

ORIGINAL ARTICLE

Climatology and Water Management

Irrigation frequency and mowing height influence annual bluegrass in perennial ryegrass

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Abstract

Annual bluegrass (*Poa annua* L.) is a winter annual weed with limited herbicide control options in cool-season turfgrasses. This research evaluated the effect of irrigation frequency and mowing height on annual bluegrass cover in perennial ryegrass (*Lolium perenne* L.) in 2019 and 2020 on a 3-year-old mixed stand in North Brunswick, NJ. Treatments were arranged in a 2-by-2 factorial in a randomized split-plot design with mowing height (11 or 38 mm) as the main plot and irrigation frequency (once or thrice week⁻¹) as subplot. From June to October each year, both irrigation frequency treatments were irrigated to 60% reference evapotranspiration minus rainfall. Soil volumetric water content was consistently lower in once week⁻¹ irrigation treatments in both years. Annual bluegrass cover was affected by irrigation frequency and mowing height, but no interaction was detected. In October, annual bluegrass cover was reduced (47%) in once week⁻¹ treatments compared to thrice week⁻¹ treatments (59%). Additionally, annual bluegrass cover in October was reduced in treatments mown at 38 mm (46%) compared to 11 mm (60%). Irrigation frequency had no effect on turfgrass quality, green cover, or normalized difference vegetation index (NDVI); however, mowing height affected these response variables. When differences were present, all values were greater in the higher mown treatments. This research suggests reducing irrigation frequency reduces annual bluegrass cover without affecting turfgrass quality, green cover, or NDVI in the humid subtropical climate (near the Humid Continental climate zone). Additionally, increasing mowing height will reduce annual bluegrass cover.

Plain Language Summary

Annual bluegrass is a pervasive weed of turfgrass. It is so pervasive that it often becomes an acceptable part of the sward, as maintaining it is difficult and costly. It

Abbreviations: ET₀, reference evapotranspiration; NDVI, normalized difference vegetation index.

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needs more water and pesticide inputs than most other grasses. However, controlling it with herbicides has also proven to be difficult. It is often found in shorter mown areas such as golf course fairways and athletic fields. The goal of this research project was to determine if watering less often and mowing the grass at a higher height would reduce the amount of annual bluegrass. Watering once per week from June to October reduced annual bluegrass compared to watering three times per week and did not affect the aesthetics and functionality of the turf. Increasing the mowing height reduced the amount of annual bluegrass that was present and sometimes increased turfgrass quality. This research demonstrates some strategies that turf managers can implement into their management programs to reduce annual bluegrass.

1 | INTRODUCTION

Annual bluegrass (*Poa annua* L.) is a winter annual grassy weed that is difficult to control in turfgrass systems (Christians et al., 2017). Annual bluegrass is a prolific seed producer (Rana & Askew, 2018) and has poor tolerance to abiotic stresses (Beard et al., 1978; Espevig et al., 2014; Inguagiato et al., 2008; Vargas & Turgeon, 2004). The high inputs of fertilizer, fungicides, and irrigation required to maintain annual bluegrass are relatively expensive, making it an undesirable species for most turfgrass managers.

Herbicides and cultural practices are commonly used for annual bluegrass control (McCurdy et al., 2023). However, herbicide options are limited in cool-season turfgrass and control is difficult due to limited efficacy (Beard, 2002). Annual bluegrass populations are influenced by cultural practices but approach and timing are critical for control (Beard, 1970; Gaussoin & Branham, 1989). The exploitation of cultural practices to alleviate annual bluegrass weed pressure is a recommended approach for integrated pest management in turfgrass systems (McCurdy et al., 2025; Watschke et al., 2013). The high maintenance characteristic of annual bluegrass makes reducing inputs (i.e., fertilizer, supplemental irrigation, fungicides, etc.) an attractive option for annual bluegrass control.

Annual bluegrass is commonly found in low mown (Adams, 1980; Bogart & Beard, 1973; Neal, 1994) and frequently irrigated areas (Busey, 2003; Cain et al., 2022; Chen et al., 2018), making it problematic on highly managed turfgrass such as golf course fairways, tees, and putting greens, as well as athletic fields (Beard, 2002). Mowing height modifications can directly influence weed invasion (Busey, 2003; Calhoun et al., 2005). Averaged across three N levels, Adams (1980) observed more annual bluegrass cover (34%) in perennial ryegrass (*Lolium perenne* L.) mown at 1.3 cm compared to 2.5 and 7.5 cm (20% and 9%, respectively). Similarly, in carpetgrass (*Axonopus affinis* Chase), annual bluegrass cover was greater when mown at 3.8 cm compared to 7.5 cm (31%

and 9%, respectively) when averaged across N levels (Bush et al., 2000). Annual bluegrass seed production is higher when mown at 5–6 mm compared to 64–76 mm (Gibeault, 1966), and it commonly produces seed in low mown systems (3 mm; Reicher et al., 2020).

