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Growth Suppression of Hybrid Bermudagrass with Imazapic

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Abstract. **Imazapic is an acetolactate synthase-inhibiting herbicide labeled for weed control in pastures, rangeland, and noncrop areas. Field research was conducted in Knoxville, TN, USA, during 2020 and 2021 to evaluate the tolerance of four hybrid bermudagrass (*Cynodon dactylon* × *Cynodon transvaalensis* Burtt Davy) cultivars to applications of imazapic for growth suppression. Separate experiments were conducted on 'TifTuf', 'Tifway', 'Tahoma 31', and 'Latitude 36' hybrid bermudagrass. Experiments included plots (1.5 m^2) arranged in a randomized complete block design with four replications and were repeated. Treatments were applied 14 Aug 2020 and 6 Aug 2021, and were mixed with methylated seed oil. Imazapic rates were 0, 35, 52.5, 70, or 105 g·ha^{-1}. Cultivar tolerance was assessed via visual ratings of turfgrass injury relative to untreated check plots. Normalized differential vegetation index data were collected on each date turfgrass injury was evaluated. Growth suppression was quantified via reductions in dry clipping weight after mowing. Hybrid bermudagrass injury increased with imazapic rate for all cultivars, and peak injury (> 30%) following all imazapic treatments occurred within 14 days. At the lowest imazapic rate (35 g·ha^{-1}), injury was transient, with all hybrid bermudagrass cultivars fully recovered by 28 days. All rates of imazapic reduced hybrid bermudagrass dry clipping weight for 21 days for all cultivars. Further research is warranted to explore lower application rates than those tested in our study, in addition to determining tolerance and growth suppression of other turfgrass species commonly managed on golf courses.**

Plant growth regulators (PGRs) affecting hormone production are used to manipulate shoot growth, root growth, inflorescence production, and other functions in crop and noncrop agriculture (Rademacher 2015). The five primary types of PGRs used in turfgrass management are 1) class A compounds suppressing gibberellic acid (GA) biosynthesis late in the pathway, 2) class B compounds suppressing GA biosynthesis early in the pathway, 3) class C compounds inhibiting cell division by reducing total nonstructural carbohydrates in leaves, 4) class D compounds that are herbicides with growth-regulating properties, and 5) class E compounds that are considered phytohormones (Fidanza et al. 2006; March et al. 2013; Spak et al. 1993; Turgeon 2002). PGRs are commonly used in turfgrass to reduce mowing requirements, suppress inflorescence production, and improve overall turfgrass quality (Głąb et al. 2020; March et al. 2013; McCullough et al. 2004). Recent surveys indicate that 45% of all golf courses in the United States apply PGRs (Shaddox et al. 2023a).

Imazapic is an acetolactate synthase inhibiting herbicide used for pre- and postemergence control of grassy and broadleaf weeds in various systems, including maize, rangeland, pasture, and roadsides (Alister and Kogan 2005; Brooks et al. 2004; Mangold et al. 2013). Imazapic has also been researched as a PGR in managed and utility turfgrass (Brosnan et al. 2011, 2012; Gover et al. 2004; Hixson et al. 2007; Yelverton et al. 1997). Imazapic regulated growth and inflorescence formation effectively of tall fescue [*Festuca arundinacea* (Schreb.)] on roadsides (Gannon et al. 2016; Gover et al. 2004; Hixson et al. 2007; Jeffries et al. 2017). Hixson et al. (2007) reported that imazapic rates from 9 to 53 g·ha^{-1} provided 100% tall fescue inflorescence and vegetative growth suppression through 84 d after treatment (DAT), with ≤ 20% injury. Jeffries et al. (2017) reported similar findings, with imazapic suppressing inflorescence and growth of tall fescue for 70 DAT. Growth suppression following imazapic application reduced mowing events required to create clear sightlines for motorists (Gannon et al. 2016; Jeffries et al. 2017).

