

Assessment of cool-season turfgrass sod production characteristics of tall fescue and Kentucky
bluegrass

by

Emmanuel Uzoma Nwachukwu

B.S., Michael Okpara University of Agriculture Umudike, 2018

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Horticulture and Natural Resources
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

Approved by:

Major Professor
Dr. Ross Charles Braun

Copyright

© Emmanuel Nwachukwu 2025.

Abstract

The demand of high quality turfgrass cool-season sod is increasing in the transition and northern climatic zones of the United States. Genetic variation exists among Kentucky bluegrass (*Poa pratensis* L.) (KB) cultivars and tall fescue (*Festuca arundinacea* Schreb.) (TF) is gaining popularity to be used for sod, but the bunch type growth habit creates a limitation. My objectives in Chapter 2 were to: 1) quantify the influence of nine KB cultivars of varying classifications mixed with TF in a 95:5 (w/w) mixture ratios; and 2) quantify the influence of three KB cultivars of varying growth aggressiveness levels mixed in varying TF:KB mixtures of 97:3, 95:5, and 90:10 (w/w); on sod strength, ecological dynamics, and establishment vigor. My objectives in Chapter 3 and 4 were to quantify the speed of germination, establishment vigor, rhizome characteristics, as well as sod strength and handling of KB classifications (Shamrock, Compact, Jefferson etc.) and seven rhizomatous tall fescue (RTF) cultivars, respectively.

In Chapter 2, results revealed KB classifications or growth aggressiveness level in sod varying ratios (90:10, 95:5, or 97:3 TF:KB w/w) produced similar-to-no differences in sod strength and handling across multiple harvests (12.1 – 15.9 N-m). There was more tendency for a 90:10 or 95:5 (TF:KB w/w) sod mixtures to have higher sod strength than 100% TF sod. In Chapter 3, there were differences in sod strength among KB cultivars (~22 to 38 N-m, required work to tear; 389 to 568 N of maximum tensile load to tear sod), rhizome characteristics (rhizome number, length etc.) and germination and establishment vigor. Kentucky bluegrass classifications was not a good indicator for cultivar selection. In Chapter 4, RTF monostands did not produce similar high sod strength compared to 100% KB sod. Short rhizome lengths (<5 mm) were observed in RTF compared to >70 mm for KB. Differences were observed in germination (5 – 10 d) and establishment vigor (10 – 15 d) of RTF when compared to KB.

Table of Contents

List of Figures	viii
List of Tables	xv
Acknowledgements	xx
Dedication	xxi
Chapter 1 - Review of Literature	1
Abstract	1
Introduction.....	2
Kentucky Bluegrass	4
Tall Fescue	5
Rhizomatous Tall Fescue	6
Sod Characteristics	8
Lateral Spreading Turfgrasses	8
Sod Mixtures	8
Sod Production.....	13
Sod Tensile Strength	13
Sod Handling	15
Establishment	16
Management Practices	17
Mowing	18
Fertilization	18
Pesticide Application	19
Sod Netting	19
Conclusions.....	21
References.....	23
Chapter 2 - Seeding Mixtures Ratios and Kentucky Bluegrass Classifications Influence on the Sod Strength of Tall Fescue-Kentucky Bluegrass Mixtures.....	35
Abstract.....	35
Introduction.....	37
Materials and Methods.....	43

Field Experiment Site	43
Experiment Design and Treatments	43
Study Establishment and Management	44
Sod Strength Data	46
Ancillary Sod Harvest Data	47
Establishment Vigor.....	47
Tiller Population Counts	49
Data Analysis	49
Experiment 1 – Results and Discussion.....	50
Sod Strength Data	50
Sod Handling	53
Volumetric Water Content	54
Turf Quality	54
Establishment Vigor.....	55
Tiller Counts	57
Experiment 2 – Results and Discussion.....	59
Sod Strength Data	59
Sod Handling	62
Volumetric Water Content	63
Turf Quality	63
Establishment Vigor.....	64
Tiller Counts	66
Conclusions.....	69
References.....	71
Chapter 3 - The Influence of Kentucky Bluegrass Classifications on Germination and	
Establishment Vigor and Sod Strength.....	114
Abstract.....	114
Introduction.....	116
Materials and Methods.....	119
Field Experiment Site	119
Field Experimental Design and Establishment	120

Field Plot Maintenance	121
Sod Harvest Data Collection.....	122
Ancillary Sod Harvest Data	123
Field Establishment Vigor	124
Germination Vigor	125
Greenhouse Study	127
Greenhouse Data Collection	128
Statistical Analysis.....	129
Results and Discussion	130
Sod Strength Data	130
Sod Handling	133
Volumetric Water Content.....	135
Turf Quality	136
Establishment Vigor.....	136
Germination Vigor	138
Tiller and Rhizome Characteristics.....	142
Conclusions.....	146
References.....	148
Chapter 4 - Sod Strength Characteristics of Rhizomatous Tall Fescue and Quantifying Rhizome	
Production.....	191
Abstract.....	191
Introduction.....	193
Materials and Methods.....	196
Field Experiment Site	196
Experiment Design, Treatments, and Field Establishment.....	196
Field Plot Maintenance	197
Sod Harvest Data Collection.....	198
Ancillary Sod Harvest Data	199
Field Establishment Vigor	200
Germination Vigor	201
Greenhouse Study	202

Greenhouse Data Collection	203
Statistical Analysis.....	204
Results and Discussion	205
Sod Strength Data	205
Sod Handling	207
Volumetric Water Content.....	209
Turf Quality	209
Establishment Vigor.....	210
Germination Vigor	211
Rhizome Production.....	213
Conclusions.....	217
References.....	219
Appendix.....	252
Appendix A - Additional Figures and Tables For Chapter 2.....	253
Appendix B - Additional Figures and Tables For Chapter 3.....	260
Appendix C - Additional Figures and Tables for Chapter 4.....	269

List of Figures

- Figure 2.1. Cutting sod across plots using a Turfco KisCutter (left); Sod tensile strength device used to measure sod strength (middle); and Piece of torn sod from the sod tensile device (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Left photo by Ross Braun, middle and right photo by Emmanuel Nwachukwu..... 83
- Figure 2.2. Digital image analysis and light box (Z30 camera attached) (left); Measuring establishment speed differences of Run 1, 39 weeks after planting at the Rocky Ford Turfgrass Research Center, Manhattan, KS (right). Right photo by Emmanuel Nwachukwu, left photo by Ross Braun..... 84
- Figure 2.3. A 58 cm² sized plug cutter device used to remove plugs from non-sod harvest areas after each sod harvest (9, 10, 12 MAP) and at 20 and 24 MAP (left); tall fescue and Kentucky bluegrass plants visually counted per plug for population/percentage change (middle); plugs were returned to the experimental site after tiller counts in lab (right). Photo by Emmanuel Nwachukwu. 85
- Figure 2.4. Harvested sod pieces showing difference among treatments at 10 months after planting. Photo by Emmanuel Nwachukwu..... 86
- Figure 2.5. Correlation (r) is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX) and sod handling (SH)], turf quality (TQ), Kentucky bluegrass visual tillers percentage per square decimeter (KB tillers), and total tiller numbers [i.e., tall fescue (TF) and Kentucky bluegrass (KB)] (TN) per square decimeter was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($10 \times 4 \times 3 \times 2$; $n = 240$) for experiment 1. Note: P-value = no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels. 87
- Figure 2.6. Volumetric water content (%) at a 7.6 cm soil depth of plots at each sod harvest event, Run 1 (top) and Run 2 (bottom) for Experiment 1. Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$). 88

Figure 2.7. Field plots layout for Experiment 1, showing vegetation establishment cover at 2.3 weeks after planting at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Photo by Emmanuel Nwachukwu	89
Figure 2.8. Correlation (r) is shown using color-coded scales r = 1, positive correlation; r = -1, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX), sod handling (SH)], and turf quality (TQ) was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs (10 × 4 × 3 × 2; n = 240) for Experiment 2. Note: For <i>P</i> -value, no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels.	90
Figure 2.9. Volumetric water content (%) at a 7.6 cm soil depth of plots at each sod harvest event, Run 1 (top) and Run 2 (bottom) for Experiment 2. Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$).	91
Figure 2.10. Four-parameter sigmoidal regression model output from GraphPad prism combined across runs for Experiment 2, showing establishment cover for treatments according to mixture ratios between TF and KB at 97:3% and a 100% TF bunch type blend (top), and other mixtures ratios of 95:5 and 90:10 (TF:KB w/w) (bottom). Regression line with the steepest slopes and lowest D50 value indicates faster vegetation establishment cover.....	92
Figure 2.11. Field plots layout for Experiment 2, showing vegetation establishment cover at 2.3 weeks after planting at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Photo by Emmanuel Nwachukwu.	93
Figure 3.1. Turfco KisCutter sod cutter used to harvest sod (left), Cutting sod piece across plots (middle); Sod handling after immediately harvest (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Left and middle photo by Emmanuel Nwachukwu, right photo by Ross Braun.	160
Figure 3.2. Sod tensile strength device used for measuring sod strength (left), Clamping down sod piece on sod tensile device plates (middle); Piece of torn sod from the sod tensile device (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Middle photo by Ross Braun, left and right photo by Emmanuel Nwachukwu.....	161

Figure 3.3. Measuring vegetation cover with digital images and modified lightbox (top) and rating for visual turf cover (bottom). Both photos by Ross Braun.	162
Figure 3.4. Growth chamber (left); Petri dishes in growth chamber randomized daily for 28 days (middle); Seeds with visible structures of radicle and coleoptile counted as germinated seed (right). Left and middle photo by Emmanuel Nwachukwu, right photo by Parul Mandal.	163
Figure 3.5. Kentucky bluegrass growing in containers placed in greenhouse (left); Measuring vegetation green cover with digital image analysis and modified lightbox (31 cm × 28 cm) (middle); Destructive phenotyping harvest of Kentucky bluegrass, showing aerial shoot from rhizomes and ready to wash rhizomes and bagged for measurement in lab (right). Left and right photo by Emmanuel Nwachukwu, middle photo by Parul Mandal.	164
Figure 3.6. Measurement of Kentucky bluegrass rhizomes during destructive harvest using digital caliper (left); Rhizome and tiller count (middle); Rhizome class rated on a scale of 0 to 5 (5 = thickest, most robust; 1 = thinnest, weakest; and 0 = no >10 mm rhizomes present) (right). Left photo by Alex Stanton, middle and right photo by Emmanuel Nwachukwu.	165
Figure 3.7. Effect of Kentucky bluegrass cultivars on required work to tear sod (newton-meters, N-m) at three sod harvest timings (9, 10 , and 13 months after planting) in Manhattan, KS across both Runs. Means within a sod harvest timing with a common letter or no letters are not significantly different according to Fisher's LSD Test ($\alpha = .05$).	166
Figure 3.8. Effect of Kentucky bluegrass cultivars on maximum tensile load to tear sod (newtons, N) at three sod harvest timings (9, 10, and 13 months after planting) in Manhattan, KS across both Runs. Means within a sod harvest timing with a common letter or no letters are not significantly different according to Fisher's LSD Test ($\alpha = .05$).	167
Figure 3.9. Effect of Kentucky bluegrass cultivars on sod handling (scale 1-5) at sod harvest timings of 9, 10, and 13 months after planting in Manhattan, KS across both Runs. Means within a sod harvest timing at with a common letter or no letters are not significantly different according to Fisher's LSD Test ($\alpha = .05$).	168
Figure 3.10. Correlation (r) is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX) and sod handling (SH)] was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($19 \times 4 \times 3 \times 2$; $n = 456$). Correlation analysis between Kentucky bluegrass	

greenhouse data [e.g., Rhizome class (RC), average rhizome length (DIST), total rhizome length (TRDIST), average number of rhizome (>10 mm) per plant (RN), average aerial shoot (AAT), total aerial shoot (TAT), and total number of tillers per plant (total plant and rhizome tillers, TNT)] harvested at 4.7 months after seeding and Kentucky bluegrass sod strength data harvested at 9 months after planting. Experiment runs for greenhouse data and 9-month sod harvest data were combined, before running a correlation analysis. The sample size for greenhouse data and sod strength is $n = 38$ (19 treatments $\times$ 2 runs). Note: P-value = no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels.	169
Figure 3.11. Volumetric water content (%) measured with time-domain reflectometry at five locations per plot (treatment) at a 7.6 cm soil depth at each sod harvest event, Run 1 (top) and Run 2 (bottom). Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$).	171
Figure 3.12. Four-parameter sigmoidal regression model output from GraphPad Prism of establishment vigor for each Kentucky bluegrass cultivar across both runs arranged alphabetically (A-Y). Regression line with the steepest slopes and lowest IC ₅₀ value indicates faster establishment cover.	172
Figure 3.13. Field plots at the Rocky Ford Turfgrass Research Center, Manhattan, KS showing establishment speed differences of Kentucky bluegrass cultivars at 2 weeks after planting on 19th Sept. 2023 in Run 2, (Left), and entire field study area of Kentucky bluegrass at 2 weeks after planting on 27 Sept. 2022 in Run 1 (Right). Left photo by Emmanuel Nwachukwu, right photo by Ross Braun.	173
Figure 3.14. Four-parameter sigmoidal regression model output from GraphPad Prism of germination vigor for each cultivar of Kentucky bluegrass for experimental Run 1 arranged alphabetically (A-Y) (left) and Run 2 (right). The regression line with the steepest slopes and lowest IC ₅₀ value indicates faster germination.	174
Figure 3.15. From left to right, i) germination of Kentucky bluegrass (visible structures of radicle and coleoptile) occurring in Legend at 6 days after incubation (DAI); ii) no germination occurred in Merit at 6 DAI; iii) remaining KB seeds in Petri dish after germination counts for Jackrabbit (fast germinating cultivar) at 15 DAI and Shannon (slow germinating cultivar) at 15 DAI. Photos by Emmanuel Nwachukwu.	175

Figure 3.16. Linear regression between IC ₅₀ and D ₅₀ across Kentucky bluegrass for Run 1 (top) and Run 2 (bottom) in 2022 and 2023, respectively.	176
Figure 3.17. Martha (classification: Jefferson/Washington/Mid-Atlantic, high growth aggressiveness) harvested at 4.7 months after planting in the greenhouse in Run 1 for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.	177
Figure 3.18. Martha (classification: Jefferson/Washington/Mid-Atlantic, high growth aggressiveness) harvested at 4.7 months after planting in the greenhouse in Run 1 for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.	178
Figure 3.19. Volt (classification: Shamrock, low growth aggressiveness) (left), SR-2100 (classification: Shamrock, high growth aggressiveness) (middle), Acoustic (classification: Compact Midnight, high growth aggressiveness) (right) harvested at 4.7 months after planting in the greenhouse (Run 1) for visual tiller count and rhizome measurements. Photos by Emmanuel Nwachukwu.	179
Figure 4.1. Cutting sod (left), Kentucky bluegrass sod piece (middle), and piece of torn sod from the sod tensile device (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Left and right photo by Ross Braun, middle photo by Emmanuel Nwachukwu.	229
Figure 4.2. Measuring establishment speed differences at 39 WAP using a digital image analysis and light box (Z30 camera attached) (top); Turf quality rating 8 WAP (1-9 scale; 9=best turfgrass quality) (bottom). Both photos by Ross Braun.	230
Figure 4.3. Growth chamber (left); Peter dishes in growth chamber randomized daily for 28 days (middle); Seeds with visible structures of radicle and coleoptile counted as germinated seed (right). Left and middle photo by Emmanuel Nwachukwu, right photo by Parul Mandal.	231
Figure 4.4. Fertilizing treatments in containers placed in greenhouse (left); Destructive phenotyping harvest of Kentucky bluegrass included in the treatments ready to wash rhizomes (middle); Measurement of Kentucky bluegrass rhizomes destructive harvest using digital caliper (right). Left and right photo by Parul Mandal, middle photo by Emmanuel Nwachukwu.	232
Figure 4.5. Influence of rhizomatous tall fescue main effect on required work to tear sod (newton-meters, N-m) and maximum tensile load (newtons, N) to tear sod at sod harvest timings in Manhattan, KS. Acoustic and legend, Kentucky bluegrass cultivars (KB) included in a 100% blend at 50% each by weight (100% KB); BTF Blend, bunch-type tall	

fescue 100% blend of Supersonic, Reflection, Houndog 6 at 33% by weight each; 95:5 TF:KB, 95% BTF in 5% seed mixture with KB (Legend and Acoustic); 90:10 TF:KB of similar TF and KB cultivars; Rhizo blend, Rhizomatous tall fescue (TF) blend of Xtender, Grande 3, Titanium. Within each response variable, means within a sod harvest timing at each site with a common letter are not significantly different according to Fisher's LSD Test ($\alpha = .05$)..... 233

Figure 4.6. Kentucky bluegrass (left), Rhizomatous tall fescue (middle), and 100% bunch-type (right) sod harvested in June (9 months after planting) ready quantify sod strength using the sod tensile device in Manhattan, KS. Photo by Emmanuel Nwachukwu. 234

Figure 4.7. Influence of rhizomatous tall fescue main effect on sod handling (scale 1-5) at sod harvest timings in Manhattan, KS. Acoustic and legend, Kentucky bluegrass cultivars (KB) included in a 100% blend at 50% each by weight (100% KB); BTF Blend, bunch-type tall fescue 100% blend of Supersonic, Reflection, Houndog 6 at 33% by weight each; 95:5 TF:KB, 95% BTF in 5% seed mixture with KB (Legend and Acoustic); 90:10 TF:KB of similar TF and KB cultivars; Rhizo blend, Rhizomatous tall fescue (TF) blend of Xtender, Grande 3, Titanium. Within each response variable, means within a sod harvest timing at each site with a common letter are not significantly different according to Fisher's LSD test ($\alpha = .05$)..... 235

Figure 4.8. Correlation (r) is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX) and sod handling (SH)] was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($12 \times 4 \times 3 \times 2$; $n = 288$). Correlation analysis between rhizomatous tall fescue greenhouse data [e.g., Rhizome class (RHC), average rhizome length (Length), average number of rhizome (>10 mm) per plant (RN), and total number of tillers per plant (total plant and rhizome tillers, TNT)] harvested at 4.3 months after seeding and rhizomatous tall fescue sod strength data harvested at 9 months after planting. Experiment runs for greenhouse data and 9 month sod harvest data were combined, before running a correlation analysis. The sample size for greenhouse data and sod strength is $n = 28$ (7 treatments $\times$ 4 reps). Note: P -value = no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels. 236

Figure 4.9. Volumetric water content (%) at a 7.6 cm soil depth of plots at each sod harvest event, Run 1 (top) and Run 2 (bottom). Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$).....	237
Figure 4.10. Four-parameter sigmoidal regression model for each treatment for experimental Run 1 (left) and Run 2 (right). 100% KB, 100% Kentucky bluegrass blend of Acoustic and Legend Kentucky bluegrass; 95:5 TF:KB; 90:10 TF:KB; Rhizo blend, Rhizomatous tall fescue (TF) blend of Xtender, Grande 3, Titanium; 100% BT-TF, 100% bunch-type tall fescue blend of Supersonic, Reflection, Hounddog 6; and all other individual cultivar treatments are rhizomatous tall fescue cultivar.....	238
Figure 4.11. Four-parameter sigmoidal regression model output from GraphPad prism for each cultivar within each cool-season turfgrass species for experimental Run 1 (left) and Run 2 (right). KB, Kentucky bluegrass cultivars Acoustic and Legend; RTF, Rhizomatous tall fescue; BT-TF, Bunch-type tall fescue. Regression line with the steepest slopes and lowest IC ₅₀ value indicates faster germination.....	239
Figure 4.12. Seeds with visible structures of radicle and coleoptile counted at day 5 as germinated seeds in run 2. Kentucky bluegrass (right), Rhizomatous tall fescue (middle), and Bunch-type tall fescue (right). Photo by Emmanuel Nwachukwu.....	240
Figure 4.13. Rhizomatous tall fescue cultivar harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. photo by Emmanuel Nwachukwu.	241
Figure 4.14. Rhizomatous tall fescue cultivar (Firecracker) harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. photo by Emmanuel Nwachukwu.	242
Figure 4.15. Bunch-type tall fescue cultivar (Supersonic) harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. photo by Emmanuel Nwachukwu.	243
Figure 4.16. Kentucky bluegrass (Acoustic) harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. photo by Emmanuel Nwachukwu.	244

List of Tables

Table 2.1. Species and Cultivars that were included in both Field Experiment 1 and Field Experiment 2.	94
Table 2.2. Kentucky bluegrass classification system and growth aggressiveness classification labels.	95
Table 2.3. Seeding rate conversions for the TF:KB 95:5 (w/w) treatments and 100% TF treatment in Experiment 1.	96
Table 2.4. Seeding rate conversions for the different seeding mixture ratio TF:KB (w/w) treatments and 100% TF treatment in Experiment 2.	97
Table 2.5. Effects of Kentucky bluegrass (KB) cultivar mixed with tall fescue at a 95:5 (w/w) mixture ratio on sod strength and handling at three sod harvest timings [9, 10, and 12 months after planting (MAP)] across both experiment runs in Experiment 1.	98
Table 2.6. Turfgrass quality rating of treatments during establishment [6 to 32 weeks after seeding (WAS)] and the following spring across both experiment runs in Experiment 1....	99
Table 2.7. Turfgrass quality ratings of Experiment 1 treatments in the field for both experiment runs at each sod harvest timing from 9 to 12 months after planting (MAP).....	100
Table 2.8. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 50, 70, and 90% establishment treatments in the field across both experiment runs in Experiment 1.	101
Table 2.9. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 1 of Experiment 1.	102
Table 2.10. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 1.	103
Table 2.11. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 1 of Experiment 1.	104
Table 2.12. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 1.	105
Table 2.13. Effects of Kentucky bluegrass (KB) cultivar mixed with tall fescue at different mixture ratios (97:3, 95:5, and 90:10 TF:KB w/w) on sod strength and handling at three sod	

harvest timings [9, 10, and 12 months after planting (MAP)] combined across runs in Experiment 2.	106
Table 2.14. Turfgrass quality rating of treatments during establishment and the following spring from 6 to 32 weeks after seeding (WAS) across both experiment runs in Experiment 2. ...	107
Table 2.15. Turfgrass quality ratings of Experiment 2 treatments in the field for both experiment runs at each sod harvest timing.	108
Table 2.16. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 50, 70, and 90% establishment treatments in the field across both experiment runs in Experiment 2.	109
Table 2.17. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 1 of Experiment 2.	110
Table 2.18. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 2 of Experiment 2.	111
Table 2.19. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 1 of Experiment 2.	112
Table 2.20. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 2.	113
Table 3.1. Kentucky bluegrass treatments in the experiment.	180
Table 3.2. Turfgrass quality rating of Kentucky bluegrass during establishment and the following spring for both runs.	181
Table 3.3. Turfgrass quality ratings of Kentucky bluegrass in the field for both experiment runs at each sod harvest timing.	182
Table 3.4. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 50% establishment of Kentucky bluegrass cultivars in the field across both experiment runs.	183
Table 3.5. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 70 and 90% establishment of Kentucky bluegrass cultivars in the field for both experiment runs.	184
Table 3.6. Sigmoidal regression model (four-parameter equation); Equation (2)) results for the estimated number of days until 50, 70, and 90% germination of Kentucky bluegrass cultivars in a controlled-environment for both experiment runs.	185

Table 3.7. Parameter estimates from the four-parameter sigmoidal regression model (Equation 2) for the estimated number of days until 50% germination of Kentucky bluegrass cultivars in a controlled-environment for both experiment runs.	186
Table 3.8. Plant tiller and rhizome characteristics of Kentucky bluegrass cultivars grown in containers in a greenhouse in Run 1.	187
Table 3.9. Plant tiller and rhizome characteristics of Kentucky bluegrass cultivars grown in containers in a greenhouse in Run 2.	189
Table 4.1. Cultivars that were included in the experiment.	245
Table 4.2. Treatments and seeding rates in Run 2.	246
Table 4.3. Turfgrass quality rating of experiment treatments during establishment and the following spring for both runs.	247
Table 4.4. Turfgrass quality ratings of experiment treatments in the field for both experiment runs at each sod harvest timing.	248
Table 4.5. Field establishment speed differences of treatments.	249
Table 4.6. Germination speed differences of treatments in a controlled-environment.....	250
Table 4.7. Greenhouse experiment treatments and rhizome production and growth differences across both experiment runs.....	251

Appendices

Figure A.1. Data from mesonet.k-state.edu for Rocky Ford Turfgrass Research Center, Manhattan showing daily precipitation amount, soil temperature and air temperature averaged across hourly data throughout the study, Run 1, September 2022 to September 2023 (from left to middle), and Run 2, September 2023 to September 2024 (from middle to right).....	253
Table A.2. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 1 of Experiment 1.....	255
Table A.3. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 1.....	256
Table A.4. Visual turf cover rating (0-100%) of field establishment for 2 to 11 weeks after seeding (WAS) for Run 2 in Experiment 2.....	257
Table A.5. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 1 of Experiment 2.....	258
Table A.6. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 2.....	259
Figure B.1. Data from mesonet.k-state.edu for Rocky Ford Turfgrass Research Center, Manhattan showing daily precipitation amount, soil temperature and air temperature averaged across hourly data throughout the study, Run 1, September 2022 to September 2023 (from left to middle), and Run 2, September 2023 to September 2024 (from middle to right).....	260
Figure B.2. Daily relative humidity and air temperatures averaged across 30-minute increments from environmental sensors, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.	261
Figure B.3. Mean daily light integrals summed from 30-min incremental measurements of photosynthetically active radiation, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.....	262

Figure B.4. Correlation matrix between rhizome characteristics [(e.g., Average rhizome length (A-length), sum rhizome length (S-length), nodes, rhizome class (RC), and Total number of tillers (TNT, number of rhizome tillers and aerial shoots from rhizomes) and Establishment cover data from digital image analysis and GraphPad prism data across both experiment runs. Correlation (r) on the right top is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Means of total or average rhizome length, nodes, RC, and TNT recorded for each cultivar harvested from greenhouse (20 weeks after planting) were used to determine the relationship between variables, a total of 152 sample size (i.e., Trts x reps x runs; $19 \times 4 \times 2$).	263
Figure C.1. Data from mesonet.k-state.edu for Rocky Ford Turfgrass Research Center, Manhattan showing daily precipitation amount, soil temperature and air temperature averaged across hourly data throughout the study, Run 1, September 2022 to October 2023 (from left to middle), and Run 2, September 2023 to October 2024 (from middle to right).	269
Figure C.2. Daily relative humidity and air temperatures averaged across 30-min incremental measurements from environmental sensors, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.	270
Figure C.3. Mean daily light integrals summed from 30-min incremental measurements of photosynthetically active radiation, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.	271

Acknowledgements

Every journey has a beginning and an end. I would like to thank those who have been part of this journey here at Kansas State University, particularly the faculty, staff members, and fellow graduate students of the Department of Horticulture and Natural Resources.

I would like to sincerely thank my advisor, Dr. Ross Braun. Words cannot describe how eternally grateful I am for your continuous support, patience, motivation, mentorship, and wealth of experience. You have been an inspiration and ultimately refined my scientific and statistical skills which has helped me advance in turfgrass research.

I would like to thank my committee members, Dr. Jack Fry and Dr. Cody Domenghini, for their consistent support and guidance towards this work. I appreciate the head of the Department, Dr. Steve Keely, and Dr. Channa Rajashekar, for impacting my academic journey.

I extend appreciation to Wesley Howe, for maintaining research plots at Rocky Ford Turfgrass Research Center, and also to undergraduate students helping during peak times.

Big thanks to my lab mates, Parul Mandal and Alex Stanton, your assistance and collaborations have been instrumental in making my job easier and won't be forgotten.

I appreciate the Braun's Lab, The Lawn Institute, and the Kansas Turfgrass Foundation for their funding, as well as The Anderson, Inc. and seed companies for supporting this research.

I am grateful to Dr. Isaac Barnhart, for believing and investing in my dreams of coming to Kansas. Special thanks to Prof. Anderson Amadioha, Dr. Chinedu Eze, Rev. Dr. Chibuzor Izuogu, Rev. Ebenezer Amachaghi, and Chimdi Chikezie for their guidance and support.

I would like to thank God for giving me a wonderful big family, that has supported my dreams, especially Ugochi Nwachukwu, Chukwuemeka Nwachukwu, Chioma Ikedi, and Daniel. Special appreciation to my wonderful and praying mother, Theresa Nwachukwu. I love you.

Dedication

I dedicate this work to Almighty God, and my Late Dad, Reverend Maurice Chinedum Nwachukwu.

Chapter 1 - Review of Literature

Abstract

The knowledge of the best cool-season turfgrass species that will meet the increasing demand for sod in the northern and transitional climatic zone regions in the U.S. is essential. This chapter reviews two cool-season turfgrass species that meet the criteria for sod production, mixtures of both species, and possible ways they can substitute for each other due to their common and different genetic traits. Kentucky bluegrass (*Poa pratensis* L.) (KB) is the preferred cool-season turfgrass for sod production in the northern climates because it provides high quality and excellent recuperative potential. The rhizomatous growth habit of KB creates high sod strength and handling for sod production, individually or in mixtures with other cool-season grasses, such as tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (TF). Tall fescue has gained popularity in the central U.S. because of its superior heat, drought, and shade tolerance compared to KB. However, a limiting factor is its bunch-type growth habit (i.e., no rhizomes or stolons), although some cultivars are known to produce short rhizomes and are marketed at “rhizomatous” or “spreading” TF. Recent cool-season sod production research has focused more on KB and fine fescues (*Festuca* L. spp.), which the latter has also been shown to have good sod strength, but less heat and drought tolerance compared to TF, which is a limiting factor in the transitional climatic zone. This review summarizes research findings on these issues and proposes areas where more research is warranted. More specifically, these topics include i) sod production mixtures of tall fescue with Kentucky bluegrass, ii) growth aggressiveness differences between species and cultivars, iii) sod tensile strength, sod handling quality, intra- and inter-species variation in sod production, and iv) rhizomatous tall fescue cultivars.

Introduction

The sod industry is a significant component of the turfgrass industry. The turfgrass industry also consists of golf courses, lawns, sports fields, other grounds and parks maintenance, sales, and other systems. The combined sales of the turfgrass sod industry in the Northeast, Midwest, Plains, and Northwest areas of the U.S. in 2019 totaled more than U.S. \$583 million, which increased by \$34 million since 2014 (USDA-NASS, 2021). Moreover, there is a tendency that the demand for sod by customers will increase in the future, which is part of the strategy to lessen the effects of growing environmental concerns about soil erosion from land development, ongoing renovations, and new construction sites, as well as changes in infrastructure development.

Turfgrass sod provides many benefits, such as rapid establishment, instant soil stabilization, and an immediate functional green space. The instant green space provided by sod can begin to provide many ecosystem service benefits right away, such as preventing soil erosion, oxygen production, carbon sequestration, and instant greenspace to improve human health and wellbeing (Braun et al., 2024). For example, Krenitsky et al. (1998) reported that planted turfgrass sod reduced soil runoff compared to straw or leaving the soil uncovered (i.e., bare) on a sloped roadside. Many other ecosystem service benefits of turfgrass systems are highlighted and discussed in Braun et al. (2024).

Research has shown that many cool-season turfgrass species can be utilized to produce high-quality sod (Braun et al., 2021a, 2021b, 2022c; Braun & Patton, 2022; Friell et al., 2017). For cool-season (C_3) turfgrass species, these include Kentucky bluegrass (KB) (*Poa pratensis* L.) and tall fescue (TF) [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.], and fine fescues (*Festuca* L. spp.), specifically strong creeping red fescue

(*Festuca rubra* L. ssp. *rubra* Gaudin), and slender creeping red fescue [*F. rubra* L. ssp. *littoralis* (G. Mey.) Auquier]. These cool-season turfgrasses are some of the most commonly used for cool-season turfgrass sod production in the northern U.S. (Braun et al., 2021a, 2021b, 2022c; Braun & Patton, 2022; USDA-NASS 2016).

Kentucky bluegrass is one of the most popular cool-season turfgrass species in the northern U.S. because of its adaptability for use in many turfgrass systems (lawns, parks, athletic fields, and golf course fairways) (Christians et al., 2017; Funk, 2000; Huff, 2003). The rhizomatous growth habit of KB provides the ability for it to knit together and be transported as sod, which has helped it continue to be a preferred choice in the northern U.S. sod production industry (Braun et al., 2021a, 2022c; Christians et al., 2017; Fry & Huang, 2004). However, TF is slowly replacing KB as the preferred turfgrass species in transitional climatic zone regions and many parts of northern U.S., due to its superior heat and drought tolerance (Christians et al., 2017; Fry & Huang, 2004). Textbooks usually refer to TF as a bunch-type grass (i.e., intravaginal tillering only, no extravaginal tillering of rhizomes or stolons); therefore, it has a limited ability to spread laterally and produce high sod strength. However, researchers have reported the production of short rhizomes in some TF cultivars (St. John et al., 2009); however, this needs to be further studied. While TF is found for sale on sod farms, it may not meet the optimum requirements to be used extensively for sod production except when planted in mixtures with KB or it requires plastic netting to hold the sod together (Christians et al., 2017). More recently, Braun et al. (2021a, 2021b, 2022c) and Braun and Patton (2022) reported new cultivars of some fine fescue taxa, especially strong creeping red fescue, slender creeping red fescue, and Chewings fescue [*F. rubra* L. ssp. *Commutata* Gaudin; syn. *F. rubra* L. ssp. *fallax* (Thuill.) Nyman] can produce similar or higher sod strength and sod handling as KB in Indiana

and Minnesota. This research also reported higher sod strength and handling in fine fescue sod compared to TF (bunch-type) sod and rhizomatous TF sod, both of which have some of the poorest sod strength and handling among cool-season turfgrass mixtures (Braun et al., 2022c). This research shows the need for more research on alternative turfgrass species, such as TF and fine fescues, for sod production in comparison to standards like KB.

Kentucky Bluegrass

Kentucky bluegrass is a perennial, cool-season grass used as a forage and turfgrass (Honig et al., 2012). Research shows that KB is native to Europe, Eurasia, and possibly North America (Bonos et al., 2013; Carrier & Bort, 1916; Funk and Engel, 1984). It was likely introduced to North America by European settlers sometime after 1600 and was later spread westward by settlers (Bonos et al., 2013; Carrier & Bort, 1916). Kentucky bluegrass is adapted to various habitats and occurs on different soil types but prefers fine-textured and well-drained soils (Christians et al., 2017). Northern climates in the U.S., specifically the cool-humid and cool-arid zones, are the preferred areas to grow KB (Christians et al., 2017).

Kentucky bluegrass cultivars have been further classified into different “KB classification types” based on genetics, turfgrass characteristics, and growth rates (Bonos et al., 2000, 2013; Brilman, 2018, 2024; Honig et al., 2012, 2018; Murphy et al., 1997). For example, there are many different “KB classification system types,” such as “Shamrock,” “Compact America,” “Eurasian,” “Limousine,” “Julia” “Mid-Atlantic” “BVMG ('Baron', 'Victa', 'Merit', 'Gnome'),” and many others (Bonos et al., 2000; Brilman, 2018, 2024; Honig et al., 2012, 2018; Huff, 2003). Cultivars in these classifications have different growth aggressiveness characteristics as well as other characteristics like genetic color, abiotic and biotic stress tolerances, and more (Bonos et

al., 2000; Hoing et al., 2018; Murphy et al., 1997; Patton & Braun, 2021). Bara et al. (1993) described "Aggressive-Type" cultivars as having a high shoot density and vigorous, aggressive lateral spread with longer rhizomes than all other types except the "Mid-Atlantic Type." One key advantage of cultivars with more aggressive growth characteristics is their utilization in highly trafficked areas because of their excellent recuperative potential and potential to hasten the development of mature sod (Bonos et al., 2000). Variation in vertical growth rate among Kentucky bluegrass has been reported (Bonos et al., 2000; Patton & Braun, 2021). Different classifications of their aggressiveness could lead to the rapid expression of the cultivar's strengths or weaknesses (Bonos et al., 2000; Murphy et al., 1997). However, no research has been conducted on lateral and vertical growth differences among these classification types to better understand how this not only influences management decisions but also sod production.

Tall Fescue

Tall fescue is an introduced, cool-season, perennial grass native to Europe, Western Asia, and North Africa (Bonos et al., 2013; Borril, 1976; Buckner et al., 1979; Whyte et al., 1959). The date of its introduction to North America is unknown, but it began appearing in seed catalogs in 1870 (Kennedy, 1900). By 1892, TF began appearing in various U.S. trials from Utah to Kentucky. In 1943, It became prominent in the U.S. with the release of 'Kentucky 31' (K-31) (Buckner et al., 1979), which is still commonly used today. The continued use of Kentucky-31 TF today is a disadvantage for homeowners and turfgrass practitioners because it is a "forage-type" TF classification compared to new and improved TF cultivars, which are "turf-type" classifications. Some disadvantages of forage-type TF cultivars compared to turf-type TF cultivars are lower aesthetic and functional turf quality, less resistance to weed invasion due to a

less dense turf canopy, and a faster vertical growth rate that requires greater mowing, fertilizer, and pesticide inputs (Braun et al., 2023b; Braun & Patton, unpublished data). According to Hannaway et al. (1999), TF has a high adaptation to humid, temperate areas, and it grows best on deep, moist soils with soil pH values between 5.5 and 8.5. Regarding soil moisture, TF can grow under conditions ranging from excessively drained to poorly drained and tolerate long periods of flooding (24 to 35 days) when temperatures are below 27°C (Hannaway et al., 1999). Turf-type tall fescue may be a better option in the future for water conservation efforts because it has better drought avoidance due to its deep rooting characteristics compared to KB (Braun et al., 2022a, 2022b; Su et al., 2008).

Rhizomatous Tall Fescue

Tall fescue is a bunch-type grass (i.e., intravaginal tillers only, no extravaginal tillering of rhizomes or stolons), but studies have shown that some cultivars may produce short rhizomes (St. John et al., 2009). Rhizomes originate from the crown and develop into lateral stems beneath the soil surface, bearing roots and shoots at the nodes. The bunch-type growth habit of TF has limited its adaptation to different environments and soil conditions because of poor recuperative potential and poor sod strength and handling. In the last 30 years, turfgrass breeders have produced TF cultivars that potentially produce more and longer rhizomes than traditional bunch-type cultivars, now referred to as rhizomatous TF or spreading TF (St. John et al., 2009). Singh et al. (2005) developed a rhizomatous TF 'Labyrinth' by crossing a Portuguese rhizomatous TF with standard American and European turf-type TF. After seeding, 88% of Labarinth TF plants produced rhizomes, whereas 16 to 42% of plants in stands of other cultivars produced rhizomes (Singh et al., 2005). It would be highly desirable to have a TF that produces rhizomes because it will aid in the plant's ability to withstand traffic, enhance recuperative potential, and potentially

increase sod strength and handling. Further research is needed in this area since the number of rhizomatous TF cultivars in the market is increasing and being marketed by seed companies.

The presence of rhizomes is also beneficial to the plant because they serve as organs of carbohydrate storage and, therefore, have the potential to aid survival during temperature extremes of cold, heat, or drought stress (De Battista & Bouton, 1990). Additionally, rhizomes offer places for growth below the soil surface, where plants are better sheltered from extreme temperatures and overgrazing in forage systems or the equivalent of accidental scalping in turfgrass systems. Turfgrass plants with rhizomes have the advantage compared to bunch-type plants because they can repopulate bare soil or damaged areas, enhance sod knitting (i.e., sod strength), recover from stress more efficiently, and increase tolerance to traffic stress. Typically, advertised rhizomatous TF cultivars have high rhizome production, enhanced ground covering, dark green color, fine texture, drought tolerance, and self-repair (St John et al., 2009); however, there has been minimal research on these characteristics. Rhizome development and growth in bare areas can render interseeding (i.e., overseeding) unnecessary when slight turfgrass damage, disease, or other stresses reduce the turfgrass density.

The tillering rate and rhizome formation of the commercially available TF cultivars likely vary; however, no research has been conducted to quantify these differences and its influence on sod strength. Therefore, more research is needed to better understand rhizome production in TF and the influence it has on sod production characteristics.

Sod Characteristics

Lateral Spreading Turfgrasses

In the U.S., commercial production of turfgrass sod started around 1920 (Mitchell & Dickens, 1979). According to Beard and Rieke (1969), the term “sod” refers to blocks, plugs, squares, or strips of turfgrasses along with adhering soil. Turgeon (2006) defined “sod” as “the surface layer of turf harvested for transplanting,” which is this definition commonly agreed upon today. Sod can vary in depth and includes interrelated components of turfgrass plants, the soil that clings to their roots, and the turf's subsurface structures. Beard (1973) mentioned that a high-quality sod should possess multiple desired characteristics, which include: i) uniformity, ii) high shoot density, iii) acceptable color, iv) sufficient strength for harvesting and handling, v) free from harmful pests (including weed seeds, insects, diseases, and nematodes), vi) adequate maturity in carbohydrate reserves to allow effective rooting, and vii) minimum thatch formation. The development of automated sod cutters, the introduction of improved cultivars, and the availability of some broadleaf herbicides contributed to a considerable boost in the growth of the sod industry (Beard & Rieke, 1969).

Sod Mixtures

While turfgrass sod is often planted and sold as a single cultivar of one species for warm-season turfgrass sod (i.e., monostand), it is often planted as a polystand blend of multiple cultivars of a single species or a polystand mixture of numerous cool-season turfgrass species in cool-season sod production. Polystand mixtures of various turfgrass species or polystand blends of multiple cultivars of a single species ensure greater genetic diversity, higher adaptive potential to nonhomogeneous sites with microclimates, and a potential increase in abiotic and biotic stress tolerance compared with monostands (Beard, 1973; Dunn et al., 2002). Mixtures of turfgrass

species have also shown high recuperative ability from various forms of injury through their growth characteristics (Hall, 1980; Hall & Taylor, 1989).

Recent research has shown that TF sod has poor sod strength and handling for commercial sod production without the use of plastic netting or the inclusion of KB seed at planting (Braun et al., 2021a, 2022). When mixing TF and KB seed ratios at planting to increase sod strength, a TF:KB ratio of 90:10, 95:5, 97:3 (w/w), or similar is typically recommended and utilized in the sod production industry. Because of the rhizomatous characteristics of KB, the inclusion of 3 to 10% KB seed (by weight) anecdotally helps strengthen the TF sod compared to 100% TF sod. However, more work is required on this topic, especially on various seeding weight ratios and the influence of KB cultivar differences used in the mixture. Kentucky bluegrass is known for its diverse genetic differences among cultivars, such as growth aggressiveness differences and KB classification systems (Bonos et al., 2000, 2013; Huff, 2003).

Sod producers need more information on optimal KB seed ratios with TF and the influence of KB classification types (i.e., growth aggressiveness differences). In older research, Ross et al. (1991) evaluated several individual cultivars and two mixtures of turfgrass for rooting characteristics and sod tearing strength. They ranked ten turfgrass species in order of sod tearing strength, from strongest to weakest, which include three cultivars of KB, three cultivars of perennial ryegrass (*Lolium perenne* L.), three fine fescues (two Chewings fescue cultivars and one slender creeping red fescue) and two bentgrasses (*Agrostis* spp., which were *A. capillaris* L. and *A. castellana* L.). The findings of Ross et al. (1991) supported the report by Hurley and Skogley (1975), which concluded that KB cultivars had high sod strength, followed by fine fescues, then perennial ryegrass and *Agrostis* species. In addition, the monostands of the species mentioned above with a bunch-type growth habit are thought to create poor harvesting, handling,

and transport properties due to low mechanical strength. The two previously mentioned research experiments may not be as relevant today since they are 40+ years old, and there have been major improvements in breeding for these turfgrass species. Thus, since this research, new and improved cultivars of fine fescues through breeding programs have demonstrated enhanced sod strength and handling, at times similar to or higher than Kentucky bluegrass (Braun et al., 2021a, 2022c). Braun et al. (2022c) also carried out a research experiment on sod mixtures involving low-input turfgrass species (e.g., fine fescues) and KB to evaluate turfgrass quality, sod performance, and post-harvest storage and transplanting success. The authors reported sod mixtures of fine fescues, especially those containing strong creeping red fescues at $\geq 33\%$ by seed weight, produced high-quality sod and high sod strength similar to polystand blends of 100% KB sod. Braun et al. (2022c) also reported 100% rhizomatous TF sod, and 100% bunch-type TF sod had poor sod strength and handling during harvest. Another advantage of sod mixtures containing fescues (fine fescue or TF) with KB is a faster establishment period compared to 100% KB sod, which could reduce weed infestation and herbicide input requirements (Braun et al., 2021a, 2022c). In order to be profitable, a sod producer's objective is to grow and harvest sod as quickly as possible with minimal management inputs. This depends on factors such as the type of turfgrass species, cultivars, timing of establishment, seeding rates, potential for reestablishment after harvest, and management practices (Braun et al., 2021a). Prior to Braun et al. (2021a, 2021b, 2022c) and Braun and Patton (2022), information on alternative cool-season turfgrass sod species was scarce, and there was limited and outdated agronomic information available to sod producers (Cockerham, 1988; Holland et al., 2000). More information is needed on alternative cool-season turfgrass species to substitute for monostand and polystand-blends of

KB and meet future demands with increasing popularity of TF in the transitional climatic zone of the U.S.

The establishment vigor and population dynamics of turfgrass species should also be taken into consideration when mixing turfgrass species for sod production. Aggressive cultivars can dominate other cultivars or species when used in blends or mixtures overtime (Bonos et al., 2000, 2013; Gibeault et al., 1993). For example, KB cultivar might dominate TF or PR population in sward due to their aggressive nature which might increase the demand for higher management input requirements like fertilization, irrigation, mowing etc., as the turf mature (Brede & Duich, 1984a, 1984b; Dunn et al., 2002; Gibeault et al., 1993; Hall and Taylor, 1989; Hunt & Dunn, 1993). Irrigation needs by turfgrass, and other environmental factors might also influence species composition overtime when mixed (Dunn et al., 2002) which was contrary to the reports by Hunt and Dunn (1993), who suggest that mixtures of tall and Kentucky bluegrass stabilized after four years. A study by Dunn et al. (2002) confirmed that KB was more competitive with tall fescue in irrigated plots than non-irrigated plots, with an average population of 63% TF and 48% KB after five years which was measured with an optical-point quadrat. Furthermore, Macolino et al. (2014) in a study investigated a mixture of tall fescue and Kentucky bluegrass at a 90% TF and 10% KB (w/w), broadcasted by seed, to observe species succession on stand. They found out KB had a significant increase in their population percentage at the end of the 2-yr period, increasing by about 33 to 42% which indicates that KB was becoming more dominant in the mixture with TF over time. Similarly, Pornaro et al. (2021) in a five-year study, documented that KB increased in population overtime but had a more stable composition with rhizomatous TF when compared with non-rhizomatous TF cultivars. In comparison, if aggressive cultivars dominate a turfgrass sward, this may crowd out most weeds and withstand foot traffic

better, but it may also suppress slower-growing cultivars with less lateral spread (Bonos et al., 2013; Murphy et al., 1997). Macolino et al. (2014) reported that rhizomatous tall fescue in mixtures with KB had better turf quality and experienced less competition among species when compared with mixtures containing bunch-type TF cultivars which also agrees with Gibeault et al. (1993). This suggests that the turfgrass quality of rhizomatous TF and KB mixes, were primarily a function of a more well-established TF stand, which also aligns with report of Fiorio et al. (2012). In contrary, St. John et al. (2009), reported no differences in establishment rate between rhizomatous and bunch-type TF cultivars. It is unclear if this competitiveness among cultivars is due to their rhizomatous growth habit or increased tillering density, or if rhizomes produced by TF will influence sod strength without mixing with KB. Although Davis (1958) reported that KB had more resistance to invasion by bentgrass (*Agrostis* spp.) and differences were observed among cultivars, more KB bluegrass with distinct aggressive growth characteristics have been released and list updated by breeders and seed companies, also turf-type tall fescue, rhizomatous tall fescue. Therefore, more work is needed to understand the mixture ratios of different cultivars or species and how aggressive differences influence plant species composition, establishment vigor and sod production characteristics.

Shildrick (1982) conducted a study on the effects of mixture proportions, seeding rate, and sod tearing strength in the mixtures of KB and some other bunch-type cool-season grasses; findings showed that rhizomatous components, including KB and other bunch-type turfgrasses, were responsible for improved sod tearing strength when seeded in mixtures. Braun et al. (2021a, 2022c) reported similar findings; more specifically, species that consistently produce rhizomes, such as KB and strong creeping red fescue, resulted in greater sod strength and handling when included in mixtures compared to bunch-type *Festuca* species or rhizomatous TF. Therefore, sod

producers must carefully consider what species or mixtures they are planting because it will influence sod strength. Regardless, more research is needed on cool-season sod production to assist sod producers.

Sod Production

Sod Tensile Strength

In sod production, mechanical strength is essential to withstand harvest, transport, handling, and installation (Burns & Futral, 1980). Previous studies indicated the potential to create sufficiently strong sod from alternative turfgrass species, such as fine fescues and TF, and the need to identify proper species and mixture proportions when producing commercial sod (Braun et al., 2021a, 2022; Braun & Patton, 2022). Rieke et al. (1968) were the first scientists to define sod strength, which is the weight (measured in kilograms or pounds) required to tear apart a piece of sod into two parts. According to Ross et al. (1991), sod strength, sod tearing strength, and sod tensile strength are a variety of names and terminologies employed over time by researchers but have a similar meaning. Sod strength can be referred to as the capacity of sod to resist longitudinal stress and measured as the force needed to rip the sod (Shearman et al., 2001). Over time, the term sod tensile strength was defined as the ability of sod to withstand longitudinal stress and measured as the minimum amount of longitudinal stress needed to tear the sod (Heckman et al., 2001). Studies show that different turfgrass species and cultivars have different sod tensile strength (Braun et al., 2021a, 2022c; Braun & Patton, 2022; Gopinath et al., 2021; Han, 2009; Shearman et al., 2001).

Researchers have used several custom-designed devices to measure the sod tensile strength. Rieke and his team, in 1968, developed the first devices used to measure sod tensile

strength, which was a manually operated device to pull the sod piece apart. In 2009, Han developed another improved device to measure sod tensile strength, which followed the design principles used by Rieke et al. (1968) and Sorochan et al. (1999). His modification involved building on the position of the table. He mounted the table vertically instead of horizontally to align the force vectors exerted by the linear actuator on sod shearing and the force of gravity. Dimensions of the sod tensile strength device was 147 x 53 x 97 cm (height x width x depth), and it weighed 65 kg (excluding the battery). The device had two plates: one upper and one lower. The upper plate was stationary, while the lower plate was mobile. The sod was clamped in such a way that it was in contact with both plates. Upward pulling of the upper plate caused the sod pad to break. The peak force required to tear the sod was measured by a digital force meter (Chatillon brand, digital force instrument, Model DFIS, John Chatillon & Sons, Inc.,) and the values obtained were converted into peak force per cross-sectional area (kg dm^{-2}).

More recently, Friell et al. (2017) created a computerized sod tensile strength device and described sod tensile strength output from a device as “sod tensile load” measured in newtons (N) (energy) and plotted by separation displacement in meters.” This custom-built device has built by others and generated outputs of “maximum tensile load to tear sod” (Newtons), which is the peak force required to tear a piece of sod, and the “required work to tear a piece of sod” (i.e., force over an applied distance, N-m), which is the area under the load-displacement curve (Braun et al., 2021a, 2022c; Friell et al., 2017). These two sod strength variables have shown to be positively correlated with one another through multiple experiments [$r = 0.87$ (Braun & Patton, 2022), $r = 0.82$ to 0.88 (Braun et al., 2021a), $r = 0.85$ to 0.86 (Braun et al., 2022c), $r = 0.92$ (Friell et al., 2017)]. Furthermore, this advanced custom-built sod tensile testing device by Friell et al. (2017) and Braun et al. (2021a) had a similar concept to Instron Universal Tester used by

Burns and Futral (1980). They proposed that sod tensile strength be tested by mounting cut samples of sod on the device, clamping each end between two boards such that each was securely held within a ~30 by 30 cm area with ~11 cm spacing between the two clamped sections when pulled apart. One clamped end can slide freely while the other is fixed and then supported on the bottom by spherical roller bearings. The unit applies a tensile load to the sod by pulling the free end via a mechanical arm (i.e., linear actuator). A load is applied until a set distance is reached and usually the pieces of sod are torn into two cleanly separated pieces. The tensile load of the sod piece is measured using a load cell, and string potentiometer is used to record the total distance that the sod was stretched. Their customized digital sod device has on onboard Raspberry Pi computer to collect and store all the data points. The custom-built device by Braun and Patton (2022) and Braun et al. (2021a, 2022c) is similar to that built by Friell et al. (2017), with slight improvements to improve usability and speed of operation. The advantage of this type of computerized device is that it collects non-subjective data and has a constant tearing method each time to provide consistent data collected during a sod harvest event or across multiple sod harvest timings.

Sod Handling

Sod handling is a relatively new method developed to assess the handling quality of sod pieces (i.e., rolls or slabs) when harvested. According to different reports, Han (2009) is believed to be the first researcher to evaluate sod handling, which utilized a qualitative and numerical grading scale. He developed a straightforward and quick method for assessing harvested sod pieces. This method does not involve the use of complex equipment for assessing sod pieces. Hence, sod producers and scientists can be easily trained in the implementation of this technique (Han, 2009). His technique used to assess sod handling involved using a unit less scale with

values from one to five, where: 1 = complete breakage, inability to transport to sod tearing device (unacceptable quality); 2 = substantial cracking, but still transportable to sod tearing device; 3 = moderate cracking (this was the suggested minimum acceptable value for industry handling); 4 = very mild cracking (this was the desired minimum rating for cultivar commercialization); and 5 = no cracking. One disadvantage of this method is it can be subjective based on the user grading the sod, and there can be inconsistency between graders and between dates within the same grader. This method has been included in many past sod experiments and is strongly correlated with sod strength output from sod tensile devices ($r = 0.28$ to 0.69) (Braun et al., 2021a, 2022c; Braun & Patton, 2022; Gopinath et al., 2021; Han, 2009). Braun et al. (2022c) and Braun and Patton (2022) created grading rubric for cool-season sod production that includes all three-sod strength and handling measurements of maximum tensile load to tear sod, required work to tear sod, and sod handling.

Establishment

Turfgrass establishment vigor is very important to turfgrass practitioners and sod farmers because establishment differences are known among species and cultivars, which greatly influence plant competitiveness of desired plants with other unwanted species germinating in the field (e.g., weed species) (Braun et al., 2021a, 2022c; Harper, 1961; Ross & Harper, 1972). Braun et al. (2021a), suggested that competitiveness existing among cool-season turfgrass species has the tendencies of influencing the long-term success of turfgrass sod swards. Establishment vigor of turfgrass species is laid out into three components which include (1) germination time from seed (i.e., germination vigor), (2) visible seedling emergence above the soil surface, and (3) the seedling growth rate after emergence (i.e., seedling vigor). Past research has shown that variation occurs in the establishment vigor of turfgrass species according to their

corresponding recuperative potential, vertical and horizontal growth rates (Beard, 1973; Braun et al., 2021a, 2022c, 2023b; Braun & Patton, 2022; Brede, 2000; Christians et al., 2017; Patton & Braun, 2022). According to Braun et al. (2021a), TF reached >90% turfgrass cover 4–12 weeks sooner than KB in the field in Indiana. Furthermore, the establishment of TF in comparison to KB was not affected by an increase in N fertilizer rates from 98 kg N ha⁻¹ yr⁻¹ to either 196 or 294 kg N ha⁻¹ yr⁻¹. Due to the slow germination, emergence, and establishment of KB compared to other cool-season turfgrass species, the potential until the first successful sod harvest may take longer than other cool-season species (Braun et al., 2021a). In addition, Braun et al. (2021a) reported KB may need higher N fertilizer inputs to promote a faster establishment and reduce weed encroachment during establishment. Past research suggests establishment vigor differences among cool-season turfgrass species may or may not influence sod strength or sod production period (i.e., the time required until harvestable sod), which can also vary depending on the growing climate conditions (Braun et al., 2020, 2021a; Friell et al., 2017). More research is needed to understand the earliest possible sod harvest timings for different cool-season turfgrass species and different climates. Past KB sod research (Braun et al., 2021a, 2021b, 2022c; Friell et al., 2017; Griffith et al., 2017, Shearman et al., 2001), have documented sod production periods of KB in different sites which ranged from 10 to 20 required months in Minnesota, Wisconsin, Indiana, Nebraska, and Maryland. Therefore, production periods have a variable range and more research on improving establishment vigor may help hasten sod maturity and reduce these sod production lengths.

Management Practices

Several studies have reported on the effects of management practices on the root zone, quality, and sod production characteristics of cool-season and warm-season sod (Braun et al.,

2021a, 2021b, 2022; Braun & Patton, 2022; Brosnan et al., 2014; Hall, 1980; Hall III & Bingham, 1993; Mitchell & Dickens, 1979). Fertilization, mowing, pesticide applications, and plant growth regulators are among the regular turfgrass management practices for aesthetically pleasing, functional, and healthy sod. Sod development may be impacted positively or negatively by these management practices.

Mowing

Guertal and Evans (2006) reported that root systems become shallower as turfgrass mowing height decreases. Mowing turfgrass subjects it to continuous stress due to removing foliage, leaf tissue, and shoots necessary for photosynthesis. Mowing reduces the ability of plants to store carbohydrates required for the growth and development of shoots and roots. The plant compensates for this loss by directing the carbohydrates to the shoots to acquire greater leaf area and shoot density, thereby decreasing rooting depth. To make up for this loss, the plant directs carbohydrates to the shoots to increase leaf area and shoot density, which results in a reduction in rooting depth. Although there are generally recommended mowing heights for each turfgrass species, Hall (1980) reported that mowing heights did not influence the sod tensile strength of either TF or KB.

Fertilization

Most turfgrass species should be able to maintain maximum turf cover and quality under a range of different N fertility levels. Because of past research, each turfgrass species has a recommended annual N fertilization rate range for optimal growth in turfgrass systems (Christians et al., 2017). Although increasing N fertilizer rates resulted in better turfgrass quality across most species, Braun et al. (2021a) reported minimal-to-no sod strength and handling benefits with increased annual N fertilizer rates for multiple cool-season turfgrasses, including

both TF and KB. Braun et al. (2021a) reported that N fertilization had a slight but inconsistent influence on sod strength and handling, which shows that an increase in the annual application of N fertilizer will not consistently increase the sod strength of KB and TF. This suggests that sod producers can apply a lower amount of N fertilizer and still get good sod strength. Hall (1980) reported a decrease in sod strength at higher rates of N application ($81 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) on TF and KB sod.

Pesticide Application

Pesticide applications (i.e., herbicides, insecticides, and fungicides) are often an essential practice in commercial sod production because consumers desire high-quality sod that is uniform, healthy, and free of weeds, insect pests, and disease pests. The presence of these pests in a sod degrades the quality and aesthetics of the sod and likely the consumer price (i.e., revenue for the sod producer). Weeds can negatively impact the physiological, functional, and aesthetic qualities of turfgrass, as well as affect the visual quality, rooting, regrowth, and sod tensile strength (Brosnan et al., 2014). Fortunately, there are many different pesticide options for both cool-season and warm-season turfgrass species (Elmore et al., 2024; Patton et al., 2022).

Sod Netting

To meet the demands of the current sod market, sod producers growing TF:KB mixtures often wish to include the lowest ratio of KB, generally <5% (R. Braun, personal communication, 2022). If sod producers do not include any KB to increase sod strength and handling, then they include plastic netting at seeding or during harvest, which is another input, cost, and additional challenge (Braun et al., 2021a, 2022c). In addition, plastic netting may require many years, likely decades, to degrade and decompose in the soil, and may be a source of microplastic pollution. This plastic netting can also harm wildlife and creates turfgrass management challenges when

performing common practices such as cultural practices (i.e., aeration and verticutting) or digging holes.

The use of sod netting has become a common technique in the sod industry to improve sod-forming ability and handling at harvest (Christians et al., 2017). There are varying opinions on the preferential use of sod netting by sod producers. There are three methods of applying netting: i) below the soil surface, ii) on the surface of the recently seeded sod field, and iii) incorporating netting mechanically onto the undersurface of the big rolls of sod during harvest to provide additional strength and stability to the heavy pieces of sod. The vegetative growth in turfgrass systems combines with the net as the plants mature, and this creates a robust and consistent sod. According to Christians et al. (2017), netting is a tool primarily used in turfgrass species that have inadequate sod tensile strength for handling due to the growth habit, such as bunch-type turfgrasses. Sod netting was previously made of nylon netting (Carrow & Sills, 1980; McCalla et al., 2008), plastic mesh (Burns, 1980), and more recently biodegradable netting (Nedia Enterprises, 2018). One of the benefits of netting during sod production is that it improves sod handling characteristics of turfgrass plants and reduces production cycle time (Christians et al., 2017); however, some of the pitfalls in using sod netting are that it is cost intensive, difficult to use, and can pose a harmful threat to the ecosystem due to the non-to-slow degradable materials used (Decker, 1991, 2010). More research is needed that investigates netting practices in the sod industry and the potential of this netting to biodegrade. Because the plastic netting may be a possible form of microplastic pollution, sod research objectives should be focused on producing sod without the use of netting.

Conclusions

Cool-season sod production is a vital component of the turfgrass industry that is increasing because of the demand for high-quality turfgrass sod for athletic fields, golf courses, home lawns, commercial properties, and new construction. Research has shown that demands will likely increase due to the increasing population and changes in the residential codes and buildings. However, to meet the demand, more research is required on turfgrass species, cultivars, and mixtures that will produce the best quality sod within a short amount of time.

Research has shown that some cool-season turfgrasses, such as Kentucky bluegrass, tall fescue, and some fine fescues (i.e., strong creeping red fescue, slender creeping red fescue, and at times Chewings fescue), are preferred and have the potential for cool-season sod production in the northern and transitional climatic zones in the United States. Homeowner and turfgrass practitioner preference for tall fescue is increasing compared to Kentucky bluegrass because of its better heat and drought stress tolerance. Therefore, there is a need for more research to meet these future demands, especially related to 100% tall fescue sod or sod mixtures of tall fescue and Kentucky bluegrass. This review summarizes research on cool-season sod production involving KB and TF. More consistent sod testing of cultivars of these cool-season species needs to be evaluated for a range of varying sod production periods in the transitional climatic zone in the U.S. because this will help to identify species, cultivars, and polystand blends or mixtures that have genetically broader adaptations to the northern and transition climatic regions of the United States. There are known genetic differences among Kentucky bluegrass cultivars, thus research is required to better understand how different growth aggressiveness classifications and Kentucky bluegrass classification systems influence 100% Kentucky bluegrass sod or tall fescue-Kentucky bluegrass sod mixtures. Furthermore, more knowledge of the composition differences

(i.e., population dynamics) and compatibility over time of tall fescue and Kentucky bluegrass at different seeding mixture ratios is warranted. For example, research on different Kentucky bluegrass seeding mixture ratios with tall fescue will help not only sod producers but also turfgrass practitioners understand how the population dynamics of the two species change over time. Research on rhizomatous tall fescue cultivars is also warranted to determine lateral spread differences and rhizome influence on sod strength and handling. Little research has been done in this area even though more rhizomatous cultivars are commercially available each year.

References

- Adams, W. A., & Bryan, P. J. (1974). *Poa pratensis* L. as a turfgrass in Britain. In E. C. Roberts (Ed.) *Proceedings of the 2nd International Turfgrass Research Conference*, 41–47. International Turfgrass Society, Blacksburg, VA, USA. 19-21 June 1973. Madison, WI: ASA, CSSA. <https://doi.org/10.2135/1974.proc2ndintlurfgrass.c6>
- Ball, D. M., Pedersen, J. F., & Lacefield, G. D. (2002). The tall fescue endophyte. *Journal of American Science*, 81, 370–379.
- Bara, R. F., Dickson, W. K., Murphy, J. A., Smith, D. A., & Funk, C. R. (1993). Performance of Kentucky bluegrass cultivars and selections in New Jersey turf trials. *Rutgers Turfgrass Proceedings*, 25, 49–94.
- Beard, J. B., & Rieke, P. E. (1969). Producing quality sod. In: A. A. Hansen and F. V. Juska, (Ed.) *Turfgrass Science Monograph*, 14, 442–461. Madison, WI. USA: ASA.
- Beard, J. B. (1973). *Turfgrass: Science and Culture*. Prentice-Hall, Englewood Cliffs, New Jersey.
- Beard, J. (2013). Origins of North American Turfgrasses. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Eds.), *Turfgrass: Biology, use, and management* (pp. 1–35). American Society of America, Soil Science Society of America, and Crop Science Society of America. Madison, WI.
- Begitschke, E. G., McCurdy, J. D., Tseng, T. M., Barickman, T. C., Stewart, B. R., Baldwin, C. M., Richardson, M. P., & Ward, J. K. (2018). Preemergence herbicide effects on establishment and tensile strength of sprigged hybrid bermudagrass. *Agronomy Journal*, 110, 2243–2249. <https://doi.org/10.2134/agronj2017.12.0720>.

- Bonos, S. A., Meyer, W. A., & Murphy, J. A. (2000). Classification of Kentucky bluegrass genotypes grown as spaced-plants. *HortScience*, 35, 910–913.
<https://doi.org/10.21273/HORTSCI.35.5.91>
- Bonos, S. A., & Huff, D. R. (2013). Cool-season grasses: Biology and breeding. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Eds.), *Turfgrass: Biology, Use, and Management*, 591–660. ASA, CSSA, and SSSA. <https://doi.org/10.2134/agronmonogr56.c17>
- Borrill, M. (1976). Temperate Grasses. p. 137–142. In N. W. Simmonds (ed.). *Evolution of Crop Plants*. Longman, London and New York.
- Braun, R. C., & Patton, A. J. (2022). Species, clover-inclusion, and nitrogen fertilizer effects on sod tensile strength of fine fescue taxa. *Agronomy Journal*, 114, 1705–1716.
<https://doi.org/10.1002/agj2.21039>
- Braun, R. C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022a). Review of cool-season turfgrass water use and requirements: I. Evapotranspiration and responses to deficit irrigation. *Crop Science*, 62, 1661–1684. <https://doi.org/10.1002/csc2.20791>.
- Braun, R.C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022b). Review of cool-season turfgrass water use and requirements: II. Responses to drought stress. *Crop Science*, 62, 1685–1701. <https://doi.org/10.1002/csc2.20790>.
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021a). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: I. Establishment and sod tensile strength. *Agronomy Journal*, 113, 4176–4189. <https://doi.org/10.1002/agj2.20810>.
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021b). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod

- production: II. Management and shelf-life. *Agronomy Journal*, 113, 3460–3474.
<https://doi.org/10.1002/agj2.20777>
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2022c).
 Management, harvest, and storage characteristics of low-input cool-season turfgrass sod
 mixtures. *Agronomy Journal*, 114, 1752–1768. <https://doi.org/10.1002/agj2.21051>
- Braun, R. C., Courtney, L. E., & Patton, A. J. (2023a). Seed morphology, germination, and
 seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species.
Crop Science, 63, 1613–1627. <https://doi.org/10.1002/csc2.20936>
- Braun, R. C., Watkins, E., Hollman, A. B., & Patton, A. J. (2023b). Assessing the fertilizer and
 pesticide input needs of cool-season turfgrass species. *Crop Science*, 63, 3079–3095.
<http://doi.org/10.1002/csc2.21046>
- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in
 environmental protection and their benefits to humans: Thirty years later. *Crop Science*,
 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Brede, A. D., & Duich, J. H. (1984a). Initial mowing of Kentucky bluegrass-perennial ryegrass
 seedling turf mixture. *Agronomy Journal*, 76, 711–714.
- Brede, A. D., & Duich, J. H. (1984b). Establishment characteristics of Kentucky bluegrass-
 perennial ryegrass turf mixture as affected by seedling rate and ratio. *Agronomy Journal*,
 76, 875–879.
- Brede, A. D. (2000). Turfgrass Maintenance Reduction Handbook: Sports, Lawns, and Golf.
 Chelsea, MI: Ann Arbor Press.
- Brilman, L. A. (1998). Coming soon: Creeping tall fescues? *Golf Course Management*, 66, 64–
 66.