Drought stress reduces annual bluegrass seed viability (R. L. Green et al., 2001). Annual bluegrass is often associated with poor drought tolerance as it has a shallow root system (Gibeault & Goetze, 1972; Goss, 1974; Warwick, 1979). Irrigation frequency and quantity are both important factors to evaluate with regard to irrigation management. However, previous research has determined frequency to be more impactful on annual bluegrass emergence due to the importance of maintaining continuous moisture in the upper level of the soil profile (Chen et al., 2018; Gaussoin & Branham, 1989; Youngner, 1959). Annual bluegrass cover in creeping bentgrass (*Agrostis stolonifera* L.) was higher when irrigated daily at 75% open pan evaporation compared to thrice week⁻¹ at 110% open pan evaporation in Michigan (Gaussoin & Branham, 1989). Although 75% open pan evaporation required less water per cycle (and overall), the authors concluded that perhaps more annual bluegrass was present due to frequency rather than quantity. Similarly, Chen et al. (2018) concluded that irrigation quantity (60% or 100% of field capacity) did not affect annual bluegrass cover in a red fescue (*Festuca rubra* L.) putting green at the end of a 2-year study when irrigated thrice week⁻¹ in southern Norway. However, irrigating to 60% of field capacity, once week⁻¹ reduced annual bluegrass cover compared to irrigating to 60% or 100% of field capacity, thrice week⁻¹ (Chen et al., 2018). This suggests infrequent, but sufficient irrigation can be an effective strategy to reduce annual bluegrass infestations.

In some studies, annual bluegrass was unaffected by irrigation treatment. Lodge and Lawson (1993) found similar annual bluegrass cover across irrigation treatments of 75%–125% reference evapotranspiration (ET₀), but stated that the irrigation treatment range may have been too narrow for differences to occur. Similarly, Bell et al. (1999) found annual

bluegrass emergence in a creeping bentgrass sward to be similar when irrigated at either 50 or 100% evapotranspiration; all treatments were applied thrice week⁻¹, which may have been frequent enough to provide adequate moisture to the upper level of the soil for seed germination and where most seedling roots were present. Laskowski (2017) concluded that annual bluegrass invasion was not affected by irrigation treatment (8%, 12%, or 16% soil volumetric water content); however, the authors noted that the high stress put on the desired turfgrass species in the low soil volumetric water content treatment allowed for more annual bluegrass invasion, while the desired turfgrass species in the 12% and 16% treatments had adequate shoot density. These studies all focused on quantity, not frequency. Previous research suggests irrigation treatment alone provides inconsistent results with annual bluegrass invasion and interactions of irrigation frequency and mowing height in perennial ryegrass have not been evaluated. Additionally, the effect of irrigation frequency on annual bluegrass competitiveness in perennial ryegrass has only been reported in climates with hot, dry summers (Cain et al., 2022; Olsen et al., 2019); no work has been reported in a humid subtropical climate zone (i.e., New Jersey), which is characterized by hot, humid summers with substantial rainfall (Alvares et al., 2013).

Evaluating turfgrass color and quality of the desired turfgrass species is warranted when implementing stressful conditions such as low mowing or limited irrigation. Past research has shown a variety of perennial ryegrass quality responses based on mowing height (Carrow & Troll, 1977; DeBels et al., 2012; Hugie & Watkins, 2016), and water requirements among cool-season turfgrass species vary (Blankenship et al., 2020; Braun et al., 2022; DaCosta & Huang, 2006). Perennial ryegrass and tall fescue (*Schedonorus arundinaceus* L.) are among the cool-season species that can maintain green color as irrigation cycle intervals are extended (Blankenship et al., 2020); whereas fine fescues require the shortest irrigation intervals among cool-season species (Blankenship et al., 2020). When irrigated at the same quantity, Chen et al. (2018) observed poorer red fescue quality and color in the once week⁻¹ treatments compared with thrice week⁻¹ treatments by the end of the study. Species selection is important and choosing a desired species that can withstand longer irrigation cycle intervals is crucial. This will reduce irrigation usage and may lead to the reduction of annual bluegrass cover while maintaining turfgrass color and quality of the desired turfgrass species. The efficacy of cultural practices for annual bluegrass control may vary based on desired turfgrass species and expectations of sward health and vigor.

