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Improving winter survival of interspecific hybrid bermudagrass in the Mid-Atlantic region through cultural practices

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Abstract

Winter injury can cause significant loss of hybrid bermudagrasses [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] in the transition zone. Current research has focused on high-value, low-acreage areas like putting greens, but those practices are impractical to implement on golf course fairways. To that end, multi-year research projects were conducted at three sites across Maryland and Virginia to investigate the influence of annual N fertility [2.0 lb N 1000 ft^{-2} (early summer application) or 4.0 lb N 1000 ft^{-2} (split applied early and late summer)] across multiple fall mowing heights (0.5 inches, 0.8 inches, or 1 inch) and to elucidate the effects of wetting agent (fall, fall + winter, or none) and irrigation (0.5 inches irrigation at <15% soil volumetric water content [VWC] or none) applications during dormancy on reducing winter injury of hybrid bermudagrass. Dry-down experiments were also conducted using plugs collected from field trials to impose an artificial freeze event and elucidate the effects of soil VWC on winter injury. Turfgrass quality and percent green cover were evaluated regularly as the turfgrass entered dormancy and throughout spring green-up each year. Late-season N applications helped retain fall green coverage without increasing winter injury and increasing fall mowing height did not impact winter injury. Temporary increase in soil VWC increased bermudagrass survival after a short-term freeze event and prevented root biomass loss. These studies demonstrate late-season N applications can help retain green color and increasing soil VWC prior to a short-term freezing event can greatly reduce winter injury.

Abbreviations: ANOVA, analysis of variance; AUPC, area under the progress curve; DIA, digital image analysis; RCBD, randomized complete block design; VWC, volumetric water content.

Plain Language Summary

Hybrid bermudagrass is widely planted throughout the United States and globally. It is susceptible to cold injury during frigid winter conditions. This research focused on implementation of management strategies such as mowing, fertilizer applications, and irrigation. We found that raising mowing heights and application of more nitrogen in the late summer/early fall provided the greatest green color for hybrid bermudagrass with no negative effects on winter survival. Additionally, we observed a positive effect of irrigation application prior to a short-term freeze event. These simple management practices can be readily employed by turfgrass managers maintaining hybrid bermudagrasses.

Hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] is a highly desirable turfgrass species in intensively managed areas (i.e., golf courses or athletic fields) in the southern United States and into the transition zone due to its dense canopy, abiotic and biotic stress tolerance, and aggressive growth habit. Throughout the transition zone, winterkill associated with low-temperature exposure and tissue desiccation is a common problem of intensely managed bermudagrasses. New hybrid bermudagrass cultivars (e.g., 'OKC1131' [Tahoma 31], 'OKC1134' [Northbridge], OKC1119 [Latitude 36], 'JSC 2-21-18′ [Iron Cutter]) have improved cold tolerance compared to previously released cultivars (e.g., 'Tifway') and present an opportunity for turfgrass managers in the northern extremities of the transition zone to utilize interspecific hybrid bermudagrasses (Dunne et al., 2019; Gopinath et al., 2021; National Turfgrass Evaluation Program, 2017). However, winter survival is still a concern in areas of marginal adaptation, like the Mid-Atlantic region of the United States, where summers are warm enough for vigorous growth but winters border survivable conditions for interspecific hybrid bermudagrasses.

Tissue desiccation and low-temperature exposure are major factors in the development of winter injury in turfgrass. Prior research suggests that winter injury to warm-season turfgrasses from low-temperature exposure is likely to occur when air temperatures drop below 19.9˚F (Trenholm, 2000). Turfgrass managers can improve winter survival by placing covers over dormant bermudagrasses to insulate the turfgrass and prevent fatal injury from low-temperature exposure (DeBoer et al., 2019; Goatley et al., 2007). Covers may also help prevent tissue desiccation (Michael & Kreuser, 2020; Roberts, 1986). On creeping bentgrass (*Agrostis stolonifera* L.) putting greens in Nebraska, covers helped reduce winterkill by retaining crown moisture content and preventing tissue desiccation (Michael & Kreuser, 2020). The use of subterranean heating apparati has also become an effective tool to heat rootzones, potentially preventing winterkill (Bevard, 2024; Trulio, 1991). Two common subterranean heating apparati used to heat rootzones are (1) heated water running through underground tubing to warm soils above it or (2) heated air circulated throughout the rootzone to heat it. Deploying subterranean heating apparati or covers is a costly management practice in installation and/or labor and, as such, is reserved for the highest value areas on a golf course such as putting greens. Putting greens, on average, amount to 3.2% of the total area of managed turfgrass on a golf course (Lyman et al., 2007). Scaling up to deploy covers on fairways, which, on average, account for 29.5% of managed turfgrass area on a golf course, or nearly 10 times more area than putting greens, quickly becomes untenable (Lyman et al., 2007).