- Brilman, L. (2018). Kentucky bluegrass classification. Seed Research of Oregon. Accessed 20 June 2023.
https://www.sroseed.com/Files/Files/SRO_USA/Brochure_Etc/SRO_KB_classifications-Jan-2018_Final.pdf.
- Brilman, L. (2024). *Kentucky bluegrass classification*.
<https://www.dlfpickseed.com/professional-turf/varieties/bluegrass> Accessed 5 November 2024
- Brosnan, J. T., Breeden, G. K., Thoms, A. W., & Sorochan, J. C. (2014). Effects of pre-emergence herbicides on the establishment rate and tensile strength of cool-season grasses. *Weed Technology*, 28, 206–212.
- Burns, R. E., & Futral, J. G. (1980). Measuring sod strength with an Instron Universal Testing Instrument. *Agronomy Journal*, 72, 571–573.
- Buckner, R. C., Powell, J. B., & Frakes, R. V. (1979). Historical develop- Acremonium coenophialum in tall fescue on animal performance, 1–8. In R.C. Buckner and L.P. Bush (ed.) Tall fescue. toxicity, and stand maintenance. *Agronomy Journal* 78, 848–850. *Agronomy Monograph* 20. ASA, CSSA, and SSSA, Madison, WI
- Burns, R. E. (1980). Techniques for rapid sod production. In J. B. Beard (Ed.), Proceedings of the 3rd International. Turfgrass Research Conference, Munich, West Germany, 11–13 July 1977, 361–366. Madison, WI: ASA, CSSA, SSSA, and *International Turfgrass Society*.
- Bushman, B. S., Warnke, S. E., Amundsen, K. L., Combs, K. M., & Johnson, P. G. (2013). Molecular markers highlight variation within and among Kentucky bluegrass varieties and accessions. *Crop Science*, 53, 2245–2254. <https://doi:10.2135/cropsci2013.02.0110>

- Carrow, R. N., & Sills., M. (1980). Tall fescue sod production with plastic netting. *HortScience*, 15(6), 818–820.
- Carrow, R. N., Leuthold, L. & Campbell, R. W. (1981). Netting, tall fescue team up to produce nine-month sod. *Weeds, trees and turf*.
- Carrier, L., & Bort, K. S. (1916). The History of Kentucky Bluegrass and White Clover in the United States. *Agronomy Journal*, 8(4), 256.
<https://doi.org/10.2134/agronj1916.00021962000800040007x>
- Christians, N. E., Patton, A. J., & Law, Q. D. (2017). Fundamentals of Turfgrass Management (5th ed.). John Wiley & Sons, Inc., Hoboken, New Jersey.
<https://doi.org/10.1002/9781119308867>
- Cockerham, S. T. (1988). Turfgrass sod production (Cooperative Extension Publication 21451). Oakland: *Division of Agricultural and Natural Resources*, University of California.
- Davis, R. R. (1958). The effect of other species and mowing height on persistence of lawn grasses. *Agronomy Journal*, 50, 671–673.
<https://doi.org/10.2134/agronj1958.00021962005000110009x>
- De Battista, J. P., & Bouton., J. H. (1990). Greenhouse evaluation of tall fescue genotypes for rhizome production. *Crop Science*, 30, 536–541.
<https://doi.org/10.2135/cropsci1990.0011183X003000030012x>
- Decker, H. F. (1991). Alternative method for producing tall fescue sod. U.S. Patent 4,986,026.
- Decker, H. F. (2010). Producing sods over plastic in soilless media. *Horticultural Reviews*, 27, 317–351. <https://doi.org/10.1002/9780470650813.ch8>

- Dunn, J. H., Ervin, E. H., & Fresenburg, B. S. (2002). Turf performance of mixtures and blends of tall fescue, Kentucky bluegrass, and perennial ryegrass. *HortScience*, 37(1), 214–217.
<https://doi.org/10.21273/HORTSCI.37.1.214>
- Elmore, M., Miller, G., Patton, A., Richmond, D., Reynolds, C., & Chavarria Sanchez, M. D. (2024). Weed, Insect, and Disease Control for Turfgrass Producers, 2024–2025 edition. *Turfgrass Producers International*, Lombard, IL.
- Fiorio, S., Macolino, S., & Leinauer, B. (2012). Establishment and performance of bluegrass species and tall fescue under reduced-input maintenance in a temperate Mediterranean environment. *Horttechnology*, 22, 810–816.
- Friell, J., Watkins, E., Horgan, B.P., & Cavanaugh, M. (2017). Sod strength characteristics of 51 cool-season turfgrass mixtures. *Agronomy Journal*, 109, 1759–1757.
<https://doi.org/10.2134/agronj2016.05.0295>
- Fry, J., & Huang, B. (2004). *Applied Turfgrass Science and Physiology*. 1st ed. New Jersey: John Wileys and Sons, Hoboken, New, Jersey.
- Funk, C. R., Engel, R. E., Dickson, W. K., & Hurley, R. H. (1981). Registration of ‘Rebel’ tall fescue. *Crop Science*, 21, 632
- Funk, C. R., & Engel, R. E. (1984). Kentucky bluegrass and their culture. *Weeds Trees and Turf*, 23(6), 46–62.
- Funk, C. R. (2000). Long live Kentucky bluegrass, the king of grasses. *Diversity*, 16, 26–28.
- Gibeault, V. A., Cockerham, S. T., & Autio, R. (1993). An evaluation of tall fescue and Kentucky bluegrass mixes. *International Turfgrass Society Research Journal*, 7, 905–909.

- Gopinath, L., Martin, D. L., Moss, J. Q., Wu, Y., Yu, S., & Underwood, J. R. (2021). Sod Tensile Strength, Handling Quality, and Their Interrelationship for 39 Bermudagrasses. *HortTechnology*, 31(6), 780–785. <https://doi.org/10.21273/HORTTECH04893-21>.
- Griffith, S., Bero, N., Stier, J., Obear, G., Ruis, S., & Soldat, D. (2017). Biosolids as an alternative fertilizer for Kentucky bluegrass sod in Wisconsin. *Crop Science*, 57, S227–S237. <https://doi.org/10.2135/cropsci2016.05.0367>
- Guertal, E., & Evans, D. (2006). Nitrogen rate and mowing height effects on TifEagle bermudagrass establishment. *Crop Science*, 46, 1772–1778. <https://doi.org/10.2135/cropsci2006.01-0006>
- Hall, J. R. (1980). Effect of cultural factors on tall fescue - Kentucky bluegrass sod quality and botanical composition. *Proceedings of The Third International Turfgrass Research Conference*, 3, 367–377.
- Hall, J. R. III, & Bingham, S. (1993). Impact of growth regulators on Kentucky bluegrass sod management and installation parameters. *International Turfgrass Society Research Journal*, 7, 701–707.
- Hall, J. R. III, & Taylor, L. H. (1989). Impact of companion crop and fertilization on tall fescue sod production. *International Turfgrass Society Research Journal*, 6, 259–261.
- Harper, J. L. (1961). Approaches to the Study of Plant Competition. In F. L. Milthorpe (Ed.), *Mechanisms in Biological Competition*. Symposia of the Society for Experimental Biology, 15, 1 – 39. Cambridge University Press, Cambridge, England.
- Han, H. R. (2009). *Development Improved Turf-type Bermudagrasses*. M.S. Thesis, Oklahoma State University, Stillwater.

- Hannaway D., Fransen, S., Cropper, J., Teel, M., Chaney, M., Griggs, T., Halse, R., Hart, J., Cheeke, P., Hansen, D., Klinger, R., & Lane, W., (1999). Tall fescue (*Festuca arundinacea* Schreb.). Pacific Northwest Extension Publication, PNW 504. Corvallis, OR, USA: Oregon State University, 19 pp.
<http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/17828/pnw504.pdf;jsessionid=FFA109031C58C4EB58B5C9E1A5EC6821?sequence=1>
- Heckman, N. L., Horst, G. L., Gaussoin, R. E., & Frank, K.W. (2001). Storage and handling characteristics of trinexapac-ethyl treated Kentucky bluegrass sod. *HortScience*, 36, 1127–1130.
- Holland, R., Buchanan, J., Samples, T., & Cross, T. (2000). Commercial tall fescue-Kentucky bluegrass sod production. The University of Tennessee Agricultural Extension Service.
https://trace.tennessee.edu/utk_agexcomhort/13.
- Honig, J. A., Averello, V., Bonos, S. A., & Meyer, W. A. (2012). Classification of Kentucky bluegrass (*Poa pratensis* L.) cultivars and accessions based on microsatellite (simple sequence repeat) markers. *HortScience*, 47, 1356–1366.
<https://doi.org/10.21273/HORTSCI.47.9.1356>
- Honig, J. A., Averello, V., Kubik, C., Vaiciunas, J., Bushman, B. S., Bonos, S. A., & Meyer, W.A. (2018). An update on the classification of Kentucky bluegrass cultivars and accessions based on microsatellite (SSR) markers. *Crop Science*, 58(4) 1776–1787.
<https://doi.org/10.2135/cropsci2017.11.0689>.
- Hsiang, T. K., Carey, B. He, & Eggens, J. L. (1997). Composition of mixtures of four turfgrass species four years after seeding under non-wear conditions. *International Turfgrass Society Research Journal*, 8, 671–679.

- Huang, B., & Fu, J. (2001). Growth and physiological responses of tall fescue to surface soil drying. *International Turfgrass Society Research Journal*, 9, 291–296.
- Huff, D. R. (2003). Kentucky bluegrass. In: M.D. Casler and R.R. Duncan, editors, *Turfgrass Biology, Genetics, and Breeding*. Wiley, Hoboken, New Jersey, 27–38.
- Hurley, R. H., & Skogley, C. R. (1975). Evaluation of Kentucky bluegrass and red fescue cultivars for sod production. *Agronomy Journal*, 67, 79–82.
<https://doi.org/10.2134/agronj1975.00021962006700010022x>
- Hunt, K. L., & Dunn, J. H. (1993). Compatibility of Kentucky bluegrass and perennial ryegrass with tall fescue in transition zone turfgrass mixtures. *Agronomy Journal*, 85, 211–215.
- Kennedy, P. B. (1900). Cooperative experiments with grasses and forage plants. USDA Bull. 22.
- Krenitsky, E. C., Carrol, M. J., Hill, R. L., & Krous, J. M. (1998). Runoff and sediment losses from natural and man-made erosion control materials. *Crop Science*, 38, 1042–1046.
<https://doi.org/10.2135/cropsci1998.0011183X003800040026x>
- Lickfeldt, D. W., Voigt, T. B., & Hamblin, A. M. (2002). Cultivar composition and spatial patterns in Kentucky bluegrass blends. *Crop Science*, 42, 842–847.
<https://doi.org/10.2135/cropsci2002.0842>
- Macolino, S., Pignata, G., Giolo, M., & Richardson, M. D. (2014). Species succession and turf quality of tall fescue and Kentucky bluegrass mixtures as affected by mowing height. *Crop Science*, 54, 1220–1226. <https://doi.org/10.2135/cropsci2013.10.0669>
- McCalla, J., Richardson, M., Karcher, D., Landreth, J., & Patton, A. (2008). Sod production utilizing an improved seeded bermudagrass cultivar. *Applied Turfgrass Science*, 5, 1–9.
<https://doi.org/10.1094/ATS-2008-0118-01-RS>.

- Mitchell, C. H., & Dickens, R. (1979). Nitrogen fertilization and mowing height effects on tensile strength of bermudagrass sod. *Agronomy Journal*, 38, 1061–1062.
<https://doi.org/10.2134/agronj1979.00021962007100060039x>.
- Murphy, J. A., Bonos, S. A., & Perdomo, P. (1997). "Classification of *Poa pratensis* genotypes." *International Turfgrass Society Research Journal*, 8, 1176–1183.
- Nedia Enterprises. (2018). The natural choice for sod netting. Nedia Enterprises, Inc.
<http://biosodnet.com/>. (Accessed 12 April. 2023).
- Niehaus, M. H. (1976). Effect of cultivar, seeding rate, and nitrogen fertilization on Kentucky bluegrass-perennial ryegrass turf mixtures. *Agronomy Journal*, 68, 955–957.
- Patton, A. J., Elmore, M. T., Kao-Kniffin, J., Branham, B., Christians, N., Thoms, A., & Koch, P. (2022). Turfgrass weed control for professionals. West Lafayette, IN: Purdue University Extension Publication TURF-100.
- Patton A. J., & Braun, R. C. (2021). Measurement of turf height and growth using a laser distance device. *Crop Science*, 61, 3110–3123. <https://doi.org/10.1002/csc2.20295>
- Pornaro C., Masin, R., Macolino, S., & Richardson, M. (2021). Botanical composition of tall fescue-Kentucky bluegrass turfgrass mixtures is sustained in long-term study. *European Journal of Horticultural Science*, 86, 414–418.
<https://doi.org/10.17660/eJHS.2021/86.4.9>
- Ross, S. J., Ennos, A. R., & Fitter, A. H. (1991). Turf strength and root characteristics of ten turfgrass cultivars. *Annals of Applied Biology*, 118, 433–443.
<https://doi.org/10.1111/j.1744-7348.1991.tb05644.x>
- Ross, M. A., & Harper, J. L. (1972). Occupation of biological space during seedling establishment. *Journal of Ecology*, 60, 77–88. <https://doi.org/10.2307/2258041>

- Shearman, R. C., Turner, T. R., Morris, K. N., Gaussoin, R. E., Vaitkus, M. R., & Wit, L. A. (2001). Sod strength and lateral spread of *Poa pratensis* cultivars and experimental lines. *International Turfgrass Society Research Journal*, 9, 928–933.
- Shildrick, J. P. (1982). Mixtures and seed rates for sod production. *Journal of the Sports Turf Research Institute*, 58, 76–95.
- Singh, D., Klooster, G. V. & Wipff, J. K. (2005). Rhizome formation in tall fescue as affected by location and sampling period. In 2005 *Crop Science* abstracts. CSSA, Madison, WI. <http://crops.confex.com/crops/2005am/techprogram/P8737.HTM>
- Sorochan, J. C., Calhoun, R. N., & Rogers, J. N. III (1999). Apparatus to measure turfgrass sod strength. *Agronomy Abstracts*, 91, 137.
- St. John, R., Fry, J., Bremer, D. J., & Keeley, S. (2009). Establishment rate and lateral spread of *Festuca arundinacea* cultivars. *International Turfgrass Society Research Journal*, 11, 481–487. <http://hdl.handle.net/2097/2072>
- Su, K., Bremer, D. J., Keeley, S. J., & Fry, J. D. (2008). Rooting characteristics and canopy responses to drought of turfgrasses including hybrid bluegrasses. *Agronomy Journal*, 100(4), 949–956. <https://doi.org/10.2134/agronj2007.0292>.
- Taylor, L. H., & Schmidt, R. E. (1980). Differences in sod strength, rooting, and turfgrass quality of Kentucky bluegrass cultivars resulting from seasonal and environmental conditions. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference*, Munich, West Germany, 11–13 July 1977 (pp. 31–38). ASA, CSSA, SSSA, and International Turfgrass Society. <https://doi.org/10.2135/1974.proc3rdintlurfgrass.c4>
- Turgeon, A. J. (2006). Turfgrass Management at the National Mall. Report to Center for Park Management, Washington, D.C. 33 pages.

USDA-NASS. (2012). United States Department of Agriculture Census of Agriculture 2012.

USDA-NASS. <https://www.agcensus.usda.gov/Publications/2012/>.

USDA-NASS. (2016). Quick Stats 2.0. <https://quickstats.nass.usda.gov/>

USDA-NASS. (2021). United States Department of Agriculture Census of Agriculture 2012.

[https://www.agcensus.usda.gov/Publications/ 2021/USDA- NASS.](https://www.agcensus.usda.gov/Publications/2021/USDA-NASS.) (2021). United States Department of Agriculture Census of Agriculture 2021.

[https://www.agcensus.usda.gov/Publications/ 2021/](https://www.agcensus.usda.gov/Publications/2021/)

Whyte, R. O., Moir, T. R. G., & Cooper, J. P. (1959). Grasses in agriculture. FAO Agriculture Studies, No. 42.

Chapter 2 - Seeding Mixtures Ratios and Kentucky Bluegrass

Classifications Influence on the Sod Strength of Tall Fescue-

Kentucky Bluegrass Mixtures

Abstract

Sodding is an excellent method to provide immediate turfgrass cover and reduce the soil erosion potential at renovated sites. Because of its rhizomatous growth habit, Kentucky bluegrass (KB) (*Poa pratensis* L.) produces excellent sod strength and handling; however, tall fescue (TF) (*Festuca arundinacea* Shred.) is growing in popularity because of its excellent heat and drought tolerance. The bunch-type growth habit of TF is a limiting factor when producing 100% TF sod, which often requires plastic netting or the addition of KB to hold the sod together during harvest and transplanting. Sod producers need more information on the seeding ratio and aggressiveness classification of KB when mixed with TF to meet demands. Repeated field experiments at Kansas State University were conducted in 2022 and 2023 to evaluate the influence of seed mixture ratios (97:3, 95:5, and 90:10 w/w TF:KB) and KB classifications or growth aggressiveness labels on sod strength (maximum tensile strength and required work to tear) and sod handling (1-5 scale) at three harvests; 9, 10, and 12 months after planting (MAP). Experiment 1 results indicate a 95:5 w/w, TF:KB sod mixtures yielded similar sod strength and handling across multiple harvests (12.1 – 15.9 N-m), regardless of cultivar. Experiment 2 revealed that some 95:5 and 90:10 (w/w) mixture ratios of TF:KB produced higher sod strength (12.7 – 15.4 N-m) compared to 100% TF, but all 97:3 mixture ratios were similar to 100% TF sod (12.6 – 13.0 N-m). Establishment vigor data were similar across treatment for D₅₀, requiring 11 to 14 days to reach 50% establishment cover. There were ecological changes in mixture ratios

between TF and KB over a period of 2 years, with population tillers of medium growth aggressiveness label KB cultivars increasing by >25%. Results will assist sod producers and turfgrass practitioners with information when mixing KB with TF for commercial sod.

Introduction

Turfgrass sod provides instant green vegetation cover, and the demand for high-quality sod that is predominantly tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] (TF) is increasing due to water conservation and its drought and heat tolerance characteristics. There were more than U.S. \$583 million in combined sales of the turfgrass sod industry in the Northeast, Midwest, Plains, and Northwest U.S. regions in 2019 (USDA-NASS, 2021). As population, construction, and infrastructure upgrades continue to grow, turfgrass sod demands will likely increase as well. Kentucky bluegrass (KB) (*Poa pratensis* L.) and TF are two popular cool-season turfgrass species used for home lawns, golf course rough and fairway areas, parks, sports fields, and other grounds (Christians et al., 2017). Both of these turfgrass species are commonly planted as either seed or sod at new or renovated sites in the northern and transition climatic zones in the United States. These species are used in many different types of turfgrass systems, which provide numerous ecosystem service benefits (Braun et al., 2024). Some ecosystem service benefits include carbon sequestration, oxygen production, evaporative cooling effects, water filtration, soil stabilization and dust prevention, land reclamation and phytoremediation, and many other environmental and societal benefits that improve human well-being (Braun et al., 2024).

Kentucky bluegrass is a rhizomatous turfgrass species that forms a high-quality sod product because of the knitting characteristics of the underground lateral stems known as rhizomes (Braun et al., 2021a; 2022d; Fry & Huang, 2004; Christians et al., 2017). This excellent sod strength and handling characteristic helps the sod pieces to hold together during harvest and subsequent transport from the sod farm to the end consumer. However, KB does have some negative characteristics, such as its propensity for excessive thatch formation and high

management input requirements of nitrogen fertilization, irrigation, and mowing (Aronson et al., 1987; Braun et al., 2021a, 2023b; Christians et al., 2017; Li et al., 2011; Ross Braun and Aaron Patton; unpublished data, 2024). Thatch is an organic matter layer that forms below the turfgrass canopy and above the soil surface or it is integrated within the upper soil profile (Christians et al., 2017). Compared to KB, TF requires fewer management inputs (Braun et al., 2023b; Bremer et al., 2006; DeBels et al., 2012; Fiorio et al., 2012; Walker et al., 2007; Watkins et al., 2011; Watkins et al., 2014; Yue et al., 2012, 2017) and has better drought avoidance due to its deep rooting characteristics (Su et al., 2008; Braun et al., 2022c, 2022d). However, its limitation for sod production is the bunch-type growth habit that often forms weaker sod strength and handling (Braun et al., 2021a, 2022d). Ways to overcome the weak sod strength and handling is incorporating plastic netting, which is non-biodegradable, at planting or harvest to help hold the sod rolls together and another method is the inclusion of KB seed at planting within the sod mixture for the rhizomes to help increase sod strength and handling (Beard et al., 1980; Braun et al., 2021a; 2022d, Britton et al., 2006; Christians et al. 2017; Friel et al., 2017; Hurley & Skogley, 1975). The use of plastic netting may be detrimental to the environment because it often requires many years, likely decades, to degrade and decompose in the soil, thus it is a source of microplastic pollution. This plastic netting can also harm wildlife and create future challenges when performing common management practices such as aerification, digging, irrigation repair, and other renovation practices. These reasons often deter many sod producers to use plastic netting.

The inclusion of KB with TF for sod works well as these two species complement each other and aesthetically blend well. The rhizomatous characteristics of KB help these mixed turfgrass swards not only hold together better for sod production but also the rhizomes increase

recuperative potential and wear tolerance compared to 100% bunch-type turfgrass swards (Canaway, 1981; Christians et al., 1998; Park et al., 2005, 2010; Shearman & Beard, 1975; Shearman et al., 2001). Furthermore, research has suggested that a mixture of two or more cultivars or turfgrass species creates more genetic diversity to reduce damage from abiotic and biotic stresses and may potentially outperform the cool-season monostands (Beard 1973; Brede & Duich 1984; Gibeault et al., 1993; Hunt & Dunn, 1993; Powlen et al., 2021; Powlen et al., 2024; Reynolds et al., 2005; Steinke & Ervin, 2013; Vargas & Turgeon, 1980)

However, there are also drawbacks for including multiple species in cool-season mixtures. For example, the dominance of one species over another may create unacceptable turfgrass quality of “patchy” or “spotty” turfgrass or the dominant species may completely outcompete the other species depending on growth aggressiveness differences and growth habit characteristics, requiring higher inputs as they mature (Bouton et al., 1989; Brede, 2000; Gibeault et al., 1993; Hall & Taylor, 1989; Hunt & Dunn, 1993; Juska & Hanson 1959; Juska & Harrison, 1955; Pornaro et al., 2021; Park et al., 2017). Although >30 years old, research has investigated compatibility between perennial ryegrass (*Lolium perenne* L.) (PR) and KB, regardless many of the studied cultivars are neither no longer commercially available nor are they desired by turfgrass practitioners because of new and improved cultivars (Gibeault et al, 1980; Hunt & Dunn, 1993). The findings of Ross et al. (1991) concluded that KB cultivars had high sod strength, followed by fine fescues (*Festuca* L. spp.), then PR, *Agrostis* species (eg. *Agrostis capillaris* cv. Duchess; *Agrostis caspallana* cv. Highland) and TF. Seed mixtures of TF and KB have been used successfully for sod production of cool-season turfgrass species (Hall, 1980). Additionally, the monostands of the species mentioned above with a bunch-type growth habit created poor harvesting, handling, and transport properties because of poor sod strength.

Braun et al. (2021a, 2022) reported similar findings of high sod strength and handling with more modern-day cultivars of KB and fine fescues in comparison with TF. According to Braun et al. (2022d), sod mixtures of fine fescues, especially those containing strong creeping red fescues (*Festuca rubra* L. ssp. *rubra* Gaudin), at >33% by weight of the seed mixture, produced high-quality sod, sod strength and handling similar to polystand blends of 100% KB sod, and the weakest were 100% TF sod. Britton et al. (2006) evaluated TF with incorporation of multiple seed ratios of KB and hybrid bluegrass (*Poa pratensis* L. × *Poa arachnifera* Torr.) and also TF without netting to evaluate sod tensile strength. Britton et al. (2006) reported that 90% TF with HT produced a mean sod tensile strength of 60.6 Kg, although the highest sod tensile strength was a 70% TF rate with KB incorporated with netting (63.2 Kg). When mixing TF and KB seed ratios, a TF:KB ratio of 90:10, 95:5, 97:3 (w/w), or similar, is typically recommended and utilized in the sod production industry to help hold the TF:KB sod together during harvest (Braun et al., 2022d; Wade Wilbur, personal communication 2022). However, different optimal ratios likely depend on the growth aggressiveness (vertical and lateral growth of the KB cultivar) classification assigned by seed production companies and potentially its KB classification type (Bonos et al., 2000; Hall, 1980; Honig et al., 2012, 2018; Reynolds et al., 2005). Sod producers often limit the KB to 10% seed weight or less in a TF:KB mixtures for multiple reasons. One reason is the differences in seed size between KB and TF (Braun et al., 2023a; Christians et al., 2017), which KB has a much smaller seed size than TF (i.e., ~2,600 seeds per gram for KB compared to ~450 seed per gram for TF); therefore, more seeds per weight. For example, if a TF:KB mixture is planted at 95:5 (w/w), then the mixture may contain ~75% TF seed and ~25% KB seed because there can be four to six times as many KB seeds per weight compared to the TF. Furthermore, a TF:KB mixture planted at 90:10 (w/w) may contain a ~85% TF seed and

15% KB seed or 97:3 (w/w) mixture may contain ~60% TF and ~40% KB seed. Therefore, another reason for limiting KB inclusion in TF is that the sod producer may want to advertise the sod as mainly TF sod; however, if too much KB is included at seeding, then the turfgrass sward may be really a 50:50 TF:KB or more KB than TF. Hence, sod producers need to carefully consider how much KB to include with TF sod to improve sod strength and handling. More research is needed on these mixture ratios and how they influence sod strength and handling.

Compared to some cool-season turfgrass species, KB has a wide genetic diversity among cultivars (Bonos et al., 2013; Christians et al., 2017; Honig et al., 2012, 2018). Because of these genetic differences among KB cultivars, a KB classification system (grouping) has been used for >20 years in the turfgrass industry to help differentiate turfgrass characteristics among cultivars (Bonos et al., 2000, 2013; Brilman, 2018, 2020, 2024; Honig et al., 2012, 2018). Furthermore, seed companies often assign labels to cultivars such as “high,” “medium,” or “low” that describe their growth aggressiveness characteristics. This is often done to help inform turfgrass practitioners and sod producers to aid in cultivar selection when purchasing. There has been no work to investigate the relationship between these KB classification systems and sod strength and handling as well as other turfgrass characteristics and population dynamics. More work is needed on this topic.

The ecology and population dynamics of KB, TF or PR mixtures can be complex, and it is not clear why some seed mixtures of KB:TF or a KB:PR will shift toward a more dominated KB sward. Some researchers suggested that more aggressive or better-adapted KB cultivars in seed mixes with other turfgrass species will begin to dominate them, whereas less aggressive or poorly adapted KB cultivars maintain equal populations with others (Brede, 2000, 2008; Lickfeldt et al., 2002; Stier et al., 2005). Hsiang et al. (1997) suggested that the shift in the

species population towards to more KB may be due better environmental tolerance and greater high disease pressure of susceptible species like PR and TF. According to Proctor et al. (2015), seeding at 90:10 or 80:20 KB:PR (w/w) seed mixtures can provide establishment cover equivalent to 50:50 mixtures in areas or years with low weed pressure and will likely consist of greater than 95% KB within two years of establishment. While these past reports are helpful, some of this research is >30 years and there have been major breeding advancements across all cool-season turfgrass species (Bonos et al., 2013). Newer cultivars of TF and PR have greater tillering and density and may provide greater competition against spreading grasses like KB; however, more research is needed on this topic. One advantage of sod mixtures containing fescues (e.g., fine fescue taxa or TF) is a faster establishment period compared to KB, which could reduce weed infestation and herbicide input requirements (Braun et al., 2021b, 2022d). Overall, there is insufficient data on the population dynamics and how it changes with seed mixture ratios of TF:KB, especially with new and improved cultivars.

This chapter has multiple objectives to investigate the influence of KB classifications and seed mixture ratios of TF:KB on: i) sod strength and handling, ii) establishment vigor, and iii) population changes over time. More specifically, the objectives of Experiment 1 were to quantify the influence of nine KB cultivars of varying growth aggressiveness labels and KB classifications mixed with TF in a 95:5 (w/w) mixture, and the objectives of Experiment 2 were to quantify the influence of three KB cultivars of varying growth aggressiveness levels mixed in varying TF:KB mixtures of 97:3, 95:5, and 90:10 (w/w).

Materials and Methods

Field Experiment Site

Two field experiments (Experiment 1 and Experiment 2) were conducted to meet research objectives from 2022 to 2024 at the Rocky Ford Turfgrass Research Center in Manhattan, KS, USA (39° 13' 53" N, 96° 34' 51" W). Both field experiments were repeated over space and time [9 Sept. 2022 to 20 Sept. 2024 (Run 1) and 8 Sept. 2023 to 9 Sept. 2024 (Run 2)]. The soil at the site in both experiments was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls) with a soil pH of 6.8 to 7.2 and organic matter measurement of 78 to 81 g kg⁻¹. Soil testing at the site for both experiment runs also revealed 112 to 122 mg kg⁻¹ P (Mehlich-3 method) and 460 to 500 mg kg⁻¹ K (ammonium acetate method). All field experiments were in full sun and a weather station (<https://mesonet.k-state.edu>) was within 50 m of the experiments.

Experiment Design and Treatments

Both field experiments included KB and TF cultivars. These cool-season turfgrass species and specific cultivars used for both experiments and sources are listed in Table 2.1. Kentucky bluegrass classification, growth aggressiveness types and classification descriptions are shown in Table 2.2. Both experiments were set up in a one-way treatment design arranged in a randomized complete-block design with four complete blocks (reps). Each experiment had ten treatments for a total of 40 plots. Plot size in both experiments measured 1.2 by 1.2m (4 x 4 ft). Experiment 1 investigated a TF:KB mixture ratio of 95:5 w/w using nine different KB cultivars of varying growth aggressiveness labels (i.e., high, medium, and low aggressiveness) and KB classifications for the KB in the mixture (Table 2.3). Additionally, one polystand blend of three cultivars of 100% bunch-type TF was included as a control for comparison (Table 2.3).

Experiment 2 investigated three different TF:KB seed mixture ratios (90:10, 95:5, 97:3 w/w, TF:KB) in combination with three different growth aggressiveness classifications and also one polystand blend (three cultivars) of 100% bunch-type TF (i.e., 100:0 w/w TF:KB) for comparison (Table 2.4).

Growth aggressiveness classification labels assigned by seed companies through communication with seed scientists/suppliers (L. Brilman, personal communication, 2022; G. Munshaw, personal communication, 2022). Kentucky bluegrass classification groupings are assigned to each cultivar based on past research and materials (Bonos et al., 2000; Brilman, 2018, 2020, 2024; Honig et al., 2012, 2018).

Study Establishment and Management

Both experiments were planted on 9 Sept. 2022 and 8 Sept. 2023 Run 1 and Run 2, respectively. Before seeding, existing vegetation in the study area was eradicated with a non-selective herbicide, and the soil was tilled. The pure live seeding (PLS) rate was calculated from seed lot purities, thousand-seed weight counts, and controlled-environment germination tests were according to the standard principles and procedures of the Association of Official Seed Analysts (Association of Official Seed Analysts, 2016). All plots were seeded at a total rate of 2 pure live seed cm^{-2} accounting for different mixture ratios and polystand blend percentages (Tables 2.3 and 2.4). A starter fertilizer was applied at a rate of 204 kg ha^{-1} (i.e., 22 kg P ha^{-1} and 37 kg N ha^{-1}) ($18 \text{ N} - 24 \text{ P}_2\text{O}_5 - 12 \text{ K}_2\text{O}$; The Andersons Inc., Maumee, OH) at seeding with a walk-behind broadcast spreader across the entire study area. Individual plot seeding was done by hand-shaking seeds in multiple directions across the plot with respective premeasured seed jars. The soil surface was then lightly raked with a leaf rake within each plot to promote seed-to-soil contact, and a 14.2 g (0.5 oz) light germination blanket (PR1724, A.M. Leonard) was used to

cover the experimental area for 10 days to prevent seed movement and erosion and promote germination. Irrigation was applied through an in-ground system daily for the first 21 days to encourage turfgrass germination and establishment. After 21 days, irrigation was applied three times per week throughout the growing season with an average of 2.54 cm wk⁻¹ if no precipitation occurred. Plots for both experiments were maintained at an 8.2-cm mowing height (3.25 inches).

For both experiments and runs, a slow-release nitrogen fertilizer (43-0-0; SGN:150, polymer-coated-sulfur-coated urea; The Andersons Inc.) was applied to supply a rate of 37 kg N ha⁻¹ ~30 days after seeding. In both experiments and runs, additional N fertilizer applications with the same 43-0-0 fertilizer occurred in late-March and mid-May at a rate of 37 and 61 kg N ha⁻¹, respectively. Therefore, the total annual N rate within each experiment was 172 kg N ha⁻¹ yr⁻¹ (i.e., 3.5 lb N 1000 ft⁻² yr⁻¹), and this includes the starter fertilizer application.

For Run 1 in both experiments, an insecticide containing imidacloprid {1-[(6-Chloro-3-pyridinyl) methyl]-N-nitro-2-imidazolidinimne} (Merit 0.5 G) was applied at a rate of 0.44 kg a.i. ha⁻¹ on 16 June 2023 to prevent and control white grubs and billbugs. For Run 2 in both experiments, an insecticide containing chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl] phenyl] -1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} was applied at a rate of 0.17 kg a.i. ha⁻¹ on 21 June 2024 for insect pest prevention and control. On 3 Sept. 2024 for Run 2 in both experiments, Dinotefuron (Zylam) was applied at 0.58 kg a.i. ha⁻¹, for curative white grub control and the fungicide Azoxystrobin (Heritage) was applied at a rate of 0.61 kg a.i. ha⁻¹, for fungal disease control and prevention. For Run 1 and Run 2, commercially available herbicide mixture containing 2,4-D (2,4-dichlorophenoxyacetic acid) + mecoprop-p [(+)-(R)-2-(2 methyl-4-chlorophenoxy) propionic acid] + dicamba (3,6-dichloro-o-

anistic acid) was applied at 1.52 kg a.e. ha⁻¹ as a spot spray treatment to control very little emerged broadleaf weeds on 21 Apr. 2023 and 17 Apr. 2024, respectively.

Sod Strength Data

Sod was harvested and tested for both experiments on 14 June, 12 July, and 18 Sept. 2023 (Run 1) and 11 June, 8 July, and 2 Sept. 2024 (Run 2). These dates are equivalent to 9, 10, and 12 months after planting (MAP). On sod harvest dates, a Turfco KisCutter sod cutter (Model #85530, Turfco Manufacturing, Inc.) removed a 25-cm wide × 70 cm long sod sample with a 1.9-cm thickness (soil combination) to be torn apart in the sod tensile testing device (Figure 2.1). Similarly, to the methodology of Friell et al. (2017), the same custom-built sod tensile strength device, that was modified and used by Braun et al., (2021a, 2022d), was used for both experiments to pull apart each sod piece to measure sod strength variables of required work to tear sod and maximum tensile load to tear sod (Figure 2.1). The harvested sod piece was placed upon the sod tensile strength device and secured between two 30.4 × 30.4 cm plates. One plate was fixed, while the other plate had ball bearings underneath to be able to slide freely when electric actuator arm was pulled by the motor. Upon activation of the sod device computer (Raspberry Pi 3b single-board computer), the electric actuator pulled apart the sod piece, which was torn into two separate pieces (Figure 2.1). The tensile load (i.e., force, Newtons) was measured via an Omega LC703-300 load cell (Omega Engineering Inc.) and the total distance that the sod had been stretched was recorded using a Unimeasure LX-PA-15 string potentiometer (UniMeasure, Inc.). All data were collected using a 24-bit analog-to-digital converter at 4.7 Hz and stored on the sod device computer and also instantly saved on a USB flash drive for data retrieval. Data output from the sod tensile device consisted of the maximum tensile load to tear sod (i.e., force, Newtons) and the required word to tear the sod (i.e., force over distance, N-m),

which was calculated as the area under the load-displacement curve of measured force (N) by separation displacement in meters. Data was transferred from USB flash drives to a computer and cloud storage to prevent data loss during sod harvests.

Ancillary Sod Harvest Data

Visual turfgrass quality was rated on a 1 to 9 scale, where 1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality according to color, texture, density, and uniformity to assess aboveground sod aesthetic quality (Morris et al., 2022). Sod handling is a quick and subjective method to quantify strength following the methods of Braun & Patton (2022), Gopinath et al. (2021), and Han (2009). When the harvested sod pieces were picked up and carried over to the sod tensile testing device, it was rated on a 1 to 5 scale, where 1 = poor, unacceptable sod handling that breaks or falls apart during operator handling, 3 = minimally acceptable sod that exhibits mild but acceptable cracking during handling, and 5 = excellent sod handling where the sod piece shows no cracking of the soil and feels very tough (Braun et al., 2021a; 2022d). Soil moisture within each plot was measured to validate soil moisture levels and check for inconsistencies in soil moisture among plots and possible sod strength influences during each harvest. This was accomplished by measuring volumetric soil water content a 7.6-cm soil depth ($n = 5$ random measurements per plot) with time domain reflectometry (Field Scout TDR 300 Soil Moisture Meter, Spectrum Technologies Inc.).

Establishment Vigor

When the experiments were seeded the previous autumn in each experiment run (9 Sept. 2022 and 8 Sept. 2023), the speed of establishment (i.e., establishment vigor) was measured to assessment differences in KB classifications and ensure all plots established properly and that no establishment factors influenced sod strength at 9, 10, or 12 MAP. To accomplish this, visual

turfgrass ratings digital image analysis and through the autumn and following spring. Plots were visually rated (0–100%) for turfgrass cover every 1 to 2 weeks in autumn until mid-December, then rated again the following spring in April and May. Digital image analysis was measured using a custom lightweight lightbox (60 × 60 × 50 cm, L × W × H) and a digital camera (Nikon Z 30, Nikon Inc), manually set at ISO-125, f/4.5, exposure time 1/80 sec., 300 dpi, and 5568 × 3712 pixels (Figure 2.2). Digital images were analyzed with Turf Analyzer software (Green 155 Research Services, LLC, Fayetteville, AR) with the =thresholds: hue: 40–170; saturation: 2–100; brightness: 2–100. Afterward, days until 50, 70, and 90% vegetation establishment were estimated for both experiments and runs using a sigmoidal regression model following similar methodology as Braun et al. (2020). This involved fitting the data from digital image analysis into a four-parameter sigmoidal model regression curve using GraphPad Prism (v.10.3, GraphPad Software Inc.) and model shown in Equation 1, to see cultivars and seed mixture ratios that reached 50, 70, and 90% establishment vegetation cover in less days after seeding, and this corresponds to the output of D₅₀, D₇₀, and D₉₀ from GraphPad Prism.

Equation (1):

$$y = \text{Bottom} + \frac{\text{Top} - \text{Bottom}}{1 + \left(\frac{D_{50}}{x}\right)^{\text{hillslope}}} \quad (\text{Eq. 1})$$

where y is percent vegetation establishment cover, top and bottom are the y value at the estimated top and bottom plateau, respectively, D₅₀ is the x value when the response of either days until 50% establishment (D₅₀), which is halfway between top and bottom, days until 70% establishment (D₇₀), which is 70% of the top value, or days until 90% establishment (D₉₀), which is 90% of the top value; and Hillslope (no units) describes the slope of the curve at D₅₀.

Additional measurements, when needed, included visual weed cover (0–100%) collected in the autumn and spring for winter annual grassy weeds [i.e., annual bluegrass (*Poa annua* L.)].

Tiller Population Counts

For both experiments, the number of visual tillers were counted to determine the sward dynamics of the TF:KB mixture ratios over two years. Two 58 cm² grass plugs (Sod Plugger, model ISP-33, Yard Butler) were collected after each sod harvest (9, 10, and 12 MAP), and three plugs (58 cm²) at 20 and 24 MAP were removed in non-sod harvested areas within each plot and transported to an indoor laboratory to visually count tillers within 48 h (Figure 2.3). The number of TF and KB tillers were counted for each plug (Figure 2.3). Visual tiller counts were then extrapolated to percent TF and percent KB for each plug based on total TF + KB tillers within a plug. Tiller count density (shoots per square decimeter), similar to Beard (1973), was calculated for both TF and KB tillers for each plug. Tiller data was then averaged across the two plugs (9, 10, and 12 MAP) or three plugs per plot (20 and 24 MAP) prior to data analysis. After indoor tiller counts, plug samples were returned to respective field plots to recover (Figure 2.3).

Data Analysis

Data for both experiments were analyzed for each run separately in SAS (v.9.4, SAS Institute Inc.) with PROC GLIMMIX and treatment set as a fixed effect and block set as a random effect. Residual normality was checked with the w statistic of the Shapiro-Wilk test using PROC UNIVARIATE in SAS (Shapiro & Wilk, 1965). For each experiment, the effect of the experiment run was tested to determine if data could be combined across runs. Treatment × run interactions were not significant for both experiment runs in Experiment 1 and Experiment 2 for sod strength data (i.e., required work to tear, maximum tensile strength, and sod handling, turfgrass quality) and establishment vigor (D₅₀, D₇₀, and D₉₀), so the following data were

combined across runs. Treatment $\times$ run interactions were significant for tiller count data for both experiments; therefore, runs were analyzed and presented separately. Before analyzing tiller count, raw data counts for percentage tiller count and per square decimeter with “0” or “<1” (i.e., TF or KB counts) were log and square-root transformed in Microsoft Excel (Microsoft Corporation) for SAS analysis.

All sigmoidal regression and regression analysis was conducted using GraphPad Prism (v 10.1.3, GraphPad Software Inc.). Correlation analysis between sod harvest response variables (i.e., required work to tear sod, maximum tensile load to tear sod, and sod handling), visual turf quality, and KB percentage tillers across all treatments and runs were conducted using GraphPad Prism for Experiment 1. Before the correlation analysis in GraphPad Prism, KB tiller count data was also log-transformed. Correlations between sod harvest response variables and turf quality were conducted for Experiment 2. Means were separated with Fisher’s Protected LSD test ($\alpha = .05$) when the F -tests were significant ($P \leq .05$).

Experiment 1 – Results and Discussion

Sod Strength Data

For Experiment 1, [growth aggressiveness labels and KB classifications in 95:5 (w/w, TF:KB)], data from sod tensile device (required work to tear and maximum tensile load to tear sod) combined across runs revealed no differences among treatments across the three harvest timings of 9, 10 and 12 MAP (Table 2.5 and Figure 2.4). Required work to tear sod values ranged from 13 to 15 N-m at 9 MAP, 11 to 16 N-m at 10 MAP, and 12 to 16 N-m at 12 MAP. Average required work to tear sod for 95:5 TF:KB (w/w) mixtures was 14 N-m across all three sod harvests, and the 100% TF was an average of 12 N-m across all three harvests. Maximum

tensile load to tear sod values ranged from 187 to 325 N across all three sod harvests. Average maximum tensile load to tear sod for 95:5 TF:KB (w/w) mixtures was 255 N across all three sod harvests, and the 100% TF was an average of 222 N across all three harvests. Under the conditions of our study, there appeared to be no benefit in maximum tensile load to tear TF sod when KB was mixed at 5% by weight. Although, a slight numerical decline was observed with required work to tear and maximum tensile strength in most KB cultivars at 10 MAP which we suspect may be due to summer stress that occurred between July and August (Figure A.1).

One would expect a 100% TF sod to produce the weakest sod strength due its bunch-type growth characteristics, but that was not the case in this experiment. The 100% TF sod often had lower numerically sod strength values compared to most other treatment at harvests but there were no statistical differences, possibly due to high variability among blocks (reps). It was anticipated that adding 5% weight of KB seed into TF sod during seeding would increase sod strength due to the rhizomatous growth characteristics and aggressiveness nature of KB cultivars; however, we did not observe this. Furthermore, there were no consistent results among KB classifications (e.g., Compact America, Compact Midnight, Jefferson, Shamrock) or growth aggressiveness labels. This finding suggests that growth aggressiveness labels or KB classifications may not offer a good indication for increasing sod strength in a 95:5 (w/w, TF:KB) sod mixture. This finding concurs with Nwachukwu (2025), who reported no consistent results in sod strength with KB classifications or growth aggressiveness labels when grown as KB monostands. Braun et al. (2021a, 2022d) reported a range of 5.5 to 15.4 N-m for required work to tear 100% TF sod at 10, 11, 12, 14, 20, and 22 MAP in Indiana and Minnesota across multiple studies. For maximum tensile load to tear sod, Braun et al. (2021a, 2022d) reported a range of 154 to 342 N for 100% TF sod at 10, 11, 12, 14, 20, and 22 MAP in Indiana and

Minnesota across multiple studies. Both sod strength device output values fell within the range of these past studies.

According to Braun and Patton (2022) and Friell et al. (2017), required work to tear sod values may provide more relevant sod strength device output information, since required work to tear sod is the applied load (i.e., energy) over a distance required to tear a sod piece apart when compared to maximum tensile load to tear sod which is the peak force or maximum load required one time to tear a sod. Regardless, no treatment differences were observed with either output from the sod device. Often, the 95:5 TF:KB (w/w) mixtures had higher numerical values in both output data, but again, no statistical differences. This is novel information because to the author's knowledge there is no past research that investigated TF:KB sod mixtures at a 95:5 (w/w) ratio. One thing to mention is that we only tested nine cultivars and there is a lot of known genetic variability among KB cultivars (Bonos et al., 2000, 2013; Honig et al., 2012, 2018); therefore, this warrants more research. Thus, more research is needed on additional KB cultivars and classifications.

Braun et al. (2022d) reported that 90:10 (TF:KB w/w) mixture ratio sod (included Maestro as one of the TF cultivars in their TF sod, which was similar to the TF cultivar included in our 100% TF blend), produced a lower sod strength than KB sod but increased at 20 months harvest for site at Indiana and Minnesota. Our findings further suggest that mixtures of aggressiveness classification types of KB with TF seeds may require additional months beyond 12 months to start showing differences in sod strength and sod handling. Macolino et al. (2021) suggested that KB requires more than two years to show their aggressive growth. Our findings agree with past research by Braun et al., (2022d) and Nwachukwu (2025), who reported similar results with seed mixture ratios of 95:5 and 90:10 (TF:KB w/w), and results in their individual

finding, resulted to a weaker sod strength when compared to a 100% KB blend sod or monostand KB sod. Recall, we only tested nine cultivars from the list of numerous KB cultivars commercially available with distinct genetic variability and aggressiveness growth differences and characteristics.

Sod Handling

Similar to the sod strength data, there were no differences in sod handling among treatments in Experiment 1 combined across runs (Table 2.5). Mean sod handling was ≥ 3 (minimal acceptable sod handling) for most treatments at each sod harvest with a few exceptions that often included 100% TF sod. On a 1 to 5 scale, the subjective sod handling values ranged from 2.5 to 3.4 at 9 MAP, 3 to 3.5 at 10 MAP, and 2.9 to 3.6 at 12 MAP (Table 2.5). Average sod handling for 95:5 TF:KB (w/w) mixtures was 3.3 across all three sod harvests, and the 100% TF was an average of 2.9 across all three harvests. There were numerical trends, such as 100% TF sod often producing a mean sod handling rating of ≤ 3 to the TF:KB 95:5 (w/w), which were more often ≥ 3 . Regardless, no statistical differences occurred. Similarly, Braun et al. (2021a, 2022d) reported mean sod handling ratings between 2.5 to 3.9 for 100% TF sod at 11, 12, 14, 20, 22, or 24 MAP in Indiana and Minnesota across multiple studies.

Correlation analysis of data combined across experimental runs revealed a strong positive relationship between required work to tear sod and maximum tensile load to tear sod ($r = 0.81$; $P \leq 0.0001$), and a moderate positive relationship between sod handling and required work to tear ($r = 0.30$; $P \leq 0.0001$) and between sod handling and max tensile strength ($r = 0.33$; $P \leq 0.0001$) (Figure 2.5). This strong relationship between the two sod strength variables (i.e., required work to sod and maximum tensile load to tear sod) has been reported by others [$r = 0.87$ (Braun & Patton, 2022), $r = 0.82$ to 0.88 (Braun et al., 2021a), $r = 0.85$ to 0.86 (Braun et al., 2022d), $r =$

0.92 (Friell et al., 2017)]. Past correlation analysis between required sod handling and sod tensile strength output has revealed similar findings as well [$r = 0.59$ to 0.69 (Braun & Patton, 2022), $r = 0.28$ to 0.62 (Braun et al., 2021a), $r = 0.58$ to 0.63 (Braun et al., 2022d), $r = 0.92$ (Gopinath et al., 2021)].

Volumetric Water Content

Volumetric soil water content measured using a time domain reflectometry at each sod harvest timings in both experiment runs revealed no differences among treatments (Figure 2.6). In Run 1, volumetric water content ranged from 38 to 41% at 9 MAP, 43 to 49% at 10 MAP, and 41 to 48% at 12 MAP. In Run 2, volumetric water content ranged from 35 to 38% at 9 MAP, 42 to 45% at 10 MAP, and 41 to 43% at 12 MAP (Figure 2.6). Data analysis of plots (treatments) and based on the ranges provided confirm uniformity, and there were no differences in soil moisture during harvest events to potentially affect sod strength or sod handling results.

Turf Quality

For visual turf quality, statistical differences were not observed among treatments from 6 to 39 weeks after seeding and 4 to 39 weeks after seeding in Run 1 and Run 2, respectively (Table 2.6). In Run 1, all treatments had turf quality ≥ 8 , which was above acceptable turf quality (≥ 6 rating), and this was observed from 6 weeks after seeding to the end of the study (Table 2.6). In Run 2, similar results were observed across treatments, and all had acceptable turf quality at 4 weeks after seeding and onward (Table 2.6). The inclusion of 5% KB (by weight) in 95% TF, might have influenced turf quality during the establishment phase, which slowed establishment but as time and field establishment progressed, they were near or at the highest possible rating of “9” (Table 2.6). Furthermore, during each sod harvest event (i.e., 9, 10, and 12 MAP), and for both experiment runs, they all had the highest turf quality (9 rating) (Table 2.7). Although

differences were not observed with turf quality, they all also had similar sod strength and handling. A correlation analysis between turf quality and sod strength data (i.e., required work, max tensile and sod handling) across runs and three sod harvest dates, revealed a very weak positive relationship between turf quality and required to tear ($r = 0.20$, $P = 0.01$), and between turf quality and max tensile strength ($r = 0.18$, $P = 0.01$) (Figure 2.5). This also agrees with past sod weak relationship between visual turf quality and sod strength and handling (Braun et al., 2021a, 2022d; Braun & Patton, 2022). This further confirms that visual turf quality does not help in distinguishing sod strength and handling differences among treatments, but only informs us about visual and aboveground functional characteristics of turfgrass systems.

Establishment Vigor

There was no Treatment by Run effect for sigmoidal model estimates of establishment vigor, therefore experiment runs were combined. Establishment vigor calculated from the digital image analysis and the four-parameter sigmoidal model estimates revealed no differences among treatments for the number of estimated days to reach 50, 70, and 90% vegetation establishment (Table 2.8 and Figure 2.7). Numerically, the 100% TF treatment had the lowest D_{50} , D_{70} , D_{90} values; however, there were no statistical differences, and the differences in days were often only 1 to 2 days different than other treatments. It is well known that TF has faster germination and often associated establishment compared to KB (Braun et al., 2021a, 2022d, 2023a; Christians et al., 2017). Therefore, we anticipated the 100% TF treatment to have slightly faster establishment than treatments containing only 95% TF by weight; however, the other treatments likely still had enough TF to have similar establishment vigor as the 100% TF treatment. Overall, results show that adding KB of 5% by weight to the TF seed mixture will not hinder establishment vigor. These results are promising for sod producers and turfgrass practitioners, which faster

establishment vigor may help the turfgrass sward resist annual weed invasion. Our results did not align with past reports (Beard, 1973; Gibeault et al., 1993; Hunt & Dunn, 1993), who suggested that a 95:5 seed mixture ratio (TF:KB w/w) would produce a fast establishment cover and higher turfgrass quality than a monostand blend of TF. However, those studies are over 30+ years old and included older cultivars. Results of fast establishment observed due to more TF included in the mixture aligns with reports by Brede (2000) and Christian et al. (2017), who ranked turfgrass species from the fastest to slowest establishing cool-season turfgrass species starting from tall fescue > Kentucky bluegrass, thereby revealing the undesirable, establishment characteristic of Kentucky bluegrass compared to others.

Parameters estimated from GraphPad included Hillslope, Top (i.e., total establishment percentage), and R^2 values from the model output. All of these followed similar trends as the D_{50} , D_{70} , and D_{90} values (Table 2.8). The overall establishment percentage (Top) shows that all tested cultivars had $\geq 96\%$ establishment vegetation cover for both runs and 100% visual turf cover by the following spring (Table 2.8; Table A.1). Hillslope which describes the steepness and transition region of the sigmoidal curve at D_{50} . Overall, data confirmed that all treatments reached 90% establishment cover within the first 30 to 40 days and by the first sod harvest at 9 MAP everything had 100% visual turf cover (Table A.1). There were no establishment vigor differences due to the inclusion of slower establishing KB seed at 5% by weight included during seeding. Overall establishment vigor was similar among all treatments and had no influence sod strength and handling when harvested at a later date at 9 MAP. Further research on TF:KB mixtures is warranted to test more KB cultivars proven to have germination and establishment vigor differences and measure their influence on sod strength and handling.

Tiller Counts

Tiller count data revealed differences in the number and percentage of visual tillers TF and KB within plots across sod harvests (9, 10, 12 MAP) and additional timings of 20 and 24 MAP for both runs of Experiment 1 (Tables 2.9 and 2.10). For both runs, KB classifications and growth aggressiveness labels appear to have minimal influence on the population mixture of TF:KB at 9 through 24 MAP in Run 1 and 9 through 12 MAP in Run 2. There is no data for 20 and 24 MAP in Run 2 because data collection is still ongoing. There were differences among the 95:5 TF:KB (w/w) mixtures because of KB cultivar; however, no consistent trends occurred over sampling dates from 9 to 24 MAP. For example, in Run 1, some cultivars like Sombrero appeared to have higher or a similar high percentage of KB at 9 through 12 MAP compared to other KB cultivars but then by 20 and 24 MAP it was similar or lower than many other KB cultivars (Table 2.9). One clear finding is that most KB cultivars increased in proportion of the TF:KB mixture with a range of 5 to 34.1% (mean of 16%) within the first year after seeding (9 to 12 MAP) from the initial 5% KB seed by weight included in the mixture in Run 1. Thereafter in Run 1, data collection continued at later dates of 20 and 24 MAP. For most cultivars, the proportion of KB in the turfgrass sward appeared to continue to increase and TF decrease at these later dates in Run 1. By 20 and 24 MAP, KB often accounted for >18% (mean of 20%) of the turfgrass sward even though it was seeded at 5% by weight (Table 2.9). This was especially true for cultivars with a “high” or “medium” growth aggressiveness label. In Run 2, similar ranges of KB were observed (mean 13.7% KB) between 9 to 12 MAP; however, the 20 and 24 MAP has not yet been conducted (Table 2.10). Overall, there appeared to be less differences between growth aggressiveness labels of medium and high aggressiveness and more often the “low” aggressiveness cultivars did have a lower KB% but not always. Results agree with past

research (Beard & Hall, 1980; Dunn et al., 2002; Gibeault et al., 1993; Hunt & Dunn, 1993; Juska et al., 1959, 1969; Macolino et al., 2014; Park et al., 2017; Pornaro et al., 2021), which TF, when mixed with KB, percentage often decreased as time progressed as KB percentage increased.

Results for tiller counts per square decimeter tell a similar story as percent tillers (Tables 2.11 and 2.12). This calculation provides more precise number for tillers of each species and treatment and allows comparison to other research. In both runs, results revealed no difference in the number of TF tillers per square decimeter among all treatments, including 100% and 95:5 TF:KB mixtures across all measurement timings from 9 to 20 MAP. At 24 MAP in Run 1, there were differences in the number of TF tillers per square decimeter (Table 2.11). At 24 MAP, A few KB cultivars, such as Armada, Bolt, Fullback, Hampton, all had less TF tiller per square decimeter than the 100% TF treatment. This was likely due to these respective KB cultivars also some of the higher numbers of KB tillers per square decimeter at 24 MAP. Similar to percent tiller data, the tillers per square decimeter demonstrates how the density (tillers per square decimeter) of KB is increasing over time with some KB cultivars more than others when seeded at 5% by weight with TF. Additional data collected was the total number of combined tillers of TF and KB at each measurement date (Table A.2 and A.3). Results indicated no differences among treatments and plant population counts, which were all similar across treatments across measurement dates. This may be due to the simultaneous percentage increase or decrease between KB and TF tillers within the period of study (Tables 2.11, 2.12, and A.2).

Key findings is that the growth aggressiveness labels of KB in a standard seed mixture ratio with TF (95:5 w/w TF:KB) did not consistently influence ecological changes over two years. Results revealed more population differences occurred in the 2 years after planting and

continual maintenance (i.e., 20 and 24 MAP), with some cultivars either increasing or reducing in population. This result confirms a cultivar effect and possibly growth aggressiveness labels could help aid in understanding population changes in a TF:KB sward. Depending on the TF:KB mixture, this could suggest that the longer the sod is grown in the field, the sod strength and handling may either increase or decrease as time and population changes progress. This information informs sod producers about cultivars, and growth aggressiveness labels when selecting KB cultivars to mix with TF at a 95:5 (w/w) mixture ratio. Additional consideration on long or short-term production cycles should be factored in.

Overall, our findings suggest that at 9 MAP, most cultivars with “high” growth aggressiveness label had the highest KB population percentage increase, while few had a less consistent increase in percentage at 24 MAP. A decrease with population percentage was observed at the start of the second spring (20 MAP), and this was likely due to impact of summer stress (Figure A.1). Results will help turfgrass practitioners and end users, such as homeowners in understanding the population dynamics of a TF:KB sward while mixing both species during planting.

Experiment 2 – Results and Discussion

Sod Strength Data

For Experiment 2 (growth aggressiveness labels and mixture ratios TF:KB), data output from sod tensile device combined across runs, revealed minimal to no differences for maximum tensile strength and required work to tear, respectively, across three harvest timings (Table 2.13). Required work to tear a sod piece values ranged from 13 to 16 N-m at 9 MAP, 12 to 15 N-m at 10 MAP, and 12 to 16 N-m at 12 MAP. The average required work to tear for all

mixture ratios (90:10, 95:5, and 97:3 TF:KB w/w), was 14 N-m across all harvest dates (9,10, 12 MAP), with 100% having an average of 13 N-m. For maximum tensile load to tear sod, values ranged from 213 to 313 N across three sod harvest dates. An average max tensile strength of 257 N for all mixture ratios was observed across sod harvest timings, while a 100% TF treatment had an average of 226 N across all three sod harvest (Table 2.13). At 10 MAP, we observed slight numerical sod strength decline (required work to tear and maximum tensile strength) in a few treatment, which may be as a result of summer stress that occurred between July and August (Figure A.1).

Surprisingly, the 100% TF, which we anticipated to produce the weakest sod strength due to its non-lateral spread bunch-type growth characteristics, produced similar required work to tear sod like those containing mixtures of KB across three harvest events. However, at times, 100% TF sod had similar to slightly lower numerically max tensile value when compared to a few others. Results reveal that under the conditions of our study, there were slight benefits in maximum tensile load to tear TF sod when KB was mixed at different percentages by weight. Contrary to the results in Experiment 1 [KB classifications in 95:5 (w/w, TF:KB)], we observed differences in max tensile strength in cultivars at 9 and 12 MAP when KB was mixed at 10% by weight only. This may indicate a greater KB cultivar influence on sod strength when included in TF:KB mixtures at more than 5% by weight. For example, KB cultivar of ‘Fullback’ at 90:10 (TF:KB w/w) and had higher maximum tensile load to tear sod than ‘Armada’ (90:10) at 12 MAP (Table 2.13). One would expect that inclusion of more KB seeds (5 or 10 % w/w) in a TF sod would increase sod strength due to the rhizomatous spreading and aggressive nature of KB cultivars; however, this trend was not consistent when increasing KB seed weight ratios in our study. Similar to Experiment 1, KB classifications [e.g., Compact America, Compact Midnight,

Compact America (Midnight)] or growth aggressiveness labels (i.e., high, medium, and low aggressiveness) did not show any consistent results with sod strength and sod handling.

Furthermore, including KB seeds by weight at a 3 to 10% range in TF sod did not consistently enhance sod strength and sod handling, but rather it was more about cultivar effect. This further suggests that growth aggressiveness labels or KB classifications may not be a good indication in selecting cultivars to increase sod strength and inclusion of 3 to 10% KB by weight in TF sod, might not be sufficient to improve sod strength of TF in mixtures with KB. This finding aligns with Nwachukwu (2025), who also reported no consistent results in the sod of KB belonging to the same growth aggressiveness classification labels, when planted as monostands.

These results align with the results in Experiment 1 [KB classifications or growth aggressiveness labels in 95:5 (w/w, TF:KB)], which sod strength device output values fell within a similar range. Past findings by Braun et al. (2021a, 2022d) in Indiana and Minnesota, reported similar ranges for required work to tear sod (5.5 to 15.4 N-m) and max tensile strength (154 to 342 N) for 100% TF sod harvested at 10, 11, 12, 14, 20, and 22 MAP. It is important to note that we only tested three KB cultivars and three classification systems [i.e., Armada (Compact America), Fullback (Compact Midnight) and Legend Compact America (Midnight)], in three different mixture ratios [90:10, 95:5, and 97:3 (TF:KB, w/w)], due to time and space limitations. The Genetic variability existing among KB cultivars (Bonos et al., 2000, 2013; Honig et al., 2012, 2018) warrants a need to investigate many more KB cultivars commercially available as well as other classifications systems of KB mixed with TF at more different seeding mixture ratios.

Sod Handling

For sod handling, a subjective rating for sod strength, we observed no differences among treatments [KB classifications or aggressiveness labels and three different mixture ratios (i.e., 90:10, 95:5, and 97:3, TF:KB w/w) across all harvest events (Table 2.13). Treatment by Run effect was not observed in both experiment runs, so data were combined across runs. For each sod harvest timings, the majority of the treatments had mean sod handling ≥ 3 (minimal acceptable sod handling) and there were no differences among treatments (Table 2.13). Sod handling values across harvests ranged from 2.6 to 3.4 at 9 MAP, 2.6 to 3.4 at 10 MAP, and 2.8 to 3.8 at 12 MAP (Table 2.13). Most often, the TF:KB sod mixtures maintained a sod handling rating of ≥ 3 (Table 2.13). Regardless, they were not any different with 100% TF which had a sod handling rating of ≤ 3 . Sod handling results followed similar trends observed with sod strength data (required work to tear and max tensile strength), and this was also consistent with results in Experiment 1. Our findings also concur with Braun et al. (2021a, 2022d), who reported similar sod handling ratings in a 100% TF sod, with means ranging from 2.5 to 3.9 at 11, 12, 14, 20, 22, or 24 MAP in Indiana and Minnesota across multiple studies.

When correlation analysis was conducted, results revealed a positive relationship between maximum tensile strength and required work to tear ($r = 0.81$; $P \leq 0.0001$), required work to tear and sod handling ($r = 0.27$; $P \leq 0.0001$), and sod handling and maximum tensile strength ($r = 0.37$; $P \leq 0.0001$) (Figure 2.8). This result is consistent to correlation results in Experiment 1 and further aligns with past sod research (Braun et al., 2021a, 2022d; Braun & Patton, 2022; Gopinath et al., 2021; Han, 2009).

Volumetric Water Content

Analysis of volumetric water content data measured with a time domain reflectometry revealed no differences among treatments within each sod harvest timings in both each experiment runs. While no differences occurred, volumetric water content across plots and harvest months ranged from 33 to 44% and from 39 to 49%, for Run 1 and Run 2, respectively (Figure 2.9). The differences in the volumetric water content across plots for each sod harvest month were anywhere between 2 to 5% soil moisture differences occurring between plots. These minimal percentage differences with soil moisture content likely did not affect sod strength or handling. The reason for measuring volumetric water content was to ensure that all plots had a uniform or near uniform soil moisture content during each sod harvest.

Turf Quality

Differences were not observed for visual turf quality among treatments [KB classifications or growth aggressiveness labels in mixture ratios (90:10, 95:5, and 97:3 TF:KB w/w)] for both experiment runs. For Run 1, majority of the treatments were near or at the highest possible rating of “9” from 6 to 10 weeks after seeding (Table 2.14). For Run 2, all treatment had above acceptable turf quality (6 rating), >7 rating from 4 to 32 weeks after seeding (Table 2.14). Surprising, treatments containing more KB seed in mixtures had similar turf quality rating with 100 TF% at 4 weeks after seeding (Table 2.14). Due to the slow establishment of KB included in TF, we expected differences to occur between 100% TF and those containing KB at different seed ratios, but that was not the case. However, as time progressed and as they continued to establish and mature, they all had the highest turf quality rating of 9. Table 2.15 displays that all treatments had a turf quality of 9 during each three sod harvest timings from 9 MAP through 12 MAP for both experiment runs. This agrees with our findings in Experiment 1 as discussed

above, which reported that visual turf quality ratings did not influence sod strength and sod handling across harvest timings. Furthermore, the correlation analysis revealed a negative relationship between visual turf quality and required work to tear ($r = -0.15$, $P \leq 0.01$) (Figure 2.8). This finding is consistent with past sod research (Braun et al., 2021a, 2022d; Braun & Patton, 2022; Taylor & Schmidt, 1980).

Establishment Vigor

Establishment vigor results calculated from digital image analysis and sigmoidal model estimates in GraphPad using the four-parameter sigmoidal model, revealed minimal differences among treatments for estimated days for establishment vigor (Table 2.16; Figure 2.10 and 2.11). Treatment by Run effect was not significant so data were combined across experiment runs. The estimated days required to reach either 50, 70, and 90% vegetation establishment cover corresponds to D_{50} , D_{70} , and D_{90} values, respectively. Treatments with lowest D_{50} , D_{70} , or D_{90} values indicate less days required to reach 50, 70, or 90% vegetation establishment cover. For D_{50} , (i.e., days to 50% establishment), the average number of numbers to reach 50% establishment across treatments containing KB was 13 days, and D_{50} ranged from 11.5 to 14.7 days across treatments (Table 2.16). We observed that treatments containing 10% KB had the highest D_{50} values and required between 13.2 to 14.7 days to reach 50% vegetation cover. Meanwhile TF:KB mixtures containing 3 or 5% KB, required between 11.5 to 12.8 days to reach 50% vegetation cover (Table 2.16). This was expected due to less KB included in mixtures with TF, thereby allowing TF to hasten establishment cover. As expected, 100% TF had the lowest D_{50} values (11.3 d), and this was similar to majority of the treatments that contained 3% by weight of KB at seeding. While some treatments had faster establishment (i.e., lower D_{50})

estimates than others, the largest difference between the fastest treatment and the slowest treatment estimate was only 3.4 days.

The sigmoidal regression model was also estimated for days until 70 and 90% establishment (D_{70} and D_{90} , respectively), and differences were also observed across treatments. For D_{70} , average estimates indicated a range between 14.2 and 19 days to reach 70% vegetation cover, with a difference of 4.8 days occurring between the fastest and the slowest treatment (Table 2.16). For D_{90} , average estimates indicated 20.4 and 28.4 days to reach 90% field establishment. The difference between the fastest and slowest treatment for D_{90} was 8 days. More often, either 100% TF or treatments containing 97% TF (i.e., 3% KB) were among the faster-establishing treatments, as indicated by D_{50} , D_{70} , or D_{90} values. Most treatments that had faster D_{50} translated to a faster D_{70} or D_{90} , and vice versa for slower treatments at D_{50} , with few exceptions. Treatments containing 3% KB often had similar establishment vigor as 100% TF sod. It has been documented in previous research (Braun et al., 2021a, 2022d, 2023a; Christians et al., 2017) that TF had faster germination, which often translates to faster establishment vigor when compared to KB.