The objective of this study was to evaluate the effects of irrigation frequency and mowing height on annual bluegrass cover in perennial ryegrass in a humid subtropical climate zone. We hypothesize annual bluegrass cover in perennial ryegrass will be reduced most at a higher mowing height when irrigated infrequently.

Core Ideas

- Annual bluegrass cover was reduced in perennial ryegrass when irrigated once week⁻¹ compared to thrice week⁻¹.
- Annual bluegrass cover was reduced in perennial ryegrass when mown at 38 mm compared to 11 mm.
- Irrigation frequency did not affect turfgrass quality, green cover, or normalized difference vegetation index.

2 | MATERIALS AND METHODS

2.1 | Experimental site

A field trial was conducted from April 2019 to April 2021 on a 3-year-old perennial ryegrass field that was naturally infested with annual bluegrass. The annual bluegrass on the site exhibited primarily an upright growth habit (i.e., bunch-type growth habit and no stoloniferous growth) characteristic of *P. annua* ssp. *erecta* and a minority component exhibited a creeping growth habit (i.e., elongated, branched stems growing along the ground that develop roots at the nodes) characteristic of *P. annua* var. *reptans* (Hausskn.) T. Koyama (Vargas & Turgeon, 2004). The field was located at the Rutgers University Horticulture Farm No. 2 in North Brunswick, NJ and maintained on a sandy loam soil with 1.5% organic matter and a pH of 5.6. Soil samples were collected each spring to measure soil nutrient content, and fertilizer applications were made based on soil test recommendations to achieve sufficiency. All plots received 150 kg N ha⁻¹ year⁻¹ during the study. Nitrogen was applied twice monthly from June to August each year at 5 kg N ha⁻¹. Approximately half of the total N received each year came in the autumn. Dolomitic limestone was applied to the entire field in autumn 2019 at 2200 kg ha⁻¹ to raise soil pH and increase soil Mg. The site was managed on a preventative weed, insect, and disease program that is standard for a perennial ryegrass-annual bluegrass athletic field. This included a twice monthly fungicide application for preventative anthracnose (caused by *Colletotrichum cereale* Manns.), dollar spot (caused by *Clarireedia jacksonii*), summer patch (caused by *Magnaporthe poae*), and brown patch (caused by *Rhizoctonia solani*) control from mid-April through August using azoxystrobin, boscalid, chlorothalonil, cyazofamid, fluzazinam, fluoxastrobin, isofetamid, and tebuconazole. Annual grassy weeds were managed with postemergence applications of fenoxaprop, quinclorac, and topramezone, which are safe on annual bluegrass; no preemergence herbicides were applied. Chlorantraniliprole was applied in May for preventative white grub control. To prevent localized dry spot, a

wetting agent (TriCure, Mitchell Products LLC) was applied monthly at 12.7 L ha⁻¹ from May through August each year.

2.2 | Treatments and experimental design

Treatments were arranged in a 2-by-2 factorial with four blocks, and the experimental design was a randomized split-plot design with mowing height as the main plot and irrigation frequency as subplot. Each subplot was 1.5 by 1.5 m with 1.2 m between blocks and 0.9 m between treatments. These borders were effective in minimizing irrigation runoff between treatments and used as a mower turnaround zone for the walk-behind mower. Whole plots were mown twice week⁻¹ at 11 or 38 mm throughout the growing season and on an as needed basis in the off-season. The entire field was mown with a triplex (John Deere, 2653A) mower bench set to 38 mm, and a 56-cm reel walk-behind mower (Jacobson, PGM22) was bench set to 11 mm for the low-mown treatments. Clippings from all mowing events were returned throughout the entire study.

Subplot treatments were irrigated once (Wednesday) or thrice (Monday, Wednesday, and Friday) week⁻¹, typically between 8:00 a.m. and 1200 p.m., from June to October of each year. No irrigation was applied to the experimental site outside of this period, as natural rainfall was sufficient for turf quality; no drought symptoms were observed in the off-season. Uniform irrigation was supplied using 1.5 by 1.5 m irrigation frames that were constructed similar to methods described by Olsen et al. (2019). A Rain Bird 1800 series pop-up fixed spray head (Rain Bird Corporation) was mounted in each corner of the irrigation frame and contained an MPR 5Q 90-degree nozzle. Each spray head operated at 207 kPa and all frames were audited each spring, prior to initiation of irrigation treatment. The mean precipitation rate was 37 and 36 mm h⁻¹ in 2019 and 2020, respectively. Distribution patterns were calculated and uniformity between plots was excellent (>0.9). The quantity of water applied at each irrigation cycle was determined by calculating 60% ET₀ since previous irrigation event minus precipitation total since previous irrigation event. Monthly and yearly irrigation amount applied to each treatment is presented in Table 1. An on-site weather station (<100 m from the center of the experimental plots; Campbell Scientific) was used to measure rainfall and calculate ET₀ using the Penman–Monteith equation as described by Allen et al. (1998). The runtime required for each treatment was determined using the following equation:

$$Y = \frac{ET_0(0.6) - R}{P}$$

where Y is the irrigation runtime needed to complete irrigation treatment (min), ET_0 is the reference evapotranspiration for the specified time period (mm), R is the rainfall amount for

the specified time period, and P is the mean precipitation rate (mm min⁻¹). To ensure infiltration and limit lateral surface water movement between plots, no more than 6 mm of water was applied in a 30-min span with ≥30-min interval between irrigation cycles.

