for comparative genomics purposes. However, probable genes are highlighted in **Figure 8**.

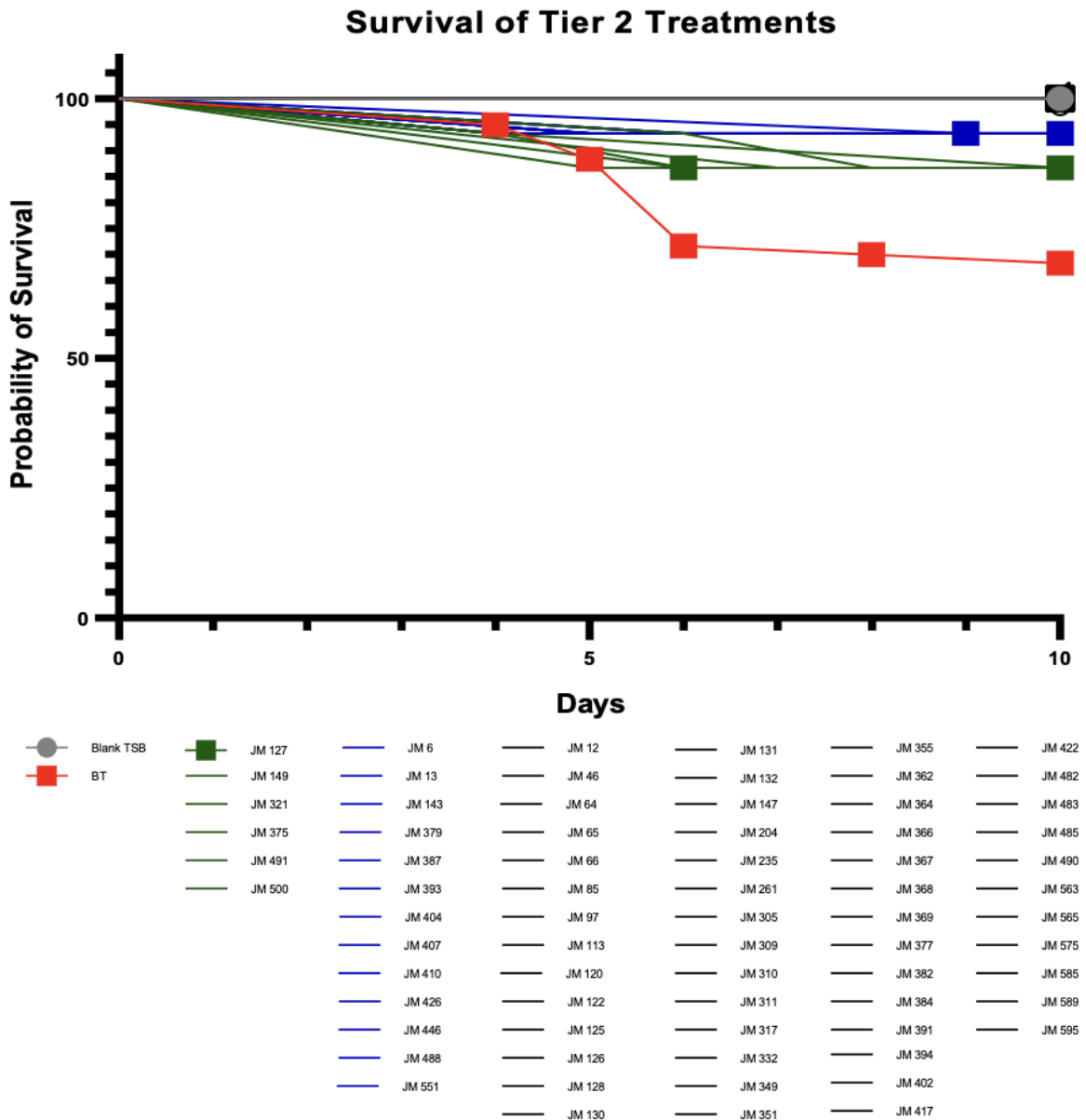


Figure 1. Survival Analysis of 1st Instar FAW. The grey line is the negative TSB control. The red line is the positive BT control. All other lines are diverse PGPR treatments. The green and blue lines are strains that expressed some killing that was not significant. The black lines are strains that expressed no killing.

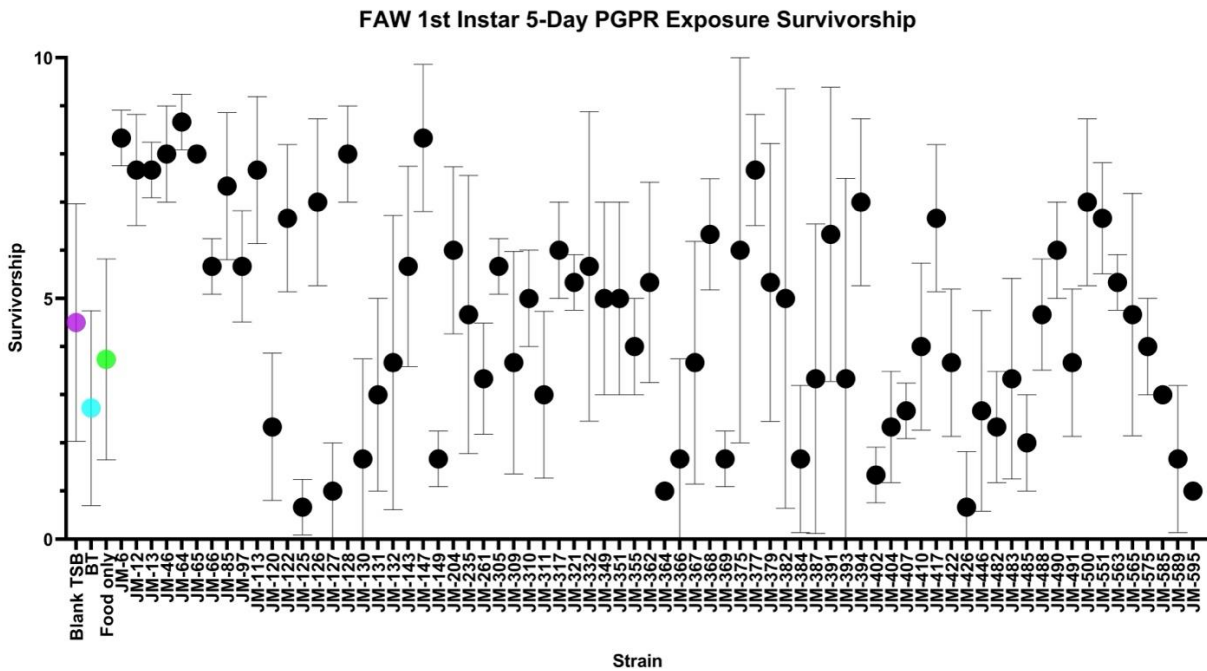


Figure 2. Survivorship of 1st instar FAW. The purple circle is negative TSB control. The blue circle is positive BT control with weak killing. The green circle is artificial diet only. All other circles received unique PGPR strain treatments. Some strains showed killing, but the variation was too great to be statistically significant. Dots are means from 3 replicates with 10 larvae each.

FAW PGPR Exposure Survivorship 3rd Instar 5 days

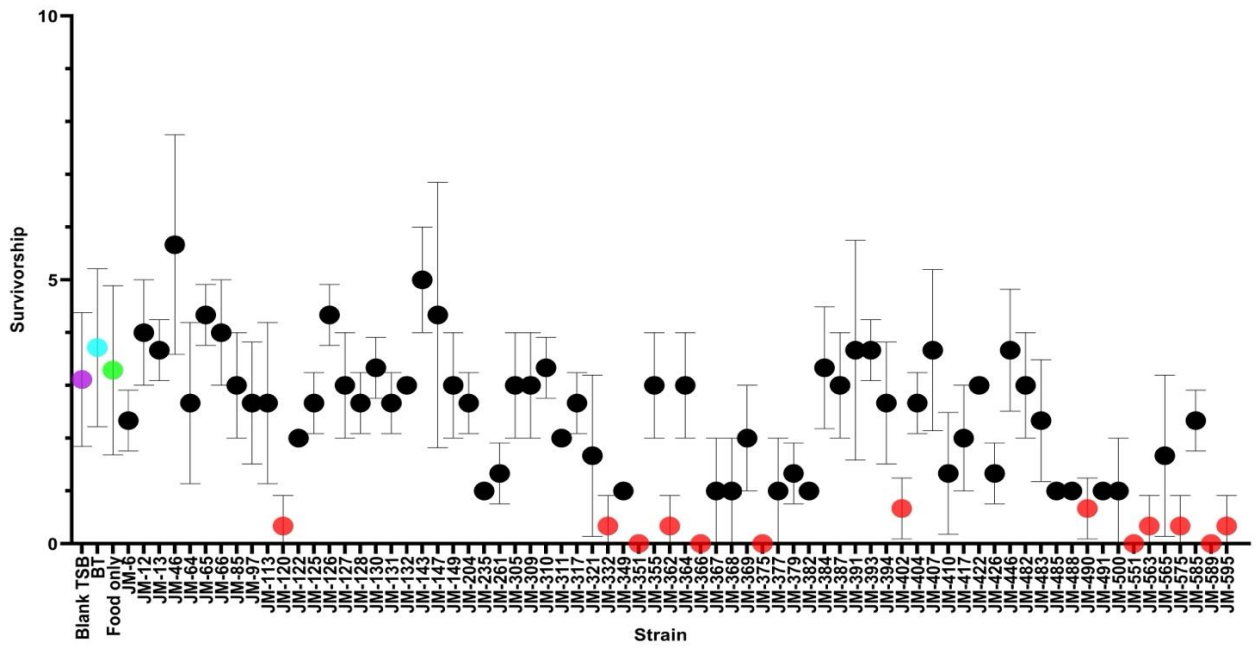


Figure 3. Survivorship of 3rd instar FAW. All circles are color coded as above. Red circles indicate potential killing strains with statistically significant results when compared against the TSB negative control. Dots are means from 3 replicates with 10 larvae each.

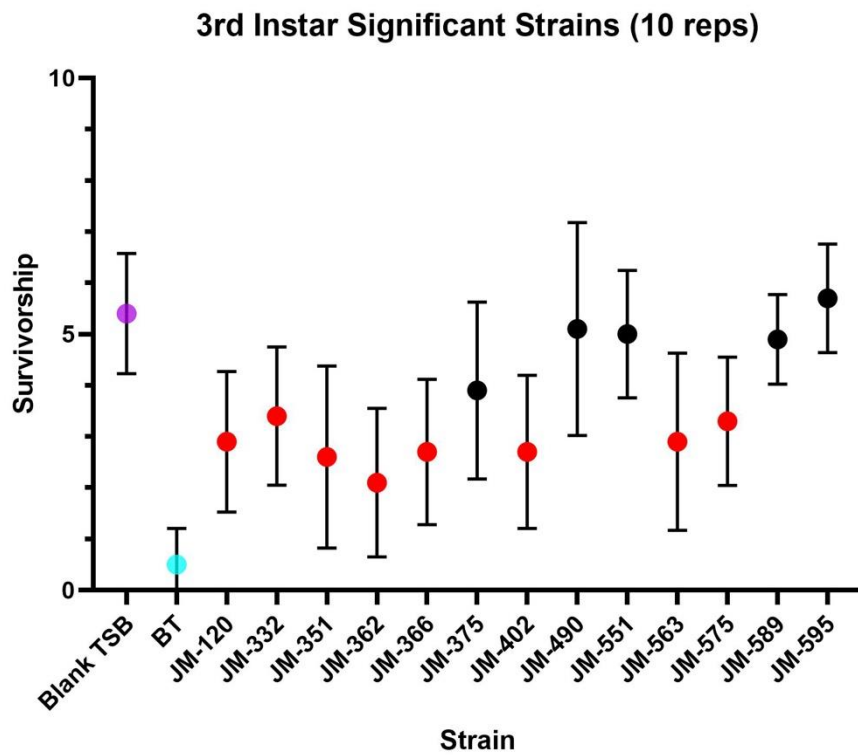


Figure 4. Survivorship 3rd instar FAW (increasing replicates of significant strains). Red circles indicate killing strains with statistically significant results compared against the TSB control with increased replicates. Dots are means from 10 replicates with 10 larvae each. This screen was conducted 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 0.25m² 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.

Survival proportions: Survival of Grass Test survival

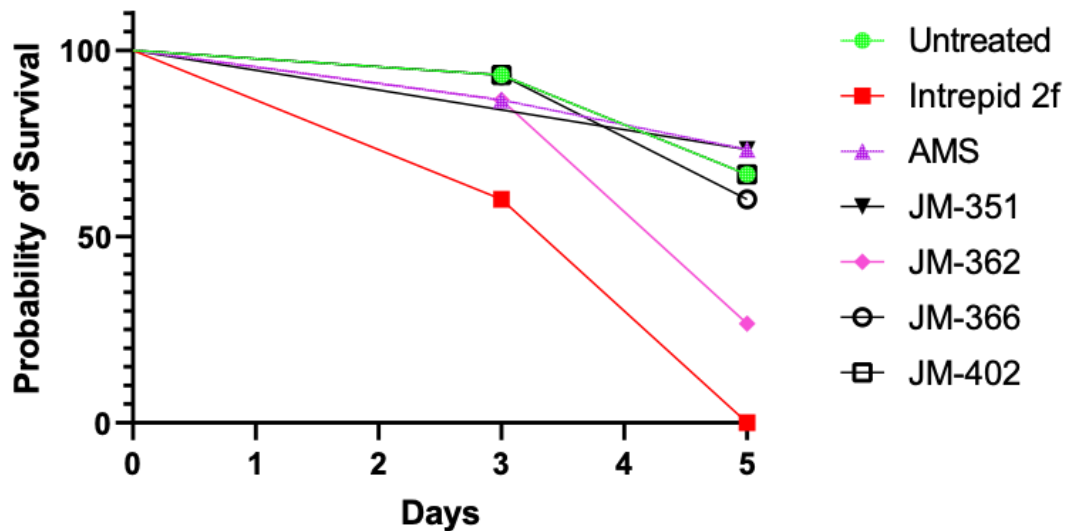


Figure 5. Grass Test Survival Analysis of 3rd Instar FAW. The green line is negative untreated control. The red line is a positive insecticide control. The purple line is a fertilizer treatment. The black lines are PGPR treatments which caused no significant difference in survivorship. The pink line (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**).

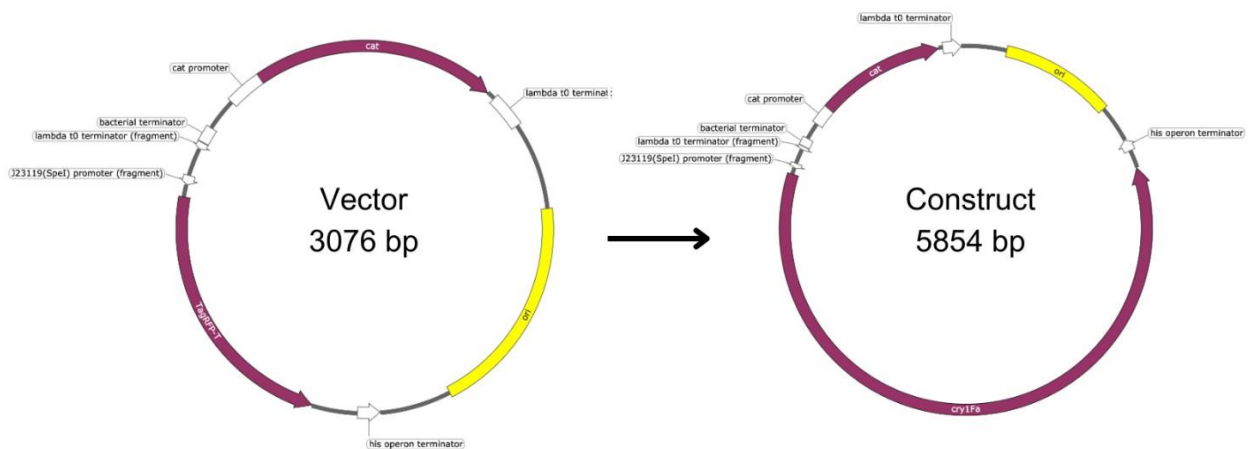


Figure 6. Plasmid map of shuttle vector before and after replacement the of florescent marker gene (*tagRFP-T*) with a Cry gene (*cry1Fa*).

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.

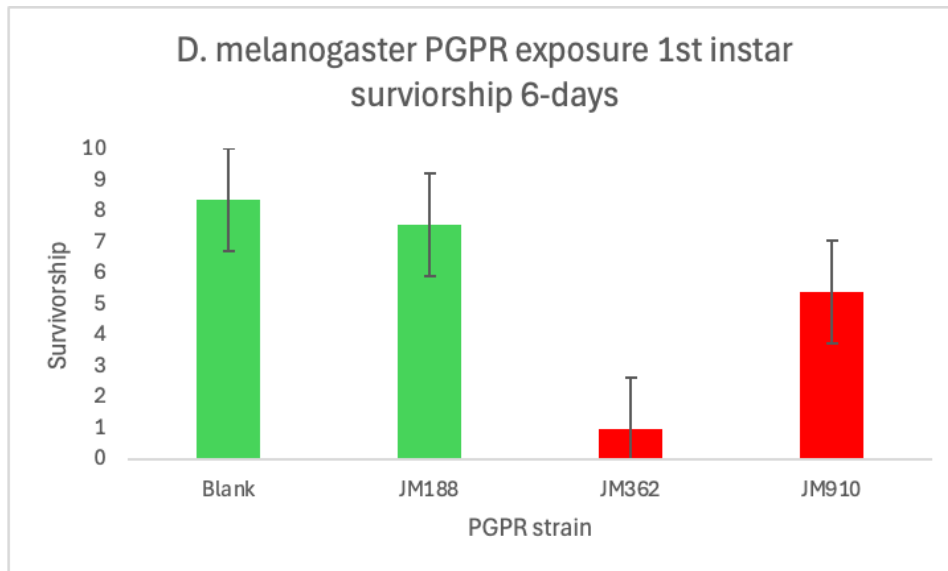


Figure 7. survivorship of 1st instar *D. melanogaster* larvae. 3 PGPR strains from the JM library were tested against *D. melanogaster* larvae to determine cross-species killing behavior. Red indicates statistically significant killing, and each bar represents an average from 5 replicates with 10 larvae each.

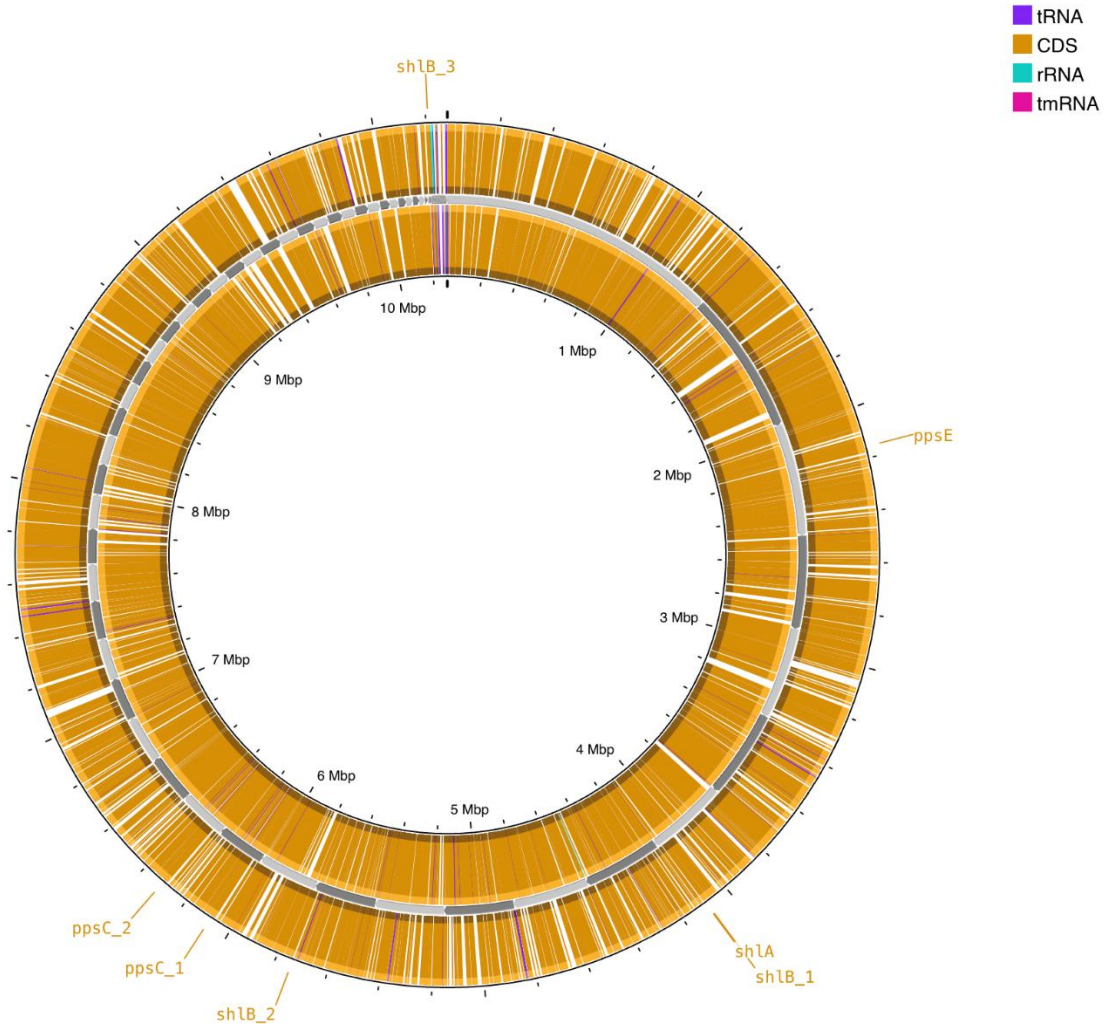


Figure 8. visualization of JM 362 genome. Selected genes unique to the killing bacteria are shown. PpsE, ppsC_1 and ppsC_2 are all involved in the synthesis of polyketides, which is a class of molecules with insecticidal properties. Sh1A, sh1B_1, sh1B_2, and sh1B_3 are all hemolysin proteins.

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. Given that we have observed off-target effects, we will need to be cautious about proceeding to vast sprays. We will need to do some safety and approval testing – in addition to increasing the number of small field tests.

References:

- Bano, A., & Muqarab, R. (2017). Plant defence induced by PGPR against *Spodoptera litura* in tomato (*Solanum lycopersicum* L.). *Plant Biology*, 19(3), 406–412.
<https://doi.org/10.1111/plb.12535>
- Bohorova, N., Cabrera, M., Abarca, C., Quintero, R., Maciel, A. M., Brito, R. M., Hoisington, D., & Bravo, A. (1997). Susceptibility of Four Tropical Lepidopteran Maize Pests to *Bacillus thuringiensis* CryI-Type Insecticidal Toxins. *Journal of Economic Entomology*, 90(2), 412–415. <https://doi.org/10.1093/jee/90.2.412>
- Heinze, S., Kornberger, P., Grätz, C., Schwarz, W. H., Zverlov, V. V., & Liebl, W. (2018). Transmating: Conjugative transfer of a new broad host range expression vector to various *Bacillus* species using a single protocol. *BMC Microbiology*, 18(1), 56.
<https://doi.org/10.1186/s12866-018-1198-4>
- Kloepper, J. W., Ryu, C.-M., & Zhang, S. (2004). Induced Systemic Resistance and Promotion of Plant Growth by *Bacillus* spp. *Phytopathology*®, 94(11), 1259–1266.
<https://doi.org/10.1094/PHYTO.2004.94.11.1259>
- Pineda, A., Zheng, S.-J., Van Loon, J. J. A., Pieterse, C. M. J., & Dicke, M. (2010). Helping plants to deal with insects: The role of beneficial soil-borne microbes. *Trends in Plant Science*, 15(9), 507–514.
<https://doi.org/10.1016/j.tplants.2010.05.007>
- Murphy, R. O., Cotton, J. S., Owens, I. M., Carroll, J. D., Martin, K. M., Held, D., Lawrence, K., & Beckmann, J. F. (2025). Fast screening libraries of plant growth promoting rhizobacteria (PGPRs) for insecticidal activity. *Journal of applied microbiology*, 136(3)

USGA ID#: 2025-09-840

Title: Enhancing the transfer of autonomous targeted weed control technology to turfgrass systems

Project Leaders: Pawel Petelewicz, Ph.D., Mikerly M. Joseph, Chang Zhao, Ph.D., Arnold W. Schumann, Ph.D., Nathan S. Boyd, Ph.D.