Overall, results shows that the inclusion of 5 or 10% KB with TF during seeding may slightly reduce establishment vigor; however, it may be a difference of only 3 to 8 days to reach 50 to 90% vegetation cover. Some KB cultivars may be less competitive in mixtures with TF during establishment compared to a monostand; more research is needed in this area. Furthermore, we observed that neither KB classification system, nor assigned growth aggressiveness labels (high, medium or low aggressiveness) was a good indicator of establishment vigor differences. Regardless, there is a need to investigate more KB cultivars in different mixture ratios with TF to understand these dynamics between these two species which

are often planted together. These results can assist sod producers and turfgrass practitioners with more information when considering mixture of TF and KB to ensure faster vegetation cover that may resist encroachment of annual weeds.

Similar to Experiment 1, the additional output from four-parameter sigmoidal regression model in GraphPad included Hillslope, Top (i.e., total establishment percentage), and R^2 values. Output from GraphPad revealed that overall establishment percentage (Top) showed that all treatments including 100% TF blend had >96% establishment vegetation cover and visual turf cover reached 100% (0 to 100 visual rating) by the following spring (Table 2.16 and A.4). The key takeaway was that minimal differences were observed among establishment vigor among KB classifications or growth aggressiveness labels in mixtures with TF at different ratios.

Tiller Counts

Tiller count data revealed differences in the number and percentage of visual tillers TF and KB within plots across sod harvests (9, 10, 12 MAP) and additional timings of 20 and 24 MAP for both runs of Experiment 2 (Table 2.17 and 2.18). For both experiment runs, KB classifications or growth aggressiveness labels (i.e., high, medium and low aggressiveness), did not appear to influence population mixture of TF:KB at 9 through 24 MAP in Run 1 and again from 9 through 12 MAP in Run 2. Experiment Run 2 is still in progress, therefore data for 20 and 24 MAP are not included (Table 2.18).

Minimal differences among cultivars were observed within each population mixture of TF:KB (90:10, 95:5 or 97:3) from 9 through 24 MAP (Table 2.17 and 2.18). For example, in Run 1, a similar KB population percentage occurred from 9 to 20 MAP among all three cultivars in the 97:3 treatments (Table 2.17). Within the 95:5 and 90:10 treatments, a similar trend occurred with the exception of ‘Fullback,’ which was often higher than the other two cultivars

within a respective weight ratio (Table 2.17). There were few inconsistencies observed between cultivars. For example, most KB cultivars experienced a proportion increase from 9 to 24 MAP, except for ‘Armada’ at 10% weight (Table 2.17). As expected, we more often observed higher KB percentages in the mixture ratios of 90:10 or 95:5 compared to 97:3 in both Runs (Table 2.17 and 2.18). Similar results were observed for Run 2, which was between 9 to 12 MAP, and data collection is still ongoing (Table 2.18). One key thing to note is that the proportion of KB in the TF:KB turfgrass sward fluctuated over time but most often had the tendency to increase for most cultivars and mixture ratios in both runs. Similar to Experiment 1, the growth aggressiveness labels (i.e., high, medium or low growth aggressiveness) and KB classification system did not indicate either a high or low proportion percentage of KB mixed with TF during seeding. However, ‘Fullback’ most often had the highest KB percentage regardless of mixture ratio during seeding. Therefore, genetic differences among KB cultivars may play a larger role in the KB proportion when mixed with TF compared to growth aggressiveness or KB classification system labels. Further research is warranted on the influence of additional KB cultivars mixed with TF. This agrees with past research by Beard and Hall (1980), who reported that some KB cultivars required more time to grow in order to express more rhizome spread. Overall, results are in agreement with past research (Beard & Hall, 1980; Dunn et al., 2002; Gibeault et al., 1993; Hunt & Dunn 1993; Juska et al., 1959, 1969; Macolino et al., 2014; Park et al., 2017; Pornaro et al., 2021), which TF percentage, when was mixed with KB, often decreased as time progressed as KB percentage increased.

For tiller counts, tillers per square decimeter was calculated to provide a more precise number of tillers for each species and treatment and this also helps to compare with other research (Tables 2.19 and 2.20). This data shares similar information observed in percent tillers

and differences with tiller counts per square decimeter for all treatments, across sampling dates (9 to 24 MAP) and for both runs (Tables 2.19 and 2.20). At 24 MAP, minimal differences were observed for tiller counts per square decimeter (Table 2.19). Tillers per square decimeter data demonstrates how the density (tillers per square decimeter) of both TF and KB fluctuate over time. Some KB cultivars fluctuated more than others when seeded at different ratios with TF and similar trends were observed in Run 2 (9 to 12 MAP) (Table 2.20). Other data collected was total number of combined tillers of TF and KB at each measurement date (Table A.5 and A.6). As noted in Experiment 1, no differences were observed among treatments and plant population counts for total number of tillers, and all were similar for all treatments across measurement dates. The reason for this maybe also the simultaneous percentage increase or decrease observed between KB and TF tillers within the period of study, as also seen in Experiment 1 (Table 2.11 and 2.12).

A key takeaway from the tiller count data is that growth aggressiveness labels of KB or mixture ratios of 3 to 10% by weight KB had minimal to no influence on ecological changes over two years. The measured increases in KB proportions were more due to cultivar differences. In comparison with 9 to 12 MAP, both TF and KB populations fluctuated due to both environmental conditions and continual field maintenance practices. We suspect that summer stress at the start of the second spring (20 MAP) decreased population percentage (Figure A.1). Because of these fluctuations in TF and KB over time, varying sod growing cycles and harvest timings may either increase or decrease sod strength and sod handling as time and population changes in a sward. However, more research is needed in this area. This information further strengthens previous research on TF and KB sod mixtures at different percentage and informs sod producers about KB cultivars, and the lack of information provided by growth

aggressiveness labels and the KB classification system labels. Sod producers need to consider multiple factors such as establishment vigor in addition to sod strength and population dynamics when mixing TF and KB at 90:10, 95:5 and 97:3 (TF:KB w/w). Future research might be to consider more classification types, different mixture ratios and different sod production cycles.

Conclusions

The sod tensile device revealed minimal-to-no differences in the sod strength (i.e., required work to tear sod and maximum tensile load to tear sod) when TF is mixed with KB at varying ratios (90:10: 95:5 or 97:3 TF:KB w/w) or cultivars. Results reveal that KB classification system and KB growth aggressiveness labels are not good indicators for sod strength and handling differences. There was more tendency for a 90:10 or 95:5 (TF:KB w/w) sod mixtures to have higher maximum sod tensile strength than 100% TF sod, and this warrants further research with additional KB cultivars.

There were no differences in establishment vigor among 95:5 TF:KB and 100% TF treatments in Experiment 1. For Experiment 2, treatments containing 3% KB by weight had similar establishment vigor as 100% TF and slightly faster establishment, at times, than 95:5 and 90:10 TF:KB treatments. The findings suggest that the inclusion of KB at 10% by weight with TF at seeding will slightly hinder establishment vigor.

Differences were observed for plant tiller count and ecological population changes between TF and KB in mixtures for both experiments. There was a population percentage and tiller increase between mixture ratios of TF and KB, and mostly due to cultivar differences. As time progressed, some KB cultivars consistently increased in proportion to TF while others fluctuated more irrespective of their mixture ratios or KB classification labels. Results from

Experiment 2 further highlight that TF:KB mixture ratios of 3 to 10% KB by weight and KB labeling systems do not consistently follow a similar trend with ecological changes of TF and KB mixtures over time. The population changes observed in the TF:KB sward was more of a cultivar effect and KB cultivars belonging to either the ‘high’ or ‘medium’ growth aggressiveness labels often showed more population fluctuations over time. However, the differences in population changes over time among treatments did not translate to sod strength and sod handling differences.

Overall, results indicated that the majority of these TF:KB sod mixtures will produce high-quality sod. Additional sod production and tiller population research is warranted, especially with other KB cultivars, TF:KB mixture ratios, sod production durations, and management practices. This research adds more scientific knowledge about producing TF:KB sod mixtures and TF:KB ecological changes over time for turfgrass practitioners. These findings will assist sod producers with decision-making about KB cultivar selections, mixture ratios, and sod production growing cycles, and provide more information on TF sod production to meet market demands.

References

- Aronson, L. J., Gold, A. J., & Hull, R. J. (1987). Cool-season turfgrass responses to drought stress. *Crop Science*, 27, 1261–1266.
<https://doi.org/10.2135/cropsci1987.0011183X002700060035x>
- Beard, J. B. (1973). *Turfgrass: Science and Culture*. Prentice-Hall, Englewood Cliffs, New Jersey.
- Beard, J. B., Martin, D. P., & Mercer, F. B. (1980). Investigation of net-sod production as a new technique. In J. B. Beard (Ed.), *Proceedings of the 3rd International. Turfgrass Research Conference, Munich, West Germany, 11–13 July 1977* (p. 353–360). Madison, WI: ASA, CSSA, SSSA, and International Turfgrass Society.
- Bertin, C., Senesac, A. F., Rossi, F. S., DiTommaso, A., & Weston, L. A. (2009). Evaluation of selected fine-leaf fescue cultivars for their turfgrass quality and weed suppressive ability in field settings. *HortTechnology*, 19, 660–668.
- Bonos, S. A., Meyer, W. A., & Murphy, J. A. (2000). Classification of Kentucky bluegrass genotypes grown as spaced-plants. *HortScience*, 35, 910–913.
<https://doi.org/10.21273/HORTSCI.35.5.910>
- Bonos, S. A., & Huff, D. R. (2013). Cool-season grasses: Biology and breeding. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Ed.), *Turfgrass: Biology, use, and management* (pp. 591–660). ASA-CSSA-SSSA. <https://doi.org/10.2134/agronmonogr56.c17>
- Bouton, J. H., Whitehead, F. C., & De Battista, J. P. (1989). Tall fescue rhizome production as influenced by bermudagrass competition and cutting frequency. *Agronomy Journal*, 81, 220–223. <https://doi.org/10.2134/agronj1989.00021962008100020016x>

- Braun, R. C., Patton, A. J., Braithwaite, E. T., & Kowalewski, A. R. (2020). Establishment of low-input turfgrass from seed with patch and repair mixtures: Mulch and starter fertilizer effects. *Crop Science*, 60, 3362–3376. <https://doi.org/10.1002/csc2.20266>
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021a). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: I. Establishment and sod tensile strength. *Agronomy Journal*, 113, 4176–4189. <https://doi.org/10.1002/agj2.20810>
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021b). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: II. Management and shelf life. *Agronomy Journal*, 113, 3460–3474. <https://doi.org/10.1002/agj2.20777>
- Braun, R. C., Braithwaite, E. T., Kowalewski, A. R., Watkins, E., Hollman, A. B., & Patton, A. J. (2022a). Nitrogen fertilizer and clover-inclusion effects on the establishment of fine fescue taxa. *Crop Science*, 62, 947–957. <https://doi.org/10.1002/csc2.20704>
- Braun, R.C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022b). Review of cool-season turfgrass water use and requirements: I. Evapotranspiration and responses to deficit irrigation. *Crop Science*, 62, 1661–1684. <https://doi.org/10.1002/csc2.20791>
- Braun, R.C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022c). Review of cool-season turfgrass water use and requirements: II. Responses to drought stress. *Crop Science*, 62, 1685–1701. <https://doi.org/10.1002/csc2.20790>
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2022d). Management, harvest, and storage characteristics of low-input cool-season turfgrass sod mixtures. *Agronomy Journal*, 114, 1752–1768. <https://doi.org/10.1002/agj2.21051>

- Braun, R. C., Courtney, L. E., & Patton, A. J. (2023a). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, 63, 1613–1627. <https://doi.org/10.1002/csc2.20936>
- Braun, R. C., Watkins, E., Hollman, A. B., & Patton, A. J. (2023b). Assessing the fertilizer and pesticide input needs of cool-season turfgrass species. *Crop Science*, 63, 3079–3095.
- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in environmental protection and their benefits to humans: Thirty years later. *Crop Science*, 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Brede, A. D. & Duich, J. M. (1984). Establishment characteristics of Kentucky bluegrass–perennial ryegrass turf mixtures as affected by seeding rate and ratio. *Agronomy Journal*, 76, 875– 879.
- Brede, A. D. (2000). *Turfgrass Maintenance reduction handbook: Sports, lawns, and golf*. Ann Arbor Press, Chelsea, MI, USA.
- Brede, A. D. (2008). Multi-way Kentucky bluegrass blends and their effect on turfgrass quality. *ISHS Acta Horticulturae*, 783: II International Conference on Turfgrass Science and Management for Sports Fields, 19– 28. <https://doi.org/10.17660/ActaHortic.2008.783.1>
- Bremer, D. J., Su, K., Keeley, S. J., & Fry, J. D. (2006) Performance in the transition zone of two hybrid bluegrasses compared with Kentucky bluegrass and tall fescue. *Applied Turfgrass Science*. <https://doi.org/10.1094/ATS-2006-0808-02-RS>
- Brilman, L. (2018). *Kentucky bluegrass classification*. Seed Research of Oregon. Accessed 20 June 2023. https://www.sroseed.com/Files/Files/SRO_USA/Brochure_Etc/SRO_KB_classifications-Jan-2018_Final.pdf.

Brilman, L. (2020). *Kentucky bluegrass classification*. Seed Research of Oregon. Accessed 15 September 2023.

https://www.dlfpickseed.com/Files/Files/SRO_USA/Brochure_Etc/Kentucky_Bluegrass_Classification_2020_Final.pdf

Brilman, L. (2024). *Kentucky bluegrass classification*.

<https://www.dlfpickseed.com/professional-turf/varieties/bluegrass> Accessed 5 November 2024.

Britton, R., Pacumbaba, R. O., Beyl, Jr. C., & Sabota, C. (2006). Multiple seeding ratios of turf-type fescue with Kentucky and hybrid bluegrass for the elimination of sod net in turf production. *SNA Research Conference*, 51, 121–123.

Burns, R. E. (1980). Techniques for rapid sod production. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference, Munich, West Germany, 11–13 July 1977* (p. 361–366). Madison, WI: ASA, CSSA, SSSA, and International Turfgrass Society.

Bushman, B. S., Warnke, S. E., Amundsen, K. L., Combs, K.M., & Johnson, P.G. (2013). Molecular markers highlight variation within and among Kentucky bluegrass varieties and accessions. *Crop Science*, 53, 2245–2254. <https://doi:10.2135/cropsci2013.02.0110>.

Carrow, R. N., & Sills, M. (1980). Tall fescue sod production with plastic netting. *HortScience*, 15, 818–820.

Canaway, P. M. (1981). Wear tolerance of turfgrass species. *The Journal of the Sports Turf Research Institute*, 57, 65–83.

- Christians, N. E., Patton, A. J., & Law, Q. D. (2017). *Fundamentals of Turfgrass Management* (5th ed.). John Wiley & Sons, Inc., Hoboken, New Jersey. <https://doi.org/10.1002/9781119308867>
- DeBels, B. T., Griffith, S. E., Kreuser, W. C., Melby, E. S., & Soldat, D. S. (2012). Evaluation of mowing height and fertilizer application rate on quality and weed abundance of five home lawn grass. *Weed Technology*, 26, 826–831. <https://doi.org/10.1614/WT-D-12-00062.1>
- Dunn, J. H., Ervin, E. H. & Fresenburg, B. S. (2002). Turf performance of mixtures and blends of tall fescue, Kentucky bluegrass, and perennial ryegrass. *HortScience*, 37, 214– 217.
- Friell, J., Watkins, E., Horgan, B. P., & Cavanaugh, M. (2017). Sod strength characteristics of 51 cool-season turfgrass mixtures. *Agronomy Journal*, 109, 1759–1757. <https://doi.org/10.2134/agronj2016.05.0295>
- Fiorio, S., Macolino, S., & Leinauer, B. (2012). Establishment and performance of bluegrass species and tall fescue under reduced-input maintenance in a temperate Mediterranean environment. *HortTechnology*, 22, 810–816.
- Fry, J., & B. Huang. (2004). *Applied Turfgrass Science and Physiology*. John Wiley and Sons, Hoboken, New Jersey, USA.
- Gibeault, V. A., Autio, R., Spaulding, S., & Youngner, V. B. (1980). Mixing turfgrasses controls fusarium blight. *California Agriculture*, 34, 11–12. <https://doi.org/10.3733/ca.v034n10p11>
- Gibeault, V. A., Cockerham, S. T., & Autio, R. (1993). An evaluation of tall fescue and Kentucky bluegrass mixes. *International Turfgrass Society Research Journal*, 7, 905–909

- Gopinath, L., Martin, D. L., Moss, J. Q., Wu, Y., Yu, S., & Underwood, J. R. (2021). Sod Tensile Strength, Handling Quality, and Their Interrelationship for 39 Bermudagrasses. *HortTechnology*, 31, 780–785. <https://doi.org/10.21273/HORTTECH04893-21>.
- Griffith, S., Bero, N., Stier, J., Obear, G., Ruis, S., & Soldat, D. (2017). Biosolids as an alternative fertilizer for Kentucky bluegrass sod production in Wisconsin. *Crop Science*, 57, S227–S237. <https://doi.org/10.2135/cropsci2016.05.0367>
- Juska, F. V., Tyson, J., & Harrison, C. M. (1955). The Competitive Relationship of Merion Kentucky Bluegrass as Influenced by Various Mixtures, Cutting Heights, and Levels of Nitrogen. *Agronomy Journal*, 47, 513–518.
<http://dx.doi.org/10.2134/agronj1955.00021962004700110006x>
- Juska, F. V., & Hanson, A. A. (1959). Evaluation of cool-season turfgrasses alone and in mixtures. *Agronomy Journal*, 51, 597–600.
<https://doi.org/10.2134/agronj1959.00021962005100100009x>
- Juska F. V., Hanson A. A., & Hovin, A. W. (1969). Evaluation of tall fescue, *Festuca arundinacea* Schreb., for turf in the transition zone of the United States. *Agronomy Journal*, 61, 625–628. <https://doi.org/10.2134/agronj1969.00021962006100040042x>
- Hall, J. R. (1980). Effect of cultural factors on tall fescue-Kentucky bluegrass sod quality and botanical composition. *Proceedings of The Third International Turfgrass Research Conference*, 3, 367–377. <https://doi.org/10.2135/1974.proc3rdintlurfgrass.c43>
- Hall, J. R. III, & Taylor, L. H. (1989). Impact of companion crop and fertilization on tall fescue sod production. *International Turfgrass Society Research Journal*, 6, 259–261.
- Han, H. R. (2009). *Development Improved Turf-type Bermudagrasses*. Oklahoma State University, Stillwater, master's thesis.

- Honig, J. A., Averello, V., Bonos, S. A., & Meyer, W. A. (2012). Classification of Kentucky bluegrass (*Poa pratensis* L.) cultivars and accessions based on microsatellite (Simple Sequence Repeat) markers. *HortScience*, 47, 1356–1366.
<https://doi.org/10.21273/HORTSCI.47.9.1356>
- Honig, J. A., Averello, V., Kubik, C., Vaiciunas, J., Bushman, B. S., Bonos, S. A., & Meyer, W. A. (2018). An update on the classification of Kentucky bluegrass cultivars and accessions based on microsatellite (SSR) markers. *Crop Science*, 58(4) 1776–1787.
<https://doi.org/10.2135/cropsci2017.11.0689>.
- Hsiang, T., Carey, K., He, B. & Eggens, J. L. (1997). Composition of mixtures of four turfgrass species four years after seeding under non-wear conditions. *International Turfgrass Society Research Journal*, 8, 671–679.
- Hunt, K. L., & Dunn, J. H. (1993). Compatibility of Kentucky bluegrass and perennial ryegrass with tall fescue in transition zone turfgrass mixtures. *Agronomy Journal*, 85, 211–215.
- Huff, D. R. (2003). Kentucky bluegrass. In: M.D. Casler and R.R. Duncan, editors, *Turfgrass biology, genetics, and breeding*. Wiley, Hoboken, New, Jersey, 27–38.
- Hurley, R. H., & Skogley, C. R. (1975). Evaluation of Kentucky bluegrass and red fescue cultivars for sod production. *Agronomy Journal*, 67, 79–82.
<https://doi.org/10.2134/agronj1975.00021962006700010022x>
- Li, D., Fang, W., & Han, L. (2011). Nitrogen fertilization influences shear strength and quality of Kentucky bluegrass sod grown on clay. *Agronomy Journal*, 103, 565–599.
<https://doi.org/10.2134/agronj2010.0470>

- Lickfeldt, D. W., Voigt, T. B., & Hamblin, A. M. (2002) Composition and characteristics of blended Kentucky bluegrass stands. *HortScience*, 37, 1124–1126.
<https://doi.org/10.21273/HORTSCI.37.7.1124>
- Macolino, S., Pignata, G., & Maurizio, G. (2014). Species succession and turf quality of tall fescue and Kentucky bluegrass mixtures as affected by mowing height. *Crop Science*, 54, 1220–1226. <https://doi.org/10.2135/cropsci2013.10.0669>
- Morris, K. N., Kne, L., Graham, S., & Qu, Y. (2022). An Improved User Interface to Identify Sustainable Turfgrasses within National Turfgrass Evaluation Program Data. *International Turfgrass Society Research Journal*, 14, 1035–1041.
<https://doi.org/10.1002/its2.127>.
- Nwachukwu, E. U. (2025). *Assessment of Cool-season Turfgrass Sod Production Characteristics of Tall Fescue and Kentucky Bluegrass*. M.S. Thesis. Kansas State University, Manhattan.
- Park, B. S., Murphy, J. A., Meyer, W. A., Bonos, S. A., den Haan, J., Smith, D. A., & Lawson, T. J. (2005). Performance of Kentucky bluegrass within phenotypic classifications as affected by traffic. *International Turfgrass Society Research Journal*, 10, 618–626.
- Park, B. S., Lawson, T. J., Samaranayake, H., & Murphy, J. (2010). Tolerance and recovery of Kentucky bluegrass subjected to season wear. *Crop Science*, 50, 1526–1536.
<https://doi.org/10.2135/cropsci2009.09.0479>
- Park, B. S., Samaranayake, H., & Murphy, J. (2017). Response of tall fescue and Kentucky bluegrass mixtures to wear. *International Turfgrass Society Research Journal*, 13, 346–352. <https://doi.org/10.2134/itsrj2016.06.0503>

- Pornaro C., Masin, R., Macolino, S., & Richardson, M. (2021). Botanical composition of tall fescue-Kentucky bluegrass turfgrass mixtures is sustained in long-term study. *European Journal of Horticultural Science*, 86, 414–418.
<https://doi.org/10.17660/eJHS.2021/86.4.9>
- Powlen, J. S., Bigelow, C. A., Patton, A. J., Jiang, Y., & Fraser, M. L. (2021). Minimal irrigation requirements of Kentucky bluegrass and tall fescue blends in the northern transition zone. *Crop Science*, 61, 2939–2948. <https://doi.org/10.1002/csc2.20340>.
- Powlen, J. S., McCall, D. S., Hensler, K. L., Kerns, J. P., Fidanza, M. A., & Bigelow, C. A. (2024). Blend ratios and mixtures of brown patch susceptible and resistant tall fescue cultivars. *Agronomy Journal*, 116, 2690–2700. <https://doi.org/10.1002/agj2.21712>
- Proctor, C. A., Weisenberger, D. V., & Reicher, Z. J. (2015). Kentucky bluegrass and perennial ryegrass mixtures for establishing midwest lawns. *HortScience*, 50, 137–140.
<https://doi.org/10.21273/HORTSCI.50.1.137>
- Reynolds, W. C., Butler, E. L., Wetzel, H. C., Bruneay, A. H., & Tredway, L. P. (2005). Performance of Kentucky bluegrass-tall fescue mixtures in the southeastern United States. *International Turfgrass Society Research Journal*, 10, 525–530.
- Ross, S. J., Ennos, A. R., & Fitter, A. H. (1991). Turf strength and root characteristics of ten turfgrass cultivars. *Annals of Applied Biology*, 118, 433–443.
<https://doi.org/10.1111/j.1744-7348.1991.tb05644.x>
- Segars, C. A., Moss, J.Q., Martin, D. L., & Wu, Y. (2022). Sod production characteristics: How strong is your bermudagrass? *International Turfgrass Society Research Journal*, 14, 256–261. <https://doi.org/10.1002/its2.4>

- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52, 591–611. <https://doi.org/10.1093/biomet/52.3-4.591>
- Shearman, R. C., & Beard, J. B. (1975). Turfgrass wear tolerance mechanisms: I. Wear tolerance of seven turfgrass species and quantitative methods for determining turfgrass wear injury. *Agronomy Journal*, 67, 208–218
<http://doi.org/10.2134/agronj1975.00021962006700020009x>
- Shearman, R. C., Turner, T. R., Morris, K. N., Gaussoin, R. E., Vaitkus, M. R., & Wit, L. A. (2001). Sod strength and lateral spread of *Poa pratensis* cultivars and experimental lines. *International Turfgrass Society Research Journal*, 9, 928–933.
- Shildrick, J. P., & Peel, C. H. (1987). Football-stud wear on turf-type cultivars of tall fescue. [*Journal of the Sports Turf Research Institute*](#), 59, 124–132.
- Steinke, K., & Ervin, E. H. (2013). Turfgrass ecology. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Eds.), *Turfgrass: Biology, use, and management* (Vol. 56, pp. 347–382). ASA, CSSA, SSSA. <https://doi.org/10.2134/agronmonogr56.c10>
- Stier, J. C., Bae, J., & Jung, G. (2005). Composition of Kentucky bluegrass and perennial ryegrass mixtures subjected to traffic. *International Turfgrass Society Research Journal*, 10, 645–653.
- Stier, J. C., Koeritz, E. J., & Garrison, M. (2008). Timing the establishment of Kentucky bluegrass: Perennial ryegrass mixtures for football fields. *HortScience*, 43, 240–244.
<https://doi.org/10.21273/HORTSCI.43.1.240>.
- Su, K., Bremer, D. J., Keeley, S. J., & Fry, J. D. (2008). Rooting characteristics and canopy responses to drought of turfgrasses including hybrid bluegrasses. *Agronomy Journal*, 100, 949–956. <https://doi.org/10.2134/agronj2007.0292>.

- Taylor, L. H., & Schmidt, R. E. (1980). Differences in sod strength, rooting, and turfgrass quality of Kentucky bluegrass cultivars resulting from seasonal and environmental conditions. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference, 11–13 July 1977, Munich, West Germany* (pp. 31–38). ASA, CSSA, SSSA, and International Turfgrass Society. <https://doi.org/10.2135/1974.proc3rdintlurfgrass.c4>
- USDA-NASS. (2016). Quick Stats 2.0. <https://quickstats.nass.usda.gov/>.
- Vargas, J. M., & Turgeon, A. J. (1980). The principles of blending Kentucky Bluegrass cultivars for disease resistance. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference, Munich, West Germany, 11–13 July 1977* (p. 45–52). Madison, WI: ASA, CSSA, SSSA, and International Turfgrass Society. <https://doi.org/10.2135/1974.proc3rdintlurfgrass.c6>
- Walker, K. S., Bigelow, C. A., Smith, D. R., Van Scoyoc, G. E. & Reicher, Z. J. (2007). Aboveground response of cool-season lawn species to nitrogen rates and application timings. *Crop Science*, 47, 1225–1236. <https://doi.org/10.2135/cropsci2006.09.0595>
- Watkins, E., Fei, S., Gardner, D., Stier, J., Bughrara, S., Li, D., Biglelow, C., Schleicher, L., Horgan, B., & Diesburg, K. (2011). Low-Input turfgrass species for the North-central United States. *Applied Turfgrass Science*, 8, 1–11 <https://doi.org/10.1094/ats-2011-0126-02-rs>
- Watkins, E., Gardner, D. S., Stier, J. C., Soldat, D. J., St. John, R. A., Christians, N. E., Hathaway, A.D., Diesburg, K. L., Poppe, S. R., & Gaussoin, R. E. (2014). Cultivar performance of low-input turfgrass species for the North Central United States. *Applied Turfgrass Science*, 11, 1–7. <https://doi.org/10.2134/ATS-2013-0101-RS>

Yue, C., Hugie, K., & Watkins, E. (2012). Are consumers willing to pay more for low-input turfgrasses on residential lawns? Evidence from choice experiments. *Journal of Agricultural and Applied Economics*, 44, 549–560.

Yue, C., Wang, J., Watkins, E., Bonos, S. A., Nelson, K. C., Murphy, J. A., & Horgan, B. P. (2017). Heterogeneous consumer preferences for turfgrass attributes in the United States and Canada. *Canadian Journal of Agricultural Economics*, 65, 347–383.

<https://doi.org/10.1111/cjag.12128>



Figure 2.1. Cutting sod across plots using a Turfco KisCutter (left); Sod tensile strength device used to measure sod strength (middle); and Piece of torn sod from the sod tensile device (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Left photo by Ross Braun, middle and right photo by Emmanuel Nwachukwu.



Figure 2.2. Digital image analysis and light box (Z30 camera attached) (left); Measuring establishment speed differences of Run 1, 39 weeks after planting at the Rocky Ford Turfgrass Research Center, Manhattan, KS (right). Right photo by Emmanuel Nwachukwu, left photo by Ross Braun.



Figure 2.3. A 58 cm² sized plug cutter device used to remove plugs from non-sod harvest areas after each sod harvest (9, 10, 12 MAP) and at 20 and 24 MAP (left); tall fescue and Kentucky bluegrass plants visually counted per plug for population/percentage change (middle); plugs were returned to the experimental site after tiller counts in lab (right). Photo by Emmanuel Nwachukwu.



Figure 2.4. Harvested sod pieces showing difference among treatments at 10 months after planting. Photo by Emmanuel Nwachukwu.

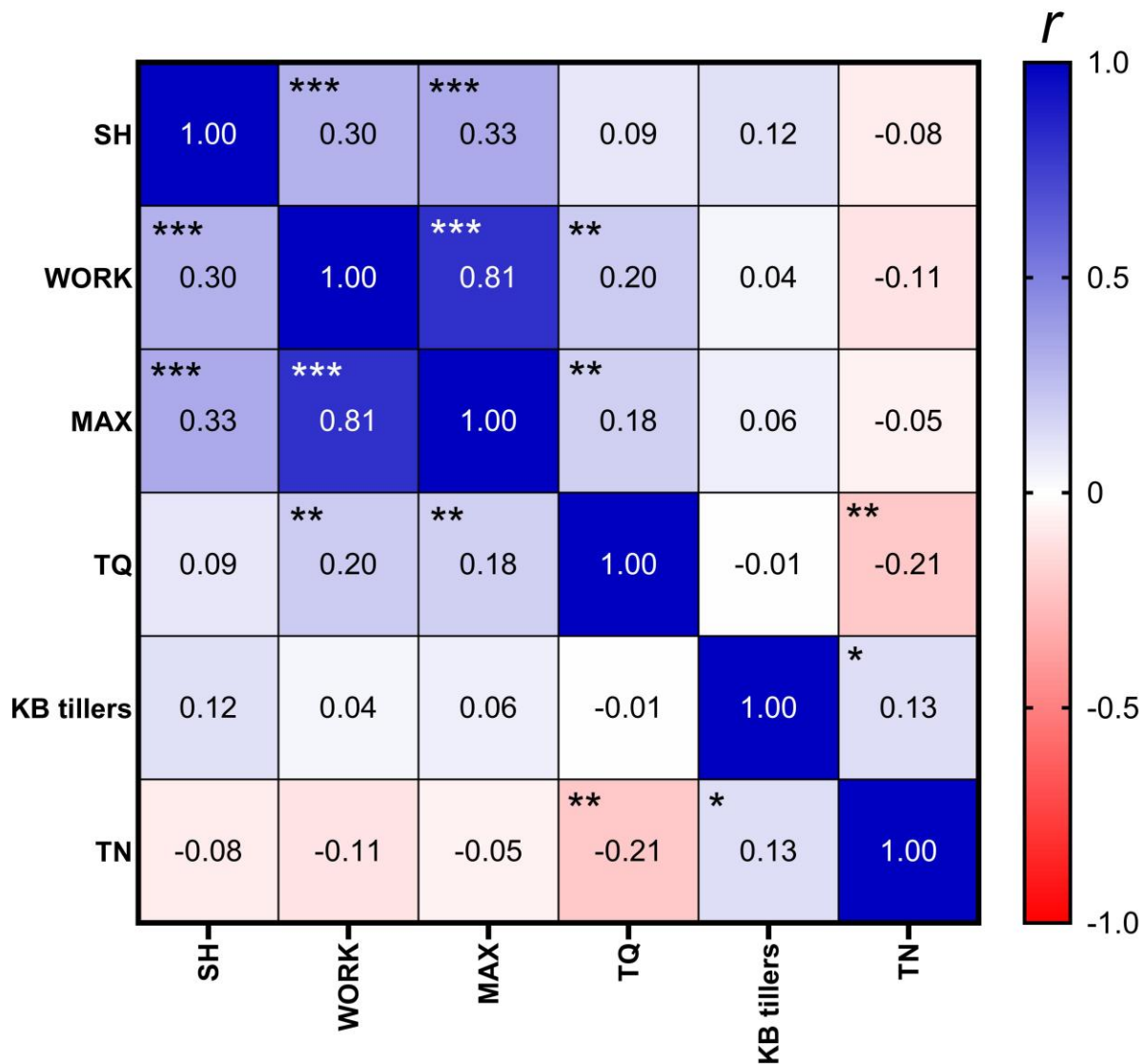


Figure 2.5. Correlation (r) is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX) and sod handling (SH)], turf quality (TQ), Kentucky bluegrass visual tillers percentage per square decimeter (KB tillers), and total tiller numbers [i.e., tall fescue (TF) and Kentucky bluegrass (KB)] (TN) per square decimeter was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($10 \times 4 \times 3 \times 2$; $n = 240$) for experiment 1. Note: P-value = no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels.

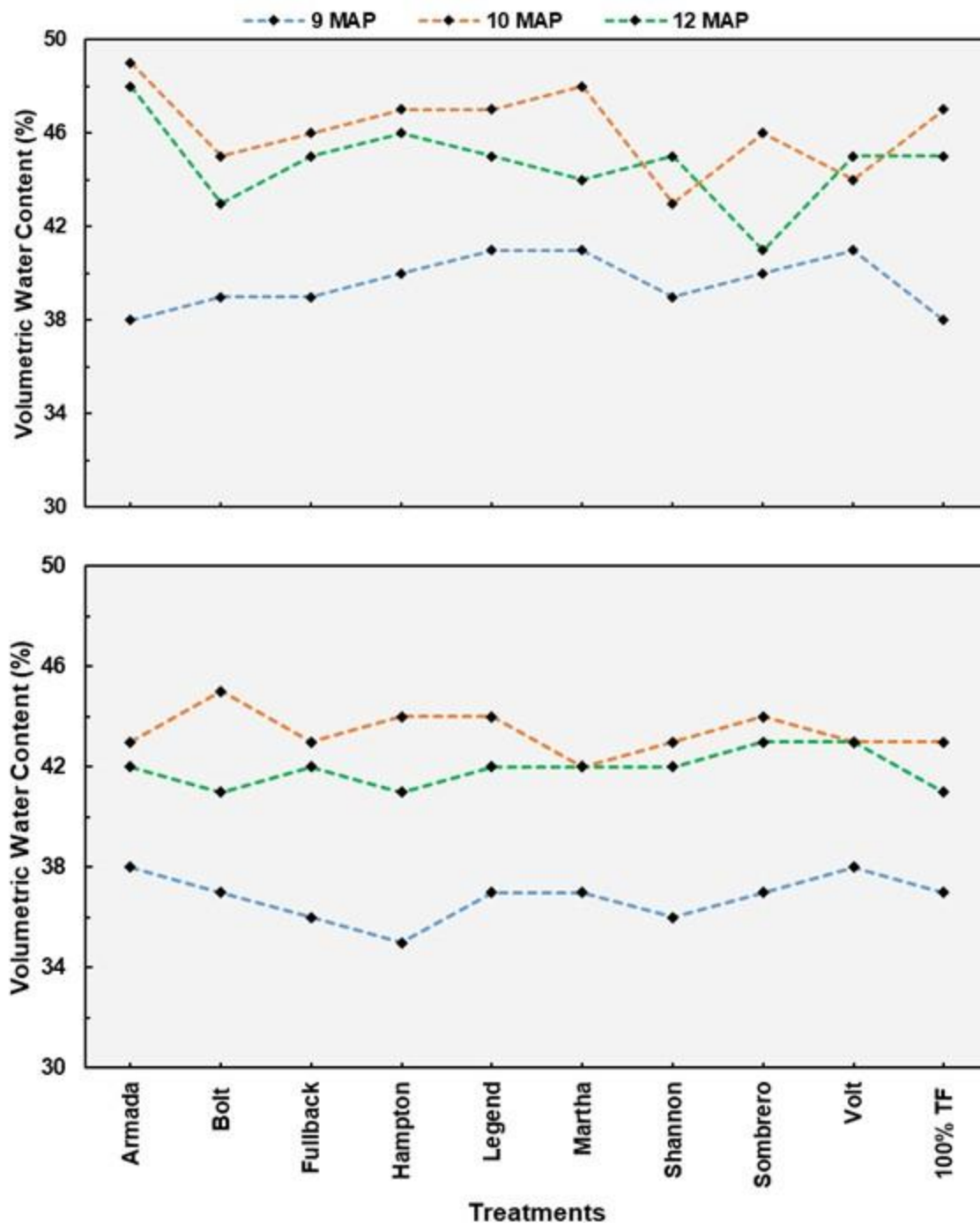


Figure 2.6. Volumetric water content (%) at a 7.6 cm soil depth of plots at each sod harvest event, Run 1 (top) and Run 2 (bottom) for Experiment 1. Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$).



Figure 2.7. Field plots layout for Experiment 1, showing vegetation establishment cover at 2.3 weeks after planting at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Photo by Emmanuel Nwachukwu

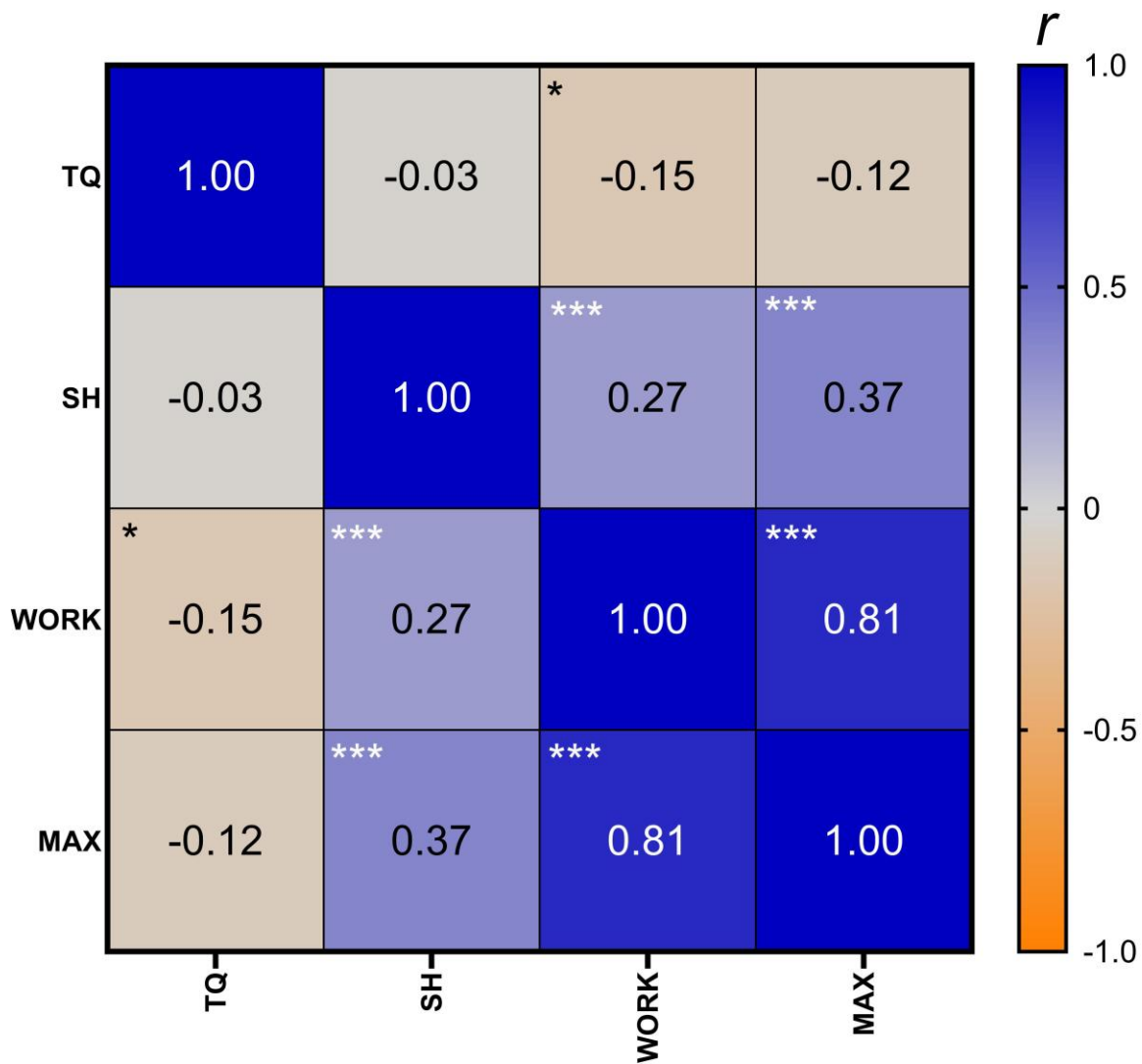


Figure 2.8. Correlation (r) is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX), sod handling (SH)], and turf quality (TQ) was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($10 \times 4 \times 3 \times 2$; $n = 240$) for Experiment 2. Note: For P -value, no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels.

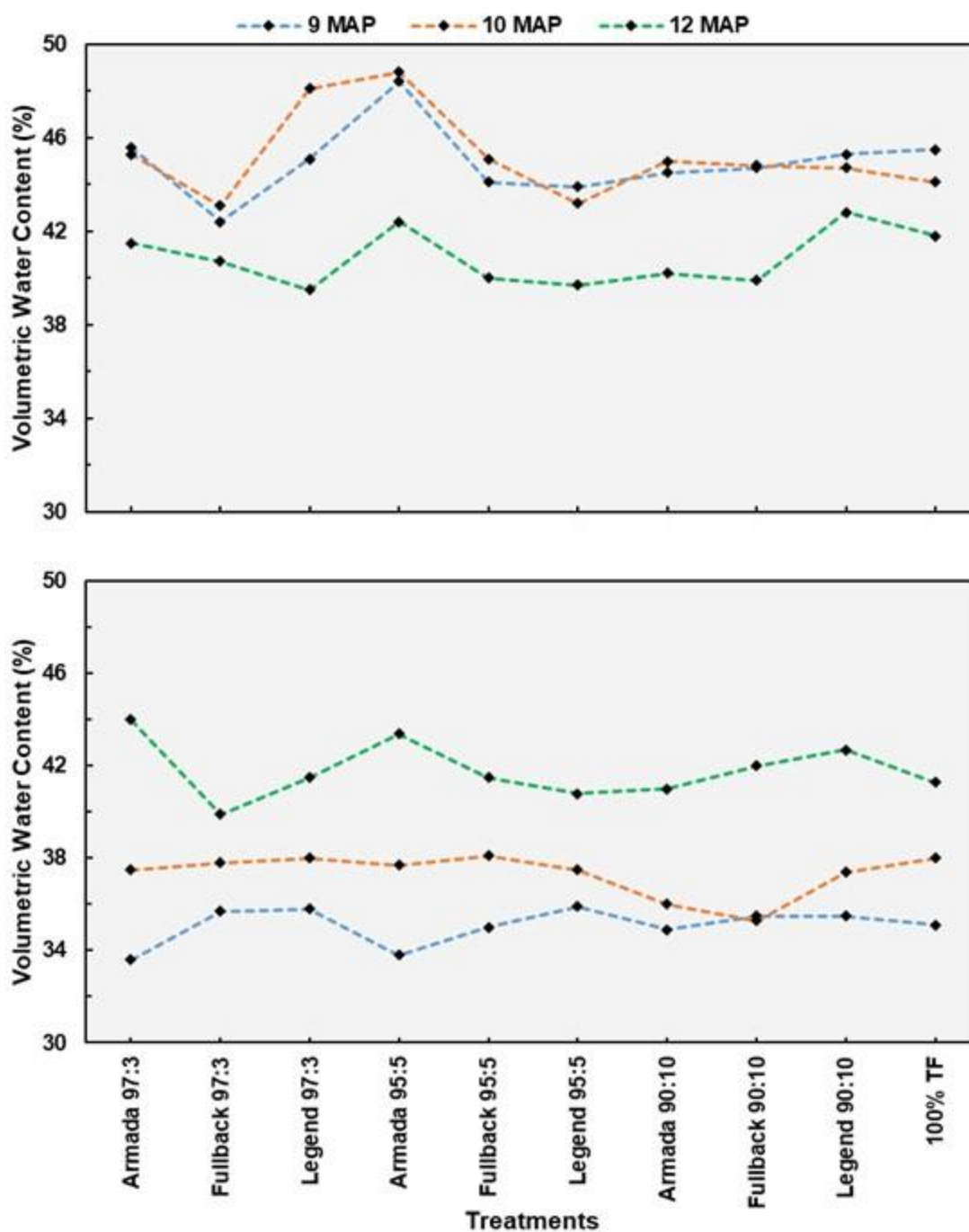


Figure 2.9. Volumetric water content (%) at a 7.6 cm soil depth of plots at each sod harvest event, Run 1 (top) and Run 2 (bottom) for Experiment 2. Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$).

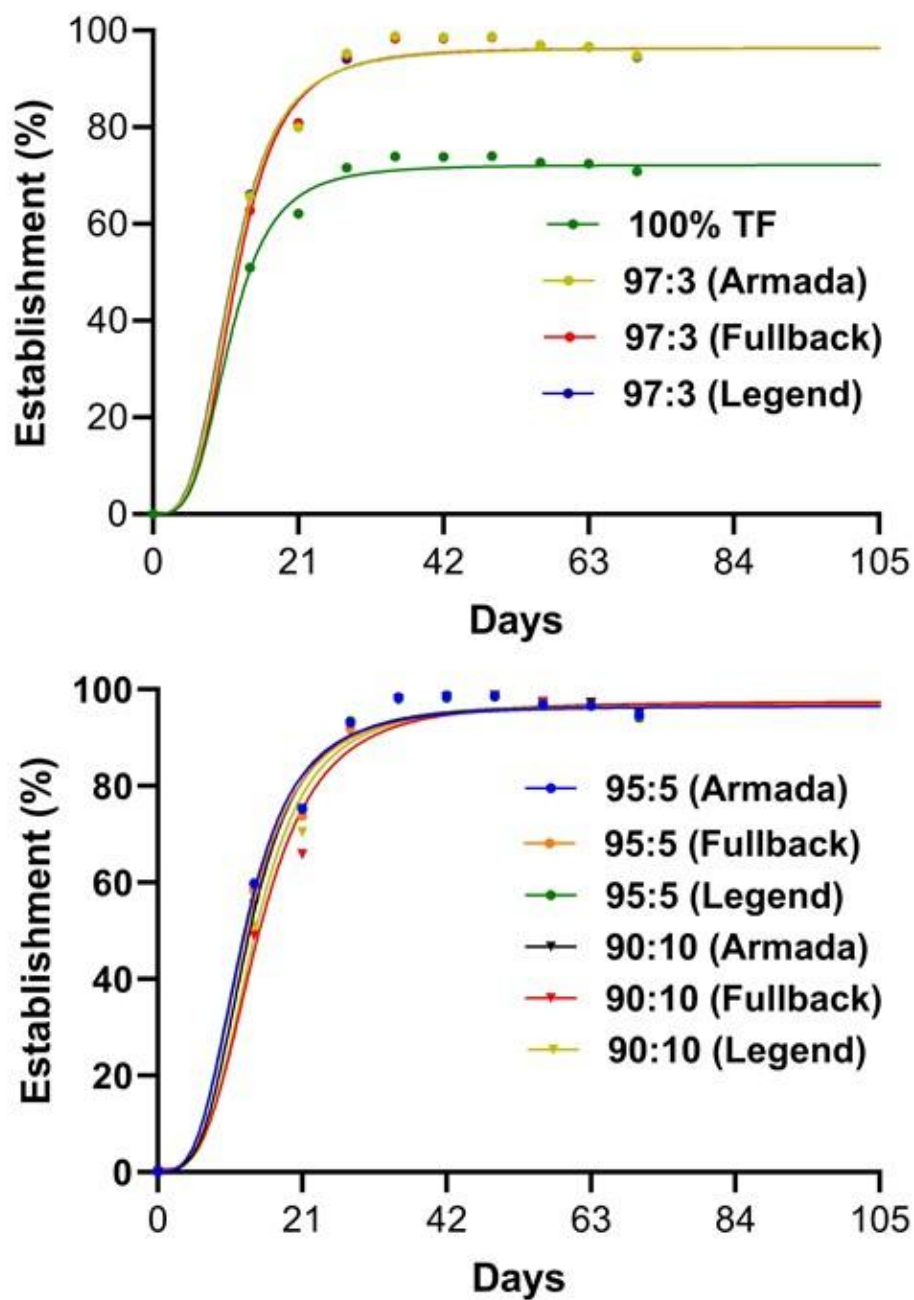


Figure 2.10. Four-parameter sigmoidal regression model output from GraphPad prism combined across runs for Experiment 2, showing establishment cover for treatments according to mixture ratios between TF and KB at 97:3% and a 100% TF bunch type blend (top), and other mixtures ratios of 95:5 and 90:10 (TF:KB w/w) (bottom). Regression line with the steepest slopes and lowest D₅₀ value indicates faster vegetation establishment cover.



Figure 2.11. Field plots layout for Experiment 2, showing vegetation establishment cover at 2.3 weeks after planting at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Photo by Emmanuel Nwachukwu.

Table 2.1. Species and Cultivars that were included in both Field Experiment 1 and Field Experiment 2.

Species	Common name	Cultivar	Growth habit	Company
<i>Poa pratensis</i>	Kentucky bluegrass	Armada	Rhizomatous	DLF Pickseed
<i>Poa pratensis</i>	Kentucky bluegrass	Bolt	Rhizomatous	Mountain View Seed Company
<i>Poa pratensis</i>	Kentucky bluegrass	Fullback	Rhizomatous	Landmark Seed Company
<i>Poa pratensis</i>	Kentucky bluegrass	Hampton	Rhizomatous	Landmark Seed Company
<i>Poa pratensis</i>	Kentucky bluegrass	Legend	Rhizomatous	Mountain View Seed Company
<i>Poa pratensis</i>	Kentucky bluegrass	Martha	Rhizomatous	DLF Pickseed
<i>Poa pratensis</i>	Kentucky bluegrass	Shannon	Rhizomatous	Landmark Seed Company
<i>Poa pratensis</i>	Kentucky bluegrass	Sombrero	Rhizomatous	DLF Pickseed
<i>Poa pratensis</i>	Kentucky bluegrass	Volt	Rhizomatous	Mountain View Seed Company
<i>Festuca arundinacea</i>	Tall fescue	Avenger 3	Bunch-type	Mountain View Seed Company
<i>Festuca arundinacea</i>	Tall fescue	Blackwatch 2	Bunch-type	DLF Pickseed
<i>Festuca arundinacea</i>	Tall fescue	Maestro	Bunch-type	Landmark Seed Co.

Table 2.2. Kentucky bluegrass classification system and growth aggressiveness classification labels.

Cultivar	Kentucky Bluegrass Classification^a	Growth Aggressiveness Classification^b	Kentucky Bluegrass Classification Descriptions^c
Armada	Compact America	Low	Fast germination and establishment, excellent shear strength, finer leaf, high turf quality and density.
Bolt	Jefferson/Washington	Medium	Excellent heat and high summer stress tolerance, deep, extensive roots and rhizomes vigorous turf and high density.
Fullback	Compact Midnight	Medium	Low, compact growth, good heat tolerance.
Hampton	Compact	High	Low, compact growth, high turf quality.
Legend	Compact America (Midnight)	Medium	Low, compact growth, high turf quality, higher density, moderate summer recovery, good heat tolerance.
Martha	Jefferson/Washington/Mid-Atlantic	High	Excellent heat and high summer stress tolerance, deep, extensive roots and rhizomes vigorous turf and high density.
Shannon	Compact America × Shamrock	High	Rapid germination and establishment, high sod strength, quick knit sod and repair, aggressive lateral growth, high shoot density.
Sombrero	Limousine	High	High turf quality, superb density, heat & drought tolerant.
Volt	Shamrock	Low	Good turf quality and sod strength, strong rhizome development.

^a Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Classification descriptions based on Brilman (2018, 2020 2024).

Note: Armada, Fullback, and Legend cultivars were included in Field Experiment 2 only, while all cultivars were included in Field Experiment 1.

Table 2.3. Seeding rate conversions for the TF:KB 95:5 (w/w) treatments and 100% TF treatment in Experiment 1.

Treatment ^a	Run 1				Run 2			
	TF	KB	TF	KB	TF	KB	TF	KB
	g of seed m ⁻²		lb of seed 1000 ft ⁻²		g of seed m ⁻²		lb of seed 1000 ft ⁻²	
Armada KB	37	2	8	0.4	39	2.1	8.0	0.4
Shannon KB	37	2	8	0.4	39	2.1	8.0	0.4
Volt KB	36	2	7	0.4	39	2.0	7.9	0.4
Bolt KB	35	2	7	0.4	37	2.0	7.6	0.4
Fullback KB	35	2	7	0.4	36	1.9	7.3	0.4
Martha KB	35	2	7	0.4	38	2.0	7.6	0.4
Hampton KB	36	2	7	0.4	39	2.0	8.0	0.4
Legend KB	35	2	7	0.4	37	2.0	7.6	0.4
Sombrero KB	35	2	7	0.4	37	1.9	7.5	0.4
Avenger 3 + Blackwatch 2 + Maestro	47	0	10	0	50	0.0	10.2	0.0

Note. All plots were seeded at a seed mixture rate of 2 pure live seed cm⁻². TF = tall fescue, KB = Kentucky bluegrass.

^a For Experiment 1, KB cultivars were included in the sod mixture seeding ratio 5% by weight of the 95:5 (w/w, TF:KB). Tall fescue included with each Kentucky bluegrass was Avenger 3 + Blackwatch 2 + Maestro at even proportion to account for 95% weight of the TF in the 95:5 w/w TF:KB mixture and an even proportion in the 100% TF treatment.

Table 2.4. Seeding rate conversions for the different seeding mixture ratio TF:KB (w/w) treatments and 100% TF treatment in Experiment 2.

Treatment ^a	Run 1				Run 2			
	TF	KB	TF	KB	TF	KB	TF	KB
	g of seed m ⁻²		lb of seed 1000 ft ⁻²		g of seed m ⁻²		lb of seed 1000 ft ⁻²	
Armada (97:3)	40	1.2	8.2	0.3	43	1.3	8.8	0.3
Fullback (97:3)	38	1.2	7.7	0.2	40	1.3	8.2	0.3
Legend (97:3)	39	1.2	8.0	0.3	42	1.3	8.5	0.3
Armada (95:5)	37	1.9	7.5	0.4	39	2.1	8.0	0.4
Fullback (95:5)	33	1.8	6.8	0.4	36	1.9	7.3	0.4
Legend (95:5)	35	1.9	7.2	0.4	37	2.0	7.6	0.4
Armada (90:10)	29	3.3	6.0	0.7	32	3.5	6.5	0.7
Fullback (90:10)	25	2.8	5.2	0.6	27	3.0	5.5	0.6
Legend (90:10)	28	3.1	5.7	0.6	29	3.2	6.0	0.6
Avenger 3 + Blackwatch 2 + Maestro	47	0.0	9.6	0.0	50	0.0	10.2	0.0

Note. All plots were seeded at a seed mixture rate of 2 pure live seed cm⁻². TF = tall fescue, KB = Kentucky bluegrass.

^a Avenger 3, Blackwatch 2, and Maestro (TF blend of 33.3% each, by weight) was included in all treatments, including KB treatments in both experiments.

Table 2.5. Effects of Kentucky bluegrass (KB) cultivar mixed with tall fescue at a 95:5 (w/w) mixture ratio on sod strength and handling at three sod harvest timings [9, 10, and 12 months after planting (MAP)] across both experiment runs in Experiment 1.

Tall fescue (% weight)	KB Cultivar ^a (5% weight)	Growth Aggressiveness Classification ^b	9 MAP Required	10 MAP work to tear sod	12 MAP work to tear sod	9 MAP Maximum tensile load to tear sod	10 MAP Maximum tensile load to tear sod	12 MAP Maximum tensile load to tear sod	9 MAP Sod handling	10 MAP Sod handling	12 MAP Sod handling
				(N-m)			(N)			(1-5)	
95% TF	Armada	Low	14.2	12.1	14.4	248	196	278	2.5	3.1	3.3
95% TF	Bolt	Medium	15.0	12.1	14.8	294	209	305	3.1	3.4	3.1
95% TF	Fullback	Medium	14.2	12.0	15.6	267	187	325	2.9	3.4	3.4
95% TF	Hampton	High	14.3	13.6	15.9	272	215	283	3.1	3.3	3.5
95% TF	Legend	High	13.9	13.0	14.1	267	207	253	3.4	3.3	3.4
95% TF	Martha	Medium	14.0	12.6	15.1	275	201	271	3.0	3.3	3.4
95% TF	Shannon	Low	14.6	12.7	14.6	284	224	269	3.4	3.5	3.4
95% TF	Sombrero	High	14.3	15.2	12.4	252	243	226	3.1	3.3	3.4
95% TF	Volt	Low	14.5	12.4	15.4	299	226	295	3.1	3.1	3.6
100% TF	---	---	13.6	11.5	12.0	254	190	221	2.9	3.0	2.9
<i>P</i> -value			0.9901	0.1274	0.0513	0.6184	0.2783	0.0609	0.2549	0.8944	0.5284

^a KB cultivars were included in the sod mixture seeding ratio of 95:5 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

Note. All plots were seeded at a seed mixture rate of 2 pure live seed cm⁻². TF = tall fescue, KB = Kentucky bluegrass. Means within each column with a common letter or no letters are not significantly different according to Fisher’s LSD test ($\alpha = .05$).

Table 2.6. Turfgrass quality rating of treatments during establishment [6 to 32 weeks after seeding (WAS)] and the following spring across both experiment runs in Experiment 1.

Tall fescue (% weight)	KB Cultivar ^a (5% weight)	Growth Aggressiveness Classification ^b	Run 1			Run 2				
			6 WAS	8 WAS	10 WAS	4 WAS	6 WAS	8 WAS	10 WAS	32 WAS
			----- 1 to 9 scale ^c -----							
95% TF	Armada	Low	8.3	9.0	9.0	7.5	8.8	8.8	9.0	9.0
95% TF	Bolt	Medium	8.8	9.0	9.0	6.8	8.3	8.3	9.0	9.0
95% TF	Fullback	Medium	8.8	9.0	9.0	7.0	8.8	8.8	9.0	9.0
95% TF	Hampton	High	8.5	9.0	9.0	8.0	8.8	8.8	9.0	9.0
95% TF	Legend	High	8.5	9.0	9.0	7.3	9.0	8.5	9.0	9.0
95% TF	Martha	Medium	8.5	9.0	9.0	7.0	8.5	8.8	9.0	9.0
95% TF	Shannon	Low	8.8	9.0	9.0	7.0	8.8	9.0	9.0	9.0
95% TF	Sombrero	High	8.8	9.0	9.0	7.3	9.0	9.0	9.0	9.0
95% TF	Volt	Low	8.5	9.0	9.0	7.5	9.0	8.3	8.8	9.0
100% TF	---	---	8.8	9.0	9.0	7.5	9.0	8.8	9.0	9.0
<i>P</i> -value			0.5817	1.000	1.000	0.0916	0.0739	0.2603	0.4635	1.000

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) for each month during the turfgrass establishment.

Note: Means within each column followed by the same letter or no letter are not different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 2.7. Turfgrass quality ratings of Experiment 1 treatments in the field for both experiment runs at each sod harvest timing from 9 to 12 months after planting (MAP).

Tall fescue (% weight)	KB Cultivar ^a (% weight)	Growth Aggressiveness Classification ^b	Run 1			Run 2		
			9 MAP	10 MAP	12 MAP	9 MAP	10 MAP	12 MAP
			----- 1 to 9 scale ^c -----					
97% TF	3% Armada	Low	9.0	9.0	9.0	9.0	9.0	9.0
97% TF	3% Fullback	Medium	9.0	9.0	9.0	9.0	9.0	9.0
97% TF	3% Legend	High	9.0	9.0	9.0	9.0	9.0	9.0
95% TF	5% Armada	Low	9.0	9.0	9.0	9.0	9.0	9.0
95% TF	5% Fullback	Medium	9.0	9.0	9.0	9.0	9.0	9.0
95% TF	5% Legend	High	9.0	9.0	9.0	9.0	9.0	9.0
90% TF	10% Armada	Low	9.0	9.0	9.0	9.0	9.0	9.0
90% TF	10% Fullback	Medium	9.0	9.0	9.0	9.0	9.0	9.0
90% TF	10% Legend	High	9.0	9.0	9.0	9.0	9.0	9.0
100% TF	--	--	9.0	9.0	9.0	9.0	9.0	9.0
<i>P-value</i>			1.000	1.000	1.000	1.000	1.000	1.000

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) during sod harvest dates.

Note: Means within each column followed by the same letter or no letter are not different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 2.8. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 50, 70, and 90% establishment treatments in the field across both experiment runs in Experiment 1.

Tall fescue (% weight) ^a	KB Cultivar (5% weight) ^a	Kentucky bluegrass Classification ^b	Growth Aggressiveness Classification ^b	D ₅₀ ^c	D ₇₀ ^c	D ₉₀ ^c	Top ^d	Hillslope ^d	R ²
				-----	d	-----	%		
95% TF	Armada	Compact America	Low	12.3	16.1	24.8	96.8	3.3	0.9795
95% TF	Bolt	Jefferson/Washington	Medium	12.8	16.4	24.6	97.1	3.5	0.9841
95% TF	Fullback	Compact Midnight	Medium	11.6	15.5	24.6	97.2	2.9	0.9811
95% TF	Hampton	Compact	High	12.5	16.6	26.2	97.0	3.1	0.9820
95% TF	Legend	Compact America (Midnight)	High	12.4	16.6	26.4	97.3	2.9	0.9852
95% TF	Martha	Jefferson/Compact Mid- Atlantic	Medium	12.1	16.0	25.1	96.9	3.1	0.9816
95% TF	Shannon	Compact America x Shamrock	Low	11.7	15.6	24.9	97.3	3.0	0.9819
95% TF	Sombrero	Limousine	High	11.7	15.8	25.5	97.4	2.9	0.9780
95% TF	Volt	Shamrock	Low	11.4	15.0	23.7	96.8	3.1	0.9812
100% TF	--	--	--	10.8	14.0	21.4	96.8	3.3	0.9878
<i>P-value</i>				0.1146	0.1343	0.2062	0.2662	0.2519	0.5881

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c D₅₀, estimated number of days until 50% establishment; D₇₀, estimated number of days until 70% establishment; D₉₀, estimated number of days until 90% establishment.

^d Top (%) is the maximum establishment estimate; ^d Higher hillslope (not units) values indicate more rapid establishment speed.

Note: Means within each column followed by the same letter or no letter are not different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 2.9. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 1 of Experiment 1.

TF (% by weight) ^a	KB cultivar (5% weight) ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP		20 MAP		24 MAP	
			TF	KB	TF	KB	TF	KB	TF	KB	TF	KB
----- % ^c -----												
95% TF	Armada	Low	94.8 ab	5.2 de	86.9	13.1 a	89.1 bc	10.9 cd	80.2 bcd	19.8 abc	78.8 de	21.2 bc
95% TF	Bolt	Medium	80.9 de	19.1 ab	82.7	17.3 a	80.9 cd	19.1 bc	77.8 cd	22.2 ab	70.3 ef	29.7 ab
95% TF	Fullback	Medium	83.5 cde	16.5 abc	83.4	16.6 a	82.9 bcd	17.1 bcd	78.5 bcd	21.5 abc	71.7 def	28.3 abc
95% TF	Hampton	High	74.3 e	25.7 a	80.5	19.5 a	85.3 bcd	14.7 bcd	75.1 d	24.9 a	66.4 f	33.6 a
95% TF	Legend	High	87.8 bcd	12.2 bcd	91.5	8.5 ab	87.1 bc	13.0 cd	81.1 bcd	18.9 abc	89.8 bc	10.2 d
95% TF	Martha	Medium	87.6 bcd	12.4 bcd	80.2	19.8 a	76.6 d	23.4 b	75.8 d	24.2 a	74.8 def	25.2 abc
95% TF	Shannon	Low	92.6 abc	7.4 cde	89.2	10.8 ab	91.6 ab	8.4 de	87.4 b	12.6 c	92.3 ab	7.7 d
95% TF	Sombrero	High	78.5 de	21.5 ab	80.2	19.8 a	65.9 e	34.1 a	78.5 bcd	21.5 abc	80.7 cd	19.3 c
95% TF	Volt	Low	84.0 b-e	15.0 bc	85.3	14.7 a	83.6 bcd	16.4 cd	86.7 bc	13.3 bc	93.5 ab	6.5 de
100% TF	---	---	100 a	0.0 e	100	0.0 b	100 a	0.0 e	100 a	0.0 d	100 a	0.0 e
<i>P-value</i>			0.0022	0.0010	0.0544	0.0335	<.0001	<.0001	0.0004	<0.0001	<0.0001	<0.0001

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Percentage of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table 2.10. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 1.

TF (% by weight) ^a	KB cultivar (5% weight) ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP		^a Tall fescue was
			TF	KB	TF	KB	TF	KB	
			----- % ^c -----						
95% TF	Armada	Low	91.0 abc	9.0 bc	90.6	9.4 bcd	87.5	12.6 c	
95% TF	Bolt	Medium	86.2 bc	13.8 ab	78.7	21.3 a	88.5	11.5 c	
95% TF	Fullback	Medium	86.0 bc	14.0 ab	84.4	15.6 abc	79.5	20.5 b	
95% TF	Hampton	High	81.1 c	18.9 a	83.8	16.2 abc	85.9	14.1 c	
95% TF	Legend	High	81.4 c	18.6 a	92.3	7.7 cd	88.9	11.1 c	
95% TF	Martha	Medium	90.5 abc	9.5 ab	87.3	12.7 abc	88.9	11.1 c	
95% TF	Shannon	Low	92.3 ab	7.7 bc	86.7	13.3 abc	95.0	5.0 d	
95% TF	Sombrero	High	81.1 c	18.9 a	83.1	16.9 ab	72.5	27.5 a	
95% TF	Volt	Low	88.9 bc	10.1 ab	90.2	9.8 bcd	88.1	11.9 c	
100% TF	---	---	100 a	0.0 c	97.2	0.0 d	100	0.0 d	
<i>P-value</i>			0.0124	0.0062	0.1633	0.0107	0.0597	<0.0001	

^a ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Percentage of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table 2.11. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 1 of Experiment 1.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP		20 MAP		24 MAP	
			TF	KB	TF	KB	TF	KB	TF	KB	TF	KB
			----- Tillers per square decimeter ^c -----									
95% TF	Armada	Low	132.6	7.5 d	108.5	17.9 ab	94.7	12.3 cd	119.6	29.7 ab	88.4 bc	23.3 c
95% TF	Bolt	Medium	116.9	29.7 ab	113.2	25.4 ab	104.2	28.0 abc	115.5	34.9 a	84.5 bc	35.9 ab
95% TF	Fullback	Medium	125.3	25.0 ab	96.0	21.3 ab	125.3	24.3 abc	115.5	29.7 ab	74.2 c	29.0 bc
95% TF	Hampton	High	99.7	32.9 a	97.3	20.9 ab	96.0	17.2 bcd	111.9	36.7 a	85.1 bc	43.1 a
95% TF	Legend	High	120.8	17.2 bc	110.9	9.5 b	106.8	16.8 bcd	121.0	27.4 ab	100.2 ab	11.1 d
95% TF	Martha	Medium	119.1	16.6 abc	120.8	29.3 ab	93.2	32.7 ab	128.6	39.3 a	94.0 abc	31.9 abc
95% TF	Shannon	Low	106.8	8.2 cd	121.0	15.1 ab	110.2	10.3 d	108.5	17.8 b	100.9 ab	8.5 d
95% TF	Sombrero	High	111.1	30.1 ab	85.3	21.3 ab	87.4	44.6 a	78.8	22.8 ab	101.6 ab	24.8 bc
95% TF	Volt	Low	93.2	15.9 bcd	109.6	20.0 ab	114.5	20.2 bcd	108.6	17.8 b	111.7 ab	8.3 d
100% TF	---	---	116.9	0.0 e	134.1	0.0 c	116.3	0.0 e	134.8	0.0 c	116.5 a	0.0 e
<i>P-value</i>			0.4394	<0.0001	0.1141	0.0041	0.4094	<.0001	0.5450	<0.0001	0.0172	<0.0001

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Tillers per square decimeter of each TF and KB calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.
Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table 2.12. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 1.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP	
			TF	KB	TF	KB	TF	KB
			----- Tillers per square decimeter ^c -----					
95% TF	Armada	Low	126.2	11.0 b	86.3	8.6 bc	91.5	12.5 b
95% TF	Bolt	Medium	97.3	14.0 ab	69.8	19.2 a	93.4	12.1 b
95% TF	Fullback	Medium	100.5	16.6 ab	92.6	18.5 ab	97.1	23.5 a
95% TF	Hampton	High	99.0	23.7 a	82.0	16.8 ab	88.3	14.6 b
95% TF	Legend	High	93.9	20.5 a	91.9	7.8 c	87.2	10.3 b
95% TF	Martha	Medium	109.6	11.8 ab	92.6	13.8 abc	94.1	13.1 b
95% TF	Shannon	Low	93.9	7.5 b	77.9	11.1 abc	101.4	5.4 c
95% TF	Sombrero	High	94.7	22.8 a	90.6	17.9 a	80.7	29.1 a
95% TF	Volt	Low	98.2	12.5 ab	91.5	9.9 abc	110.0	14.2 b
100% TF	Armada	Low	128.1	0.0 c	103.3	0.0 d	106.6	0.0 d
<i>P-value</i>			0.0999	0.0005	0.2471	<0.0001	0.4945	<0.0001

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Tillers per square decimeter of each TF and KB calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table 2.13. Effects of Kentucky bluegrass (KB) cultivar mixed with tall fescue at different mixture ratios (97:3, 95:5, and 90:10 TF:KB w/w) on sod strength and handling at three sod harvest timings [9, 10, and 12 months after planting (MAP)] combined across runs in Experiment 2.