2.3 | Response variables

Soil volumetric water content was measured in the top 7.5 cm of the soil twice monthly from June to October using a FieldScout TDR-300 portable soil moisture meter (Spectrum Technologies Inc.). On each rating date, five subsample readings were recorded within each subplot. Each subsample was measured by vertically inserting the probe into the soil profile in five locations within each subplot (one in the middle of the plot and one near each corner). Subsamples visually appeared to be good representatives of their entire subplot and were measured from approximately the same location within each subplot on each rating date. All subsamples measured on the same rating date within a subplot were averaged prior to analysis. Soil volumetric water content measurements were typically recorded between 12:00 p.m. and 6:00 p.m. on the day before the once week⁻¹ irrigation treatments were applied. This was the most appropriate time of measurement as both once and thrice week⁻¹ treatments were near their respective maximum intervals since last irrigation cycle. Annual bluegrass coverage was measured each October and the following April through line-intersect grid counts. The grid consisted of 100 evenly spaced intersects at 83-mm increments. The grid was randomly placed twice in each plot and a tally was given each time an annual bluegrass leaf was directly below an intersect. Grid counts were averaged across subsamples and converted to percent annual bluegrass cover. Turfgrass quality was visually rated twice monthly from June to October of each year using the National Turfgrass Evaluation Program 1–9 scale, where 1 represents low-quality turfgrass, 9 represents high-quality turfgrass, and 6 represents the minimum acceptable level of turfgrass quality (Morris & Shearman, 1998). Green cover was determined twice monthly through digital image analysis of lightbox photos using Turf Analyzer software (Karcher et al., 2017). Images were captured over a 0.32 m² area using a digital camera (Canon EOS Rebel T6i) mounted to a lightbox containing four 1200 lm; 19 W; 5500 K (BlueMax HD Lighting) white light bulbs. Normalized difference vegetation index (NDVI) was measured twice monthly from June to October by making a single pass down the center of each plot with a RapidSCAN CS-45 reflectance meter (Crop Circle, Holland Scientific) at approximately 56 cm above the soil. This device has a data frequency of 2.5 Hz or one reading every 0.4 s (Jiang et al., 2020). Readings took approximately 3–4 s (7–10 readings) plot⁻¹ and were averaged across subsamples prior to analysis.

TABLE 1 Observed temperature, reference evapotranspiration (ET_0), precipitation, and irrigation applied by month in 2019 and 2020 in North Brunswick, NJ.

Month	Temperature (°C)						ET_0^a (cm)		Precipitation (cm)			Irrigation applied (cm)			
	2019		2020		30-Year average low	30-Year average high	2019	2020	2019	2020	30-Year average	2019		2020	
	Average low	Average high	Average low	Average high								Once week ⁻¹	Thrice week ⁻¹	Once week ⁻¹	Thrice week ⁻¹
May	11.6	22.2	9.9	20.9	9.8	22.1	–	–	18.2	5.9	10.6	–	–	–	–
June	15.6	26.9	15.9	28.2	15.6	27.1	8.8	10.1	13.8	7.4	11.2	0	2.7	3.5	4.3
July	19.8	31.6	20.6	31.6	18.3	29.8	11.3	10.3	16.0	28.9	12.9	1.6	4.2	1.2	3.2
Aug.	18.9	29.2	19.3	29.7	17.5	28.8	10.2	8.6	11.6	14.5	10.5	2.9	4.2	0	2.0
Sept.	14.2	27.1	14.1	25.1	12.8	25.2	7.4	7.7	3.9	11.7	11.5	1.2	2.9	1.1	3.4
Oct.	9.3	19.9	8.7	19.0	6.1	18.9	1.8 ^b	0.3 ^c	13.2	14.4	9.7	0.9 ^b	0.9 ^b	0 ^c	0 ^c
Total	–	–	–	–	–	–	39.5 ^d	37.0 ^e	58.5 ^f	76.9 ^f	55.8	6.6 ^d	14.9 ^d	5.8 ^e	12.9 ^e

Note: Temperature, ET_0 , and precipitation were measured by an on-site weather station <100 m from the site. The 30-year average temperature and precipitation in North Brunswick, NJ were obtained from the National Center for Environmental Information at the National Oceanic and Atmospheric Administration.