Affiliation: University of Florida, Institute of Food and Agricultural Sciences

Objectives:

1. To expedite the development procedure and maximize potential performance of operational turfgrass-specific ground-based weed recognition models with emphasis on industry-identified priority species and early detection.
2. To develop a ground-based platform for comprehensive testing of performance and interactions between the weed recognition models and sensing section for the future use in autonomous targeted sprayer.
3. To identify and optimize critical internal and external factors impacting the in-field performance of the prototype sprayer's sensing component.

Start Date: 2025

Project Duration: 3 years (2025-2027)

Total Funding: \$100,051

Summary Points:

- The imagery database for the project was established and continues to expand using plant material grown in the greenhouse (currently three priority species: goosegrass, crabgrass, and purple nutsedge, with imagery collected across multiple growth stages) and from in-field collections (spotted spurge, annual bluegrass, goosegrass) captured under diverse turfgrass management contexts and infestation densities (Objective 1).
- A preliminary analysis conducted showed that Stable Diffusion can generate synthetic plant material images in bare-ground soil for use to expedite model development and improve performance. However, currently the resulting images appear unnatural and distorted, indicating that both shape realism and resolution require further refinement in methodology, prior to expanding across weed species and growth stages (Objective 1).
- The ground-based platform for comprehensive field testing of model performance and interactions between the weed-recognition models and sensing components was successfully assembled, adapted to turfgrass research conditions, and validated through initial field testing, enabling its full incorporation into research objectives (Objective 2).
- The YOLOv12-M model tested performed best with detailed imagery at 50-100 cm of ground resolution, maintaining highest detection under well-exposed imagery, while reduced illumination caused declines in accuracy (Objective 3).
- Reliable field performance depended on both ground resolution and adequate daylight, with 50 cm resolution offering the most consistent results and light levels above 50 kLux needed to maintain acceptable detection, which artificial lighting could not fully replicate (Objective 3).

- Detection declined as platform speed increased, especially at ground resolution of 100 cm, whereas 50 cm maintained acceptable (>50%) performance across all speeds, indicating that fast field operation will require additional camera units covering same/similar area to sustain detection capacity.

Summary:

Objective 1

Materials and Methods

The imagery database supporting weed recognition model development, refinement, and synthetic images generation for transfer learning continues to expand using images collected from field and greenhouse conditions. Field images of goosegrass (*Eleusine indica*), spotted spurge (*Chamaesyce maculata*), and annual bluegrass (*Poa annua*) are collected using a “lightbox” with a built-in light source and downward-facing camera (a6400, Sony) across varying turfgrass backgrounds, mowing regimes, and infestation levels. Images are incorporated into the existing library, and the annotation for object detection (bounding boxes) and segmentation (polygons) is ongoing in Roboflow. With sufficient imagery collected, species-specific models are trained using the latest iterations of the You Only Look Once (YOLO) architecture. To date, three pre-trained YOLO variants (v8-M, v11-M, and v12-M) have been fine-tuned on a balanced dataset of 4,500 spotted spurge images. All models were trained using the same protocol, evaluated using overall performance metric of mean Average Precision at 50 percent Intersection over Union (mAP@50), and deployed for field testing in other objectives.

To generate greenhouse material, goosegrass, large crabgrass (*Digitaria sanguinalis*) seed and purple nutsedge (*Cyperus rotundus*) tubers were placed in trays with potting-mix media. After emergence, plants were transplanted into new trays or pots to control density. Plants were irrigated approximately three times per day, fertilized as needed, and clipped every two days to mimic mowing. Images were collected daily using the lightbox and a wooden jig ensuring consistent sample placement. Raw images were cropped to standardize the region of interest and processed into two versions: original-background images and background-removed images isolating plant material. A Stable Diffusion–based generative pipeline was implemented on the UF/IFAS HiPerGator high-performance computing cluster. A Low-Rank Adaptation (LoRA) model trained on goosegrass was used to generate artificial images of weeds in bare-ground soil.

Results and Future Expectations

Three YOLO model iterations trained achieved 0.68, 0.69, and 0.70 (mAP@50; considered successful if >0.50) for the v8-M, v11-M, and v12-M variants. These results show only marginal improvement over earlier models and indicate that exceeding the 0.70 threshold, even with most current architectures, will likely require the supporting strategies evaluated in this project. As the library expands and annotation progresses, the first training-ready batches for additional weed species are expected next year.

Preliminary results from the Stable Diffusion–LoRA pipeline showed it can generate synthetic plant images, but image quality remains insufficient for the species-specific detection-training workflow. Limited control over morphology and background features results in unrealistic representations (Figure 1). Further refinement is required, including dataset adjustments, LoRA retraining, and evaluation of alternative generative approaches. Once

acceptable image quality is obtained, expected next year, synthetic images will be incorporated into the transfer-learning workflow.

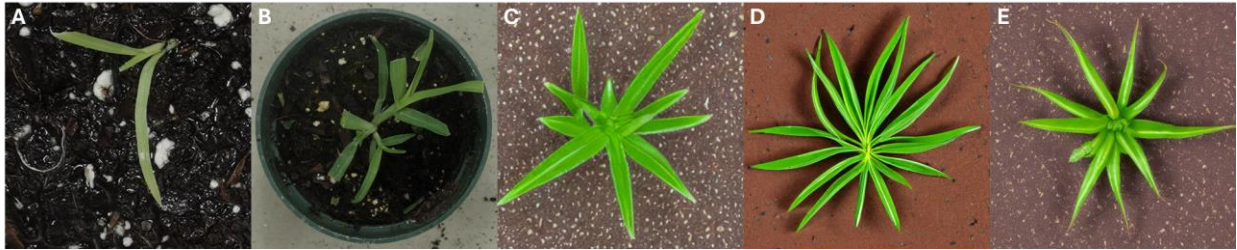


Figure 1. Examples of representative entry imagery data collected from (A) trays and (B) individual pots used for model training, and (C, D, E) examples of generated synthetic plants exhibiting unrealistic feature representation, indicating a substantial need for refinement of the image-generation procedure. Photo credit: Mikerly M. Joseph, UF/IFAS Agronomy.

Objective 2

Materials and Methods

A ground-based robotic platform (Amiga, Farm NG) was acquired in August 2025 and modified with caster wheels and turf tires for safe turfgrass operation (Figure 2A), allowing controlled travel speeds in 1 m s^{-1} increments up to 2.5 m s^{-1} . A computer vision system was installed, consisting of an independent power source (Explorer 2000, Jackery Inc.), a USB camera (5 MP global-shutter 50 fps, ELP) mounted on a custom adjustable aluminum rail for field-of-view and ground-resolution control, and an onboard computer (XPS 15, Dell Inc.). The system was validated under field conditions (Figure 2B).

Results and Future Expectations

The platform performed reliably and is now incorporated into other research objectives. Planned upgrades include replacing the laptop with an NVIDIA Jetson Orin Nano with touchscreen monitor as the computing core of the future targeted sprayer and adding an artificial light source to evaluate illumination effects on model performance in motion. The platform will serve as the base chassis for the research targeted sprayer.

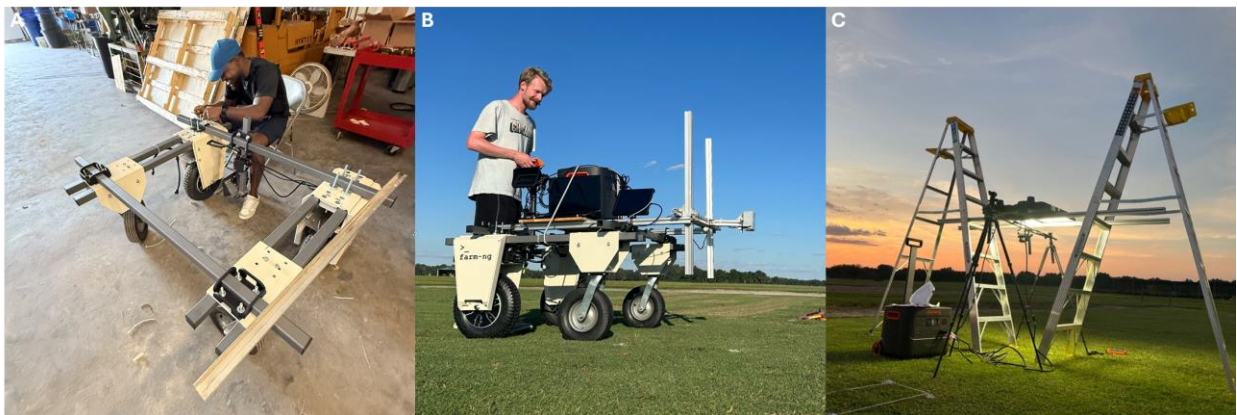


Figure 2. (A) Platform modification for safe operation in turfgrass settings, (B) the fully assembled unit with robotic chassis, onboard computer, power source, and camera system on custom aluminum rail for field data collection, and (C) field setup for testing the impacts of light conditions and ground resolution on detection performance. Photo credit: Pawel Petelewicz, UF/IFAS Agronomy (A), Mikerly M. Joseph, UF/IFAS Agronomy (B, C).

Objective 3

Materials and Methods

To assess the impacts of light conditions and ground resolution (ground sampling distance, GSD) on model performance, a field study was conducted in plots with natural spotted spurge infestation in ‘Celebration’ bermudagrass. Images were collected over a 48×30 cm grid replicated four times at three GSDs (50, 100, 150 cm field of view, adjusted by camera height). A mirrorless camera (a6400, Sony) was used with ISO 100, F6.3, 1/125 settings. A total of 270 images (90 per resolution) were selected from captures taken between 08:00 and 21:00 with and without supplemental LED lighting delivering 12,000 lux (Figure 2C). Illuminance was measured for each image, and solar elevation angle was calculated using a custom Python script. Images were cropped to represent the same ground area across GSDs, and luminance (Y) values were used to classify exposure as critically underexposed (0–60), underexposed (60–120), or well-exposed (120–200). Images were processed using YOLO v8-M, v11-M, and v12-M with a confidence threshold of 0.10. Performance was summarized as rate decline, defined as the percentage reduction in detections relative to the maximum observed. Rate decline was analyzed using factorial ANOVA with model, GSD, and exposure level as fixed factors, with Fisher’s LSD for mean separation. A generalized additive model (GAM) was fitted with rate decline as the response and lux, time of day, and light type as predictors.

To assess the impact of ground speed on detection performance, a second field study was conducted using the platform from Objective 2 (Figure 2B). Plots (20×10 m) arranged in five rows contained ten marked grids (48×30 cm) per row for standardized sampling. Videos were collected at GSDs of 50 and 100 cm while the platform traveled at speeds of 0.4, 0.6, 0.8, 1.2, 1.3, and 2.5 m s^{-1} . Frames were extracted, cropped, and processed using YOLOv12 with a 0.10 confidence threshold. Performance was summarized as rate decline and analyzed using a GAM with speed and GSD as predictors.

Results and Future Expectations

YOLOv12-M effectively detected spurge across all tested GSDs under well-exposed conditions. GSDs of 50 and 100 cm maintained 80–90 percent of full detection capacity outperforming 150 cm, confirming that higher image detail improves performance (Figure 3). Reduced exposure degraded accuracy, falling below 50% and 20% with underexposed images and critically underexposed images, respectively (Figure 3).

Under natural daily light variation, performance was driven by GSD and illuminance (Figure 4). The 150 cm GSD never exceeded 30% detection. At 50 and 100 cm, detection approached 70% at 80 kLux but declined earlier at 100 cm (Figure 4A). Probability simulations showed a 90–100% chance of achieving more than 50% performance at 50 cm GSD between 1–5 PM under non-overcast conditions, while operation outside this window or at 150 cm resulted in more than an 80% chance of underperformance (Figure 4B). These results indicate that field use should prioritize detailed imagery (50–100 cm GSD) and light levels above 50 kLux producing image brightness of 120–196. Artificial lighting improved low-light performance but never matched natural daylight (data not shown), suggesting that replicating daylight would require a much stronger light source.

Increasing platform speeds reduced detection due to motion blur. A 50 cm GSD maintained more than 50% performance at all speeds, including 2.4 m s^{-1} , while 100 cm declined rapidly falling below acceptable 50% around 0.6 m s^{-1} and never recovered (Figure 5). Because high application speed is essential for spraying efficiency, maintaining acceptable detection would require additional cameras to cover the spray width, increasing equipment/maintenance costs.

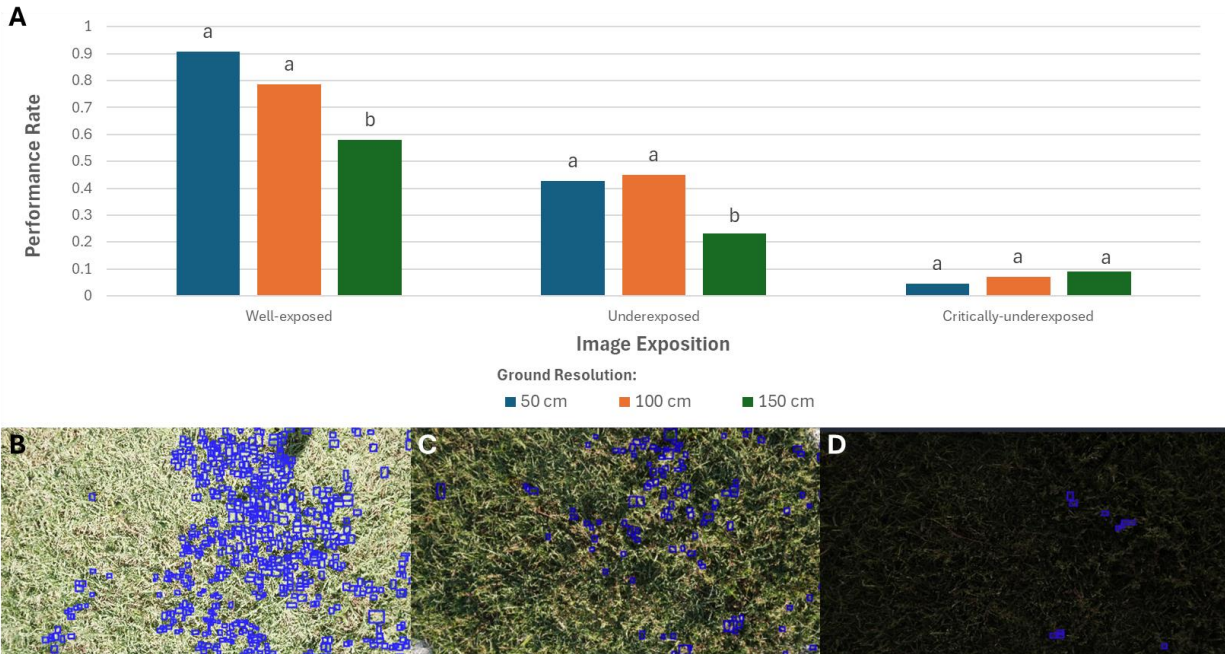


Figure 3. (A) Impact of image exposure on model performance, and (B-D) visual representation of spotted spurge detection under varying exposure settings: (B) well-exposed, (C) underexposed, and (D) critically underexposed. Chart and photo credit: Mikerly M. Joseph, UF/IFAS Agronomy.

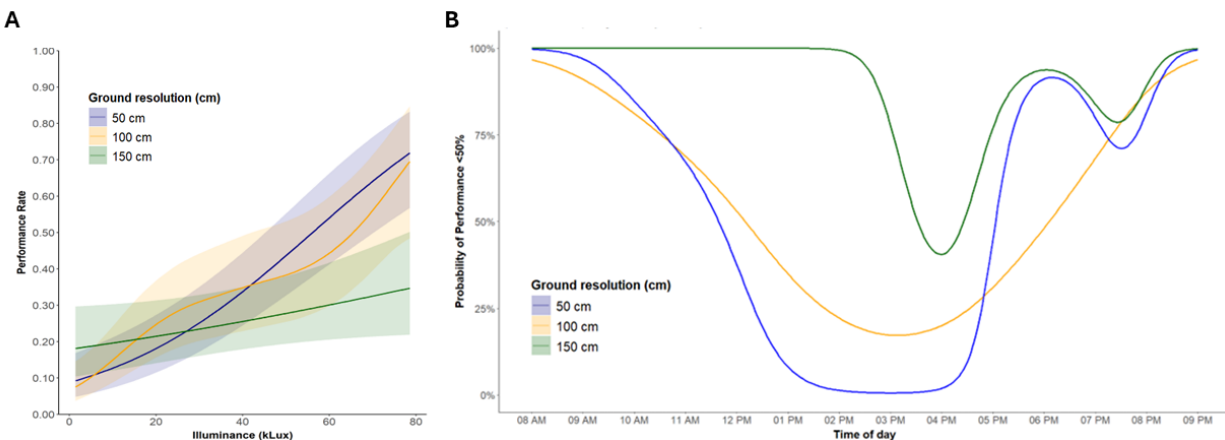


Figure 4. (A) Impact of illuminance on model performance in spotted spurge detection across varying ground resolutions, and (B) probability of model underperformance (below the 50 percent acceptability threshold) under those ground resolutions throughout the day under typical late-summer Florida conditions.. Chart credit: Mikerly M. Joseph, UF/IFAS Agronomy.

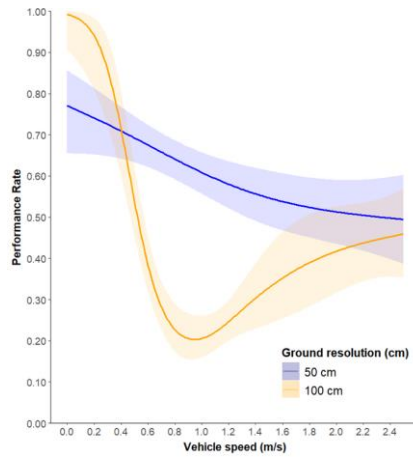


Figure 5. Impact of platform ground speed on model performance in spotted spurge detection across varying ground resolutions. Chart credit: Mikerly M. Joseph, UF/IFAS Agronomy.

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 Leaders: 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 by characterizing pollinator communities associated with renovated and unrenovated areas.

Start Date: 2022

Project Duration: 3 Years

Total Funding: \$83,628

Summary Points:

- Renovation of no-play zones consistently increased native plant abundance, richness, and flower bloom production during the first two years regardless of seeding method or timing.
- Fall drill seeding produced the earliest and most abundant floral displays, providing earlier forage for pollinators and more visible “success indicators” for golf course stakeholders.
- Renovated areas supported greater bee, butterfly and moth richness and diversity, especially during spring and fall, demonstrating rapid ecological returns from renovation.
- Early establishment was dominated by non-target species (e.g., smooth brome, Canada thistle), underscoring the importance of ongoing weed control to support continued development of the native plant community.

Summary Text

Rationale

Golf courses represent a substantial land resource in urban and peri-urban areas, with more than 2.5 million acres nationally capable of supporting biodiversity and ecosystem services when managed intentionally (Colding & Folke 2009; Terman 1997). Renovating no-play zones into native prairie habitat can reduce inputs, enhance aesthetics, and increase ecological function (Dobbs & Potter 2015; Pornaro et al. 2018). Despite growing superintendent interest, empirical data describing the early establishment trajectory of prairie vegetation and its corresponding ecological benefits, particularly pollinator support, remain scarce in golf course settings. This project addresses that gap by evaluating how seeding time and method affect plant community establishment and how resulting vegetation shifts influence pollinator abundance, richness, and diversity. The work builds on foundational restoration ecology principles (Rowe 2010; Larson et

al. 2011) and on evidence that floral resource diversity drives pollinator communities (Hopwood 2008; Hyjazie & Sargent 2022). Understanding these relationships is critical for superintendents seeking to naturalize out-of-play spaces while maintaining playability and controlling long-term resource costs.

Methodology

Renovation took place across multiple no-play zones at the Kampen-Cosler Golf Course in West Lafayette, Indiana. Site preparation began in fall 2021 with broadleaf and grass herbicide applications followed by continued weed suppression and mowing throughout 2022. Seeding treatments were applied in fall 2022 and spring 2023 using a factorial combination of seeding time (fall vs. spring) and seeding method (broadcast vs. drill seeding). A diverse mixture of native warm-season grasses, sedges, and forbs was applied at a rate conducive to achieving season-long bloom resources. Oats were included as a cover crop to improve sowing evenness and early stabilization.

Vegetation sampling occurred twice in 2023 and three times in 2024 using point-intercept frames to quantify relative abundance, species richness, diversity, and bloom density. Species were categorized as seeded natives, non-seeded natives, and non-native species to evaluate successional dynamics. This approach allowed direct comparison with published restoration assessment techniques (Larson et al. 2017; Betson & Foster 2023).

Pollinator surveys began in 2023 and included both active vacuum surveys and passive blue vane traps, which together capture complementary components of pollinator communities (Gibbs et al. 2017; Kuhlman et al. 2021). Active sampling followed standardized protocols designed to target foraging insects (Fijen & Kleijn 2017), while passive traps ran for five days per sampling period to improve detection of less abundant taxa. Pollinator abundance, richness, and diversity were analyzed with repeated-measures ANOVA to isolate treatment and temporal effects.

Results to Date

Plant Community Establishment

Across 2023–2024, renovation consistently increased prairie species abundance and richness, and total species diversity, regardless of seeding time or method (Fig. 1). This aligns with expectations from early successional prairie systems, where disturbance-adapted non-native species initially dominate but seeded species expand over time (Delang & Li 2013; Camill et al. 2004). In 2023, seeded species constituted ~18–29% of vegetation, but by fall 2024, they comprised 24–48% of the plant community indicating steady establishment momentum.

While treatment effects were subtle overall, renovated plots produced significantly greater abundance of floral blooms during most sampling periods (Fig. 2), demonstrating earlier maturation of key forb species such as *Rudbeckia hirta*. This pattern is consistent with literature showing early forb establishment (Larson et al. 2011; Applestein et al. 2018). Bloom production is particularly relevant for golf courses because it delivers both ecological function and visually compelling evidence of restoration progress.

Initial dominance by species such as smooth brome, Canada thistle and mare's tail reflected typical early-stage competition dynamics (Moore 1975), but seeded species increased markedly

without altering treatment rankings that were initially observed in 2023. These findings follow previous reports by demonstrating that strong treatment-level differences are unlikely to appear until Year 3, a result that aligns with multi-year restoration trajectories reported elsewhere (Rinella et al. 2016; Brambila et al. 2023).

Pollinator Responses

Pollinator data from 2,070 specimens collected in 2023–2024 revealed rapid ecological returns on investment, even while the plant community remained early successional. Renovated plots supported higher bee species richness, especially in spring and fall 2024 (Fig. 3), and consistently higher butterfly and moth abundance and richness across all sampling periods (Fig. 4). These patterns reinforce the strong linkage between floral resource availability and pollinator visitation (Bruckman & Campbell 2014; Simanonok et al. 2021).