Wetting agents are applied to turfgrasses on high sand-content root zones to help alleviate symptoms of hydrophobic soils and improve the uniformity of soil moisture. Late-fall wetting agent applications may help alleviate winter injury by improving soil moisture conditions during dormancy transition and retaining soil moisture during dormancy. However, research has shown mixed results in warm- and cool-season turfgrasses. On creeping bentgrass putting greens, late-fall wetting agent applications did not impact spring green up (Michael & Kreuser, 2020). Research on late-fall wetting agent applications for ultradwarf bermudagrass putting greens have had varying effects on winter injury from year-to-year (DeBoer et al., 2020, 2019). In the DeBoer et al. (2019) study, wetting agents enhanced spring green-up in the spring of 2016, yet there were no significant effects in the spring of 2017 or 2018, likely due to differing rainfall patterns each year. In the DeBoer et al. (2020) study, there were differences between years, wetting agents, and application rates on spring green-up of ultradwarf bermudagrass, with certain wetting agent and rate combinations enhancing spring green-up, others reducing spring green-up, and others having no effect. These studies show the inherent variability in researching wetting agents, but they also highlight the potential benefits of wetting usage for bermudagrass winter survival.

Historically, it has been recommended that nitrogen (N) applications to bermudagrass cease before fall (i.e., August) to minimize succulent tissue growth and boost carbohydrate reserves as the turf enters dormancy (Beard, 1973). However, research is increasingly showing that late-fall N applications can improve green color retention in the fall and even expedite spring green-up (Goatley et al., 1994; Munshaw et al., 2007; Richardson, 2002; Rimi et al., 2013). Furthermore, research has shown that late-fall N applications did not significantly reduce carbohydrate reserves (Goatley et al., 1994) nor decrease cold tolerance of rhizomes (Richardson, 2002). These research findings indicate that late-fall N applications may be a suitable method for retaining turfgrass appearance in the fall without negatively impacting winter survival.

Regarding winter survival of bermudagrass, most research has been conducted on putting greens. However, in the Mid-Atlantic region there is an increasing number of golf courses switching fairways and tees to new, more cold-tolerant bermudagrass cultivars. Increased use of bermudagrasses in northern climates warrants investigation into the impacts of management practices on winter survival in areas of marginal adaptation. To that end, multiple research projects were designed to evaluate (1) the role of fall mowing height and annual N-fertilization on winter survival of interspecific hybrid bermudagrasses and (2) the impact of wetting agents and/or soil volumetric water content (VWC) on winter injury of interspecific hybrid bermudagrasses planted on sand-based root zones.

1 | MATERIALS & METHODS

1.1 | Mowing and fertility site descriptions

A trial investigating the effects of fall mowing height and yearly N-fertilization on interspecific hybrid bermudagrass winter survival was conducted at three locations: Paint Branch Turfgrass Research Facility in College Park, MD, Independence Golf Club in Midlothian, VA, and Virginia Tech Turfgrass Research Center in Blacksburg, VA. Trial areas in College Park, Midlothian, and Blacksburg, VA were established on existing stands of Latitude 36, 'Tufcote', and 'Patriot' interspecific hybrid bermudagrasses, respectively. The study was conducted from the summer of 2019 until the spring of 2021. Mowing throughout the growing season occurred 3× wk^{-1} with a height of cut bench setting at 0.5 inches. Irrigation was applied as needed to prevent drought stress throughout the growing season. Annual weed encroachment was controlled at the College Park and Midlothian locations using pre-emergent herbicides. Only spring/early summer post-emergent herbicides were applied at the Blacksburg location.

1.2 | Mowing and fertility study design

This study utilized a strip-plot randomized complete block design (RCBD) with a 3 × 2 factorial treatment arrangement

TABLE 1 Definition of factorial treatments in mowing × fertility trial conducted in Mid-Atlantic, USA.

Main plot: Fall mowing height	Subplot: Annual N-fertilization[a]	Treatment code
0.5 inches[b]	2.0 lb N 1000^{-2}[c]	0.5 inches
	4.0 lb N 1000^{-2}[d]	0.5 inches + N
0.8 inches	2.0 lb N 1000^{-2}	0.8 inches
	4.0 lb N 1000^{-2}	0.8 inches + N
1.0 inch	2.0 lb N 1000^{-2}	1.0 inch
	4.0 lb N 1000^{-2}	1.0 inch + N

[a]Fertilizer was 100% slow-release N.
[b]Fall mowing treatments were initiated late summer each year.
[c]Broadcast applied early summer each year.
[d]Braodcast applied as split-applications early summer and late summer each year.

