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Regional response of zoysiagrass turf to glufosinate and glyphosate applied during postdormancy transition based on accumulated heat units

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Abstract

Turfgrass managers apply nonselective herbicides to control winter annual weeds during dormancy of warm-season turfgrass. Zoysiagrass subcanopies, however, retain green leaves and stems during winter dormancy, especially in warmer climates. The partially green zoysiagrass often deters the use of nonselective herbicides due to variable injury concerns in transition and southern climatic zones. This study evaluated zoysiagrass response to glyphosate and glufosinate applied at four different growing degree day (GDD)-based application timings during postdormancy transition in different locations, including Blacksburg, VA; Starkville, MS; and Virginia Beach, VA, in 2018 and 2019. GDD was calculated using a 5 C base temperature with accumulation beginning January 1 each year, and targeted application timings were 125, 200, 275, and 350 GDD_{5C}. Zoysiagrass injury response to glyphosate and glufosinate was consistent across a broad growing region from northern Mississippi to coastal Virginia, but it varied by application timing. Glyphosate application at 125 and 200 GDD_{5C} can be used safely for weed control during the postdormancy period of zoysiagrass, while glufosinate caused unacceptable turf injury regardless of application timing. Glyphosate and glufosinate exhibited a stepwise increase to maximum injury with increasing targeted GDD_{5C} application timings. Glyphosate applied at 125 or 200 GDD_{5C} did not injure zoysiagrass above a threshold of 30%, whereas glufosinate caused greater than 30% injury for 28 and 29 d when applied at 125 and 200 GDD_{5C}, respectively. Likewise, glyphosate application at 125 or 200 GDD_{5C} did not affect the zoysiagrass green cover area under the progress curve per day, whereas later applications reduced it. Glyphosate and glufosinate caused greater injury to zoysiagrass when applied at greater cumulative heat units and this was attributed to increasing turfgrass green leaf density, because heat unit accumulation is positively correlated with green leaf density. Accumulated heat unit-based application timing will allow practitioners to apply nonselective herbicides with reduced injury concerns.

Introduction

Due to favorable temperature conditions, zoysiagrass is adapted to various growing regions in the transition climatic zone and southern regions of the United States (Patton et al. 2017). Accumulated heat units or growing degree days (GDDs) have been widely used to estimate crop productivity (Major et al. 1983), to predict the phenological development of weeds (Miller et al. 2001), and to time pesticide applications (Dale and Renner 2005; Forcella and Banken 1996). Temperature variation between growing seasons was observed to be the primary factor affecting corn (*Zea mays* L.) productivity if moisture and fertility requirements were met (Major et al. 1983). For turfgrass, GDD models have been used to optimize growth regulators, herbicide, and insecticide application intervals; and to predict seed head development, weed emergence, and disease occurrence (Brosnan et al. 2010; Danneberger et al. 1987; Fidanza et al. 1996; Kreuser and Soldat 2011; McCullough et al. 2017; Reasor et al. 2018; Ryan et al. 2012). Researchers have developed GDD models for zoysiagrass establishment, but none have examined the relationship between GDD accumulation and zoysiagrass postdormancy transition (Patton et al. 2004; Sladek et al. 2011).

Nonselective herbicides are typically applied during winter months to manage winter annual weeds in dormant bermudagrass (*Cynodon dactylon* L.) (Johnson 1976; Rimi et al. 2012; Toler et al. 2007). However, turfgrass managers are often hesitant to make these applications to dormant zoysiagrass due to fear of herbicide injury and delay in spring green-up (Boyd 2016; Brosnan and Breeden 2011). Variable responses of both bermudagrass and zoysiagrass have been reported following glyphosate or glufosinate treatment at various stages of postdormancy transition in spring (Johnson 1976; Johnson and Ware 1978; Xiong et al. 2013). Previous research examining zoysiagrass response to nonselective herbicides has been conducted in upper climatic-transition zones with northern latitudes between 37° and 45°, where zoysiagrass is more likely to be fully dormant (Hoyle and Reeves 2017; Rimi et al. 2012; Velsor et al. 1989; Xiong et al. 2013). However, research is needed in warmer climatic regions to give turf managers better options in choosing nonselective herbicides to control winter annual weeds during the postdormancy transition of zoysiagrass.