Tall fescue (% weight)	KB Cultivar ^a (5% weight)	Growth Aggressiveness Classification ^b	9 MAP Required work to tear sod	10 MAP Required work to tear sod	12 MAP Required work to tear sod	9 MAP Maximum tensile load to tear sod	10 MAP Maximum tensile load to tear sod	12 MAP Maximum tensile load to tear sod	9 MAP Sod handling	10 MAP Sod handling	12 MAP Sod handling
			(N-m)			(N)			(1-5)		
97% TF	3% Armada	Low	14.1	13.6	14.1	270 ab	240	270 ab	2.9	2.8	3.3
97% TF	3% Fullback	Medium	13.0	14.9	13.7	227 b	267	267 ab	2.6	3.3	3.4
97% TF	3% Legend	High	14.0	13.8	12.9	267 ab	240	224 bc	3.1	3.3	2.8
95% TF	5% Armada	Low	14.8	13.1	12.8	272 ab	228	205 c	3.4	2.6	3.3
95% TF	5% Fullback	Medium	15.4	14.0	13.2	313 a	262	232 bc	3.3	3.3	3.5
95% TF	5% Legend	High	14.8	13.3	14.5	273 ab	246	252 abc	3.0	3.0	3.8
90% TF	10% Armada	Low	15.2	13.6	13.0	295 a	260	213 c	3.4	3.4	3.3
90% TF	10% Fullback	Medium	15.4	13.8	15.5	290 a	245	292 a	3.3	3.3	3.3
90% TF	10% Legend	High	14.7	13.9	13.5	275 ab	246	238 abc	3.1	3.0	3.1
100% TF	--	--	13.0	12.6	12.7	230 b	226	223 bc	2.8	2.9	3.0
<i>P-value</i>			0.0700	0.8234	0.1820	0.0487	0.8893	0.0367	0.2497	0.2755	0.3279

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

Note. All plots were seeded at a seed mixture rate of 2 pure live seed cm⁻². TF = tall fescue, KB = Kentucky bluegrass. Means within each column with a common letter or no letters are not significantly different according to Fisher’s LSD test ($\alpha = .05$).

Table 2.14. Turfgrass quality rating of treatments during establishment and the following spring from 6 to 32 weeks after seeding (WAS) across both experiment runs in Experiment 2.

Tall fescue (% weight)	KB Cultivar ^a (% weight)	Growth Aggressiveness Classification ^b	Run 1			Run 2				
			6 WAS	8 WAS	10 WAS	4 WAS	6 WAS	8 WAS	14 WAS	32 WAS
			----- 1 to 9 scale ^c -----							
97% TF	3% Armada	Low	9.0	9.0	9.0	7.8	9.0	8.8	9.0	9.0
97% TF	3% Fullback	Medium	9.0	9.0	9.0	7.5	9.0	8.8	9.0	9.0
97% TF	3% Legend	High	9.0	9.0	9.0	7.3	9.0	9.0	9.0	9.0
95% TF	5% Armada	Low	9.0	9.0	9.0	7.0	8.8	9.0	9.0	9.0
95% TF	5% Fullback	Medium	8.8	9.0	9.0	7.5	8.8	9.0	9.0	9.0
95% TF	5% Legend	High	8.5	9.0	9.0	7.5	9.0	8.5	9.0	9.0
90% TF	10% Armada	Low	8.8	9.0	9.0	7.0	9.0	8.8	9.0	9.0
90% TF	10% Fullback	Medium	8.8	9.0	9.0	7.5	8.8	9.0	9.0	9.0
90% TF	10% Legend	High	9.0	9.0	9.0	7.0	9.0	8.8	9.0	9.0
100% TF	--	--	8.9	9.0	9.0	7.6	9.0	9.0	9.0	9.0
<i>P-value</i>			0.4173	1.000	1.000	0.5249	0.6217	0.5057	1.000	1.000

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) for each month during the turfgrass establishment.

Note. All plots were seeded at a seed mixture rate of 2 pure live seed cm⁻². TF = tall fescue, KB = Kentucky bluegrass. Means within each column with a common letter or no letters are not significantly different according to Fisher’s LSD test ($\alpha = .05$).

Table 2.15. Turfgrass quality ratings of Experiment 2 treatments in the field for both experiment runs at each sod harvest timing.

Tall fescue (% weight)	KB Cultivar ^a (% weight)	Growth Aggressiveness Classification ^b	Run 1			Run 2		
			9 MAP	10 MAP	12 MAP	9 MAP	10 MAP	12 MAP
			----- 1 to 9 scale ^c -----					
97% TF	3% Armada	Low	9.0	9.0	9.0	9.0	9.0	9.0
97% TF	3% Fullback	Medium	9.0	9.0	9.0	9.0	9.0	9.0
97% TF	3% Legend	High	9.0	9.0	9.0	9.0	9.0	9.0
95% TF	5% Armada	Low	9.0	9.0	9.0	9.0	9.0	9.0
95% TF	5% Fullback	Medium	9.0	9.0	9.0	9.0	9.0	9.0
95% TF	5% Legend	High	9.0	9.0	9.0	9.0	9.0	9.0
90% TF	10% Armada	Low	9.0	9.0	9.0	9.0	9.0	9.0
90% TF	10% Fullback	Medium	9.0	9.0	9.0	9.0	9.0	9.0
90% TF	10% Legend	High	9.0	9.0	9.0	9.0	9.0	9.0
100% TF	--	--	9.0	9.0	9.0	9.0	9.0	9.0
<i>P-value</i>			1.000	1.000	1.000	1.000	1.000	1.000

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) during sod harvest timings for both runs.

Note. All plots were seeded at a seed mixture rate of 2 pure live seed cm⁻². TF = tall fescue, KB = Kentucky bluegrass. Means within each column with a common letter or no letters are not significantly different according to Fisher’s LSD test ($\alpha = .05$).

Table 2.16. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 50, 70, and 90% establishment treatments in the field across both experiment runs in Experiment 2.

Tall fescue (% weight) ^a	KB Cultivar (weight) ^a	Kentucky bluegrass Classification ^b	Growth Aggressiveness Classification ^b	D ₅₀ ^c	D ₇₀ ^c	D ₉₀ ^c	Top ^d	Hillslope ^d	R ²
				----- d -----			%		
97% TF	3% Armada	Compact America	Low	11.5 ef	14.6 ef	21.5 de	96.4 c	3.5	0.9803
97% TF	3% Fullback	Compact Midnight	Medium	12.1 c-f	15.3 def	22.1 cde	96.6 bc	3.9	0.9845
97% TF	3% Legend	Compact America (Midnight)	High	11.5 def	14.7 ef	21.8 de	96.5 bc	3.6	0.9827
95% TF	5% Armada	Compact America	Low	12.5 cde	16.1 cde	24.1 bcd	96.6 bc	3.4	0.9790
95% TF	5% Fullback	Compact Midnight	Medium	12.8 c	16.6 bcd	25.1 bc	97.0 ab	3.3	0.9788
95% TF	5% Legend	Compact America (Midnight)	High	12.6 cd	16.2 cde	24.4 bcd	96.9 bc	3.5	0.9789
90% TF	10% Armada	Compact America	Low	13.2 bc	16.9 bc	25.1 bc	97.1 ab	3.5	0.9840
90% TF	10% Fullback	Compact Midnight	Medium	14.1 ab	19.0 a	28.4 a	97.6 a	3.4	0.9743
90% TF	10% Legend	Compact America (Midnight)	High	14.7 a	17.9 ab	26.3 ab	96.8 bc	3.6	0.9781
100% TF	--	--	--	11.3 f	14.2 f	20.4 e	96.4 c	3.8	0.9830
<i>P-value</i>				<.0001	<.0001	<.0001	0.0061	0.1785	0.1880

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c D₅₀, estimated number of days until 50% establishment; D₇₀, estimated number of days until 70% establishment; D₉₀, estimated number of days until 90% establishment.

^d Top (%) is the maximum establishment estimate; ^d Higher hillslope (not units) values indicate more rapid establishment speed.

Note: Means within each column followed by the same letter or no letter are not different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 2.17. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 1 of Experiment 2.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP		20 MAP		24 MAP	
			TF	KB	TF	KB	TF	KB	TF	KB	TF	KB
			% ^c									
97% TF	3% Armada	Low	98.3 a	1.7 c	96.5 ab	3.5 cd	94.9 a	5.1 d	93.5 ab	6.5 de	88.7 b	11.3 bc
97% TF	3% Fullback	Medium	96.3 a	3.7 c	92.5 b	7.5 c	91.5 abc	8.5 cd	85.4 bcd	14.6 bcd	73.9 c	26.1 a
97% TF	3% Legend	High	97.8 a	2.2 c	93.9 b	6.1 c	97.2 a	2.8 d	89.6 cd	10.4 cd	92.1 ab	7.9 cd
95% TF	5% Armada	Low	95.4 a	4.6 c	92.7 b	7.3 c	92.5 ab	7.5 cd	89.7 bc	10.3 cd	81.6 b	18.4 b
95% TF	5% Fullback	Medium	92.6 ab	7.4 bc	81.4 c	18.6 b	80.9 c	19.1 b	78.1 cd	21.9 ab	69.9 c	30.1 a
95% TF	5% Legend	High	93.3 ab	6.7 c	92.1 b	7.9 c	91.2 abc	8.8 bcd	83.6 cd	16.4 bc	88.6 b	11.4 bc
90% TF	10% Armada	Low	85.9 bc	15.1 ab	83.9 c	16.1 b	90.9 abc	9.1 bcd	81.2 de	18.8 bc	86.1 b	13.9 bc
90% TF	10% Fullback	Medium	74.0 c	26.0 a	63.8 d	36.2 a	68.5 d	31.5 a	70.5 e	29.5 a	70.1 c	29.9 a
90% TF	10% Legend	High	90.9 ab	9.1 bc	79.7 c	20.3 b	80.9 bc	19.1 bc	81.5 cd	18.5 bc	88.4 b	11.6 bc
100% TF	---	---	100 a	0.0 c	100 a	0.0 d	100 a	0.0 d	100 a	0.0 e	100 a	0.0 d
<i>P-value</i>			0.0016	0.0016	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Percentage of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table 2.18. Tiller count data of percent tall fescue (TF) and percent Kentucky bluegrass (KB) at 9, 10, 12, 20, and 24 months after planting (MAP) in Run 2 of Experiment 2.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP	
			TF	KB	TF	KB	TF	KB
			----- % ^c -----					
97% TF	3% Armada	Low	95.8 ab	4.2 de	95.5 ab	5.5 de	95.3 ab	4.7 de
97% TF	3% Fullback	Medium	95.5 ab	4.5 cde	91.30 b	8.7 d	90.1 bc	9.9 cd
97% TF	3% Legend	High	95.7 ab	4.3 de	94.2 ab	5.8 de	94.8 abc	5.2 d
95% TF	5% Armada	Low	94.8 abc	5.2 cde	93.0 ab	7.0 d	89.5 cde	10.5 bc
95% TF	5% Fullback	Medium	92.1 bc	7.9 bcd	82.8 cd	17.2 bc	84.8 de	15.3 bc
95% TF	5% Legend	High	94.6 abc	5.4 ce	88.4 bc	11.6 cd	88.1 de	11.9 bc
90% TF	10% Armada	Low	87.4 c	12.6 b	78.7 de	21.3 ab	88.4 de	11.6 bc
90% TF	10% Fullback	Medium	76.2 d	23.8 a	72.2 e	27.8 a	71.0 f	29.0 a
90% TF	10% Legend	High	88.5 bc	11.5 bc	76.0 de	24.0 ab	84.3 e	15.7 b
100% TF	---	---	100 a	0.0 e	100 a	0.0 e	100 a	0.0 e
<i>P-value</i>			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Percentage of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table 2.19. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 1 of Experiment 2.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP		20 MAP		24 MAP	
			TF	KB	TF	KB	TF	KB	TF	KB	TF	KB
			----- Tillers per square decimeter ^c -----									
97% TF	3% Armada	Low	137.4 a	2.4 cd	161.9 ab	5.8 e	117.5	5.4 de	128.2 ab	9.9 c	93.9 ab	3.4 bc
97% TF	3% Fullback	Medium	115.8 ab	4.5 bcd	137.1 ab	10.1 de	120.6	10.1 bcd	125.7 ab	21.1 abc	61.6 c	6.5 a
97% TF	3% Legend	High	121.0 ab	3.0 cd	146.6 ab	9.5 de	132.2	3.2 de	153.0 a	17.5 abc	95.9 ab	2.9 d
95% TF	5% Armada	Low	110.0 ab	5.4 bcd	136.5 a	9.9 de	95.2	8.2 d	130.2 ab	14.8 bc	88.7 b	4.3 cd
95% TF	5% Fullback	Medium	107.2 ab	8.2 bcd	119.9 bc	26.9 b	89.1	23.7 abc	116.8 ab	32.7 a	73.2 bc	5.6 ab
95% TF	5% Legend	High	118.0 ab	9.3 bcd	133.3 b	11.4 cd	111.1	10.6 bcd	121.6 ab	26.4 ab	83.1 bc	3.2 cd
90% TF	10% Armada	Low	74.9 c	17.4 ab	99.0 cd	18.1 c	84.2	10.8 cd	97.0 bc	22.3 ab	78.1 bc	3.6 bc
90% TF	10% Fullback	Medium	93.4 bc	34.9 a	90.2 d	51.5 a	91.1	39.8 a	73.6 c	32.3 a	70.2 bc	5.5 ab
90% TF	10% Legend	High	121.4 ab	11.6 bc	127.9 b	32.7 b	120.6	24.8 ab	89.7 bc	21.7 abc	79.2 bc	3.2 cd
100% TF	---	---	131.4 ab	0.0 d	145.4 ab	0.0 f	113.3	0.0 e	125.2 ab	0.0 d	116.4 a	0.0 e
<i>P-value</i>			0.0271	0.0097	<0.0001	<0.0001	0.1948	0.0001	0.0163	<.0001	0.0156	<0.0001

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Tillers per square decimeter of each TF and KB calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP. Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table 2.20. Tiller count data of tillers per square decimeter of tall fescue (TF) and Kentucky bluegrass (KB) at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 2.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP		10 MAP		12 MAP	
			TF	KB	TF	KB	TF	KB
			----- Tillers per square decimeter ^c -----					
97% TF	3% Armada	Low	106.1 ab	4.7 bc	134.1 a	7.5 b	96.0 abc	4.7 d
97% TF	3% Fullback	Medium	95.8 bc	4.5 b	116.3 ab	9.9 b	111.5 ab	12.3 bc
97% TF	3% Legend	High	116.3 ab	4.5 b	101.4 bc	6.6 bc	114.5 a	6.2 cd
95% TF	5% Armada	Low	102.9 b	6.0 bc	97.7 bc	7.5 b	97.3 abc	12.1 bc
95% TF	5% Fullback	Medium	103.8 ab	9.5 b	92.1 bc	20.2 a	103.6 ab	18.7 b
95% TF	5% Legend	High	105.5 ab	6.2 b	86.5 c	11.2 b	96.7 abc	13.1 b
90% TF	10% Armada	Low	77.3 c	12.3 b	86.1 c	23.5 a	90.4 bc	11.8 bc
90% TF	10% Fullback	Medium	88.7 bc	28.2 a	62.9 d	25.0 a	78.6 c	32.7 a
90% TF	10% Legend	High	95.8 bc	12.7 b	84.4 cd	26.7 a	93.9 abc	17.9 b
100% TF	---	---	132.3 a	0.0 c	132.5 a	0.0 c	116.1 a	0.0 e
<i>P-value</i>			0.0256	0.0001	0.0002	0.0001	0.0386	<0.0001

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Tillers per square decimeter of each TF and KB calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP. Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Chapter 3 - The Influence of Kentucky Bluegrass Classifications on Germination and Establishment Vigor and Sod Strength

Abstract

Kentucky bluegrass (KB) (*Poa pratensis* L.) is an excellent option for turfgrass systems in the northern and transition climatic zones in the U.S. because of its aggressive and rhizomatous growth habit. There are known growth aggressiveness differences and classifications among Kentucky bluegrass cultivars, but little is known about how this impacts sod strength for sod producers. Therefore, objectives were to investigate the influence of Kentucky bluegrass cultivars with different classifications and aggressiveness labels on sod strength and handling, germination, and establishment. Replicated field and greenhouse experiments at Kansas State University were conducted to quantify growth aggressiveness labels (e.g., high, medium, and low aggressiveness) of 19 commercially available KB cultivars. Field experiments involved quantifying sod strength [maximum tensile load to tear sod (newtons) and required work to tear sod (N-m)] and sod handling (1-5 scale) at three harvests; 9, 10, and 13 months after planting (MAP) in 2023 and 2024. These same 19 KB cultivars were grown in 6.5 cm diameter containers for 5 months, and aggressive differences were quantified by measuring non-destructive phenotyping (visible tiller count and lightbox) and destructive phenotyping at harvest [rhizome number, length, type, number of nodes, and aerial tillers]. Germination tests were conducted with Petri dishes in a growth chamber for 28 days in 2022 and 2023 to quantify germination speed differences. A four-parameter sigmoidal regression model was fitted to the data to estimate the number of days until 50% germination (IC_{50}). Establishment vigor was measured from 2 to 39 weeks after planting (WAP) in the field. Results in the field experiment indicated sod strength and handling differences among cultivars at 9 and 10 MAP but no differences occurred at 13

MAP. Kentucky bluegrass cultivars ranged from ~22 to 38 N-m of required work to tear sod and 389 to 568 N of maximum tensile load to tear sod. Sod strength declined over time, suggesting an early summer sod harvest is preferred compared to late-summer in the transitional climatic zone. Greenhouse experiments revealed differences in the number of rhizomes produced and total rhizome length among cultivars. Germination and establishment vigor results indicated faster-germinating KB cultivars reached 50% germination and establishment within 5 to 8 days and 20 to 23 days, respectively compared to slower-cultivars reaching 50% germination and establishment in ≥ 9 days and ≥ 24 days, respectively. Kentucky bluegrass classifications or growth aggressiveness labels, and rhizome characteristics and establishment vigor, did not correspond to sod strength and handling differences. Additional knowledge of KB cultivar classifications and aggressiveness characteristics will potentially help sod and seed producers in cultivar selection and communication with turfgrass practitioners.

Introduction

The sod industry is a major component of the turfgrass industry. For example, US \$583 million in combined sales of sod in 2019 was generated within the northern regions of the United States (USDA-NASS, 2021). The demand for high-quality turfgrass sod continues to rise because of land renovations and new construction along with its ability to prevent soil erosion. Additionally, sod offers instant turfgrass ecosystems services, such as soil erosion prevention, carbon sequestration, oxygen production, instant greenspace for recreation and relaxation to increase human wellbeing, and many others (Braun et al., 2024).

Kentucky bluegrass (KB) (*Poa pratensis* L.) is a cool-season turfgrass species that provides a high-quality sod option for sod farmers to produce and sell for use in home lawns, athletic fields, parks, and other turfgrass systems in the transition and northern climatic zones of the United States. Along with Kentucky bluegrass, tall fescue [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] is another popular cool-season turfgrass option grown in the U.S., and both of these turfgrass species are used individually or together in mixtures for sod. Northern sod producers are familiar with the production cycle of KB and it is often preferred for cool-season sod production over many different cool-season turfgrass species due to its extensive rhizomatous growth and superior sod-forming qualities which provides an instant turf when installed (Agnew & Christians, 1992; Bushman et al., 2013; Ross et al., 1991). The knitting potential of KB rhizomes helps to create high sod strength, which creates less handling challenges during harvest from the field and transportation to clientele (Braun et al., 2021a, 2022d). Previous research has recorded that the presence of rhizomes in KB improves recuperative potential, wear tolerance, recovery from environmental stress, and high sod strength and handling (Braun et al., 2021a, 2021b, 2022d; Park et al., 2005;

Friel et al., 2017; Meyer & Funk, 1989; Su et al., 2008). Some disadvantages of KB are the slow germinating characteristics, slow establishment vigor, and higher input requirements needed to maintain acceptable turfgrass quality compared to other cool-season turfgrass species (Askew et al., 2013; Braun et al., 2023b; DeBels et al., 2012; Meyer & Pedersen, 2000; Watkins et al., 2014).

Kentucky bluegrass requires an average of 10-28 days to germinate when seeded, strongly influencing establishment vigor, vegetation cover, weed encroachment, and management inputs (Braun et al., 2021a, 2022d, 2023a; Christians et al., 2017). Whereas tall fescue and perennial ryegrass (*Lolium perenne* L.) are known for their quick establishment when seeded, often requiring five to ten days to germinate, and thus outcompeting germinating weeds (Braun et al., 2021a; Christians et al., 2017; Stir et al., 2008). There is growing interest in faster germinating and establishing KB cultivars with also the potential to produce high-quality turfgrass sod with lower maintenance inputs (Barnes et al., 2018; Hugie et al., 2012; Yue et al., 2012, 2017). Research has reported increasing N fertilization rates up to a specific amount during the first 8 weeks after planting hastened establishment vigor among fine fescue taxa (*Festuca* L spp.) (Braun et al., 2022a). This effect was also confirmed in KB by Braun et al., (2021a), who reported greater KB establishment cover associated with increased N fertilizer rates during establishment, but no fertilizer effects were observed on three faster germinating turfgrass species [Chewings fescue (*Festuca rubra* L. ssp. *commutata* Gaudin), strong creeping red fescue (*Festuca rubra* L. ssp. *rubra* Gaudin), and tall fescue].

It is well known that there is much genetic variability among KB cultivars (Bonos et al., 2000; Ebdon & Petrovic, 1998; Honig et al., 2012, 2018; Murphy et al., 1997). Several KB classifications exist among cultivars, and additional details and understanding of these

classifications have increased as time progressed and breeding advancements have been made (Bonos et al., 2000; Bonos, 2007; Honig et al., 2012, 2018; Murphy et al., 1997). Plant breeders have adopted a classification system to characterize KB cultivars based on, but not limited to the following characteristics; rhizome length and spread, turfgrass color, leaf texture, density, plant height, spring-green up, abiotic and biotic stress tolerance, and more (Bara et al., 1993; Bonos et al., 2000; Brilman, 2018, 2020, 2024; Ebdon & Petrovic, 1998; Honig et al., 2012, 2018; Murphy et al., 1997; Shortell et al., 2009). Classification systems used by plant breeders were designed to help in cultivar selections or to define similarities or differences between cultivars, and this information further serves as a guide to help turfgrass managers increase diversity and uniformity when planting blends of KB. Often, seed companies will apply an additional “classification” to cultivars to help describe growth characteristics for consumers (e.g., sod producers, homeowners, turfgrass practitioners) (“DLF pick Seed”, 2024; “Landmark Seed Company”, 2023; “Mountainview Seeds”, 2017; “Newsom Seed”, 2022; “Seed Research Oregon”, 2018). With these self-applied growth classifications on seed company websites, it can create challenges to understand what these growth classifications actually mean regarding turfgrass growth characteristics, such as “vertical growth” or “horizontal growth”, or a combination of both? More research is needed to understand these growth classifications. Research has reported that “Aggressive-type” KB classification types displayed high shoot density and vigorous, aggressive lateral spread with longer rhizomes to hasten the development of mature sod compared to other classification types (Bara et al., 1993; Bonos et al., 2000; Burt & Christians, 1990). Variation in vertical growth rate among KB cultivars has also been reported (Bonos et al., 2000; Patton & Braun, 2021). Many new KB cultivars have been released since the previous classifications and other older cultivars have been discontinued (Bonos et al., 2000;

Bonos, 2007; Brilman, 2024). Advancements in KB breeding have led to new and improved cultivars with more robust rhizomes, vigor, density, and increased abiotic and biotic stress tolerances (Bonos & Huff, 2013). Regardless, information is lacking on the growth differences, germination vigor, and establishment vigor of marketed KB by seed companies as “high,” “medium,” and “low” aggressiveness classifications as well as the different KB classification system types (e.g., Shamrock, Julia, Compact America, Compact Midnight, Limousine, many others). There is limited and outdated information on KB rhizome characteristics. Thus, there is a need to conduct research on new cultivars based on the KB classification system and their growth aggressiveness labels. Furthermore, the influence of KB classification systems and cultivar differences on germination vigor and establishment vigor is poorly understood and documented. Overall, further research is needed to provide more information on the influence of rhizome differences and growth characteristics among KB cultivars on sod strength and sod handling. Therefore, the objectives of this study were to quantify the speed of germination, establishment vigor, rhizome characteristics, as well as sod strength and handling of KB cultivars to assist seed growers, sod producers, turfgrass breeders, and turfgrass practitioners with more information on the KB classification system.

Materials and Methods

Field Experiment Site

Field studies were conducted from 9 Sept. 2022 to 8 Oct. 2023 (Run 1) and repeated between 8 Sept. 2023 to 17th Oct. 2024 (Run 2) at the Rocky Ford Turfgrass Research Center in Manhattan, KS, USA (39° 13' 53" N, 96° 34' 51" W). Soil analysis from soil tests revealed the soil for experimental sites was a Chase silty clay loam (fine, smectitic, mesic Aquertic

Argiudolls) with a pH of 6.8 to 7.1, and consisted of 75 to 78 g kg⁻¹ organic matter, 109 to 112 mg kg⁻¹ P (Mehlich-3 method), and 485 to 501 mg kg⁻¹ K (ammonium acetate method). Both experiment runs were conducted in a full-sun environment with no shade.

Field Experimental Design and Establishment

The experimental design was set up in a one-way treatment design with nineteen treatments arranged in a randomized, complete-block design with four complete blocks (reps) totaling 76 plots. Plots measured 1.2 by 1.2 m (4 × 4 ft). Treatments consisted of nineteen commercially available Kentucky bluegrass cultivars based on seed company recommendations, KB growth classification system (e.g., Shamrock, BVMG, Julia, Jefferson, Compact America, etc.), and seed company “growth aggressiveness” classifications (i.e., high, medium, and low aggressiveness) (Table 3.1). Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman (2018, 2020, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022) (Table 3.1).

Existing vegetation was eradicated with a non-selective herbicide, and the soil tilled before seeding in each experiment run. Pure live seeding (PLS) rates from seed lots purities, thousand-seed weight counts, and controlled-environment germination tests were quantified using the methods of the Association of Official Seed Analysts (Association of Official Seed Analysts, 2016). Field plots were individually seeded with hand shaker jars in multiple directions on 9 Sept. 2022 and 8 Sept. 2023 for Run 1 and Run 2, respectively. To eliminate seeding rate effects, all plots were seeded at 2 PLS cm⁻², which corresponded to the seeding rates ranges of 6.2 to 10.9 g of seed m⁻² (1.3 to 2.2 lb of seed 1000 ft⁻²) across both runs (Table 3.1). A starter

fertilizer was applied at a rate of 204 kg ha⁻¹ (i.e., 22 kg P ha⁻¹ and 37 kg N ha⁻¹) (18 N – 24 P₂O₅ – 12 K₂O; The Andersons Inc., Maumee, OH) across the entire study area at seeding. The soil surface was lightly raked using a leaf rake after seeding to promote seed-to-soil contact and then covered with a 14.2 g (0.5 oz) light germination blanket (PR1724, A.M. Leonard) for 10 days to promote seed germination and prevent seed movement. Thereafter, irrigation was applied to the study area through an in-ground system at a daily frequency for the first 21 days to promote turf establishment.

Field Plot Maintenance

After 21 days, irrigation application continued three times per week throughout the growing season, for an average of 2.54 cm wk⁻¹ if no precipitation occurred. Plots were maintained at an 8.2 cm mowing height (3.25 inches) for the entire study period. The entire study area was fertilized with a slow-release nitrogen fertilizer (43–0–0; SGN:150, polymer-coated-sulfur-coated urea; The Andersons Inc.) at a rate of 37 kg N ha⁻¹ ~30 days after seeding in both experiment runs. Additional fertilizer applications with the same fertilizer occurred in late-March and mid-May the following spring at rates of 37 and 61 kg N ha⁻¹, respectively. One final application in each experiment run occurred in early-September with the same slow-release N fertilizer at a rate of 61 kg N ha⁻¹ to aid in summer stress damage recovery before October sod harvest. Annual N fertilizer rate for both experiment runs was 233 kg N ha⁻¹ yr⁻¹ (4.75 lb N 1000 ft⁻² yr⁻¹), which includes the starter fertilizer at planting.

To prevent and control white grubs in Run 1, an insecticide containing imidacloprid {1-[(6-Chloro-3-pyridinyl) methyl]-N-nitro-2-imidazolidinimne} (Merit 0.5 G), was applied at a rate of 0.44 kg a.i. ha⁻¹ on 16 June 2023. In Run 1, an insecticide containing chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino) carbonyl] phenyl] –1-(3-chloro-2-

pyridinyl)-1H-pyrazole-5-carboxamide} was applied at a rate of 0.17 kg a.i. ha⁻¹ on 21 June 2024 for same prevention measures. On 3 Sept. 2024 for Run 2, Dinotefuron {N-methyl-N'-nitro-N''-[(tetrahydro-3-furanyl)methyl]guanidine} (Zylam) at 0.58 kg a.i. ha⁻¹ was applied for curative white grub control and the fungicide Azoxystrobin (methyl (E)-2-{2-[6-(2-cyanophenoxy) pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate) (Heritage) as applied at 0.61 kg a.i. ha⁻¹ for fungal disease control and prevention. No preemergence herbicides were applied for either experiment run. Very little broadleaf weed control was necessary, when broadleaf weeds were present, A commercially available herbicide mixture containing 2,4-D (2,4-dichlorophenoxyacetic acid) + mecoprop-p [(+)-(R)-2-(2 methyl-4-chlorophenoxy) propionic acid] + dicamba (3,6-dichloro-o-anisic acid) was applied at 1.52 kg a.e. ha⁻¹ as a spot spray treatment on 21 Apr. 2023 and 17 Apr. 2024 to control emerged broadleaf weeds.

Sod Harvest Data Collection

Sod harvests for Run 1 occurred on 14 June, 12 July, and 8 Oct. in 2023, and for Run 2, harvests were conducted on 11 June, 8 July, and 17th Oct. in 2024, and these harvest dates correspond to 9, 10, and 13 months after planting (MAP), respectively. At each sod harvest, a Turfco KisCutter sod cutter (Model #85530, Turfco Manufacturing, Inc.) was used to cut a sod piece measuring 25-cm wide × 70-cm long × ~1.9-cm thickness (sod/soil combination) in each plot (Figure 3.1). Sod tensile strength of each sod piece was calculated using the same custom-built sod tensile testing device as Braun et al. (2021a, 2022d), which was a modified version of Friell et al. (2017). Sod pieces secured on the device between two 30.4 × 30.4 cm plates. One clamped-end was fixed, and the other clamped-end allowed to slide freely through a spherical roller bearings underneath and attached to a mechanical arm (i.e., electric actuator). Upon activation of the sod device computer (Raspberry Pi 3b single-board computer), a load was

applied, and an electric actuator (mechanical arm) consistently pulled apart the sod piece and tore it into two separate pieces (Figure 3.2). A load cell (Omega LC703-300, Omega Engineering Inc.) that was connected to a single-board computer recorded the output of the position, load (energy), and a timestamp for each position. The total distance that the sod had been stretched was also recorded using a Unimeasure LX-PA-15 string potentiometer (UniMeasure, Inc.). A 24-bit analog-to-digital converter at 4.7 Hz recorded the output and data was stored using a Raspberry Pi 3b single-board computer and also saved on a USB flash drive for easy data retrieval. Maximum tensile load to tear sod [measured in newtons (N) and plotted by separation displacement in meters] and the area under the load-displacement curve were both recorded and were then calculated to acquire the required work to tear sod (i.e., force over distance, N-m). All data from the USB flash drives were immediately transferred to a computer after each rep was harvested and uploaded to cloud storage to prevent data loss during and after each sod harvest event.

Ancillary Sod Harvest Data

Sod handling was measured following the methods of past sod studies (Braun et al., 2021a, 2022b; Braun & Patton, 2022; Gopinath et al., 2021). This consisted of assigning a sod handling rating by the same rater throughout the study on a 1 to 5 scale; i) 1 = complete breakage, unacceptable sod with failure to transport to sod tearing device; ii) 2 = substantial sod cracking, but still transportable to sod tearing device; iii) 3 = moderate cracking (minimum acceptable sod handling for industry); iv) 4 = mild cracking; and v) 5 = no cracking, (best). Turfgrass quality was visually assessed and rated on a scale of 1 to 9 by the same rate throughout the study following industry standard practice and according to Morris et al. (2022), where 1 = poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to

color, texture, density, and uniformity (Figure 3.3). Volumetric soil water content was measured using a time domain reflectometry (Field Scout TDR 300 Soil Moisture Meter, Spectrum Technologies Inc.), collected at 5 random locations at a 7.6-cm depth per plot and averaged to ensure soil moisture content uniformity across plots.

Field Establishment Vigor

To differentiate establishment vigor among the Kentucky bluegrass cultivars, vegetation cover data was collected starting 2 weeks after seeding (WAS) [Run 1 (9 Sept. 2022) and Run 2 (8 Sept. 2023)], and continued weekly to every two weeks during each autumn, and monthly the following spring before sod harvests (Figure 3.3). This was accomplished by digital image analysis (0-100% cover) using a custom lightweight lightbox and a digital camera (Nikon Z 30, Nikon Inc.) manually set at ISO-125, f/4.5, exposure time 1/80 sec., 300 dpi, and 5568 × 3712 pixels (Figure 3.3). Digital pictures were analyzed in Turf Analyzer (Green 155 Research Services, LLC) using the following threshold settings: hue: 40–170; saturation: 2–100; brightness: 2–100 to analyze pixels to calculate the percent green vegetation cover. Green vegetation cover data of each plot on each date was fitted into a four-parameter sigmoidal model regression curve using GraphPad Prism (v.10.3, GraphPad Software Inc.) to estimate the number of days required to reach 50%, 70%, and 90% establishment cover after seeding using Equation (1):

$$y = \text{Bottom} + \frac{\text{Top} - \text{Bottom}}{1 + \left(\frac{EC_z}{x}\right)^{\text{hillslope}}} \quad (\text{Eq. 1})$$

where y is percent green vegetation cover, top is the y value at the estimated top plateau, bottom is the y value at the estimated bottom plateau, EC_z is the x value when the response of either days until 50% establishment (D_{50}), which is halfway between top and bottom, days until 70%

establishment (D_{70}), which is 70% of the top value, or days until 90% establishment (D_{90}), which is 90% of the top value; and Hillslope (no units) describes the slope of the curve at D_{50} .

These establishment vigor measurements were done to verify that all plots were established properly and that there were no establishment influences on sod strength at future sod harvests (Figure 3.3). Other data collected during field establishment were visual turfgrass and weed cover. These ratings were measured at a 0-100% rating scale every 1 to 2 weeks in the autumn until mid-December, and again the following spring in April and May for each run for visual turf cover, and multiple timings in the autumn and following spring for visual weed cover to assess the encroachment of winter annual weeds, such as annual bluegrass (*Poa annua* L.).

Germination Vigor

Germination tests were conducted to quantify germination speed (i.e., germination vigor) and overall germination percentage differences among the nineteen cultivars (Figure 3.4). Repeated germination tests [Run 1 (15 Jul. to 12 Aug. 2022) and Run 2 (19 Jun to 17 Jul. 2023)] were conducted for 28 d in a growth chamber (E15, Controlled Environments Ltd.) at Kansas State University, Manhattan, KS. Before germination tests, seeds were prechilled at 3°C for ≥ 2 months. The germination tests were conducted following the principles and procedures of the Association of Official Seed Analysts (AOSA, 2016). The growth chamber settings were 25/15°C (day/night cycle), 8 h day photoperiod, and photosynthetic photon flux of 100 $\mu\text{mol m}^{-2} \text{s}^{-1}$ for 28 days (Figure 3.4). Approximately 100 seeds of each cultivar were placed on blue blotter paper (PBB 325, Hoffman Manufacturing, Inc.) in a 100 × 15 mm (diameter × height) Petri dish with lid, replicated 4 times, and then incubated in a growth chamber for 28 d. Petri dishes were arranged by block and randomized daily in the growth chamber. Seeds were observed daily for germination counts and moistened as needed with KNO_3 water solution at

0.2% (v/v) (Figure 3.4). Seeds were considered “germinated” if their radicle and coleoptile were both visible, and germinated seeds were immediately recorded and discarded. The cumulative germination percentage over time of each petri dish was calculated in GraphPad Prism (v.10.3, GraphPad Software Inc.). The method of Braun et al. (2023a) was followed to determine seed germination vigor, which was calculated from total and cumulative germination percentage over time regressed against days by GraphPad Prism and data from each petri dish fitted into a four-parameter sigmoidal regression model to estimate days until 50%, 70% and 90% germination using Equation (1):

$$y = \text{Bottom} + \frac{\text{Top} - \text{Bottom}}{1 + \left(\frac{EC_z}{x}\right)^{\text{Hillslope}}} \quad (\text{Eq. 2})$$

where y is percent germination, top and bottom are the y value at the estimated top and bottom plateaus, respectively, EC_z is the x value when the response of either days until 50% germination (IC_{50}), which is halfway between top and bottom, days until 70% germination (IC_{70}), which is 70% of the top value, or days until 90% germination (IC_{90}), which is 90% of the top value; and Hillslope (no units) describes the slope of the curve at IC_{50} .

Another method to quantify germination vigor is mean germination time (MGT), which is expressed in days and was calculated for each Petri dish following the methods of Ellis and Roberts (1980) and Larsen and Andreasen (2004) and this was estimated using Equation (3):

$$\text{MGT} = \frac{\sum n_i d_i}{\sum n_i} \quad (\text{Eq. 3})$$

where n_i is the number of seeds that germinated in time i (not the accumulated number, but the number correspondent to the i^{th} observation), and d_i is number of days from the start of the germination test (i.e incubation period) to the i^{th} observation.

Greenhouse Study

To examine rhizome characteristics among the KB cultivars tested in the field experiment, repeated greenhouse studies [Run 1 (12 Jun. to 1 Nov. 2023) and Run 2 (11 Mar. to 31 Jul 2024)] were conducted at the Throckmorton Plant Science Center greenhouses, Kansas State University, Manhattan, KS (Figure 3.5). The greenhouse environment was set at 23/18°C day/night with a ~15 hr photoperiod. Environmental sensors (HOBO USB Micro Station Data Logger with Photosynthetic Light (PAR) Smart Sensor, H21-USB, HOBO Data Loggers) were installed to monitor temperature, relative humidity, and photon flux density.

The greenhouse experiment was arranged in a one-way treatment structure with the same 19 treatments arranged in a randomized complete-block design, replicated five times (Table 3.1). Cultivars were seeded in a separate ≥ 10.2 cm greenhouse pot with germination mixture media (BM2, Seed Germination, Berger Peat Moss Ltd.) and placed in a germination misting room for 3 weeks. After three weeks, one individual plant of each cultivar was transplanted into 37.2 cm² size containers filled with potting mix (BM6 All Purpose, Berger Peat Moss Ltd.) at a depth of 3 cm (~1.2 inches). Conetainers were placed in the greenhouse while maintaining the environmental settings mentioned above. For the first two weeks after transplanting, irrigation (non-fertilized municipal water) was applied frequently (i.e., multiple times a day) to encourage proper rooting and then irrigation frequency was reduced to once every three days throughout the study to prevent drought stress. All conetainers were fertilized with urea (46-0-0) at a rate of 49 kg N ha⁻¹ at 4, 9, and 13 weeks after seeding, which corresponded to 2, 6, 10 weeks after transplanting, respectively, for total N fertilizer rate of 147 kg N ha⁻¹. A scissors was used to mow the conetainers approximately every 7 days when turfgrass reached a 7.6 cm height, and clippings were collected.

Greenhouse Data Collection

Data was collected following the methods of Saxena et al. (2014), which involved destructive phenotyping measurements to quantify rhizome characteristics of different aggressive classification types (Figure 3.5 and Figure 3.6). Plants were harvested at 4.7 months after seeding [20 weeks after seeding (17 weeks after transplanting seedling)], washed, bagged, and stored in a cooler for less than 24 hours while measurements were completed (Figure 3.5). Rhizome length was measured using a digital caliper (mm) to measure all rhizomes from each plant (Figure 3.6). Data collected included: i) average number of plant tillers, which was the total number of visible plant tillers per conetainer that includes all tillers, rhizome tillers, and aerial shoots growing from rhizomes; ii) Average number of rhizomes per conetainer, which is the total number of rhizomes per plant (conetainer) that measured >10 mm; iii) Average rhizome length, which is the mean length of >10 mm rhizomes per conetainer; iv) Total rhizome length is the summed length of all >10 mm rhizomes per conetainer; v) Average number of nodes per rhizome, which is the average number of nodes counted on >10 mm rhizomes per conetainer; vi) Total aerial shoots on rhizomes is the number of aerial shoots counted on >10 mm rhizomes per conetainer; and vii) Rhizome class, which is a visual rating of all rhizomes produced by the plant, and rated on a scale of 0 to 5 (5 = thickest, most robust; 1 = thinnest, weakest; and 0 = no >10 mm rhizomes present) (Figure 3.6).

Prior to destructive phenotyping and plant harvest, digital image analysis of green vegetation cover was measured with the same digital camera, settings, and software but with a different modified lightbox (31 cm × 28 cm) (Figure 3.5). Data measurement began three weeks after seeding (1 week after transplanting) and continued every week for the first 10 weeks after transplanting and then every other week until plant harvest. Additional non-destructive

phenotyping measurements included visual plant tiller counts aboveground starting two weeks after transplanting (i.e., five weeks after seeding) and continued every other week until plant harvest.

Statistical Analysis

Data were analyzed for each run separately with SAS version 9.4 (SAS Institute Inc.), utilizing the GLIMMIX procedure with block as a random effect. Treatment $\times$ Run interactions were not significant for field establishment vigor of D₅₀ (days to 50% establishment) as well as the measured variables for the field sod data; therefore, data were combined across experimental runs for these respective variables. Treatment $\times$ Run interactions were significant for seed germination vigor (IC₅₀, IC₇₀ and IC₉₀) and MGT (mean germination time), greenhouse (rhizome) experiment data, and field establishment vigor (D₇₀ and D₉₀), therefore, data were not combined across runs and were analyzed separately. The UNIVARIATE procedure of Shapiro-Wilk of SAS was used to test residual normality as well as detect any significant outliers.

Means were separated with Fisher's protected least significant different (LSD) test ($\alpha = .05$) when the F tests were significant ($P \leq .05$). Correlation between sod harvest response variables (i.e., required work to tear sod, and maximum tensile load to tear sod, and sod handling) were conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($19 \times 4 \times 3 \times 2$; $n = 456$). Correlations between greenhouse rhizome characteristics data (i.e., rhizome length, nodes, total tiller shoot including rhizome, total rhizome number, and rhizome class) and sod harvest response variables were conducted across all cultivars and runs. Before correlation analysis of greenhouse rhizome data and sod strength field data, rep 4 and 5 were combined to be a fourth rep. Also, the four reps for treatments in each run were combined ($19 \text{ treatments} \times 2 \text{ runs}$; $n = 36$). Linear regression analysis between

establishment vigor (D_{50}) and controlled-environment data on seed germination vigor (IC_{50}) for both runs was also conducted. All regression and correlation analyses were conducted using GraphPad Prism.

Results and Discussion

Sod Strength Data

Differences occurred among KB cultivars with the sod device output data of required work to tear sod and maximum tensile load to tear sod at the first two sod harvest timings analyzed across runs (Figure 3.7 and 3.8). For both sod device output data variables, there was a greater separation of differences among cultivars at 9 MAP compared to 10 MAP, and no differences occurred at 13 MAP (Figure 3.7 and 3.8). Some cultivars, such as ‘Fielder’, ‘Fullback’, ‘Hampton’, ‘Martha’, ‘Merit’, and ‘Yellowstone’ were more often in the highest statistical grouping for required work to tear sod. Similarly, for Fielder, Martha, Merit, Yellowstone, along with ‘Bolt’, were more often in the highest statistical grouping for the maximum tensile load to tear sod. Likewise, cultivars such as ‘Sombrero’, ‘Shannon’, ‘SR-2100’, ‘SPF-30’, ‘Jackrabbit’, ‘Blue bank’, ‘Armada’, ‘Acoustic’ and ‘Legend’ were never in the highest statistical grouping for either sod strength output variable at 9 or 10 MAP. A few cultivars such as ‘BlueNote’, ‘Kenblue’, ‘Volt’, and ‘Bolt’ were less frequently ranked in the highest statistical grouping for sod strength variables.

At 13 MAP (i.e., early October), there were no differences in sod strength variables among KB cultivars. Numerically, there are some visible trends at 13 MAP similar to 9 and 10 MAP; however, there may have been too large of variability between reps, resulting in no statistical differences. The greater variability among plots and reps may have been due to the

high summer stress that occurred each growing season during July to early September (Figure B.1). This common abiotic stress can reduce aboveground visual KB turf quality and possibly weaken belowground structures of rhizomes like it does with roots (DaCosta et al., 2013; Huang et al., 1998a, 1999; Jiang & Huang, 2000, 2001; Liu et al., 2008). More research is needed to measure the effects of soil heat stress on KB rhizomes. This similar decline in sod strength performance was observed with KB in other field experiments (Nwachukwu, 2025).

Across all cultivars and runs, the following ranges for required work to tear sod were 22.0 to 37.5 N-m (mean 29.7 N-m) at 9 MAP, 17.7 to 27.7 newton-m (mean 22.8 N-m) at 10 MAP, and 16.5 to 22.8 newton-meter (mean 19.8 N-m) at 13 MAP (Figure 3.7). Across all cultivars and runs, the following ranges for and maximum tensile load to tear sod were 389 to 568 newtons (mean 466 N) at 9 MAP, 329 to 493 newtons (mean 408 N) at 10 MAP, and 288 to 384 newtons (mean 341 N) at 13 MAP (Figure 3.8). Even though sod strength decreased in both sod device variables over time from 9 to 13 MAP, the values were still in an acceptable range at all sod harvest timings based on past research (Braun et al, 2021a, 2022d; Braun & Patton, 2022). For example, Braun and Patton (2022) proposed that required work to tear sod values of 11-14 N-m are “minimally acceptable,” 14-18 N-m are “good,” and >18 N-m are “exceptional.” For maximum tensile load to tear sod, values of 250-325 newtons are “minimally acceptable,” 325-400 newtons are “good,” and >400 newtons are “exceptional” (Braun & Patton, 2022). This rubric by Braun and Patton (2022) was created based on numerous sod experiments and adapted from earlier rubrics by Griffith et al. (2017) and Gopinath et al. (2021). Reflecting on the required work to tear sod and maximum tensile load to tear sod ranges in this experiment, they are all above “minimally acceptable,” and most often in the “good” or “exceptional” ranking, including cultivars at 13 MAP.

Sod strength results from this experiment show there are sod strength differences among KB cultivars; however, these differences may only be evident during early sod harvest timings. As time progresses and the turfgrass ages and endures more abiotic or biotic stresses, these sod strength differences among KB cultivars may be less pronounced. These results also indicate sod producers growing KB sod in the transition zone should target earlier sod harvest timings before the onset of summer stress because as summer stress progresses, sod strength may decrease. Nevertheless, Kentucky bluegrass can still produce highly acceptable sod strength even post-summer stress due to its rhizomatous growth habit.

When looking at either the growth aggressive classification of “high”, “medium” or “low” assigned by seed companies, or the KB classification system (Table 3.1), it appears neither of these classifications accurately describes sod strength characteristics (Figure 3.7 and 3.8). For example, the “Shamrock” classification of cultivars Fielder, SR-2100, Yellowstone, and Volt all performed differently in terms of sod strength variables of required work to tear sod and maximum tensile load to tear sod (Figure 3.7 and 3.8; Table 3.1). The KB classification of Compact Midnight aligns with this finding as well. For example, Fullback, Acoustic, and Bluebank are all “Compact Midnight” classifications, but they vary considerably in their sod strength values. Furthermore, the growth aggressiveness classification of “high” assigned by seed companies was assigned to Hampton, Martha, BlueNote, Acoustic, SPF-30, SR-2100, and Sombrero; however, only the first three cultivars mentioned consistently produced high sod strength values at 9 and 10 MAP. Also, multiple “low” and “medium” aggressive classification cultivars, such as Merit (low), Yellowstone (low), Fullback (medium), and Fielder (medium) were often ranked in the highest grouping for required work to tear sod, maximum tensile load to

tear sod, or both at 9 and 10 MAP. Therefore, while these classification systems may be useful to describe certain turfgrass characteristics, neither accurately communicates sod strength.

Sod Handling

When combined across both runs, sod handling ratings revealed differences among KB cultivars at 9 and 10 MAP, but no differences occurred at 13 MAP (Figure 3.9). Jackrabbit, Blue bank, and SPF-30 appeared to have lower sod handling than the other 16 cultivars because they were only three cultivars to never rank in the highest statistical grouping. The remaining 16 cultivars were often similar to one another at 9 MAP, 10 MAP, or both harvest dates. Similar to the sod strength data, no differences occurred at 13 MAP; however similar visible trends occurred. The suspected reason for the lack of differences at 13 MAP is mentioned above. Overall, sod handling averages across cultivars ranged between 3.9 to 4.9 (mean 4.4) at 9 MAP, 4.0 to 5.0 (mean 4.6) at 10 MAP, and 3.8 to 4.5 (mean 4.2) at 13 MAP (Figure 3.9). Therefore, all nineteen cultivars averaged above the minimal sod handling rating of three at all three sod harvest events, including 13 MAP. These sod handling values agree with the reports by Braun et al. (2021a, 2022d), which reported similar sod handling values for monostand KB sod. Similar to sod strength data, neither the KB classification system, nor growth aggressiveness descriptions assigned by seed companies accurately conveys sod handling differences. More sod research is needed on this issue since we only tested 19 KB cultivars while >50 KB cultivars are often commercially available each year. Furthermore, due to field space limitations, we did not test all KB classifications, and we also did not test multiple cultivars of some KB classifications to make those comparisons possible.

When analyzed across both runs and all cultivars, there were positive correlational relationships between sod handling and sod strength variables (Figure 3.10). There were

moderate to strong positive relationships between maximum tensile load to tear sod and required work to tear sod ($r = 0.82$; $P \leq .0001$), required work to tear sod and sod handling ($r = 0.70$; $P \leq .0001$), and sod handling and maximum tensile load to tear sod ($r = 0.63$; $P \leq .0001$). (Figure 3.10). This was expected because past sod research has shown similar positive relationships between sod handling and sod strength device output data ($r = 0.28$ to 0.69) (Braun et al., 2021a, 2022d; Braun & Patton, 2022; Gopinath et al., 2021; Han, 2009). There was an even stronger relationship between the two sod device output data variables (Figure 3.10). Results highlight a strong positive relationship between required work to tear sod and maximum tensile load to tear sod ($r = 0.80$; $P \leq .0001$) (Figure 3.10). This positive correlation aligns with past studies, such as $r = 0.87$ (Braun & Patton, 2022), $r = 0.82$ to 0.88 (Braun et al., 2021a), $r = 0.85$ to 0.86 (Braun et al., 2022d), $r = 0.92$ (Friell et al., 2017). While required work to tear sod and maximum tensile load to tear sod are highly correlated, previous authors (Braun et al., 2022d; Friell et al., 2017) mention that the required work to tear sod data provides more relevant data since the measurement is the tensile load applied over a longer distance compared to the one time-point data of maximum tensile load to tear sod.

Overall, our results also revealed that sod handling and sod strength slightly reduced during and after the warmer summer months (i.e., summer stress) (Figure 3.7, 3.8, and 3.9). This suggests that an early sod harvest in spring to early-summer might provide greater success for sod producers in order to avoid potential sod strength decline during summer or post-summer sod harvests. Harvesting sod earlier in the spring or early summer will also potentially help reduce maintenance inputs for sod producers. While earlier sod harvests may be recommended, more research is needed with KB, and we must recognize the timing of sod harvest is largely driven by consumer demand. Therefore, while the sod producer may wish to harvest sod earlier, if the

demand (i.e., purchase order) is not present, the harvest will not occur. This early sod harvest recommendation did completely not align with past findings of KB sod research. For example, Braun et al. (2021a), reported the highest required work to tear sod values (>20 N-m) with KB sod occurred at 20 MAP in both Indiana and Minnesota compared to 11, 12, and 14 MAP. Braun et al. (2022d) did not report a decline in sod strength or sod handling values of 100% KB sod when harvested at 11, 12, 14, 20, and 22 MAP; however, this sod was grown in slightly cooler climates of Indiana and Minnesota. Other recommended KB sod production periods have been reported to be ~15 months in Minnesota (Friell et al., 2017) and 12 to 20 months in Wisconsin (Griffith et al., 2017). These sod production cycle differences are most likely due to environmental and climate differences. Overall, in a warmer climate, like Kansas, in the transition zone may require less time for sod production, 9 MAP based on this research or sooner but more research is required.

Volumetric Water Content

Analysis for soil water content measured with a time domain reflectometry in five locations per plot at each sod harvest event confirmed no differences among plots at each sod harvest in each experiment run (Figure 3.11). Average volumetric water content across treatments ranged from 35 to 44% at 9 MAP, 32 to 40% at 10 MAP, and 36 to 44% at 13 MAP in Run 1 (Figure 3.11). In Run 2, average volumetric water content across treatments ranged from 32 to 38% at 9 MAP, 32 to 37% at 10 MAP, and 29 to 36% at 13 MAP (Figure 3.11). Overall, volumetric water content was fairly consistent across plots at each harvest event. The percent difference between maximum and minimum volumetric water content means at each sod harvest was between 14 to 23% difference, and thus likely had minimal-to-no influence on the sod strength or sod handling results.

Turf Quality

With a few exceptions, visual turf quality revealed minimal differences among cultivars between 6 to 14 WAS for both runs (Table 3.2). While statistical differences occurred, the majority of the cultivars had acceptable turf quality (≥ 6 rating) with few exceptions in some cultivars (≥ 5 rating) at 4-8 WAS (Table 3.2). As time and field establishment progressed, turf quality differences diminished. Turf quality for both runs and across all cultivars was near or at the highest possible rating of “9” by 9 through 13 MAP sod harvests (Table 3.3). Some turf quality differences were more noticeable among cultivars at 13 MAP due to recovery from summer heat stress, but all were still above acceptable quality. The turf quality differences during establishment and at a few sod harvest timings likely had no influence on sod strength and handling at 9 through 13 MAP (Table 3.2 and 3.3) Like other sod research (Braun et al., 2021a, 2022d; Braun & Patton, 2022; Taylor & Schmidt, 1980), visual turf quality ratings did not influence sod strength, and therefore we agree that aboveground visual turf quality does not inform of sod strength and handling characteristics but does help differentiate visual and aboveground functional characteristics.

Establishment Vigor

Digital image analysis values integrated into the four-parameter sigmoidal model (Eq. 1) revealed minimal differences in the establishment speed based on D_{50} among KB cultivars planted in the field (Figure 3.12 and 3.13, and Table 3.4). Treatment by run effects were not significant for D_{50} (estimated days to reach 50% establishment), therefore, runs were combined (Table 3.4). The average number of days to reach 50% establishment across all KB cultivars was 24 days, and D_{50} ranged from 20.5 to 27.1 days across cultivars (Table 3.4). While some KB cultivars had faster establishment (i.e., lower D_{50}) estimates than other KB cultivars, the

difference between the fastest cultivar estimate and the slowest cultivar estimate was only 6.6 days.

When the sigmoidal regression model also estimated days until 70 and 90% establishment (D_{70} and D_{90} , respectively), then treatment by run effect was significant; therefore, the results are presented separately for each run (Table 3.5). Due to slightly varying environmental conditions between runs and as time extended past D_{50} , cultivars (treatments) may have had different responses between runs. For D_{70} , average estimates indicated 30.3 and 28.7 days to reach 70% field establishment in Run 1 and Run 2, respectively. The difference between the fastest cultivar estimate and the slowest cultivar estimate for D_{70} was 6.6 and 7 days in Run 1 and Run 2, respectively. For D_{90} , average estimates indicated 41.5 and 40.6 days to reach 90% field establishment in Run 1 and Run 2, respectively. The difference between the fastest cultivar and the slowest cultivar for D_{90} was 11.4 days in Run 1, and no differences were present in Run 2. One interesting finding is that cultivars that had faster D_{50} did not always translate over to a faster D_{70} or D_{90} , and vice versa for slower cultivars at D_{50} (Table 3.4 and 3.5). For example, Fielder had a low (faster) D_{50} and D_{70} estimate (required less days to reach 50% and 70% establishment in both runs), but D_{90} was higher or similar to other KB cultivars. Another example is Kenblue, which had higher D_{50} estimates (i.e., slower establishment to 50% cover) but then it was similar to some faster D_{50} cultivars like Fielder and others by D_{70} and D_{90} . We suspect germination vigor, which is discussed below, influences initial field establishment speed (i.e., D_{50}); however, as time progresses and the turfgrass begins to mature, produce tillers, and fills in voids, then germination vigor data becomes less relevant and D_{50} does not always translate to indicate the fastest to full (100%) establishment cover of turfgrass. The differences

with growth differences among KB cultivars was also reported by Law et al. (2016), who reported slight variabilities with the growth rates and mowing requirements in the field.

Neither the KB classification system nor the assigned growth aggressiveness labels consistently aligned with field establishment differences in Run 1 or Run 2 (Table 3.4 and 3.5). There were multiple instances of a “high” growth aggressiveness classification requiring more days until 50, 70, or 90% establishment compared to “medium” or “low” cultivars. We suspected these growth aggressiveness classifications may better align with D_{70} and D_{90} because more time had passed, and it may be an indication of turfgrass horizontal growth (tillering) and vertical growth, but the data does not show these trends consistently. More research is warranted to understand establishment differences and classifications among KB cultivars.

Germination Vigor

The four-parameter sigmoidal regression model (Eq. 2) results for Runs 1 and 2 indicated differences among cultivars with germination speed (i.e., number of days to reach 50%, 70%, and 90% germination which correspond IC_{50} , IC_{70} , and IC_{90} , respectively) (Figure 3.14 and 3.15; Table 3.6). Interestingly, some cultivars had a faster germination speed (i.e., less days to reach 50% germination) when compared to others within the same growth classifications (e.g., Shamrock, Compact America, Compact Midnight) and growth aggressiveness types (i.e., high, medium and low aggressiveness (Figure 3.14; Table 3.6). In Run 1, ‘Felder’ (Shamrock; medium) had the fastest germination speed (i.e., lowest IC_{50} value) and reached 50% germination in 5.9 days when compared to other Shamrock classifications such as ‘Volt’ (low) and ‘SR-2100’ (high), which required 9.1 and 10.9 days to reach 50% germination, respectively (Figure 3.14; Table 3.6). A few other cultivars, irrespective of their classifications and growth aggressiveness types had fast germination similar to Felder, these included ‘Acoustic’, ‘Legend’, ‘Jackrabbit’,

and a few others reached 50% germination within 6.2 – 7.6 days when compared to slower germinating cultivars requiring >9 days to reach 50% germination, such as Shannon, Sombrero, and Merit, and Kenblue to name a few (Figure 3.14; Table 3.6). For Run 2, most of the fast-germinating cultivars observed in Run 1 maintained a similar germination speed, although there was a ~1-day decline in germination speed with a few cultivars likely due to seed aging (Table 3.6). This insignificant decline within years is consistent with past studies (Bass, 1959; Rincker, 1986), who reported that Kentucky bluegrass seed-maintained viability when harvested after 30 months, and when stored in ambient warehouse conditions for 7 years, did not decline in viability.

Overall, the number of days to reach 50% germination in both experiment runs ranged from 5.9 to 11.9 days, and KB classifications and growth aggressiveness classifications were not good predictors of selecting fast germinating cultivars (Table 3.6). Furthermore, similar trends were observed for IC_{70} and IC_{90} , (i.e., days to 70% or 90% germination speed) (Table 3.6). For example, in Run 1, Fielder required 6.7 and 8.2 days to reach 70% and 90% germination, respectively, when compared to slower germinating cultivars (i.e., SR-2100, Shannon, Merit, others) requiring 12 and 15 days to reach 70% and 90% germination, respectively (Table 3.3 and 3.6). Similar results were observed in Run 2. While growth aggressiveness classifications did not consistently align with germination speed, there were more occurrences of cultivars with “high” or “medium” growth aggressiveness having fast germination (i.e., low IC_{50}) compared to “low” aggressiveness classifications; however, again this was not consistent across all classifications (Table 3.6). The greatest difference in IC_{50} between the slowest and fastest germinating cultivars was 5.1 and 5.8 days for Run 1 and Run 2, respectively (Table 3.6). The greatest difference in IC_{70} between the slowest and fastest germinating cultivars was 5.5 and 6.5 days for Run 1 and

Run 2, respectively. The greatest difference in IC_{90} between the slowest and fastest germinating cultivars were 6.6 and 7.8 days for Run 1 and Run 2, respectively. Folck et al. (2023) reported a similar range of days for the estimated number of days until 50% germination of KB in a similar controlled-environment experiment that tested 21 KB cultivars. Braun et al. (2023a) reported an IC_{50} of 9.2 days across three KB cultivars, which is similar to the average 8.1 days until 50% germination across all cultivars and both runs in this experiment. It is important to note that KB is generally known for its slow germinating characteristics in the field, which may influence establishment according to the International Seed Testing Association (ISTA, 1999) and Christians et al. (2017); however, our results further confirm the findings of Folck et al. (2023) and Kim (2014, 2015) who reported that faster germinating cultivars do exist. Nwachukwu (2025) reported KB cultivars, Acoustic and Legend had similar germination vigor compared to some tall fescue cultivars when tested alongside in a controlled-environment study. Overall, no clear relationships exist between germination speeds and KB classifications or growth aggressive labels based on our results.

Results for mean germination time (MGT) (Eq. 3) shown in Table 3.7, revealed that the mean values followed a similar trend as IC_{50} output for both runs among KB cultivars. Cultivars that were most fast-germinating cultivars based on IC_{50} through IC_{90} estimates also had lower MGT values (i.e., faster germination time). Therefore, either method accurately explains germination time differences among KB cultivars. Our findings for MGT further aligns with past reports (Braun et al., 2023; Larsen and Andreasen, 2004; Larsen and Bibby, 2004), who reported cultivars from the lowest to highest MGT values, perennial ryegrass, fine fescue taxa, tall fescue, and Kentucky bluegrass, indicating time fast to slowest germination.

Additional germination parameter estimates from the sigmoidal model included Hillslope, Top (i.e., total germination percentage), and R^2 , which is presented in Table 3.7 for IC_{50} . Results revealed that the majority of Top (overall germination percentage) values for both runs were $\geq 88\%$, which indicates that all cultivars had high germination percentages (Table 3.7). While lower germination values were measured in Run 2, this was expected because of seed aging during seed storage. Regardless, the majority of Top values were $>88\%$ germination. This finding is consistent with past studies (Folck et al., 2023; Naylor, 1989), who found out that as germination speed decreased, total germination decreases as well with Kentucky bluegrass and perennial ryegrass, respectively. Hillslope values can also be an indication of germination speed (i.e., higher values indicate more rapid germination speed based on the steepness of the slope). There were slight differences observed among cultivars, with slow and fast germinating cultivars having either high or low hillslope on a range of 5.0 to 9.2 across both runs (Table 3.7). However, Folck et al. (2023) suggested that Hillslope may not be a good predictor of germination vigor, and so we might not rely much on the data as much as IC_{50} estimates.

For this study, seed morphological characteristics were not measured among KB cultivars similar to what has been conducted in other studies (Braun et al., 2023a; Larsen & Andreasen, 2004; Larsen & Bibby, 2004). These past studies reported that seed morphology (i.e., seed area, length, width etc.) might not be a strong predictor for germination vigor.

Overall, results show differences in the germination vigor of KB cultivars across multiple KB classification types and growth aggressiveness labels. There were both fast and slow germinating KB cultivars observed within the same KB classification systems and growth aggressive labels. Therefore, neither of these classification systems may be a good indicator for selecting fast-germinating cultivars, and we recommend that the actual cultivars that sod

producers or turfgrass practitioners are considering should be tested to verify. This research shows there is more work to be done on KB cultivars and classification systems to better understand the germination vigor differences due to the wide genetic variability among KB cultivars.

When looking at the relationships between establishment vigor and germination vigor, linear regression between D_{50} and IC_{50} for both runs revealed a weak positive relationship (Run 1: $R^2 = 0.1572$, $P \leq .0001$; Run 2: $R^2 = 0.1808$, $P \leq .0003$) (Figure 3.16). These results indicate that a weak relationship exists between fast germinating cultivars IC_{50} , and fast germinating cultivars (D_{50}) (Figure 3.16). Overall, a few cultivars that were among the statistical ranking for fastest germination vigor were also fastest for establishment vigor (e.g., Jackrabbit, Fielder, Sombrero) and vice versa for slower cultivars (Tables 3.4 3.5, and 3.6). However, this trend was not consistent across all cultivars, thus the weaker positive relationship that is presented.

Tiller and Rhizome Characteristics

Tiller and rhizome data collected from greenhouse experiments to potentially help explain sod strength and establishment differences revealed differences among the nineteen KB cultivars tested (Table 3.8 and 3.9). Treatment $\times$ Run effects were significant for the majority of data response variables; therefore, runs were analyzed separately for all tiller and rhizome data (Table 3.8 and 3.9). This run effect may have been due to the greenhouse experiment being conducted at slightly different times of the year even though it was in a controlled environment [Run 1 (12 Jun. to 1 Nov. 2023) and Run 2 (11 Mar. to 31 Jul 2024)] (Figure B.2 and B.3). There were noticeably less plant tiller and rhizomes numbers in Run 2 compared to Run 1 and different statistical rankings that also led to significant treatment by run effects.