Active sampling proved particularly sensitive to treatment differences, detecting higher bee diversity in renovated areas, whereas passive trapping identified higher butterfly and moth metrics. Similar method-specific patterns have been documented in other system-level assessments (Pei et al. 2022; Mathis et al. 2024), highlighting the importance of using complementary methods in renovation monitoring programs.

Compared to findings from earlier annual reports, the 2024 data show stronger and more consistent treatment effects, particularly for butterflies and moths. This suggests that the increasing density and diversity of seeded forbs in renovated areas are translating into meaningful habitat improvements. This is an encouraging sign for superintendents seeking quantifiable ecological benefits within a two-year timeframe.

Future Expectations

The third growing season (2025) is expected to mark a significant transition toward a more stable and characteristic prairie community. Although a prescribed burn was initially planned for 2025, concerns about smoke incursion into adjacent neighborhoods prompted a delay to spring of 2026 when reduce the amount of smoke produced (Spring burning typically produces less smoke). The planned burn is expected to:

- Suppress cool-season grasses and early successional weeds
- Stimulate germination and growth of warm-season grasses such as big bluestem and little bluestem
- Increase structural complexity important for bee nesting and lepidoptera microhabitats
- Improve light availability for mid- and late-successional forbs.

These outcomes are consistent with fire-mediated prairie development reported across restoration literature (Link et al. 2017; Henn & Damschen 2022). Superintendents can expect more noticeable changes in vegetation appearance, more continuous bloom across the growing season, and progressively stronger pollinator responses. By the end of Year 3, renovated areas are likely to deliver measurable reductions in maintenance inputs (e.g., mowing, broadleaf herbicide) alongside enhanced biodiversity and visual appeal—findings that echo broader assessments of naturalized golf-course habitats (Dobbs & Potter 2016; Thompson et al. 2022).

Ongoing monitoring will be critical for understanding how plant and pollinator communities stabilize and to guiding long-term management decisions that maintain habitat quality. Looking ahead, expanding this research to additional golf courses and pursuing new funding opportunities would allow us to evaluate these renovation strategies across a wider range of environmental and management contexts, ultimately strengthening recommendations for scalable, course-level biodiversity enhancement.

References Cited

- Applestein, C., Bakker, J. D., Devlin, E. G., & Hamman, S. T. (2018). Evaluating seeding methods and rates for prairie restoration. *Natural Areas Journal*, 38(5), 347–355.
- Betson, N., & Foster, B. L. (2023). Seasonal shifts in diversity and composition of a tallgrass prairie restoration have for time. *Ecological Restoration*, 41(1), 16–24.
- Brambila, A., Reed, P. B., Bridgham, S. D., Roy, B. A., Johnson, B. R., Pfeifer-Meister, L., & Hallett, L. M. (2023). Disturbance: A double-edged sword for restoration in a changing climate. *Restoration Ecology*, 31(1), e13675.
- Bruckman, D., & Campbell, D. R. (2014). Floral neighborhood influences pollinator assemblages and effective pollination in a native plant. *Oecologia*, 176(2), 465–476.
- Camill, P., McKone, M., Sturges, S., Severud, W., Ellis, E., Limmer, J., Martin, C., Navratil, R., Purdie, A., Sandel, B., Talukder, S., & Trout, A. (2004). Community- and ecosystem-level changes in a species-rich tallgrass prairie restoration. *Ecological Applications*, 14(6), 1680–1694.
- Colding, J., & Folke, C. (2009). The role of golf courses in biodiversity conservation and ecosystem management. *Ecosystems*, 12(2), 191–206.
- Delang, C. O., & Li, W. M. (2013). *Ecological succession on fallowed shifting cultivation fields*. Springer Netherlands.
- Dobbs, E. K., & Potter, D. A. (2015). Forging natural links with golf courses for pollinator-related conservation, outreach, teaching, and research. *American Entomologist*, 61(2), 116–123.
- Dobbs, E. K., & Potter, D. A. (2016). Naturalized habitat on golf courses: Source or sink for natural enemies and conservation biological control? *Urban Ecosystems*, 19(2), 899–914.
- Fijen, T. P. M., & Kleijn, D. (2017). How to efficiently obtain accurate estimates of flower visitation rates by pollinators. *Basic and Applied Ecology*, 19, 11–18.
- Gibbs, J., Joshi, N. K., Wilson, J. K., Rothwell, N. L., Powers, K., Haas, M., Gut, L., Biddinger, D. J., & Isaacs, R. (2017). Does passive sampling accurately reflect the bee communities pollinating apple and cherry orchards? *Environmental Entomology*, 46(3), 579–588.
- Henn, J. J., & Damschen, E. I. (2022). Grassland management actions influence soil conditions and plant community responses to winter climate change. *Ecosphere*, 13(10).
- Hopwood, J. L. (2008). The contribution of roadside grassland restorations to native bee conservation. *Biological Conservation*, 141(10), 2632–2640.
- Hyjazie, B. F., & Sargent, R. D. (2022). Floral resources predict the local bee community: Implications for conservation. *Biological Conservation*, 273, 109679.
- Kuhlman, M. P., Burrows, S., Mummey, D. L., Ramsey, P. W., & Hahn, P. G. (2021). Relative bee abundance varies by collection method and flowering richness: Implications for understanding patterns in bee community data. *Ecological Solutions and Evidence*, 2(2), e12071.

- Larson, D. L., Bright, J. B., Drobney, P., Larson, J. L., Palaia, N., Rabie, P. A., Vacek, S., & Wells, D. (2011). Effects of planting method and seed mix richness on the early stages of tallgrass prairie restoration. *Biological Conservation*, 144(12), 3127–3139.
- Larson, D. L., Bright, J. B., Drobney, P., Larson, J. L., & Vacek, S. (2017). Persistence of native and exotic plants 10 years after prairie reconstruction. *Restoration Ecology*, 25(6), 953–961.
- Link, A., Kobiela, B., DeKeyser, S., & Huffington, M. (2017). Effectiveness of burning, herbicide, and seeding toward restoring rangelands in southeastern North Dakota. *Rangeland Ecology & Management*, 70(5), 599–603.
- Mathis, C. L., McNeil, D. J., Kammerer, M., Larkin, J. L., & Skvarla, M. J. (2024). Distance models reveal biases associated with passive trapping methods for measuring wild bee abundance. *Frontiers in Ecology and Evolution*, 12, 1380622.
- Moore, R. J. (1975). The biology of Canadian weeds: 13. *Cirsium arvense*. *Canadian Journal of Plant Science*, 55(4), 1033–1048.
- Pei, C. K., Hovick, T. J., Duquette, C. A., Limb, R. F., Harmon, J. P., & Geaumont, B. A. (2022). Two common bee-sampling methods reflect different assemblages of the bee community in mixed-grass prairie systems. *Journal of Insect Conservation*, 26(1), 69–83.
- Pornaro, C., Macolino, S., De Luca, A., Sallenave, R., & Leinauer, B. (2018). Plant species diversity of naturalized roughs as affected by conversion strategies. *Agronomy Journal*, 110(5), 1709–1717.
- Rinella, M. J., Espeland, E. K., & Moffatt, B. J. (2016). Studying long-term, large-scale grassland restoration outcomes to improve seeding methods and reveal knowledge gaps. *Journal of Applied Ecology*, 53(5), 1565–1574.
- Rowe, H. I. (2010). Tricks of the trade: Techniques and opinions from 38 experts in tallgrass prairie restoration. *Restoration Ecology*, 18, 253–262.
- Simanonok, S. C., Otto, C. R. V., & Buhl, D. A. (2021). Floral resource selection by wild bees and honey bees in the Midwest United States: Implications for designing pollinator habitat. *Restoration Ecology*, 29(8), e13456.
- Terman, M. R. (1997). Natural links: Naturalistic golf courses as wildlife habitat. *Landscape and Urban Planning*, 38(3–4), 183–197.
- Thompson, C., Kridel, D. J., & Kenna, M. P. (2022). Economic and sustainability benefits of the United States Golf Association’s research investment in putting green construction, naturalized rough, and turfgrass breeding. *Crop, Forage & Turfgrass Management*, 8(2), e20188.

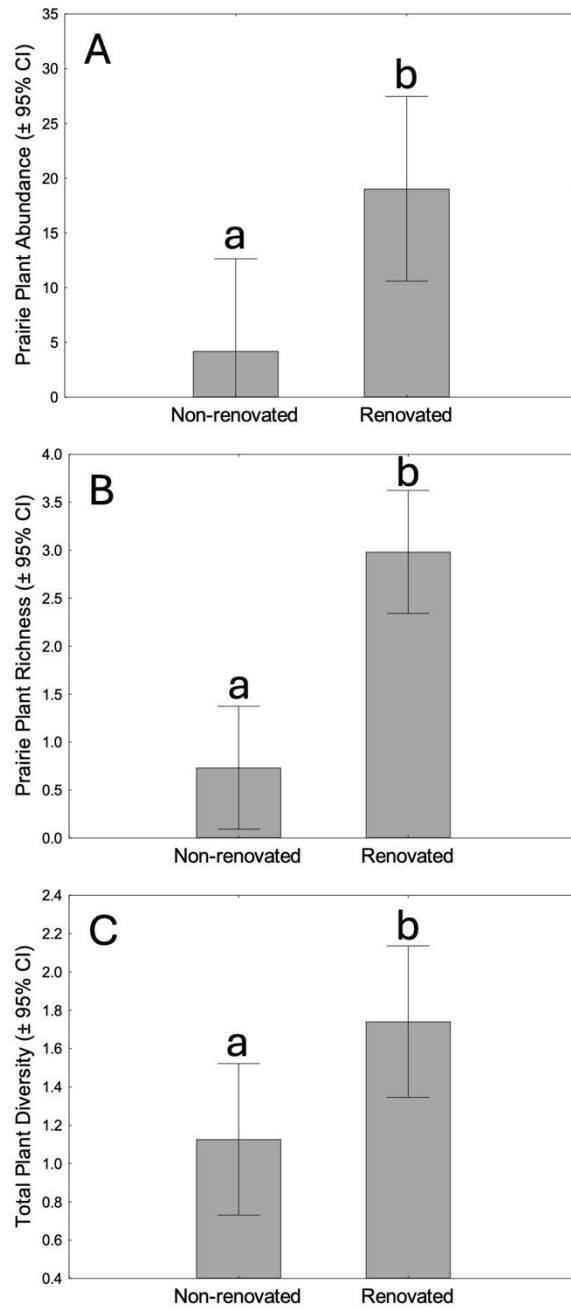


Figure 1. Influence of native prairie renovation on prairie plant diversity (A) and abundance (B) and total plant diversity (C) in golf course no play zones.

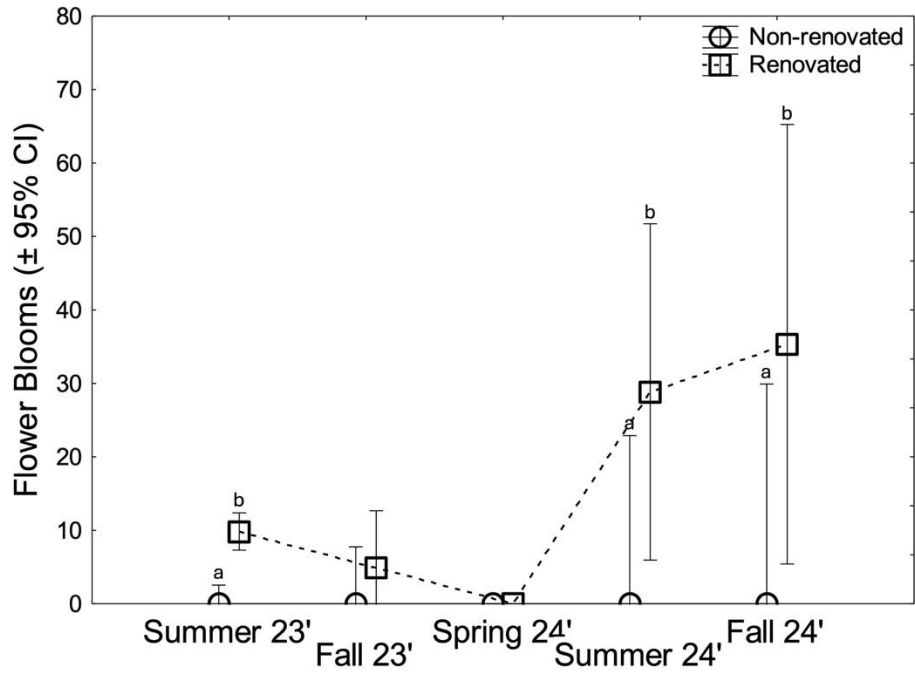


Figure 2. Influence of prairie renovation on the density of flower blooms in golf course no play zones.

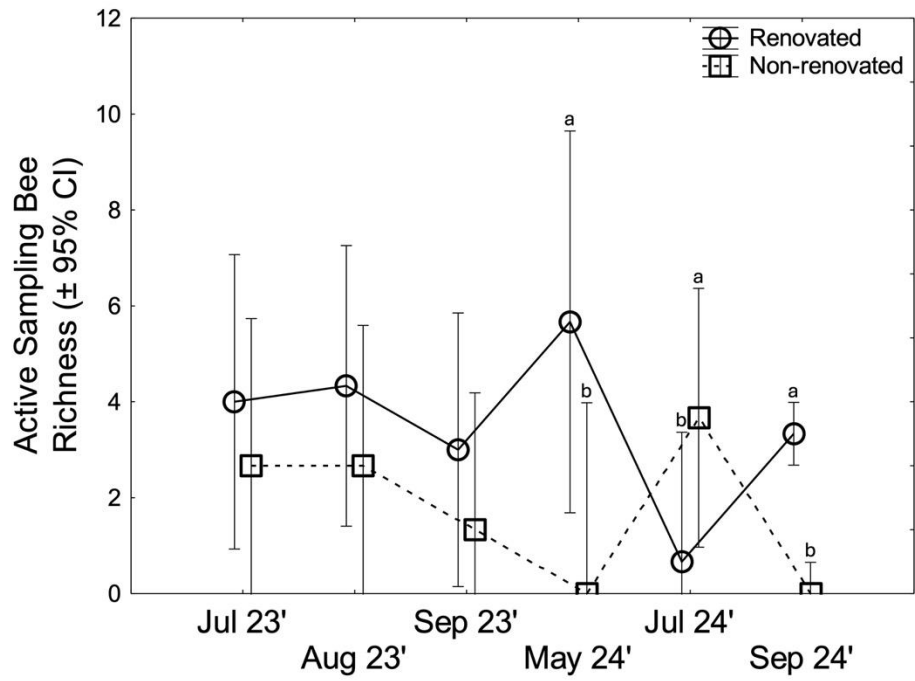


Figure 3. Influence of prairie renovation on bee species richness in golf course no play zones.

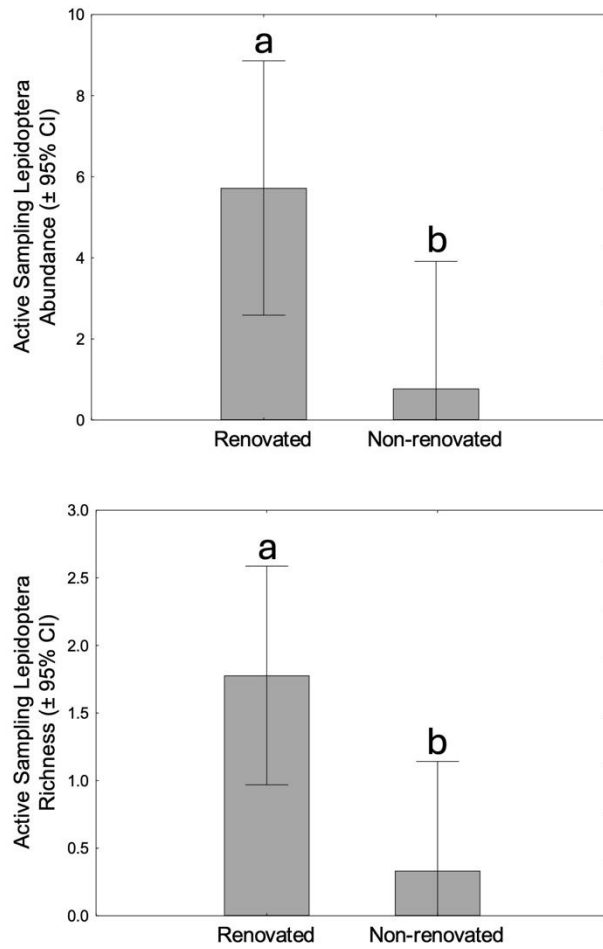


Figure 4. Influence of prairie renovation on the abundance and species richness of butterflies and moths (Lepidoptera) in golf course no play zones.

USGA ID#: 2023-19-786

Title: Climate Change Vulnerabilities Of U.S. Golf Courses And Potential Adaptation Opportunities

Project Leaders: Arden Drake 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:

- Conducted interviews with stakeholders at five golf courses that are being impacted by climate change and drafted case studies showcasing vulnerability and adaptation at these courses, which will be included in the final report.
- Completed the online survey and literature review, which are being used to inform the information presented in the final report.
- Synthesized literature review results into summaries for vulnerability and adaptation topics and began to develop regional summaries for nine U.S. regions, each highlighting stressors, climate projections, and relevant studies.
- Submitted a proposal to present project findings at the 2026 National Adaptation Forum.

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 3 of this project, we have completed most of the main project activities, and are now focused primarily on drafting our main deliverable: a comprehensive report outlining general climate change vulnerabilities and potential adaptation opportunities for U.S. golf courses. We will be using information from the online survey and literature review (both completed in previous years) to inform this report, and are also drafting case studies and regional summaries to go along with it.

From winter through summer 2025, we conducted a series of interviews with representatives from golf courses and country clubs across the United States. We contacted a total of 14 courses and secured interviews with five: the Kittansett Club in Marion, Massachusetts; La Rinconada Country Club in Los Gatos, California; Palmer Hills Golf Course in Bettendorf, Iowa; Langston Golf Course in Washington, DC; and the Fishers Island Club in Fishers Island, New York (Figure 1). Four of these will be developed into full-length case studies that will complement the final report. One course preferred not to be named directly in the report, but the information provided in the interview will be incorporated at a high level to support key findings. Content gathered during the interviews will also be used as examples within the literature review portion of the report, offering practical, on-the-ground context for the strategies and actions highlighted in that section. We were able to obtain photographs and technical data from the participating courses, and received permission to include these materials in the final report. The case studies are undergoing review by representatives from each course. We have also

incorporated input from the USGA team regarding content, level of technical detail, and the types of information that will be most useful for the USGA audience. We will continue to refine these case studies in early 2026.



Figure 1. Map showing the golf courses and country clubs interviewed for case studies.

For our literature review, we synthesized literature findings into sections that highlight information on vulnerabilities affecting golf courses (e.g., flooding, drought) and adaptation strategies available to them (e.g., reducing erosion, selecting heat- and drought-tolerant turfgrass). These summaries form the foundation for organizing the body of our final report. We are also in the process of creating regional summaries that present a snapshot of projected climate changes and trends, potential impacts, and important non-climate stressors. We are creating these summaries for Alaska, Hawai'i, the Midwest and Great Plains, the Northwest, the Northeast, Puerto Rico, the Southeast, the Southwest, and California.

Results to Date

As we comb through the literature we identified and draft the final report, a few observations have arisen. First, and perhaps most notably, there is a notable lack of published literature that directly addresses climate change in the golf industry. Of the 364 articles and reports that we identified as potentially useful sources, less than a third of those (111, or 30%) incorporated climate change at all, and many that did mentioned it briefly in the introduction but didn't directly consider it within the study design or results interpretation and discussion (Figure 2). Climate change was less likely to be mentioned or directly incorporated into articles related to turfgrass

than other topics; while many of these addressed drought, heat, flooding, or other stressors, they generally only compared across sites or microclimates. This is an important finding because climate change has the potential to shift conditions in sudden, non-linear ways and impact systems through compounding stressors (Peters et al. 2004; Rial et al. 2004; Rocha et al. 2018), such that evaluation of even extreme current conditions without explicit consideration of the added stresses associated with climate change is insufficient.

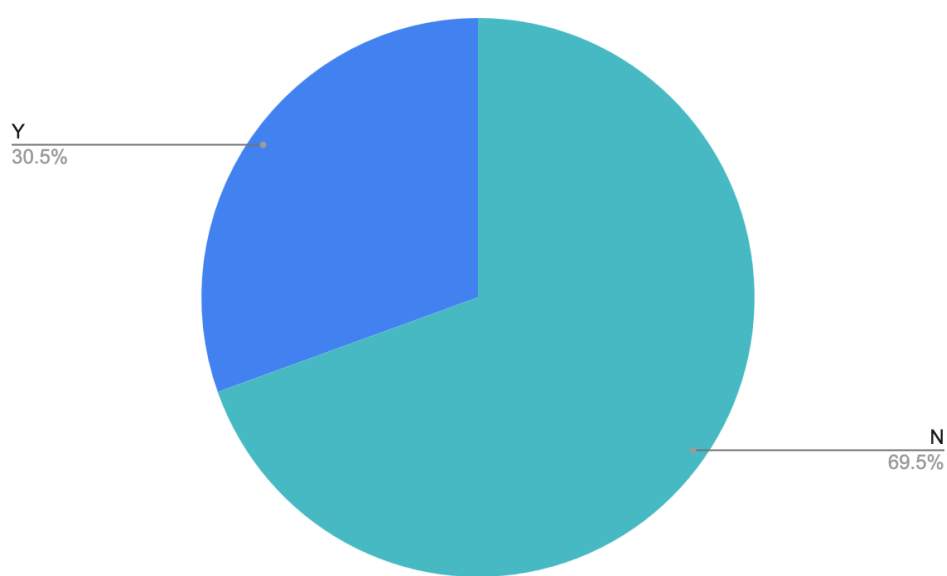


Figure 2. Proportion of literature review sources that explicitly mention or incorporate climate change.

Other observations include a disproportionate focus on turfgrass research (though again, note that few explicitly consider climate change) compared to other topics. In particular, there are very few articles available related to sea level rise and coastal erosion in relation to golf courses, or on human impacts such as player satisfaction or health and safety. Some of the sources that most directly address climate change appear to be white papers, many of which are no longer available, highlighting the challenges of ensuring that important research that isn't published in peer-reviewed journals remains accessible.

Finally, as we have begun to draft the report we have been considering the challenges of communicating vulnerability and adaptation opportunities across such a large area (i.e., the entire U.S.). This is particularly noticeable when talking about turfgrass, where the research has been extensive but there are many different drivers of plant growth and survival across the country (e.g., weather/climate, soils, management practices, etc.). In most cases, we are unable to make specific statements about species or management recommendations as nothing we can say will be widely applicable and we want to avoid having people look to this report for specific predictions or instructions. Rather, we intend it to be used as general guidance for how different impacts might occur and why they would be relevant to the golf industry, with the goal of guiding readers to consider whether each might be relevant to their specific area and

situation, based on their own knowledge of site-specific factors. We hope that this report can help people understand why vulnerability and adaptation are important, what questions to ask, and which factors to consider, empowering them to incorporate consideration of climate change into the work they are already doing and the significant expertise that exists.

We have submitted a proposal for the 2026 National Adaptation Forum, which is scheduled for May 12 to 14, 2026, in Pittsburgh, Pennsylvania, to provide a poster presentation of the findings of this project. The Forum will provide a significant platform for sharing the research findings of this project with a broad professional audience.