Brosnan et al. (2011) indicated that herbicide application timing is crucial to zoysiagrass safety and weed control. However, application timings are often described as the time before green-up or based strictly on calendar dates (Rimi et al. 2012; Velsor et al. 1989; Xiong et al. 2013). Velsor et al. (1989) reported that glyphosate applied on April 1 in Missouri caused significant injury, but the same application on March 1 did not injure zoysiagrass. Xiong et al. (2013) observed zoysiagrass injury from glyphosate and glufosinate when applied "2 to 3 d before green-up" but not when applied "2 to 3 wk before green-up" in Columbia, MO, and Carbondale, IL. The "early applications" in previous studies showcase the disparity between years when calendar day–based treatments are expressed as accumulated heat units. The treatments by Xiong et al. (2013) equate to 206 and 189 GDD_{5C} at two sites in 2010, and 375 GDD_{5C} in Columbia, MO, in 2011. The treatments by Velsor et al. (1989) at Columbia, MO, in 1985 and 1986 equate to 94 and 246 GDD_{5C}, respectively.

Growth and development of zoysiagrass based on the GDD has been reported (Patton et al. 2004), but restricted to limited geographical regions. Although zoysiagrass response to glyphosate and glufosinate has differed based on accumulated GDDs in Virginia (Craft et al. 2023) and in Italy (Rimi et al. 2012), regional variations in factors such as seasonal precipitation legacy (Shen et al. 2015) and winter severity (Schwab et al. 1996) have altered plant responses between locations. Therefore, the objective of this study was to evaluate zoysiagrass turf response to glyphosate and glufosinate when applied at four GDD-based application timings spanning the period before and during the postdormancy transition of zoysiagrass at different sites in the transition zone and warm climatic region of the United States.

Materials and Methods

Four trials were conducted to evaluate zoysiagrass response to GDD-based glyphosate and glufosinate application timings in spring 2018, and repeated in 2019. Two trials were conducted at the Virginia Tech Turfgrass Research Center in Blacksburg, VA (37.21°N, 80.41°W) each year. One trial site consisted of a mature stand of 'Meyer' (*Zoysia japonica*) zoysiagrass mown with a reel mower at 1.5 cm during active growth, while the second trial site was a mixed stand of 'Zenith' (*Z. japonica*) and 'Companion' (*Z. japonica*) zoysiagrass mown with a rotary mower at 6.5 cm during active growth (Figure 1). The soil type was a Groseclose urban loam (clayey, mixed, mesic, Typic Hapludalft), pH 6.2, with 2.8% to 4.1% organic matter. A third trial was conducted at the Virginia Tech Hampton Roads Agricultural Research and Extension Center in Virginia Beach, VA (36.89°N, 76.18°W), on a mature stand of 'Compadre' (*Z. japonica*) zoysiagrass mown with a rotary mower at 6.3 cm during active growth. The soil type was a Tetolum loam (fine-loamy, mixed, thermic Aquic Hapludult), pH 5.4, with 2.9% organic matter. In 2018, the Virginia Beach site had heavy weed pressure that made it difficult to evaluate zoysiagrass green-up. Therefore, 2,4-D + mecoprop-p acid + dicamba acid + carfentrazone-ethyl (SpeedZone®; PBI Gordon, Shawnee, KS) at 420 g ai ha^{-1} and flazasulfuron (Katana®; PBI Gordon) at 26.3 g ai ha^{-1} were applied in January 2019 to control winter annual weeds and to ensure the site had a uniform zoysiagrass stand for the duration of the trial. A fourth trial location was the RR Foil Plant Science Research Center at Mississippi State University in Starkville, MS (33.47°N, 88.78°W), on a mature stand of 'Meyer' zoysiagrass mown with a reel mower at 1.9 cm during active growth (Figure 1). The Starkville site soil was a native Marietta fine sandy loam (fine-loamy, siliceous, active, Fluvaquentic Eutrudept) soil, pH 6.2, with 2.1% organic matter. Irrigation, fertility, and pesticide applications were withheld during the evaluation period of the experiment.