with four replications (Table 1). Main plots measured 6.0 ft × 12.0 ft and were split into two 6.0 ft × 6.0 ft subplots. A 6.0 ft buffer was placed between the main plots. Beginning late summer and carrying into dormancy each year, the bench setting height of cut for main plots was switched to 0.5 inches, 0.8 inches, or 1 inch. Mowing treatments were delivered using walk-behind reel mowers. At the College Park, MD location, clippings were collected during every mowing event using clipping baskets on the front of the mowers; however, at the Blacksburg, VA location, clippings were returned to the canopy. Excess mower traffic (i.e., turning and transport between plots) was confined to the buffers placed between main plots. The subplot factor examined two annual N-fertilization regimes: 2.0 lb N 1000 ft^{-2} applied in early summer only or 2.0 lb N 1000 ft^{-2} applied in both early and late summer. In the first year of the trial, fertilizer treatments were applied on June 21, 2019, and Aug. 13, 2019, in Blacksburg. In the second year of the trial, fertilizer treatments were applied on 30 Jun 2020 and 02 Sep 2020 in Blacksburg. Specific application dates for both years at the College Park, MD, and Midlothian, VA, locations are unknown, but the first application for each year occurred in May or June and the second application for each year occurred between mid-August and mid-September. These treatments were applied to plots as water-insoluble, 100% slow-release N (Shaw's 44-0-0 100% SurfCote-4 [Knox Fertilizer Company]) using a 3.0-ft wide Gandy Lawn Drop Spreader (Gandy Company) at College Park and a shaker jar at Blacksburg and Midlothian.

1.3 | Winter desiccation site descriptions

A research trial investigating the impact of soil VWC was also established at College Park, MD, Midlothian, VA, and Blacksburg, VA. Interspecific hybrid bermudagrass cultivars at College Park, Midlothian, and Blacksburg were Tahoma 31, Tufcote, and Latitude 36, respectively. Each location's

TABLE 2 Definition of factorial treatments in winter desiccation trial conducted in Mid-Atlantic, USA.

Main plot: Winter irrigation	Subplot: Wetting agent
0.5 inches[a]	Fall alkoxylated polyols[b]
	Fall + Winter alkoxylated polyols[c]
	None
No irrigation	Fall alkoxylated polyols
	Fall + Winter alkoxylated polyols
	None

[a]Applied when soil volumetric water content dropped below 15%.
[b]Applied at 16.0 fl oz 1000 ft^{-2} in mid-Oct each year. Watered in after application.
[c]Applied at 16.0 fl oz 1000 ft^{-2} in mid-Oct and mid-Jan each year. Watered in after application.

trial area was on predominantly sand-based root zones. Root zone mixes were as follows: 80-15-5 (sand-soil-biosolid by volume) at College Park and sand-capped native soil at Midlothian and Blacksburg. Mowing during the growing season was performed 3× wk^{-1} with a 0.5-inch bench setting height of cut. Fertilizer, herbicides, and irrigation were applied as necessary throughout the growing season to maintain healthy turfgrass.

1.4 | Winter desiccation study design

The trial utilized a split-plot RCBD with a 2 × 3 factorial treatment arrangement (Table 2). Main plots measured 6.0 ft × 18.0 ft and were subdivided into three 6.0 ft × 6.0 ft subplots. A 2.0 ft border was placed between the main plots. The main plot factor examined irrigation (none or 0.5 inches of irrigation) applied during dormancy to maintain soil VWC. To assess VWC, Toro Turf Guard Wireless Soil Monitoring Sensors (The Toro Company) were placed in each replicate of the irrigation-only treatment. An additional sensor was placed in one replicate of the non-treated control to serve as a baseline for overall soil moisture throughout the winter. When remote sensors measured VWC below 20%, VWC of each plot was monitored by hand daily using a FieldScout TDR 350 Soil Moisture Meter (Spectrum Technologies, Inc.,) equipped with 1.5-inch probes. Irrigation was applied to main plots when soil VWC dropped below 15%.

The subplot factor examined combinations of late-fall and winter wetting agent applications (none, mid-Oct, or mid-Oct + mid-Jan). Wetting agents were applied as alkoxylated polyols (Hydra-Last; HydraSmart) at 16.0 fl oz 1000 ft^{-2} using a CO_2-pressurized system using an air-induction nozzle calibrated to apply 2.0 gallons 1000 ft^{-2} evenly across the plot. Wetting agent treatments were watered in either with rainfall or irrigation immediately after application with the exception of two treatments for the winter 2021 application in Blacksburg, VA, due to an irrigation malfunction.