Future expectations

Over the remainder of the project, which we plan to complete in June 2026, we will focus on compiling all information collected through the literature review, case studies, and the survey into a final report and a corresponding web-based resource that presents our findings.

Literature Cited:

- Peters DPC, Pielke RA, Bestelmeyer BT, Allen CD, Munson-McGee S, Havstad KM. 2004. Cross-scale interactions, nonlinearities, and forecasting catastrophic events. *Proceedings of the National Academy of Sciences* **101**:15130–15135. *Proceedings of the National Academy of Sciences*.
- Rial JA et al. 2004. Nonlinearities, feedbacks and critical thresholds within the Earth's climate system. *Climatic Change* **65**:11–38.
- Rocha JC, Peterson G, Bodin Ö, Levin S. 2018. Cascading regime shifts within and across scales. *Science* **362**:1379–1383. *American Association for the Advancement of Science*.

USGA ID#: 2025-14-845

Title: EARLY SPRING ROOT DAMAGE PROJECT

Project Leader: Eric Watkins and Andrew Hollman

Affiliation: University of Minnesota

Objectives: The objectives of the project were to (1) separate root shear from turfgrass crown damage; and (2) determine feasibility of manipulating field soils in future research.

Start Date: 2025

Project Duration: 2

Total Funding: \$7,500

Summary Points:

- Early spring root damage on golf greens in cold climates is often attributed to root shearing.
- We attempted to mimic root shearing damage in the field but were unable to observe damage.
- Future method development will focus on creating variable warming in soil profile that could lead to better testing conditions.

The United States Golf Association has described damage caused during the spring thaw period as likely caused due to root shearing, as shown [in this video](#). There is, however, little scientific evidence to support this as the primary cause of damage. It seems unlikely that a large area of thawed soil above an area of frozen soil would move in such a way as to cause massive root shearing. Easier to imagine is the opposite: a frozen upper surface moving in a large section above a thawed layer below. Other possible explanations for the observed injury are ice layer formations in the soil resulting in root damage due to the expansion force of the ice; compression of the thin thawed soil layer against the frozen lower layer; and damage to the turfgrass crown due to surface traffic with the uncompressible frozen sublayers. Therefore, there is a need to examine the potential mechanisms responsible for root shearing.

As a first step, we proposed the following objectives:

1. **Separate root shear from turfgrass crown damage:** Identifying the extent to which root shearing and crown damage might be occurring in a thawing soil is an important first step in this project. We utilized a greens-height plot area on a USGA specification green at the Turfgrass Research, Outreach, and Education center on the University of

Minnesota St. Paul campus. Using currently installed soil temperature sensors, we monitored soil temperatures in search of a condition where the upper part of the soil was thawed (shallowest sensor just under the turf surface at 1.3 cm) while the deeper sensors (7.6 and 15.2 cm) remained frozen. We observed this from sensors (Figure 1) at the end of February, began treatments February 26, 2025, and continued weekly with the last application occurring on April 7, 2025. Treatments included: (i) a circular blade with a blade also through the diameter to simulate root shear by inserting just into the soil and twisting (Figures 2 & 3); (ii) a 0.5 kg Clegg impact soil tester dropped 3 times to simulate mechanical crown damage that might be experienced by foot or other traffic; (iii) combination of i and ii; (iv) untreated control. Each of these treatments was repeated 4 times on each treatment date on creeping bentgrass (cultivar 'Piranha') and annual bluegrass (cultivar 'Two-Putt') plots.

There was no damage caused by the shearing, impact or the combination of the treatments on the putting green if the plugs were in the ground. Lack of soil contact between the shear piece of turf and the underlying soil did cause a few plugs to dry out and led to desiccation injury. The movement of these pieces out of their treatment spots was likely the result of curious avian and canine that frequent the area.

2. ***Determine feasibility of manipulating field soils in future research:*** A second stage of research would likely include some sort of traffic and/or large soil area shifting that is imposed on plots areas that include the following soil scenarios: (i) frozen upper layer, frozen lower layer; (ii) thawed upper layer, frozen lower layer; (iii) thawed upper layer, thawed lower layer. In a previous project on tall fescue deacclimation, we designed and implemented heated tents that were able to increase surface soil temperatures. During spring 2026, we will use a similar approach to thaw the soil surface and create the three proposed soil scenarios.

We have small A-frame greenhouses with 3x4 ft footprint which sit flush with the putting green surface. The greenhouses increase air temperature on sunny days, and additional heat is added to the inside of the structure using a small PTC heater and a plug-in greenhouse thermostat (Figure 4). A solar shield was created from white coroplast to limit solar radiation from influencing the temperature probe and the Bluetooth data logger. The logger allows for easy monitoring and recording of air temperature. Soil temperature is monitored with Hobo data loggers buried in the putting green.

Figure 1. Soil temperatures from sensors installed in the USGA Specified putting green.

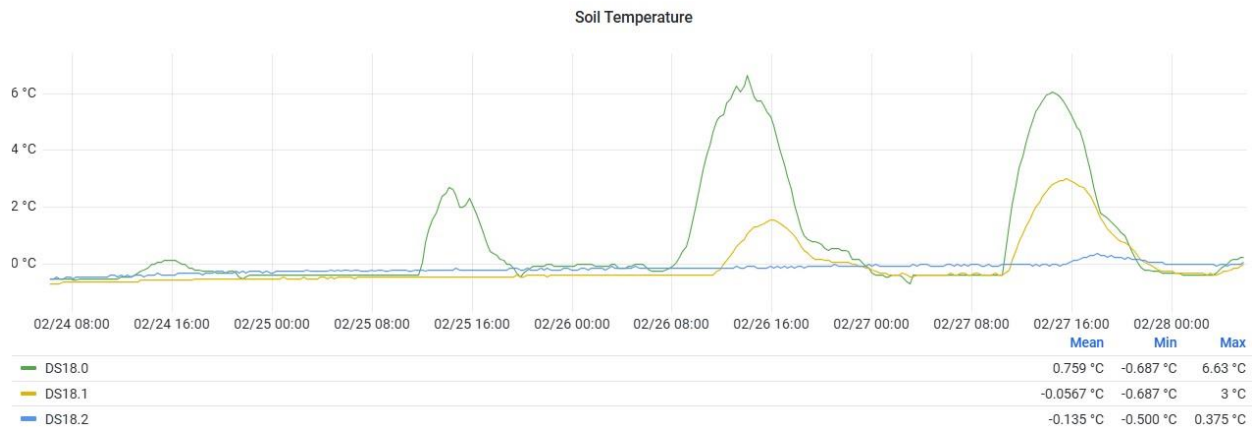


Figure 2. University of Minnesota USGA putting green with a circular piece of creeping bentgrass turf sheared out of the ground by a custom circular cutter with a blade running the diameter (February 26, 2025)



Figure 3. Handle with strain gauge used to turn the circular cutting head and shear the turfgrass roots from the frozen soil below.

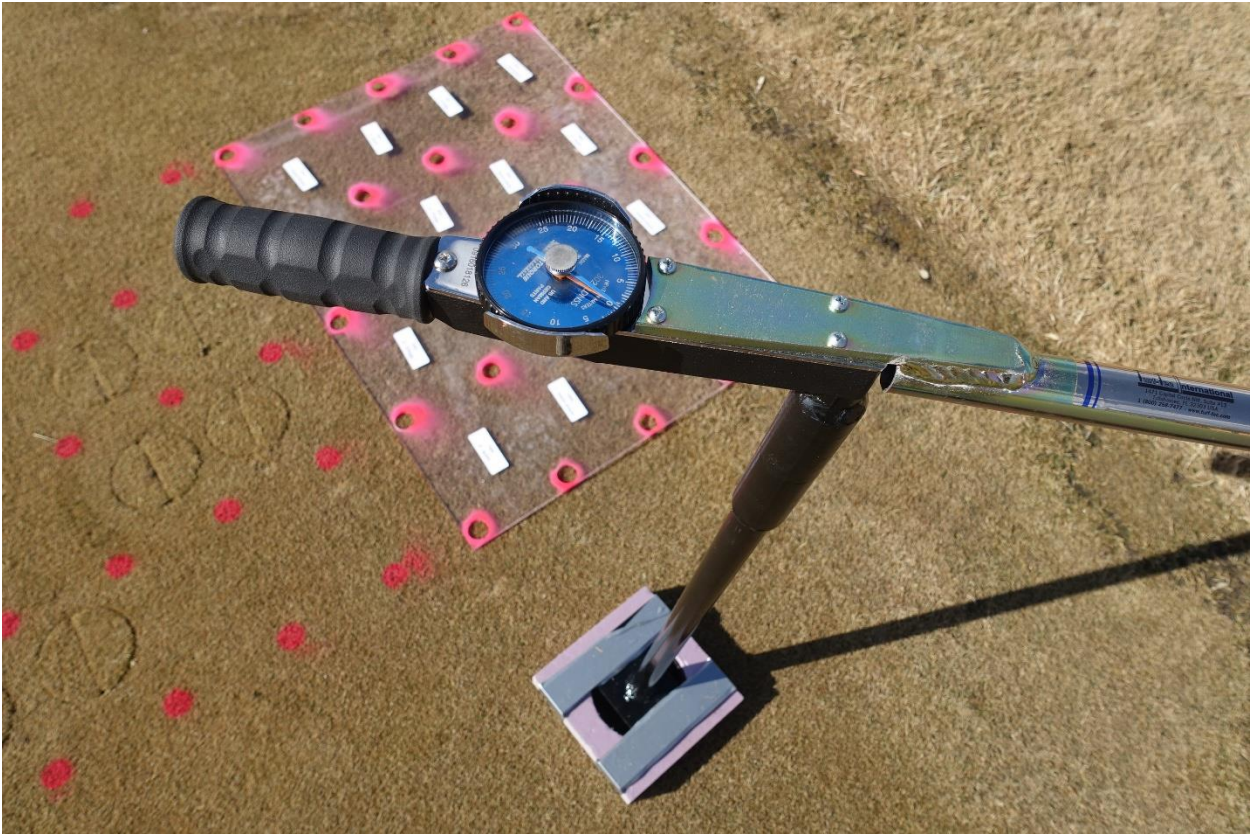


Figure 4. A radiation shield, thermostat probe, Bluetooth temperature logger and small heater placed under A-frame greenhouses to maintain a warmer air temperature to thaw out the soil surface.



USGA ID#: 2025-13-844

Title: Evaluating the Effects of Common Plant Growth Regulators on Winter Survival, Fall Color Retention, and Spring Green-Up of Bermudagrass Putting Greens

Project Leader: Mingying Xiang

Affiliation: Oklahoma State University

Objectives:

To quantify the impact of four plant growth regulators (trinexapac-ethyl, ethephon, prohexadione calcium, and paclobutrazol) on the freeze tolerance of a bermudagrass putting green.

Start Date: January 1, 2025

Project Duration: 1 year

Total Funding: \$10,000

Summary Points:

- Selected plant growth regulator (PGR) application during the growing season had impacts on the winter survivability of bermudagrass putting green.
- At selected rates, both trinexapac-ethyl and paclobutrazol enhanced turf recovery after exposure to various freezing temperatures, but this occurred intermittently.
- At selected rates, paclobutrazol enhanced spring green up bermudagrass putting green.

Summary Text:

Managing bermudagrass (*Cynodon dactylon* × *C. transvaalensis*) on putting greens in the transitional climatic region poses agronomic and economic challenge for the golf industry. Winter stress remains a primary concern, limiting bermudagrass use and increasing the risk of winterkill. Mitigation approaches such as “priming,” which involve applying chemical or biological agents to enhance a plant’s innate stress-tolerance mechanisms, offer promising avenues for winter survival improvement. Previous research on cool-season turfgrass, such as annual bluegrass (*Poa annua* L.), has demonstrated the efficacy of certain plant growth regulators (PGRs) like mefluidide in improving winter survival (Laskowski et al., 2018). Similar potential is suggested for Type II PGRs (e.g., flurprimidol, paclobutrazol, trinexapac-ethyl) and other compounds like abscisic acid (ABA), and jasmonic acid, which have shown promise in improving winter survivability under ice cover in other species (Laskowski and Merewitz, 2020). However, limited information is available regarding the impact of plant growth regulators on bermudagrass winter survivability.

The objective of this study was to address these critical information gaps by evaluating a comprehensive suite of PGRs to develop a program that enhances the winter survivability of warm-season turfgrasses. The study was conducted on a 3-year-old ‘OKC3920’ bermudagrass putting green. The experimental design was a two-way factorial arrangement within a randomized complete block design (RCBD) with four replications. Individual plot size was 5 ft × 5 ft. The PGR treatments included Trinexapac-ethyl (Primo Maxx®), Ethephon (Proxy®), Prohexadione calcium (Anuew®), Paclobutrazol (Trimmit®), and an Untreated Control. Each

PGR was applied at three rates: 0.5X, 1X (labeled rate), and 2X of the manufacturer's recommended label rate for putting greens. Applications were made bi-weekly during two key seasonal windows: May-June (active growth) and August-early October (acclimation period). Applications were performed using a CO₂-pressurized boom sprayer calibrated to deliver 2 gallons per 1,000 sq. ft.



Figure 1. Application of plant growth regulator treatments to bermudagrass research plots using a CO₂-pressurized boom sprayer.

Data Collection: Visual fall color retention was assessed in autumn and spring green-up was evaluated in spring. In addition, a freeze chamber study was conducted to quantify the recovery after freeze stress when grasses were fully dormant. To do so, eight 1.5-inch diameter turf plugs were sampled from each treatment plot and transferred to cone-tainers. Plugs were then subjected to a controlled freeze test in a programmable freeze chamber. The chamber temperature was lowered linearly from 26.6°F at a rate of 1.8°F per hour, exposing samples to a soil temperature range of 23°F to 10.4°F. At predetermined target temperatures, samples were removed, thawed overnight at 35.6°F, and then transferred to a greenhouse for a 3-week recovery period. Percent green coverage of each plug was evaluated weekly for three weeks following the freeze treatment. Data were analyzed using Analysis of Variance (ANOVA), and treatment means were

separated using Fisher's Protected Least Significant Difference (LSD) test at a 5% probability level ($P \leq 0.05$).



Figure 2. Turf plug extraction from research plots in preparation for controlled freeze tolerance testing. Plugs were sampled in the field and were transferred to cone-tainers for the freeze test.

Results: At selected application rates, paclobutrazol enhanced the spring green-up of the OKC3920 bermudagrass putting green (data not shown). In freeze chamber trials, both paclobutrazol and trinexapac-ethyl intermittently improved turf recovery after exposure to various freezing temperatures, although results were inconsistent (Table 1). However, field observations during the growing season revealed phytotoxicity in paclobutrazol-treated plots. Therefore, future research should investigate the use of a safener or adjusted formulation to reduce phytotoxicity, potentially optimizing paclobutrazol's efficacy for improving freeze tolerance in bermudagrass.

Table 1. Effect of plant growth regulator (PGR) treatments on the post-recovery green coverage of ‘OKC3920’ bermudagrass following a controlled freeze cycle, Stillwater, OK, 2025.

	Temp	Control	Trinexapac-ethyl			Ethephon			Paclobutrazol			Prohexadione calcium		
			0.5X	1X	2X	0.5X	1X	2X	0.5X	1X	2X	0.5X	1X	2X
Week 1	-4	60.0 abc*	55.0 a-d	53.3 a-e	60.0 abc	40.0 b-k	38.3 b-k	45.0 a-h	55.0 a-d	46.7 a-g	63.3 ab	26.7 f-q	39.3 b-k	40.0 b-k
	-5	35.0 c-l	46.7 a-g	43.3 a-i	66.7 a	36.7 c-l	38.3 b-k	41.7 a-j	51.7 a-f	33.3 d-m	53.3 a-e	35.0 c-l	23.3 g-r	31.7 d-n
	-6	40.0 b-k	43.3 a-i	53.3 a-e	25.0 g-r	28.3 e-p	35.0 c-l	15 k-r	53.3 a-e	43.3 a-i	45.0 a-h	38.3 b-k	46.7 a-g	26.7 f-q
	-7	36.7 c-l	36.7 c-l	55.0 a-d	33.3 d-m	28.3 e-p	25.0 g-r	26.7 f-q	28.3 e-p	30.0 d-o	40.0 b-k	19.3 h-r	18.3 i-r	26.7 f-q
	-8	30.0 d-o	41.7 a-j	26.7 f-q	23.3 g-r	15.0 k-r	8.3 m-r	17.7 i-r	30.0 d-o	15.0 k-r	33.3 d-m	16.7 j-r	21.7 g-r	26.7 f-q
	-9	19.3 h-r	21.7 g-r	51.7 a-f	31.7 d-n	11.0 l-r	5.3 o-r	16.0 j-r	23.3 g-r	12.0 l-r	18.3 i-r	7.3 m-r	14.3 k-r	16.7 j-r
	-10	4.0 o-r	6.0 n-r	21.0 g-r	1.7 qr	2.0 qr	0 r	6.0 n-r	2.7 p-r	7.3 m-r	0 r	2.7 p-r	0.7 qr	0.7 qr
	-11	0.7 qr	1.7 qr	0 r	0 r	0 r	0 r	0 r	0 r	0 r	1.0 qr	0 r	0 r	0.3 r
Week 2	-4	69.7 a-c	68.3 a-d	68.3 a-d	71.7 ab	58.3 a-i	56.7 a-j	61.7 a-g	70.0 a-c	68.3 a-d	75.0 a	75.0 a	41.7 c-p	53.3 a-k
	-5	51.7 a-l	63.3 a-f	60.0 a-h	75.0 a	56.7 a-j	60.0 a-h	58.3 a-i	51.7 a-l	58.3 a-i	70.0 a-c	70.0 a-c	46.7 a-n	43.3 b-o
	-6	65 a-e	51.7 a-l	64.7 a-e	37.3 e-q	46.7 a-n	60.0 a-h	40.0 d-q	65.0 a-e	48.3 a-m	53.3 a-k	53.3 a-k	53.3 a-k	65.0 a-e
	-7	51.7 a-l	56.7 a-j	65.0 a-e	35.0 f-r	50.0 a-l	48.3 a-m	40.0 d-q	40.0 d-q	43.3 b-o	56.7 a-j	56.7 a-j	33.3 g-s	36.7 e-q
	-8	41.7 c-p	56.7 a-j	36.7 e-q	28.3 j-u	28.3 j-u	25.0 k-u	33.3 g-s	50.0 a-l	20.0 m-u	41.7 c-p	41.7 c-p	28.3 j-u	35.0 f-r
	-9	25.0 k-u	31.7 h-s	58.3 a-i	48.3 a-m	26.7 k-u	16.0 o-u	30.0 i-t	38.3 e-q	15.0 o-u	31.0 h-s	31.0 h-s	15.0 o-u	24.0 l-u
	-10	6.7 r-u	11.0 q-u	18.3 n-u	5.0 s-u	5.3 s-u	1.7 tu	12.7 p-u	5.0 s-u	14.3 o-u	1.7 tu	1.7 tu	6.0 r-u	5.0 s-u
	-11	1.7 tu	1.7 tu	1.7 tu	0 u	0.7 u	0 u	0 u	0 u	1.0 tu	1.0 tu	1.0 tu	0 u	0 u
Week 3	-4	73.3 a-i	85.0 a-c	73.3 a-i	88.3 a	68.3 a-k	71.7 a-i	65.0 a-m	83.3 a-d	80.0 a-f	86.7 ab	56.7 b-p	68.3 a-k	76.7 a-g
	-5	63.3 a-n	76.7 a-g	68.3 a-k	80.0 a-f	63.3 a-n	68.3 a-k	78.3 a-g	80.0 a-f	73.3 a-i	81.7 a-e	68.3 a-k	65 a-m	73.3 a-i
	-6	63.3 a-n	65.0 a-m	71.7 a-i	55.0 c-p	61.7 a-n	76.7 a-g	55.0 c-p	70.0 a-j	60.0 a-o	83.3 a-d	75.0 a-h	78.3 a-g	55.0 c-p
	-7	56.7 b-p	66.7 a-l	70.0 a-j	78.3 a-g	50.0 f-q	63.3 a-n	61.7 a-n	48.3 g-r	56.7 b-p	80.0 a-f	48.3 g-r	60.0 a-o	53.3 d-q
	-8	50.0 f-q	66.7 a-l	36.7 l-v	38.3 k-u	40.0 j-u	33.3 n-x	51.7 e-q	63.3 a-n	30.0 o-y	56.7 b-p	35 m-w	48.3 g-r	45.0 h-s
	-9	33.3 n-x	43.3 i-t	55.0 c-p	51.7 e-q	29.3 o-y	18.3 r-y	43.3 i-t	43.3 i-t	13.3 t-y	38.3 k-u	15.7 s-y	26.7 p-y	26.7 p-y
	-10	7.3 v-y	11.7 u-y	23.3 q-y	4.3 w-y	4.7 w-y	1.7 y	15.7 s-y	4.0 xy	15.0 s-y	1.0 y	6 v-y	6.3 v-y	2.7 xy
	-11	1.7 y	1.7 y	1.7 y	0 y	0.7 y	0.7 y	0 y	0 y	1.7 y	1.0 y	0 y	0 y	2.7 xy

*Means followed by same letter within a week are not significantly different from one another, according to Fisher’s protected LSD at $P = 0.05$

Reference Cited

Laskowski, K., K. Frank, and E. Merewitz. 2018. Chemical plant protectants and plant growth regulator effects on annual bluegrass survival of ice cover. *Journal of agronomy and crop science*, 205(2), 202-212.

Laskowski, K. and E. Merewitz. 2020. Chemical priming to improve annual bluegrass survival of ice encasement. *Agronomy Journal*, 112(6), 5002-5011.

USGA ID#: 2025-12-843

Title: The impact of light quality on putting green daily light integral (DLI) requirements

Project Leader: Dominic Petrella

Affiliation: University of Minnesota

Objectives: Examine how a reduction in the red to far-red (R:FR) ratio influences light requirements on a putting green

Start Date: 2025

Project Duration: 1

Total Funding: \$10,000

Summary Points:

1. The R:FR ratio influenced creeping bentgrass response to light intensity
2. Creeping bentgrass putting green plots responded better to low light intensity when the R:FR ratio was lower
3. At the lowest light intensities (90% reductions from full sun), a reduced R:FR ratio (0.46) increased turfgrass cover compared to a high R:FR ratio (1.20).

Summary Text: Plants shaded from foliage of trees and/or shrubs are exposed to both reductions in light intensity [photosynthetic photon flux (PPF)] and alterations to the quality of light (foliar shade), namely a reduction in the ratio of red to far-red light (i.e. R:FR ratio). Plants respond to reductions in PPF and the R:FR ratio using both related and different mechanisms. In some instances, plants respond better to reductions in PPF when the R:FR ratio is reduced, and vice versa. However, a majority of research examining the impact of shade on golf course surfaces only has imposed treatments that reduce the PPF. Because of this, management practices and/or cultivars developed using PPF reduction treatments may not respond accordingly to real-world foliar shade as light quality is also altered in these environments.

To better understand how alterations in the R:FR ratio impacts putting green quality we performed an experiment on a creeping bentgrass putting green ('Penn A4', USGA root zone) in summer 2025 with treatments that reduced light intensity by 0, 50, 80, or 90% with a R:FR ratio of ~1.0 (full sun, natural) or ~0.46 (moderate foliar-shade). This experiment was performed in Saint Paul, MN.

Plots were mowed 3 days per week at 0.125 inches, fertilized every 14 days with 0.10 lb./N via foliar urea, fungicide was applied on 7/24/25 (chlorothalonil), insecticide was applied on 7/31/25 (imidacloprid), and soil surfactant (Duplex) was applied monthly. Treatments were imposed on 4 ft. x 4 ft. plots with a combination of shade cloth and photoselective filters (Clearwater blue, Rosco) to achieve our desired light treatments (Table 1) from 8/13 – 8/28/25 (15 total days). A randomized complete block design with 3 replicates was used. Filters and cloth were taped under plexiglass to protect the photoselective from the water, dirt, and dust (Figure 1).