All experiments conducted on 8-site years were implemented as a randomized complete-block design with a two-factor treatment structure replicated four times. The factors included herbicide and GDD-based application timings. Plots measured 1.8 m by 1.8 m at the Blacksburg and Starkville sites and 1.8 m by 10 m at the Virginia Beach site. Herbicide treatments included glyphosate (Roundup Pro® Concentrate; Bayer Environmental Sciences, Research Triangle Park, NC) at 520 g ae ha^{-1} and glufosinate (Finale®; Bayer Environmental Sciences) at 1,680 g ai ha^{-1}. Herbicide rates were based on recommended rates used to control annual bluegrass (*Poa annua* L.) in late winter and early spring (Xiong et al. 2013). Herbicide treatments were applied at all sites using CO_2-pressurized boom sprayers equipped with TTI nozzles (TeeJet® Technologies, Springfield, IL) calibrated to deliver 280 L ha^{-1} spray solution. GDDs were calculated daily using a 5 C base temperature beginning on January 1, as used in previous studies (McMaster and Wilhelm 1997; Patton et al. 2004). Targeted glufosinate and glyphosate application timings were 125, 200, 275, and 350 GDD_{5C} (Figure 1). Actual accumulated GDDs at the time of application across the 8 site years varied due to factors such as inclement weather and were 126 ± 60, 192 ± 75, 256 ± 72, and 337 ± 44 GDD_{5C}.

The number of green zoysiagrass leaves per square decimeter was counted before each treatment by randomly choosing a 10-cm by 10-cm area in each plot and counting all leaves within the canopy that were at least partially green. Zoysiagrass injury was assessed visually on a 0% to 100% scale, where 0% indicated that plots had equivalent green zoysiagrass vegetation compared to the nontreated control, and 100% indicated all green vegetation of the zoysiagrass turf was eliminated. Zoysiagrass green cover was assessed on a scale of 0% to 100% as a visually estimated percentage of the plot area, with 0% indicating no green cover and 100% indicating complete green coverage of zoysiagrass. Measurements of normalized difference vegetation index (NDVI) were collected at the 6 site years associated with Blacksburg and Starkville using a Crop Circle ACS 210 multispectral analyzer (Holland Scientific Inc., Lincoln, NE) affixed 43 cm above the turf that collected 50 ± 5 readings per plot that represented a 0.5-m × 1.6-m area of turf canopy in the center of each plot at the Blacksburg site, and a RapidScan CS45 handheld multispectral analyzer (Holland Scientific Inc.) held 110 cm above and perpendicular to the canopy to scan three 1-m-long transects along the center of each

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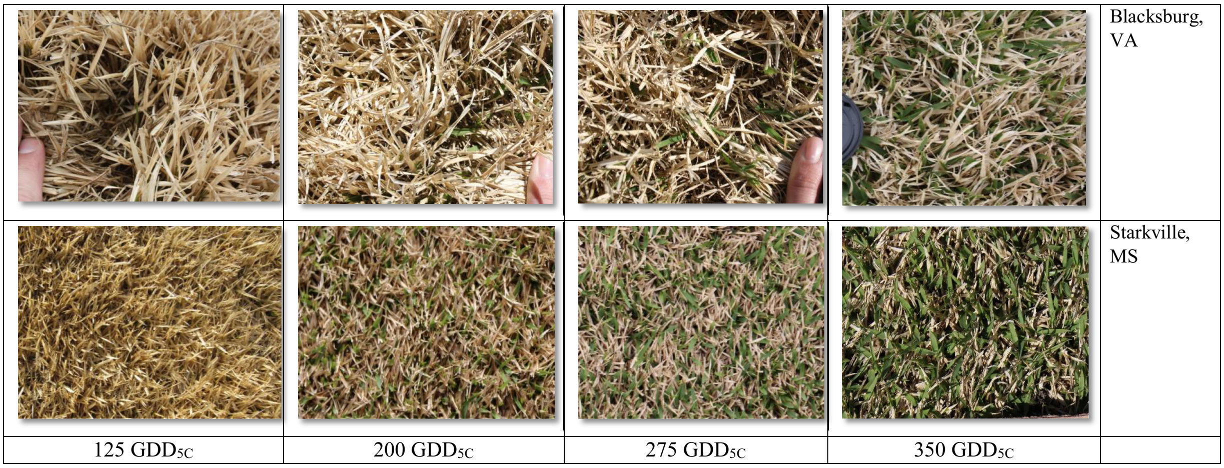

Figure 1. Zoysiagrass turf at four application timings and two locations. GDD_{5c} indicates growing degree days calculated using a base temperature of 5 C.

plot at the Starkville, MS, site. NDVI data were not collected at the Virginia Beach site. Assessments were made at 0, 7, 14, 21, 28, 42, 56, 70, 84, 98, and 112 d after initial treatment.