There were differences in the average number of plant tillers, average number of rhizomes per plant, and total summed rhizome length per plant in both runs (Table 3.8 and 3.9). While some cultivars, such as Hampton and SR-2100, consistently ranked in the lowest statistical grouping for total summed rhizome length in both runs, there was a lot of inconsistency in measured tiller and rhizome characteristics between runs. For example, a high or low number of total plant tillers did not always correspond to the plant also producing a respective high or low number of rhizomes that were >10 mm, some examples would be Hampton in Run 1, Merit and Sombrero in both runs, and other (Table 3.8 and 3.9). However, the cultivar ‘Martha’ is one that consistently produced a high number of tiller and rhizomes counts and total summed rhizome lengths in both runs (Figure 3.17; Table 3.8 and 3.9). Furthermore, some KB cultivars had more tillering at the crown and less activity of rhizome production (i.e., Hampton and Merit in Run 1) and others that produced moderate plant tiller numbers also had moderate rhizomatous activity. Likewise, there were cultivars that produced both low plant tiller numbers and a low number of rhizomes >10 mm in Run 1, Run 2, or both runs, some examples include: Armada, Jackrabbit, Kenblue, Legend, and SR-2100 in Run 1 while Fielder, Jackrabbit, SR-2100, and Volt in Run 2 (Figure 3.18 and 3.19). Overall, KB cultivars produced an average of 13 to 48 plant tillers (mean 27), 3 to 11 rhizomes >10 mm (mean 6) with an average 5 to 12 nodes per rhizome (mean 9), and 2 to 6 aerial shoots (mean 3) in Run 1. In Run 2, KB cultivars produced an average of 6 to 22 plant tillers (mean 12), 1 to 6 rhizomes >10 mm (mean 3) with an average 5 to 10 nodes per rhizome (mean 8), and 1 to 4 aerial shoots (mean 2).

Average rhizome length, which averaged 151 and 129 mm in length in Run 1 and Run 2, respectively, was not different among Kentucky bluegrass (Table 3.8 and 3.9). However, there

were differences in total summed rhizome lengths among Kentucky bluegrass cultivars, this may be expected since there were also differences in the average number of rhizomes among KB cultivars; therefore, cultivars producing more rhizomes will also have greater total sum rhizome lengths (Table 3.8 and 3.9). For example, cultivars that consistently ranked in the highest order or second to third highest order of average number of rhizomes often ranked in the highest to third highest order for total sum rhizome lengths. There were also large differences between the lowest and highest cultivars with total sum rhizome length in each run. For instance, Martha at 1850 mm had 1448 mm more rhizome production length than Hampton at 402 mm in Run 1. In Run 2, Armada at 1022 mm had 859 mm more rhizome production than SPF-30 at 163 mm. Overall, results provide novel data on tiller and rhizome production and characteristic differences and further work is needed on KB cultivars due to the wide genetic variability. Similar to other response variables in this chapter such as sod strength, establishment vigor, and other, KB classifications and growth aggressiveness classifications do not assist in communicating tiller and rhizome production characteristics. Results clearly illustrate no trends among either classification systems and tiller and rhizome data.

According to Etter (1951), strongly intravaginally tillered plants seldom had many extravaginal tillers (i.e., rhizomes), but this was not the case with our findings. Similarly, Saxena (2014), in a three-month greenhouse study investigating tall fescue genotypes, reported ‘1109’, which produced the highest number of plant tillers (71%), exhibited the lowest number of rhizomes and aerial shoot from rhizomes. The differences observed with rhizome and tiller numbers among cultivars in our experiment may be due to genetic differences among cultivars, greenhouse conditions, or combination of both, which agrees with past research (Assuero & Tognetti, 2010; Moser et al., 1968; Pollock, 1990).

Additional data collected was “Rhizome Class”, a subjective visual rating on a scale of 0 to 5 (5 = thickest, most robust; 1 = thinnest, weakest; and 0 = no >10 mm rhizomes present), which was done to quantify rhizome girth to ascertain if it influences sod strength or establishment (Table 3.8 and 3.9). Minimal differences occurred in Run 1, where rhizome class scores ranged from 1.4 to 2.8; however, these trends did not carry over to Run 2. Average rhizome class scores across cultivars were 2.1 in Run 1 and 2.5 in Run 2. We conclude that our Rhizome class rating may not have been a good estimator of rhizome differences since it is a subjective rating.

A correlation analysis using Pearson's correlation coefficient revealed some potential relationships between greenhouse data and their corresponding treatment for 9-month sod strength and handling data (i.e., required work to tear, maximum tensile strength and sod handling) (Figure 3.10). Weak positive relationships were observed between the total number of tillers and required work to tear sod ($r = 0.30$; $P \leq .0002$) and maximum tensile strength ($r = 0.30$; $P \leq .0002$), between rhizome numbers (RN) and required work to tear ($r = 0.19$; $P \leq .0208$) and maximum tensile strength ($r = 0.25$; $P \leq .002$). However, correlation analysis also revealed no relationship between 9-month sod strength and other greenhouse rhizome data (i.e., Average rhizome length (DIST), Total rhizome length (TDIST), Rhizome Class (RC) etc.). Our findings partly align with past research (Ross et al., 1991; Segars et al., 2020; Taylor & Schmidt, 1980), who reported minimal to negative relationships between sod strength and rhizome growth characteristics. Segars et al. (2020) reported no correlation between rhizome strength, rhizome diameter vs sod tensile strength ($r = 0.07$; $r = -0.03$) in a rhizome vs sod strength trial of bermudagrass (*Cynodon dactylon*). In a Kentucky bluegrass experiment, Taylor and Schmidt (1980) reported a negative relationship between aerial shoots from rhizomes and sod strength.

Segars et al. (2020) further reported a positive relationship between rhizome dry weight and sod strength of bermudagrass. This suggests rhizome weight improved sod strength, and this might be a potential area of research for KB to confirm the influence on sod strength differences because it was not studied in our experiment. Overall, results in this experiment demonstrate rhizome numbers or total number of tillers may indicate sod strength of Kentucky bluegrass cultivars, regardless more research is warranted on this.

Conclusions

Sod tensile device data provided sufficient information on sod strength (i.e., required work to tear sod and maximum tensile load to tear sod) differences among commercially available KB cultivars. Furthermore, the subjective rating of sod handling also revealed differences among KB cultivars at multiple sod harvest timings. While some cultivars produced more consistently higher sod strength and handling, this was not specific to KB classification system or growth aggressiveness assigned labels (i.e., high, medium, or low). Thus, results demonstrate that the KB classification system and growth aggressiveness labels assigned by seed companies may not be good indicators for selecting cultivars with high sod strength for sod producers. While there were differences in sod strength and handling, all nineteen KB cultivars in this experiment produced high visual turf quality and sod quality at each sod harvest timing. We also found that harvesting KB sod at 9 MAP (early summer) compared to 10 MAP (mid-summer) or 13 MAP (autumn) in the transition zone may provide higher sod strength and handling for sod producers.

Output from the four-parameter sigmoidal regression model successfully estimated the number of days until 50, 70 and 90% germination and establishment vigor. There were differences in both germination vigor and establishment vigor among KB cultivars, which indicates that a fast-germinating cultivar is possible with KB. A weak relationship does exist between germination vigor and establishment vigor, and this requires further research for exploration. Overall, while some KB cultivars may have fast

germination speeds in a controlled-environment, it does not always correspond to fast establishment vigor in the field, and a fast germinating or establishing cultivar did not produce greater sod strength and handling when sod harvested at 9 (June) through 12 months sod harvest.

Differences were also observed with tiller and rhizome production characteristics among cultivars, however there were only a few significant relationships between rhizome growth characteristics (i.e., rhizome number, total tiller number, and total aerial tillers) and sod strength. Results demonstrate that KB rhizome numbers or total tiller numbers grown in a greenhouse may indicate slightly higher sod strength in the field. Future research is warranted on the influence of rhizome weight on sod strength and longer periods of greenhouse studies to allow sufficient time for rhizome growth.

Overall, growth aggressiveness classification and KB classification systems may not be a strong indicator of sod strength or establishment vigor to be considered during cultivar selection. Information obtained from this research will help sod growers and turfgrass practitioners in their decision-making process while selecting fast germinating and establishing cultivars in order to align establishment rate expectations. Furthermore, this research benefits turfgrass plant breeders and provides more information to improve germination vigor, seedling vigor and rhizome characteristics in order to increase precision in classification systems. Further research is warranted to investigate other classification systems and shorter sod production intervals in different locations within the northern region and transition climatic zones of the United States.

References

- Association of Official Seed Analysts. (2016). *Principles and Procedures*, 2016 (Volume 1). Washington, DC: Association of Official Seed Analysts, Inc.
- Agnew, M. L., & Christians, N. E. (1992). Sod reestablishment of five Kentucky bluegrass cultivars. *Journal of Production Agriculture*, 5(1), 50–52.
<https://doi.org/10.2134/jpa1992.0050>
- Assuero, S. G., & Tognetti, J. A. (2010). Tillering regulation by endogenous and environmental factors and its agricultural management. *The American Journal of Plant Sciences and Biotechnology*, 4, 35–48.
- Bara, R. F., Dickson W. K., Murphy, J. A., Smith, D. A., & Funk, C. R. (1993). Performance of Kentucky bluegrass cultivars and selections in New Jersey turf trials. *In: 1993 Rutgers Turfgrass Proceedings Atlantic City, NJ*, 25, 49–94.
- Barnes, M. R., Nelson, K. C., Meyer, A. J., Watkins, E., Bonos, S. A., Horgan, B. P., Meyer, W. A., Murphy, J., & Yue, C. (2018). Public land managers and sustainable urban vegetation: The case of low-input turfgrasses. *Urban Forestry & Urban Greening*, 29, 284–292. <https://doi.org/10.1016/j.ufug.2017.12.008>
- Bass, L. N. (1959). Packaging and storage of Kentucky bluegrass and creeping red fescue seed. *Proceedings of the Association of Official Seed Analysts*, 49, 173–181.
<https://www.jstor.org/stable/45135352>.
- Bonos, S. A., Meyer, W. A., & Murphy, J. A. (2000). Classification of Kentucky Bluegrass genotypes grown as spaced-plants. *Hortscience*, 35, 910–913.
<https://doi.org/10.21273/hortsci.35.5.910>

- Bonos, S. A. (2007). Commercially available cool-season turfgrass species and cultivar resource list. *Rutgers Turfgrass Proceedings*, 38, 159–178.
- Bonos, S. A., & Huff, D. R. (2013). Cool-season grasses: Biology and breeding. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Eds.), *Turfgrass: Biology, use, and management* (pp. 591–660). ASA-CSSA-SSSA. <https://doi.org/10.2134/agronmonogr56.c17>
- Brilman, L. (2018). *Kentucky bluegrass classification*. Seed Research of Oregon. https://www.sroseed.com/Files/Files/SRO_USA/Brochure_Etc/SRO_KB_classifications-Jan-2018_Final.pdf. Accessed 20 June 2023.
- Brilman, L. (2020). *Kentucky bluegrass classification*. Seed Research of Oregon. https://www.dlfpickseed.com/Files/Files/SRO_USA/Brochure_Etc/Kentucky_Bluegrass_Classification_2020_Final.pdf Accessed 15 September 2023.
- Brilman, L. (2024). *Kentucky bluegrass classification*. <https://www.dlfpickseed.com/professional-turf/varieties/bluegrass> Accessed 5 November 2024
- Braun, R. C., Patton, A. J., Watkins, E., Koch, P., Anderson, N. P., Bonos, S. A., & Brilman, L. A. (2020). Fine fescues: A review of the species, their improvement, production, establishment, and management. *Crop Science*, 60, 1142–1187. <https://doi.org/10.1002/csc2.20122>
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021a). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: I. Establishment and sod tensile strength. *Agronomy Journal*, 113, 4176–4189. <https://doi.org/10.1002/agj2.20810>

- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021b). Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: II. Management and shelf life. *Agronomy Journal*, 113, 3460–3474. <https://doi.org/10.1002/agj2.20777>
- Braun, R. C., & Patton, A. J. (2022). Species, clover-inclusion, and nitrogen fertilizer effects on sod tensile strength of fine fescue taxa. *Agronomy Journal*, 114, 1705–1716. <https://doi.org/10.1002/agj2.21039>
- Braun, R. C., Braithwaite, E. T., Kowalewski, A. R., Watkins, E., Hollman, A. B., & Patton, A. J. (2022a). Nitrogen fertilizer and clover-inclusion effects on the establishment of fine fescue taxa. *Crop Science*, 62, 947–957. <https://doi.org/10.1002/csc2.20704>
- Braun, R. C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022b). Review of cool-season turfgrass water use and requirements: I. Evapotranspiration and responses to deficit irrigation. *Crop Science*, 62, 1661–1684. <https://doi.org/10.1002/csc2.20791>
- Braun, R. C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022c). Review of cool-season turfgrass water use and requirements: II. Responses to drought stress. *Crop Science*, 62, 1685–1701. <https://doi.org/10.1002/csc2.20790>
- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2022d). Management, harvest, and storage characteristics of low-input cool-season turfgrass sod mixtures. *Agronomy Journal*, 114, 1752–1768. <https://doi.org/10.1002/agj2.21051>
- Braun, R. C., Courtney, L. E., & Patton, A. J. (2023a). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, 63, 1613–1627. <https://doi.org/10.1002/csc2.20936>

- Braun, R. C., Watkins, E., Hollman, A. B., & Patton, A. J. (2023b). Assessing the fertilizer and pesticide input needs of cool-season turfgrass species. *Crop Science*, 63, 3079–3095. <https://doi.org/10.1002/csc2.21046>
- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in environmental protection and their benefits to humans: Thirty years later. *Crop Science*, 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Burt, M. G., & Christians, N. E. (1990). Morphological and growth characteristics of low- and high-maintenance Kentucky bluegrass cultivars. *Crop Science*, 30, 1239–1243. <https://doi.org/10.2135/cropsci1990.0011183X003000060016x>
- Bushman, B. S., Warnke, S. E., Amundsen, K. L., Combs, K. M., & Johnson, P. G. (2013). Molecular markers highlight variation within and among Kentucky bluegrass varieties and accessions. *Crop Science*, 53, 2245–2254. <https://doi:10.2135/cropsci2013.02.0110>
- Christians, N. E., Patton, A. J., & Law, Q. D. (2017). *Fundamentals of Turfgrass Management* (5th ed.). John Wiley & Sons, Inc., Hoboken, New Jersey.
- DaCosta, M., Huang, B., Stier, J. C., Horgan, B. P., & Bonos, S. A. (2013). Heat-Stress Physiology and Management. *Agronomy Monograph. Turfgrass: Biology, Use, and Management*, 56. <https://doi.org/10.2134/agronmonogr56.c7>.
- DeBels, B. T., Griffith, S. E., Kreuser, W. C., Melby, E. S., & Soldat, D. S. (2012). Evaluation of mowing height and fertilizer application rate on quality and weed abundance of five home lawn grass. *Weed Technology*, 26, 826–831. <https://doi.org/10.1614/WT-D-12-00062.1>
- DLF Pick Seeds. (2024). Kentucky bluegrass. <https://www.dlfpickseed.com/professional-turf/varieties/bluegrass>

- Ebdon, J. S., & Petrovic, A. M. (1998). Morphological and growth characteristics of low- and high- water use Kentucky bluegrass cultivars. *Crop Science*, 38(1), 143–152.
<https://doi.org/10.2135/cropsci1998.0011183X003800010024x>
- Ellis, R. H., & Roberts, E. H. (1980). Towards a rational basis for testing seed quality. In P. D. Hebblethwaite (Ed.). *Seed Production* (pp. 605–635). Butterworths
- Etter, A. G. (1951). How Kentucky Bluegrass Grows. *Annals of the Missouri Botanical Garden*, 38(3), 293. <https://doi.org/10.2307/2394639>.
- Folck, A. J., Bigelow, C. A., Jiang, Y., & Patton, A. J. (2023). Genotypic variation in germination rate, seedling vigor, and seed phenotype of Kentucky bluegrass cultivars. *Crop Science*, 63, 3065–3078. <https://doi.org/10.1002/csc2.21045>
- Friell, J., Watkins, E., Horgan, B. P., & Cavanaugh, M. (2017). Sod strength characteristics of 51 cool-season turfgrass mixtures. *Agronomy Journal*, 109, 1759–1757.
<https://doi.org/10.2134/agronj2016.05.0295>
- Friell, J., Watkins, E., Horgan, B. P., & Cavanaugh, M. (2017). Sod strength characteristics of 51 cool-season turfgrass mixtures. *Agronomy Journal*, 109, 1759–1757.
<https://doi.org/10.2134/agronj2016.05.0295>.
- Gopinath, L., Martin, D. L., Moss, J. Q., Wu, Y., Yu, S., & Underwood, J. R. (2021). Sod Tensile Strength, Handling Quality, and Their Interrelationship for 39 Bermudagrasses. *HortTechnology*, 31(6), 780–785. <https://doi.org/10.21273/HORTTECH04893-21>
- Griffith, S., Bero, N., Stier, J., Obear, G., Ruis, S., & Soldat, D. (2017). Biosolids as an alternative fertilizer for Kentucky bluegrass sod production in Wisconsin. *Crop Science*, 57, S227–S237. <https://doi.org/10.2135/cropsci2016.05.0367>

- Han, H. R. (2009). Development improved turf-type bermudagrasses. Oklahoma State University, Stillwater, master's thesis.
- Honig, J. A., Averello, V., Bonos, S. A., & Meyer, W. A. (2012). Classification of Kentucky bluegrass (*Poa pratensis* L.) cultivars and accessions based on microsatellite (Simple Sequence Repeat) markers. *Hortscience*, 47(9), 1356–1366.
<https://doi.org/10.21273/HORTSCI.47.9.1356>
- Honig, J. A., Averello, V., Kubik, C., Vaiciunas, J., Bushman, B. S., Bonos, S. A., & Meyer, W.A. (2018). An update on the classification of Kentucky bluegrass cultivars and accessions based on microsatellite (SSR) markers. *Crop Science*, 58(4) 1776–1787.
<https://doi.org/10.2135/cropsci2017.11.0689>.
- Huang, B., & Gao, H. (1999). Physiological responses of diverse tall fescue cultivars to drought stress. *Hortscience*, 34, 897–901. <https://doi.org/10.21273/hortsci.34.5.897>.
- Huff, D. R. (2003). Kentucky bluegrass. In: M.D. Casler and R.R. Duncan, editors, Turfgrass biology, genetics, and breeding. Wiley, Hoboken, New, Jersey, 27–38.
- Hugie, K. L., & Watkins, E. (2016). Performance of low-input turfgrass species as affected by mowing and nitrogen fertilization in Minnesota. *Hortscience*, 51, 1278–1286.
<https://doi.org/10.21273/HORTSCI11007-16>
- International Rules of Seed, ISTA (1999). Testing (Supplement rules), *Seed Science and Technology*, 27, 25–30.
- Jiang, Y., & Huang, B. (2000). Effects of Drought or Heat Stress Alone and in Combination on Kentucky Bluegrass. *Crop Science*, 40, 1358–1362.
<https://doi.org/10.2135/cropsci2000.4051358x>.

- Jiang, Y., & Huang, B. (2001). Physiological Responses to Heat Stress Alone or in Combination with Drought: A Comparison between Tall Fescue and Perennial Ryegrass. *Hortscience*, 36(4), 682–686. <https://doi.org/10.21273/HORTSCI.36.4.682>.
- Kim, Kyoung-Nam. (2014). Comparison of Germination Characteristics and Daily Seed Germinating Pattern in 15 New Cultivars of Kentucky Bluegrass Grown under Alternating Temperature Conditions. *Weed & Turfgrass Science*, 3(1), 29–40. <https://doi.org/10.5660/WTS.2014.3.1.29>.
- Kim, Kyoung-Nam. (2015). Comparison of Seed Germinating Vigor, Germination Speed and Germination Peak in Kentucky Bluegrass Cultivars under Different Germination Conditions. *Journal of the Korea Society of Environmental Restoration Technology*, 18(3), 23–38. <https://doi.org/10.13087/KOSERT.2015.18.3.23>
- Landmark Seeds. (2023). Kentucky bluegrass. <https://landmarkseed.com/products/kentucky-bluegrass-seed>
- Larsen, S. U., & Andreassen, C. (2004). Comparison of germination criteria in red fescue (*Festuca rubra* ssp. *litoralis*), perennial ryegrass (*Lolium perenne*) and Kentucky bluegrass (*Poa pratensis*). *Seed Science and Technology*, 32, 342–354. <https://doi.org/10.15258/sst.2004.32.2.07>
- Larsen, S. U., & Bibby, B. M. (2004). Use of germination curves to describe variation in germination characteristics in three turfgrass species. *Crop Science*, 44, 891–899. <https://doi.org/10.2135/cropsci2004.8910>
- Law, Q. D., Bigelow, C. A., & Patton, A. J. (2016). Selecting turfgrasses and mowing practices that reduce mowing requirements. *Crop Science*, 56(6), 3318–3327. <https://doi.org/10.2135/cropsci2015.09.0595>

- Meyer, W. A., & Funk, C. R. (1989). Progress and benefits to humanity from breeding cool-season grasses for turf 31 48 Sleper D. A., Asay K.H. & Pederson J. F. Contributions from breeding forage and turf grasses CSSA Spec. Published 15. *Crop Science Society of America*, Madison, WI. <https://doi.org/10.2135/cssaspecpub15.c4>.
- Meyer, M. H., & Pedersen, B. (2000). Low maintenance alternative turf trials. *Journal of Turfgrass Management*, 3, 49–57. https://doi.org/10.1300/J099v03n02_04.
- Morris, K. N., Kne, L., Graham, S., & Qu, Y. (2022). An Improved User Interface to Identify Sustainable Turfgrasses within National Turfgrass Evaluation Program Data. *International Turfgrass Society Research Journal*, 14, 1035–1041. <https://doi.org/10.1002/its2.127>.
- Moser, L. E., Anderson, S. R., & Miller, R. W. (1968). Rhizome and tiller development of Kentucky bluegrass (*Poa pratensis* L.) as influenced by photoperiod, cold, treatment, and variety. *Agronomy Journal*, 60(6), 632–635. <https://doi.org/10.2134/agronj1968.00021962006000060014x>
- Mountain View Seeds. (2022). Kentucky bluegrass. <https://www.mtviewseeds.com/turf-kentucky-bluegrass>
- Murphy, J. A., Bonos, S., & Perdomo, P. (1997). Classification of *Poa pratensis* genotypes. *International Turfgrass Society Research Journal*, 8, 1176–1183.
- Naylor, R. E. L. (1989). An analysis of the differences in germination of seed lots of perennial ryegrass in response to artificial ageing. *The Journal of Agricultural Science*, 112(3), 351–357. <https://doi.org/10.1017/S0021859600085804>
- Newsom Seed. (2022). Kentucky bluegrass. <https://newsomseed.com/resources/KentBlueClass.pdf>

- Nwachukwu, E. U. (2025). *Assessment of Cool-season Turfgrass Sod Production Characteristics of Tall Fescue and Kentucky Bluegrass*. M.S. Thesis. Kansas State University, Manhattan.
- Park, B. S., Murphy, J. A., Meyer, W. A., Bonos, S. A., den Haan, J., Smith, D. A., & Lawson T. J. (2005). Performance of Kentucky bluegrass within phenotypic classifications as affected by traffic. *International Turfgrass Society Research Journal*, 10, 618–626.
- Patton, A. J., & Braun, R. C. (2021). Measurement of turf height and growth using a laser distance device. *Crop Science*, 61, 3110–3123. <https://doi.org/10.1002/csc2.20295>
- Pollock, C. J. (1990). The response of plants to temperature change. *Journal Agricultural Science (Cambridge)*, 155, 1-5.
- Rincker, C. M. (1986). Germination of grass seeds after 8 years of weekly removal from subfreezing storage. *Crop Science*, 26, 165–166.
<https://doi.org/10.2135/cropsci1986.0011183x002600010039x>
- Ross, S. J., Ennos, A. R., & Fitter, A. H. (1991). Turf strength and root characteristics of ten turfgrass cultivars. *Annals of Applied Biology*, 118, 433–443.
<https://doi.org/10.1111/j.1744-7348.1991.tb05644.x>
- Saxena, P., Huang, B., Bonos, S. A., & Meyer, W. A. (2014). Photoperiod and temperature effects on rhizome production and tillering rate in tall fescue [*Lolium arundinaceum* (Schreb.) Darby.]. *Crop Science*, 54, 1205–1210.
<https://doi.org/10.2135/cropsci2013.08.0565>
- Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature Methods*, 9, 671–675. <https://doi.org/10.1038/nmeth.2089>.

- Segars, C. A., Moss, J. Q., Martin, D. L., & Wu, Y. (2022). Sod production characteristics: How strong is your bermudagrass? *International Turfgrass Society Research Journal*, 14, 256–261. <https://doi.org/10.1002/its2.4>
- Shearman, R. C., Turner, T. R., Morris, K. N., Gaussoin, R. E., Vaitkus, M. R., & Wit, L. A. (2001). Sod strength and lateral spread of *Poa pratensis* cultivars and experimental lines. *International Turfgrass Society Research Journal*, 9, 928–933.
- Shortell, R. R., Meyer, W. A., & Bonos, S. A. (2009). Classification and Inheritance of Morphological and Agronomic Characteristics in Kentucky Bluegrass (*Poa pratensis* L.). *Hortscience*, 44, 274–279. <https://doi.org/10.21273/HORTSCI.44.2.274>
- Seed Research Oregon. (2018). Kentucky bluegrass. <https://www.sroseed.com/find-a-product/bluegrass>
- St. John, R., Fry, J., Bremer, D., & Keeley, S. (2009). Establishment rate and lateral spread of *Festuca arundinacea* cultivars. *International Turfgrass Society Research Journal*, 11, 481–487. <http://hdl.handle.net/2097/2072>
- Stier, J. C., Koeritz, E. J., & Garrison, M. (2008). Timing the Establishment of Kentucky Bluegrass: Perennial Ryegrass Mixtures for Football Fields. *Hortscience*, 43, 240–244. Retrieved Jan 8, 2025, from <https://doi.org/10.21273/HORTSCI.43.1.240>.
- Su, K., Bremer, D. J., Keeley, S. J., & Fry, J. D. (2007). Effects of high temperature and drought on hybrid bluegrass compared with Kentucky bluegrass and tall fescue. *Crop Science*, 47, 2152–2161. <https://doi.org/10.2135/cropsci2006.12.0781>
- Su, K., Bremer, D. J., Keeley, S. J., & Fry, J. D. (2008). Rooting characteristics and canopy responses to drought of turfgrasses including hybrid bluegrasses, *Agronomy Journal*, 100, 949–956. <https://doi.org/10.2134/agronj2007.0292>

- Taylor, L. H., & Schmidt, R. E. (1980). Differences in sod strength, rooting, and turfgrass quality of Kentucky bluegrass cultivars resulting from seasonal and environmental conditions. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference, 11–13 July 1977, Munich, West Germany* (pp. 31–38). ASA, CSSA, SSSA, and International Turfgrass Society. <https://doi.org/10.2135/1974.proc3rdintlurfgrass.c4>
- USDA-NASS. (2021). United States Department of Agriculture Census of Agriculture 2012. <https://www.agcensus.usda.gov/Publications/2021/USDA-NASS.> (2021). United States Department of Agriculture Census of Agriculture 2021. [https://www.agcensus.usda.gov/Publications/2021/.](https://www.agcensus.usda.gov/Publications/2021/)
- Watkins, E., Gardner, D. S., Stier, J. C., Soldat, D. J., St. John, R. A., Christians, N. E., Hathaway, A.D., Diesburg, K. L., Poppe, S. R. & Gaussoin, R. E. (2014). Cultivar performance of low-input turfgrass species for the North Central United States. *Applied Turfgrass Science*, 11, 1–7. [h https://doi.org/10.2134/ATS-2013-0101-RS](https://doi.org/10.2134/ATS-2013-0101-RS)
- Yue, C., Hugie, K., & Watkins, E. (2012). Are consumers willing to pay more for low-input turfgrasses on residential lawns? Evidence from choice experiments. *Journal of Agricultural and Applied Economics*, 44, 549–560. <https://doi.org/10.1017/S107407080002410X>.
- Yue, C., Wang, J., Watkins, E., Bonos, S. A., Nelson, K. C., Murphy, J. A., & Horgan, B. P. (2017). Heterogeneous consumer preferences for turfgrass attributes in the United States and Canada. *Canadian Journal of Agricultural Economics*, 65, 347–383. <https://doi.org/10.1111/cjag.12128>.

Zhou, Y., Lambrides, C. J., & Fukai, S. (2015). Associations between drought resistance, regrowth and quality in a perennial C₄ grass. *European Journal of Agronomy*, 65, 1–9.
<https://doi.org/10.1016/j.eja.2014.12.007>



Figure 3.1. Turfco KisCutter sod cutter used to harvest sod (left), Cutting sod piece across plots (middle); Sod handling after immediately harvest (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Left and middle photo by Emmanuel Nwachukwu, right photo by Ross Braun.



Figure 3.2. Sod tensile strength device used for measuring sod strength (left), Clamping down sod piece on sod tensile device plates (middle); Piece of torn sod from the sod tensile device (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Middle photo by Ross Braun, left and right photo by Emmanuel Nwachukwu.



Figure 3.3. Measuring vegetation cover with digital images and modified lightbox (top) and rating for visual turf cover (bottom). Both photos by Ross Braun.



Figure 3.4. Growth chamber (left); Petri dishes in growth chamber randomized daily for 28 days (middle); Seeds with visible structures of radicle and coleoptile counted as germinated seed (right). Left and middle photo by Emmanuel Nwachukwu, right photo by Parul Mandal.



Figure 3.5. Kentucky bluegrass growing in containers placed in greenhouse (left); Measuring vegetation green cover with digital image analysis and modified lightbox (31 cm × 28 cm) (middle); Destructive phenotyping harvest of Kentucky bluegrass, showing aerial shoot from rhizomes and ready to wash rhizomes and bagged for measurement in lab (right). Left and right photo by Emmanuel Nwachukwu, middle photo by Parul Mandal.



Figure 3.6. Measurement of Kentucky bluegrass rhizomes during destructive harvest using digital caliper (left); Rhizome and tiller count (middle); Rhizome class rated on a scale of 0 to 5 (5 = thickest, most robust; 1 = thinnest, weakest; and 0 = no >10 mm rhizomes present) (right). Left photo by Alex Stanton, middle and right photo by Emmanuel Nwachukwu.

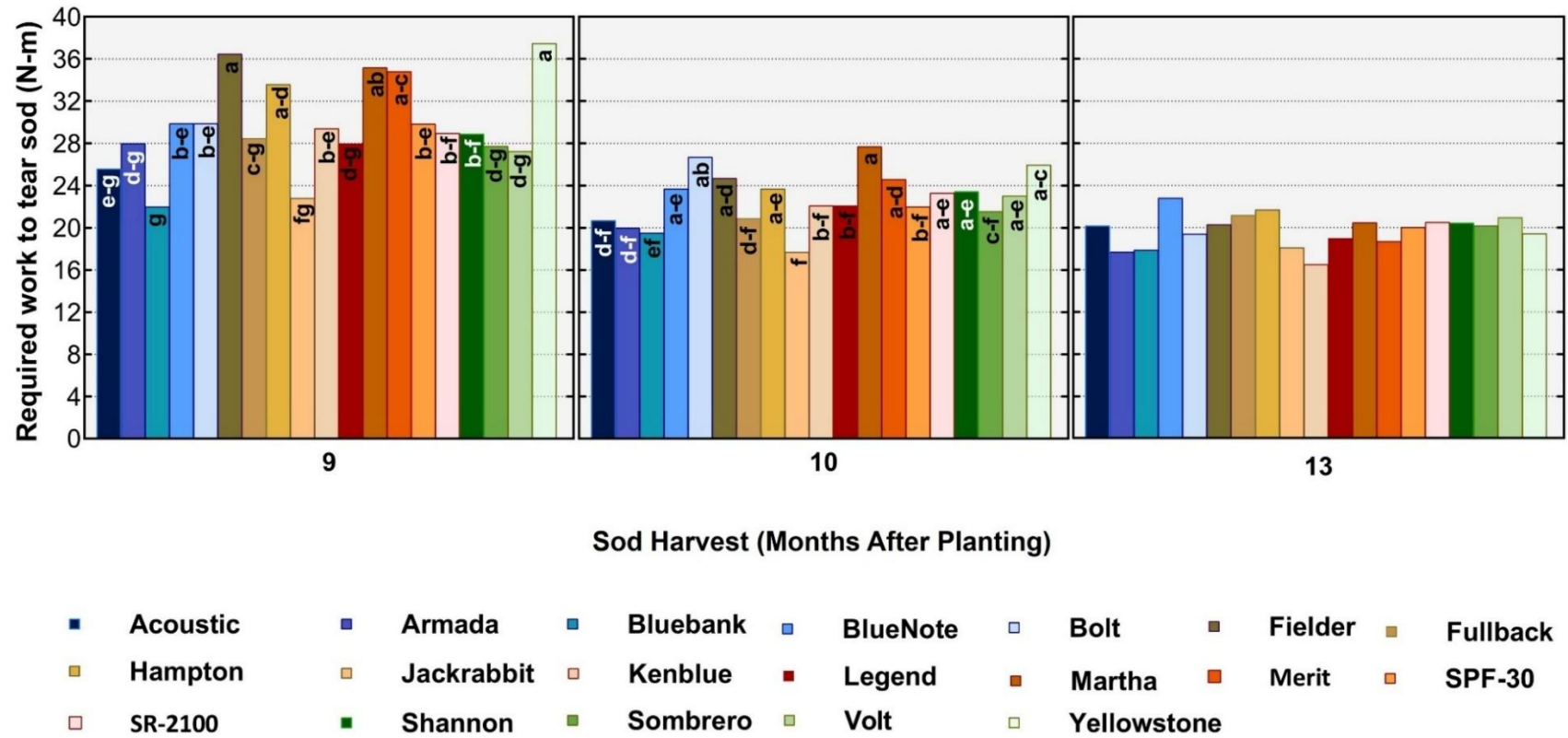


Figure 3.7. Effect of Kentucky bluegrass cultivars on required work to tear sod (newton-meters, N-m) at three sod harvest timings (9, 10 , and 13 months after planting) in Manhattan, KS across both Runs. Means within a sod harvest timing with a common letter or no letters are not significantly different according to Fisher's LSD Test ($\alpha = .05$).

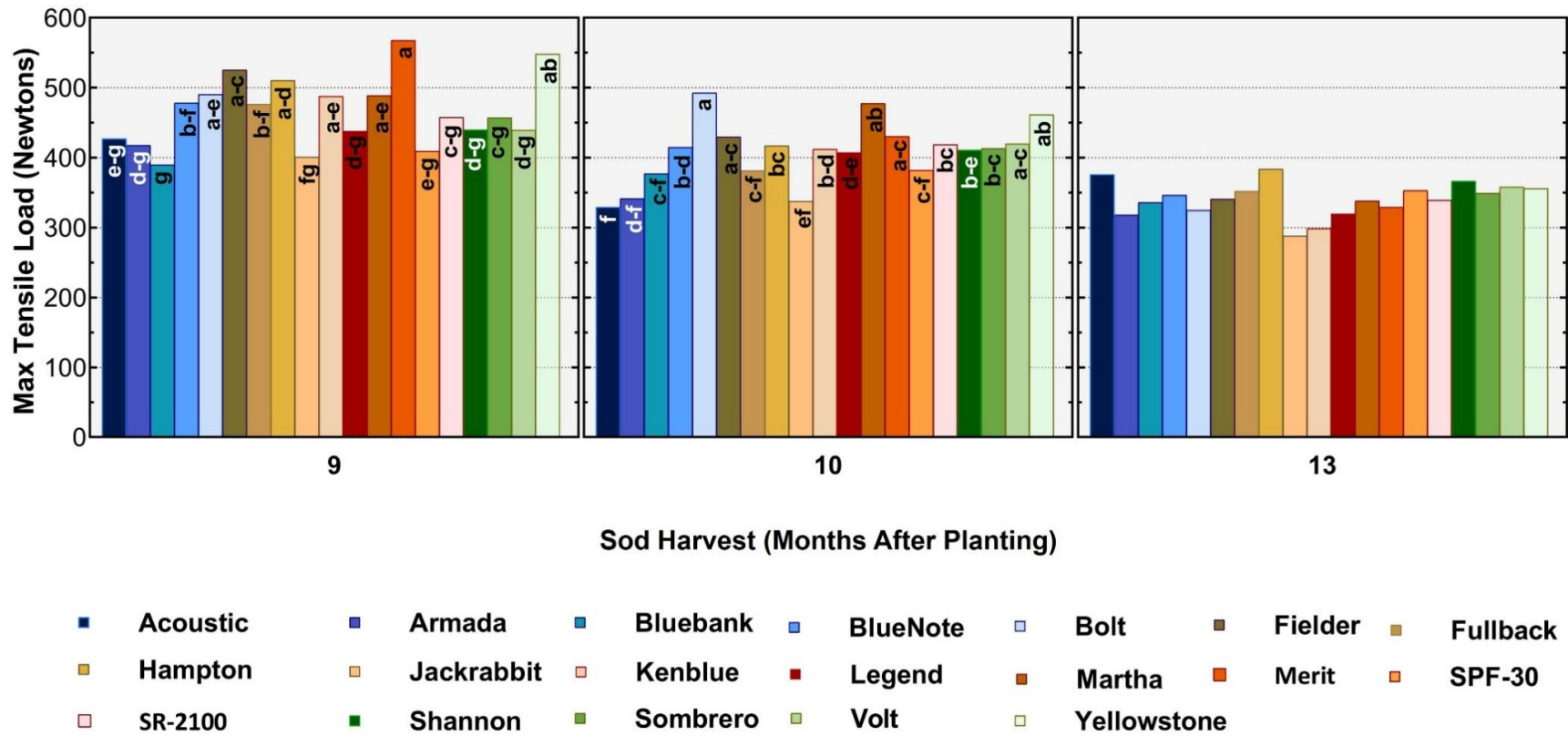


Figure 3.8. Effect of Kentucky bluegrass cultivars on maximum tensile load to tear sod (newtons, N) at three sod harvest timings (9, 10, and 13 months after planting) in Manhattan, KS across both Runs. Means within a sod harvest timing with a common letter or no letters are not significantly different according to Fisher's LSD Test ($\alpha = .05$).

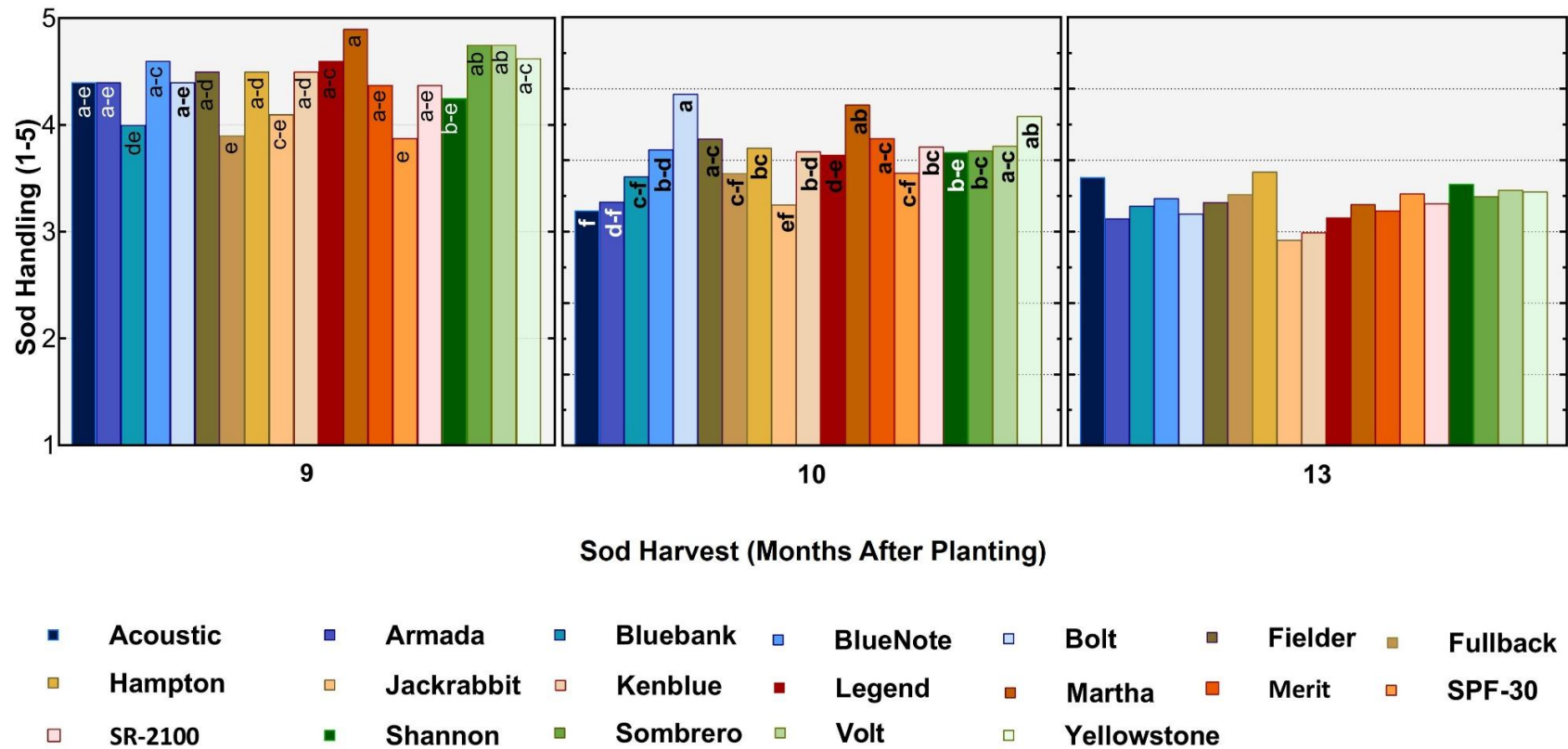


Figure 3.9. Effect of Kentucky bluegrass cultivars on sod handling (scale 1-5) at sod harvest timings of 9, 10, and 13 months after planting in Manhattan, KS across both Runs. Means within a sod harvest timing at with a common letter or no letters are not significantly different according to Fisher's LSD Test ($\alpha = .05$).

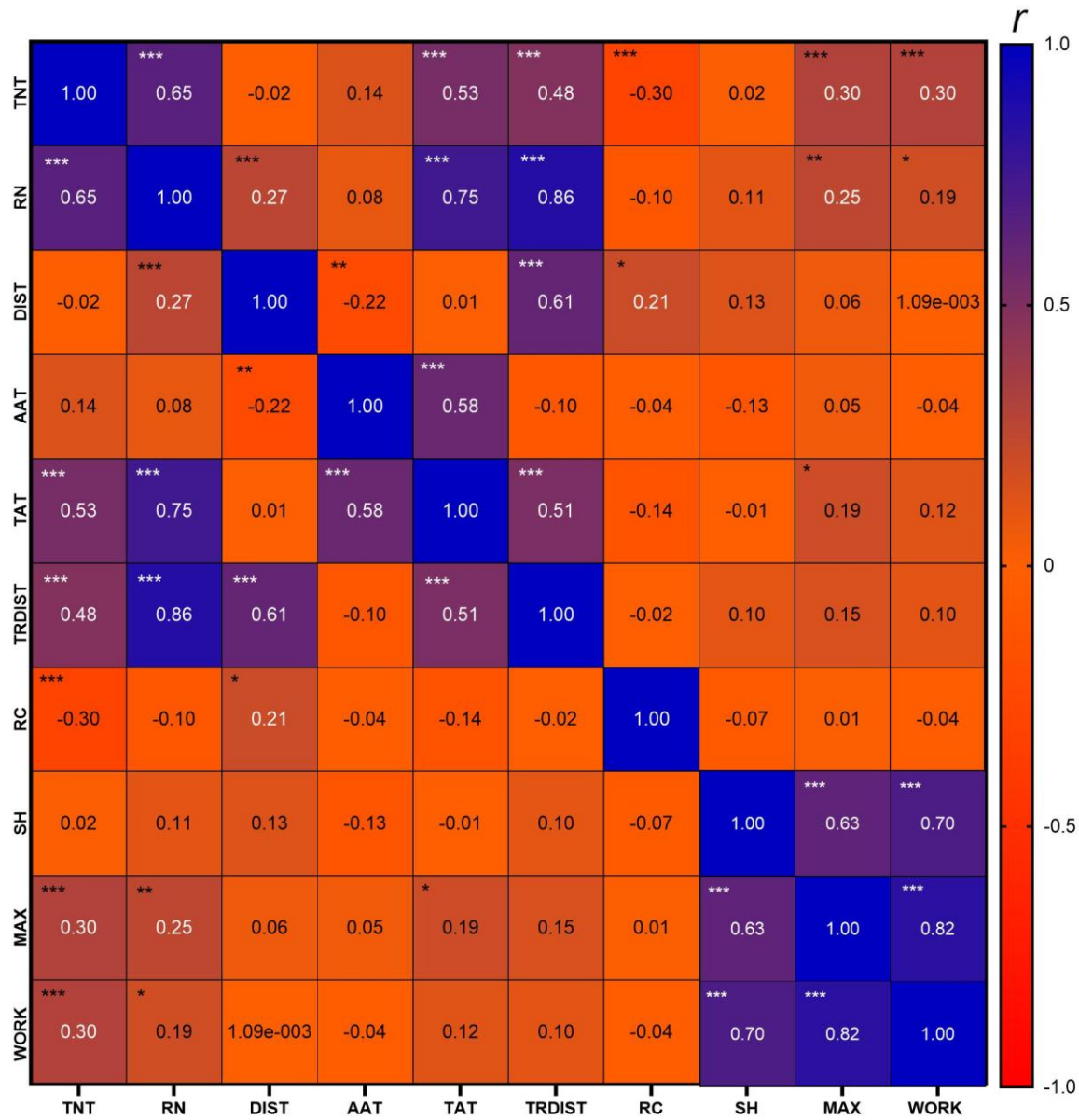
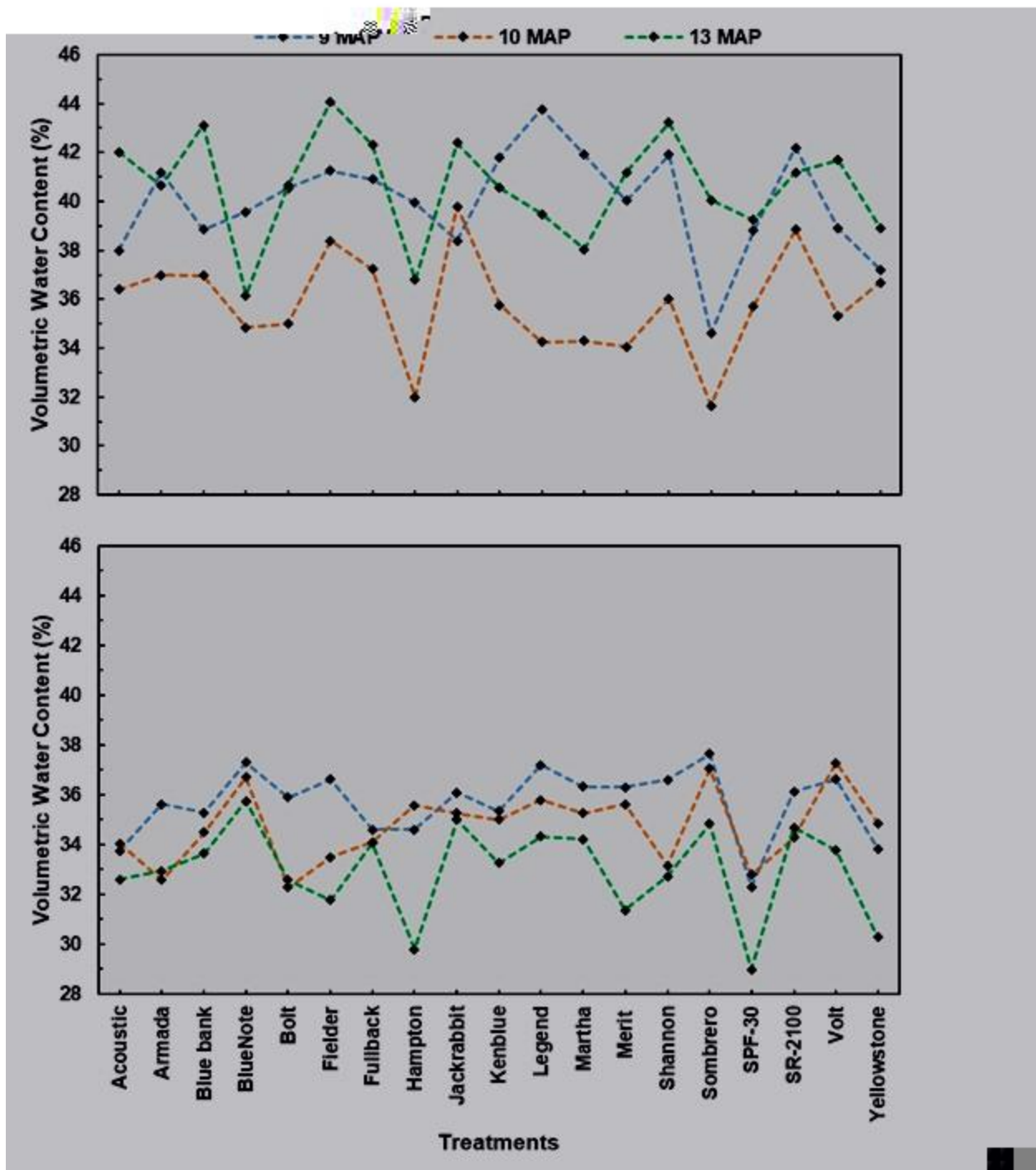


Figure 3.10. Correlation (r) is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX) and sod handling (SH)] was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($19 \times 4 \times 3 \times 2$; $n = 456$). Correlation analysis between Kentucky bluegrass greenhouse data [e.g., Rhizome class (RC), average rhizome length (DIST), total rhizome length (TRDIST), average number of rhizome (>10 mm) per plant (RN), average aerial shoot (AAT), total aerial shoot (TAT), and total number of tillers per plant (total plant and rhizome tillers, TNT)] harvested at 4.7 months after seeding and Kentucky bluegrass sod strength data harvested at 9 months after planting. Experiment runs for greenhouse data and 9-month sod harvest data were combined, before running a correlation analysis. The sample size for greenhouse data and sod strength is $n = 38$ (19 treatments $\times$ 2 runs). Note: P-value = no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels.



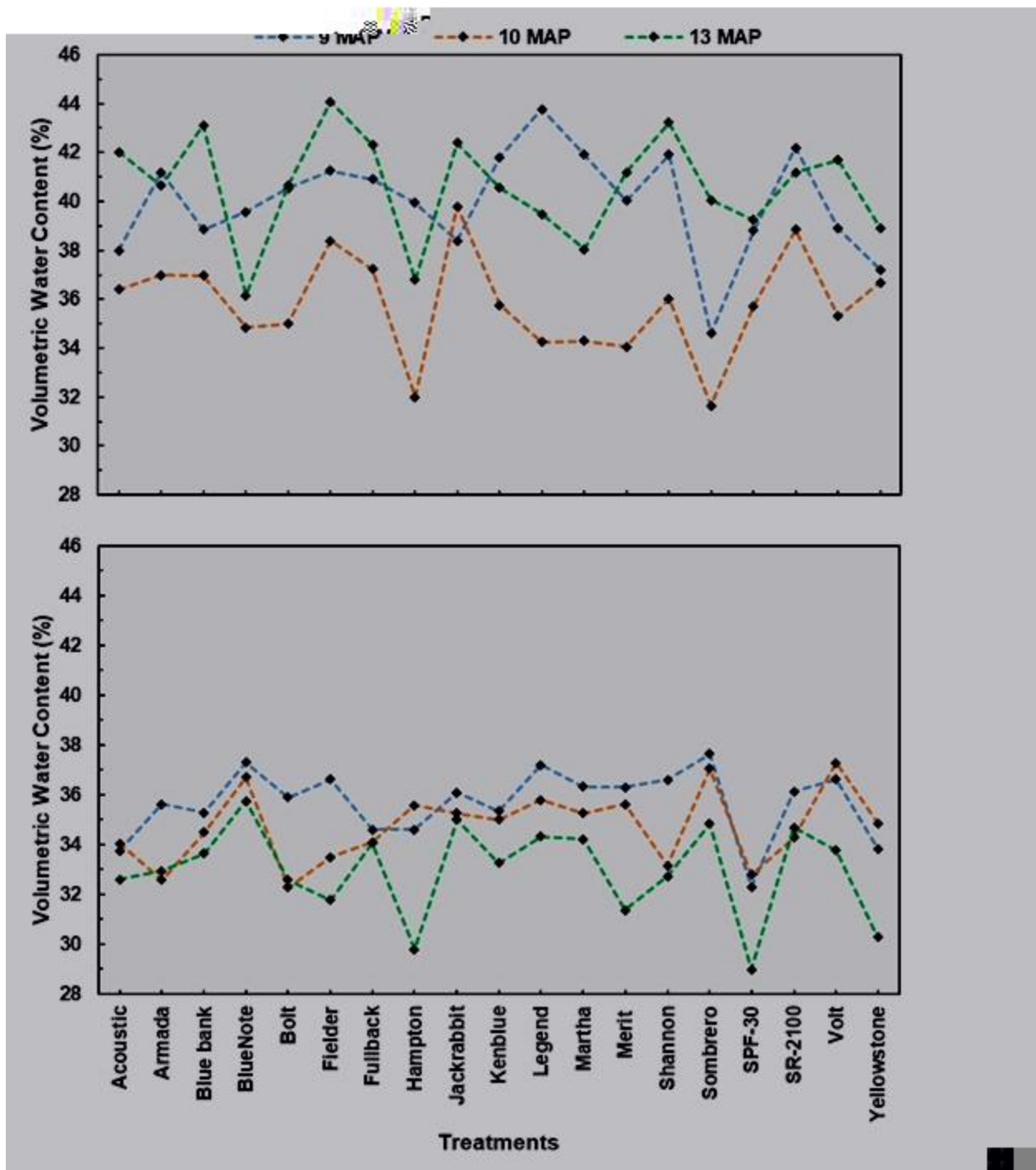


Figure 3.11. Volumetric water content (%) measured with time-domain reflectometry at five locations per plot (treatment) at a 7.6 cm soil depth at each sod harvest event, Run 1 (top) and Run 2 (bottom). Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$).

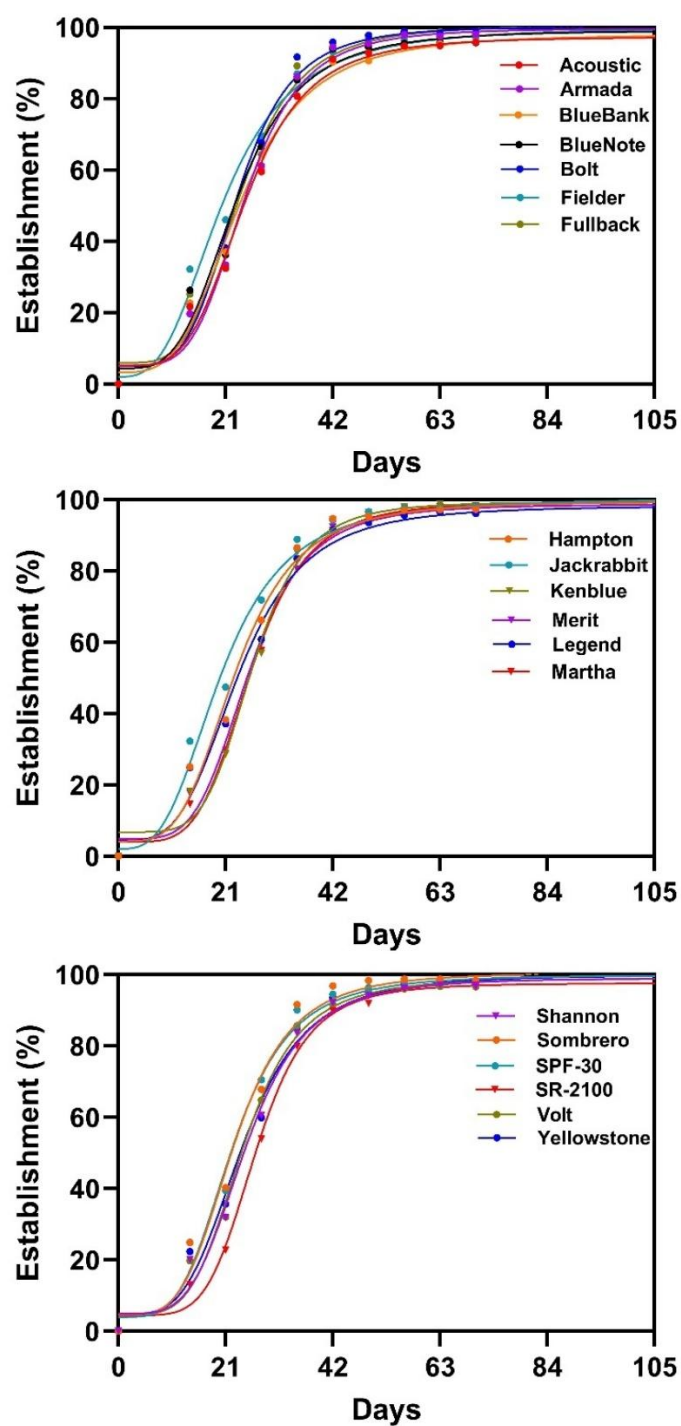


Figure 3.12. Four-parameter sigmoidal regression model output from GraphPad Prism of establishment vigor for each Kentucky bluegrass cultivar across both runs arranged alphabetically (A-Y). Regression line with the steepest slopes and lowest IC_{50} value indicates faster establishment cover.



Figure 3.13. Field plots at the Rocky Ford Turfgrass Research Center, Manhattan, KS showing establishment speed differences of Kentucky bluegrass cultivars at 2 weeks after planting on 19th Sept. 2023 in Run 2, (Left), and entire field study area of Kentucky bluegrass at 2 weeks after planting on 27 Sept. 2022 in Run 1 (Right). Left photo by Emmanuel Nwachukwu, right photo by Ross Braun.

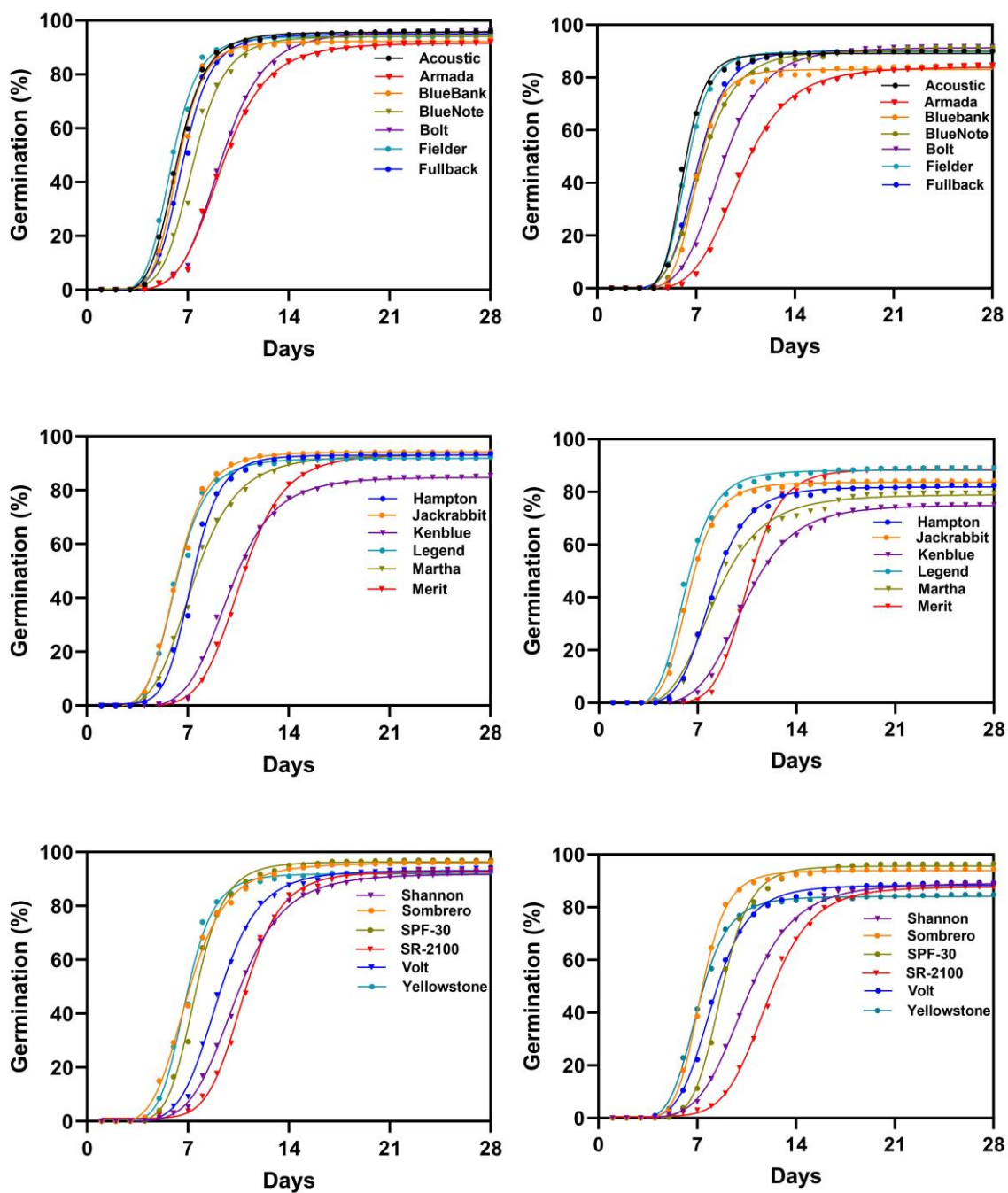


Figure 3.14. Four-parameter sigmoidal regression model output from GraphPad Prism of germination vigor for each cultivar of Kentucky bluegrass for experimental Run 1 arranged alphabetically (A-Y) (left) and Run 2 (right). The regression line with the steepest slopes and lowest IC_{50} value indicates faster germination.

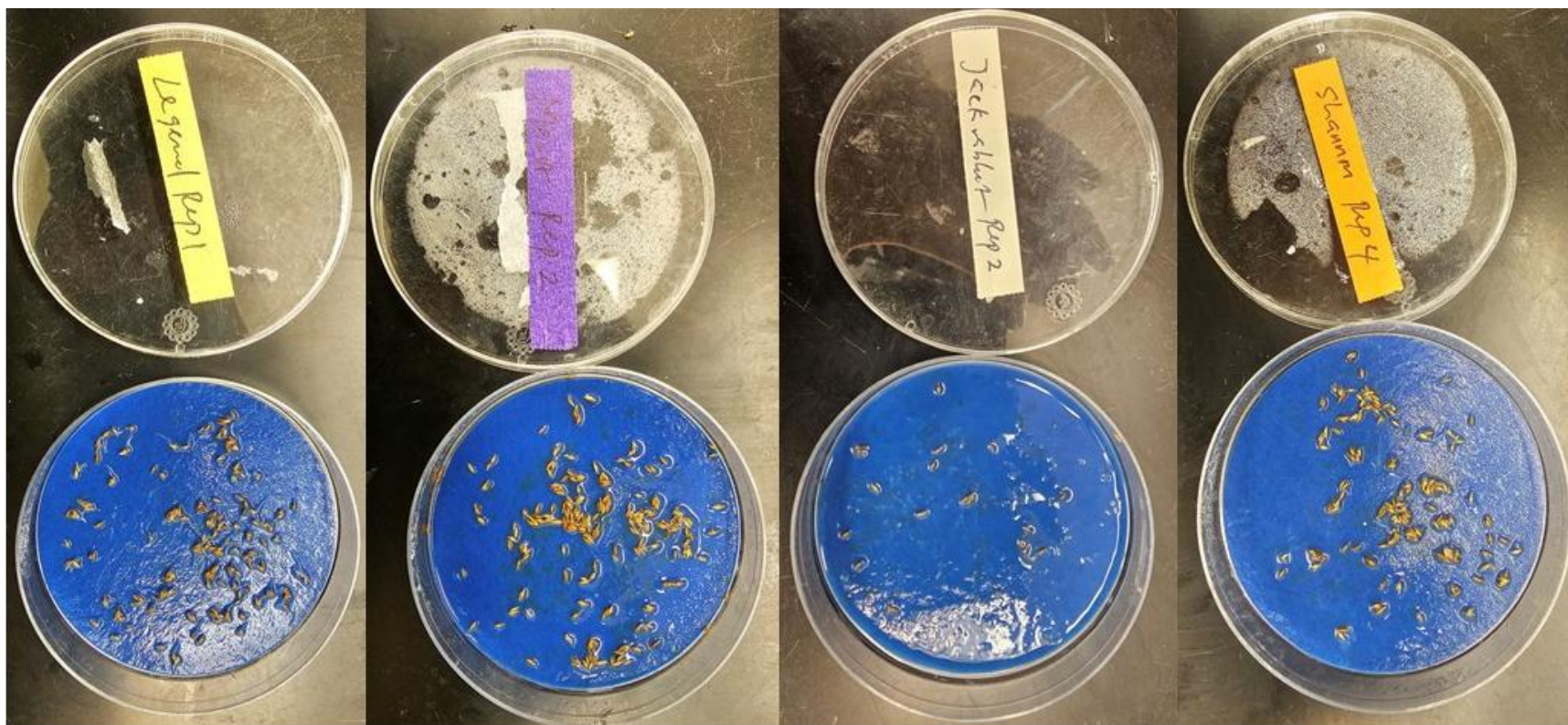


Figure 3.15. From left to right, i) germination of Kentucky bluegrass (visible structures of radicle and coleoptile) occurring in Legend at 6 days after incubation (DAI); ii) no germination occurred in Merit at 6 DAI; iii) remaining KB seeds in Petri dish after germination counts for Jackrabbit (fast germinating cultivar) at 15 DAI and Shannon (slow germinating cultivar) at 15 DAI. Photo by Emmanuel Nwachukwu.

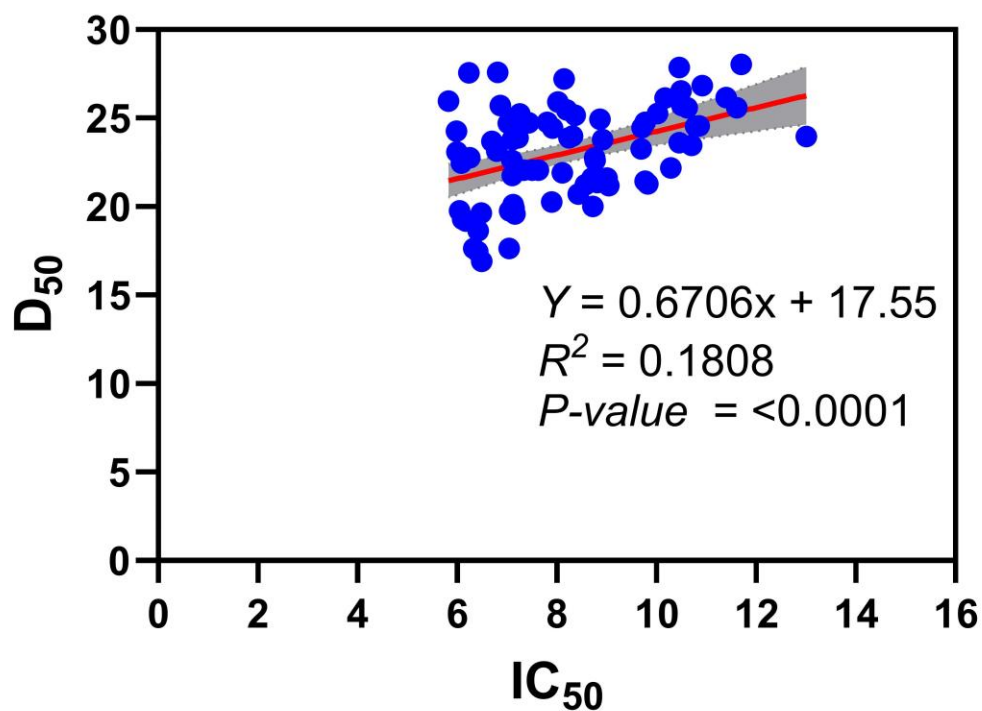
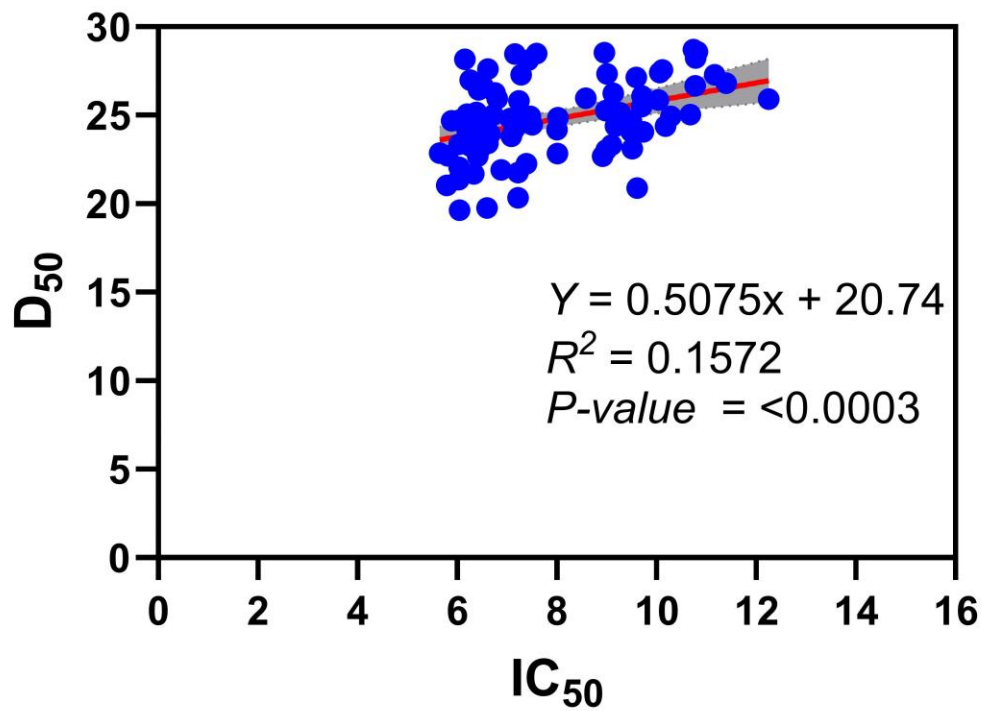


Figure 3.16. Linear regression between IC_{50} and D_{50} across Kentucky bluegrass for Run 1 (top) and Run 2 (bottom) in 2022 and 2023, respectively.