^aReference evapotranspiration was calculated by an on-site weather station (<100 m from the center of the experimental plots; Campbell Scientific) using the Penman–Monteith equation.

^bOctober data only through October 16, 2019. Irrigation and weather data collection ceased thereafter.

^cOctober data only through October 7, 2020. Irrigation and weather data collection ceased thereafter.

^dTotal is for June through October 16, 2019.

^eTotal is for June through October 7, 2020.

^fPrecipitation total is for June through October.

2.4 | Statistical analyses

All data were subjected to analysis of variance (ANOVA) in SAS (v. 9.4, Statistical Analysis Software Institute Inc.) using PROC GLIMMIX, and assumptions of ANOVA were met. No main-effect-by-year interaction was detected in annual bluegrass cover; therefore, data were pooled across year. Mowing height and irrigation frequency were considered fixed effects, and block and year were considered random effects in the model. Year was analyzed separately for soil volumetric water content, turfgrass quality, green cover, and NDVI data as significant main-effect-by-year interactions were detected at multiple rating dates. Mowing height and irrigation frequency were treated as fixed effects and block was included as a random effect in the model. Fisher's protected least significant difference (LSD) was used to separate means when F -test values were significant ($\alpha = 0.05$).

3 | RESULTS AND DISCUSSION

3.1 | Weather data

Differences in temperature and rainfall total in 2019 and 2020 were apparent at the Rutgers University Horticulture Farm No. 2 in North Brunswick, NJ. In 2019, monthly precipitation exceeded the 30-year average throughout the summer with precipitation falling below the 30-year average in September only (Table 1). In 2020, precipitation was below the 30-year average for May and June and more than doubled the 30-year average in July, although the majority of the

July precipitation came from two tropical storms that made landfall nearly 3 weeks apart. There were multiple >14-day periods with no precipitation from May through August 2020 in North Brunswick, NJ (none occurred in 2019). In addition, air temperature was well above average throughout the summer of 2020 (Table 1), with July 2020 ranking as the hottest month ever recorded in the state of New Jersey (Robinson, 2020). It appears that summer stresses were much more of a factor in 2020 than 2019 as the combination of a drier May and June, warmer June, July, and August, and higher June ET_0 rates were present in 2020 (Table 1).

3.2 | Soil volumetric water content

Irrigation frequency caused differences in soil volumetric water content from July 29 through October 16 in 2019 (Figure 1); once week⁻¹ treatments consistently had lower soil volumetric water content than thrice week⁻¹ treatments. In 2020, differences were detected at all rating dates, and once week⁻¹ treatments had lower soil volumetric water content than thrice week⁻¹ treatments (Figure 1). Similarly, Cain et al. (2022) found once week⁻¹ irrigation in a perennial ryegrass–annual bluegrass field reduced soil volumetric water content compared to four times week⁻¹ irrigation.

3.3 | Annual bluegrass cover

Irrigation frequency and mowing height affected annual bluegrass cover but no interaction was detected ($\alpha = 0.05$).

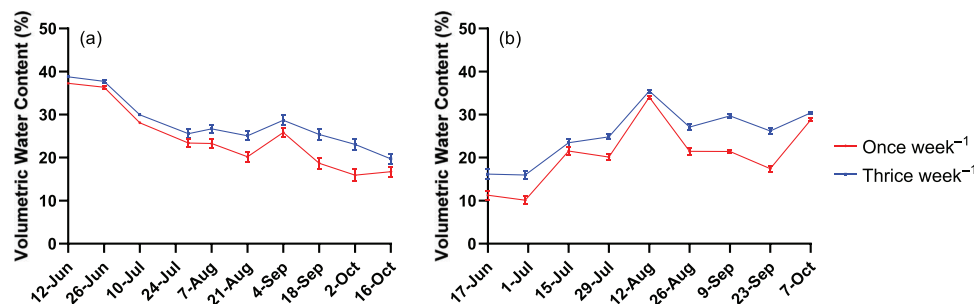


FIGURE 1 Soil volumetric water content as affected by irrigation frequency in 2019 (a) and 2020 (b). Means presented are aggregated across mowing height, subsamples, and replications ($n = 40$). Error bars represent Fisher's protected least significant difference (LSD) ($\alpha = 0.05$).

TABLE 2 Annual bluegrass coverage as affected by irrigation frequency and mowing height in a perennial ryegrass turf in North Brunswick, NJ.