1.5 | Freeze chamber desiccation experiments

Due to mild and wet winter conditions, a supplemental dry-down experiment using plugs collected from field plots was necessary to evaluate the effects of desiccation on survival of interspecific hybrid bermudagrass exposed to freezing temperatures. In January 2021, three 2.5-inch diameter plugs were extracted to a depth of 2.0 inches from random locations within each plot of the aforementioned winter desiccation field trials. The study was not repeated over time, but it was repeated over space three times with plugs from College Park, MD, Midlothian, VA, and Blacksburg, VA, each serving as separate experimental runs. Plugs were placed into D27L cone-tainers (2.7 inches × 17.0 inches, Stuewe & Sons, Inc.) that were backfilled with a 90% sand and 10% peat (v:v) rootzone mix. Once the plugs were planted into the cone-tainers and backfilled, cone-tainers were arranged in an outdoor covered area to dry down in temperature conditions similar to the field trial. A fan was used to facilitate the dry-down process, and the cone-tainers were moved regularly to ensure even exposure to direct wind. Daily VWC measurements were taken at a 1.5-inch depth with a TDR 350 (Spectrum Technologies, Inc.) until all cone-tainers dried down below 15% VWC. Once all cone-tainers had VWCs below 15%, half of the cone-tainers were left non-irrigated and half of the cone-tainers were irrigated to saturation and allowed to drain for 24 h to reach field capacity. Final VWC ranges across all three runs of the trial were 8.0-14.6% for non-irrigated cone-tainers and 19.3-28.6% for irrigated cone-tainers, respectively.

Cone-tainers were then placed into a freezer at 5.0˚F for 5 h. All non-irrigated plugs had VWCs of $<$ 15% and all irrigated plugs had VWCs of $>$ 19% at the time of sub-freezing temperature exposure. Temperature and time exposure were determined from a preliminary pilot study (data not shown). After 5 h in the freezer, cone-tainers were removed and placed on a greenhouse bench to measure survival and green-up. Beginning nine days after sub-freezing temperature exposure, plugs were assessed weekly for three weeks. Additionally, the plugs were monitored for green-up for $>$ 6 weeks. No significant green-up ($\leq$ 6%) occurred for non-irrigated treatments after 6 weeks, so the bermudagrass injury was deemed lethal—not just delayed green-up. Greenhouse environmental conditions were maintained with a 12–13 h photoperiod and daily high and low temperatures of 80.0˚F and 60.0˚F, respectively. Irrigation was provided to maintain adequate soil moisture (i.e., 20–25% VWC) during the green-up period.

A follow-up freeze chamber desiccation experiment using cone-tainers was conducted at the University of Arkansas in Fayetteville, AR, from late winter of 2023 to spring of 2023 to determine the relationship of various VWC levels on cold temperature injury to interspecific hybrid bermudagrass. The experiment was set up as a completely randomized design and

TABLE 3 Main effects of late summer and fall mowing height and fertility on percent green cover area under the progress curve (% Green Cover AUPC) in Blacksburg, VA.

	Late-season fertility[a]		Fall mowing height[b]		
	No late-season fertility	Late-season fertility	0.5 inches	0.8 inches	1.0 inch
Fall 2019	2249b[c]	2886a	NS	NS	NS
Spring 2020	1123b	1864a	NS	NS	NS
Fall 2020	3177b	3944a	NS	NS	NS
Spring 2021	1938b	2430a	2569a	1779c	2204b

Abbreviation: NS, not significant.

[a]Both treatments received 2.0 lb N 1000 ft^{-2} early summer each year and late-season fertility treatments received an additional 2.0 lb N 1000 ft^{-2} late summer.

[b]Fall mowing heights initiated late summer each year.

[c]Data subjected to ANOVA and treatments were compared within each season. Means of late-season fertility within a row with a common letter are not significantly different according to a Student's *t*-test ($p < 0.05$). Means of mowing height within a row with a common letter are not significantly different according to Tukey's HSD ($p < 0.05$).

repeated across space. Tifway interspecific hybrid bermudagrass plugs were extracted from a sand-based field during winter dormancy and plugs were planted and dried down following similar methods of the aforementioned study. Once the VWC of the soil in all cone-tainers was below 15%, the plugs were treated with either 25, 38, 50, 63, 75, 88, 100, 113, 125, 138, or 150 mL of water to achieve a wide range of soil moisture levels. The range was 7.3%–21.5% VWC for the first experimental run and 12.9%–23.0% VWC for the second experimental run. Once the plugs were irrigated and VWC measured, they were then placed into a freezer at 15.8˚F for 2, 4, 6, or 8 hours. After exposure to 15.8˚F for the allotted times, the plugs were then placed in a greenhouse to recover and green up. Plugs not exposed to 15.8˚F were also included as controls for comparison.

1.6 | Data collection and analysis

Field studies were rated during spring green-up each year for visual percent green cover and turfgrass quality (1–9 scale; 9 = best, 6 = minimally acceptable). Counts of *Poa annua* L. were collected each winter at the Blacksburg, VA location only. Visual percent green cover and turfgrass quality were assessed for cone-tainers in the desiccation freeze chamber experiments. Additionally, digital images of cone-tainers were collected every 7–14 d and analyzed for green pixel count using the TurfAnalyzer software (http://turfanalyzer.com; Karcher et al., 2017).

At the conclusion of the green-up period in the first greenhouse experiment, root biomass was assessed by loss on ignition. Plugs were removed from cone-tainers, and all foliage was removed. Root samples were then dried in a 140.0˚F oven for 48 h. Once dried, non-root organic debris was removed, and samples were weighed and placed into a muffle furnace at 1022.0˚F for > 3 h. Samples were then re-weighed to determine the weight of organic carbon that was lost.