Figure 3.17. Martha (classification: Jefferson/Washington/Mid-Atlantic, high growth aggressiveness) harvested at 4.7 months after planting in the greenhouse in Run 1 for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.



Figure 3.18. Fielder (classification: Shamrock, medium growth aggressiveness) harvested at 4.7 months after planting in the greenhouse in Run 1 for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.



Figure 3.19. Volt (classification: Shamrock, low growth aggressiveness) (left), SR-2100 (classification: Shamrock, high growth aggressiveness) (middle), Acoustic (classification: Compact Midnight, high growth aggressiveness) (right) harvested at 4.7 months after planting in the greenhouse (Run 1) for visual tiller count and rhizome measurements. Photos by Emmanuel Nwachukwu.

Table 3.1. Kentucky bluegrass treatments in the experiment.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	Kentucky Bluegrass Classification Descriptions ^c	Company	Seed Lot Number	Seeding rate g m ⁻²
Acoustic	Compact Midnight	High	Compact growth, deep, extensive root and rhizomes, vigorous turf, medium-high density, good heat tolerance.	Mountain View Seed Co.	GBS-DM21-KB1131-1	7.2
Armada	Compact America	Low	Fast germination and establishment, excellent shear strength, finer leaf, high turf quality and density.	DLF Pickseed	7-2020-340/38	8.8
Bluebank	Compact Midnight	Medium	Low, compact growth, good heat tolerance.	Mountain View Seed Co.	H4-20-94565	7.3
BlueNote	Compact America	High	Fast germination and establishment, excellent shear strength, drought tolerant, high turf quality.	Mountain View Seed Co.	GBS-LHF21-BN-4	7.4
Bolt	Jefferson/Washington	Medium	Excellent heat and high summer stress tolerance, deep, extensive roots and rhizomes vigorous turf and high density.	Mountain View Seed Co.	GBS-WHB21-BOLT-3	7.2
Fielder	Shamrock	Medium	Rapid establishment, superior summer performance.	DLF Pickseed	7-2020-340/49	8.0
Fullback	Compact Midnight	Medium	Low, compact growth, good heat tolerance.	Landmark Seed Co.	H4-21-96509	6.2
Hampton	Compact	High	Low, compact growth, high turf quality.	Landmark Seed Co..	H4-21-96529	8.0
Jackrabbit	Julia	Medium	Fast germination and establishment, excellent tillering, excellent stress tolerance, high density, high turf quality.	DLF Pickseed	7-2020-340/35	8.2
Kenblue	Eurasian-Midwest (Common)	Low	Erect growth and narrow leaf blades, summer stress tolerance.	DLF Pickseed	7-2021-340/51	6.5
Legend	Compact America (Midnight)	Medium	Low, compact growth, high turf quality, higher density, moderate summer recovery, good heat tolerance.	Mountain View Seed Co.	GBS-LHF21-LEG-3	7.5
Martha	Jefferson/Washington//Mid-Atlantic	High	Excellent heat and high summer stress tolerance, deep, extensive roots and rhizomes vigorous turf and high density.	DLF Pickseed	7-2020-340/52	6.6
Merit	BVMG	Low	Medium-good turf and texture, low growth and wide leaf.	DLF Pickseed	7-2020-340/50	10.4
SPF-30	Texas × KB hybrid	High	Extensive rhizomes, heat tolerant, drought tolerant.	Landmark Seed Co.	U21-21-95M26-4	8.2
SR-2100	Shamrock	High	Rapid germination, high sod strength, quick knit sod and repair, aggressive lateral growth, high shoot density.	DLF Pickseed	7-2018-340/30	9.5
Shannon	Compact America × Shamrock	High	Rapid germination and establishment, high sod strength, quick knit sod and repair, aggressive lateral growth, high shoot density.	Landmark Seed Co.	J18-21-771-SN	9.3
Sombrero	Limousine	High	High turf quality, superb density, heat & drought tolerant.	DLF Pickseed	7-2019-340/29	7.0
Volt	Shamrock	Low	Good turf quality and sod strength, strong rhizome development.	Mountain View Seed Co.	J6-21-VO905	8.6
Yellowstone	Shamrock (Jefferson/Washington)	Low	Aggressive lateral growth, deep, extensive roots and rhizomes, high shoot density, quicky knit sod and repair.	Mountain View Seed Co.	H4-19-92801	7.7

^a Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Classification descriptions based on Brilman (2018, 2024).

Note: Run 1 seeding rates are shown, Run 2 seeding rates are not shown but are equivalent to the seeding weights to Run 1. All plots were seeded at a total rate of 2 pure live seed (PLS) cm⁻². Pure live seed was calculated based on the methods of standard principles and procedures of the Association of Official Seed Analysts (Association of Official Seed Analysts, 2016) from seed lot purities, thousand-seed weight counts, and controlled-environment germination tests for each year.

Table 3.2. Turfgrass quality rating of Kentucky bluegrass during establishment and the following spring for both runs.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	Run 1			Run 2				
			Weeks After Planting			Weeks After Planting				
			6	8	10	4	6	8	14	32
			----- 1 – 9 ^c -----			----- 1 – 9 -----				
Acoustic	Compact Midnight	High	5.0 f	5.3 e	5.8 e	5.0 ab	5.5 cde	7.0 def	8.3 a-d	8.8
Armada	Compact America	Low	6.0 bcd	6.0 b-e	7.0 abc	4.5 bc	5.8 cde	7.3 cde	8.5 abc	9.0
Blue bank	Compact Midnight	Medium	5.0 f	5.8 cde	6.0 de	5.3 ab	5.0 e	6.5 efg	7.8 cd	8.0
BlueNote	Compact America	High	5.3 ef	5.5 cde	6.5 cde	5.3 ab	5.8 cde	5.8 g	7.5 d	8.0
Bolt	Jefferson/Washington	Medium	6.5 ab	6.8 ab	7.0 abc	5.3 ab	6.0 bcd	7.8 bcd	8.3 a-d	8.8
Fielder	Shamrock	Medium	5.3 ef	6.3 a-d	6.3 cde	5.0 ab	6.0 bcd	6.5 efg	8.3 a-d	8.8
Fullback	Compact Midnight	Medium	6.3 abc	6.5 abc	7.5 a	5.8 a	7.0 a	8.8 a	9.0 a	9.0
Hampton	Compact	High	5.5 def	5.5 de	6.3 cde	5.8 a	6.0 bcd	7.0 def	7.5 d	8.8
Jackrabbit	Julia	Medium	6.0 bcd	6.0 b-e	7.0 abc	5.3 ab	6.8 ab	8.5 ab	8.8 ab	8.5
Kenblue	Eurasian-Midwest (Common)	Low	6.8 a	7.0 a	7.3 ab	4.3 bc	6.3 abc	7.5 cd	8.0 bcd	8.3
Legend	Compact America (Midnight)	Medium	5.3 ef	5.3 e	6.5 b-e	5.0 ab	6.0 bcd	6.3 fg	8.0 bcd	8.5
Martha	Jefferson/Washington/Mid-Atlantic	High	5.3 ef	6.0 b-e	6.8 a-d	4.5 bc	5.5 cde	6.5 efg	7.8 cd	8.5
Merit	BVMG	Low	5.3 ef	5.8 cde	6.3 cde	5.8 a	5.8 cde	7.3 cde	8.3 a-d	7.8
SPF-30	Texas × KB hybrid	High	5.8 cde	6.3 a-d	6.0 de	5.0 ab	6.0 bcd	6.5 efg	8.0 bcd	8.8
SR-2100	Shamrock	High	5.5 def	5.8 cde	6.3 cde	5.3 ab	6.0 bcd	6.5 efg	8.3 a-d	8.5
Shannon	Compact America × Shamrock	Low	5.8 cde	5.8 cde	6.0 de	4.5 bc	5.3 de	6.5 efg	8.3 a-d	8.5
Sombrero	Limousine	High	6.8 a	6.8 ab	7.3 ab	5.3 ab	6.8 ab	8.0 abc	8.8 ab	8.8
Volt	Shamrock	Low	6.3 abc	6.3 a-d	6.8 a-d	4.5 bc	5.5 cde	6.5 efg	7.8 cd	8.8
Yellowstone	Shamrock (Jefferson/Washington)	Low	5.8 c-f	5.8 de	6.8 a-d	3.8 c	5.5 cde	7.8 bcd	8.8 ab	9.0
<i>P-value</i>			<0.0001	0.0015	0.0007	0.0469	0.0008	<0.0001	0.0078	0.4198

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) for each month during the turfgrass establishment.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 3.3. Turfgrass quality ratings of Kentucky bluegrass in the field for both experiment runs at each sod harvest timing.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	Run 1			Run 2		
			Months After Planting			Months After Planting		
			9	10	13	9	10	13
			----- 1 – 9 ^c -----			----- 1 – 9 -----		
Acoustic	Compact Midnight	High	9.0	9.0	9.0 a	9.0	9.0	9.0 a
Armada	Compact America	Low	9.0	9.0	8.8 ab	8.8	9.0	9.0 a
Blue bank	Compact Midnight	Medium	9.0	9.0	9.0 a	8.8	9.0	9.0 a
BlueNote	Compact America	High	9.0	9.0	8.5 ab	9.0	9.0	9.0 a
Bolt	Jefferson/Washington	Medium	9.0	9.0	9.0 a	8.8	9.0	9.0 a
Felder	Shamrock	Medium	9.0	9.0	8.5 ab	8.8	9.0	9.0 a
Fullback	Compact Midnight	Medium	9.0	9.0	8.8 ab	9.0	9.0	9.0 a
Hampton	Compact	High	9.0	9.0	9.0 a	8.8	9.0	9.0 a
Jackrabbit	Julia	Medium	9.0	9.0	8.5 ab	9.0	9.0	8.8 b
Kenblue	Eurasian-Midwest (Common)	Low	9.0	9.0	6.5 d	8.5	9.0	8.5 c
Legend	Compact America (Midnight)	Medium	9.0	9.0	7.3 cd	9.0	9.0	9.0 a
Martha	Jefferson/Washington//Mid-Atlantic	High	9.0	9.0	8.8 ab	9.0	9.0	9.0 a
Merit	BVMG	Low	9.0	9.0	8.3 abc	8.8	9.0	9.0 a
SPF-30	Texas × KB hybrid	High	9.0	9.0	7.8 bc	8.5	9.0	9.0 a
SR-2100	Shamrock	High	9.0	9.0	9.0 a	8.5	9.0	9.0 a
Shannon	Compact America × Shamrock	Low	9.0	9.0	8.5 ab	8.8	9.0	9.0 a
Sombrero	Limousine	High	9.0	9.0	7.3 cd	8.5	9.0	9.0 a
Volt	Shamrock	Low	9.0	9.0	8.3 abc	9.0	9.0	9.0 a
Yellowstone	Shamrock (Jefferson/Washington)	Low	9.0	9.0	8.8 ab	9.0	9.0	9.0 a
<i>P-value</i>			1.000	1.000	0.0002	0.5215	1.000	0.0178

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) for each month during sod harvest dates.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 3.4. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 50% establishment of Kentucky bluegrass cultivars in the field across both experiment runs.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	D ₅₀ ^c	Top ^c	Hillslope ^c	R ²
			days	%		
Acoustic	Compact Midnight	High	24.9 c-f	97.35 h	4.1 d-g	0.9806 gh
Armada	Compact America	Low	24.7 b-e	99.66 abc	4.5 cde	0.9896 abc
Bluebank	Compact Midnight	Medium	23.9 c-g	98.29 fg	3.5 g-i	0.9829 e-g
BlueNote	Compact America	High	23.1 efg	99.00 de	3.8 fgh	0.9807 fg
Bolt	Jefferson/Washington	Medium	23.2 d-g	99.79 abc	4.6 bcd	0.9874 b-e
Fielder	Shamrock	Medium	20.7 h	99.72 abc	3.0 i	0.9860 b-f
Fullback	Compact Midnight	Medium	23.7 d-g	99.82 ab	4.4 c-f	0.9845 d-g
Hampton	Compact	High	23.1 efg	99.29 b-e	3.9 efg	0.9845 c-g
Jackrabbit	Julia	Medium	20.5 h	100.00 a	3.2 hi	0.9855 b-g
Kenblue	Eurasian-Midwest (Common)	Low	26.2 ab	99.28 b-e	5.4 a	0.9883 a-d
Legend	Compact America (Midnight)	Medium	23.8 d-g	98.07 g	3.8 f-h	0.9781 h
Martha	Jefferson/Washington//Mid-Atlantic	High	25.9 ab	99.24 cde	4.8 abc	0.9933 a
Merit	BVMG	Low	25.8 abc	98.73 ef	4.6 bcd	0.9891 abc
SPF-30	Texas × KB hybrid	High	22.6 g	99.75 abc	4.1 d-g	0.9860 b-f
SR-2100	Shamrock	High	27.1 a	97.77 gh	5.2 ab	0.9904 ab
Shannon	Compact America × Shamrock	Low	25.0 bcd	99.02 de	4.3 c-f	0.9901 ab
Sombrero	Limousine	High	22.9 fg	99.9 a	4.2 c-f	0.9816 f-h
Volt	Shamrock	Low	24.5 b-f	98.86 e	4.7 bcd	0.9870 b-e
Yellowstone	Shamrock (Jefferson/Washington)	Low	24.7 c-f	99.43 a-d	4.2 def	0.9865 b-f
<i>P-value</i>			<0.0001	<.00001	<.00001	<.00001

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c D₅₀, estimated number of days until 50% establishment; ^cTop (%) is the maximum establishment estimate; ^d Higher hillslope (not units) values indicate more rapid establishment speed.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 3.5. Sigmoidal regression model (four-parameter equation); Equation (1)) results for the estimated number of days until 70 and 90% establishment of Kentucky bluegrass cultivars in the field for both experiment runs.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	Run 1		Run 2	
			D ₇₀ ^c	D ₉₀ ^c	D ₇₀	D ₉₀
			----- d -----			
Acoustic	Compact Midnight	High	31.6 abc	42.7 bcd	29.1 abc	42.2
Armada	Compact America	Low	31.5 abc	41.8 b-f	28.3 a-d	39.5
Bluebank	Compact Midnight	Medium	32.5 ab	48.3 a	28.5 a-d	41.9
BlueNote	Compact America	High	29.5 cde	42.2 b-e	28.6 a-d	41.7
Bolt	Jefferson/Washington	Medium	28.5 ef	37.1 fg	27.7 bcd	39.3
Fielder	Shamrock	Medium	28.9 de	45.3 ab	25.9 de	40.7
Fullback	Compact Midnight	Medium	30.3 b-e	39.5 c-g	27.6 bcd	40.2
Hampton	Compact	High	28.8 def	40.8 b-g	28.6 a-d	40.7
Jackrabbit	Julia	Medium	29.2 cde	43.9 abc	24.1 e	37.3
Kenblue	Eurasian-Midwest (Common)	Low	30.5 b-e	37.8 e-g	31.1 a	42.6
Legend	Compact America (Midnight)	Medium	29.9 cde	42.0 b-e	29.5 abc	43.0
Martha	Jefferson/Washington//Mid-Atlantic	High	32.4 ab	42.0 b-e	29.5 abc	40.5
Merit	BVMG	Low	31.0 a-d	42.6 bcd	31.0 a	41.0
SPF-30	Texas × KB hybrid	High	29.0 def	40.4 c-g	26.9 cde	38.1
SR-2100	Shamrock	High	33.2 a	43.2 bcd	30.6 ab	39.7
Shannon	Compact America × Shamrock	Low	31.4 abc	42.5 b-e	29.5 abc	41.3
Sombrero	Limousine	High	26.6 f	36.9 g	29.4 abc	40.4
Volt	Shamrock	Low	29.3 cde	38.8 d-g	29.9 abc	41.2
Yellowstone	Shamrock (Jefferson/Washington)	Low	31.5 abc	43.7 bcd	28.9 a-d	39.7
<i>P-value</i>			<0.0001	0.0018	0.0040	0.2174

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c D₇₀, estimated number of days until 70% establishment; D₉₀, estimated number of days until 90% establishment.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 3.6. Sigmoidal regression model (four-parameter equation); Equation (2)) results for the estimated number of days until 50, 70, and 90% germination of Kentucky bluegrass cultivars in a controlled-environment for both experiment runs.

			Run 1			Run 2		
		Growth Aggressiveness Classification ^b	IC ₅₀ ^c	IC ₇₀ ^c	IC ₉₀ ^c	IC ₅₀	IC ₇₀	IC ₉₀
Cultivar	Kentucky Bluegrass Classification ^a		----- d -----					
Acoustic	Compact Midnight	High	6.3 hi	7.1 hi	8.8 ijk	6.1 g	6.8 h	8.0 j
Armada	Compact America	Low	9.4 cd	10.7 cd	13.4 bcd	10.1 c	11.6 b	14.6 b
Blue bank	Compact Midnight	Medium	6.3 ghi	7.1 hi	8.5 jk	7.0 f	7.8 g	9.1 ghi
BlueNote	Compact America	High	7.4 ef	8.4 ef	10.2 g	7.3 f	8.4 f	10.7 ef
Bolt	Jefferson/Washington	Medium	9.3 cd	10.6 cd	13.2 cd	8.8 d	10.1 c	12.7 c
Fielder	Shamrock	Medium	5.9 i	6.7 i	8.2 k	6.30 g	7.0 h	8.4 ij
Fullback	Compact Midnight	Medium	6.7 gh	7.5 gh	9.2 h-k	7.1 f	8.0 fg	9.8 fg
Hampton	Compact	High	7.3 ef	8.2 fgh	9.7 ghi	8.0 e	9.1 e	11.2 de
Jackrabbit	Julia	Medium	6.2 hi	7.1 hi	8.9 ijk	6.4 g	7.2 h	8.9 g-j
Kenblue	Eurasian-Midwest (Common)	Low	9.9 bc	11.2 bc	13.7 bc	10.3 bc	11.8 b	14.7 b
Legend	Compact America (Midnight)	Medium	6.2 hi	7.1 hi	8.9 ijk	6.2 g	7.1 h	8.8 hij
Martha	Jefferson/Washington//Mid-Atlantic	High	7.4 ef	8.8 e	11.5 f	8.2 e	9.8 c	12.8 c
Merit	BVMG	Low	11.0 a	12.2 a	14.3 ab	10.5 b	11.5 b	13.4 c
SPF-30	Texas × KB hybrid	High	7.6 e	8.4 e	10.1 gh	8.7 d	9.6 cd	11.3 de
SR-2100	Shamrock	High	10.9 a	12.0 a	14.2 ab	11.9 a	13.3 a	15.8 ab
Shannon	Compact America × Shamrock	Low	10.1 b	11.7 ab	14.8 a	10.5 bc	12.0 b	15.1 ab
Sombrero	Limousine	High	6.4 ghi	7.3 hi	8.9 ijk	7.4 f	8.1 fg	9.6 gh
Volt	Shamrock	Low	9.1 d	10.4 d	12.7 de	8.1 e	9.2 de	11.4 de
Yellowstone	Shamrock (Jefferson/Washington)	Low	6.9 fg	7.7 fgh	9.3 h-k	7.0 f	8.0 fg	9.6 g
P-value			<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c IC₅₀, estimated number of days until 50% germination; IC₇₀, estimated number of days until 70% germination; IC₉₀, estimated number of days until 90% germination.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 3.7. Parameter estimates from the four-parameter sigmoidal regression model (Equation 2) for the estimated number of days until 50% germination of Kentucky bluegrass cultivars in a controlled-environment for both experiment runs.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	Run 1				Run 2			
			Top ^c	Hillslope ^d	R ²	MGT	Top	Hillslope	R ²	MGT
			%			days	%			days
Acoustic	Compact Midnight	High	95.6 abc	6.4 efg	0.9982 a-d	7.2 ijk	89.2 cd	8.8 ab	0.9978 abc	7.1 h
Armada	Compact America	Low	91.6 f	6.2 fg	0.9980 a-d	10.4 de	84.0 e	6.0 ef	0.9978 abc	11.3 b
Blue bank	Compact Midnight	Medium	92.2 ef	7.3 b-e	0.9975 a-d	7.2 ijk	83.1 e	8.6 ab	0.9973 abc	8.1 fg
BlueNote	Compact America	High	94.2 b-e	7.0 c-f	0.9965 de	8.3 fg	90.4 cd	6.0 ef	0.9980 ab	8.5 f
Bolt	Jefferson/Washington	Medium	96.0 ab	6.4 efg	0.9990 ab	10.3 e	91.4 bc	6.0 ef	0.9990 ab	9.8 c
Fielder	Shamrock	Medium	94.1 b-f	6.6 d-g	0.9982 a-d	6.6 k	89.8 cd	7.7 b-d	0.9983 ab	7.1 h
Fullback	Compact Midnight	Medium	94.9 a-d	6.9 c-f	0.9980 a-d	7.5 ijk	90.3 cd	6.8 de	0.9990 ab	7.9 g
Hampton	Compact	High	93.2 c-f	8.0 ab	0.9970 cde	8.1 fgh	81.9 ef	6.6 e	0.9985 ab	9.0 e
Jackrabbit	Julia	Medium	94.2 a-e	6.2 fg	0.9975 a-d	7.0 jk	83.6 e	6.7 de	0.9985 ab	7.3 h
Kenblue	Eurasian-Midwest (Common)	Low	84.7 g	6.8 c-f	0.9980 a-d	11.0 cd	75.1 g	6.2 e	0.9978 a-c	11.3 b
Legend	Compact America (Midnight)	Medium	91.8 f	6.2 fg	0.9955 e	7.2 ijk	88.2 cd	6.1 ef	0.9960 cd	7.3 h
Martha	Jefferson/Washington/ Mid-Atlantic	High	93.2 def	5.0 h	0.9980 a-d	8.5 f	79.2 f	5.0 f	0.9953 d	9.6 cd
Merit	BVMG	Low	93.1 def	8.5 a	0.9992 a	11.9 a	88.5 cd	9.2 a	0.9988 ab	11.4 b
SPF-30	Texas × KB hybrid	High	96.4 ab	7.7 abc	0.9972 b-e	8.4 f	95.7 a	8.6 ab	0.9980 ab	9.6 c
SR-2100	Shamrock	High	92.8 def	8.5 a	0.9987 abc	11.6 ab	87.6 d	7.9 bc	0.9990 ab	12.7 a
Shannon	Compact America × Shamrock	Low	92.6 def	5.7 gh	0.9990 ab	11.2 bc	89.2 cd	6.1 ef	0.9993 a	11.4 b
Sombrero	Limousine	High	96.7 a	6.6 d-g	0.9972 b-e	7.1 jk	93.9 ab	7.9 bc	0.9985 ab	8.1 fg
Volt	Shamrock	Low	93.2 c-f	6.7 def	0.9987 abc	10.1 e	88.4 cd	6.5 e	0.9988 ab	9.2 de
Yellowstone	Shamrock (Jefferson/Washington)	Low	92.0 ef	7.5 bcd	0.9972 b-e	7.8 ghi	89.2 e	6.8 cde	0.9983 ab	8.1 g
<i>P-value</i>			<0.0001	<0.0001	0.0156	<0.0001	<0.0001	<0.0001	0.0075	<0.0001

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Top (%) is the maximum germination estimate.

^d Higher hillslope (not units) values indicate more rapid germination speed.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table 3.8. Plant tiller and rhizome characteristics of Kentucky bluegrass cultivars grown in containers in a greenhouse in Run 1.

Cultivar	Kentucky Bluegrass Classification^a	Growth Aggressiveness Classification^b	Average Number of Plant Tillers^c #	Average Number of Rhizomes^c #	Average Rhizome Length^c mm	Total Rhizome Length^c mm	Average Number of Nodes Per Rhizome #	Total Aerial Shoots on Rhizomes #	Rhizome Class 0 to 5
Acoustic	Compact Midnight	High	32.8 bc	6.8 b-e	118	904 b-e	7.0	4.6	1.6 cd
Armada	Compact America	Low	21.2 def	3.6 fg	151	782 cde	7.9	1.8	2.4 abc
Blue bank	Compact Midnight	Medium	38.6 ab	7.0 b-e	126	895 b-e	7.8	5.8	1.4 d
BlueNote	Compact America	High	28.6 b-e	7.4 bc	175	1406 abc	11.6	2.6	2.4 abc
Bolt	Jefferson/Washington	Medium	32.0 bc	5.6 b-g	98	580 de	5.5	4.2	2.2 a-d
Fielder	Shamrock	Medium	31.8 bc	8.4 ab	183	1540 ab	11.3	3.8	2.4 abc
Fullback	Compact Midnight	Medium	21.0 def	5.0 c-g	213	953 b-e	11.4	4.8	2.8 a
Hampton	Compact	High	34.2 bc	3.2 g	93	402 e	5.8	1.8	1.6 cd
Jackrabbit	Julia	Medium	14.8 f	4.6 c-g	140	785 cde	8.3	3.0	1.8 bcd
Kenblue	Eurasian-Midwest (Common)	Low	21.0 def	4.8 c-g	125	709 de	7.0	2.6	2.0 a-d
Legend	Compact America (Midnight)	Medium	13.6 f	4.4 d-g	196	790 cde	10.4	2.6	2.6 ab
Martha	Jefferson/Washington/Mid-Atlantic	High	48.4 a	10.8 a	169	1850 a	9.9	6.4	1.6 cd
Merit	BVMG	Low	29.6 bcd	3.8 fg	135	595 de	7.7	2.8	2.2 a-d
SPF-30	Texas × KB hybrid	High	26.0 cde	6.4 b-f	193	1217 a-d	11.5	2.0	1.8 bcd
SR-2100	Shamrock	High	14.4 f	4.2 efg	150	642 de	8.4	2.0	2.6 ab
Shannon	Compact America × Shamrock	Low	26.8 cde	7.2 bcd	164	1226 a-d	9.3	4.2	2.0 a-d
Sombrero	Limousine	High	19.2 ef	6.4 b-f	162	1037 b-e	9.0	2.6	2.0 a-d
Volt	Shamrock	Low	27.4 cde	5.6 b-g	134	783 cde	7.9	2.6	2.8 a
Yellowstone	Shamrock (Jefferson/Washington)	Low	25.8 cde	5.2 c-g	139	689 de	9.0	3.4	2.4 abc
<i>P-value</i>			<0.0001	<0.0001	0.2107	0.0072	0.2349	0.0757	0.0384

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Total Number of Plant Tillers is the number of visible plant tillers, rhizome tillers, and aerial shoots growing from rhizomes per container; Average Number of Rhizomes is the number of rhizomes per plant (container) that measured >10 mm; Average Rhizome Length is the mean length of >10 mm rhizomes per container; Total Rhizome Length is the summed length of all >10 mm rhizomes per container; Average Number of Nodes Per Rhizome is the average number of nodes counted on >10 mm rhizomes per container; Total Aerial Shoots on Rhizomes is the number of aerial tillers counted on rhizomes >10 mm per container; Rhizome Class is visual rating of all rhizomes produced by the plant, and rated on a scale of 0 to 5 (5 = thickest, most robust; 1 = thinnest, weakest; and 0 = no >10 mm rhizomes present).

Note: Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha < 0.05$).

Table 3.9. Plant tiller and rhizome characteristics of Kentucky bluegrass cultivars grown in conetainers in a greenhouse in Run 2.

Cultivar	Kentucky Bluegrass Classification^a	Growth Aggressiveness Classification^b	Average Number of Plant Tillers^c #	Average Number of Rhizomes^c #	Average Rhizome Length^c mm	Total Rhizome Length^c mm	Average Number of Nodes Per Rhizome #	Total Aerial Shoots on Rhizomes #	Rhizome Class 0 to 5
Acoustic	Compact Midnight	High	15.8 bcd	3.6 bcd	98	342 b-e	6.5	2.4 a-e	2.2
Armada	Compact America	Low	18.4 ab	6.0 a	130	1022 a	8.0	4.0 a	2.2
Blue bank	Compact Midnight	Medium	9.0 efg	2.8 b-e	141	284 b-e	7.8	1.6 c-f	2.0
BlueNote	Compact America	High	11.2 def	3.8 bc	155	650 ab	9.8	1.0 ef	2.4
Bolt	Jefferson/Washington	Medium	21.8 a	3.6 bcd	125	433 b-e	7.7	3.2 abc	2.6
Fielder	Shamrock	Medium	9.8 efg	2.2 cde	138	288 b-e	8.2	0.8 ef	3.0
Fullback	Compact Midnight	Medium	9.6 efg	3.0 b-e	173	623 a-d	9.8	0.8 ef	3.6
Hampton	Compact	High	13.0 cde	2.8 b-e	70	217 de	4.5	2.0 b-f	1.8
Jackrabbit	Julia	Medium	6.8 fg	2.2 cde	163	409 b-e	9.2	1.2 ef	2.8
Kenblue	Eurasian-Midwest (Common)	Low	8.6 efg	3.0 b-e	170	642 abc	9.3	1.2 ef	3.0
Legend	Compact America (Midnight)	Medium	10.0 efg	2.0 cde	147	300 b-e	8.2	1.4 def	2.0
Martha	Jefferson/Washington//Mid-Atlantic	High	17.6 abc	4.6 ab	153	643 abc	8.7	3.0 a-d	2.8
Merit	BVMG	Low	12.4 de	4.4 ab	99	533 b-e	6.6	3.4 ab	2.2
SPF-30	Texas × KB hybrid	High	12.4 de	1.2 e	66	164 e	4.7	0.8 ef	2.0
SR-2100	Shamrock	High	5.8 g	1.2 e	97	193 e	6.2	0.6 f	2.4
Shannon	Compact America × Shamrock	Low	13.4 cde	2.2 cde	147	382 b-e	9.1	0.8 ef	2.4
Sombrero	Limousine	High	11.2 def	3.8 bc	148	547 b-e	8.8	2.4 a-e	2.8
Volt	Shamrock	Low	9.8 efg	1.6 de	126	226 cde	8.5	1.2 ef	1.8
Yellowstone	Shamrock (Jefferson/Washington)	Low	12.0 de	2.0 cde	100	253 b-e	6.2	1.6 c-f	3.0
<i>P-value</i>			<0.0001	0.0013	0.8095	0.0118	0.9281	0.0011	0.3287

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Total Number of Plant Tillers is the number of visible plant tillers, rhizome tillers, and aerial shoots growing from rhizomes per container; Average Number of Rhizomes is the number of rhizomes per plant (container) that measured >10 mm; Average Rhizome Length is the mean length of >10 mm rhizomes per container; Total Rhizome Length is the summed length of all >10 mm rhizomes per container; Average Number of Nodes Per Rhizome is the average number of nodes counted on >10 mm rhizomes per container; Total Aerial Shoots on Rhizomes is the number of aerial shoots counted on rhizomes >10 mm per container; Rhizome Class is visual rating of all rhizomes produced by the plant, and rated on a scale of 0 to 5 (5 = thickest, most robust; 1 = thinnest, weakest; and 0 = no >10 mm rhizomes present).

Note: Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha < 0.05$).

Chapter 4 - Sod Strength Characteristics of Rhizomatous Tall

Fescue and Quantifying Rhizome Production

Abstract

Tall fescue (TF) (*Festuca arundinacea* Shred.) has continued to increase in popularity in the northern and transitional climatic zone of the U.S. because of its superior heat and drought tolerance compared to Kentucky bluegrass (KB) (*Poa pratensis* L.). However, most turf-type TF cultivars have a bunch-type growth habit that hinders their potential to produce high sod strength for sod producers. Many TF cultivars have been marketed as spreading or rhizomatous tall fescue (RTF) during the last 30 years. More information is needed on sod strength and handling of these RTF to potentially help sod producers and turfgrass practitioners. Repeated field experiments at Kansas State University were conducted to evaluate the influence of RTF on sod strength [maximum tensile strength (newtons) and required work to tear (N-m)] and sod handling (1-5 scale) at three harvests; 9, 10, and 12 months after planting (MAP). In addition, plants were sown in containers and tiller and rhizome characteristics were measured in repeated greenhouse experiments. Field experiment results indicated that a 100% KB produced the highest sod strength and sod handling across all three sod harvests. Rhizomatous tall fescue did not consistently produce better sod strength than 100% non-rhizomatous (bunch-type) TF. At 9 months sod harvest, 100% KB bluegrass required more energy to tear a sod, with a ~25 (N-m) required work to tear a sod and max tensile strength of 426.2 N when compared to the top performing RTF, at ~15(N-m of required work to tear sod) and 299.5 N of maximum tensile load to tear sod. Kentucky bluegrass sod strength declined over the summer, but it was still in the top-performing sod ranking, suggesting an early summer sod harvest is optimal compared to late-

summer in the transitional climatic zone. Greenhouse experiments revealed minimal rhizome production in RTF cultivars after 4.3 months. Short rhizome lengths between 1 to 3.1 mm were observed in RTF compared to >80 mm in KB cultivars. Both bunch-type and RTF often had faster germination and establishment vigor than KB but this did not correspond to greater sod strength. Rhizome production and sod strength is considerably less in TF compared to KB and results will help sod producers and turfgrass practitioners in future selections and growing challenges to meet market demands.

Introduction

Demand for low-input high-quality turfgrass sod is increasing due to changes in building and residential codes, new construction, water conservation demands, and increased revenue generation for the sod industry in the transitional climatic zone and Northern climatic regions of the U.S. (Barnes et al., 2018; Hugie et al., 2012; Yue et al., 2017; Watkins et al., 2014; USDA-NASS, 2021). Kentucky bluegrass (KB) (*Poa pratensis* L.) and tall fescue (TF) [*Festuca arundinacea* Schreb.; syn. *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons.] are cool-season turfgrass species used for sod production and many different turfgrass systems in northern and transitional climatic zones of the United States. Both turfgrass provide many of the same ecosystem services (e.g., carbon sequestration, oxygen production, greenspace for recreation and relaxation, water filtration, etc.) like many other turfgrass species (Braun et al., 2024). Kentucky bluegrass, because of its rhizomatous growth habit, is the leading cool-season turfgrass species preferred for sod production in the northern U.S. (Braun et al., 2021a). However, KB often requires high maintenance (e.g., mowing, irrigation, fertilizer, pesticide) inputs and has lower drought resistance than TF (Askew et al., 2013; Braun et al., 2023b, 2022a, 2022b, 2022c; Debels et al., 2012; Meyer & Pederson, 2000). Therefore, there is a need for TF sod, which reflects the current industry trends of its increasing popularity due to less input requirements, excellent shade, and drought and heat tolerance compared to KB (Badra et al., 2004; Braun et al., 2023b; Fiorio et al., 2012; Goldsby et al., 2015; Hall & Taylor, 1989; Jiang & Huang, 2001; Karcher et al., 2008; Qian et al., 1997; Richardson et al., 2012; Su et al., 2007; Tegg & Lane, 2004). The deep rooting system of TF provides good drought avoidance and is one of the reasons for its prolonged drought tolerance (Braun et al., 2022a, 2022b; Fry & Huang, 2004; Sheffer et al., 1987; Su et al., 2008).

Textbooks usually refer to TF as a bunch-type grass (i.e., no extravaginally tillering of rhizomes or stolons); therefore, it creates a poor choice for sod production and has a limited ability to spread laterally during establishment or once established to fill in damaged or bare ground (Braun et al., 2021, 2022c; Christians et al., 2017). The non-lateral spread of TF creates weak sod strength, and there is a high tendency to break apart (poor sod handling) when rolled and transported from the sod producer's site to the customer's site (Braun et al., 2021a, 2021b; Braun et al., 2022c). Currently, bunch-type TF sod production is possible when included in seeded mixtures with KB at planting or the use of plastic netting at planting or harvest to help hold it together and improve sod strength (Beard et al., 1980; Braun et al., 2022c; Burns, 1980; Carrow & Sills, 1980; Christians et al., 2017). Over the last 30 years, there has been an increase in marketed rhizomatous ("spreading") tall fescue cultivar options. Before this, Porter (1958) found some structures morphologically equivalent to rhizomes on tall fescue plants seen on the university farm of The Ohio State University and on the interstate highway in Ohio. Sawhney (1965) reported short rhizomes in a forage-type variety called "Alta" but it still has "bunch-type" growth habit due to the short rhizome characteristics. Others have also reported spreading TF cultivars to produce short rhizomes (Cowan, 1956; D' Uva, 1982; Porter, 1958). More recently, turfgrass breeders at land-grant Universities have released TF cultivars that produce short-to-moderate rhizome-like structures compared to traditional bunch-type TF cultivars, which are now referred to as "rhizomatous TF" (RTF) or spreading TF (St. John et al., 2009). The presence of rhizomes is beneficial not only because it can improve its recuperative ability, but also because they can serve as organs of carbohydrate storage and, therefore, have the potential to aid survival during temperature extremes of cold, heat, or drought stress (De Battista et al., 1990). It would be highly desirable to have RTF sod similar to other *Festuca* spp. like some of the fine

fescue taxa (*Festuca* L. spp.), such as strong creeping red fescue (*F. rubra* L. ssp. *rubra* Gaudin) and slender creeping red fescue [*F. rubra* ssp. *littoralis* (G. Mey.) Auquier] that produce rhizomes (Braun et al., 2021a, 2021b, 2022c). Research has demonstrated that the presence of robust rhizomes aid in the turfgrass's ability to withstand traffic, enhance recuperative potential, and increase sod strength and handling (Braun et al., 2021a, 2022c; Braun & Patton, 2022; Christians et al., 2017; Dunn et al., 2002; Park et al., 2005; Park et al., 2010; Singh et al., 2005).

While there has been an increase in commercially available RTF, the rhizome characteristics and influence on sod production have not been adequately studied. Research has documented that rhizomatous fine fescue taxon (i.e., strong creeping red fescue and slender creeping red fescue) and mixtures with other cool-season turfgrass species (Braun et al., 2021a, 2022c) produced high sod strength equal to KB; however, further research is needed on RTF cultivars to update sod producers with accurate information. Additionally, further information on the rhizome characteristics of RTF may assist plant breeders. Therefore, research is needed in this area since the number of marketed RTF cultivars is increasing, and there is a growing information gap. Thus, the objectives of this study were to quantify germination speed, establishment vigor, rhizome characteristics, and sod strength and handling of rhizomatous tall fescue cultivars.

Materials and Methods

Field Experiment Site

Replicated field experiments were established from 9 Sept. 2022 to 18 Sept. 2023 (Run 1) and 8 Sept. 2023 to 2 Sept. 2024 (Run 2) at the Rocky Ford Turfgrass Research Center in Manhattan, KS, USA (39° 13' 53" N, 96° 34' 51" W). The soil for both experiment runs was a Chase silty clay loam (fine, smectitic, mesic Aquertic Argiudolls), with a soil pH of 7.1 and 75 g kg⁻¹ organic matter, 122 mg kg⁻¹ P (Mehlich-3 method), and 501 mg kg⁻¹ K (ammonium acetate method). Both experiment runs were conducted in a full-sun environment (i.e., no shade) and weather station (<https://mesonet.k-state.edu>) was installed within 50 m of this experiments.

Experiment Design, Treatments, and Field Establishment

The field experiment was set up in a one-way treatment structure arranged in a randomized complete-block design with four complete blocks for a total of 48 plots. Each plot size measured 1.2 by 1.2m (4 × 4 ft) (with no alleyways between plots). The experiment consisted of 12 treatments, which included 7 rhizomatous tall fescue treatments, one 100% bunch-type TF blend treatment, one 100% KB blend treatment, and two TF:KB mixture treatments, all listed in Tables 4.1 and 4.2.

A non-selective herbicide was used to eradicate previous vegetations and the soil was tilled before seeding each year. The methods of standard principles and procedures of the Association of Official Seed Analysts (Association of Official Seed Analysts, 2016) were followed each year to calculate pure live seeding rate from seed lot purities, thousand-seed weight counts, and controlled-environment germination tests. Field plots were seeded on 9 Sept. 2022 and 8 Sept. 2023 for Run 1 and Run 2, respectively. This was accomplished by hand-shaking pre-measured seeds in multiple directions across each plot (Table 4.2). All plots were

seeded at a total rate of 2 pure live seed (PLS) cm^{-2} including mixture ratios and RTF blend percentages. A starter fertilizer was applied during seeding at a rate of 204 kg ha^{-1} (i.e., 22 kg P ha^{-1} and 37 kg N ha^{-1}) ($18 \text{ N} - 24 \text{ P}_2\text{O}_5 - 12 \text{ K}_2\text{O}$; The Andersons Inc., Maumee, OH) across the entire study area. The soil surface was then lightly raked with a leaf rake within each plot to promote seed-to-soil contact, and a 14.2 g (0.5 oz) light germination blanket (PR1724, A.M. Leonard) was used to cover the experimental area for 10 days to prevent erosion, seed movement, and to promote seed germination. Irrigation was applied through an in-ground system daily for the first 21 days as needed to encourage turf establishment.

Field Plot Maintenance

Fertilizer applications were conducted with a slow-release nitrogen fertilizer (43–0–0; SGN:150, polymer-coated-sulfur-coated urea; The Andersons Inc.) in both experiment runs. These fertilizer applications occurred at a rate of 37 kg N ha^{-1} at ~30 days after seeding in both experiment runs, and two additional fertilizer applications occurred in late-March and mid-May the following spring at rates of 37 and 61 kg N ha^{-1} , respectively. For both experiment runs, the annual N rate was $172 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ($3.5 \text{ lb N } 1000 \text{ ft}^{-2} \text{ yr}^{-1}$). Irrigation was applied three times per week to the study area throughout the growing season, for an average of 2.54 cm wk^{-1} if no precipitation occurred. Plots were maintained at an 8.2-cm mowing height (3.25 inches).

On 16 June 2023, an insecticide containing imidacloprid {1-[(6-Chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinimne} (Merit 0.5 G), was applied at a rate of $0.44 \text{ kg a.i. ha}^{-1}$ to control and prevent white grubs and billbugs in Run 1. An insecticide containing chlorantraniliprole {3-Bromo-N-[4-chloro-2-methyl-6-[(methylamino)carbonyl] phenyl] -1-(3-chloro-2-pyridinyl)-1H-pyrazole-5-carboxamide} was applied at a rate of $0.17 \text{ kg a.i. ha}^{-1}$ on 21 June 2024 for prevention of insect pest damage in Run 2. for Run 2, Dinotefuron {N-methyl-N'-

nitro-N''-[(tetrahydro- 3-furanyl)methyl]guanidine} (Zylam) at 0.58 kg a.i. ha⁻¹ was applied on 3 Sept. 2024, as curative white grub control. Fungal disease were controlled and prevented by applying Azoxystrobin (methyl (E)-2-{2-[6-(2-cyanophenoxy) pyrimidin-4-yloxy]phenyl}-3-methoxyacrylate) (Heritage) at a rate of 0.61 kg a.i. ha⁻¹. For both experiment runs, preemergence herbicides were not applied. When broadleaf weeds were present, a commercially available herbicide mixture containing 2,4-D (2,4-dichlorophenoxyacetic acid) + mecoprop-p [(+)-(R)-2-(2 methyl-4-chlorophenoxy) propionic acid] + dicamba (3,6-dichloro-o-anisic acid) was applied at a rate of 1.52 kg a.e. ha⁻¹ on 21 Apr. 2023 and 17 Apr. 2024.

Sod Harvest Data Collection

Sod was harvested on 14 June, 12 July, and 18 Sept. 2023 for Run 1, and on 11 June, 8 July, and 2 Sept. 2024 for Run 2, and these dates correspond to 9, 10, and 12 months after planting (MAP), respectively. On each sod harvest date, a Turfco KisCutter sod cutter (Model #85530, Turfco Manufacturing, Inc.) cut sod in each plot at the dimensions of 25-cm wide – 70-cm long and ~1.9-cm thickness (sod/soil combination) (Figure 4.1). Sod tensile strength for each sod piece was measured using the same custom-built sod tensile testing device used by Braun et al. (2021a, 2022c), which was a modified version compared to Friell et al. (2017). The sod strength of each sod sample was quantified by mounting and clamping down sod pieces on the device, with each end secured between two plates (30.4 × 30.4 cm area). One clamped-end was fixed, and the other clamped-end allowed to slide freely, which was supported underneath by spherical roller bearings when a mechanical arm (i.e., electric actuator) pulled the motor. Upon activation of the sod device computer (Raspberry Pi 3b single-board computer), a load was applied, and an electric actuator pulled apart the sod piece until it was torn into two cleanly equal separate pieces (Figure 4.1). A load cell (Omega LC703-300, Omega Engineering Inc.) attached

to a motor and connected to a single-board computer provided output of position, load (energy), and a timestamp for each position. The total distance that the sod had been stretched was recorded using a Unimeasure LX-PA-15 string potentiometer (UniMeasure, Inc.). Data was collected using a 24-bit analog-to-digital converter at 4.7 Hz and stored using a Raspberry Pi 3b single-board computer that was also instantly saved on a USB flash drive for easy data retrieval. Maximum tensile load [measured in newtons (N) and plotted by separation displacement in meters] and the area under the load-displacement curve were both recorded and from there, the required work to tear a piece of sod (i.e., force over distance, N-m) was calculated. All data from the USB flash drives were immediately transferred to a computer and uploaded to cloud storage to prevent data loss during and after each sod harvest event.

Ancillary Sod Harvest Data

Additional data collected during each sod harvest included sod handling, turf quality, and soil moisture content. Sod handling, which is a quick method to quantify sod strength in the field, was done by subjectively rating sod on a 1 - 5 scale following the methods of Han (2009), Gopinath et al. (2021), and Braun et al. (2021a). The sod handling scale represents; 1 = poor unacceptable sod handling, breaks or falls apart during handling, 3 = minimally acceptable sod handling with some cracking during handling, and 5 = excellent sod handling with no cracking. Turfgrass quality was rated on a scale of 1 to 9 following industry standard practice and according to Morris et al. (2022), where 1 = poorest quality, 6 = minimally acceptable, and 9 = highest quality according to color, texture, density, and uniformity. Time domain reflectometry (Field Scout TDR 300 Soil Moisture Meter, Spectrum Technologies Inc.) was used to measure volumetric soil water content ($n = 5$ per plot) at a 7.6-cm soil depth to ensure that soil moisture

levels were uniform among plots and to consider any inconsistencies that might influence sod strength and handling.

Field Establishment Vigor

Measurement of establishment speed differences and green vegetation cover commenced 2 weeks after planting (WAP) [Run 1 (9 Sept. 2022) and Run 2 (8 Sept. 2023)]. Measurements continued weekly to every two weeks during each autumn, and monthly the following spring before sod harvests (Figure 4.2). These measurements were done to verify that all plots established properly and that there were no establishment factors that influenced sod strength at future sod harvests. Digital image analysis (0–100% cover) with a custom lightweight lightbox and a digital camera (Nikon Z 30, Nikon Inc.) manually set at ISO-125, f/4.5, exposure time 1/80 sec., 300 dpi, and 5568×3712 pixels], was used to measure green vegetation cover and establishment speed differences among plots (Figure 4.2). Turf Analyzer software (Green 155 Research Services, LLC) with the following threshold settings: hue: 40–170; saturation: 2–100; brightness: 2–100 was used to analyze pixels within digital images to calculate percent green vegetation cover. Green vegetation cover data was fitted into a four-parameter sigmoidal model regression curve using GraphPad Prism (v.10.3, GraphPad Software Inc.) that calculated the number of days to reach 50% and 90% establishment cover after seeding, which corresponds to the output of D_{50} and D_{90} , respectively from GraphPad Prism using Equation (1):

$$y = \text{Bottom} + \frac{\text{Top} - \text{Bottom}}{1 + \left(\frac{EC_z}{x}\right)^{hillslope}} \quad (\text{Eq. 1})$$

where y is percent green vegetation cover, top is the y value at the estimated top plateau, bottom is the y value at the estimated bottom plateau, EC_z is the x value when the response of either days until 50% establishment (D_{50}), which is halfway between top and bottom, and days until 90%

establishment (D_{90}), which is 90% of the top value; and Hillslope (no units) describes the slope of the curve at D_{50} .

Additionally, visual turfgrass cover ratings (0–100%) were measured every 1 to 2 weeks in the autumn until mid-December, then rated again the following spring in April and May. Visual weed cover (0–100%) was also rated in the autumn and spring for winter annual grassy weeds [i.e., annual bluegrass (*Poa annua* L.)].

Germination Vigor

A germination test was conducted for 28 d in a growth chamber (Controlled Environments Ltd., E15) at Kansas State University, Manhattan, KS, starting on 7 May 2022 (Run 1) and 19 June 2023 (Run 2) to observe germination speed differences and overall germination percentage differences of treatments used in both the field and greenhouse experiments. The germination test was conducted following the principles and procedures of the Association of Official Seed Analysts (AOSA, 2016). Before germination tests, seeds were prechilled at 3°C for ≥ 2 months. The growth chamber was set at 25/15 °C (day/night cycle), 8 h day photoperiod, and photosynthetic photon flux of $100 \mu\text{mol m}^{-2} \text{s}^{-1}$ for 28 days (Figure 4.3). Approximately 100 seeds of each cultivar were placed on a piece of blue blotter paper (PBB 325, Hoffman Manufacturing, Inc.) in a 100×15 mm (diameter $\times$ height) Petri dish with lid, replicated 4 times, and then incubated in a growth chamber for 28 d. Petri dishes were arranged by block, randomized daily in the growth chamber, and moistened daily or as needed with KNO_3 water solution at 0.2% (v/v) (Figure 4.3). Seeds were observed daily for germination counts. Germinated seeds with a visible radicle and coleoptile were counted, recorded, and discarded, and the cumulative germination percentage over time of each petri dish was recorded for analysis in GraphPad Prism (v.10.3, GraphPad Software Inc.). Seed germination vigor for each petri dish

was done following similar methods as Braun et al. (2023a) which was calculated from total and cumulative germination percentage over time regressed against days by GraphPad Prism and fitted into a four-parameter sigmoidal regression model as shown in Equation (2):

$$y = \text{Bottom} + \frac{\text{Top} - \text{Bottom}}{1 + \left(\frac{\text{IC}_{50}}{x}\right)^{\text{Hillslope}}} \quad (\text{Eq. 2})$$

where y is percent germination, bottom is the y value at the estimated bottom plateau, top is the y value at the estimated top plateau, IC_{50} is the x value when the response of IC_{50} is halfway between bottom and top (days until 50% germination), and Hillslope (no units) describes the slope of the curve at IC_{50} . Days until 50% germination (IC_{50}) were calculated from the regression curves.

Greenhouse Study

Replicated greenhouse experiments were carried out to examine rhizome production and characteristics of all cultivars tested in the field sod experiment at the Throckmorton Plant Science Center greenhouses at Kansas State University, Manhattan, KS. Run 1 was from 15 June to 26 Sept. 2023 and Run 2 was from 11 Mar. to 22 July 2024. Greenhouse environment settings were 23/18°C day/night and a ~15 hr photoperiod. Environmental sensors (HOBO USB Micro Station Data Logger with Photosynthetic Light (PAR) Smart Sensor, H21-USB, HOBO Data Loggers) were installed to monitor temperature, relative humidity, and photon flux density.

The experimental design was a one-way treatment structure of 12 treatments arranged in a randomized complete-block design, replicated six times (Table 4.3). Treatments were the same as those in the field experiment, except all cultivars were individually grown and analyzed, (i.e., no cultivar blends were used). Each cultivar was seeded in a 10.2 to 15.2 cm greenhouse pot with germination mixture media (BM2, Seed Germination, Berger Peat Moss Ltd.) and placed in a misting room for 2 weeks. After two weeks, one individual plant was transplanted into 37.2 cm²

size containers filled with potting mix (BM6 All Purpose, Berger Peat Moss Ltd.). Plants were then placed in the greenhouse at the settings mentioned above. Irrigation (non-fertilized municipal water) was applied frequently multiple times a day during the first two weeks after transplanting to allow proper rooting. Then irrigation frequency was reduced to application of once every three days throughout the remainder of the study to prevent drought stress. All plants were fertilized at a rate of 49 kg N ha⁻¹ with urea (46-0-0) at 4 weeks after transplanting and again at 7 and 13 weeks after transplanting for a total of 147 kg N ha⁻¹ (Figure 4.4). Mowing with scissors was conducted approximately every 7 days when turfgrass reached a 7.62 cm height and clippings were collected.

Greenhouse Data Collection

Destructive phenotyping measurements at 4.3 months after seeding [19 weeks after planting (17 weeks after transplanting)] were conducted to measure rhizome production and characteristics (Figure 4.4). The methodology was paralleled Saxena et al. (2014), in which harvested plants were washed, bagged, and stored in a cooler for less than 24 hours while all measurements were completed. Rhizome lengths for each plant were measured using a digital caliper (mm). The following measurements were collected; (i) Average rhizome length (Length), which is the mean length of >10 mm rhizomes per container; (ii) Total rhizome length is the summed length of all >10 mm rhizomes per container; (iii) Average number of rhizomes (RN) per container, which is the number of rhizomes per plant (container) that measured >10 mm; (iv) Total aerial tillers (TAT) on rhizomes is the number of aerial shoots counted on >10 mm rhizomes per container; (v) Total number of plant tillers (TNT), which was the number of visible plant tillers per container that includes all tillers, rhizome tillers, and aerial shoots growing from rhizomes (vi) Average number of nodes per rhizome. Additional data collected

was a subjective rating based on all rhizomes produced by the plant, this “rhizome class” (RHC) factored in rhizome widths and lengths and was rated on a scale of 0 to 5 (5 = thickest, most robust, 1 = thinnest, weakest, and 0 = no >10 mm rhizomes present).

Before destructive phenotyping, visual turfgrass cover (0–100%) was rated. Also, digital image analysis of green vegetation cover was measured with the same digital camera, settings, and software but with a different modified lightbox (31 cm × 28 cm). Both visual turfgrass cover and digital images began three weeks after seeding (1 week after transplanting) and continued every week for the first 10 weeks after seeding and then every other week until destructive plant harvests. A non-destructive phenotyping measurement that involves counting visual plant tiller (daughter plants from the same crown) was conducted four weeks after seeding and continued every other week until plant harvest.

Statistical Analysis

Data from all experiment runs were analyzed separately with SAS version 9.4 (SAS Institute Inc.), utilizing the GLIMMIX procedure with block as a random effect. For each experiment and response variable, the effect of the experiment run × treatment was tested to determine if data could be combined across experimental runs. Treatment × run interactions were not significant for both field (sod harvest data) and greenhouse experiments (i.e., rhizome characteristics); therefore, data were combined across runs for each response variable within each experiment. However, treatment × run interactions were significant for the establishment vigor data in the field experiment and the seed germination vigor data in the controlled-environment experiment; therefore, data were not combined across runs and analyzed separately. Residual normality was tested with the *w* statistic of the Shapiro–Wilk test via the UNIVARIATE procedure (Shapiro & Wilk, 1965). Before analyzing Greenhouse studies, raw

data counts from destructive rhizome harvest and rhizome measurements with “0” or “<1” (i.e., rhizomes length, number of nodes, total aerial shoot numbers, and rhizome class) were log and square-root transformed in Microsoft Excel (Microsoft Corporation) for SAS analysis and only log-transformed for correlation analysis in GraphPad Prism. Normality was tested and statistical analysis conducted, and then means were back-transformed for presentation. Means were separated with Fisher’s Least Significant Difference (LSD) test ($\alpha = .05$) when the *F*-tests were significant ($P \leq .05$).

All sigmoidal regression (i.e., D_{50} , D_{90} , and IC_{50}), and correlation analysis between sod harvest data and turf quality was conducted all 12 treatments, all four reps, three harvest timings in each year, and both experiment runs ($n = 288$) using GraphPad Prism. Correlation analysis between greenhouse rhizome measurements and 9-month sod harvest data was conducted to measure the relationship among the seven RTF cultivars only (combining rep 3 & 4 as rep 3; rep 5 & 6 as rep 4) and their corresponding 9 months sod harvest response variables (i.e., required work to tear sod, and maximum tensile load to tear sod, and sod handling) combined across both experiment runs ($n = 28$) using GraphPad Prism.

Results and Discussion

Sod Strength Data

There were minor differences among RTF cultivars with the sod device output data of required work to tear sod (Figure 4.5). The 100% KB sod produced the highest required work to tear sod values at all three sod harvests. The 100% KB sod required more work to tear sod than all of the TF (both bunch-type and RTF) treatments at all sod harvests with only a few exceptions at 12 MAP, these were RTF cultivars ‘Firecracker’ and ‘Regenerate,’ and the 90:10

(TF:KB w/w). The 90:10 TF:KB also produced higher required work to tear sod values at all three sod harvests compared to some, but not all, of the RTF cultivars. The RTF cultivar ‘Nightcrawler’ often produced numerically higher required work to tear sod values compared to a few other RTF cultivars or 100% bunch-type TF blend, but there were only a few instances of statistical differences.

For maximum tensile sod strength, similar trends as required work to tear sod were observed at all sod harvests (Figure 4.5). Like required work to tear sod, there were minimal and inconsistent differences in maximum tensile sod strength among RTF cultivars, and many were similar to the 100% bunch-type TF sod blend. The 100% KB treatment had the highest maximum tensile sod strength at 9 and 10 MAP, but then there were no differences among treatments at 12 MAP (Figures 4.5 and 4.6). This may have been due to typical high summer stress from late July through August in each year that weakened the KB more than the TF and resulted in more variability among treatments, thus less statistical differences (Figure C.1). This was also observed for the required work to tear sod but there were still statistical differences present.

These results agree with Braun et al. (2021a, 2022c), who reported that 100% KB consistently produces high sod strength (i.e., required work to tear sod and maximum tensile load to tear sod) when compared to bunch-type TF sod and RTF in Indiana and Minnesota. In our study, when 100% KB sod produced higher sod strength at 9 and 10 MAP, it was almost double the value of many of the TF treatments. Results verify that without the incorporation of plastic netting or mixing KB seed at planting, 100% TF, regardless of bunch-type or marketed rhizomatous cultivars, will produce weak sod strength compared to KB. One interesting finding was that the bunch-type TF included in mixture ratios of 95:5 and 90:10 (TF: KB w/w) did not

consistently produce similar sod strength compared to the 100% KB blend (Figure 4.5). Braun et al. (2022c) also informed that a 90:10 TF:KB w/w) mixture resulted in lower sod strength values compared to 100% KB sod, and it often had similar sod strength compared to a 100% bunch-type TF or RTF sod.

Sod Handling

Similar to the sod strength output, there were minimal differences among RTF cultivars at the sod harvest timings (Figures 4.6 and 4.7). The 100% KB treatment was in the top sod handling ranking at all three harvests, and this was especially evident at 9 and 10 MAP (Figure 4.7). However, by 12 MAP, the same trend of lower KB values as described above for sod strength output was observed with sod handling (Figures 4.5 and 4.7). Therefore, there were less differences in sod handling at 12 MAP. The RTF cultivars produced similar sod handling as 100% bunch-type TF sod at all three harvests, and there were instances at 12 MAP where the 100% bunch-type TF sod had better sod handling compared to some RTF cultivars. The 100% KB sod always had an average sod handling rating ≥ 3 (minimally acceptable), while all the other treatments, which incorporated TF in the treatment, were often around an average sod handling rating of 3 or even below acceptable levels at some harvest events. Similarly, Braun et al. (2021a, 2022c) reported sod handling ranges of 3.8 to 4.8 for 100% KB sod and 2.3 to 3.8 for any sod that included TF, whether 100% bunch-type TF, 100% RTF, or TF:KB sod mixtures.

When data were analyzed across all treatments and runs ($n = 288$), there were moderate to strong positive relationships between required work to tear sod and max tensile load to tear sod ($r = 0.79$; $P \leq .0001$), between sod handling and required to tear sod ($r = 0.48$; $P \leq .0001$), and between sod handling and max tensile load to tear sod ($r = 0.50$; $P \leq .0001$) (Figure 4.8). These positive relationships agree with Braun et al. (2021a, 2022c), who reported a strong

positive relationship between required work to tear and max tensile strength in different studies ($r = 0.82$; $r = 0.85\text{--}0.86$), and Braun and Patton (2022) ($r = 0.87$) and Friell et al. (2017) ($r = 0.92$). Additionally, past correlation analysis between sod handling and sod strength device output reported similar findings [$r = 0.59$ to 0.69 (Braun & Patton, 2022), $r = 0.28$ to 0.62 (Braun et al., 2021a), $r = 0.58$ to 0.63 (Braun et al., 2022c), $r = 0.92$ (Gopinath et al., 2021)].

Overall, the results indicate that sod handling and sod strength slightly reduced during the summer months, especially in KB. This experiment had successful KB sod harvest as early as 9 MAP, this is similar to the findings Braun et al. (2021a) in sod research at a Minnesota and Indiana site, where the highest required work to tear a sod piece apart was observed at 20 MAP. Similar with the report of Braun et al. (2022c) who reported no decline in sod strength and handling when harvested at 11, 12, 14, 20 and 22 MAP, Friell et al. (2017) in Minnesota, and Griffith et al. (2017) in Wisconsin, have all recommended KB sod production to be ~15 months, and between 12 to 20 months, respectively. The reason for the differences with sod production cycles maybe due to environmental and climate differences in sod production sites in the United States; however, our results demonstrates that a 9-month sod harvest timing or earlier may be achievable in the transitional climatic zone, which has a warmer climate. Further research should investigate early sod harvest timings (<9 months) in combination with mixture ratios and additional cultivars to potentially hasten the sod production for sod growers to be more profitable. Sod producers might want to consider a spring or early-summer sod harvest if using KB in the sod mixture or by itself. This would help with reducing the effects of summer stress and a potential decline in sod strength. It is also important to note that only seven RTF were tested in this experiment due to time and space limitations; however, there are many other commercially available RTF cultivars, and these should be tested to confirm these results.

Volumetric Water Content

Volumetric water content measured with time domain reflectometry at a 7.6 cm soil depth in each plot at each sod harvest timing revealed minimal differences among treatments (Figure 4.9). For Run 1, volumetric water content ranged from 37 to 48% in field plots during the sod harvests, 31 to 44% for Run 2 (Figure 4.9). When statistical differences among treatments occurred in Run 2 at each sod harvest, means only varied by 6% volumetric water content. Overall, data analysis of volumetric water content confirmed little influence on overall sod strength or handling results.

Turf Quality

There were minimal differences for visual turf quality during turfgrass establishment for Run 1 (6 to 8 WAP) and Run 2 (4 to 36 WAP). For both experiment runs, the majority of the treatments had acceptable turf quality (≥ 6 rating) with exceptions in 100% KB blend (≥ 5 rating) at 6 WAP for Run 2. This was likely due to the slower establishment of KB compared to TF. As time and field establishment progressed, turf quality differences diminished, and visual turf quality was near or at the highest level of “9” by 9 through 12 MAP sod harvests (Table 4.4). There were minimal differences in turf quality among treatments during establishment and sod harvests, which correlation analysis revealed turf quality had no influence on sod strength or handling data (Table C.1). Past sod research (Braun et al., 2021a, 2022c; Braun & Patton, 2022; Taylor & Schmidt, 1980) also confirmed that visual turf quality rating does not influence sod strength and handling characteristics, although helps differentiate visual and aboveground functional characteristics.

Establishment Vigor

Data from digital image analysis and four-parameter sigmoidal models revealed differences in field establishment speed among treatments (Table 4.5 and Figure 4.10). For both runs, most RTF cultivars were comparable to one another and ranked in the lowest or second to third lowest D_{50} and D_{90} (i.e., less days to reach 50% or 90% establishment cover) (Table 4.5 and Figure 4.10). If only petri dish data was considered (mentioned below), one might suspect KB to establish as fast as TF; however, the 100% KB blend required the most time to reach 50% establishment cover (i.e., highest D_{50}). This is not surprising and aligns with past reports comparing field establishment speed among these same species (Brede, 2000; Braun et al., 2021a, 2022c; Christians et al., 2017; Reicher, et al., 2000; St. John et al., 2009). Mixture ratios (95:5 and 90:10 TF:KB w/w) were, at times, slower or similar to 100% bunch-type TF or RTF. For example, the mixture ratios of 95:5 and 90:10 (TF:KB) reached 50% establishment between 12 to 15.4 days, which was ~7 to 13 days faster than 100% KB because of the incorporation of faster germinating TF within the mixture. Overall, there were minimal differences between 100% bunch-type TF and RTF, which ranged from 10.8 to 14.7 days among these treatments.

Similar trends were observed for D_{90} , (i.e., days to 90% establishment cover) across treatments (Table 4.5). Most RTF cultivars that reached 50% in fewer days (i.e., low D_{50} value) compared to 100% KB, consistently reached 90% establishment cover between 23.6 to 29 days, including a 100% TF fescue, when compared to 100% KB, which required about 42 days to reach 90% establishment cover (Table 4.5). A similar trend was observed with visual turfgrass rating data (0-100% scale), with 100% KB blend producing the least establishment turf cover (>40 turf cover) between 2 to 8 weeks after planting. However, 100% KB did reach 88% at 11 weeks after planting (Table C.2).

Results suggest that mixtures of TF and KB may slightly enhance establishment speed in the field, comparable to results of Braun et al. (2022c) and Nwachukwu (2025); however, it may be only a benefit one to two weeks sooner to reach 50% or 90% establishment compared to 100% KB. Although one to two weeks may not seem like much difference, the slower establishment period with KB may yield more weed infestation. Moreover, these results also confirm Braun et al. (2022c) and provide more information on establishment speed comparisons between cultivars of both bunch-type TF and RTF. Overall, establishment speed differences were minimal among bunch-type and rhizomatous TF cultivars, which confirm the report by St John et al. (2009), who further reported that non-rhizomatous TF cultivar ‘Kentucky – 31’, had more rapid establishment than those of the RTF cultivars (Grande II, etc.).