Main effect	Annual bluegrass cover ^a (%)	
	October 28	April 15
Irrigation frequency ^b (week ⁻¹)		
Once	47	48
Thrice	59	60
<i>p</i> -value	0.002	0.0202
Mowing height (mm)		
11	60	62
38	46	46
<i>p</i> -value	0.0004	0.003

^aCoverage was determined through line-intersect grid counts on October 28 in 2019 and 2020 and April 15 in 2020 and 2021.

^bIrrigation was applied from June to October in 2019 and 2020.

Once week⁻¹ irrigation treatments had less annual bluegrass cover (47%) in October than thrice week⁻¹ irrigation treatments (59%; Table 2). The reduction in annual bluegrass in the less frequently irrigated turfgrass echoes previous research in cool-season turfgrass, which found modest reductions in annual bluegrass cover when irrigation frequency was reduced (Cain et al., 2022; Gaussoin & Branham, 1989; Kowalewski et al., 2025; Youngner, 1959). Irrigation frequency appears to be a more critical factor than irrigation amount (Cain et al., 2022; Chen et al., 2018). Frequent irrigation leads to continuous moisture in the upper level of the soil profile, favoring the shallow-rooted annual bluegrass, which allocates $\geq 75\%$ of its total root mass in the 0- to 3-cm soil depth range (Lyons et al., 2011). Additionally, most annual bluegrass seed is concentrated near the soil surface (T. O. Green et al., 2019; Vuković, unpublished data, 2025) and continuous soil moisture promotes germination. In contrast, less frequent irrigation likely reduced establishment from seed because the soil surface dried beyond the threshold needed for seed germination.

Anecdotally, we did not observe perennial ryegrass encroaching voids left by declining annual bluegrass. Perennial ryegrass and annual bluegrass are among the turfgrass

species that have the highest evapotranspiration and water use rates (Huang, 2011), and while annual bluegrass is highly drought-susceptible (Braun et al., 2022), perennial ryegrass is generally only considered slightly more drought-tolerant by most researchers (Beard, 1989; Braun et al., 2022; Christians et al., 2017; Fry & Huang, 2004). Thus, reduced irrigation primarily weakened annual bluegrass rather than enhancing perennial ryegrass competitiveness. Importantly, annual bluegrass cover remained lower in once week⁻¹ treatments the following April of each year (Table 2). This suggests irrigating once weekly from June to October, then resuming irrigation the following June is a sustainable strategy for suppressing annual bluegrass in North Brunswick, NJ.

One limitation in this data is that the statistical difference observed in annual bluegrass cover over the 2-year study may not be noticeable to end-users. Additional years of implementing this approach may be needed to substantially reduce annual bluegrass, which may not be an acceptable timeline for some end-users. Integrating other cultural practices, such as an autumn overseeding of the desired turfgrass species, could further reduce annual bluegrass and deserves more study. Overseeding could potentially accelerate the reduction of annual bluegrass cover by introducing desirable species into voids and competing with germinating annual bluegrass seedlings (Henry et al., 2005). However, others found overseeding alone was not effective, likely because practices that promote seedling establishment (e.g., disturbing soil surface and frequent irrigation) also promote annual bluegrass establishment from the seed bank (Park et al., 2019).

Annual bluegrass cover in October was lower when mown at 38 mm compared to 11 mm (46% and 60%, respectively; Table 2). Similar to irrigation frequency, observations the following April mimic the October ratings. This coincides with Adams (1980) who observed greater annual bluegrass infestation in perennial ryegrass mown at 13 mm compared to 25 or 75 mm. While many turf managers cannot adjust their mowing heights as dramatically as in this study, tweaks in mowing height may be acceptable at certain times of the year (e.g., athletic field offseason). Additionally, increasing the mowing

height in a park or lawn setting to the upper end of the desired species' preferred range is more practical; this has been a recommended strategy in the past to reduce weeds such as annual bluegrass (Busey, 2003).

Based on previous research, we hypothesized that annual bluegrass cover would be reduced the most in perennial ryegrass when mown at a higher mowing height and irrigated infrequently. While annual bluegrass cover was reduced the most when mown at a higher mowing height and when irrigated infrequently, there was no interaction. This result was somewhat surprising as integrated weed management guidelines commonly describe implementing a combination of various cultural practices leads to improved weed control, including the classic example of “many little hammers” as described by Liebman and Gallandt (1997). Perhaps an interaction would have occurred if two consecutive summers with high air temperature and limited rainfall had occurred. This most likely would have put more emphasis on the irrigation treatments, which had a higher p -value at each respective rating date compared to the mowing height treatments (Table 2). A longer term study may be required to observe an interaction between mowing height and irrigation treatment. However, the time interval required to obtain these results may not be practical for a turf manager, although the greater number of cultural practices (e.g., overseeding, fertilization, and clipping removal) implemented may reduce the amount of time needed to observe an interaction.