For the freeze chamber desiccation study testing bermudagrass plugs from the College Park, MD, Midlothian, VA, and Blacksburg, VA, locations, percent green cover, turfgrass quality, and percent green pixels were converted to area under the progress curve (AUPC) values using the trapezoidal method to produce summative ratings (Madden et al., 2007). Data were subjected to analysis of variance (ANOVA), and means were separated, when appropriate, using a Student's *t*-test for factors with 2 levels or Tukey's HSD for factors with 3 levels ($p \leq 0.05$) in JMP Pro 15 (SAS Institute, Cary, NC). However, for the freeze chamber desiccation experiment conducted in Fayetteville, AR, runs were analyzed separately and % VWC and % visual green-up as well as % VWC and % green pixels using digital image analysis (DIA) on each rating date for each exposure time were subjected to linear regression in JMP Pro 16 (SAS Institute). Only data from 6 h of exposure are presented in this manuscript.

2 | RESULTS

2.1 | Late-season fertility

Late-season fertility increased percent green cover each fall by >19% and increased spring green-up by >20% at the Blacksburg, VA, location (Table 3). Percent green cover at the College Park, MD, location was only affected by late-season fertility in the fall of 2020, where late-season fertility increased percent green cover by 5% on Oct. 19 (Table 4). The differences dissipated by the next rating date and did not return during spring green-up. Percent green cover was not affected by late-season fertility at the Midlothian, VA, location (data not shown). Late-season fertility increased turfgrass quality each fall and spring by at least 16% at the Blacksburg location (Table 5). Similarly, turfgrass quality at the Midlothian location was increased >6% by late-season fertility in the spring and fall of 2020 (Table 6).

TABLE 4 Main effects of late summer and fall mowing height and fertility on percent green cover by date in College Park, MD.

	Late-season fertility[a]		Fall mowing height[b]		
	No late-season fertility	Late-season fertility	0.5 inches	0.8 inches	1.0 inch
Oct. 19, 2020	79.2b[c]	83.8a	86.3a	78.8b	79.4ab
Nov. 30, 2020	NS	NS	35.6a	21.6ab	16.1b
Mar. 31, 2021	NS	NS	NS	NS	NS
Apr. 12, 2021	NS	NS	74.4a	57.5ab	54.4b
May 5, 2021	NS	NS	NS	NS	NS

Abbreviation: NS, not significant.

[a]Both treatments received 2.0 lb N 1000 ft^{-2} early summer each year and late season fertility treatments received an additional 2.0 lb N 1000 ft^{-2} late summer.

[b]Fall mowing heights initiated late summer each year.

[c]Data subjected to ANOVA and treatments were compared within each season. Means of late-season fertility within a row with a common letter are not significantly different according to a Student's *t*-test ($p < 0.05$). Means of mowing height within a row with a common letter are not significantly different according to Tukey's HSD ($p < 0.05$).

TABLE 5 Main effects of late summer and fall mowing height and fertility on turf quality area under the progress curve (Turf Quality AUPC) in Blacksburg, VA.

	Late-season fertility[a]		Fall mowing height[b]		
	No late-season fertility	Late-season fertility	0.5 inches	0.8 inches	1.0 inch
Fall 2019	168b[c]	200a	NS	NS	NS
Spring 2020	108b	145a	NS	NS	NS
Fall 2020	235b	297a	255b	257ab	285a
Spring 2021	130b	163a	164a	126c	149b

Abbreviation: NS, not significant.

[a]Both treatments received 2.0 lb N 1000 ft^{-2} early summer each year and late-season fertility treatments received an additional 2.0 lb N 1000 ft^{-2} late summer.

[b]Fall mowing heights initiated late summer each year.

[c]Data subjected to ANOVA and treatments were compared within each season. Means of late-season fertility within a row with a common letter are not significantly different according to a Student's *t*-test ($p < 0.05$). Means of mowing height within a row with a common letter are not significantly different according to Tukey's HSD ($p < 0.05$).

TABLE 6 Main effects of late summer and fall mowing height and fertility on turf quality area under the progress curve (Turf Quality AUPC) in Midlothian, VA.

	Late-season fertility[a]		Fall mowing height[b]		
	No late-season fertility	Late-season fertility	0.5 inches	0.8 inches	1.0 inch
Fall 2019	NS	NS	NS	NS	NS
Spring 2020	268b[c]	287a	NS	NS	NS
Fall 2020	311b	332a	NS	NS	NS

Abbreviation: NS, not significant.

[a]Both treatments received 2.0 lb N 1000 ft^{-2} early summer each year and late-season fertility treatments received an additional 2.0 lb N 1000 ft^{-2} in Aug.

[b]Fall mowing heights initiated late summer each year.