Data Analysis

Maximum observed turfgrass injury was reported as the highest injury data recorded on any assessment date. Visually estimated zoysiagrass injury data from the 11 assessment dates were used to calculate the number of days over a threshold of 30% injury (DOT_{30}) to assess the duration of unacceptable turf injury (Cox et al. 2017). The DOT_{30} was calculated by subjecting observed injury over time from all combinations of the 8 site years, application timing, herbicide treatment, and replicates to the Gaussian function:

$$y = ae^{\left[\frac{-(x-b)^2}{2c^2}\right]} \quad [1]$$

where a is maximum injury, b is the number of days after treatment at which maximum injury occurred, and c is one standard deviation from b. The parameter c can be multiplied by 6 to determine the number of days comprising 3 standard deviations, an approximation of the duration of injury. Fit of the curve was based on least sums of squares using the Gauss-Newton method of the NLIN procedure with SAS software (version 9.2; SAS Institute, Cary, NC). The output from the NLIN procedure was then subjected to a logical operation with SAS software using parameters a and c from Equation 1 as follows:

if $a < 30$ then Do; $DOT_{30} = 0$; End;

$$\text{Else } DOT_{30} = 2 * \{sqrt[2 * (\text{Log}\{1/[(a-30)/a]\})]\} * c \quad [2]$$

Zoysiagrass percentage green cover and NDVI data over time were converted to the area under the progress curve (AUPC) using Equation 3:

$$\partial = \sum_{i=1}^{ni-1}\{\left[\frac{y_i + y_{(i-1)}}{2}\right]\left[t_{(i+1)} - t_{(i)}\right]\} \quad [3]$$

where ∂ is the AUPC, i is the ordered sampling date, ni is the number of sampling dates, y is turf green cover or NDVI measurements at a given date, and t is the time in days. The AUPC was then converted to the average per day by dividing by the number of days spanned by the assessment period. Campbell and Madden (1990) applied this equation to disease epidemiology, and Askew et al. (2013) and Brewer et al. (2017) used it for weediness over time in a turfgrass comparison study. The AUPC is useful in situations where long-duration response variables are assessed by repeated measures. Zoysiagrass green cover and NDVI data over time were also subjected to linear regression, and slopes from each experimental unit were analyzed for treatment effects. The slopes, expressed as the change in response per day, allow for the estimation of trends over time that otherwise would not be evident from AUPC per day data. Slope and AUPC per day data for zoysiagrass green cover and NDVI along with injury maxima and DOT_{30} were subjected to ANOVA with sums of squares partitioned to reflect replication, site, year, and site by year as random effects and herbicide, application timing, and herbicide by application timing as fixed effects. The model included all possible combinations of interactions between the random effects of site, year, and site by year and the fixed effects or interactions. Mean square error associated with herbicide, application timing, and herbicide by application timing were tested with the mean square associated with their interaction with the random variables (McIntosh 1983). Data were discussed separately by site, year, or site by year if a significant interaction was detected ($P < 0.05$). Otherwise, data were pooled over site and/or year. Appropriate interactions or main effects were subjected to Fisher's protected LSD test at $\alpha = 0.05$. The relationship between accumulated GDD_{5C} and zoysiagrass leaves per square decimeter was further investigated via linear regression (Figure 2). An additional data set from four previously conducted studies in Blacksburg, VA, (Craft 2021) where numerous green leaf counts were taken, was combined with associated GDD_{5C} accumulated at each assessment date and included in the regression analysis. These data were separated by mowing height, and each regression consisted of 6 site years and 546 observations.

Results and Discussion

The herbicide by application timing interaction was significant ($P = 0.0002$) and not dependent on year ($P = 0.0671$), location ($P = 0.2028$), or year by location ($P = 0.2478$) for maximum zoysiagrass injury, so data were pooled over 7 of the 8 site years (Table 1). Zoysiagrass response data for the Virginia Beach trial site in 2019 was confounded by disease pressure and not included in