Figure 1: Photoselective filters and shade cloth taped under plexiglass

Table 1: Light treatment and their approximate properties measured via a quantum sensor and spectroradiometer.

Treatment	Average PPF reduction (%)	Average R:FR ratio
Plexiglass	10	1.20
Photoselective filter only (Clearwater blue)	50	0.46
40% neutral density shade cloth	50	1.20
Filter + 40% shade cloth	80	0.46
80% shade cloth	80	1.20
Filter + 80% shade cloth	90	0.46
60% shade cloth + 50% shade cloth	90	1.20

Two levels of control were used, a full sun control that had no plexiglass and a plexiglass control. Plexiglass reduced PPF by ~10% and did not alter turfgrass growth compared to the full sun control (data not shown). Light intensity was measured under all treatments within a replicate using a quantum sensor (Apogee SQ-100 and microcache data logger). These data were collected for replicate 1 on 8/12, replicate 2 from 8/13 – 8/14, and replicate 3 from 8/15-8/17. Spectral quality was spot checked near solar noon using a spectroradiometer (Apogee Insight) on 8/12 and 8/24/25. Data were collected prior to the start of the experiment, on 8/16 (3 days), 8/24 (11 days), and 8/28/25 (15 days). Data collection included visual turfgrass quality, RGB images to calculate percent green cover, turfgrass height using a prism gauge, and NDVI.

Light intensity reductions and the R:FR ratio exhibited interactions for all data collected. Turfgrass response to PPF reductions were dependent on the R:FR ratio. For example, for turfgrass height, plants exposed to a R:FR ratio of 0.46 and an 80% reduction in PPF etiolated much more in the first week of treatment compared to plots exposed to a R:FR ratio of 1.20 (Figure 2).

Turfgrass quality data showed that plots exposed to a 60% reduction in PPF performed worse when the R:FR ratio was reduced, but as the PPF reduction increased the situation reversed and a low R:FR ratio slightly improved turfgrass quality (Figure 3).

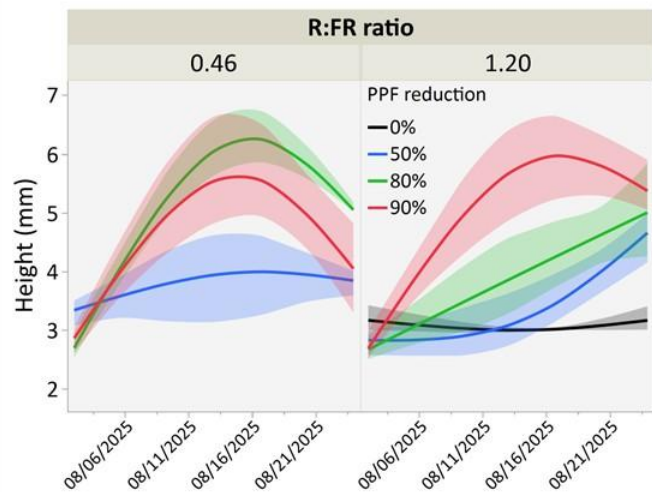


Figure 2: Turfgrass height over time as influenced by PPF reductions and the R:FR ratio.

For percent turfgrass cover, there was little difference between 1.20 and 0.46 R:FR ratios for 60% PPF reductions, but as the PPF reduction increased, a low R:FR ratio actually increased turfgrass (Figure 3).

Using percent turfgrass cover data from 8/28/25 (last day of treatment), we performed a 3-point logistic non-linear regression to examine how light requirements change due to the R:FR ratio (Table 2).

Inverse predictions using data from this regression show that plots exposed to a R:FR ratio of 0.46 require less light to maintain turfgrass coverage compared to a R:FR ratio of 1.20 (Table 2). These results only pertain to this short term (15 day) exposure to shade treatments, and the minimum light requirements would be expected to change from longer term exposure.

Overall, our results show how the R:FR ratio influences creeping bentgrass response to light intensity. In this specific case, a reduced R:FR ratio improved responses to reducing light intensity. This was with a R:FR ratio of 0.46, and these results may differ with a lower or higher R:FR ratio. Based on a previous experiment a R:FR ratio of ~0.18 did the opposite of what we observed here, and reduced turfgrass performance at a 90% PPF reduction compared to plots with a R:FR of 1.20.

Based on these results, future experiments should take into account the R:FR ratio in the foliar-shade environment they are trying to simulate, as it more than likely will influence their results.

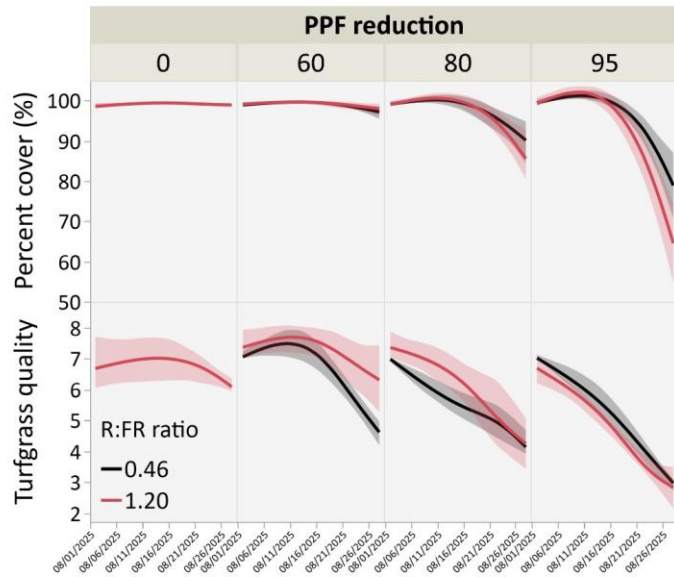


Figure 3: Change in turfgrass quality and percent cover (%) over time as influenced by PPF reductions and the R:FR ratio.

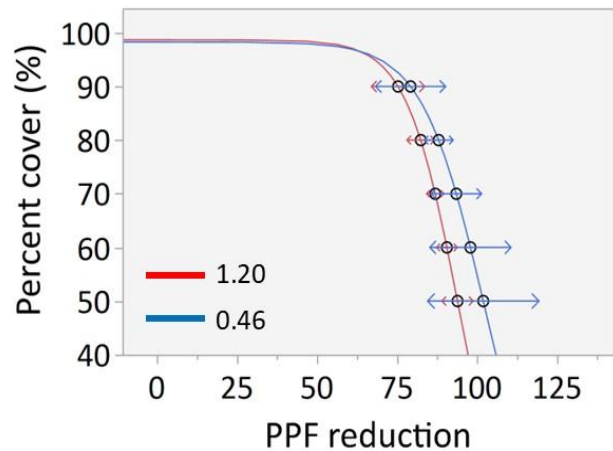


Figure 4: A 3-point logistic regression for percent turfgrass cover and the PPF reduction for both 1.20 (red) and 0.46 (blue) R:FR ratios. Arrows represent a 95% confidence interval for inverse predictions.

Table 2: Predicted PPF reductions that lead to 90, 80, 70, 60, and 50% turfgrass coverage for R:FR ratios of 1.20 or 0.46. Predicted Daily Light Integral (DLI) requirements are calculated based on an average August DLI for central Minnesota of $40 \text{ mol m}^{-2} \text{ d}^{-1}$. These predictions only represent stress from shade treatments for 15 days and do not necessarily indicate requirements for longer exposure.

Percent cover (%)	R:FR ratio	Predicted PPF reduction	Predicted Daily Light Integral (DLI) requirement
90	1.20	75.4 ± 4.3	10
	0.46	79.4 ± 5.6	8.4
80	1.20	82.5 ± 2.2	6.8
	0.46	88.1 ± 2.3	4.8
70	1.20	87.1 ± 1.4	5.2
	0.46	93.7 ± 4.0	2.4
60	1.20	90.7 ± 1.8	3.6
	0.46	98.1 ± 6.5	0.8
50	1.20	94.0 ± 2.5	2.4
	0.46	102.1 ± 8.9	0

USGA ID#: 2025-12-843 - PART 2

Title: The safety and efficacy of auxin transport inhibitors on creeping bentgrass putting greens

Project Leader: Dominic Petrella

Affiliation: University of Minnesota

Objectives: Examine how different auxin transport inhibitors impact a creeping bentgrass putting green when combined with gibberellin synthesis inhibitors

Start Date: 2025

Project Duration: 1

Total Funding: \$10,000

Summary Points:

1. None of the auxin transport inhibitors tested resulted in phytotoxicity in the creeping bentgrass used in these experiments, regardless of GA synthesis inhibitor they were combined with
2. Combinations with chlorflurenol led to improvements in turfgrass quality, green cover, color, and NDVI throughout the entire summer
3. Auxin transport inhibitors combined with Anuew and Primo reduced turfgrass height, but not with paclobutrazol

Summary Text: Auxins are plant hormones (phytohormones) that are involved in all aspects of plant growth and development and stress responses. In some instances, decreasing the transport or movement of auxins can be beneficial as these phytohormones can be negative regulators. For instance, auxins are considered one of the primary regulators of branching/tillering, but suppress tillering when in high concentrations in undeveloped tillers (i.e. the apical dominance phenomena). We've hypothesized that the application of auxin transport inhibiting chemicals could increase or maintain tillering of stressed creeping bentgrass, in particular thinning areas that are shaded. However, we currently do not know how safe auxin transport inhibitors are for creeping bentgrass putting greens, especially when applied in combination with standard gibberellin (GA) synthesis inhibiting plant growth regulators (PGRs).

Table 1: Treatments used in this experiment

Gibberellin synthesis inhibitor (Factor 1)	Auxin transport inhibitor (Factor 2)
None	None
Trinexapac-ethyl (Primo MAXX, 7 fl. oz./acre)	Solvent control (0.10% DMSO and 0.20% Tween-20)
Paclobutrazol (Pac-Low, 16 fl. oz./acre)	Chlorflurenol (Maintain CF 125) 10 µM
Prohexadione-Ca (Anuew EZ, 18 fl. oz./acre)	N-1-naphthylphthalamic acid (NPA) 10 µM
	2,3,5-triiodobenzoic acid (TIBA) 10 µM
	Chlorflurenol (Maintain CF 125) 100 µM
	N-1-naphthylphthalamic acid (NPA) 100 µM
	2,3,5-triiodobenzoic acid (TIBA) 100 µM

We designed an experiment to examine how three different auxin transport inhibitors (NPA, TIBA, and chlorflurenol) impact creeping bentgrass growth and quality during the summer months when combined with the three most common PGRs (trinexapac-ethyl, paclobutrazol, prohexadione-Ca). This experiment was performed on a creeping bentgrass putting green ('Penn A4', USGA root zone) during summer 2025 in Saint Paul, MN.

Plots were mowed 3 days per week at 0.125 inches, fertilized every 14 days with 0.10 lb./N via foliar urea, fungicide was applied on 7/24/25 (chlorothalonil), insecticide was applied on 7/31/25 (imidacloprid), and soil surfactant (Duplex) was applied monthly. Plots were treated on 7/18 and 8/3/25 using a CO₂ backpack sprayer (1.7 gallons/M, TeeJet 8006, 40 psi). The experiment was a 2-factor split-plot design with gibberellin synthesis inhibitor as the main plot with 3 levels and auxin transport inhibitor as the sub-plot with 8 levels (Table 1). Each auxin transport inhibitor was evaluated dissolved in dimethyl sulfoxide (DMSO) and diluted to a final concentration of 0.10% v/v DMSO. A non-ionic surfactant was added to all treatments at 0.20% v/v (Tween-20) due to adding this to the auxin transport inhibitor treatments. The combination of 0.10% DMSO and 0.20% Tween-20 was considered a solvent control and included with the factorial treatment combinations.

Data were collected pre-treatment (7/17), 7/27, 8/2 (15 days post app. 1), 8/10, 8/16, and 8/24/25 (21 days post app. 2). Data were collected for visual turfgrass quality, NDVI, turfgrass height using a prism gauge, and RBG images for percent green cover. Data were integrated over time using the area under the curve (AUC), and analysis of variance performed withing plant growth regulator treatment.

Both visual turfgrass quality and percent green cover data (Figure 1) showed that not only did the auxin transport inhibitors not lead to phytotoxicity, but in many instances increased turfgrass quality/cover. However, on their own (at the concentrations tested), auxin transport inhibitors did not show any change in turfgrass quality or cover.

The auxin transport inhibitors generally improved turfgrass quality/cover when mixed with Anuew, Paclobutrazol, or Primo MAXX. The concentration of the auxin transport inhibitor

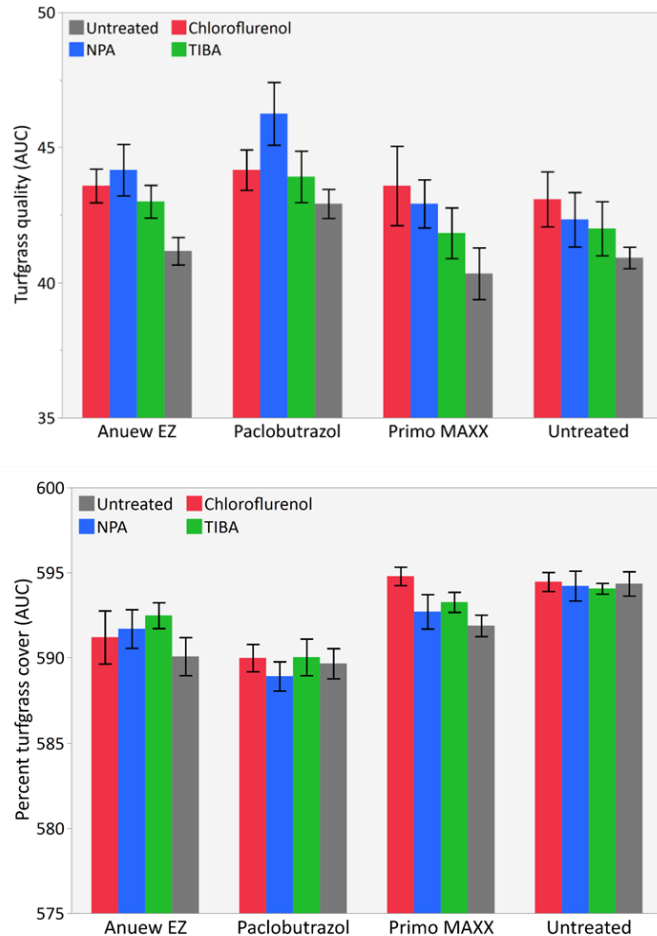


Figure 1: Turfgrass quality and percent green cover area under the curve (AUC) data for plots treated with plant growth regulators and auxin transport inhibitors. Error bars represent the standard error.

never showed an effect. Combinations with chlorflurenol led to the most consistent increase across the GA synthesis inhibitors tested, followed by NPA. Data for turfgrass color, both NDVI and DGCI (Figure 2) showed a similar trend with chlorflurenol improving turfgrass color, in particular with Primo.

When combined with GA synthesis inhibitors, auxin transport inhibitors also influenced creeping bentgrass growth. This was only significant for Anuew and Primo (both class A), but not paclobutrazol (class B). For Primo, the addition of NPA significantly reduced turfgrass height across time, and for Anuew, chlorflurenol led to the most significant decrease in height across time (Figure 3). There was no difference between 10 or 100 μ M for all auxin transport inhibitors, and because no negative effects were observed, higher concentrations could be tested in future research.

Overall, our results show potential value of combining auxin transport inhibitors with GA synthesis inhibitors. These mixtures were very safe in our experiment on ‘Penn-A4’, but cultivar and location could change this. Because of the safety and growth regulation effects, these combinations should be examined under different stresses; in particular, foliar-shade, in which the combination could improving tillering and carbon allocation.

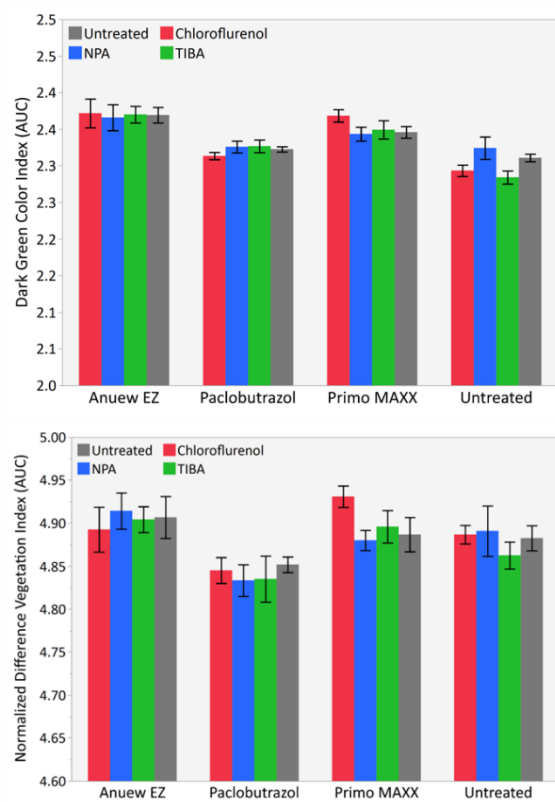


Figure 2: Dark green color index and normalized difference vegetation index area under the curve (AUC) data for plots treated with plant growth regulators and auxin transport inhibitors. Error bars represent the standard error.

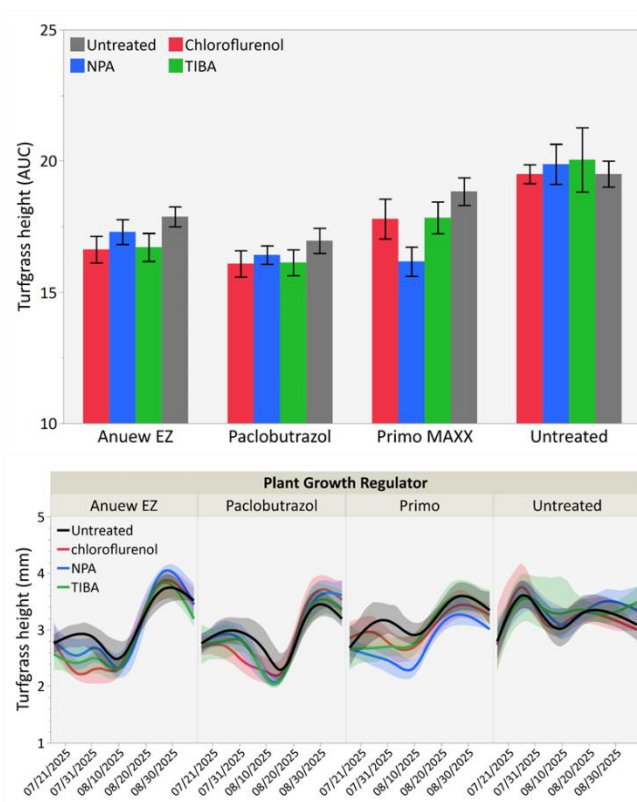


Figure 3: Turfgrass height and area under the curve (AUC) data and height data presented across time for plots treated with plant growth regulators and auxin transport inhibitors. Error bars and bands represent the standard error.

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.

Did not see green speed responses as in 2024 from PGR applications.

'Luminary' creeping bentgrass seems to provide some consistent results across higher nitrogen rates.

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.

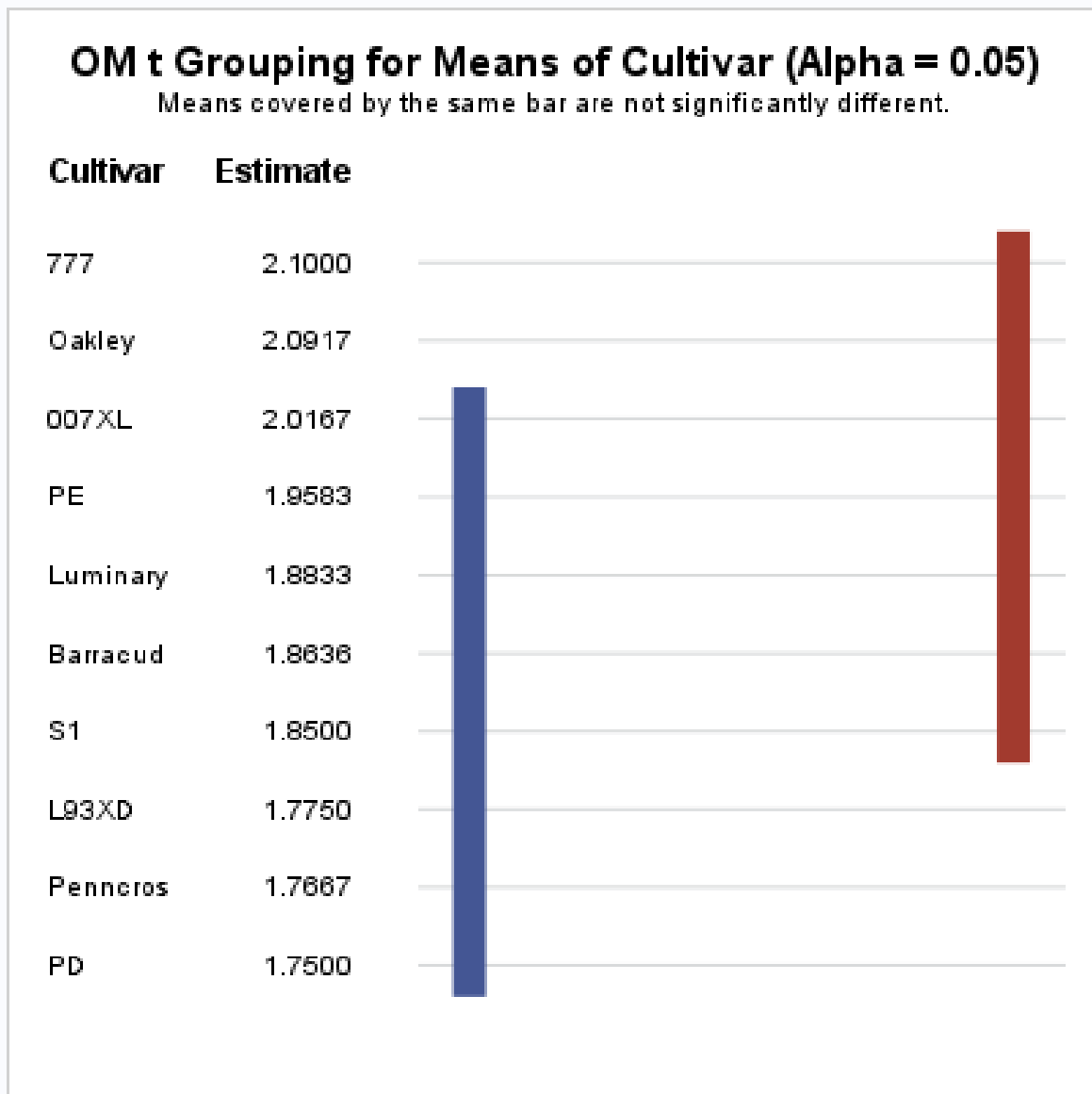
To date the research has shown that differences in responses to the nitrogen rates are seen across multiple parameters and between the cultivars. ‘Penncross’ which could still be considered the predominant creeping bentgrass cultivar in use across the United States clearly shows a need for higher rates of nitrogen as its various ratings and shear strength values (Figure 4) 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 (June 22, 2025).