3.4 | Turfgrass quality

There were no differences in turfgrass quality when soil volumetric water content was similar between treatments, and irrigation frequency had no effect on turfgrass quality throughout the study. Similarly, Jordan et al. (2003) found irrigation frequency had no effect on creeping bentgrass putting green quality in a year with frequent rainfall. However, Jordan et al. (2003) found irrigating creeping bentgrass putting greens every 4 days did improve turfgrass quality compared to every 1 or 2 days in a separate year. Chen et al. (2018) found no red fescue putting green quality effects from irrigation frequency in 1 year of a 2-year study; turfgrass quality did improve in more frequently irrigated turf the following year. Olsen et al. (2019) determined more frequent irrigation (four times week⁻¹) resulted in the best perennial ryegrass quality in Oregon where the average total precipitation for July and August is <10 mm and evapotranspiration rates are typically high. Depending on species selection, irrigation regimen, and climatic region, turfgrass quality may not be affected by irrigation treatment. Our data suggest irrigating perennial ryegrass once week⁻¹ in North Brunswick, NJ can reduce annual bluegrass cover (compared to thrice week⁻¹) without hindering turfgrass quality.

In 2019, turfgrass quality differences were apparent with mowing height, but only from August through October where higher mown turfgrass had better turfgrass quality than the lower mown turfgrass (Table 3). Tall fescue, Chewings fescue, Kentucky bluegrass (*Poa pratensis* L.), and perennial ryegrass have displayed similar responses to mowing height with respect to turfgrass quality (DeBels et al., 2012; Voigt et al., 2001). Neither mowing height treatment resulted in poor turfgrass quality, but the lower mown treatment was mown slightly lower than what is recommended for perennial ryegrass (Turgeon & Kaminski, 2019); it can be expected that turfgrass quality will decrease as mowing height moves away from the recommended range. Nevertheless, this is a common mowing height for perennial ryegrass fairways in this region. In 2020, precipitation was below average in May and June. Consequently, differences in soil volumetric water content were apparent at the first rating date (June 17). Likewise, turfgrass quality differences among treatments appeared at both rating dates in June. However, these differences were based on mowing height and not irrigation frequency; the higher mown treatments had greater turfgrass quality (Table 3). In July, turfgrass quality differences departed and turfgrass quality became unacceptable for all treatments. This is most likely attributed to the record high temperatures in July (“Robinson, 2020”) and prolonged periods without precipitation throughout the month of July. In August, the turfgrass swards started to recover in all treatments; the lower mown turfgrass appeared to be recovering faster, although, there was no apparent biologically significant difference in turfgrass quality and all treatments were still considered unacceptable.

3.5 | Green cover

Irrigation frequency had no effect on green cover ($\alpha = 0.05$), which is similar to previous research (Lodge & Lawson, 1993). Green cover was similar at both mowing heights in June and July 2019 (Table 4). However, differences were observed from August 7 to October 2, 2019; green cover was greater in the higher mown turfgrass. This follows a similar pattern to turfgrass quality data where differences were only observed from August through October in 2019, with greater values in the higher mown turfgrass (Table 3). Green cover differences were negligible throughout 2020 (Table 4). The higher-than-normal drought and heat stress in the summer of 2020 appears to have reduced green cover equally across mowing height and irrigation frequency.

3.6 | Normalized difference vegetation index

NDVI values were unaffected by irrigation frequency, similar to findings in turfgrass quality and green cover data.

TABLE 3 Turfgrass quality as affected by mowing height in North Brunswick, NJ.

Mowing height (mm)	Turfgrass quality (1–9)									
	2019									
	June 12	June 26	July 10	July 29	Aug. 7	Aug. 21	Sept. 4	Sept. 18	Oct. 2	Oct. 16
11	6.4	7.0	7.4	6.9	7.1	6.9	7.0	6.9	6.9	7.3
38	6.9	7.4	7.4	7.4	7.9	7.9	8.3	8.3	8.3	7.8
<i>p</i> -value	0.16	0.20	0.82	0.06	0.07	<0.01	<0.0001	<0.01	<0.01	<0.01
Mowing height (mm)	Turfgrass quality (1–9)									
	2020									
	June 17	June 30	July 15	July 29	Aug. 12	Aug. 26	Sept. 9	Sept. 23	Oct. 7	
11	5.6	3.9	4.3	3.8	4.2	5.3	5.8	6.6	7.2	
38	6.8	5.8	5.6	4.6	4.2	4.3	4.7	6.0	7.2	
<i>p</i> -value	<0.01	<0.01	0.15	0.378	0.95	<0.05	0.06	0.10	0.76	

Note: Turfgrass quality was determined visually on a 1 (dead) to 9 (ideal) scale with 6 considered the minimum acceptable level of turfgrass quality.