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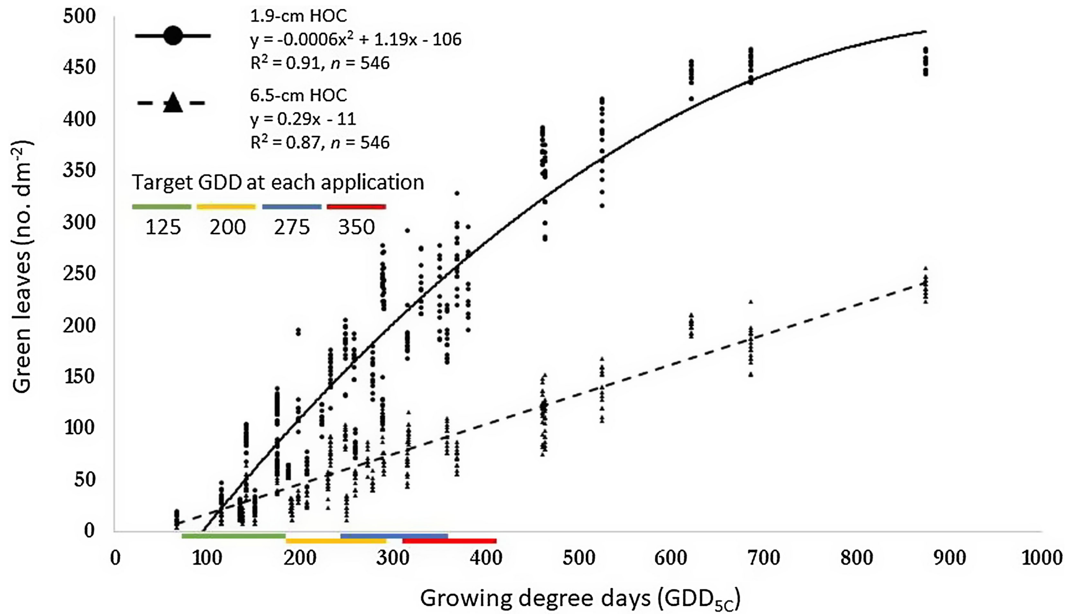

Figure 2. Effect of cumulative growing degree days (GDDs) at base 5 C on the number of zoysiagrass green leaves per square decimeter from 12 site years comprised of two Blacksburg, VA, sites each conducted in 2016 and 2017, and two Blacksburg, VA, sites; one Starkville, MS, site; and one Virginia Beach, VA site each conducted in 2018 and 2019. The data are split equally such that six sites were maintained at 1.9-cm height of cut (HOC) and six sites that were maintained at 6.5-cm HOC. Only nontreated and non-injurious treatments are included.

the analysis. Glufosinate was more injurious than glyphosate regardless of application timing, and both herbicides exhibited a stepwise increase in maximum injury with increasing targeted GDD_{5C} application timings (Table 1). The maximum zoysiagrass injury caused by glufosinate was at least 23% more than that caused by glyphosate regardless of application timing (Table 1). Glyphosate at 125 or 200 GDD_{5C} application timings did not injure zoysiagrass by more than 23%. Results suggest that glufosinate applied at the maximum label-recommended rate is more injurious to zoysiagrass than glyphosate and supports current glufosinate label restrictions prohibiting its use on zoysiagrass. Our results regarding increased turf injury when herbicides are applied at later zoysiagrass developmental stages agree with previous reports (Rimi et al. 2012; Velsor et al. 1989). The maximum injury data did not indicate the duration of injury response, and DOT_{30} was used for this purpose with data from 11 assessments made over a 112-d period.