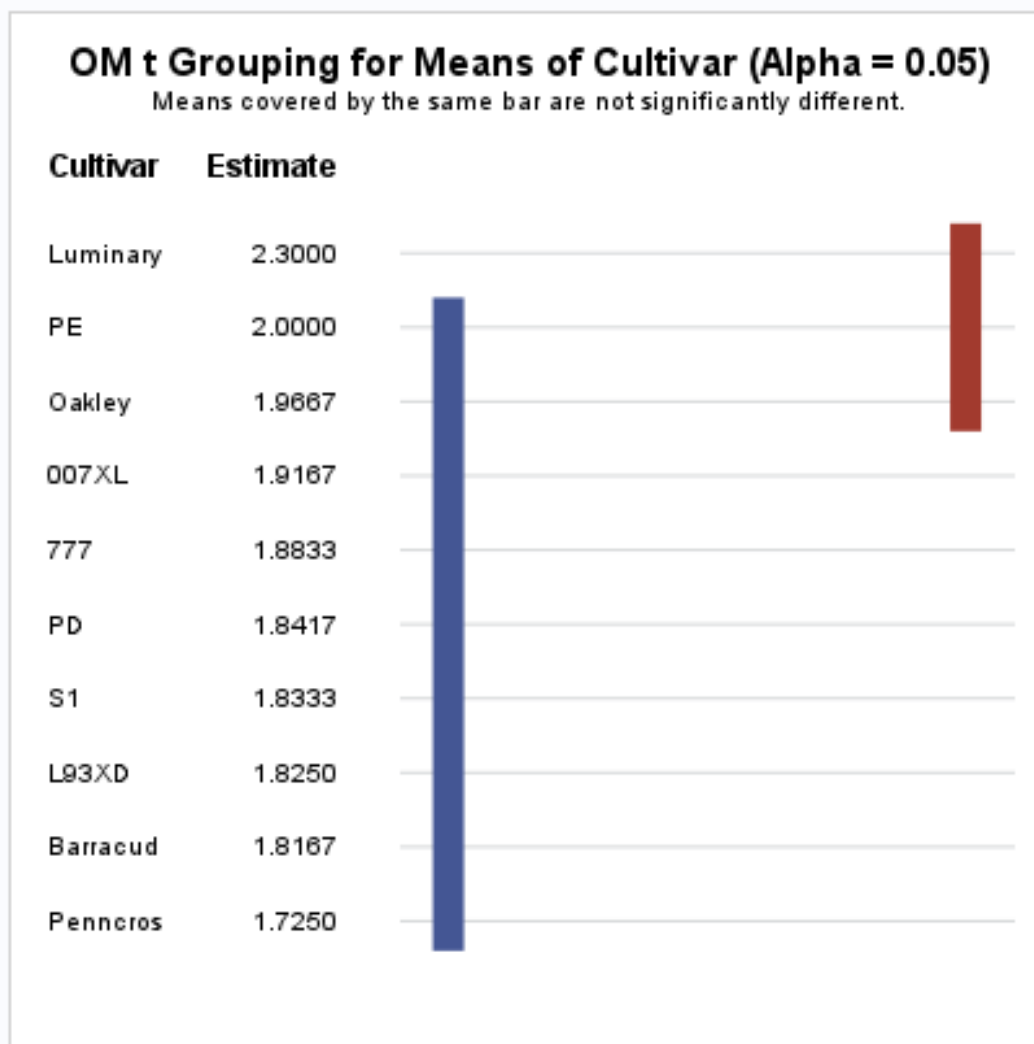
Differences between cultivars certainly occurred by the end of the 2025 trial period. At the highest nitrogen rate (2lbs/N per year) cv's '777' and 'Oakley' developed organic matter levels significantly higher than cv's 'L93XD' 'Penncross' and 'Pure Distinction' (Figure 1).

Figure 1. Organic matter levels in Creeping bentgrass *Agrostis stolonifera* cultivars that received 2lbs N annually in Wooster OH 2025.



However at the lower rates of nitrogen (0.5lbs/N per year) creeping bentgrass cultivar 'Luminary' produced significantly higher ($p=0.05$) levels of organic matter than 7 other cultivars including 'Penncross' 'S1' and others (Figure 2).

Figure 2. Organic matter levels in Creeping bentgrass *Agrostis stolonifera* cultivars that received 0.5lbs N annually in Wooster OH 2025.



Cultivars responded differently also in regards to playability. Creeping bentgrass cultivars ‘Pure eclipse’ and ‘L93-XD’ were found to provide significantly faster speeds compared to ‘Penncross and Luminary’ at 2lbs/N annually (Figure 3) with approximately 11ft in length while at 0.5lbs/N significantly higher green speeds were noted in ‘Pure Eclipse compared to all other cultivars (Figure 4).

Figure 3. Average green speeds for Creeping bentgrass *Agrostis stolonifera* cultivars that received 2lbs N annually in Wooster OH 2025.

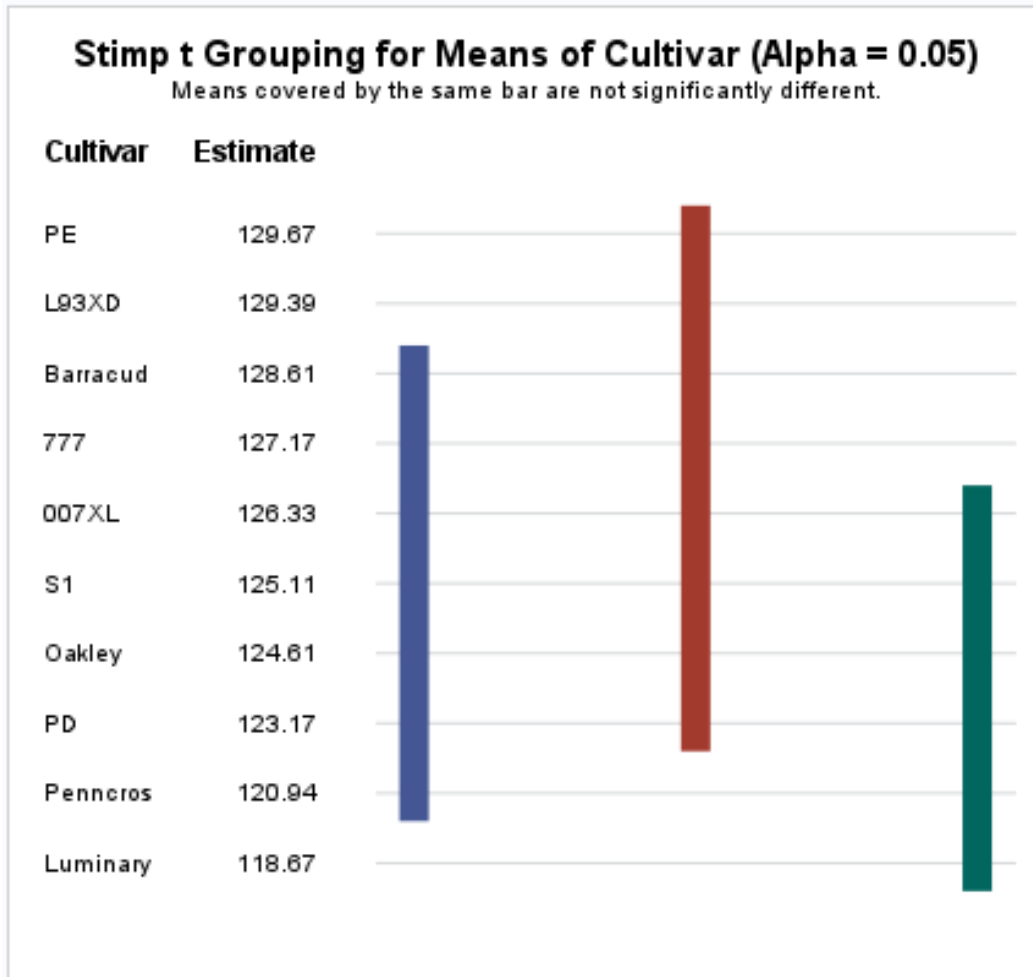
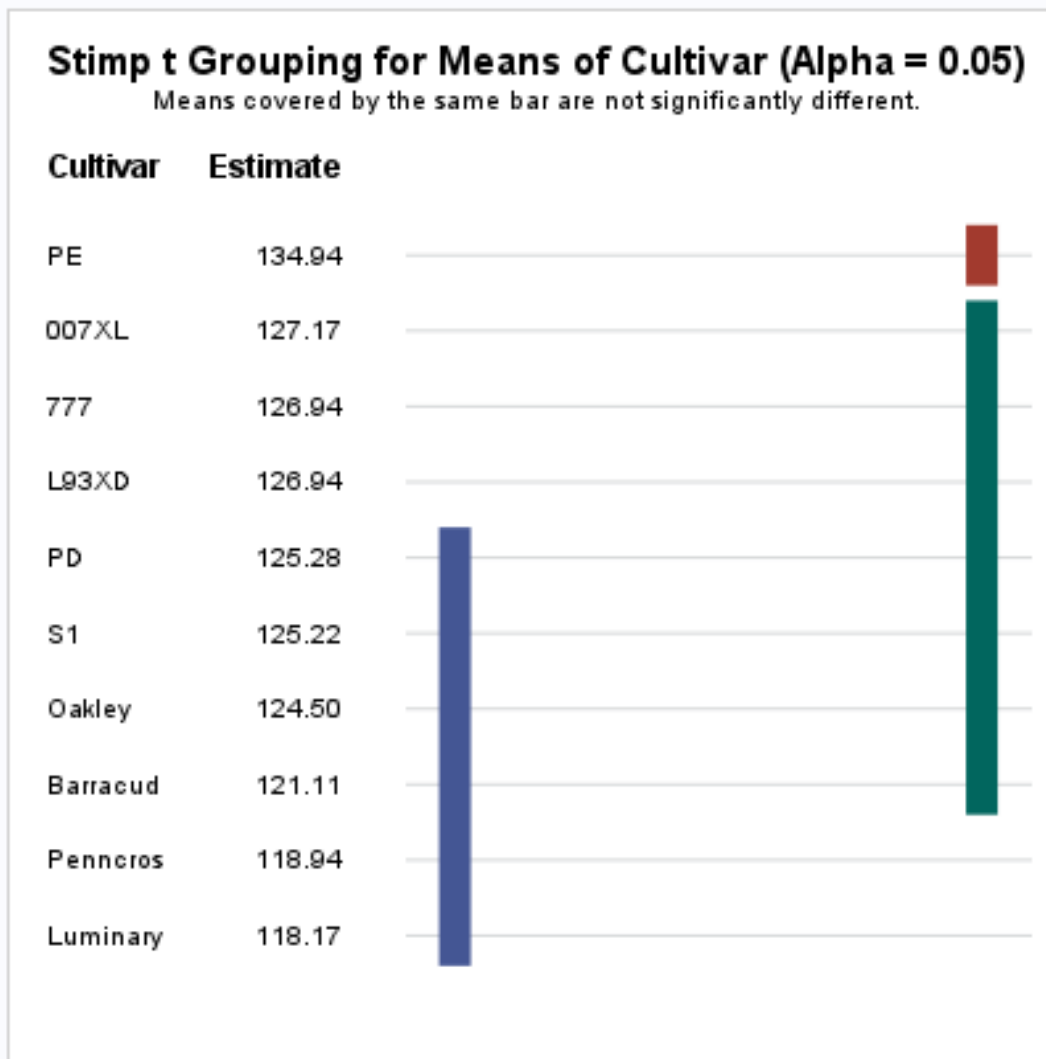


Figure 4 . Average green speeds (ln) for Creeping bentgrass *Agrostis stolonifera* cultivars that received 0.5lbs N annually in Wooster OH 2025.



Interestingly cultivar ‘Luminary’ provided significantly higher shear strength values at higher nitrogen rates (2lbs/N) (Figure 5) versus at lower nitrogen rates (0.5lbs/N) (Figure 6) indicating a possible benefit for a higher rate for that cultivar. Consistently low shear strength values were noted in ‘Penncross’ regardless of N rate.

Figure 5. Differences between cultivars in relation to shear strength data (Newtons) collected in Wooster OH during evaluation of bentgrass cultivars for responses to annual nitrogen rates of 2lb/N per year.

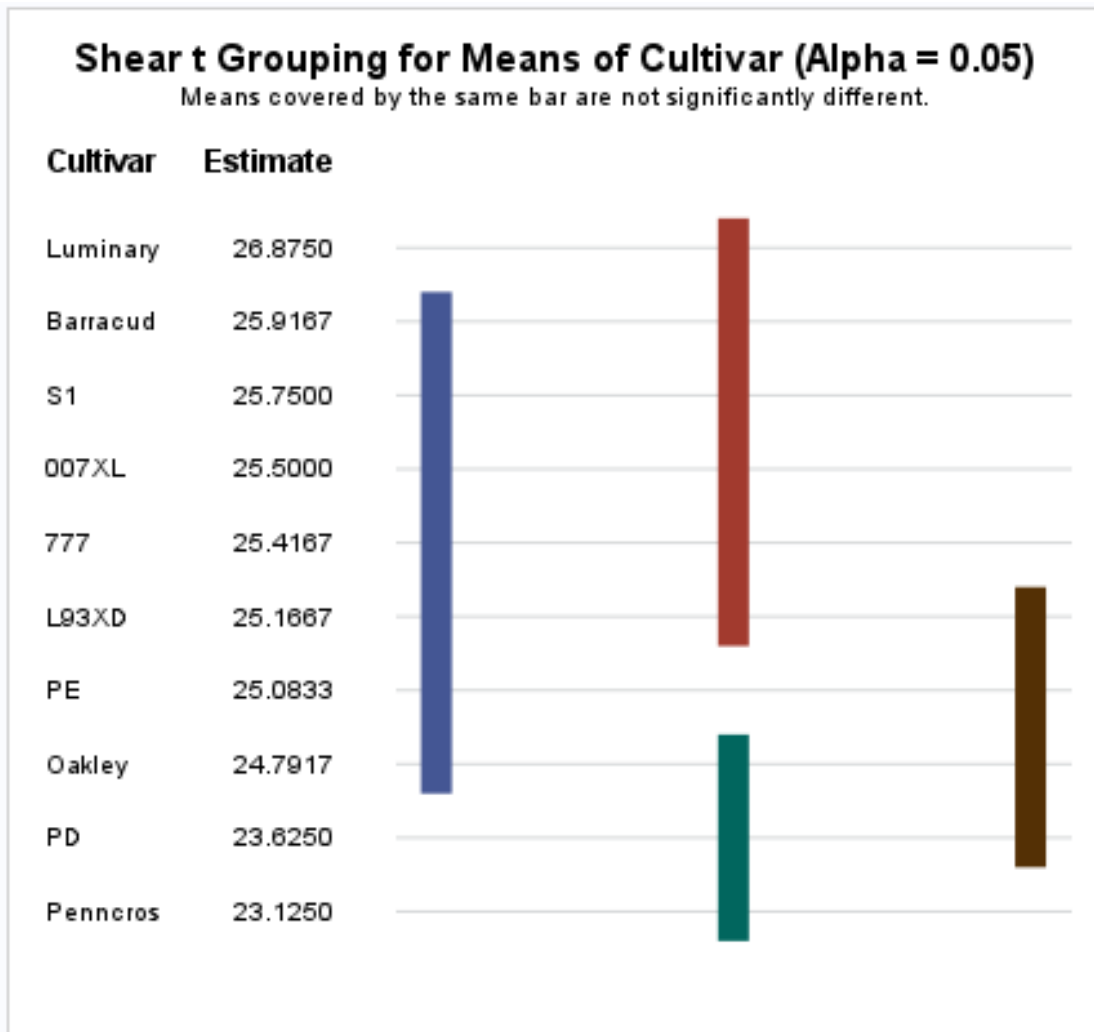
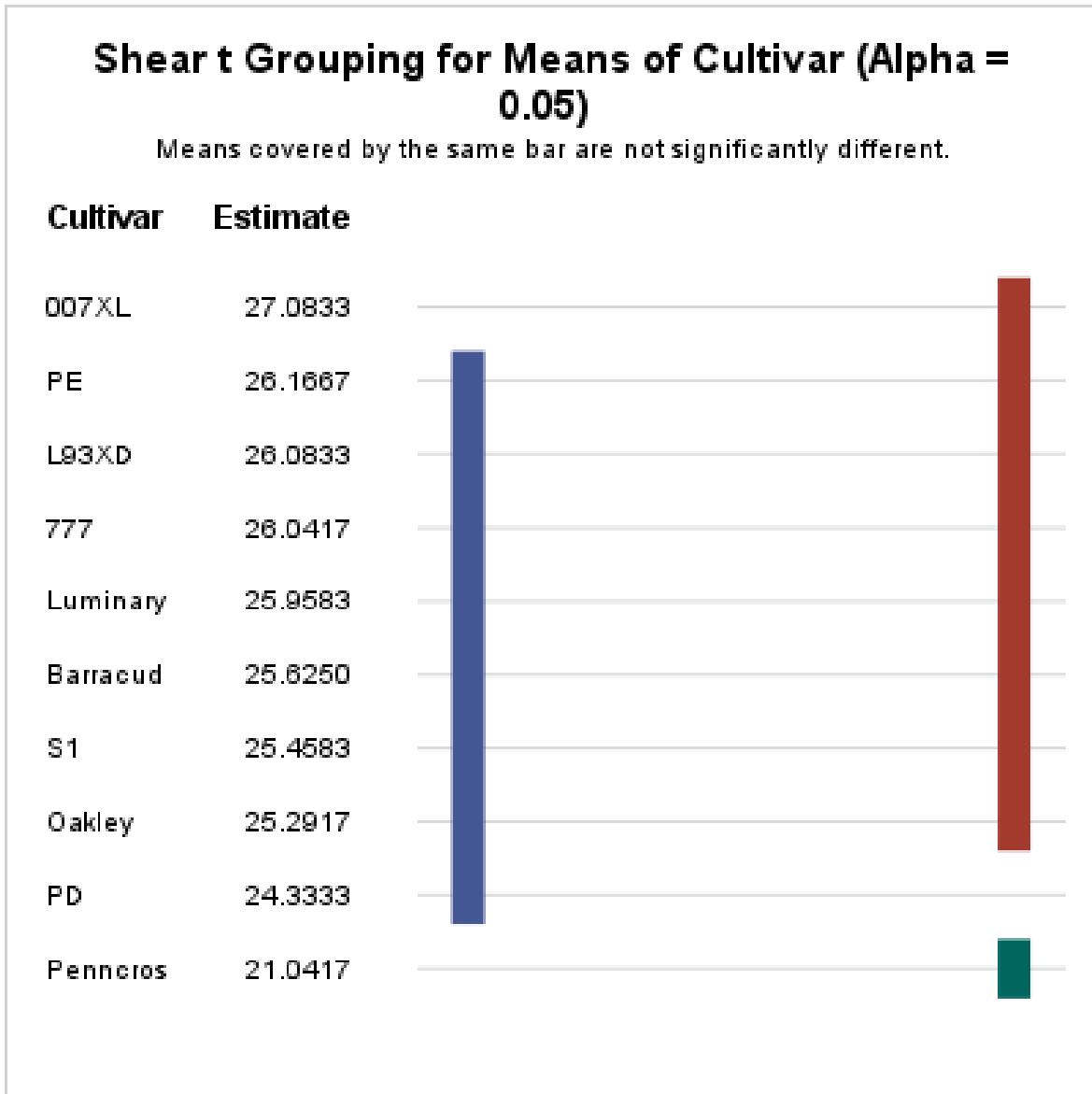
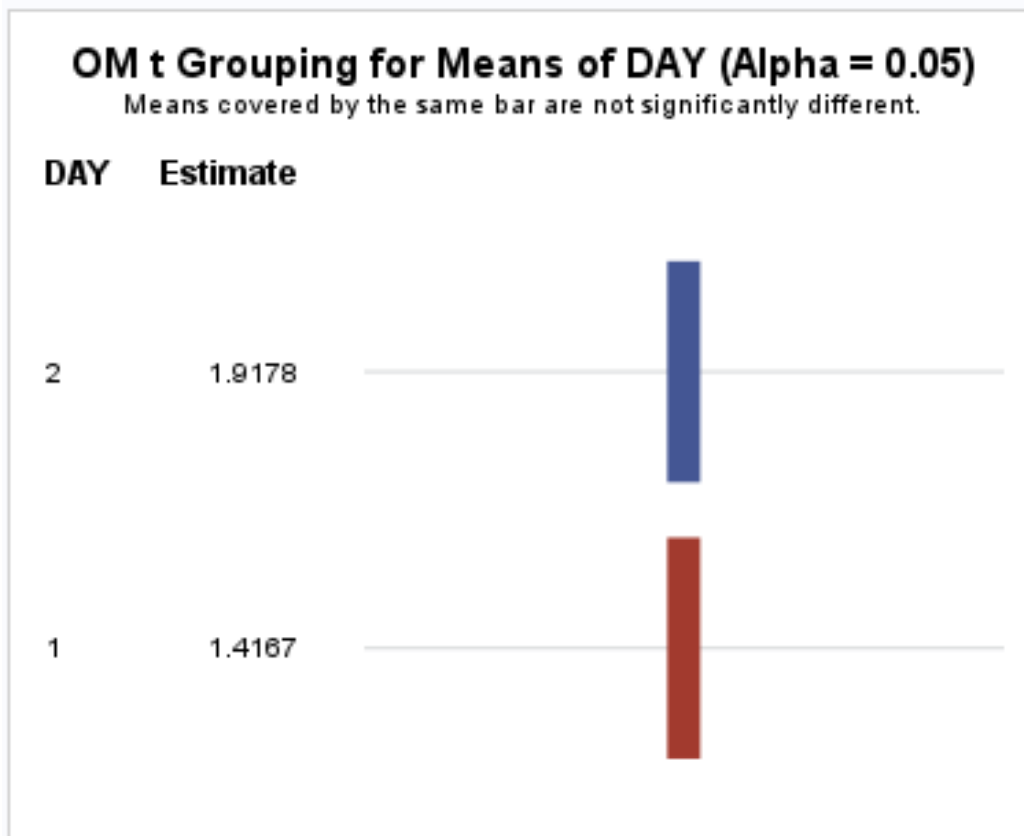


Figure 6. Differences between cultivars in relation to shear strength data (Newtons) collected in Wooster OH during evaluation of bentgrass cultivars for responses to annual nitrogen rates of 0.5lb/N per year.



The two sampling dates in 2025 were found to be significantly different with an approximate 0.5% difference between in organic matter values the start of the year and end of the season on average (Figure 7). Data was separately analyzed for the dates then – the 2nd date being at the end of the season.

Figure 7. Organic matter comparisons (%) between rating dates in Wooster OH Summer 2025 in Creeping bentgrass *Agrostis stolonifera* cultivars that received varying rates of nitrogen.



Growth regulator responses were not as clear as previous years with the untreated check providing similar shear strength data to the growth regulators used (Figure 8). Further to this without parsing N rates the untreated check actually provided higher greenspeeds compared to Anuew based on 2025 data collected (Figure 9).

Figure 8. Shear strength data for plant growth regulators applied in Wooster, OH Summer 2025 to Creeping bentgrass *Agrostis stolonifera* cultivars that received varying rates of nitrogen.