[c]Data subjected to ANOVA and treatments were compared within each season. Means of late-season fertility with a common letter are not significantly different according to a Student's *t*-test ($p < 0.05$).

2.2 | Fall mowing height

Increasing fall mowing height above 0.5 inches decreased percent green cover by at least 10% in spring 2021 but did not affect percent green cover in fall 2019, spring 2020, and fall 2020 at the Blacksburg, VA, location (Table 3). At the College Park, MD, location, maintaining fall mowing height at 0.5 inches retained fall green color and increased spring green-up compared to increasing fall mowing height to 0.8 inches or 1.0 inch (Table 4). Fall mowing height did not affect percent green cover at the Midlothian, VA, location (data not shown). Turfgrass quality was not affected by fall

TABLE 7 Main effects of late summer and fall mowing height and fertility on Poa annua counts and weed coverage (% plot area) in Blacksburg, VA.

	Late-season fertility[a]		Fall mowing height[b]		
	No late-season fertility	Late-season fertility	0.5 inches	0.8 inches	1.0 inch
***Poa annua* counts**					
Winter 2020	NS[c]	NS	26.4 a	11.5 b	7.6 b
Winter 2021	NS	NS	87.3a	18.3b	9.6b
Weed coverage (% plot area)					
Winter 2020	10.4a	7.2b	15.4a	5.9b	5.1b
Winter 2021	2.9a	1.8b	5.0a	1.2b	1.0b

Abbreviation: NS, not significant.

[a]Both treatments received 2.0 lb N 1000 ft^{-2} early summer each year and late-season fertility treatments received an additional 2.0 lb N 1000 ft^{-2} late summer.

[b]Fall mowing heights initiated late summer each year.

[c]Data subjected to ANOVA and treatments were compared within each season. Means of late-season fertility within a row with a common letter are not significantly different according to a Student's *t*-test ($p < 0.05$). Means of mowing height within a row with a common letter are not significantly different according to Tukey's HSD ($p < 0.05$).

mowing height at the Midlothian location (Table 6) and the College Park location (data not shown). Fall mowing height differentially influenced turfgrass quality at the Blacksburg location (Table 5). Raising fall mowing heights to 1.0 inch resulted in 11% higher turfgrass quality in fall 2020 compared to the 0.5-inch mowing height (Table 5). Conversely, turfgrass quality in spring 2021 was highest in plots mown at 0.5 inches, while turfgrass quality was lower at the 1.0-inch mowing height and lowest at the 0.8-inch mowing height (Table 5).

There was significant *P. annua* pressure at the College Park, MD, location; therefore, pre-emergent herbicides were used. At the Blacksburg, VA, location, where pre-emergent herbicides were not applied, *P. annua* encroachment was reduced by at least 56% in the winter of 2020 and at least 79% in the winter of 2021 in plots with fall mowing heights of 0.8 inches and 1.0 inch compared to plots mown at 0.5 inches (Table 7, Figure 1). Additionally, total percent weed coverage was lower in plots with fall mowing heights of 0.8 inches and 1.0 inch (Table 7).

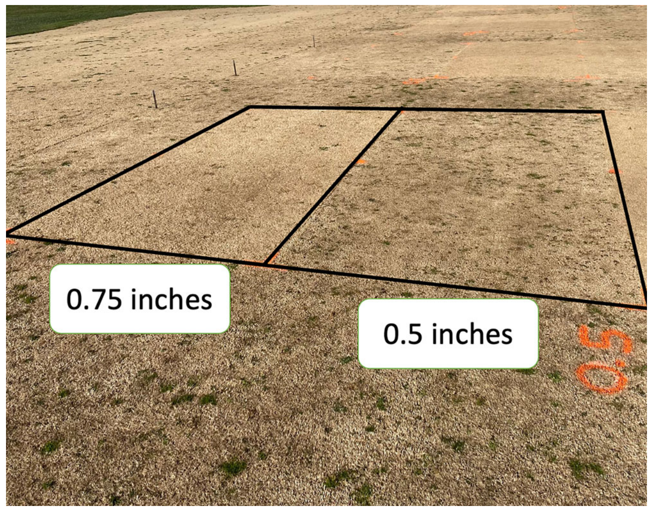

FIGURE 1 Influence of fall mowing height on winter weed cover on 'Patriot' bermudagrass in Blacksburg, VA.

2.3 | Winter desiccation

There were no significant differences between treatments in the winter desiccation field trials at any location (data not shown). In freeze chamber experiments, irrigation prior to a simulated freeze event significantly improved visual percent green cover (>99%), turfgrass quality (>68%), and green pixel counts (>98%) for plugs collected from each location (Table 8, Figure 2). Additionally, for plugs collected from the Midlothian, VA, and College Park, MD, locations, root biomass was at least 60% greater for plugs that received irrigation prior to the simulated freeze event (Table 8). For the freeze chamber experiment conducted in Fayetteville, AR, there was a significant positive effect of VWC on percent green-up for both visual and DIA assessments for the 6-h exposure treatments (Tables 9 and 10).