The DOT_{30} response variable was also dependent on the interaction of herbicide and application timing ($P < 0.05$) but it was not dependent on year, location, or year by location ($P > 0.05$). Glyphosate did not injure zoysiagrass above a threshold of 30% when applied at targeted timings of 125 and 200 GDD_{5C} and only resulted in an estimated 1.6 d over the 30% zoysiagrass injury threshold when applied at 275 GDD_{5C} (Table 1). Glufosinate increased DOT_{30} compared to that of glyphosate at each evaluated application timing (Table 1). Glyphosate and glufosinate injured zoysiagrass above a 30% threshold for 36 or 46 d, respectively, when applied at 350 GDD_{5C} (Table 1), as previous reports indicate that both herbicides are more injurious when applied to zoysiagrass during the postdormancy transition (Velsor et al. 1989; Xiong et al. 2013). Glufosinate applied at 125 GDD_{5C} injured zoysiagrass for 28 d over the 30% injury threshold (Table 1), suggesting that glufosinate may injure zoysiagrass even when applied closer to full dormancy with few green leaves or stems found within the zoysiagrass canopy. Injury from such early applications of nonselective herbicides may not be detectable by turf managers unless nontreated test strips or accidental sprayer skips are evident. At the 125 GDD_{5C} target application timing, zoysiagrass turf had less than 2% green cover and 8 to 48 predominately subcanopy green leaves dm^{-2} at the assessed sites (Figure 2). At 350 GDD_{5C} targeted application timing, zoysiagrass green leaves per square decimeter were dependent on mowing height (Figure 2). At the 4 site years where zoysiagrass was mown at 1.9 cm, polynomial regression estimates that turf had 237 green leaves dm^{-2} at 350 GDD_{5C}. However, when zoysiagrass was mown at 6.5 cm at the other four site years, zoysiagrass had 91 green leaves dm^{-2} (Figure 2). Previous research conducted in Blacksburg, VA, on turf mown within the same height ranges indicates that the 237 green leaves dm^{-2} at 1.9 cm height of cut (HOC) would result in 39% green turf, and the 91 green leaves at 6.5 cm HOC would result in 20% green turf cover of zoysiagrass (Craft et al. 2023). These estimates agree with the actual observed green cover at 350 GDD_{5C}, which averaged 49% and 18% over the 4 site years each for turf maintained at 1.8 and 6.5 cm, respectively (data not shown).

The interaction of herbicide and application timing was significant for average turf green cover AUPC per day ($P = 0.0002$). The nontreated plots across all sites averaged 47% green cover AUPC $^{-1}$ (Table 1), but the green cover was initially less than 5% and increased over time to reach near 100% cover at the last assessment date. The 47% zoysiagrass cover AUPC d^{-1} in nontreated plots allows for comparison between treatments using data that capture all of the variances across 11 assessments, but it does not approximate the actual daily cover levels over the 112-d assessment period. Glyphosate did not reduce turf cover AUPC per day when applied at a targeted GDD_{5C} of 125 or 200 in contrast to later application timings when cover AUPC per day was reduced (Table 1). Glufosinate reduced turf cover AUPC per day regardless of application timing, with more reduction in zoysiagrass cover AUPC per day with increasing cumulative GDD_{5C} (Table 1). Previous researchers also reported that glyphosate and glufosinate

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Table 1. Influence of herbicides and GDD-based application timings on zoysiagrass injury maxima, DOT_{30}, green cover, and NDVI expressed as AUPC d^{-1}.[a,b,c]

Targeted application timing	Injury maxima		DOT_{30}		Zoysiagrass green cover AUPC			Zoysiagrass NDVI AUPC		
	Glyphosate	Glufosinate	Glyphosate	Glufosinate	Nontreated	Glyphosate	Glufosinate	Nontreated	Glyphosate	Glufosinate
GDD_{5C}	%		d		Avg. d^{-1}			Avg. d^{-1}		
125	16*	39*	0.0*	28*	47	46*	43*†	0.4924	0.4808*	0.4639*†
200	23*	58*	0.0*	29*	–	44*	37*†	–	0.4727*†	0.4373*†
275	38*	71*	1.6*	44*	–	39*†	29*†	–	0.4693*†	0.4169*†
350	58*	87*	36*	46*	–	35*†	22*†	–	0.4430*†	0.3873*†
LSD (0.05)	7.4	6.0	3.6	3.0		2.8	2.8		0.0093	0.0178

[a]Abbreviations: AUPC d^{-1}, area under the progress curve per day; DOT_{30}, days over threshold of 30% injury; GDD, growing degree days; GDD_{5C}, GDD calculated using a base temperature of 5 C; LSD, least significant difference; NDVI, normalized difference vegetative index.

[b]All response variables were based on 11 assessments over a 112-d period averaged over 7 site years from Blacksburg, VA, Starkville, MS, and Virginia Beach, VA, in 2018 and 2019, except NDVI AUPC d^{-1}. NDVI data were based on 6 site years because data were not collected at the Virginia Beach, VA, site in both years.

[c]Means followed by an asterisk (*) were significantly different between herbicides within a given application timing. Means followed by a dagger (†) were significantly different compared to that of the nontreated control based on single-degree-of-freedom comparisons. LSD figures compare between application timings within a given herbicide.

reduce zoysiagrass "green-up" when these herbicides were applied closer to the postdormancy transition period (Velsor et al. 1989; Xiong et al. 2013).