TABLE 4 Green cover as affected by mowing height in North Brunswick, NJ.

Mowing height (mm)	Green cover ^a (%)									
	2019									
	June 12	June 26	July 10	July 29	Aug. 7	Aug. 21	Sept. 4	Sept. 18	Oct. 2	Oct. 16
11	68	86	85	74	75	64	79	78	78	94
38	78	86	80	83	86	85	93	89	88	95
<i>p</i> -value	0.15	0.93	0.24	0.10	<0.01	<0.001	<0.001	<0.0001	<0.01	0.61
Mowing height (mm)	Green cover (%)									
	2020									
	June 17	June 30	July 15	July 29	Aug. 12	Aug. 26	Sept. 9	Sept. 23	Oct. 7	
11	40	22	70	59	49	45	67	83	98	
38	40	33	62	52	42	42	71	87	96	
<i>p</i> -value	0.99	0.34	0.20	0.38	0.30	0.64	0.50	0.13	<0.01	

^aCoverage was determined via digital image analysis of lightbox photos using Turf Analyzer software (Karcher et al., 2017).

TABLE 5 Normalized difference vegetation index as affected by mowing height in North Brunswick, NJ.

Mowing height (mm)	Normalized difference vegetation index									
	2019									
	June 12	June 26	July 10	July 29	Aug. 7	Aug. 21	Sept. 4	Sept. 18	Oct. 2	Oct. 16
11	0.7229	0.7966	0.7463	0.7648	0.6958	0.6837	0.7653	0.7333	0.7072	0.8001
38	0.7812	0.8342	0.7694	0.8159	0.7706	0.7421	0.8363	0.8210	0.7858	0.8343
<i>p</i> -value	0.14	0.09	0.38	0.07	<0.0001	<0.001	<0.01	<0.0001	<0.0001	<0.05
Mowing height (mm)	Normalized difference vegetation index									
	2020									
	June 17	June 30	July 15	July 29	Aug. 12	Aug. 26	Sept. 9	Sept. 23	Oct. 7	
11	0.6220	0.4803	0.7058	0.5578	0.5972	0.6062	0.7125	0.5628	0.7241	
38	0.6618	0.5524	0.6309	0.5535	0.5636	0.5818	0.7135	0.5880	0.6921	
<i>p</i> -value	0.28	0.20	0.12	0.90	0.07	0.28	0.97	0.22	0.46	

Note: Normalized difference vegetation index was determined using a RapidSCAN CS-45 reflectance meter (Crop Circle, Holland Scientific) at approximately 56 cm above the soil.

Mowing height influenced NDVI values in 2019 but not 2020 (Table 5). Similar to turfgrass quality and green cover, mowing height had no effect on NDVI in June and July of 2019. Differences were observed from August through October 2019 with greater values observed in the higher mown turfgrass (Table 5); this coincides with turfgrass quality and green cover (Tables 3 and 4). In 2020, NDVI values were similar regardless of mowing height; this aligns with green cover where no biologically significant differences were detected in 2020.

4 | CONCLUSION

Annual bluegrass cover was reduced in perennial ryegrass when irrigated once week⁻¹ compared to thrice week⁻¹ in the humid subtropical climate zone (near the Humid Continental climate zone) where this research was conducted (Beck et al., 2018). While differences in annual bluegrass cover were observed among irrigation treatments, perhaps several years of implementation are required for substantial differences to become more apparent. Turfgrass quality, green cover, and NDVI were unaffected by irrigation frequency. Higher mown turfgrass reduced annual bluegrass cover and occasionally provided better turfgrass quality. In two summers where heat and drought stress intensity were different, annual bluegrass cover response was similar. This research suggests that irrigating 60% ET₀ once week⁻¹ (rather than thrice week⁻¹) can reduce annual bluegrass cover and maintain similar turfgrass quality. Future research should evaluate the addition of overseeding desired turfgrass species in the autumn to compete with annual bluegrass seedlings and fill in voids of turfgrass swards from summer decline.

AUTHOR CONTRIBUTIONS

Brandon C. McNally: Data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft; writing—review and editing. **Matthew T. Elmore:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. **Alexander R. Kowalewski:** Conceptualization; investigation; methodology; project administration. **Emily T. Braithwaite:** Investigation; methodology; validation; writing—review and editing. **Alyssa B. Cain:** Investigation; methodology; validation.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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