3 | DISCUSSION

Our data show late-season applications of N fertility can be beneficial in retaining fall color without sacrificing cold hardiness. These findings are similar to what has been observed in other studies across different regions of the transition zone (Goatley et al., 1994; Munshaw et al., 2007; Richardson, 2002). At the Blacksburg, VA, location, late-season fertility consistently increased percent green cover, yet at the

TABLE 8 Visual percent green cover (% GC) area under the progress curve (AUPC), turf quality (1–9) (TQ) AUPC, digital image analysis green pixel count (GP) AUPC, and root biomass (mg) for desiccation freeze chamber studies conducted in Mid-Atlantic, USA, in 2021.

	% GC AUPC[a]		TQ AUPC[b]		GP AUPC[c]		Root biomass[d]	
Location	**I**[e]	**N**	**I**	**N**	**I**	**N**	**I**	**N**
Blacksburg, VA	597a[f]	2b	52a	15b	254a	3b	–	–
Midlothian, VA	424a	1b	44a	14b	348a	2b	245a	97b
College Park, MD	1128a	0b	84a	14b	887a	2b	409a	61b

[a]Visual percent green cover area under the progress curve.
[b]Turfgrass quality area under the progress curve.
[c]Green pixel count area under the progress curve.
[d]Root biomass, measured as loss on ignition.
[e]I and N represent irrigated and non-irrigated prior to freezing event, respectively.
[f]Data subjected to ANOVA and treatments were compared within each season. Means for each parameter measured within a row with a common letter are not significantly different according to a Student's *t*-test ($p < 0.05$).

College Park, MD, location, percent green cover was only affected by fertility on one date. Moreover, at the Midlothian, VA, location, percent green cover was not affected by late-season fertility. The additional N applications in the fall never increased the amount of cold injury or winterkill at any location. This supports the notion that sensible applications of N in the fall could help turfgrass managers retain more green color without increasing their risk of injury.

Our data suggest that fall mowing height at 0.5 inches increased green color retention going into dormancy and increased spring green-up when mowing height was significant. The greater fall green color at the lowest mowing height could potentially be explained by the process of hydrodynamic instability described by Ackerson et al. (2015) and Thompson & Daniels (2010). However, with bermudagrasses mowed at extremely low heights like what are found on golf course putting greens, raising mowing height has been shown to enhance cold tolerance and regrowth after exposure to sub-freezing temperatures (Xiang et al., 2023). Although our study did not result in a clear effect of mowing height on bermudagrass winter survivability, Xiang et al. (2023) reported increased green-up and survivability to sub-freezing temperatures with putting green-type interspecific hybrid bermudagrasses when raising mowing heights. Their study was conducted in a controlled environment with consistent sub-freezing temperatures, whereas our study was in a field setting with mild winters. Additionally, the Xiang et al. (2023) study examined the effects of mowing heights at much lower heights of cut (0.1 to 0.3 inches), whereas our study examined much higher heights of cut ranging from 0.5 to 1.0 inches. These two key differences help explain why there were effects of mowing height on bermudagrass survival in the Xiang et al. (2023) study yet no obvious mowing height effects on bermudagrass winter survival in our study.

Turfgrass quality was generally unaffected by fall mowing height. Increasing mowing height in the fall is commonly recommended to growers with bermudagrass in the transition zone. This recommendation comes from the notion that increasing mowing height can encourage greater rooting and enhance bermudagrass cold tolerance (Tucker et al., 2006; Xiang et al., 2023). Our data show no evidence of negative effects on winter survival from any of the tested mowing heights. In fact, our data suggest increasing fall mowing height may delay spring green-up. The delay in spring green-up with higher mowing heights could be potentially, at least partially, explained due to more dead bermudagrass leaf tissue obstructing the plot rater's view of green tissue closer to the ground. Although soil temperatures within individual plots were not monitored in this study, another possible explanation is that lower mowing heights may have allowed for the soil to warm up faster due to more sun exposure than soil in the plots with higher heights of cut. The reasons for the delayed green-up in higher mown plots are not entirely clear. Regardless, increasing fall mowing height above 0.5 inches may still be advisable in areas of marginal adaptation for interspecific hybrid bermudagrass due to its potential to decrease *P. annua* and other weed species encroachment as the interspecific hybrid bermudagrass enters dormancy.

FIGURE 2 Influence of irrigation on interspecific hybrid bermudagrass survival prior to simulated short-term freeze event.

Finally, our data suggest increasing soil moisture prior to short-term freeze events significantly reduces cold-related

TABLE 9 Regression models for visual percent green cover for a freeze chamber desiccation study conducted in Fayetteville, AR in 2023. Data from dates in which both visual ratings were collected and digital analysis was conducted are presented below regardless of significance levels.