NDVI was 91% correlated to zoysiagrass green cover with an intercept of 0.2197 NDVI at near-zero turf cover and a slope of 0.0053 NDVI per unit increase in the percentage of turf green cover (Figure 3). The above-mentioned trend is independent of locations and year, as the regression consists of more than 2,000 assessments over 11 dates across 6 of the 8 site years, as NDVI data were not collected at Virginia Beach, VA. Likewise, the interaction of herbicide by application timing for average NDVI AUPC per day was significant ($P = 0.0070$) and not dependent on year, location, or year by location ($P > 0.05$). Thus, data were pooled over the 6 site years for comparison (Table 1). Herbicide and application timing effects on average NDVI AUPC per day mirrored trends in turf green cover AUPC per day with one exception. Average NDVI AUPC per day was not reduced by glyphosate compared to that of nontreated turf only when applied at 125 GDD_{5C}, while average turf green cover AUPC per day was not reduced by glyphosate application at 125 and 200 GDD_{5C} timings (Table 1). Glufosinate, however, consistently reduced both turf cover AUPC per day and NDVI AUPC per day compared to glyphosate and nontreated turf, regardless of application timing (Table 1).

Turf green cover typically exhibited a linear positive response over time, but the rate of green cover increase varied between locations and year. The interaction of location by year by herbicide by application timing was significant for slopes of green cover over time ($P = 0.0004$). Zoysiagrass green cover data were separated by year and locations, and further labeled to indicate the zoysiagrass HOC at each location (Table 2). The interaction was likely caused by variable rates of green cover accumulation between HOCs at the various locations and differential weather conditions between sites and year (data not shown).

Glufosinate reduced turf green cover slopes compared to nontreated and glyphosate-treated turf in 21 and 16 comparisons, respectively from a total of 28 comparisons at all site years (Table 2). Glyphosate applied at 125 or 200 GDD_{5C} did not reduce the slope of green cover compared to that of nontreated turf at any site with the exception of the 6.5-cm HOC site at the Blacksburg location in 2018. Temporal slopes of turf green cover from nontreated plots varied between locations and year but were generally higher in locations characterized by warmer climates. Based on these slopes, the range of time required to reach 100% green turf cover varied from 90 d at the 6.5-cm HOC Blacksburg site in 2018 to 75 d at the 1.8-cm HOC Starkville site in 2019. The most extreme delay in turf green cover accumulation was caused by glufosinate treatment at 350 GDD_{5C} at the 6.5-cm HOC Virginia Beach site in 2018 where the temporal slope was reduced to 0.2 resulting in only 23% green cover after the 112-d assessment period was concluded.

Our findings suggest that glufosinate is more injurious to zoysiagrass than glyphosate when applied during postdormancy transition. Glufosinate was used in these studies at the maximum allowable rate recommended for use in bermudagrass turf based on attempts to maximize utility for annual bluegrass control during winter conditions. Lower glufosinate rates or earlier application timings may reduce turf phytotoxicity. Recent research showed that glufosinate at the same rate as the current study injured zoysiagrass not more than 25% when applied at 97 GDD_{5C} (Craft 2021). When the glufosinate rate was reduced to 840 g ha^{-1}, maximum injury was reduced to 13% with glufosinate alone and 22% with glufosinate mixed with flumioxazin at 428 g ha^{-1}

Table 2. Effect of herbicides and GDD-based application timings on linear slopes expressed as Δ d^{-1} of green zoysiagrass turf cover over time based on 11 assessments over a 112-d period over 7 site years in 2018 and 2019 separated by two mowing heights.[a,b]

	Green turf cover slopes at 1.8 cm height of cut											
	Blacksburg, VA						Starkville, MS					
	Nontreated		Glyphosate		Glufosinate		Nontreated		Glyphosate		Glufosinate	
Targeted application timing	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
GDD_{5C}	Δ d^{-1}											
125	1.24	1.16	1.18	1.18*	1.11†	1.09*†	1.15	1.34	1.17	1.32	1.17	1.39
200	–	–	1.15*	1.18*	0.97*†	1.05*†	–	–	1.13*	1.33	1.27*	1.35
275	–	–	1.09*†	1.12*	0.62*†	0.96*†	–	–	1.16*	1.31	0.83*†	1.30
350	–	–	0.95*†	0.68*†	0.36*†	0.50*†	–	–	0.96*†	1.23†	0.69*†	1.06†
LSD (0.05)			0.12	0.06	0.09	0.06			0.10	NS	0.17	0.15