Germination Vigor

Output from the four-parameter sigmoidal models for Run 1 and Run 2 indicated statistical differences among treatments with germination speed (i.e., number of days to reach 50% germination, IC_{50}) (Table 4.6; Figures 4.11 and 4.12). Some bunch-type TF and RTF had slower germination speed (i.e., higher IC_{50} values) compared to KB or other TF cultivars. In Run 1 and Run 2, ‘Titanium’ had the fastest germination speed (i.e., lowest IC_{50} value) and reached 50% germination in 5.2 and 5.4 days, respectively, whereas ‘Nightcrawler’ and ‘Turfway’ both required >8 days to reach 50% germination in both experiment runs. Overall, the number of days to 50% germination in both experiment runs ranged from 5.2 to 9.4 days, and many treatments were similar to one another. The greatest difference between treatments was only 4.2 days apart to reach 50% germination (Table 4.6). It was surprising that KB had similar IC_{50} values to many of the TF cultivars. Kentucky bluegrass is known for its slow germination characteristics, which often correspond to slower field establishment (Bremer et al., 2006; Christians et al., 2017;

Fiorio et al., 2012; Reicher et al., 2000). The fast germination speed observed with KB cultivars tested agrees with similar findings reported by Nwachukwu (2025), which confirmed that Legend and Acoustic had a fast germination speed and required fewer days to reach 50% germination compared to many other KB cultivars. Therefore, Legend and Acoustic may be considered faster germinating cultivars, with similar germination speeds as some TF cultivars. If other KB cultivars were included in this experiment, then it is likely they would have seen slower germination speeds with KB cultivars in comparison to TF cultivars. Thus, KB cultivar selection, just like RTF cultivar selection, is important if germination speed is a concern to sod producers.

Other data from this Petri dish experiment included Hillslope, Top (i.e., total germination percentage), and R^2 values from the model output. All of these followed similar trends as the IC_{50} (Table 4.6) The overall germination percentage (Top) shows that all tested cultivars had $\geq 80\%$ germination (Table 4.6) As expected, the Top in the first run was higher compared to the second run, which the seed had been stored longer compared to the first run (Table 4.6). Hillslope which describes the steepness and transition region of the sigmoidal curve at IC_{50} , which revealed slight differences among cultivars with slow and fast germinating cultivars having either high or low hillslope on a range of 3.2 to 6.4 (Table 4.6). Recently, Folck et al. (2023) suggested that we should not rely much on Hillslope as a predictor for germination vigor.

Our results show minimal differences in germination vigor among RTF and Bunch-type TF cultivars. While we did not measure seed morphology characteristics among RTF cultivars and other treatments, past studies (Braun et al., 2023a; Larsen & Andreassen, 2004; Larsen & Bibby, 2004) found no evidence that seed morphology could be a strong predictor for germination vigor (speed of germination).

Overall, some RTF had faster germination vigor across runs compared to a bunch-type TF cultivar, but there was variability among RTF cultivars. For example, while some RTF cultivars had the fast germination vigor, some RTF cultivars also exhibited the slowest germination vigor. Surprisingly, no research has been published on germination vigor and seedling vigor of RTF cultivars. Based on these results, there is a high possibility to help turfgrass breeders in their selection of fast-germinating RTF cultivars, and also to help inform turfgrass practitioners and sod producers in their choice of TF cultivars to improve establishment speed.

Rhizome Production

When tillers and rhizomes were measured in greenhouse experiments among cultivars included in these experiments, data obtained further assisted in explaining sod strength and establishment differences (Table 4.7). Data were combined across runs because there was no treatment by experiment run effects across response variables (Table 4.7). Both the bunch-type and rhizomatous TF cultivars produced a higher number of intravaginal tillers from the plant crown compared to KB cultivars; however, there were minimal differences among TF cultivars (Table 4.7 and C.3; Figures 4.13, 4.14, 4.15, and 4.16). While KB cultivars had less visible intravaginal tillers, there was more extravaginal tillers (i.e., rhizomes) and average rhizome lengths were 79.8 to 103 mm. Kentucky bluegrass rhizomes were longer than RTF cultivars that produced rhizomes and bunch-type TF cultivars, that produced no rhizomes (Figure 4.13, 4.14, 4.15, and 4.16). We observed that the rhizomes produced by RTF cultivars were inconsistent across plants, and when they were present, they were short and very weak (thin) in appearance compared to KB cultivars (Figure 4.13). Four of the RTF cultivars produced no qualifying rhizomes and RTF cultivars that did produce rhizomes had an average length of <3.1 mm (<0.12

inch), which helps provide clarity of the poor sod strength and handling observed in the field study (Figure 4.13 and 4.16). The inconsistent presence of rhizomes in RTF aligns with the findings of St. John et al. (2009), who confirmed that not all plants within the seed lot of RTF produced rhizomes. Furthermore, the average rhizome length of KB cultivars ranged from ~80 to 103 mm (~3.2 to 4 inches), which is >96% greater length in rhizomes compared to RTF cultivars. The average number of rhizomes produced by KB ranged from ~2 to 4 when compared to RTF that were inconsistent and had either 1 or no rhizomes in both experiments run (Table 4.7). Therefore, when summed for all rhizomes present in each container, total rhizome length of KB ranged from ~226 to 298 mm, as compared to RTF cultivars ~1.0 to 3.1 mm (Table 4.7). Consistent trends were observed with the number of nodes and total aerial shoots on rhizomes with rhizome numbers and length (Table 4.7). Our findings further agree with research by St. John et al. (2009), who observed ≤ 2 rhizome numbers with ~22.5 mm (0.89 inch) rhizome length in RTF cultivars ‘Labarinth’ and ‘Torpedo’, as compared to Kentucky bluegrass, > 18 rhizome numbers with 305 mm (12.0 inches) rhizome length each. However, they were 26 mm longer than ‘Kentucky-31’ forage-type tall fescue at 12 months after planting. Similarly, Singh et al. (2005) observed differences with rhizome numbers among 9 RTF cultivars. Singh et al. (2005) reported that 88% Labarinth RTF produced more rhizome length and shoots per rhizome than other RTF cultivars, which only 16 to 33% of each produced rhizome. It is important to note that both RTF studies by Singh et al. (2005) and St John et al. (2009), were measured from 10 to 20 months after planting, as compared to our 4 months after planting, which may suggest that RTF might need more time to produce more rhizomes.

Subjective ratings of “rhizome class” on a scale of 0 to 5 (5= thickest rhizome present, 1= thinnest rhizome present, 0 = no rhizome present), reflect similar trends and the KB rhizome

morphology appeared to be thicker and stronger than RTF cultivars (Table 4.7). Thus, we observed fewer total tillers surrounding the main plant in KB cultivars compared to TF cultivars (Table C.3); however, the KB cultivars were partitioning energy to make extravaginal tillering of underground tillers in the form of more robust and longer rhizomes (Table 4.7). Past research by Saxena et al. (2014) reported a longer photoperiod (18 hr) promotes rhizome production in rhizomatous tall fescue cultivars, but this was not consistent with our results even though our greenhouse environment was set at ~15 hr photoperiod for both runs. In our study with a ~15 hr photoperiod, we did not still observe more or longer rhizome length characteristics among the RTF cultivars. Based on our field and greenhouse data, these longer and thicker rhizomes of KB are the key factors influencing sod strength and handling.

For the seven RTF cultivars across both runs, correlation analysis between greenhouse data (e.g., rhizome class, average rhizome length, rhizome number, total tiller numbers) and 9 months sod harvest data, indicated that no relationship exists between tiller and rhizome measurements and earliest (9 MAP) sod strength data (Figure 4.8).

These findings are consistent with past research by Segars et al. (2020) who reported no correlation between rhizome characteristics and sod tensile strength with ten entries of bermudagrass (*Cynodon dactylon*). For example, they observed no relationship between rhizome strength, rhizome diameter (i.e., size or girth) vs sod strength data ($r^2 = 0.07$; $r^2 = -0.03$). Although, a positive relationship was observed between rhizome dry weight sod strength data ($r^2 = 0.67$). Similarly, Ross et al. (1991) in a KB and TF study, reported that KB cultivars which had smallest root mass (i.e., large number of short, thin roots) produced better sod when compared to others. Similarly, Krans et al. (1992), suggested that differences in rhizome characteristics did not improve sod strength in bermudagrass.

There were slight variations with air temperatures, relative humidity, and daily light integrals in the controlled environment between experiment runs because of the different seasonal timings (Figure C.2 and C.3). Regardless, tiller and rhizome measurements were similar across runs (Table C.3, C.4 and Table 4.7). We suspect one may see similar results when comparing RTF rhizomes to KB rhizomes even though only seven RTF cultivars were evaluated. Results from these greenhouse studies demonstrate that some RTF cultivars produce higher intravaginal tillers and had fast establishment vigor but it did not correspond to high sod strength and handling. Another key takeaway from this research is that “rhizomes” produced by TF should not be considered to have similar rhizome characteristics (length, width, aggressiveness) as KB rhizomes. One area that needs more research is the effect of soil type on rhizome production because Singh et al. (2005) reported greater RTF rhizome production in sandy loam soil compared to the silty clay loam soil of St. John et al. (2009). Therefore, this warrants further research. We suspect that commercially available perennial ryegrass (*Lolium perenne* L.) cultivars now being marketed as “rhizomatous” or “spreading” perennial ryegrass may likely fall within these same limitations as RTF, but research is warranted on this topic. Educators, extension specialists, turfgrass practitioners, sod producers, and seed sales representatives need to understand the dramatic difference in rhizome characteristics of TF and KB, so our expectations align with reality.

Conclusions

Sod tensile device output efficiently quantified sod strength (i.e., required work to tear sod and maximum tensile load to tear sod) differences among treatments. While some RTF cultivars do produce very short rhizomes compared to bunch-type TF and KB, results from these experiments demonstrate that it is not enough to enhance the sod strength and handling or establishment vigor. Thus, RTF and bunch-type TF will have similar sod strength and handling, which is weaker than 100% KB sod at early summer harvest timings. Therefore, RTF cultivars will not produce similar high-quality sod strength and handling when compared to a 100% KB sod, which also produced >96% greater rhizome lengths than RTF cultivars. Moreover, differences observed in intra- and extravaginal plant tiller numbers did not translate to high sod strength and handling. Data from these experiments clearly show that it is more based on rhizome length and thickness.

The four-parameter sigmoidal regression model successfully estimated the number of days until 50% germination and establishment. Rhizomatous TF cultivars had some of the fastest germination speeds (i.e., low IC_{50}) and required ~1 to 2 weeks less to reach 50% establishment cover in the field than 100% KB. There were only 1 to 4 days differences among RTF cultivars, which will help sod growers in their selection criteria in minimizing weed encroachment and N fertilization rate at seeding. However, these faster germinating and establishing TF (both bunch-type TF and RTF) will not enhance sod strength and handing when harvested at 9 through 12 months after planting. Future research should investigate sod harvests at earlier timing of <9 months to see if TF cultivars may have similar or slightly improved sod strength and handling compared to KB because of the faster establishment vigor. Findings also support previous reports of the germination vigor and establishment differences of bunch-type TF and RTF, and this

knowledge will help sod producers and turfgrass practitioners align establishment rate expectations and potential management practices. Additionally, the results reveal that fast germinating cultivars do not consistently correspond to fast field establishment vigor, and the presence of rhizomes in either species do not hasten establishment in the field. More information on both germination and establishment speeds will help sod producers and turfgrass practitioners to select KB and TF cultivars that will hasten establishment and possibly reduce weed infestation challenges and inputs. Also, this research benefits turfgrass plant breeders and provides information on where more research is needed and potential gaps in breeding to discover TF cultivars with better rhizome production compared to the inadequate rhizome characteristics of the cultivars observed in this study. These experiments confirm that 100% RTF and bunch-type TF will not produce high sod quality compared to 100% KB sod but data should encourage sod producers to be more meticulous in cultivar selection and expectations with RTF. Further research is warranted to investigate more RTF cultivars available, improved bunch-type TF cultivars, newly emerging “rhizomatous” “spreading” perennial ryegrass, and mixtures of these cool-season species with Kentucky bluegrass, as well as shorter sod production intervals in different locations within the northern region and transition climatic zone.

References

- Askew, W. B., Goatley, J. M., Jr., Askew, S. D., Hensler, K. L., & McKissack, D. R. (2013). A comparison of turfgrasses for cemeteries and other low-input areas. *International Turfgrass Society Research Journal*, 12, 245–250.
- Association of Official Seed Analysts. (2016). *Principles and Procedures*, 2016 (Volume 1). Washington, DC: Association of Official Seed Analysts, Inc.
- Barnes, M. R., Nelson, K. C., Meyer, A. J., Watkins, E., Bonos, S. A., Horgan, B. P., Meyer, W. A., Murphy, J., & Yue, C. (2018). Public land managers and sustainable urban vegetation: The case of low-input turfgrasses. *Urban Forestry & Urban Greening*, 29, 284–292. <https://doi.org/10.1016/j.ufug.2017.12.008>
- Badra, A., Parent, L. E., Desjardins, Y., Allard, G., & Tremblay, N. (2004). Quantitative and qualitative responses of an established Kentucky bluegrass (*Poa pratensis* L.) turf to N, P, and K additions. *Canadian Journal of Plant Science*, 85, 193–204. <https://doi.org/10.4141/P03-125>
- Beard, J. B., Martin, D. P., & Mercer, F. B. (1980). Investigation of net sod production as a new technique. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference*, Munich, West Germany, 11–13 July 1977 (p. 353–360). Madison, WI: ASA, CSSA, SSSA, and International Turfgrass Society.
- Bouton, J. H., Whitehead, F. C., & De Battista, J. P. (1989). Tall fescue rhizome production as influenced by Bermudagrass competition and cutting frequency. *Agronomy Journal*, 81, 220–223.
- Braun, R. C., Patton, A. J., Watkins, E., Koch, P., Anderson, N. P., Bonos, S. A., & Brilman, L. A. (2020). Fine fescues: A review of the species, their improvement, production,

establishment, and management. *Crop Science*, 60, 1142–1187.

<https://doi.org/10.1002/csc2.20122>

Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021a).

Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: I. Establishment and sod tensile strength. *Agronomy Journal*, 113, 4176–4189. <https://doi.org/10.1002/agj2.20810>

Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2021b).

Investigation of cool-season species, seeding rate, and nitrogen fertilization in sod production: II. Management and shelf life. *Agronomy Journal*. 113, 3460-3474. <https://doi.org/10.1002/agj2.20777>

Braun, R. C., & Patton, A. J. (2022). Species, clover-inclusion, and nitrogen fertilizer effects on sod tensile strength of fine fescue taxa. *Agronomy Journal*, 114, 1705–1716.

<https://doi.org/10.1002/agj2.21039>

Braun, R. C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022a). Review of cool-season turfgrass water use and requirements: I. Evapotranspiration and responses to deficit irrigation. *Crop Science*, 62, 1661–1684. <https://doi.org/10.1002/csc2.20791>

Braun, R. C., Bremer, D. J., Ebdon, J. S., Fry, J. D., & Patton, A. J. (2022b). Review of cool-season turfgrass water use and requirements: II. Responses to drought stress. *Crop Science*, 62, 1685–1701. <https://doi.org/10.1002/csc2.20790>

Braun, R. C., Courtney, L. E., & Patton, A. J. (2023a). Seed morphology, germination, and seedling vigor characteristics of fine fescue taxa and other cool-season turfgrass species. *Crop Science*, 63, 1613–1627. <https://doi.org/10.1002/csc2.20936>

- Braun, R. C., Watkins, E., Hollman, A. B., Mihelich, N. T., & Patton, A. J. (2022c). Management, harvest, and storage characteristics of low-input cool-season turfgrass sod mixtures. *Agronomy Journal*, 114, 1752–1768. <https://doi.org/10.1002/agj2.21051>
- Braun, R. C., Watkins, E., Hollman, A. B., & Patton, A. J. (2023b). Assessing the fertilizer and pesticide input needs of cool-season turfgrass species. *Crop Science*, 63, 3079–3095. <https://doi.org/10.1002/csc2.21046>
- Braun, R. C., Mandal, P., Nwachukwu, E., & Stanton, A. (2024). The role of turfgrasses in environmental protection and their benefits to humans: Thirty years later. *Crop Science*, 64, 2909–2944. <https://doi.org/10.1002/csc2.21383>
- Brede, A. D. (2000). *Turfgrass Maintenance reduction handbook: Sports, lawns, and golf*. Ann Arbor Press, Chelsea, MI, USA.
- Bremer, D. J., Su, K., Keeley, S. J., & Fry, J. D. (2006) Performance in the transition zone of two hybrid bluegrasses compared with Kentucky bluegrass and tall fescue. *Applied Turfgrass Science*. <https://doi.org/10.1094/ATS-2006-0808-02-RS>
- Burns, R. E. (1980). Techniques for rapid sod production. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference*, Munich, West Germany, 11–13 July 1977 (p. 361–366). Madison, WI: ASA, CSSA, SSSA, and International Turfgrass Society.
- Carrow, R. N., & Sills, M. (1980). Tall fescue sod production with plastic netting. *Hortscience*, 15, 818–820.
- Christians, N. E., Patton, A. J., & Law, Q. D. (2017). *Fundamentals of Turfgrass Management* (5th ed.). John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

Cowan, J. R. (1956). Tall fescue. *Advances in Agronomy*, 8, 283–320.

[https://doi.org/10.1016/S0065-2113\(08\)60692-6](https://doi.org/10.1016/S0065-2113(08)60692-6)

DeBels, B. T., Griffith, S. E., Kreuser, W. C., Melby, E. S., & Soldat, D. S. (2012). Evaluation of mowing height and fertilizer application rate on quality and weed abundance of five home lawn grass. *Weed Technology*, 26, 826–831.

De Battista, J. P., & Bouton, J. H. (1990). Greenhouse evaluation of tall fescue genotypes for rhizome production. *Crop Science*, 30, 536–541.

<https://doi.org/10.2135/cropsci1990.0011183X003000030012x>

D' Uva, P. (1982). *Rooted Stem and Rhizome Production of Tall fescue (Festuca arundinacea Shreb.)*. M.S. Thesis. University of Georgia, Athens.

Dunn, J. H., Ervin, E. H., & Fresenburg, B. S. (2002). Turf performance of mixtures and blends of tall fescue, Kentucky bluegrass, and perennial ryegrass. *HortScience*, 37(1), 214–217.

<https://doi.org/10.21273/HORTSCI.37.1.214>

Elias, S. G., Copeland, L. O., McDonald, M. B., & Baalbaki, R. Z. (2012). Speed of Germination and Seedling Growth Rate. *Seed testing: Principles and practices* (pp. 155–192).

Michigan State University Press, East Lansing, MI, USA.

<http://www.jstor.org/stable/10.14321/j.ctt7zt51m>

Friell, J., Watkins, E., Horgan, B. P., & Cavanaugh, M. (2017). Sod strength characteristics of 51 cool-season turfgrass mixtures. *Agronomy Journal*, 109, 1759–1757.

<https://doi.org/10.2134/agronj2016.05.0295>.

Fiorio, S., Macolino, S., & Leinauer, B. (2012). Establishment and performance of bluegrass species and tall fescue under reduced-input maintenance in a temperate Mediterranean environment. *HortTechnology*, 22, 810–816.

- Fry, J., & Huang, B. (2004). *Applied Turfgrass Science and Physiology*. John Wiley and Sons, Hoboken, New Jersey, USA.
- Folck, A. J. (2022). Germination and Growth Rate Differences Among Kentucky Bluegrass Cultivars. M.S. Thesis. Purdue University, *Purdue University Research Repository*.
<https://doi.org/10.25394/PGS.21663398.v2>
- Folck, A. J., Bigelow, C. A., Jiang, Y., & Patton, A. J. (2023). Genotypic variation in germination rate, seedling vigor, and seed phenotype of Kentucky bluegrass cultivars. *Crop Science*, 63, 3065–3078. <https://doi.org/10.1002/csc2.21045>
- Goldsby, A. L., Bremer, D. J., Fry, J. D., & Keeley, S. J. (2015). Response and recovery characteristics of Kentucky bluegrass cultivars to extended drought. *Crop, Forage & Turfgrass Management*, 1–8. <https://doi.org/10.2134/cftm2014.0087>
- Gopinath, L., Martin, D. L., Moss, J. Q., Wu, Y., Yu, S., & Underwood, J. R. (2021). Sod Tensile Strength, Handling Quality, and Their Interrelationship for 39 Bermudagrasses. *HortTechnology*, 31(6), 780–785. <https://doi.org/10.21273/HORTTECH04893-21>
- Griffith, S., Bero, N., Stier, J., Obear, G., Ruis, S., & Soldat, D. (2017). Biosolids as an alternative fertilizer for Kentucky bluegrass sod production in Wisconsin. *Crop Science*, 57, S227–S237. <https://doi.org/10.2135/cropsci2016.05.0367>
- Han, H. R. (2009). *Development Improved Turf-type Bermudagrasses*. Oklahoma State University, Stillwater, master's thesis.
- Harper, J. L. (1961). Approaches to the Study of Plant Competition. In F. L. Milthorpe (Ed.), *Mechanisms in Biological Competition. Symposia of the Society for Experimental Biology*, 15, 1 – 39. Cambridge University Press, Cambridge, England.

- Hugie, K. L., & Watkins, E. (2016). Performance of low-input turfgrass species as affected by mowing and nitrogen fertilization in Minnesota. *HortScience*, 51, 1278–1286.
<https://doi.org/10.21273/HORTSCI11007-16>
- Jiang, Y., & Huang, B. (2001). Physiological responses to heat stress alone or in combination with drought: A comparison between tall fescue and perennial ryegrass. *HortScience*, 36, 682–686. <https://doi.org/10.21273/HORTSCI.36.4.682>
- Karcher, D. E., Richardson, M. D., Hignight, K., & 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>
- Krans, J. V., Philley, H. W., Goatley, J. M., & Tomaso-Peterson, M. (1992). The relationships of rhizome density, sod strength, and spring green-up in bermudagrass. *Agronomy abstract* 84, 172.
- Larsen, S. U., & Andreassen, C. (2004). Comparison of germination criteria in red fescue (*Festuca rubra* ssp. *litoralis*), perennial ryegrass (*Lolium perenne*) and Kentucky bluegrass (*Poa pratensis*). *Seed Science and Technology*, 32, 342–354.
<https://doi.org/10.15258/sst.2004.32.2.07>
- Larsen, S. U., & Bibby, B. M. (2004). Use of germination curves to describe variation in germination characteristics in three turfgrass species. *Crop Science*, 44, 891–899.
<https://doi.org/10.2135/cropsci2004.8910>
- Meyer, M. H., & Pedersen, B. (2000). Low maintenance alternative turf trials. *Journal of Turfgrass Management*, 3, 49–57. https://doi.org/10.1300/J099v03n02_04
- Morris, K. N., Kne, L., Graham, S., & Qu, Y. (2022). An Improved User Interface to Identify Sustainable Turfgrasses within National Turfgrass Evaluation Program Data.

International Turfgrass Society Research Journal, 14, 1035–1041.

<https://doi.org/10.1002/its2.127>.

Nwachukwu, E. U. (2025). *Assessment of Cool-season Turfgrass Sod Production Characteristics of Tall Fescue and Kentucky Bluegrass*. M.S. Thesis. Kansas State University, Manhattan.

Park, B. S., Murphy, J. A., Meyer, W. A., Bonos, S. A., Haan, J. D., Smith, D. A., & Lawson, T. J. (2005). Performance of Kentucky bluegrass within phenotypic classifications as affected by traffic. *International Turfgrass Society Research Journal*, 10, 618–626.

Park, B. S., Lawson, H. S., & Murphy, J. A. (2010). Tolerance and recovery of Kentucky bluegrass subjected to season wear. *Crop Science*, 50, 1527–1536.

<https://doi.org/10.2135/cropsci2009.09.0479>.

Porter, H. L. (1958). Rhizomes in tall fescue. *Agronomy Journal*, 50, 493–494.

Qian, Y. L., Fry, J. D., & Upham, W. S. (1997). Rooting and drought avoidance of warm-season turfgrasses and tall fescue in Kansas. *Crop Science*. 37, 905–910.

<https://doi.org/10.2135/cropsci1997.0011183X003700030034>

Reicher, Z. J., Throssell, C. S., & Weisenberger, D. V. (2000). Date of seeding affects establishment of cool-season turfgrasses. *HortScience*, 35, 1166–1169.

<https://doi.org/10.21273/HORTSCI.35.6.1166>

Richardson, M. D., Karcher, D. E., Hignight K., & Hignight, D. (2012). Irrigation requirements of tall fescue and Kentucky bluegrass cultivars selected under acute drought stress.

Online. *Applied Turfgrass Science*, 9, 1–13. <https://doi.org/10.1094/ATS-2012-0514-01-RS>

- Ross, S. J., Ennos, A. R., & Fitter, A. H. (1991). Turf strength and root characteristics of ten turfgrass cultivars. *Annals of Applied Biology*, 118, 433–443.
<https://doi.org/10.1111/j.1744-7348.1991.tb05644.x>
- Sawhney, J. S. (1965). *The Structure of the Rhizomes of Agropyron repens, beau., Poa pratensis l., and Festuca arundinacea schreb., variety alta*. Ph.D Dissertation, The Ohio State University.
- Saxena, P., Huang, B., Bonos, S. A., & Meyer, W. A. (2014). Photoperiod and temperature effects on rhizome production and tillering rate in tall fescue [*Lolium arundinaceum* (Schreb.) Darby.]. *Crop Science*, 54, 1205–1210.
<https://doi.org/10.2135/cropsci2013.08.0565>
- Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, 52, 591–611. <https://doi.org/10.1093/biomet/52.3-4.591>
- Shearman, R. C., Turner, T. R., Morris, K. N., Gaussoin, R. E., Vaitkus, M. R., & Wit, L. A. (2001). Sod strength and lateral spread of *Poa pratensis* cultivars and experimental lines. *International Turfgrass Society Research Journal*, 9, 928–933.
- Sheffer, K. M., Dunn, J. H., & Minner, D. D. (1987). Summer drought responses and rooting depth of three cool-season turfgrasses. *HortScience* 22, 296–297.
<https://doi.org/10.21273/HORTSCI.22.2.296>
- Singh, D., Klooster, G. V., & Wipff, J. K. (2005). Rhizome formation in tall fescue as affected by location and sampling period. In 2005 *Crop Science abstracts*. CSSA, Madison, WI.
<http://crops.confex.com/crops/2005am/techprogram/P8737.HTM>

- St. John, R., Fry, J., Bremer, D., & Keeley, S. (2009). Establishment rate and lateral spread of *Festuca arundinacea* cultivars. *International Turfgrass Society Research Journal*, 11, 481–487. <http://hdl.handle.net/2097/2072>
- Su, K., Bremer, D. J., Keeley, S. J., & Fry, J. D. (2007). Effects of high temperature and drought on hybrid bluegrass compared with Kentucky bluegrass and tall fescue. *Crop Science*, 47, 2152–2161. <https://doi.org/10.2135/cropsci2006.12.0781>
- Taylor, L. H., & Schmidt, R. E. (1980). Differences in sod strength, rooting, and turfgrass quality of Kentucky bluegrass cultivars resulting from seasonal and environmental conditions. In J. B. Beard (Ed.), *Proceedings of the 3rd International Turfgrass Research Conference, 11–13 July 1977, Munich, West Germany* (pp. 31–38). ASA, CSSA, SSSA, and International Turfgrass Society. <https://doi.org/10.2135/1974.proc3rdintlurfgrass.c4>
- Tegg, R. S., & Lane, P. A. (2004). A comparison of the performance and growth of a range of turfgrass species under shade. *Australian Journal of Experimental Agriculture*, 44(3), 353. <https://doi.org/10.1071/EA02159>
- USDA-NASS. (2012). United States Department of Agriculture Census of Agriculture 2012. <https://www.agcensus.usda.gov/Publications/2012/>
- USDA-NASS. (2016). Quick Stats 2.0. <https://quickstats.nass.usda.gov/>
- Watkins, E., Gardner, D. S., Stier, J. C., Soldat, D. J., St. John, R. A., Christians, N. E., Hathaway, A.D., Diesburg, K. L., Poppe, S. R. & Gaussoin, R. E. (2014). Cultivar performance of low-input turfgrass species for the North Central United States. *Applied Turfgrass Science*, 11, 1–7. <https://doi.org/10.2134/ATS-2013-0101-RS>

Yue, C., Wang, J., Watkins, E., Bonos, S., Nelson, K., Murphy, J. A., ...Horgan, B. (2017).

Consumer preferences for information sources of turfgrass products and lawn care.

Agronomy Journal, 109, 1726–1733. <https://doi.org/10.2134/agronj2016.05.0310>



Figure 4.1. Cutting sod (left), Kentucky bluegrass sod piece (middle), and piece of torn sod from the sod tensile device (right) at the Rocky Ford Turfgrass Research Center, Manhattan, KS. Left and right photo by Ross Braun, middle photo by Emmanuel Nwachukwu.



Figure 4.2. Measuring establishment speed differences at 39 WAP using a digital image analysis and light box (Z30 camera attached) (top); Turf quality rating 8 WAP (1-9 scale; 9=best turfgrass quality) (bottom). Both photos by Ross Braun.



Figure 4.3. Growth chamber (left); Peter dishes in growth chamber randomized daily for 28 days (middle); Seeds with visible structures of radicle and coleoptile counted as germinated seed (right). Left and middle photo by Emmanuel Nwachukwu, right photo by Parul Mandal.



Figure 4.4. Fertilizing treatments in containers placed in greenhouse (left); Destructive phenotyping harvest of Kentucky bluegrass included in the treatments ready to wash rhizomes (middle); Measurement of Kentucky bluegrass rhizomes destructive harvest using digital caliper (right). Left and right photo by Parul Mandal, middle photo by Emmanuel Nwachukwu.

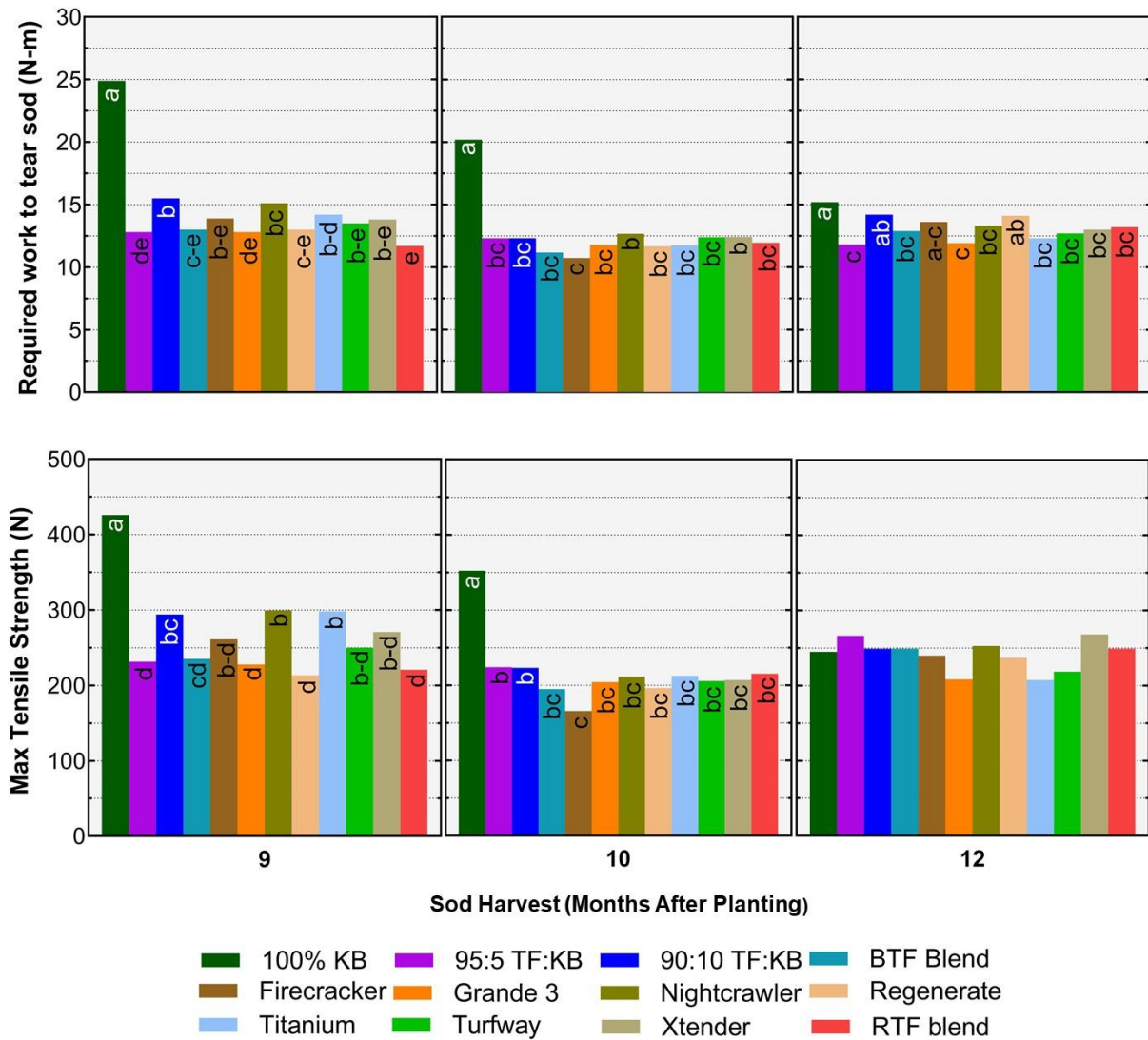


Figure 4.5. Influence of rhizomatous tall fescue main effect on required work to tear sod (newton-meters, N-m) and maximum tensile load (newtons, N) to tear sod at sod harvest timings in Manhattan, KS. Acoustic and legend, Kentucky bluegrass cultivars (KB) included in a 100% blend at 50% each by weight (100% KB); BTF Blend, bunch-type tall fescue 100% blend of Supersonic, Reflection, Houndog 6 at 33% by weight each; 95:5 TF:KB, 95% BTF in 5% seed mixture with KB (Legend and Acoustic); 90:10 TF:KB of similar TF and KB cultivars; Rhizo blend, Rhizomatous tall fescue (TF) blend of Xtender, Grande 3, Titanium. Within each response variable, means within a sod harvest timing at each site with a common letter are not significantly different according to Fisher's LSD Test ($\alpha = .05$).



Figure 4.6. Kentucky bluegrass (left), Rhizomatous tall fescue (middle), and 100% bunch-type (right) sod harvested in June (9 months after planting) ready quantify sod strength using the sod tensile device in Manhattan, KS. Photo by Emmanuel Nwachukwu.

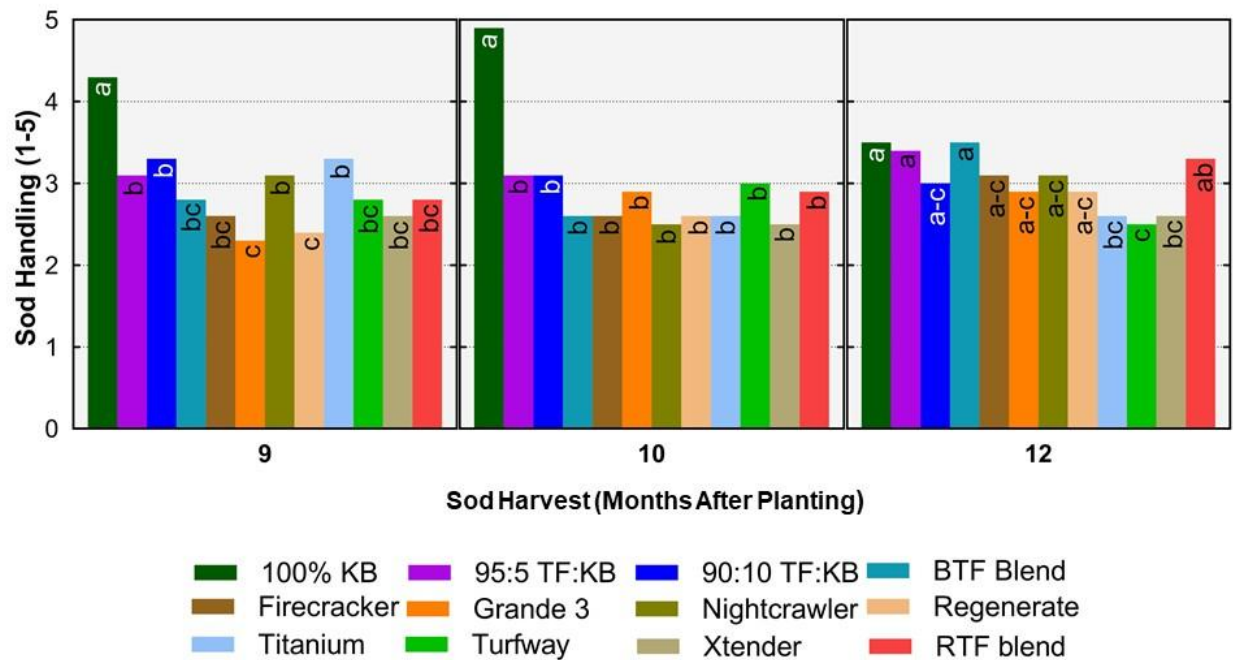


Figure 4.7. Influence of rhizomatous tall fescue main effect on sod handling (scale 1-5) at sod harvest timings in Manhattan, KS. Acoustic and legend, Kentucky bluegrass cultivars (KB) included in a 100% blend at 50% each by weight (100% KB); BTF Blend, bunch-type tall fescue 100% blend of Supersonic, Reflection, Houndog 6 at 33% by weight each; 95:5 TF:KB, 95% BTF in 5% seed mixture with KB (Legend and Acoustic); 90:10 TF:KB of similar TF and KB cultivars; Rhizo blend, Rhizomatous tall fescue (TF) blend of Xtender, Grande 3, Titanium. Within each response variable, means within a sod harvest timing at each site with a common letter are not significantly different according to Fisher's LSD test ($\alpha = .05$).

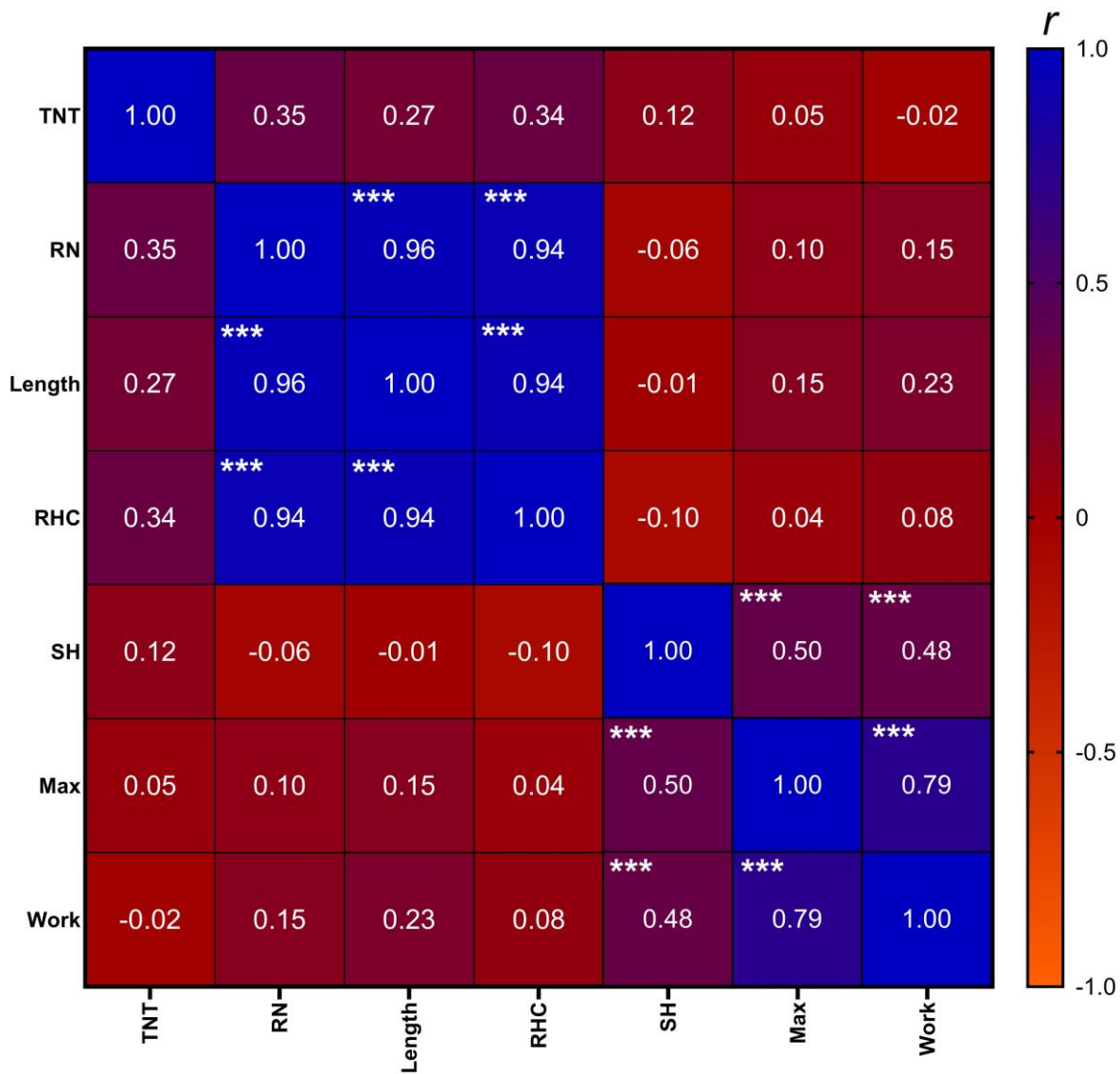


Figure 4.8. Correlation (r) is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Correlation analysis between sod strength data [i.e., required to tear (WORK), maximum tensile load to tear sod (MAX) and sod handling (SH)] was conducted across all treatments, reps, three sod harvest timings (i.e., 9, 10, and 12 months), and both experiment runs ($12 \times 4 \times 3 \times 2$; $n = 288$). Correlation analysis between rhizomatous tall fescue greenhouse data [e.g., Rhizome class (RHC), average rhizome length (Length), average number of rhizome (>10 mm) per plant (RN), and total number of tillers per plant (total plant and rhizome tillers, TNT)] harvested at 4.3 months after seeding and rhizomatous tall fescue sod strength data harvested at 9 months after planting. Experiment runs for greenhouse data and 9 month sod harvest data were combined, before running a correlation analysis. The sample size for greenhouse data and sod strength is $n = 28$ (7 treatments $\times$ 4 reps). *Note:* P -value = no asterisk = not significant, * = 0.05, ** = 0.01, *** = <0.001 , represents significance levels.

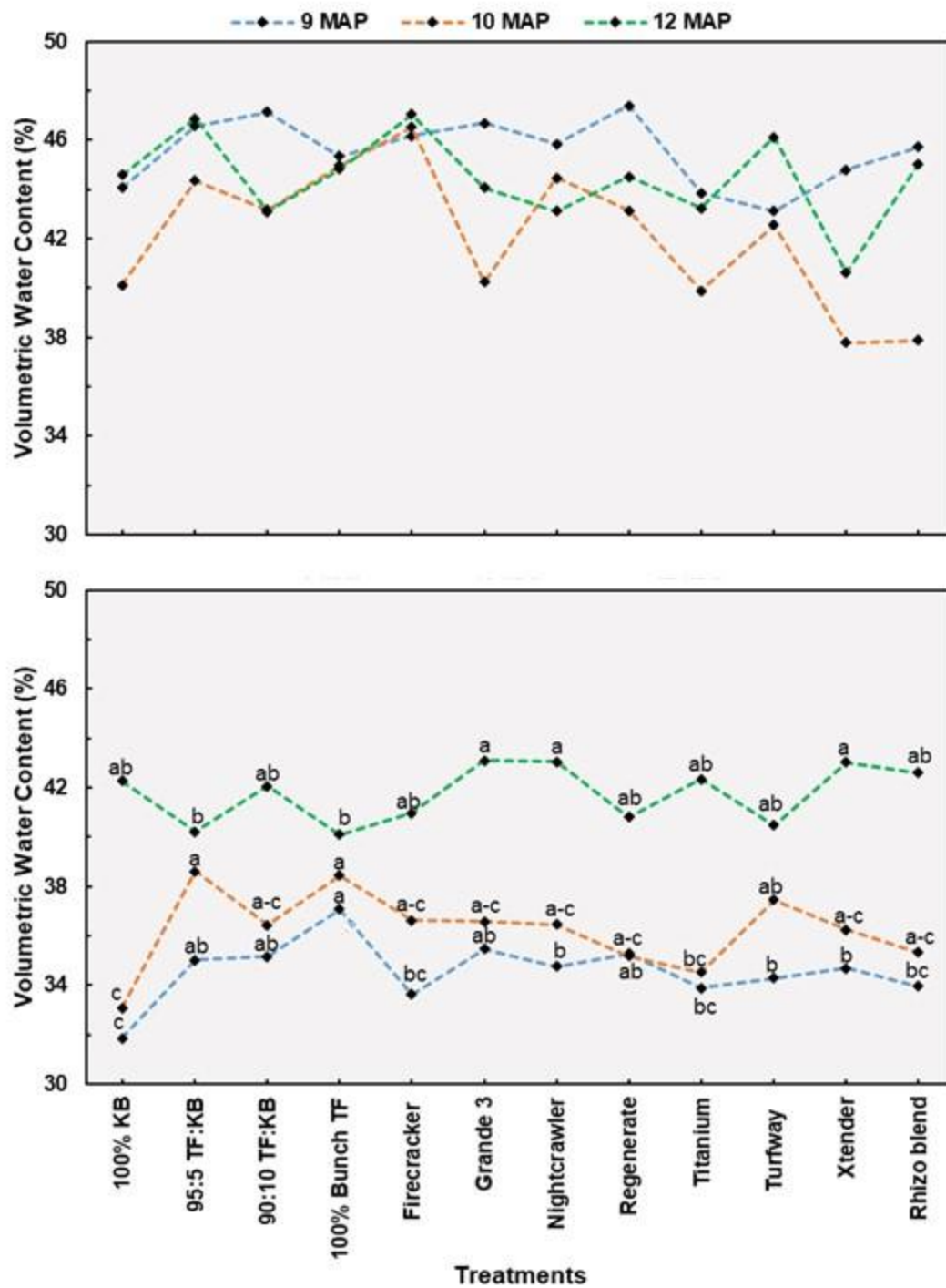


Figure 4.9. Volumetric water content (%) at a 7.6 cm soil depth of plots at each sod harvest event, Run 1 (top) and Run 2 (bottom). Means within a sod harvest within a year with a common letter or no letters are not significantly different according to Fisher's LSD test ($\alpha = .05$).

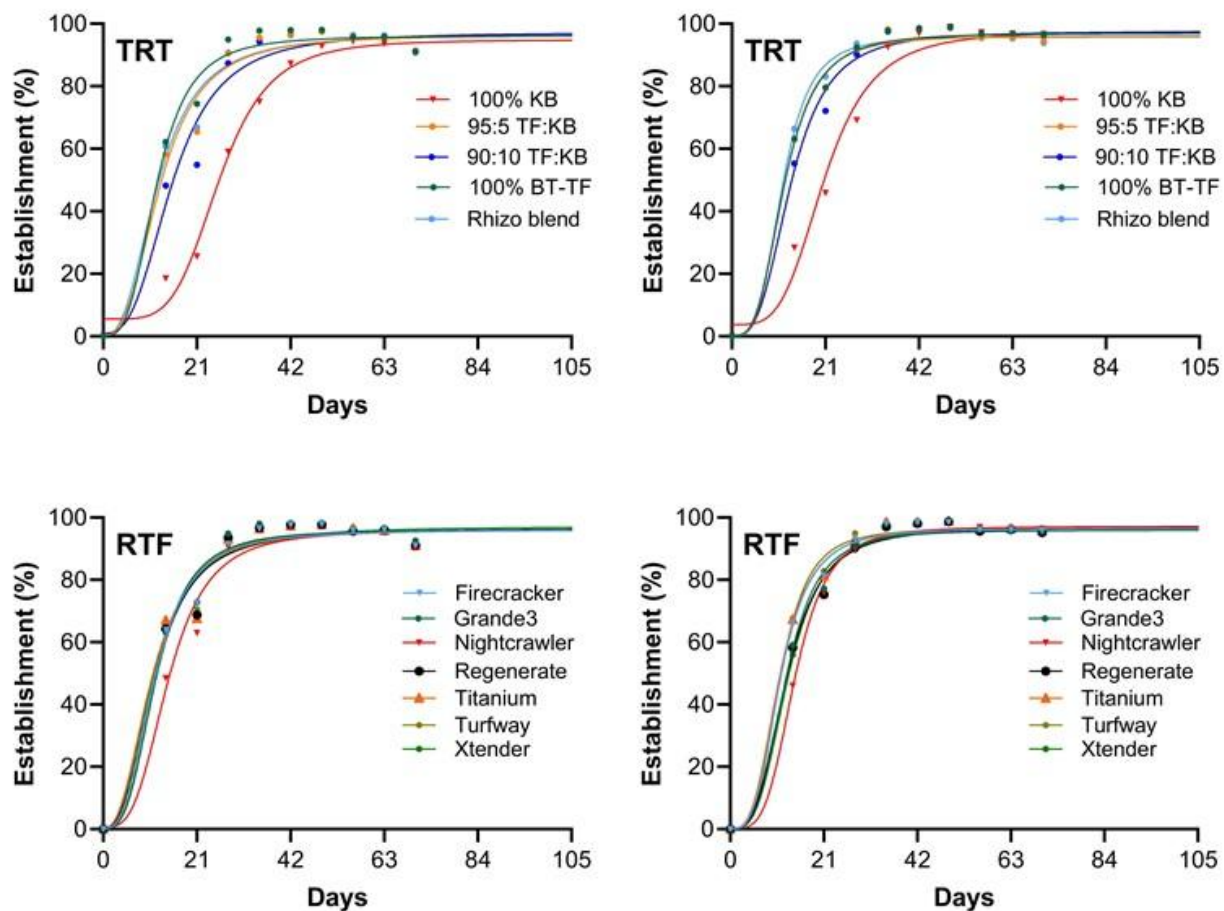


Figure 4.10. Four-parameter sigmoidal regression model for each treatment for experimental Run 1 (left) and Run 2 (right). 100% KB, 100% Kentucky bluegrass blend of Acoustic and Legend Kentucky bluegrass; 95:5 TF:KB; 90:10 TF:KB; Rhizo blend, Rhizomatous tall fescue (TF) blend of Xtender, Grande 3, Titanium; 100% BT-TF, 100% bunch-type tall fescue blend of Supersonic, Reflection, Houndog 6; and all other individual cultivar treatments are rhizomatous tall fescue cultivar.

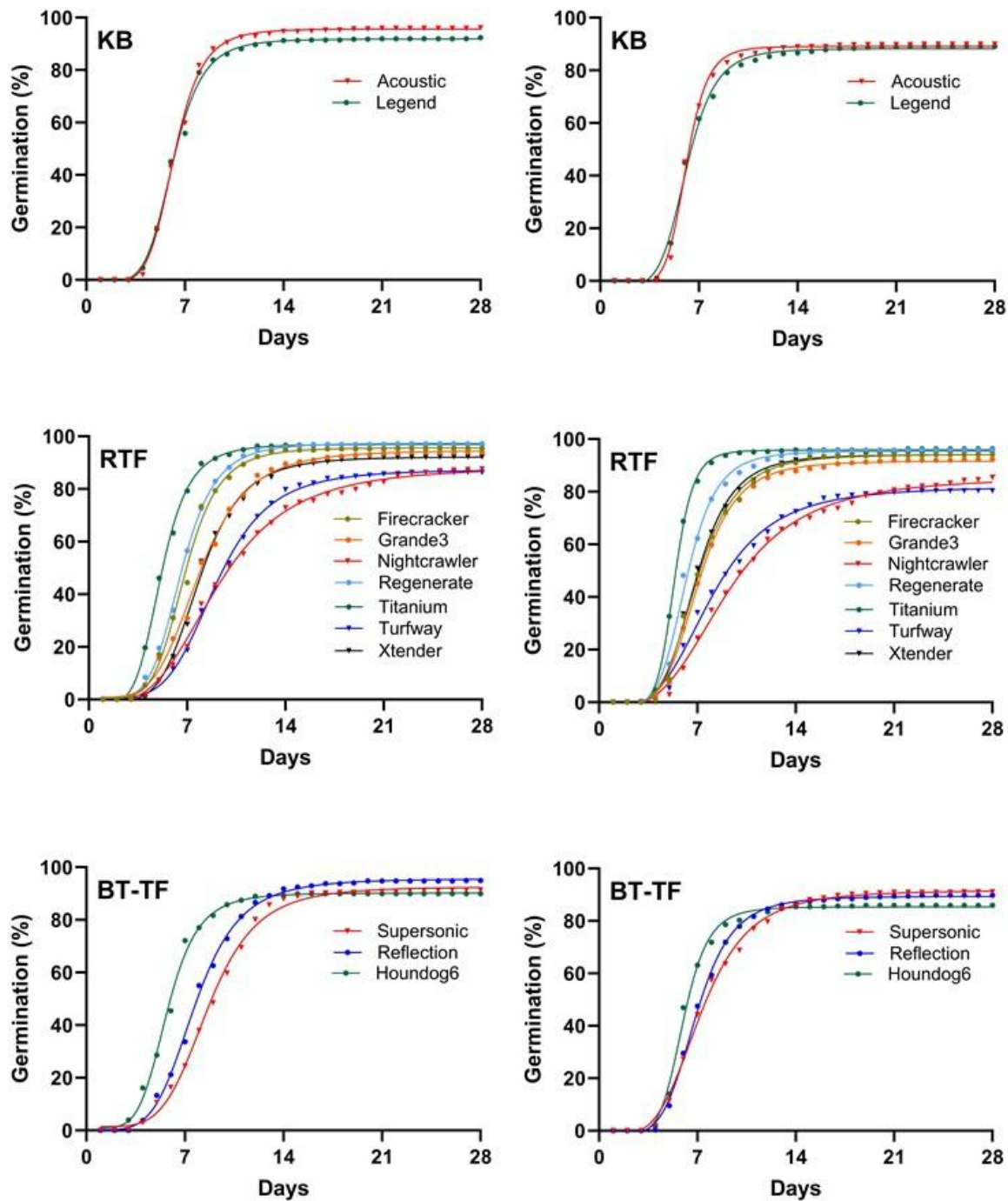


Figure 4.11. Four-parameter sigmoidal regression model output from GraphPad prism for each cultivar within each cool-season turfgrass species for experimental Run 1 (left) and Run 2 (right). KB, Kentucky bluegrass cultivars Acoustic and Legend; RTF, Rhizomatous tall fescue; BT-TF, Bunch-type tall fescue. Regression line with the steepest slopes and lowest IC_{50} value indicates faster germination.

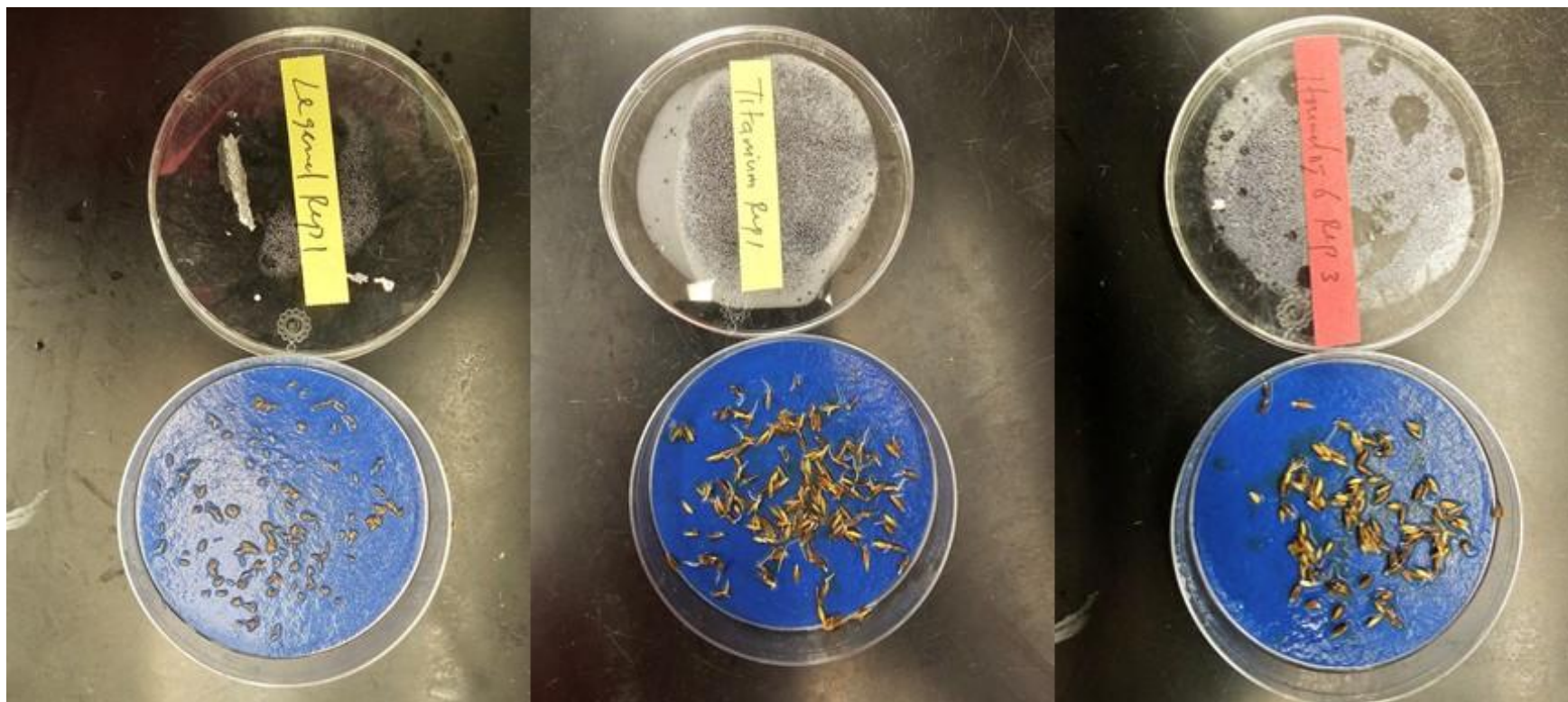


Figure 4.12. Seeds with visible structures of radicle and coleoptile counted at day 5 as germinated seeds in run 2. Kentucky bluegrass (right), Rhizomatous tall fescue (middle), and Bunch-type tall fescue (left). Photo by Emmanuel Nwachukwu.



Figure 4.13. Rhizomatous tall fescue cultivar harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.



Figure 4.14. Rhizomatous tall fescue cultivar (Firecracker) harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.



Figure 4.15. Bunch-type tall fescue cultivar (Supersonic) harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.



Figure 4.16. Kentucky bluegrass (Acoustic) harvested at 4.3 months after planting in the greenhouse for visual tiller count and rhizome measurement. Photo by Emmanuel Nwachukwu.

Table 4.1. Cultivars that were included in the experiment.

Species	Common name	Cultivar	Growth habit	Company
<i>Poa pratensis</i>	Kentucky bluegrass	Acoustic	Rhizomatous	Mountain View Seed Co.
<i>Poa pratensis</i>	Kentucky bluegrass	Legend	Rhizomatous	Mountain View Seed Co.
<i>Festuca arundinacea</i>	Tall fescue	Hounddog 6	Bunch-type	DLF Pickseed
<i>Festuca arundinacea</i>	Tall fescue	Reflection	Bunch-type	Landmark Seed Co.
<i>Festuca arundinacea</i>	Tall fescue	Supersonic	Bunch-type	Mountain View Seed Co.
<i>Festuca arundinacea</i>	Tall fescue	Firecracker GLS	Rhizomatous	Mountain View Seed Co.
<i>Festuca arundinacea</i>	Tall fescue	Grande 3	Rhizomatous	DLF Pickseed
<i>Festuca arundinacea</i>	Tall fescue	Nightcrawler	Rhizomatous	DLF Pickseed
<i>Festuca arundinacea</i>	Tall fescue	Regenerate	Rhizomatous	Landmark Seed Co.
<i>Festuca arundinacea</i>	Tall fescue	Titanium GLS	Rhizomatous	Mountain View Seed Co.
<i>Festuca arundinacea</i>	Tall fescue	Turfway	Rhizomatous	DLF Pickseed
<i>Festuca arundinacea</i>	Tall fescue	Xtender	Rhizomatous	Landmark Seed Co.

Table 4.2. Treatments and seeding rates in Run 2.

Treatments	Cultivar seeding rate	Cultivar seeding rate
	----- g m ⁻² -----	----- lb 1000 ft ⁻² -----
100% KB blend	Legend (3.9) Acoustic (3.9)	Legend (0.8) Acoustic (0.8)
95:5 TF:KB	Supersonic (12.1), Reflection (12.1), Houndog 6 (11.7):Legend (0.9) and Acoustic (0.9)	Supersonic (2.5), Reflection (2.5), Houndog 6 2.4):Legend (0.2) and Acoustic (0.2)
90:10 TF:KB	Supersonic (9.4), Reflection (9.4), Houndog 6 (9.4):Legend (1.6) and Acoustic (1.6)	Supersonic (1.9), Reflection (1.9), Houndog 6 (1.9):Legend (0.3) and Acoustic (0.3)
100% Bunch TF	Supersonic (16.2), Reflection (15.7), Houndog 6 (15.7)	Supersonic (3.3), Reflection (3.2), Houndog 6 (3.2)
Rhizomatous TF	Firecracker GLS (45.5)	Firecracker GLS (9.3)
Rhizomatous TF	Grande 3 (55.5)	Grande 3 (11.4)
Rhizomatous TF	Nightcrawler (57.2)	Nightcrawler (11.7)
Rhizomatous TF	Regenerate (47.8)	Regenerate (9.8)
Rhizomatous TF	Titanium GLS (37.7)	Titanium GLS (7.7)
Rhizomatous TF	Turfway (52.1)	Turfway (10.7)
Rhizomatous TF	Xtender (47.9)	Xtender (9.8)
Rhizomatous blend	Xtender (17.4), Grande 3 (14.3), Titanium GLS (14.3)	Xtender (3.6), Grande 3 (2.9), Titanium GLS (2.9)

Note: Run 1 seeding rates are not shown but were equivalent or the seeding weights were an average 3% lower than Run 2 rates due to higher germination percentage of seed in Run 1. All plots were seeded at a total rate of 2 pure live seed (PLS) cm⁻² including mixture ratios and RTF blend percentages. Pure live seed was calculated based on the methods of standard principles and procedures of the Association of Official Seed Analysts (Association of Official Seed Analysts, 2016) from seed lot purities, thousand-seed weight counts, and controlled-environment germination tests for each year.

Table 4.3. Turfgrass quality rating of experiment treatments during establishment and the following spring for both runs.

Treatment	Cultivar	Run 1			Run 2					
		Weeks After Planting			Weeks After Planting					
		6	8	10	4	6	8	10	12	36
		----- 1 to 9 scale ^a -----			----- 1 to 9 scale -----					
100% KB blend	(A + L) ^b	5.5 d	6.3 b	9.0	6.3 d	6.3 d	6.5 c	7.5 b	7.8 b	8.5 b
95:5 TF:KB	(S + R + H) (A + L) ^{bc}	7.8 c	8.8 a	9.0	7.0 cd	9.0 a	9.0 a	9.0 a	9.0 a	9.0 a
90:10 TF:KB	(S + R + H) (A + L)	8.0 bc	9.0 a	9.0	7.0 cd	8.0 c	8.8 ab	9.0 a	9.0 a	9.0 a
100% Bunch TF	(S + R + H) ^c	9.0 a	9.0 a	9.0	7.3 bc	8.5 abc	8.8 ab	9.0 a	9.0 a	9.0 a
Firecracker GLS	Rhizomatous TF	8.8 ab	9.0 a	9.0	7.8 abc	8.8 ab	8.5 ab	8.8 a	9.0 a	9.0 a
Grande 3	Rhizomatous TF	9.0 a	9.0 a	9.0	8.0 ab	8.8 ab	8.5 ab	8.5 a	9.0 a	9.0 a
Nightcrawler	Rhizomatous TF	8.3 abc	8.8 a	9.0	7.3 bc	8.5 abc	8.5 ab	8.8 a	9.0 a	9.0 a
Regenerate	Rhizomatous TF	8.8 ab	9.0 a	9.0	7.0 cd	8.5 abc	8.5 ab	9.0 a	9.0 a	9.0 a
Titanium	Rhizomatous TF	8.8 ab	9.0 a	9.0	8.3 a	8.8 ab	8.5 ab	8.5 a	9.0 a	9.0 a
Turfway	Rhizomatous TF	8.8 ab	9.0 a	9.0	8.0 ab	8.8 ab	9.0 a	9.0 a	9.0 a	9.0 a
Xtender	Rhizomatous TF	8.5 abc	9.0 a	9.0	7.3 bc	8.3 bc	8.3 b	9.0 a	9.0 a	9.0 a
Rhizomatous blend	(Xtender, Grande 3, Titanium)	8.3 abc	8.8 a	9.0	7.8 abc	8.8 ab	8.8 ab	9.0 a	9.0 a	9.0 a
Legend		<0.0001	<0.0001	1.000	0.0023	<0.0001	<0.0001	0.0004	<0.0001	0.0071

^a Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) for each month during the turfgrass establishment.

^b Supersonic (S), Reflection (R), Houndog 6 (H), are the bunch-type tall fescue cultivars included a 100% blend at 33% by weight each.

^c Acoustic (A) and legend (L), Kentucky bluegrass cultivars included in a 100% blend at 50% each by weight.

Note: Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha < 0.05$).

Table 4.4. Turfgrass quality ratings of experiment treatments in the field for both experiment runs at each sod harvest timing.

Treatment	Cultivar	Run 1			Run 2		
		Months After Planting			Months After Planting		
		9	10	12	9	10	12
		----- 1 to 9 scale ^a -----			----- 1 to 9 scale -----		
100% KB blend	(A + L) ^c	9.0	9.0	8.5	9.0	9.0	9.0
95:5 TF:KB	(S + R + H) (A + L) ^{bc}	9.0	9.0	9.0	9.0	8.8	9.0
90:10 TF:KB	(S + R + H) (A + L)	9.0	9.0	9.0	9.0	8.8	9.0
100% Bunch TF	(S + R + H) ^b	9.0	9.0	9.0	9.0	8.3	9.0
Firecracker GLS	Rhizomatous TF	9.0	9.0	9.0	9.0	9.0	9.0
Grande 3	Rhizomatous TF	9.0	9.0	9.0	9.0	8.8	9.0
Nightcrawler	Rhizomatous TF	9.0	9.0	9.0	9.0	8.5	9.0
Regenerate	Rhizomatous TF	9.0	9.0	9.0	9.0	8.8	9.0
Titanium	Rhizomatous TF	9.0	9.0	9.0	9.0	9.0	9.0
Turfway	Rhizomatous TF	9.0	9.0	9.0	9.0	8.8	9.0
Xtender	Rhizomatous TF	9.0	9.0	9.0	9.0	9.0	9.0
Rhizomatous blend	(Xtender, Grande 3, Titanium)	9.0	9.0	8.8	9.0	9.0	9.0
<i>P-value</i>		1.000	1.000	0.0630	1.000	0.1689	1.000

^a Turf quality visually rated on a scale of 1 to 9 (1= poorest turf quality, 6 = minimally turf acceptable, and 9 = highest turf quality according to color, texture, density, and uniformity) for each month during sod harvest dates.

^b Supersonic (S), Reflection (R), Houndog 6 (H), are the bunch-type tall fescue cultivars included a 100% blend at 33% by weight each.

^c Acoustic (A) and legend (L), Kentucky bluegrass cultivars included in a 100% blend at 50% each by weight.

Note: Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha < 0.05$).

Table 4.5. Field establishment speed differences of treatments.