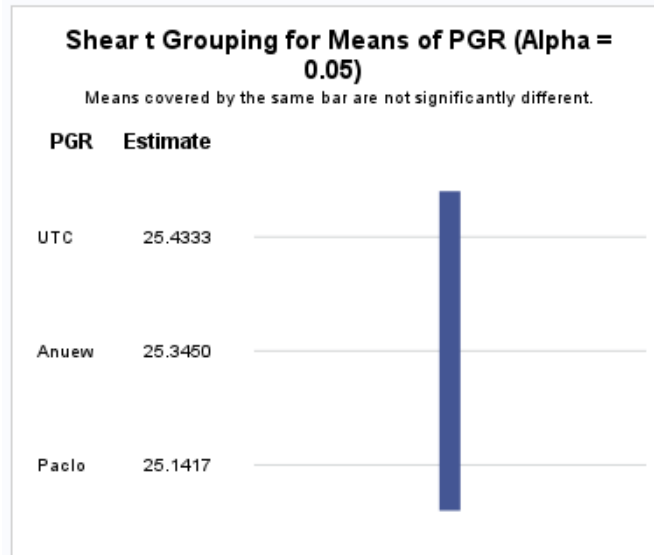
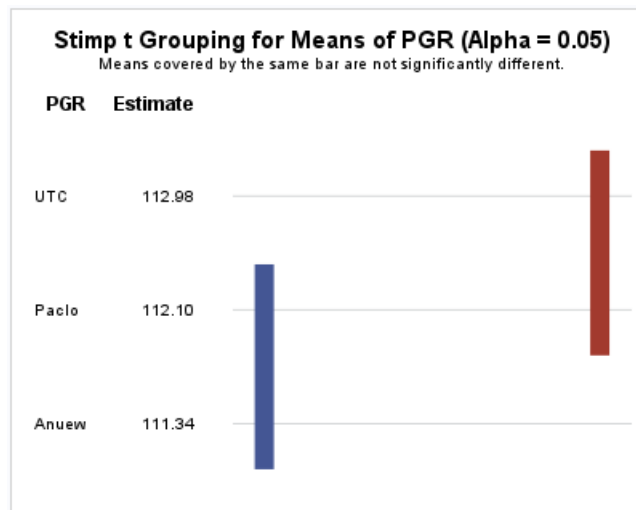


Figure 9. Green speed (ln) for plant growth regulators applied in Wooster, OH Summer 2025 to Creeping bentgrass *Agrostis stolonifera* cultivars that received varying rates of nitrogen



Current conclusions:

Penncross continues to underperform in a range of settings with what would be considered lower nitrogen rates

Creeping bentgrass cv. 'Luminary' may provide better responses at higher baseline nitrogen rates while not overproducing organic matter.

Green speeds not consistent compared to previous years with PGR use

Shear strength data as currently evaluated shows cultivars responding differently to different nitrogen rates.

The trial has been completed and work is ongoing with the aim of further analysis and to parse out differences with the aim of providing superintendents information with where they can start baseline annual nitrogen rates for these new cultivars. Further to this – the variation in response to growth regulators warrants a further area of look as well as trying to understand the rationale as to why turfgrass cultivars from the same species are accumulating organic matter differentially even when same nitrogen rates are applied.

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 Points:

- Tif3D and TifEagle achieved greater estimated percent cover during establishment than Mach 1.
- Celebration Dwarf, Tif3D, and TifEagle generally ranked highest for visual quality, percent green cover, and NDVI.
- Celebration Dwarf had the shortest ball roll distances and greatest surface penetration likely due to its higher growth rate.
- Celebration Dwarf's growth characteristics may require alternative management strategies for putting greens in Florida.

Summary Text:

Recent advances in turfgrass breeding have led to the release of several new commercially available bermudagrass cultivars. However, limited research has evaluated these materials with respect to putting green establishment, performance, and playability, particularly under Florida conditions. Therefore, the objective of this study is to compare three newly developed bermudagrass cultivars with a commonly used standard cultivar in terms of their establishment, performance, and playability on putting greens.

A three-year field study is being conducted at the University of Florida Plant Science Research and Education Unit in Citra, Florida. Four bermudagrass cultivars – Celebration Dwarf (Sod Solutions; Mississippi State University), Tif3D (University of Georgia), Mach 1, and TifEagle (included as the standard) – are being evaluated. All cultivars were established from sprigs at a uniform sprigging rate of 15 bushels per 1,000 ft² on August 13, 2024. Fertility is being managed according to UF/IFAS recommendations, and routine putting green maintenance practices (i.e., mowing, topdressing, aeration, irrigation, and applications of plant growth regulators and pesticides) are being performed throughout the study period. Pesticides are applied on an as-needed basis to prevent excessive damage. The cultivars were arranged in a randomized complete block design with four replications (Figure 1).

During the establishment phase (Year 1), data collection included monthly visual quality ratings, visually estimated percent cover, Normalized Difference Vegetation Index (NDVI), and digital images for digital image analysis (DIA) to quantify percent green cover. Measurements were taken throughout the growing season or until plots reached full establishment.

Following establishment (Years 2 and 3), data collection will consist of monthly visual quality ratings, NDVI, percent green cover, clipping dry weight, ball roll distance (Stimpmeter), and surface penetration/firmness (TruFirm). Additionally, divot recovery assessments will be conducted once during each of the second and third years. A standardized divot will be created within each plot, after which digital images will be

collected periodically to determine percent cover until complete recovery from injury is achieved (Figure 2).

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 results indicate a significant cultivar effect on estimated percent cover and clipping dry weight, as well as a significant cultivar \times date interaction for visual quality, percent green cover, NDVI, ball roll distance, and surface penetration/firmness. During the establishment phase, Tif3D and TifEagle exhibited greater estimated percent cover than Mach 1, whereas Celebration Dwarf did not differ significantly from any of the cultivars (data not shown). For clipping production, Celebration Dwarf and TifEagle produced greater clipping dry weight compared with Tif3D and Mach 1.

Overall, on rating dates where significant differences were observed, Celebration Dwarf, Tif3D, and TifEagle were generally grouped within the highest statistical category for turfgrass visual quality, percent green cover, and NDVI (Figures 3, 4, and 5). In contrast, Mach 1 was typically placed in the lowest statistical group for these parameters.

With respect to turfgrass performance metrics (i.e., ball roll and surface firmness), Celebration Dwarf consistently exhibited the shortest ball roll distances and the greatest surface penetration relative to the other cultivars (Figures 6 and 7). This response is likely attributable to the increased growth rate observed in Celebration Dwarf, which also contributed to more challenging thatch management. As a result, alternative management practices may be necessary for optimal putting green performance of this cultivar in Florida.

Analysis of divot recovery data is ongoing and will be reported in future updates. Turfgrass quality, cover, performance, and recovery will continue to be monitored, and the study is scheduled for completion on December 12, 2026.



Figure 1. Overview of the experimental site during establishment.



Figure 2. Example of the divot created for the recovery portion of the trial.

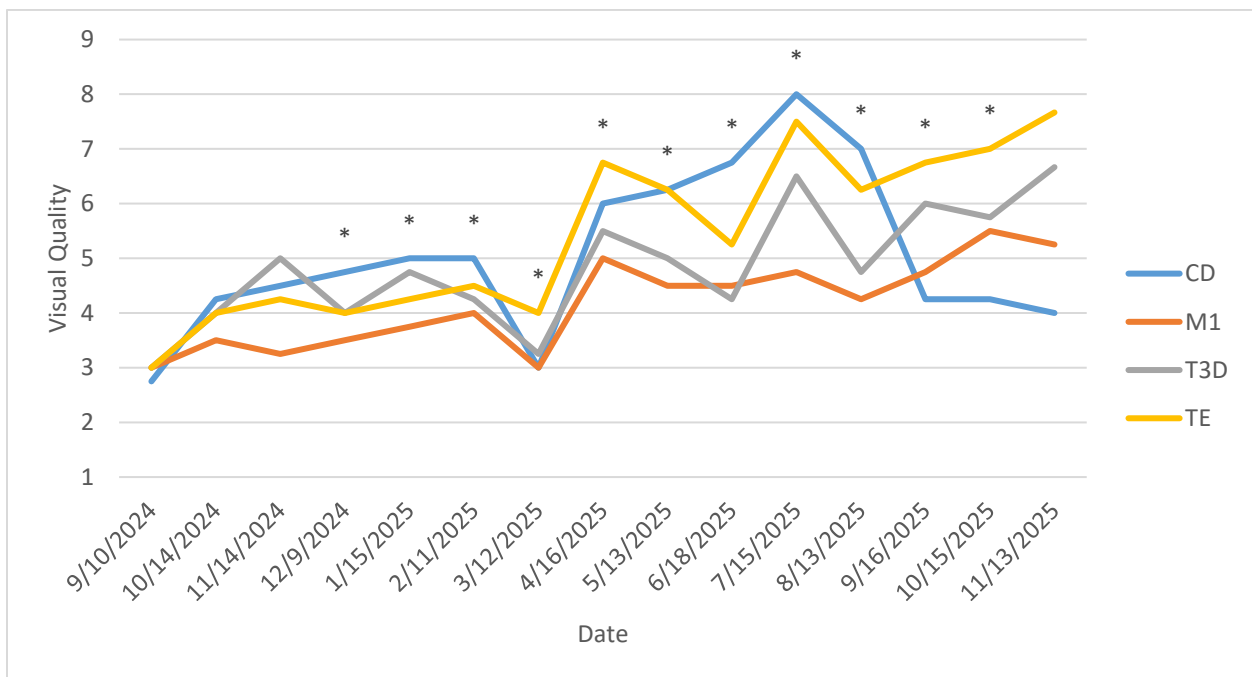


Figure 3. Bermudagrass cultivars visual quality (1-9, 6 minimally acceptable). * Indicates significant differences for cultivar means within a rating date according to Fisher's least significant difference (LSD) ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

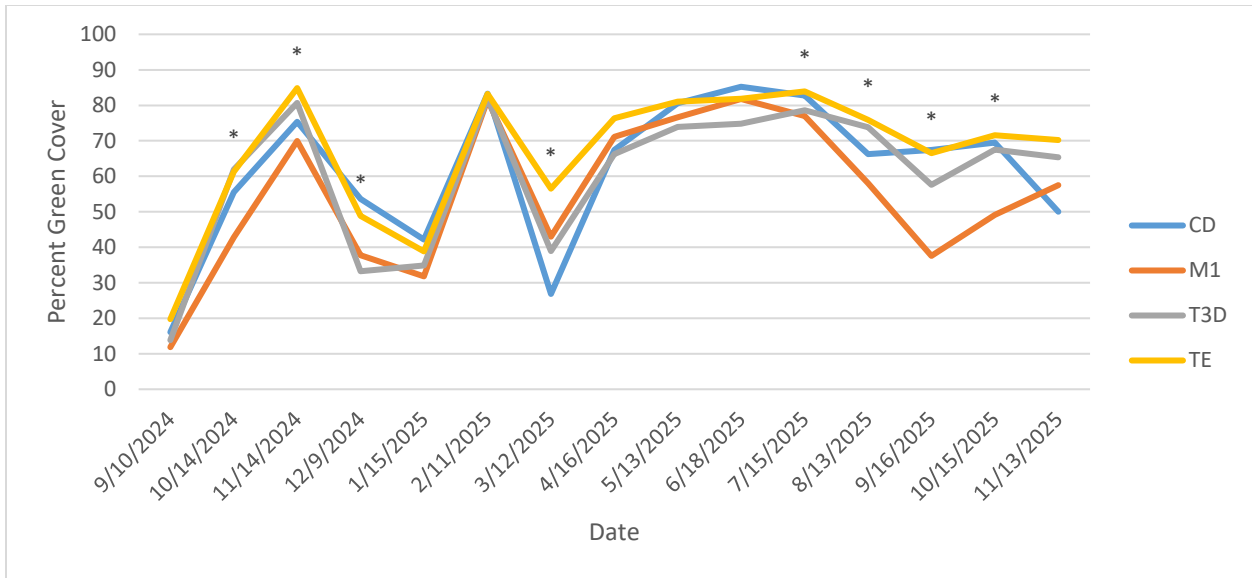


Figure 4. Bermudagrass cultivars percent green cover. * Indicates significant differences for cultivar means within a rating date according to Fisher's least significant difference (LSD) ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

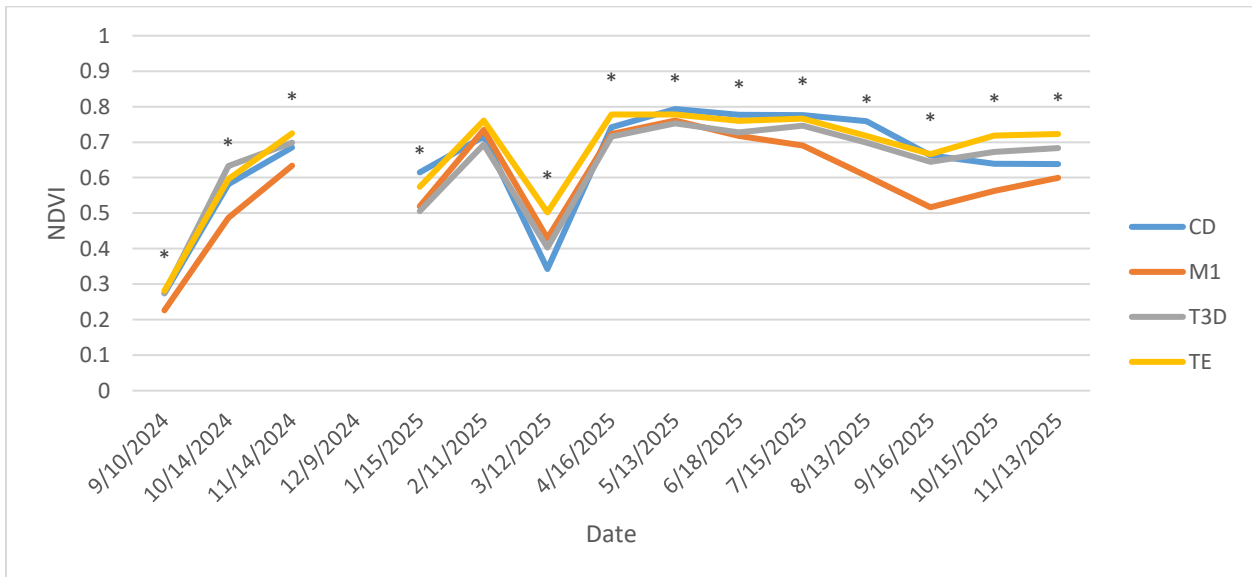


Figure 5. Bermudagrass cultivars Normalized Difference Vegetation Index (NDVI; 0-1). * Indicates significant differences for cultivar means within a rating date according to Fisher's least significant difference (LSD) ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

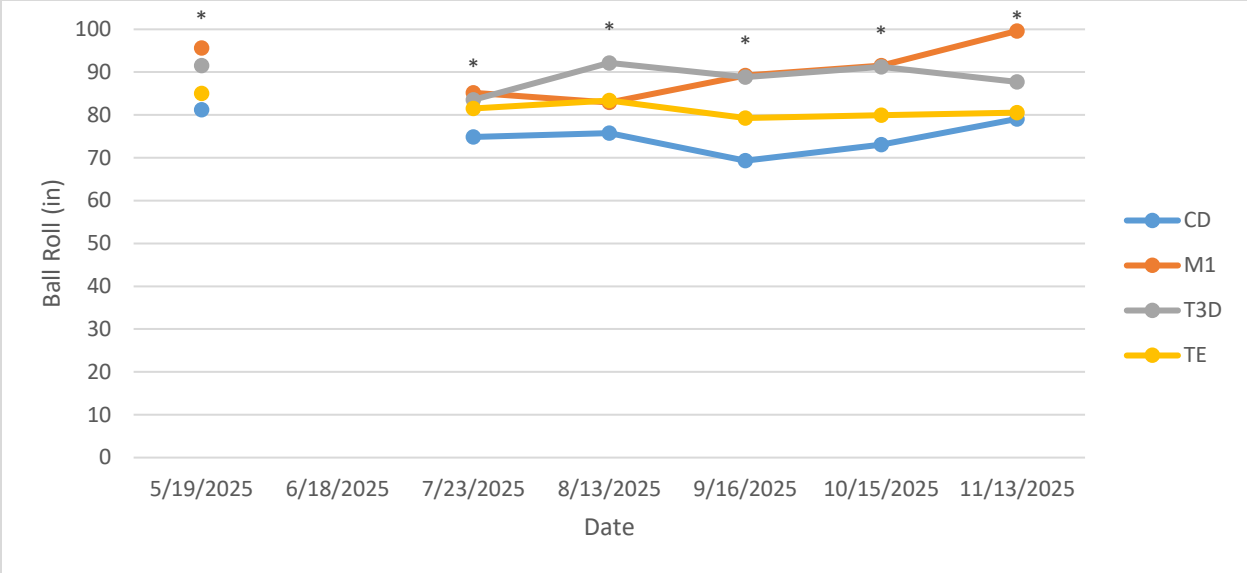


Figure 6. Bermudagrass cultivars average ball roll (in). * Indicates significant differences for cultivar means within a rating date according to Fisher's least significant difference (LSD) ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

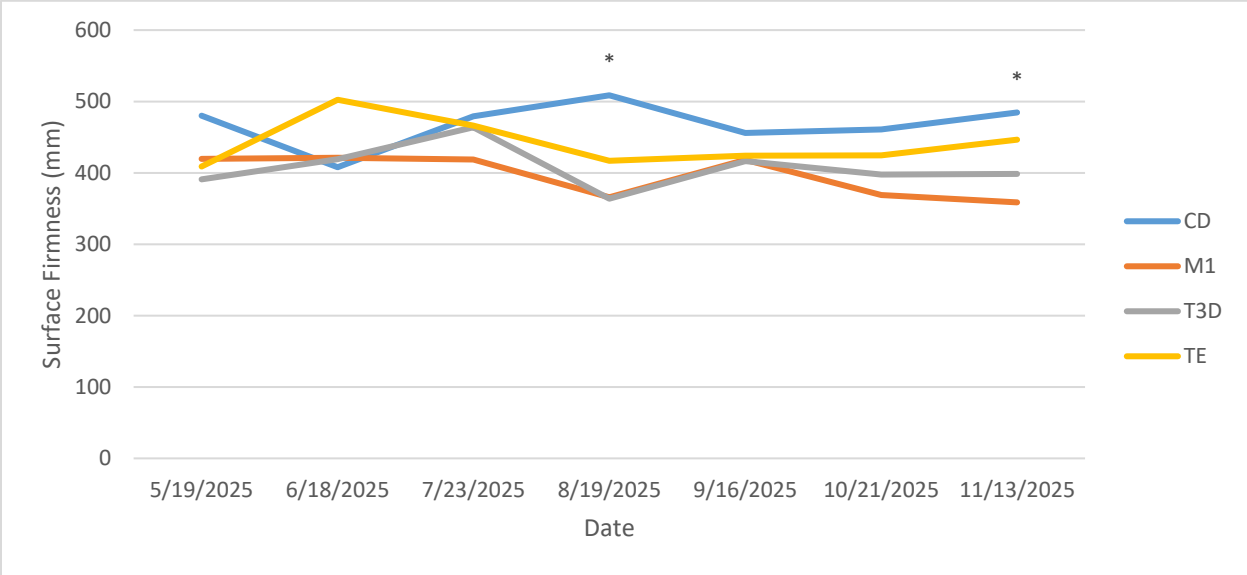


Figure 7. Bermudagrass cultivars average surface firmness (mm). * Indicates significant differences for cultivar means within a rating date according to Fisher's least significant difference (LSD) ($p \leq 0.05$). Cultivars: CD, Celebration Dwarf; M1, Mach 1; T3D, Tif3D; TE, TifEagle.

USGA ID#: 2025-15-846

Title: RAPID DETECTION AND SCOUTING OF TURFGRASS MITES USING PEST TECHNOLOGY

Project Leader: Muhammad Z. “Zee” Ahmed

Affiliation: Clemson University, Department of Plant & Environmental Sciences, Pee Dee Research and Education Center

Start Date: 2025

Project Duration: 2 years

Total Funding: \$10,000

Objectives:

1. Conduct a comprehensive sampling of eriophyid turfgrass mites, including bermudagrass mites, using a modified Pest Detection Device (PDD) / AirDNA system.
2. Perform morphomolecular identifications of eriophyid mites collected from filters.

Summary Points

- AirDNA filters (Jonah Ventures) successfully captured *Eriophyes cynodoniensis* under controlled airflow conditions, validating the feasibility of airborne eriophyid mite detection.
- DNA extracted from filter-captured mites produced amplifiable COI barcode fragments, confirming compatibility with morphomolecular identification workflows.
- A complete field-ready prototype (frame, fans, stands) was designed, assembled, and validated for operational stability (Figure 1).
- A heat-induced funnel extraction method was developed to isolate and quantify live mites, improving accuracy for future efficacy trials (Figure 2).
- No USGA funds were used in 2025; all expenses were covered by startup funds.
- The project is positioned for full field deployment in 2026.

Summary Text (2025 Progress Report)

Bermudagrass mites (*Eriophyes cynodoniensis*) remain one of the most difficult turfgrass pests to detect due to their extremely small size, cryptic feeding behavior, and tendency to leave feeding sites before symptoms appear. Their rapid life cycle, sometimes as short as five days, allows populations to increase quickly, making early detection essential for effective management. The original proposal outlined a strategy to adapt a simple, airflow-based Pest Detection Device (PDD), previously successful in capturing phantasma scale crawlers, for detecting eriophyid mites. The 2025 work focused on validating the approach's feasibility, establishing molecular workflows, and constructing a field-ready prototype for 2026 deployment.

Rationale

The handmade PDD used in earlier work successfully captured phantasma scale crawlers, which adhere to filter paper due to their legs and setae. Eriophyid mites possess similar hair-like structures (tubercles and setae), suggesting they may adhere even more readily to filter surfaces. Recent work by Jonah Ventures (2024) demonstrated that their AirDNA system can capture wind-dispersed mites and hundreds of other invertebrates, providing a commercially

manufactured analog to the PDD. This project integrates the strengths of both systems to create a practical, field-deployable tool for early detection of bermudagrass mites and potentially other eriophyid species.

Methodology and Progress to Date

1. AirDNA Filter Acquisition and Laboratory Validation

AirDNA filters were acquired in November 2025. Because eriophyid mites are among the smallest plant-feeding arthropods (Sabelis & Bruin 1996), the first priority was to determine whether the filters could physically retain them. Using a controlled airflow setup with a portable exhaust fan, individual *E. cynodontiensis* mites were placed in front of the filter (Figure 1). Capture was immediate and repeatable, with no evidence of mites bypassing or penetrating the filter matrix. This confirms that the AirDNA system is suitable for capturing eriophyid mites, validating a central assumption of the proposal.

Following capture, mites were preserved in ethanol and processed using a modified DNeasy Blood and Tissue Kit protocol (Dabert et al. 2008). DNA extracted from the filters produced amplifiable COI barcode fragments using both LepF1/LepRI (Hebert et al. 2004) and LCO1490/HCO2198 (Folmer et al. 1994) primer sets. This demonstrates that the filter substrate does not inhibit extraction and that captured mites remain suitable for morphomolecular identification.

2. Prototype Construction for Field Deployment

A field-ready prototype was constructed to support 2026 sampling. The system includes:

- a rigid, lightweight frame,
- a fan assembly capable of stable, continuous airflow, and
- adjustable stands for variable canopy heights.

Structural components are shown in Figure 2. The prototype is modular, durable, and designed to operate for 4–6 hours per sampling event, consistent with the original proposal.

3. Development of a Live-Mite Extraction Method

Although not explicitly required in the original proposal, a heat-induced funnel extraction system was developed to isolate live mites from infested turfgrass material. This method separates live from dead mites and produces clean, quantifiable samples, as reported in the literature. Because viability-based counts are essential for interpreting efficacy trials, this addition strengthens the project's ability to generate biologically meaningful data.

4. Comparison to Original Proposal

The 2025 work aligns closely with the proposed objectives:

- The feasibility of airborne eriophyid mite capture has been confirmed.
- Molecular identification workflows have been validated.
- A field-ready sampling system has been constructed.