	Green turf cover slopes at 6.5 cm height of cut								
	Blacksburg, VA						Virginia Beach, VA		
	Nontreated		Glyphosate		Glufosinate		Nontreated	Glyphosate	Glufosinate
Targeted application timing	2018	2019	2018	2019	2018	2019	2018	2018	2018
GDD_{5C}	Δ d^{-1}								
125	1.11	1.15	1.11*	1.15*	1.06*†	1.07*†	1.26	1.32	1.30
200	–	–	1.04†	1.12	0.99†	1.12	–	1.21	1.10†
275	–	–	0.98*†	1.03*†	0.77*†	0.95*†	–	0.76†	0.68†
350	–	–	0.93*†	0.81*†	0.49*†	0.69*†	–	0.40†	0.20†
LSD (0.05)			0.04	0.03	0.10	0.05		0.22	0.20

[a]Abbreviations: Δ^{-1}, change in value per day; GDD, growing degree days; GDD_{5c}, GDD calculated using a base temperature of 5 C; LSD, least significant difference.
[b]Means followed by an asterisk (*) were significantly different between herbicides within a given application timing. Means followed by a dagger (†) were significantly different compared to the nontreated control based on single-degree-of-freedom comparisons. LSD figures compare between application timings within a given herbicide.

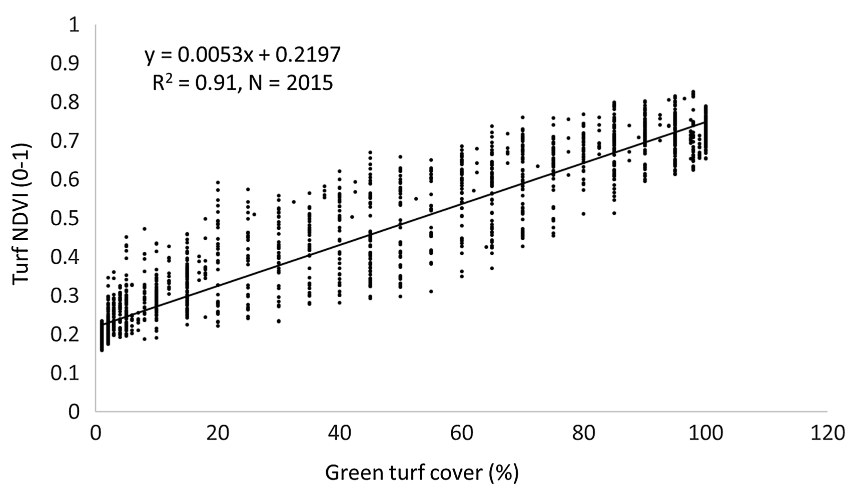

Figure 3. Relationship between normalized difference vegetative index (NDVI) and percentage green cover of zoysiagrass turf averaged across 6 site years including two sites in Blacksburg, VA, and one site in Starkville, MS in 2018 and replicated in 2019.

(Craft 2021). Zoysiagrass response to glyphosate is generally acceptable when turf is treated not later than 200 GDD_{5C}. Craft et al. (2023) demonstrated that the magnitude of herbicide injury on zoysiagrass after glyphosate application is temperature dependent, while glufosinate-injured turfgrass, regardless of temperature prevalent during application timing. Three times more glufosinate absorbed into zoysiagrass leaves compared to glyphosate and both herbicides absorbed more readily into stolons compared to leaves (Craft 2021). These findings suggest that applications of nonselective herbicides to zoysiagrass may be based on GDDs over a broad geographic range and further support previous work regarding zoysiagrass sensitivity to glufosinate.

Practical Implications

Glufosinate application to zoysiagrass is currently not recommended on any labeled products in the United States. If glufosinate were considered for use in dormant zoysiagrass turf, users should target zoysiagrass only when GDD_{5C} is less than 125 and turf has no more than 50 and 20 partially green subcanopy leaves per square decimeter when managed at 1.8 and 6.5 cm HOC, respectively. Even if these parameters are met, users should expect some level of turf phytotoxicity or growth suppression following glufosinate treatment. Glyphosate can be safely applied under these conditions with little risk to zoysiagrass and would be expected to

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elicit generally acceptable phytotoxicity or growth suppression even when applied at 200 GDD_{5C}.

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