Treatment	Cultivar	D ₅₀ ^a (days)	D ₉₀ ^b (days)	Top ^a (%)	Hillslope ^a	R ^{2a}	D ₅₀ (days)	D ₉₀ (days)	Top (%)	Hillslope	R ²
100% KB blend	(A + L) ^c	26.1 a	41.9 a	94.7	4.7 a	0.9787	20.9 a	36.8 a	97.5 a	3.9	0.9700 d
95:5 TF:KB	(S + R + H) (A + L) ^{cd}	13.1 cd	28.6 bcd	95.2	3.1 bcd	0.9627	12.0 cde	22.7 cde	95.8 cde	3.7	0.9830 bc
90:10 TF:KB	(S + R + H) (A + L)	15.4 b	33.3 b	96.3	3.0 bcd	0.9587	13.3 bc	27.0 b	97.3 a	3.2	0.9835 abc
100% Bunch TF	(S + R + H) ^d	11.9 de	23.9 de	95.0	3.5 b	0.9727	11.8 cde	23.0 cde	96.7 abc	3.4	0.9872 ab
Firecracker	Rhizomatous TF	11.5 de	24.8 cde	95.1	3.0 bcd	0.9740	11.3 e	23.5 bce	96.3 b-e	3.4	0.9862 ab
Grande 3	Rhizomatous TF	11.8 de	23.6 e	95.0	3.4 b	0.9657	12.5 cde	21.7 de	95.7 de	3.6	0.9777 c
Nightcrawler	Rhizomatous TF	14.7 bc	28.8 bc	94.9	3.4 bc	0.9682	14.6 b	25.5 bcd	96.9 ab	4.2	0.9895 ab
Regenerate	Rhizomatous TF	11.8 de	26.2 cde	95.2	3.1 bcd	0.9600	12.6 cde	25.9 bc	96.7 abc	3.1	0.9865 ab
Titanium	Rhizomatous TF	10.8 e	25.9 cde	95.2	2.7 d	0.9587	11.3 e	22.0 de	96.7 a-d	3.3	0.9877 ab
Turfway	Rhizomatous TF	11.8 de	24.6 cde	94.9	3.2 bcd	0.9600	11.1 e	20.7 e	96.2 b-e	3.8	0.9827 bc
Xtender	Rhizomatous TF	11.2 e	26.6 cde	96.1	2.7 cd	0.9583	13.1 cd	25.0 bcd	96.8 abc	3.5	0.9900 a
Rhizomatous blend	(Xtender, Grande 3, Titanium)	12.4 de	28.3 cde	95.5	2.9 cd	0.9677	11.5 de	20.6 e	95.7 e	3.9	0.9840 abc
<i>P-value</i>		<0.0001	<0.0001	0.2006	<0.0001	0.1543	<0.0001	<0.0001	0.0059	0.1616	<0.0001

^a Four-parameter sigmoidal regression model indicating days required to reach 50% green vegetation establishment cover in the field (D₅₀), and corresponding Top (mean germination percentage), Hillslope (steepness of the germination curves), and R² which ranged from 0.95 to 98 in Run 1, and 0.98 to 0.99 in Run 2 experiments.

^b D₉₀, days required to reach 90% green vegetation cover in the field.

^c Acoustic (A) and legend (L), Kentucky bluegrass cultivars included in a 100% blend at 50% each by weight.

^d Supersonic (S), Reflection (R), Houndog 6 (H), are the bunch-type tall fescue cultivars included a 100% blend at 33% by weight each.

Note: Means within each column followed by the same letter or no letter are not different according to Fisher's protected least significant difference test ($p \leq 0.05$).

Table 4.6. Germination speed differences of treatments in a controlled-environment.

Treatment	Cultivar	Run 1				Run 2			
		IC ₅₀ ^a (days)	Top (%)	Hillslope	R ²	IC ₅₀ (days)	Top (%)	Hillslope	R ²
Acoustic	Kentucky bluegrass	6.3 d	95.6 abc	6.4 a	0.9983	6.1 d	89.2 cd	8.8 a	0.9978
Legend	Kentucky bluegrass	6.2 d	91.8 cd	6.2 ab	0.9955	6.2 d	88.2 cd	6.1 cd	0.9960
Supersonic	Bunch-type TF ^b	8.7 ab	92.5 bcd	5.1 cd	0.9965	7.2 c	91.6 abc	4.3 efg	0.9965
Reflection	Bunch-type TF	7.8 bc	95.6 abc	5.1 cd	0.9983	6.9 c	89.4 bcd	5.4 de	0.9972
Houndog	Bunch-type TF	6.8 d	90.2 de	6.3 a	0.9973	6.0 de	85.3 de	7.2 bc	0.9960
Firecracker	Rhizomatous TF ^b	6.9 cd	95.8 ab	5.9 abc	0.9965	7.0 c	94.1 ab	5.2 def	0.9970
Grande 3	Rhizomatous TF	7.9 b	94.7 abc	4.7 de	0.9973	7.1 c	91.8 abc	5.3 de	0.9978
Nightcrawler	Rhizomatous TF	9.4 a	88.6 de	3.9 e	0.9960	9.2 a	85.8 de	3.4 g	0.9945
Regenerate	Rhizomatous TF	6.7 d	97.5 a	5.9 abc	0.9983	6.2 d	95.4 a	5.9 cd	0.9962
Titanium	Rhizomatous TF	5.2 e	97.0 a	5.2 bcd	0.9983	5.4 e	95.9 a	8.7 ab	0.9993
Turfway	Rhizomatous TF	9.1 a	87.2 e	5.2 cd	0.9983	8.0 b	81.9 e	3.8 fg	0.9938
Xtender	Rhizomatous TF	7.9 b	92.3 b-d	5.5 a-d	0.9978	7.0 c	94.3 a	5.7 de	0.9973
<i>P-value</i>		<0.0001	<0.0001	0.0002	0.1322	<0.0001	<0.0001	<0.0001	0.1522

^a Four-parameter sigmoidal regression model showing days required to reach 50% germination (IC₅₀) in petri dish.

^b Bunch-type and rhizomatous tall fescue cultivars

Note: Means across cultivars within each response variable followed by the same letter or no letter are not different according to Fisher's protected least significant difference test ($p \leq 0.05$).

Table 4.7. Greenhouse experiment treatments and rhizome production and growth differences across both experiment runs.

Treatment	Cultivar	Average Number of Plant Tillers ^{ab} #	Average Number of Rhizomes ^b #	Average Rhizome Length ^c mm	Total Rhizome Length ^c mm	Average Number of Nodes Per Rhizome ^c #	Total Aerial Shoots on Rhizomes ^c #	Rhizome Class ^d 0 to 5
Acoustic	Kentucky bluegrass	14.8 f	3.6 a	79.8 a	298.0 a	5.4 b	3.3 a	2.3 a
Legend	Kentucky bluegrass	8.8 g	1.8 b	103.0 a	225.7 a	7.4 a	1.5 b	2.2 a
Supersonic	Bunch-type TF	27.8 abc	0.0 c	0.0 b	0.0 b	0.0 c	0.0 c	0.0 b
Reflection	Bunch-type TF	27.3 abc	0.0 c	0.0 b	0.0 b	0.0 c	0.0 c	0.0 b
Houndog 6	Bunch-type TF	19.9 def	0.0 c	0.0 b	0.0 b	0.0 c	0.0 c	0.0 b
Firecracker GLS	Rhizomatous TF	31.9 a	0.2 c	2.0 b	2.0 b	0.0 c	0.2 c	0.3 b
Grande 3	Rhizomatous TF	24.4 bcd	0.0 c	0.0 b	0.0 b	0.0 c	0.0 c	0.0 b
Nightcrawler	Rhizomatous TF	23.8 b-e	0.2 c	3.1 b	3.1 b	0.0 c	0.2 c	0.3 b
Regenerate	Rhizomatous TF	29.4 ab	0.0 c	2.5 b	2.5 b	0.0 c	0.2 c	0.3 b
Titanium GLS	Rhizomatous TF	26.8 a-d	0.0 c	0.0 b	0.0 b	0.0 c	0.0 c	0.0 b
Turfway	Rhizomatous TF	18.1 ef	0.1 c	1.0 b	1.0 b	0.0 c	0.1 c	0.1 b
Xtender	Rhizomatous TF	21.5 cde	0.0 c	0.0 b	0.0 b	0.0 c	0.0 c	0.0 b
<i>P-value</i>		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^a Total Number of Plant Tillers is the number of visible plant tillers, rhizome tillers, and aerial shoots growing from rhizomes per container.

^b Average Number of Rhizomes is the number of rhizomes per plant (conetainer) that measured >10 mm.

^c Average Rhizome Length is the mean length of >10 mm rhizomes per conetainer; Total Rhizome Length is the summed length of all >10 mm rhizomes per conetainer; Average Number of Nodes Per Rhizome is the average number of nodes counted on >10 mm rhizomes per conetainer; Total Aerial Shoots on Rhizomes is the number of aerial tillers counted on rhizomes >10 mm per conetainer

^d Rhizome Class is visual rating of all rhizomes produced by the plant, and rated on a scale of 0 to 5 (5 = thickest, most robust; 1 = thinnest, weakest; and 0 = no >10 mm rhizomes present).

Note: There was no treatment by run effect; therefore, Run 1 and Run 2 data were combined. However, rhizome length, total rhizome length, number of nodes, total aerial shoot numbers and rhizome class data were transformed for statistical analysis and then back-transformed for presentation. Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha < 0.05$).

Appendix

Appendix A - Additional Figures and Tables For Chapter 2

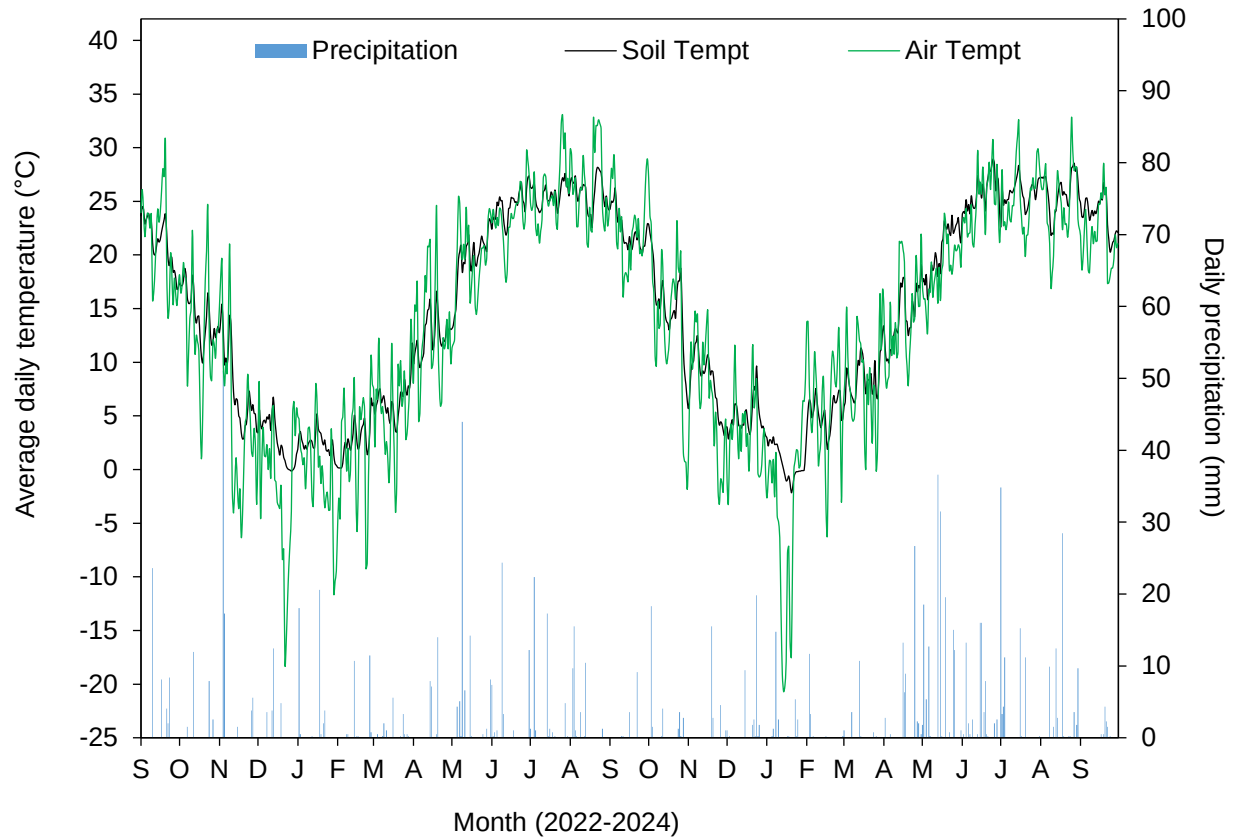


Figure A.1. Data from mesonet.k-state.edu for Rocky Ford Turfgrass Research Center, Manhattan showing daily precipitation amount, soil temperature and air temperature averaged across hourly data throughout the study, Run 1, September 2022 to September 2023 (from left to middle), and Run 2, September 2023 to September 2024 (from middle to right).

Table A.1. Visual turf cover rating (0-100%) of field establishment for 2 to 11 weeks after seeding (WAS) for Run 2 in Experiment 1.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	2 WAS	4 WAS	8 WAS	11 WAS
----- (0 – 100%) ^c -----						
95% TF	Armada	Low	62.0	66.8	89.0	93.8
95% TF	Bolt	Medium	62.3	66.8	89.0	92.5
95% TF	Fullback	Medium	60.5	66.8	89.5	93.5
95% TF	Hampton	High	60.8	68.0	90.0	93.0
95% TF	Legend	High	62.0	65.8	90.3	92.5
95% TF	Martha	Medium	64.5	68.0	90.3	93.0
95% TF	Shannon	Low	65.3	68.5	88.8	91.5
95% TF	Sombrero	High	66.3	69.3	88.8	92.8
95% TF	Volt	Low	63.3	68.0	89.0	92.0
100% TF	---	---	66.3	70.3	91.3	94.5
<i>P-value</i>			0.2436	0.2879	0.0772	0.0629

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass)

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Visual turf cover rated on 0 to 100% scale (i.e., percent vegetation establishment cover) in field for experiment Run 2.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table A.2. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 1 of Experiment 1.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP	10 MAP	12 MAP	20 MAP	24 MAP
-----total tillers per square decimeter ^c -----							
95% TF	Armada	Low	140	126	107	149	112
95% TF	Bolt	Medium	146	139	132	150	120
95% TF	Fullback	Medium	150	117	150	145	103
95% TF	Hampton	High	133	118	113	149	128
95% TF	Legend	High	138	120	124	148	111
95% TF	Martha	Medium	136	150	126	168	126
95% TF	Shannon	Low	115	136	121	126	109
95% TF	Sombrero	High	141	107	132	102	126
95% TF	Volt	Low	109	130	135	126	120
100% TF	---	---	117	134	116	135	117
<i>P-value</i>			0.3396	0.3963	0.5826	0.5281	0.3305

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Total tiller number of TF and KB per square decimeter calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table A.3. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 1.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP	10 MAP	12 MAP
---total tillers per square decimeter ^c ---					
95% TF	Armada	Low	137.1	94.9	104.0
95% TF	Bolt	Medium	111.3	88.9	105.5
95% TF	Fullback	Medium	117.1	111.1	120.6
95% TF	Hampton	High	122.7	98.8	102.9
95% TF	Legend	High	109.2	99.7	97.5
95% TF	Martha	Medium	121.4	106.4	107.2
95% TF	Shannon	Low	101.4	89.1	106.7
95% TF	Sombrero	High	117.5	108.5	109.8
95% TF	Volt	Low	110.7	101.4	124.2
100% TF	---	---	128.1	106.1	106.6
<i>P-value</i>			0.3100	0.6888	0.6888

^a Tall fescue was ‘Avenger 3’ + ‘Blackwatch 2’ + ‘Maestro’ (95% by weight of all TF) included in each 5% by seed weight of KB (Kentucky bluegrass).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Total tiller number of TF and KB per square decimeter calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table A.4. Visual turf cover rating (0-100%) of field establishment for 2 to 11 weeks after seeding (WAS) for Run 2 in Experiment 2.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	2 WAS	4 WAS	8 WAS	11 WAS
----- (0 – 100%) ^c -----						
97% TF	3% Armada	Low	66.5	70.0 ab	91.3 a	92.8
97% TF	3% Fullback	Medium	67.0	71.5 a	92.5 a	93.8
97% TF	3% Legend	High	66.8	69.5 ab	90.3 bc	92.8
95% TF	5% Armada	Low	66.5	71.5 a	91.0 bc	92.0
95% TF	5% Fullback	Medium	65.5	69.5 ab	90.3 bc	93.7
95% TF	5% Legend	High	66.5	70.8 a	91.0 bc	92.3
90% TF	10% Armada	Low	66.3	70.0 ab	89.8 c	92.0
90% TF	10% Fullback	Medium	63.3	68.0 b	90.5 bc	93.5
90% TF	10% Legend	High	62.8	68.5 b	90.3 bc	92.8
100% TF	---	---	66.8	71.2 a	91.3 ab	92.9
<i>P-value</i>			0.0724	0.0153	0.0326	0.0669

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Kentucky bluegrass classifications were assigned are according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024). Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Visual turf cover rated on 0 to 100% scale (i.e., percent vegetation establishment cover) in field for experiment Run 2.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table A.5. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 1 of Experiment 2.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP	10 MAP	12 MAP	20 MAP	24 MAP
-----total tillers per square decimeter ^c -----							
97% TF	3% Armada	Low	135.4	167.7	122.9	138.1	105.1
97% TF	3% Fullback	Medium	123.1	147.3	130.7	146.2	106.8
97% TF	3% Legend	High	119.5	156.1	135.4	170.50	103.1
95% TF	5% Armada	Low	116.5	146.4	103.3	144.95	107.5
95% TF	5% Fullback	Medium	119.7	146.8	112.8	149.55	105.8
95% TF	5% Legend	High	125.9	144.7	121.6	147.97	93.4
90% TF	10% Armada	Low	85.7	117.1	101.8	119.26	91.4
90% TF	10% Fullback	Medium	129.2	141.7	124.0	105.92	100.6
90% TF	10% Legend	High	125.3	160.6	145.3	111.37	89.3
100% TF	---	---	133.3	145.4	113.3	125.15	116.4
P-value			0.3035	0.0715	0.5080	0.1683	0.7298

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Total tiller number of TF and KB per square decimeter calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Table A.6. Total tiller numbers of tall fescue (TF) and Kentucky bluegrass (KB) per square decimeter at 9, 10, and 12 months after planting (MAP) in Run 2 of Experiment 2.

TF (% by weight) ^a	KB cultivar ^a	Growth Aggressiveness Classification ^b	9 MAP	10 MAP	12 MAP
---total tillers per square decimeter ^c ---					
97% TF	3% Armada	Low	110.9	141.7 a	100.8
97% TF	3% Fullback	Medium	100.3	126.2 ab	123.8
97% TF	3% Legend	High	120.8	107.9 bc	120.8
95% TF	5% Armada	Low	108.9	105.3 bc	109.4
95% TF	5% Fullback	Medium	113.2	112.4 bc	122.3
95% TF	5% Legend	High	111.7	97.7 c	109.8
90% TF	10% Armada	Low	89.6	109.6 bc	102.3
90% TF	10% Fullback	Medium	116.9	87.8 c	111.3
90% TF	10% Legend	High	108.5	111.1 bc	111.7
100% TF	---	---	132.3	132.5 ab	116.3
<i>P-value</i>			0.2496	0.0196	0.4472

^a KB cultivars were included in the sod mixture seeding ratios of 97:3, 95:5, and 90:10 (w/w, TF:KB). Tall fescue was ‘Avenger 3’ + Blackwatch 2’ + ‘Maestro’ at even proportion (TF blend of 33.3% each, by weight) to account for % weight of the TF in the TF:KB mixtures and 100% TF treatment.

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Total tiller number of TF and KB per square decimeter calculated from number of visual tillers counted for each species (TF and KB) averaged from two plugs (58 cm² sized plug cutter) collected from each plot at 9, 10, and 12 MAP, and three plugs at 20 and 24 MAP.

Note: Means within a column followed by the same letter or no letter are not different according to Fisher’s Protected least significant difference test ($p \leq 0.05$).

Appendix B - Additional Figures and Tables For Chapter 3

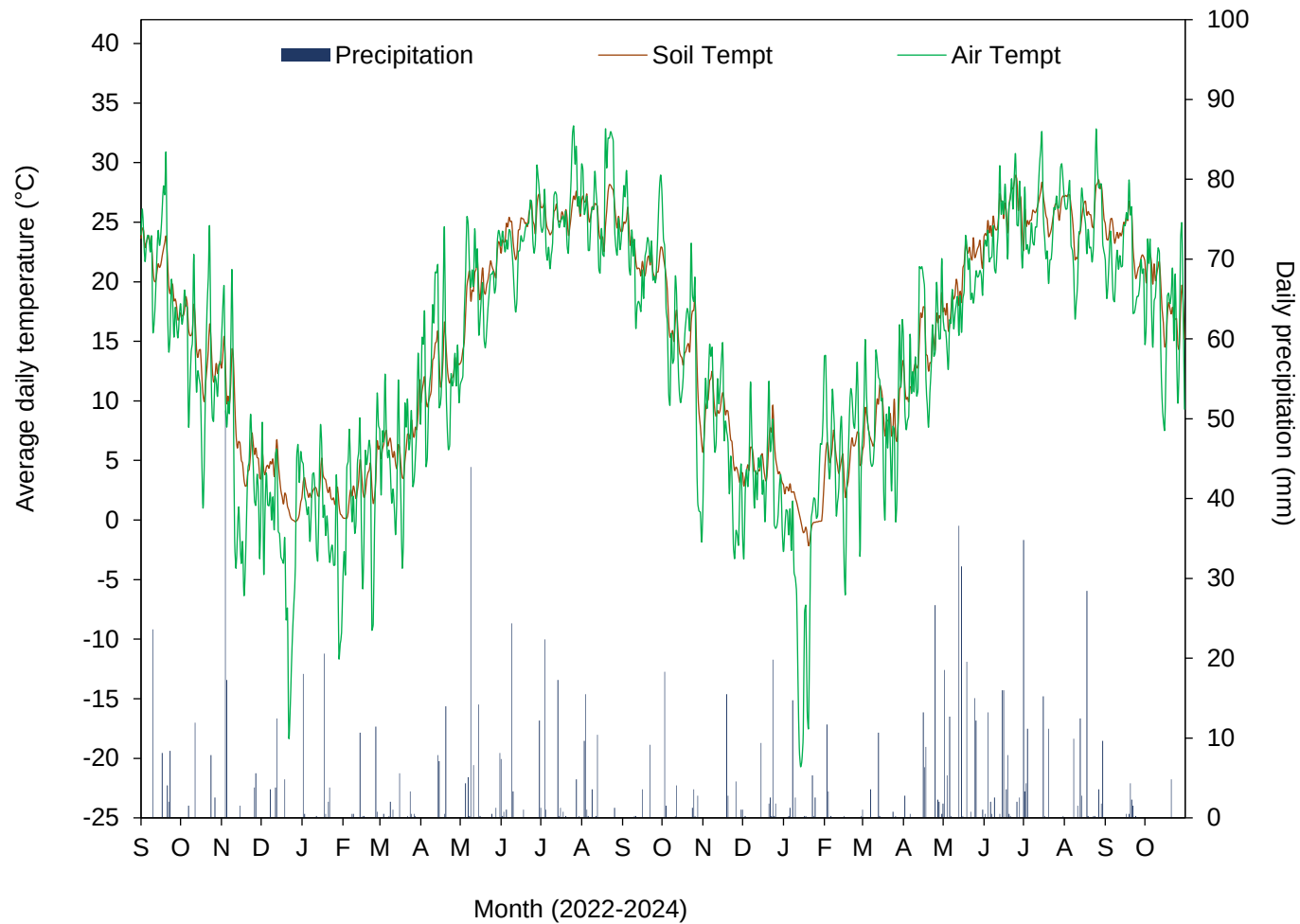


Figure B.1. Data from mesonet.k-state.edu for Rocky Ford Turfgrass Research Center, Manhattan showing daily precipitation amount, soil temperature and air temperature averaged across hourly data throughout the study, Run 1, September 2022 to September 2023 (from left to middle), and Run 2, September 2023 to September 2024 (from middle to right).

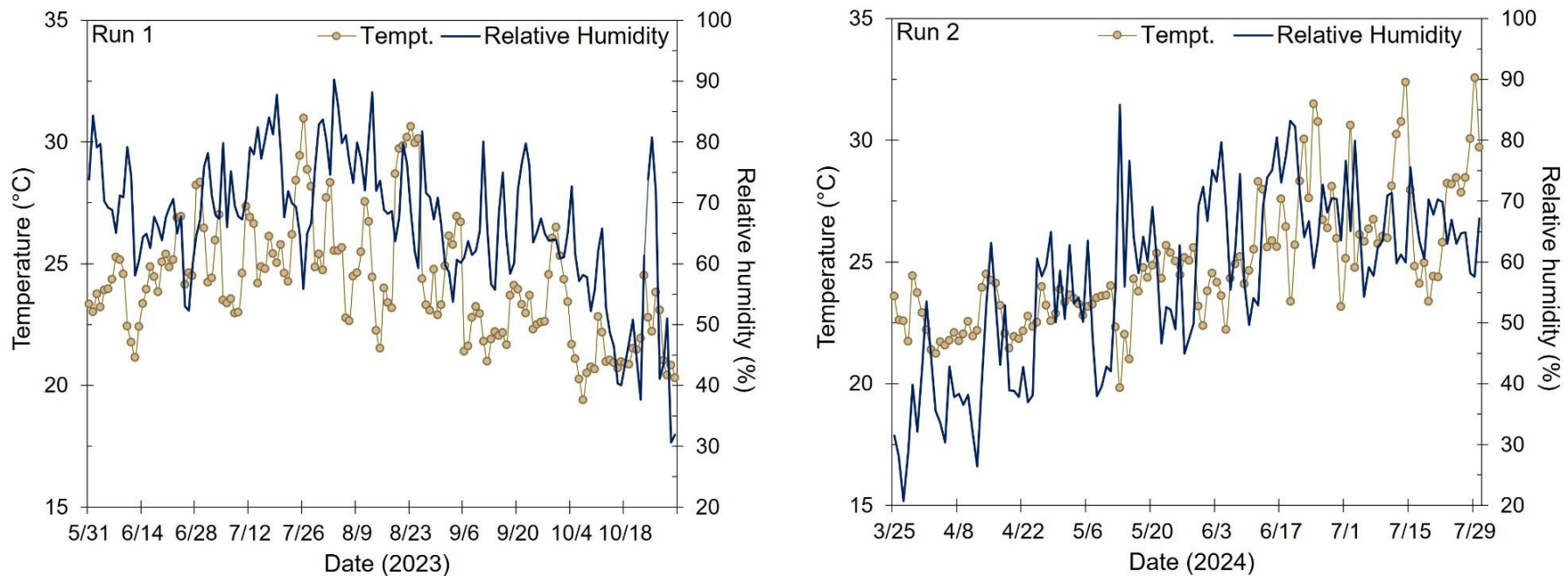


Figure B.2. Daily relative humidity and air temperatures averaged across 30-minute increments from environmental sensors, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.

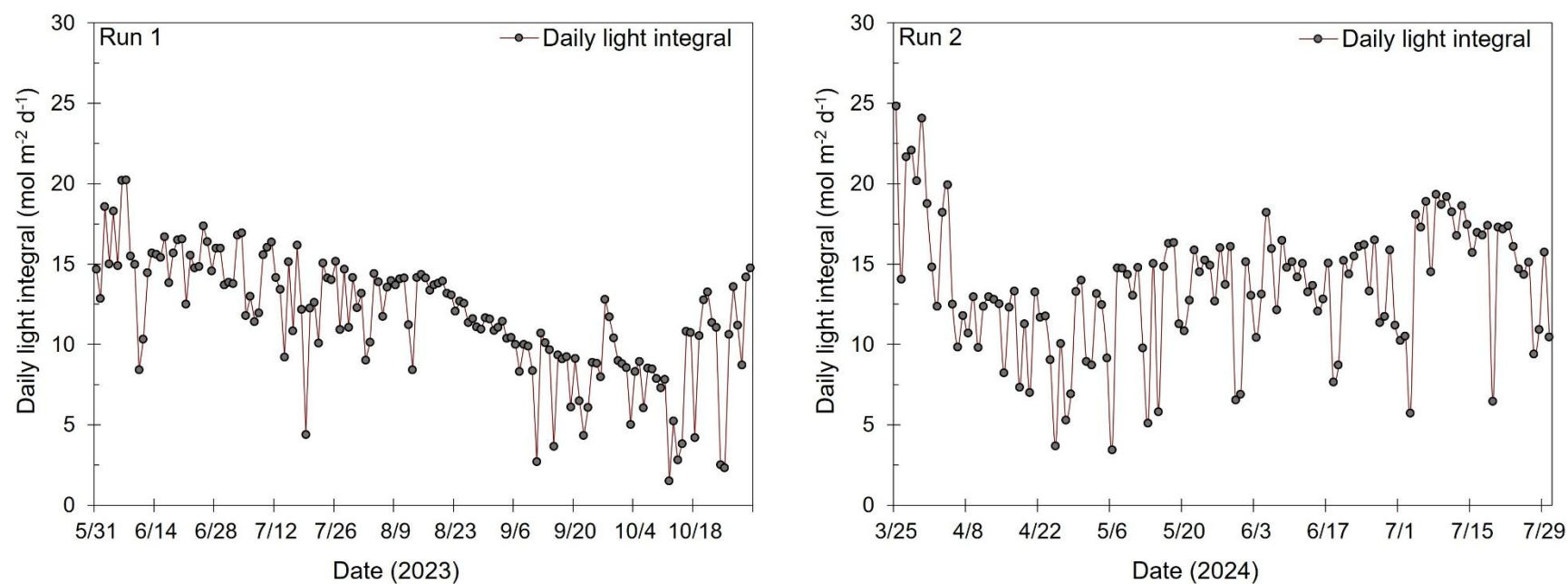


Figure B.3. Mean daily light integrals summed from 30-min incremental measurements of photosynthetically active radiation, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.

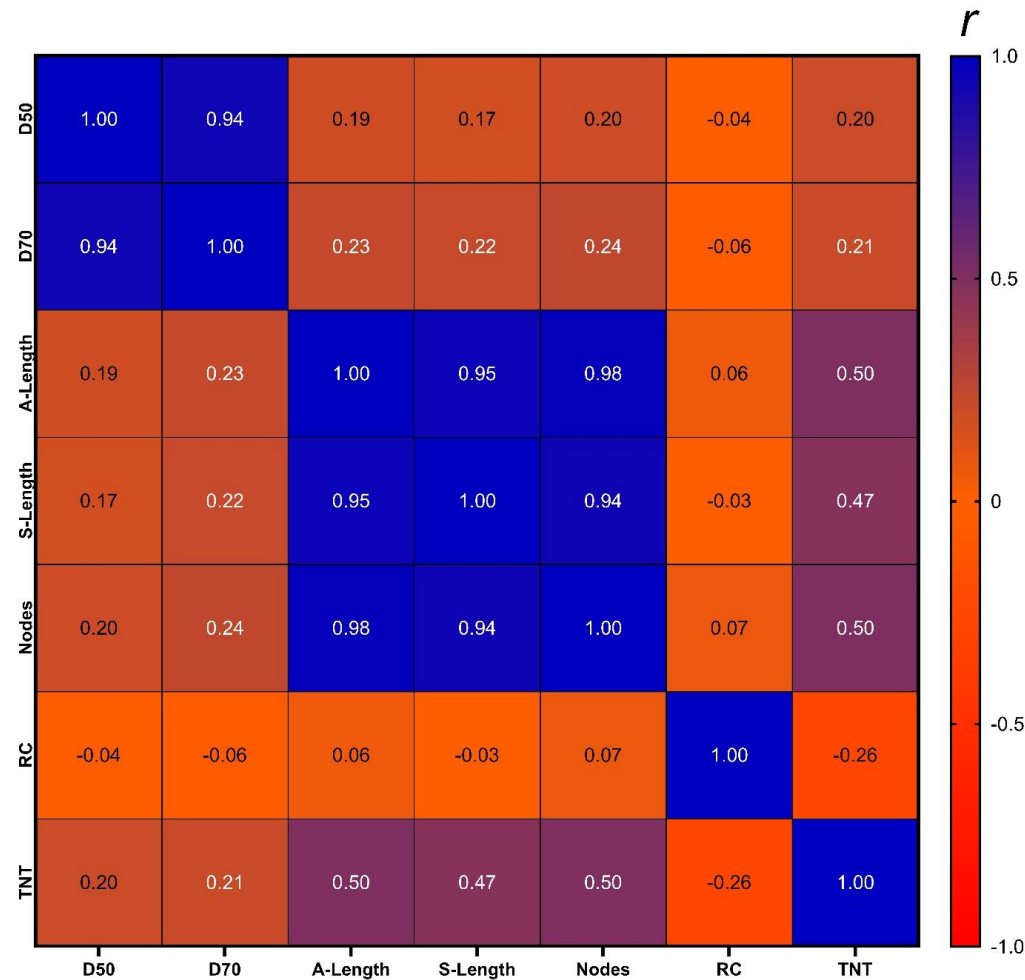


Figure B.4. Correlation matrix between rhizome characteristics [(e.g., Average rhizome length (A-length), sum rhizome length (S-length), nodes, rhizome class (RC), and Total number of tillers (TNT, number of rhizome tillers and aerial shoots from rhizomes) and Establishment cover data from digital image analysis and GraphPad prism data across both experiment runs. Correlation (r) on the right top is shown using color-coded scales $r = 1$, positive correlation; $r = -1$, negative correlation). Means of total or average rhizome length, nodes, RC, and TNT recorded for each cultivar harvested from greenhouse (20 weeks after planting) were used to determine the relationship between variables, a total of 152 sample size (i.e., Trts x reps x runs; 19 x 4 x 2).

Table B.1. Table B.1. Parameter estimates from the four-parameter sigmoidal regression model (Equation 2) for the estimated number of days until 70% germination of Kentucky bluegrass cultivars in a controlled-environment for both experiment runs.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	Run 1			Run 2		
			Top ^c	Hillslope ^d	R ²	Top	Hillslope	R ²
			%			%		
Acoustic	Compact Midnight	High	95.6 abc	6.4 efg	0.9981 a-e	89.2 cd	8.8 ab	0.9978 abc
Armada	Compact America	Low	91.6 f	6.2 fg	0.9979 a-e	84.0 e	6.0 ef	0.9978 abc
Blue bank	Compact Midnight	Medium	92.2 ef	7.3 b-e	0.9972 c-f	83.1 e	8.6 ab	0.9973 abc
BlueNote	Compact America	High	94.2 b-e	7.0 c-f	0.9965 ef	90.4 cd	6.0 ef	0.9980 ab
Bolt	Jefferson/Washington	Medium	96.0 ab	6.4 efg	0.9989 abc	91.4 bc	6.0 ef	0.9990 ab
Fielder	Shamrock	Medium	94.1 b-f	6.6 d-g	0.9981 a-e	89.8 cd	7.7 bcd	0.9983 ab
Fullback	Compact Midnight	Medium	94.9 a-d	6.9 c-f	0.9976 a-e	90.3 cd	6.8 de	0.9990 ab
Hampton	Compact	High	93.2 c-f	8.0 ab	0.9970 d-f	81.9 ef	6.6 e	0.9985 ab
Jackrabbit	Julia	Medium	94.2 a-e	6.2 fg	0.9976 a-e	83.6 e	6.7 de	0.9985 ab
Kenblue	Eurasian-Midwest (Common)	Low	84.7 g	6.8 c-f	0.9980 a-e	75.1 g	6.2 e	0.9978 abc
Legend	Compact America (Midnight)	Medium	91.8 ef	6.2 fg	0.9957 f	88.2 cd	6.1 ef	0.9960 cd
Martha	Jefferson/Washington//Mid-Atlantic	High	93.2 c-f	5.0 h	0.9982 a-e	79.2 f	5.0 f	0.9953 d
Merit	BVMG	Low	93.1 def	8.5 a	0.9992 a	88.5 cd	9.2 a	0.9988 ab
SPF-30	Texas × KB hybrid	High	96.4 ab	7.7 abc	0.9973 b-f	89.2 cd	6.1 ef	0.9993 a
SR-2100	Shamrock	High	92.8 def	8.5 a	0.9987 a-d	93.9 ab	7.9 bc	0.9985 ab
Shannon	Compact America × Shamrock	Low	92.6 def	5.7 gh	0.9989 ab	95.7 a	8.6 ab	0.9980 ab
Sombrero	Limousine	High	96.7 a	6.6 d-g	0.9972 b-f	87.6 d	7.9 bc	0.9990 ab
Volt	Shamrock	Low	93.2 c-f	6.7 def	0.9986 a-d	88.4 cd	6.5 e	0.9988 ab
Yellowstone	Shamrock (Jefferson/Washington)	Low	92.0 f	7.5 bcd	0.9973 b-f	89.2 e	6.8 cde	0.9983 ab
<i>P-value</i>			<0.0001	<0.0001	0.0174	<0.0001	<0.0001	0.0104

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Top (%) is the maximum germination estimate.

^d Higher hillslope (not units) values indicate more rapid germination speed.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table B.2. Parameter estimates from the four-parameter sigmoidal regression model (Equation 2) for the estimated number of days until 90% germination of Kentucky bluegrass cultivars in a controlled-environment for both experiment runs.

Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	Run 1			Run 2		
			Top ^c	Hillslope ^d	R ²	Top	Hillslope	R ²
			%			%		
Acoustic	Compact Midnight	High	95.6 abc	6.4 efg	0.9981 a	89.2 cd	8.8 ab	0.9978 ab
Armada	Compact America	Low	91.6 f	6.2 fg	0.9979 a-e	84.0 e	6.0 ef	0.9979 ab
Blue bank	Compact Midnight	Medium	92.2 ef	7.3 bcd	0.9972 c-f	83.1 e	8.6 ab	0.9973 ab
BlueNote	Compact America	High	94.2 b-e	7.0 c-f	0.9965 ef	90.4 cd	6.0 ef	0.9980 a
Bolt	Jefferson/Washington	Medium	96.0 ab	6.4 efg	0.9989 abc	91.4 bc	6.0 ef	0.9990 a
Fielder	Shamrock	Medium	94.1 b-f	6.6 d-g	0.9981 a-e	89.9 cd	7.7 b-d	0.9981 a
Fullback	Compact Midnight	Medium	94.9 a-d	6.9 c-f	0.9976 a-e	90.3 cd	6.8 de	0.9989 a
Hampton	Compact	High	93.2 c-f	8.0 ab	0.9970 def	81.9 ef	6.6 de	0.9984 a
Jackrabbit	Julia	Medium	94.2 a-e	6.2 fg	0.9976 def	83.6 e	6.7 de	0.9984 a
Kenblue	Eurasian-Midwest (Common)	Low	84.7 g	6.8 c-f	0.9980 a-e	75.1 g	6.2 e	0.9977 ab
Legend	Compact America (Midnight)	Medium	91.8 f	6.2 fg	0.9957 f	88.2 cd	6.1 ef	0.9961 bc
Martha	Jefferson/Washington//Mid-Atlantic	High	93.2 c-f	5.0 h	0.9982 a-e	79.2 f	5.0 f	0.9951 c
Merit	BVMG	Low	93.1 def	5.7 a	0.9992 a	88.5 cd	9.2 a	0.9985 a
SPF-30	Texas × KB hybrid	High	96.4 ab	8.5 abc	0.9973 b-f	95.7 a	8.6 ab	0.9981 a
SR-2100	Shamrock	High	92.8 def	6.7 a	0.9987 a-d	87.6 d	7.9 bc	0.9990 a
Shannon	Compact America × Shamrock	Low	92.6 def	6.6 gh	0.9989 ab	89.2 cd	6.1 ef	0.9991 a
Sombrero	Limousine	High	96.7 a	7.7 d-g	0.9972 b-f	93.9 ab	7.9 bc	0.9987 a
Volt	Shamrock	Low	93.2 c-f	7.5 def	0.9986 a-d	88.4 cd	6.5 e	0.9987 a
Yellowstone	Shamrock (Jefferson/Washington)	Low	92.0 ef	6.4 bcd	0.9973 b-f	84.1 e	6.8 cde	0.9982 a
<i>P-value</i>			<0.0001	<0.0001	0.0174	<0.0001	<0.0001	0.0104

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Top (%) is the maximum germination estimate.

^d Higher hillslope (not units) values indicate more rapid germination speed.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table B.3. Visual turf cover rating (0-100%) of field establishment for Run 2.

Cultivar	Kentucky Bluegrass Classification^a	Growth Aggressiveness Classification^b	2 WAP	4 WAP	8 WAP	11 WAP
			----- (0 – 100% scale) -----			
Acoustic	Compact Midnight	High	26.3 d-f	33.0 g	75.0 cd	83.3 b-e
Armada	Compact America	Low	29.3 b-f	38.0 c-g	77.5 a-d	84.0 a-e
Blue bank	Compact Midnight	Medium	28.5 b-f	38.0 c-g	74.0 d	80.3 e
BlueNote	Compact America	High	33.3 abc	37.0 e-g	73.0 d	80.5 de
Bolt	Jefferson/Washington	Medium	30.8 a-f	39.8 c-g	80.3 abc	86.0 abc
Fielder	Shamrock	Medium	32.8 a-d	44.3 a-d	75.5 bcd	82.3 b-e
Fullback	Compact Midnight	Medium	30.3 b-f	46.8 ab	83.0 a	89.0 a
Hampton	Compact	High	34.3 ab	43.5 a-e	74.8 cd	82.5 b-e
Jackrabbit	Julia	Medium	37.3 a	49.8 a	81.3 ab	85.5 a-d
Kenblue	Eurasian-Midwest (Common)	Low	26.3 def	35.8 fg	74.8 cd	81.3 cde
Legend	Compact America (Midnight)	Medium	32.5 a-e	40.3 b-f	74.0 d	82.8 b-e
Martha	Jefferson/Washington/Mid-Atlantic	High	25.0 f	34.3 fg	75.5 bcd	82.8 b-e
Merit	BVMG	Low	27.0 c-f	37.0 efg	77.0 a-d	84.5 a-e
SPF-30	Texas × KB hybrid	High	32.5 a-e	44.8 abc	78.0 a-d	85.0 a-e
SR-2100	Shamrock	High	24.3 f	33.0 g	73.5 d	82.3 b-e
Shannon	Compact America × Shamrock	Low	26.3 d-f	37.0 e-g	75.8 bcd	84.5 a-e
Sombrero	Limousine	High	28.8 b-f	40.0 bf	82.5 a	87.3 ab
Volt	Shamrock	Low	27.0 c-f	36.8 efg	74.5 cd	80.3 e
Yellowstone	Shamrock (Jefferson/Washington)	Low	25.8 ef	37.5 d-g	78.5 a-d	86.5 ab
<i>P-value</i>			0.0103	<0.0001	0.0198	0.0481

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Visual turf cover rated on a scale of 0 to 100% (i.e percent vegetation establishment cover) in field for experiment Run 2.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table B.4. Digital turf cover (0-100%) of plant materials in conetainers in greenhouse experiment.

			Run 1					Run 2			
			Months After Seeding ^c					Months After Seeding ^c			
Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	3	4	8	13	17	3	4	8	13
			----- (0 – 100% scale) ----- ^c					----- (0 – 100% scale) ----- ^c			
Acoustic	Compact Midnight	High	1.4 b-e	4.5 b-e	49.6	58.9 abc	56.3 abc	0.50 ab	0.89 a	23.9	45.6
Armada	Compact America	Low	0.8 e	2.4 e	40.0	58.9 abc	55.4 bcd	0.32 a-e	0.73 a-e	30.6	47.2
Blue bank	Compact Midnight	Medium	0.8 e	2.4 e	39.5	67.5 a	59.3 ab	0.22 de	0.50 ef	16.2	41.0
BlueNote	Compact America	High	1.2 b-e	3.1 cde	40.1	58.1 abc	52.0 bcd	0.34 a-e	0.60 a-f	24.4	43.7
Bolt	Jefferson/Washington	Medium	1.3 b-e	4.8 b-e	46.6	58.3 abc	51.1 bcd	0.31 b-e	0.60 a-f	25.4	50.0
Fielder	Shamrock	Medium	0.9 de	2.6 de	41.7	59.8 ab	56.5 abc	0.26 c-e	0.74 a-d	14.5	46.1
Fullback	Compact Midnight	Medium	1.7 abc	6.3 ab	57.0	59.8 ab	59.1 ab	0.16 e	0.46 f	16.3	41.4
Hampton	Compact	High	1.2 b-e	3.3 cde	49.3	59.8 ab	51.4 bcd	0.30 b-e	0.43 ef	17.6	40.9
Jackrabbit	Julia	Medium	1.2 b-e	3.0 de	30.8	43.6 d	40.5 e	0.39 a-d	0.46 def	18.3	22.3
Kenblue	Eurasian-Midwest (Common)	Low	2.3 a	8.3 a	44.0	52.9 bcd	51.5 bcd	0.30 b-e	0.46 def	19.6	36.1
Legend	Compact America (Midnight)	Medium	1.3 b-e	4.3 b-e	47.2	48.4 cd	39 2 e	0.23 de	0.57 b-f	16.4	34.9
Martha	Jefferson/Washington/Mid-Atlantic	High	1.8 ab	6.4 ab	55.5	62.2 ab	57.0 abc	0.32 b-e	0.55 c-f	14.2	34.8
Merit	BVMG	Low	0.8 e	2.6 de	43.9	61.5 ab	50.0 cd	0.32 b-e	0.86 ab	21.6	38.1
SPF-30	Texas × KB hybrid	High	1.5 bcd	5.4 bc	60.5	63.0 ab	55.1 a-d	0.53 a	0.68 a-f	26.8	39.7
SR-2100	Shamrock	High	0.9 de	3.6 cde	33.5	53.8 bcd	49.6 cd	0.44 abc	0.64 a-f	22.4	36.8
Shannon	Compact America × Shamrock	Low	0.8 e	3.2 cde	47.7	66.0 a	62.5 a	0.46 abc	0.89 a	23.3	40.6
Sombrero	Limousine	High	1.0 cde	3.8 cde	44.7	60.0 bc	50.2 cd	0.23 de	0.64 a-f	17.6	41.2
Volt	Shamrock	Low	1.3 b-e	3.2 cde	37.1	62.0 ab	56.7 abc	0.28 cde	0.57 b-f	26.2	43.1
Yellowstone	Shamrock (Jefferson/Washington)	Low	1.4 b-e	4.3 b-e	40.2	53.7 bcd	46.6 de	0.26 cde	0.43 ef	17.1	37.2
P-value			0.0025	0.0001	0.0840	0.0048	<0.0001	0.0185	0.0130	0.0809	0.1784

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Digital image analysis used to measure turf cover in conetainers scale (0 to 100% establishment) during greenhouse study.

Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Table B.5. Visual tiller count (0-100%) of plant materials in conetainers in greenhouse experiment.

			Run 1				Run 2			
			Months After Seeding ^c				Months After Seeding ^c			
Cultivar	Kentucky Bluegrass Classification ^a	Growth Aggressiveness Classification ^b	5	9	13	17	5	9	13	17
			----- (count)----- ^c				----- (count)----- ^c			
Acoustic	Compact Midnight	High	1.8 b-e	8.5	26.5 abc	32.1 a-d	2.3 abc	5.4 ab	14.0	15.1
Armada	Compact America	Low	1.1 a-e	8.5	16.8 d-g	19.1 e-h	3.0 a	7.0 a	13.0	17.5
Blue bank	Compact Midnight	Medium	1.6 b-e	11.6	29.6 ab	36.5 ab	1.3 de	4.0 b-e	11.0	13.9
BlueNote	Compact America	High	2.0 a-e	9.1	20.0 c-f	22.6 c-f	2.0 bcd	4.9 bcd	11.1	11.0
Bolt	Jefferson/Washington	Medium	2.6 a-d	10.5	23.4 bcd	28.5 b-e	1.5 cde	5.5 ab	12.3	17.4
Fielder	Shamrock	Medium	1.3 de	10.1	21.0 b-e	26.0 b-e	1.5 cde	3.6 cde	10.3	12.4
Fullback	Compact Midnight	Medium	3.0 ab	11.0	19.0 c-f	21.5 d-g	1.0 e	3.5 cde	7.0	7.3
Hampton	Compact	High	2.9 abc	12.5	27.6 abc	32.6 abc	1.0 e	4.9 bcd	11.0	13.1
Jackrabbit	Julia	Medium	1.0 e	6.0	11.1 fg	14.0 fgh	1.0 e	3.1 e	6.5	8.1
Kenblue	Eurasian-Midwest (Common)	Low	2.4 a-e	8.0	15.8 d-g	18.5 e-g	1.6 b-e	3.3 de	7.0	7.3
Legend	Compact America (Midnight)	Medium	1.8 b-e	5.4	8.4 g	10.6 h	1.3 de	5.4 ab	9.4	11.3
Martha	Jefferson/Washington/Mid-Atlantic	High	3.3 a	16.1	32.8 a	41.1 a	1.0 e	3.6 cde	9.5	12.9
Merit	BVMG	Low	2.0 a-e	14.4	24.0 a-d	28.8 b-e	1.5 cde	5.5 ab	10.3	13.1
SPF-30	Texas × KB hybrid	High	3.0 ab	10.9	19.3 c-f	21.8 d-g	2.0 bcd	5.5 ab	11.4	13.6
SR-2100	Shamrock	High	1.0 e	5.5	9.0 g	11.1 gh	1.0 e	4.1 b-e	7.1	8.5
Shannon	Compact America × Shamrock	Low	2.4 a-e	9.4	19.5 c-f	23.9 c-f	2.5 ab	5.0 bc	11.8	13.4
Sombrero	Limousine	High	1.5 cde	6.9	13.4 d-g	14.4 f-h	1.3 de	3.3 de	7.6	10.1
Volt	Shamrock	Low	1.5 cde	9.1	20.5 b-e	24.3 c-f	1.4 cde	3.9 b-e	8.9	10.9
Yellowstone	Shamrock (Jefferson/Washington)	Low	1.3 cde	8.3	19.0 c-f	23.3 c-f	1.3 de	4.4 b-e	9.5	11.0
P-value			0.0342	0.0532	<0.0001	<0.0001	0.0005	0.0014	0.0529	0.0780

^a Kentucky bluegrass classifications were assigned according to Bonos et al. (2000), Huff (2003), Honig et al. (2012, 2018), and Brilman, (2018, 2024).

^b Growth aggressiveness classifications of “high,” “medium,” and “low” were assigned based on communication with seed companies (G. Munshaw, personal communication, 2022; L. Brilman, personal communication, 2022).

^c Visual tiller cover count in conetainers to estimate turf cover and tiller differences among KB cultivars, for both experiment runs in greenhouse
Note: Means within a column followed by the same letter are not significantly different according to Fisher’s LSD test ($\alpha < 0.05$).

Appendix C - Additional Figures and Tables for Chapter 4

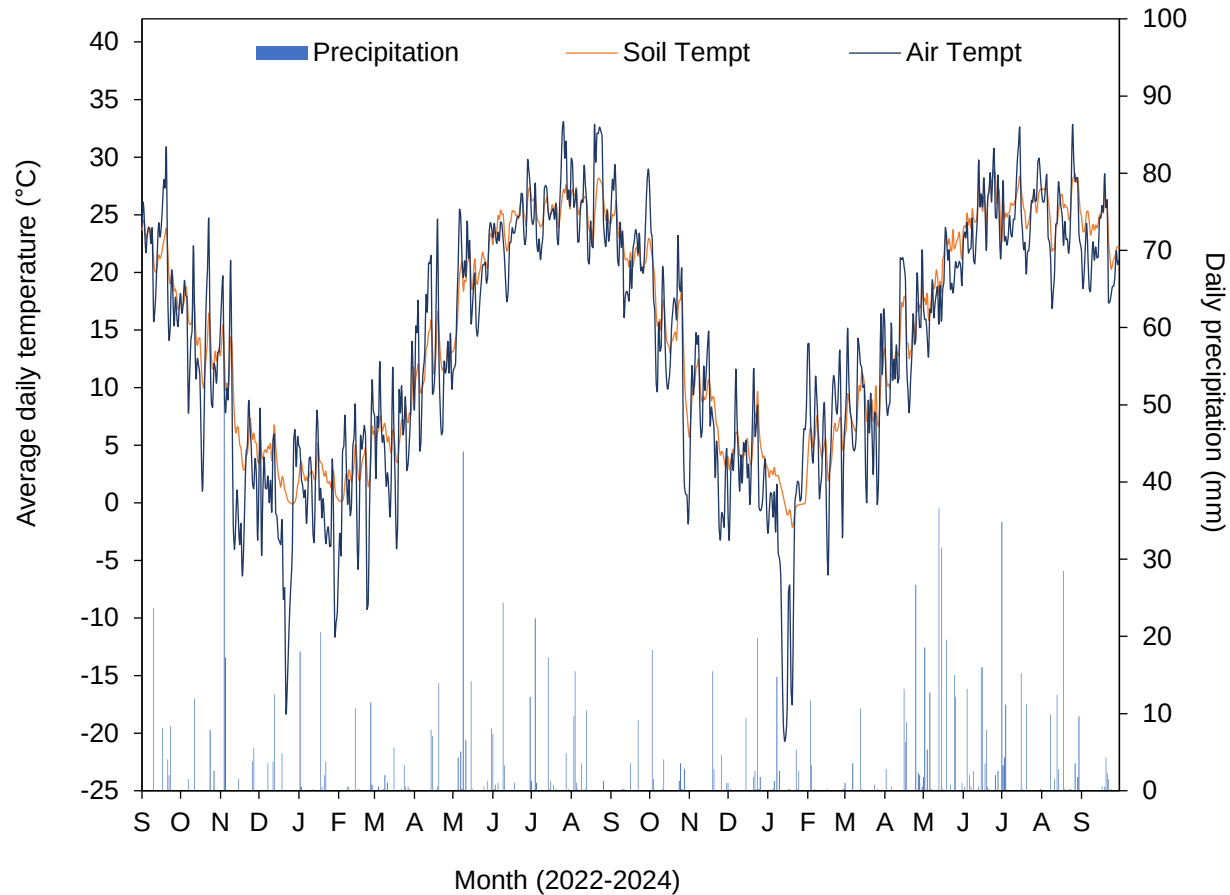


Figure C.1. Data from mesonet.k-state.edu for Rocky Ford Turfgrass Research Center, Manhattan showing daily precipitation amount, soil temperature and air temperature averaged across hourly data throughout the study, Run 1, September 2022 to October 2023 (from left to middle), and Run 2, September 2023 to October 2024 (from middle to right).

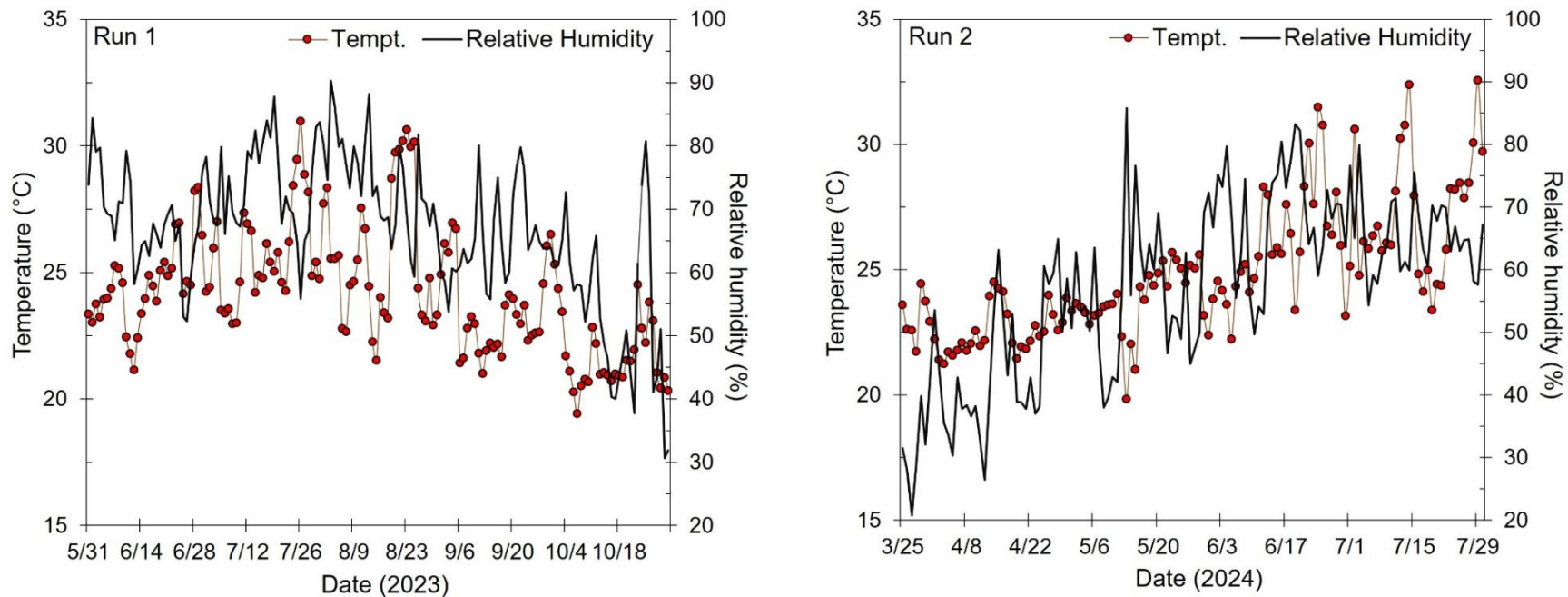


Figure C.2. Daily relative humidity and air temperatures averaged across 30-min incremental measurements from environmental sensors, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.

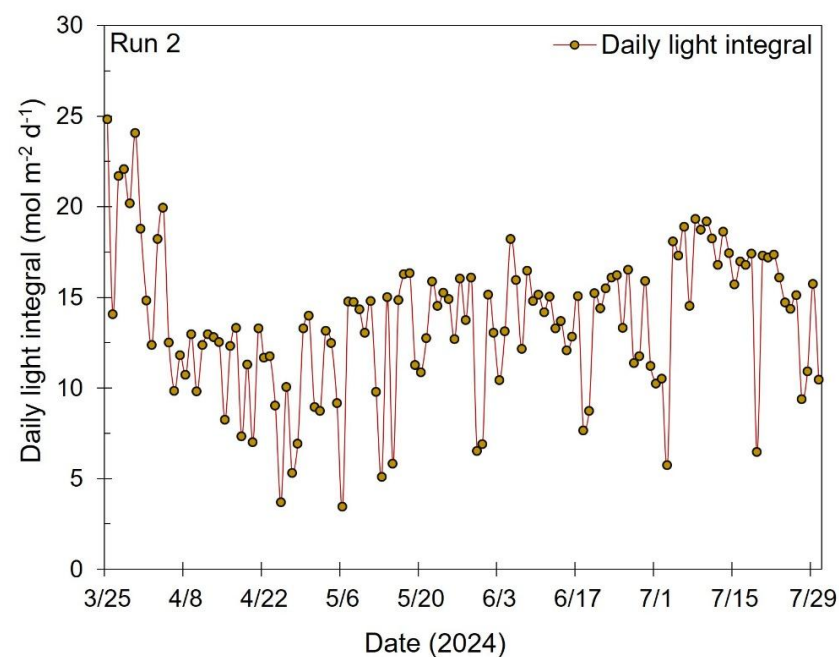
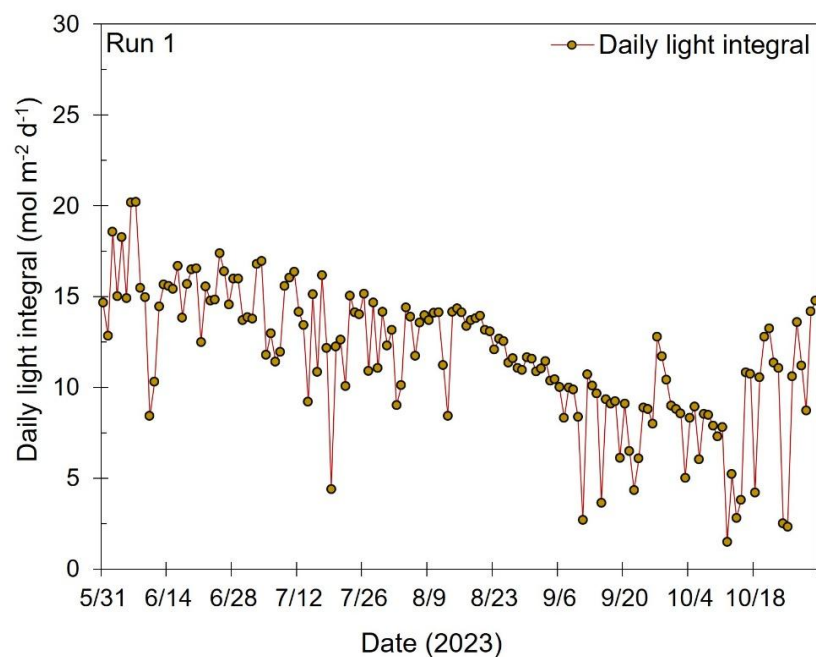


Figure C.3. Mean daily light integrals summed from 30-min incremental measurements of photosynthetically active radiation, Run 1, from May to October 2023 (left) and Run 2, from March to July 2024 (right), for greenhouse studies at Throckmorton Plant Science Center greenhouses, Kansas State University.

Table C.1. Correlation between turf quality and sod strength data across field experiment runs.

	Pearson's correlation coefficient (<i>r</i>)			
	Turf Quality	Sod Handling	Max tensile strength	Required Work
Turf quality	1.000	0.092	0.095	0.062
Sod handling	0.092	1.000	0.501	0.482
Max tensile strength	0.095	0.501	1.000	0.790
Required work to strength	0.062	0.482	0.482	1.000
	P-value			
	Turf Quality	Sod Handling	Max tensile strength	Required Work
Turf quality	ns	ns	ns	ns
Sod handling	ns	ns	***	***
Max tensile strength	ns	***	ns	***
Required work to strength	ns	***	***	ns

Note: *P-value* = ns = not significant, * = 0.05, ** = 0.01, *** = <0.001, represents significance levels.

Table C.2. Visual turf cover rating (0-100%) of field establishment for Run 2.

Treatment	Cultivar	2 WAP	4 WAP	8 WAP	11 WAP
		----- (0 – 100%) ^a -----			
100% KB blend	(A + L) ^b	41.8 c	51.8 c	78.8 e	87.8 b
95:5 TF:KB	(S + R + H) (A + L) ^{bc}	66.5 ab	69.5 ab	93.0 abc	94.0 a
90:10 TF:KB	(S + R + H) (A + L)	64.3 b	69.0 b	91.0 cd	93.0 a
100% Bunch TF	(S + R + H) ^c	65.0 ab	70.5 ab	91.0 cd	93.0 a
Firecracker GLS	Rhizomatous TF	66.8 ab	71.0 ab	93.3 ab	94.5 a
Grande 3	Rhizomatous TF	67.0 a	72.0 a	93.5 a	94.8 a
Nightcrawler	Rhizomatous TF	65.8 ab	68.8 b	91.5 a-d	93.0 a
Regenerate	Rhizomatous TF	66.0 ab	70.3 ab	91.3 bcd	94.3 a
Titanium	Rhizomatous TF	66.5 ab	71.8 a	92.5 a-d	93.3 a
Turfway	Rhizomatous TF	67.5 a	70.8 ab	92.8 abc	93.8 a
Xtender	Rhizomatous TF	67.0 a	70.3 ab	90.5 d	93.5 a
Rhizomatous blend	(Xtender, Grande 3, Titanium)	65.8 ab	71.3 ab	92.3 a-d	93.3 a
<i>P-value</i>		<0.0001	<0.0001	<0.0001	<0.0001

^a Visual turf cover rated on 0 to 100% scale (i.e., percent vegetation establishment cover) in field for experiment Run 2.

^b Acoustic (A) and Legend (L), Kentucky bluegrass cultivars included in a 100% blend at 50% each by weight.

^c Supersonic (S), Reflection (R), Houndog 6 (H), are the bunch-type tall fescue cultivars included a 100% blend at 33% by weight each.

Note: Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha < 0.05$).

Table C.3. Visual tiller count (0-100%) of plant materials in containers in greenhouse experiment before destructive phenotyping for both runs.

Treatment	Cultivar	2 WAP	4 WAP	8 WAP	11 WAP
		----- 0 – 100% ^a -----			
100% KB blend	(A + L) ^b	41.8 c	51.8 c	78.8 e	87.8 b
95:5 TF:KB	(S + R + H) (A + L) ^{bc}	66.5 ab	69.5 ab	93.0 abc	94.0 a
90:10 TF:KB	(S + R + H) (A + L)	64.3 b	69.0 b	91.0 cd	93.0 a
100% Bunch TF	(S + R + H) ^c	65.0 ab	70.5 ab	91.0 cd	93.0 a
Firecracker GLS	Rhizomatous TF	66.8 ab	71.0 ab	93.3 ab	94.5 a
Grande 3	Rhizomatous TF	67.0 a	72.0 a	93.5 a	94.8 a
Nightcrawler	Rhizomatous TF	65.8 ab	68.8 b	91.5 a-d	93.0 a
Regenerate	Rhizomatous TF	66.0 ab	70.3 ab	91.3 bcd	94.3 a
Titanium	Rhizomatous TF	66.5 ab	71.8 a	92.5 a-d	93.3 a
Turfway	Rhizomatous TF	67.5 a	70.8 ab	92.8 abc	93.8 a
Xtender	Rhizomatous TF	67.0 a	70.3 ab	90.5 d	93.5 a
Rhizomatous blend	(Xtender, Grande 3, Titanium)	65.8 ab	71.3 ab	92.3 a-d	93.3 a
<i>P-value</i>		<0.0001	<0.0001	<0.0001	<0.0001

^a Visual tiller cover count in containers to estimate turf cover and tiller differences among treatments, for both experiment runs combined in greenhouse study.

^b Acoustic (A) and Legend (L), Kentucky bluegrass cultivars included in a 100% blend at 50% each by weight.

^c Supersonic (S), Reflection (R), Houndog 6 (H), are the bunch-type tall fescue cultivars included a 100% blend at 33% by weight each.

Note: Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha < 0.05$).

Table C.4. Digital turf cover (0-100%) of plant materials in containers in greenhouse experiment before destructive phenotyping.

Treatment	Cultivar	Run 1					Run 2				
		2 WAP	4 WAP	8 WAP	12 WAP	18 WAP	2 WAP	4 WAP	8 WAP	12 WAP	18 WAP
		----- 0 – 100% ^a -----					----- (0 – 100% scale ^a -----				
Acoustic	Kentucky bluegrass	0.45 e	4.97 cd	20.10 c	25.93 c	26.15 b	0.73 de	2.09 b	26.90 d	45.75	38.25 bc
Legend	Kentucky bluegrass	0.73 de	4.59 d	19.14 c	21.81 c	15.59 b	0.66 e	2.09 b	26.79 d	47.34	33.27 c
Supersonic	Bunch-type TF	1.20 bcd	9.90 b	40.02 b	54.17 ab	49.10 a	1.28 bcd	4.76 ab	60.11 abc	68.40	55.40 a
Reflection	Bunch-type TF	1.26 bc	8.85 bc	50.58 ab	57.23 ab	50.00 a	1.55 abc	6.13 a	59.79 abc	62.41	50.82 a
Houndog 6	Bunch-type TF	0.91 b-e	7.64 bcd	48.15 ab	53.61 ab	47.01 a	1.13 cde	5.17 a	48.80 c	48.02	49.23 ab
Firecracker GLS	Rhizomatous TF	0.82 cde	7.78 bcd	52.00 ab	56.37 ab	50.00 a	1.85 ab	6.49 a	68.34 ab	63.42	55.69 a
Grande 3	Rhizomatous TF	0.93 b-e	10.24 b	51.86 ab	58.45 ab	48.69 a	1.32 bcd	5.25 a	56.05 bc	64.92	56.20 a
Nightcrawler	Rhizomatous TF	0.87 cde	9.13 bc	44.93 ab	47.01 b	47.12 a	1.31 bcd	5.74 a	56.81 abc	69.19	58.98 a
Regenerate	Rhizomatous TF	1.05 bcd	8.47 bcd	54.96 a	58.29 ab	49.05 a	1.96 a	6.69 a	64.60 ab	64.13	57.72 a
Titanium GLS	Rhizomatous TF	1.40 b	7.73 bcd	52.10 ab	64.73 a	51.67 a	1.38 abc	6.41 a	66.31 ab	61.36	56.69 a
Turfway	Rhizomatous TF	2.19 a	15.19 a	57.27 a	60.89 ab	50.62 a	1.46 abc	5.12 ab	51.37 c	63.15	55.46 a
Xtender	Rhizomatous TF	0.91 b-e	8.82 bcd	48.36 ab	55.62 ab	47.53 a	1.60 abc	7.42 a	69.18 a	61.41	55.33 a
<i>P-value</i>		<0.0001	0.0020	<0.0001	<0.0001	<0.0001	0.0021	0.0034	<0.0001	0.0635	0.0003

^a Digital image analysis used to measure turf cover in containers scale (0 to 100% establishment) during greenhouse study.

Note: Means within a column followed by the same letter or no letter are not significantly different according to Fisher's LSD test (α <0.05).