Run	Assessment date	Regression coefficients	*p*-values	Prediction equation	R^2
1	Mar. 23, 2023	0.46	0.0448	y = 0.46x – 2.83	0.34
	Mar. 30, 2023	1.04	0.0559	y = 1.04x – 5.25	0.32
	Apr. 6, 2023	1.75	0.0444	y = 1.75x – 10.04	0.35
2	Mar. 23, 2023	0.64	0.1337	y = 0.64x – 4.87	0.21
	Mar. 30, 2023	1.07	0.0482	y = 1.07x – 9.57	0.34
	Apr. 6, 2023	1.82	0.0534	y = 1.82 – 15.99	0.32

TABLE 10 Regression models for percent green pixels from digital image analysis for a freeze chamber desiccation study conducted in Fayetteville, AR in 2023. Data from dates in which both visual ratings were collected and digital analysis was conducted are presented below regardless of significance levels.

Run	Assessment date	Regression coefficients	*p*-values	Prediction equation	R^2
1	Mar. 23, 2023	0.70	0.0571	y = 0.70x – 1.37	0.32
	Mar. 30, 2023	1.32	0.0370	y = 1.32x – 5.77	0.37
	Apr. 6, 2023	1.38	0.1156	y = 1.38x + 0.28	0.23
2	Mar. 23, 2023	0.54	0.3054	y = 0.54 – 1.67	0.10
	Mar. 30, 2023	1.30	0.0872	y = 1.30 – 9.27	0.26
	Apr. 6, 2023	1.53	0.1533	y = 1.53 – 6.51	0.19

injury or winterkill. Many published extension and trade articles suggest that areas with excessive soil moisture (i.e., poorly drained areas) are highly susceptible to winterkill (Chalmers, 1986; Jacobs, 2021; McCurdy, 2018). The key discrepancy with our study is that the freezing event was short-term and not for an extended period of time. Poorly drained areas decrease bermudagrass health and can predispose it to myriad biotic and abiotic stressors over long periods of time—winterkill being one (Chalmers, 1986; McCurdy, 2018). However, higher moisture levels from an irrigation event leading into a short-term freeze event can be beneficial for bermudagrass survival as shown in our study as well as other cropping systems such as cherries, citrus, and peaches (Tsipouridis et al., 2006; Wilcox & Davies, 1981). Irrigation prior to a short-term freeze event can provide a temporary heating effect to the plant, protecting it from short-term freeze damage (Rieger, 1989). Data from the cone-tainer experiment conducted on bermudagrass collected from the College Park, MD, Midlothian, VA, and Blacksburg, VA, locations showed increased bermudagrass survival and root biomass when plugs received irrigation prior to a simulated short-term freeze event. Moreover, data from the cone-tainer experiment conducted in Fayetteville, AR, demonstrated the positive relationship between soil VWC and interspecific hybrid bermudagrass green-up when bermudagrass was exposed to a short-term freeze event. Recommending turfgrass managers to irrigate prior to extended freezing weather conditions may not prove as useful as irrigating prior to short-lived freezing weather. Moreover, it is likely to be difficult to implement, as most irrigation systems will be winterized to prevent damage to the irrigation system in areas where winterkill is a concern. The most feasible potential benefit of irrigating bermudagrass prior to a freeze event would be during the spring to prevent damage from a cold snap when freezing conditions would not persist long enough to cause concern for irrigation system damage.

Our data indicate that increased mowing height and increased fall N fertility going into winter dormancy, as well as increasing soil moisture prior to short-term freeze events can provide benefits to interspecific hybrid bermudagrass grown in the transition zone. It is important to note that winter conditions at all sites were mild for both winter seasons where field trials were conducted. Air temperatures were never continuously below 32˚F for more than 48 h at any location in either year of the study. Rainfall at all three locations occurred enough to prevent the need to apply irrigation treatments to the desiccation field trials. This limited our ability to measure treatment effects on winter survival, and these results should be validated under field conditions in future research. Findings from this research still provide deployable practices for turfgrass managers now, as well as guidance for future research. The role of soil moisture on bermudagrass winterkill needs to be further studied given the significant positive influence of soil moisture on bermudagrass survival prior to short-term freeze events in our cone-tainer studies contrasting with evidence of negative effects of excessive soil moisture on bermudagrass exposed to long-term freezing conditions (Chalmers, 1986; Jacobs, 2021; McCurdy, 2018).

AUTHOR CONTRIBUTIONS

Joseph R. Doherty: Conceptualization; data curation; formal analysis; investigation; writing—original draft. **Wendell Hutchens**: Conceptualization; data curation; formal analysis; investigation; writing—review and editing. **Jordan Booth**: Conceptualization; data curation; investigation; writing—review and editing. **David McCall**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing. **Michael V. Battaglia**: Data curation; investigation. **Eric DeBoer**: Investigation; methodology; writing—review and editing. **Joseph Roberts**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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