The only deviation from the original timeline was a delay in hiring a technician and onboarding a new graduate student. These delays did not affect the quality of foundational work, and the project remains on schedule for 2026 field sampling.

5. Future Expectations

Field deployment will occur in May–June 2026 at 2–3 locations in South Carolina, consistent with the proposal’s sampling window. At each site, 12 filters in the devices will be placed at varying distances (approximately 0.25 miles apart) from infested areas and operated for 4–6 hours. Filters will be preserved in ethanol and processed using the validated COI barcoding workflow.

The 2026 work will focus on:

- quantifying detection rates across distances,
- comparing AirDNA detection with destructive sampling and live-mite extraction,
- evaluating the device’s potential for detecting other eriophyid species, and

Successful completion of this project will provide turfgrass managers with a practical early-warning tool for bermudagrass mites, improving timing of abamectin applications, reducing unnecessary chemical use, and lowering the risk of resistance development.

Figure 1: Structural components and operational configuration of the field-ready airflow prototype. (A–C) External views of the frame, fan assembly, and dual-filter mounts. (D–E) Close-up views of the filter surface and a dead mite recovered during airflow testing to verify laboratory assimilation procedures.

Figure 2: Heat-induced funnel extraction system developed to isolate and quantify live arthropods from infested plant material. (A) External view of the assembled extraction unit. (B) Internal configuration showing the suspended funnel and collection chamber. This system improves accuracy for future efficacy trials by enabling consistent recovery and enumeration of viable individuals.

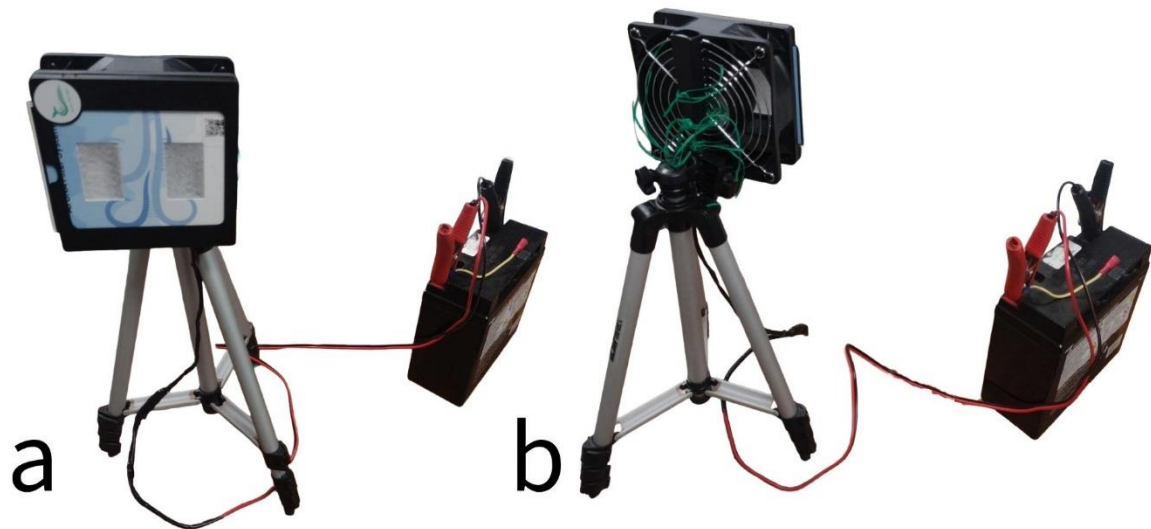


Figure 1

USGA ID#: 2025-08-839

Title: Meta-analysis to address USGA strategic initiatives

Project Leader: Keenan Amundsen

Affiliation: University of Nebraska-Lincoln

Objectives: Conduct a meta-analysis to cluster relevant texts to each of the four primary 2024 USGA strategic initiatives. The texts relevant to the priority areas will be analyzed using natural language processing and other methods. The objectives are to 1) compare and evaluate different sets of source documents including research reports, abstracts, refereed manuscripts, methods and results sections, and web resources; 2) identify research specific to USGA strategic initiatives; 3) extract and report on common methodology and results; and 4) develop publicly available workflows to support others in doing similar research.

Start Date: 2025

Project Duration: 3 years

Total Funding: \$120,633

Summary Points:

- There continues to be significant growth in turf-related research and trade journal articles
- Clustering methods can help identify articles with similar themes.
- Natural language processing methods can be used to extract sentiment and specific phrases from texts.

Summary Text: Turfgrass management is supported by a vast body of literature spanning popular press articles, trade journals, and peer-reviewed research publications. A simple web-based search for turf-related terms yields thousands of references, illustrating the breadth of available information but also the complication of navigating the information for useful content. The Turfgrass Information Center houses the largest publicly accessible collection of turfgrass research and educational materials. A targeted search of the Turfgrass Information Center database using keywords “turfgrass,” “turf management,” and “golf course management” returned 6,573 records over the past 20 years, including refereed articles, reports, proceedings, and professional trade publications (Figure 1). The results from the Turfgrass Information Center are a significant improvement over web-based searches, but there remains a significant challenge of extracting insights from individual reports; the process can take significant time.

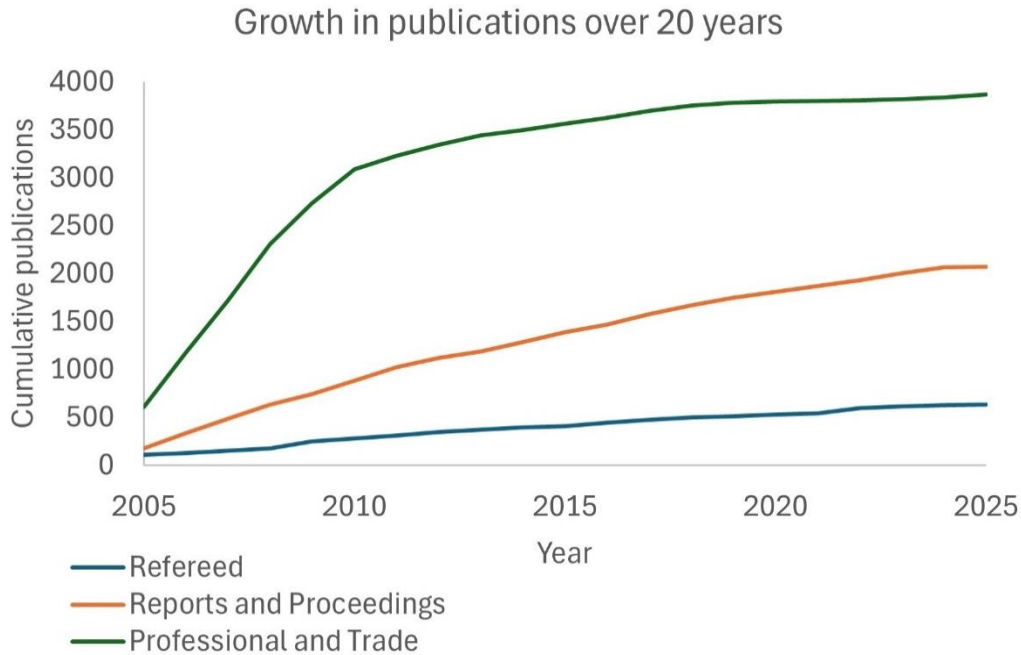


Figure 1 Cumulative growth of turf-related publications over the past 20 years.

The narrower curated sets of articles, like those identified through the Turfgrass Information Center databases typically return more relevant information, whereas larger collections introduce substantial noise, making it difficult to identify practical recommendations. This project addresses that challenge by applying contemporary computational language processing techniques to organize and analyze turf-related texts. The project goal is to cluster articles into meaningful groups, reduce the search space, and extract targeted information aligned with USGA research priorities.

The workflow for this project (Figure 2) consists of several key steps. Turf-related publications from diverse sources will be identified following database searches. The publications will be harmonized to ensure consistent formatting of data which helps prevent introduction of any bias into the analysis. The texts will be broken up into individual words and phrases (tokenized) to facilitate computational analysis. Natural language processing methods will be used to identify common words, phrases, and patterns across texts. Texts with shared tokens will be clustered which will create smaller, more manageable subsets of the texts for further analysis. Treatment, results, and other types of information will be extracted to inform turf managers about optimal turf management practices.

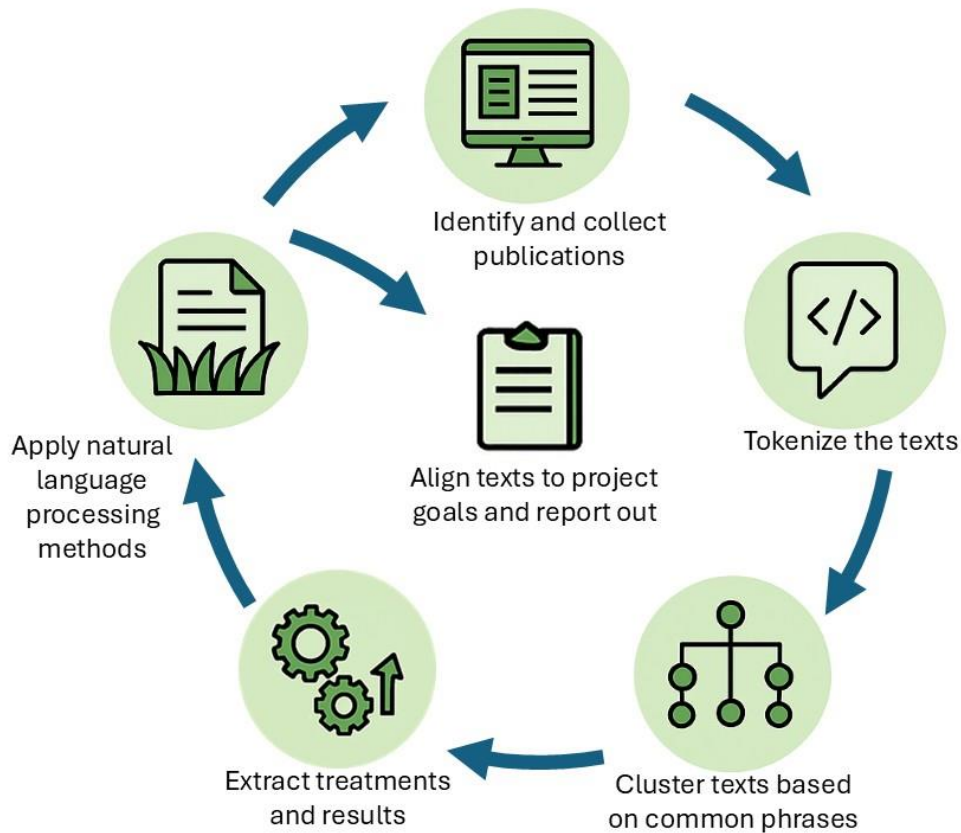


Figure 2 Natural language processing workflow to extract relevant turf information.

To test the workflow, a comparison was made between turf trade journal articles and lifestyle publications covering turf-related topics. Monthly issues of select trade journals were downloaded from the Turfgrass Information Center database, and editorial content was extracted to minimize noise. Lifestyle articles were obtained via direct URLs from major magazines. All texts ($n = 2,830$) were cleaned, converted to plain text, and harmonized for consistency. The cleaned texts were tokenized, and the natural language processing sentiment-based lexicon scoring approach was applied to classify words as negative, neutral, or positive. Results show that trade journals generally maintain a neutral tone, while lifestyle publications had a broader sentiment range (Figure 3).

A MetaTurf Github repository was created. Github is a website that is useful for storing and managing code and workflows. The MetaTurf repository will be made available at the conclusion of the project and will house all workflows associated with this project. Ultimately, these methods will help others to access targeted, evidence-based recommendations efficiently, supporting informed decision-making and advancing turfgrass management practices.

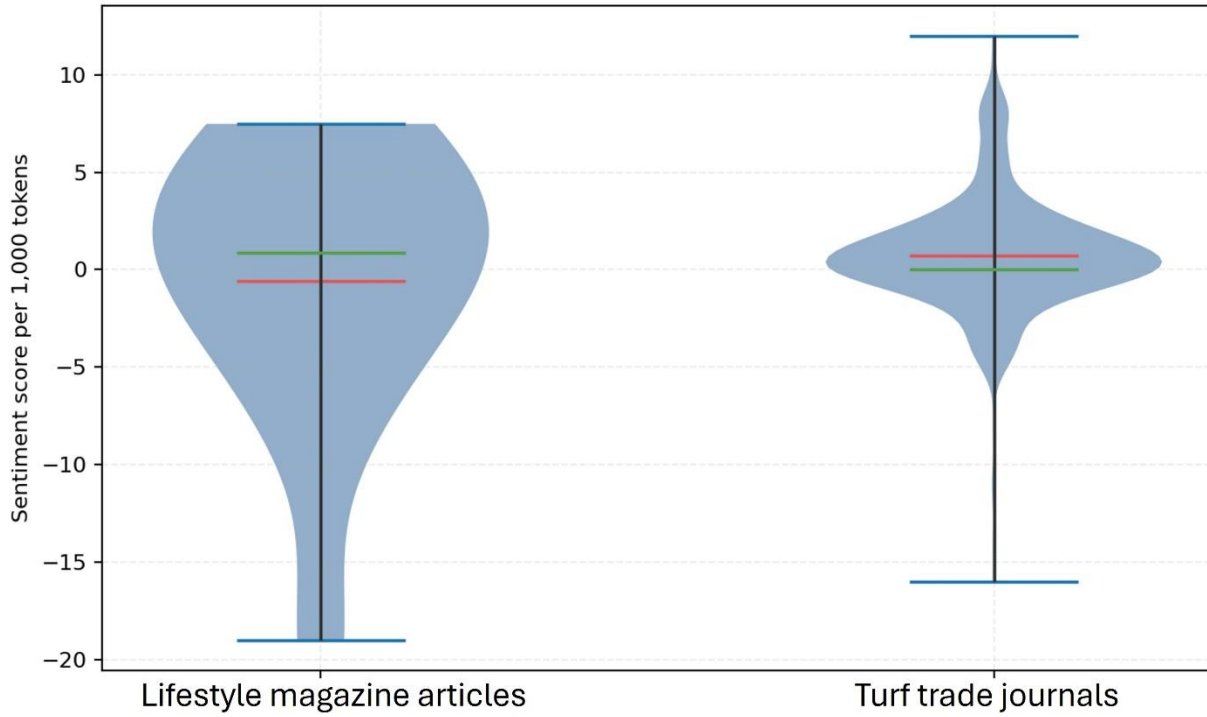


Figure 3 Sentiment analysis of turf related articles from lifestyle magazines and trade journals.

Violin plots of words and modifiers with negative (less than zero), neutral (zero), and positive (greater than zero) sentiment. The median is shown by the green bar, and the average is shown in red.

USGA DAVIS RESEARCH PROGRAM
ANNUAL REPORT
DECEMBER 5, 2025

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

- Language encouraging USDA-NASS to conduct a national turfgrass statistics survey was included in the FY26 Agricultural Appropriations bill recently signed into law
- New funding of \$250,000 annually for the National Turfgrass Evaluation Program (NTEP) was also included and passed via the FY26 Agricultural Appropriations bill
- 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
- Oversight of USDA-ARS Turfgrass Consortium funding is ongoing, considering recent personnel buyouts and resignations, with genetics, genomics and ecosystem services research continuing

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.

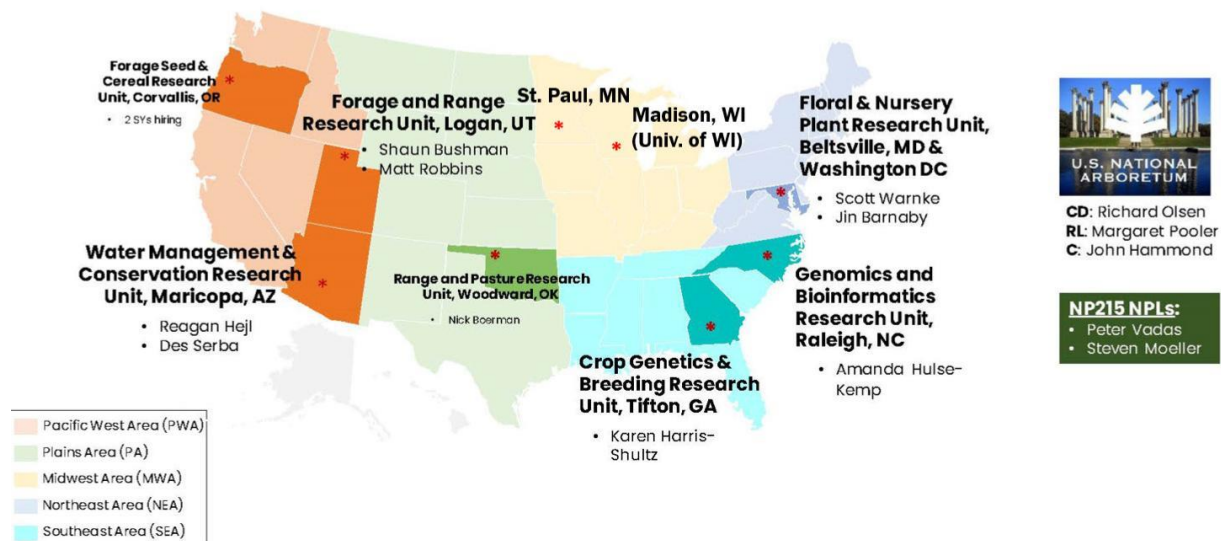
From 2000-2025, the National Turfgrass Federation (NTF) advocated for increased federal funding for turfgrass research. In 2004, as a part of this effort to increase research funding, NTF partnered with

the turfgrass industry, USDA-Agricultural Research Service (ARS) and stakeholders to develop a National Turfgrass Research Initiative (NTRI) (<http://www.turfresearch.org/initiative.htm>).

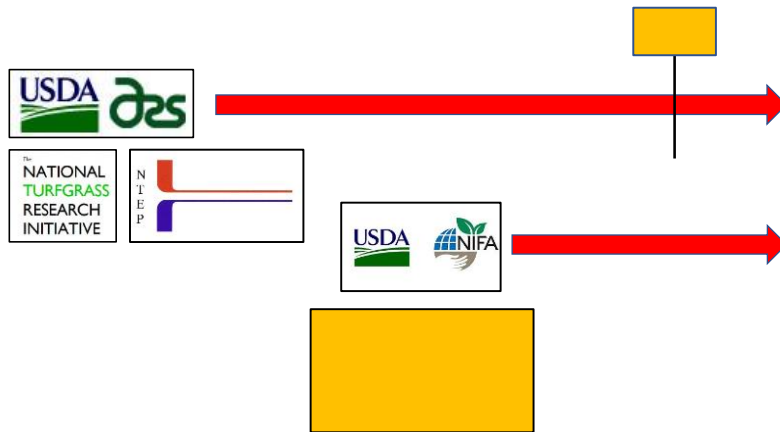
Initially, Congress responded by providing new funding for USDA-ARS labs in Beltsville, MD and Logan, UT to work on lower input and water saving turfgrass germplasm. In 2019, with advocacy from NTF and National Golf Day participants, an additional \$3,000,000 in *recurring* funds were allocated to USDA-ARS. 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.



ARS Turfgrass Consortium



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>)

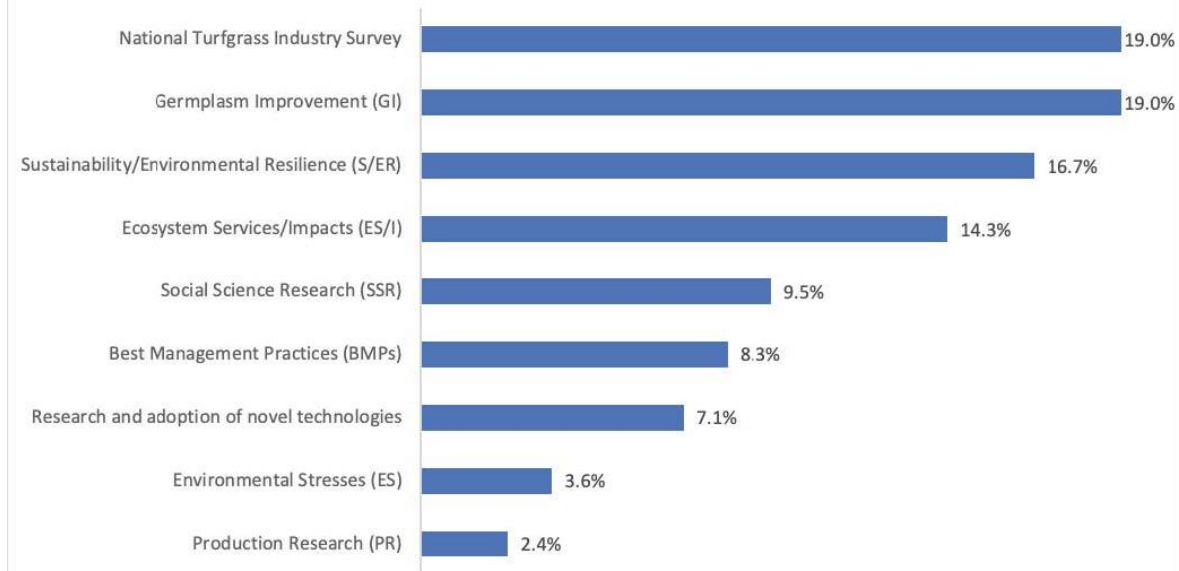


Even with these increases, federal government turfgrass research funding, including SCRI grants and USDA-ARS recurring dollars falls far below research funding for other comparably sized agricultural industries. To better address industry challenges, in September 2017, about fifty industry leaders participated 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>

What are your highest priorities for a national turfgrass research agenda? (Categories)



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 confer 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, we have 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, and 2) a national turfgrass research initiative funded at \$20,000,000 annually.

Progress in 2025

A new Farm Bill has yet to be passed by Congress, where we hope to include our requests for a national turfgrass statistics survey and the National Turfgrass Research Initiative (NTRI). A new Farm Bill will likely be extended into 2026. We will continue our advocacy efforts through 2026 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 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 turfgrass survey, with the passage of the Agriculture Appropriations bill as a part of reopening the federal government in November 2025, the following language was included:

National Turfgrass Economic Value Study.—The Committee recognizes the burgeoning natural turf industry and encourages NASS to collect data on acreage, production, and economic impact, to include employment, input costs, and retail value, of turfgrass production.

This verbiage allows us to do the following: 1) contact USDA-National Agricultural Statistics Service (NASS) about including funding for the survey in a future USDA appropriations request, 2) solicit funding from Congress for a survey in the FY27 Agricultural Appropriations bill and 3) strengthen justification for a survey via the federal grant proposal process.

We added another funding request to our list – a federal funding increase for the National Turfgrass Evaluation Program (NTEP). This critical non-profit program, connected to the USDA-Agricultural Research Service (ARS) evaluates cultivars for drought, disease, cold, etc. and is experiencing severe financial issues. As a result of our advocacy, we were able to secure \$250,000, an annual, *recurring* appropriation for NTEP. We will be working with USDA-ARS on how best to utilize this new funding for the benefit of NTEP and the industry.

Also, we have been following the \$3 million annual recurring appropriation for the USDA-ARS secured in FY20. Early in the Trump Administration's second term, an employee buyout program was initiated, which resulted in the retirement or resignation of about 15% of USDA-ARS employees. Included in these losses were some of our Turfgrass Consortium researchers, particularly at St. Paul, MN, Maricopa, AZ, Woodward, OK and Beltsville, MD. We are watching the genomic studies as well as the newly initiated multi-location ecosystem services program. Our goal is to first maintain current research projects, and second, to eventually refill the vacant positions. This effort is ongoing as hiring and staffing decisions at the administration level are uncertain and not yet settled.