Reductions in labor availability have challenged many turfgrass managers to meet the mowing requirements of bermudagrass (*Cynodon* spp.) on golf courses (Jacobs 2019). There were > 159,284 ha of maintained bermudagrass on golf courses across the United States in 2021 that required regular mowing (Shaddox et al. 2023b). Applications of imazapic as a PGR could assuage this issue. For example, imazapic at > 35 g·ha^{-1} reduced bahiagrass (*Paspalum notatum* Fluegg.) plant height ≥ 30%; however, these applications resulted in 30% to 50% injury through 119 DAT (Marques et al. 2021a). Comparatively, imazapic at 35 g·ha^{-1} only injured bahiagrass 23% 14 DAT and was reduced to 4% by 56 DAT (Marques et al. 2021a). On St. Augustinegrass [*Stenotaphrum secundatum* (Walter) Kuntze], Marques et al. (2021a) reported ≥ 28% height reduction but limited inflorescence suppression efficacy with imazapic applications at 35, 70, and 105 g·ha^{-1}. Inflorescence suppression efficacy with imazapic applications to bahiagrass and zoysiagrass (*Zoysia japonica* Steud.) has been reported in the US transition zone (Brosnan et al. 2012; Yelverton et al. 1997). On 'Riviera' bermudagrass (*Cynodon dactylon* L. Pers.), imazapic at 52 g·ha^{-1} resulted in ≤ 15% injury, but also reduced inflorescence production and suppressed growth (Brosnan et al. 2011).

Although tolerance of common bermudagrass to imazapic for use as a PGR has been explored in the transition zone of the United States (Brosnan et al. 2011), information pertaining to the response of hybrid bermudagrass (*C. dactylon* × *Cynodon transvaalensis* Burtt Davy) is lacking, considering the species constitutes 32% of all maintained turfgrass hectarage on golf courses (Shaddox et al. 2023b). Limited research has demonstrated imazapic applications at 35 to 105 g·ha^{-1} reduced hybrid bermudagrass plant height > 28%, suggesting that it could be a tool to aid turfgrass managers in reducing mowing requirements on golf courses (Marques et al. 2021b). Therefore, the objective of this study was to evaluate hybrid bermudagrass tolerance and growth suppression following applications of imazapic.

Materials and Methods

Research sites and application. Field experiments were initiated 14 Aug 2020 and repeated 6 Aug 2021 at the East Tennessee AgResearch and Education Center–Plant

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Table 1. Soil pH and organic matter content of experimental areas on four hybrid bermudagrass (*Cynodon dactylon* L. Pers. × *Cynodon transvaalensis* Burtt Davy) cultivars in 2020 and 2021.

	2020		2021	
Cultivar[i]	pH	Organic matter (%)	pH	Organic matter (%)
Tifway	5.8	2.6	5.4	3.0
TifTuf	6.7	1.5	5.9	3.2
Latitude 36	5.8	1.4	5.5	2.3
Tahoma 31	5.6	1.9	5.3	3.3

[i] Hybrid bermudagrass cultivars Latitude 36, Tahoma 31, TifTuf, and Tifway are presented by each experimental year.

Table 2. Analysis of variance of hybrid bermudagrass (*Cynodon dactylon* × *Cynodon transvaalensis* Burtt Davy) visual injury data following application of imazapic (Plateau®)[i] in 2020 and 2021.

	Latitude 36 Run B		Tahoma 31		TifTuf		Tifway	
Source of variation	2020	2021	2020	2021	2020	2021	2020	2021
Imazapic rate[ii]	**[iii]	**	**	NS	**	**	**	**
DAT[iv]	***	***	***	***	***	***	***	***
Imazapic rate × DAT	**	**	***	**	***	**	***	**

[i] Treatments were applied on 14 Aug 2020 and 6 Aug 2021. All treatments were mixed with methylated seed oil at 316 mL·ha^{-1}.

[ii] Turfgrass injury was assessed visually on a 0% (i.e., no injury) to 100% (i.e., complete kill) scale relative to untreated check plots in each replication.

[iii] NS, ***, **, *Nonsignificant or statistically significant at $P \leq 0.000$, 0.01, and 0.05, respectively.

[iv] DAT = days after treatment.

Sciences Unit (Knoxville, TN, USA) to evaluate injury and growth suppression of hybrid bermudagrass cultivars following application of imazapic. Separate experiments were conducted each year on four hybrid bermudagrass cultivars: Latitude 36, Tahoma 31, TifTuf, and Tifway. Experimental areas were maintained with a reel mower three times per week at a 1.6- or 1.3-cm height of cut in 2020 and 2021, respectively. The soil at all experimental sites was a Sequatchie silt loam (fine-loamy, siliceous, semiactive, thermic humic Hapludult) (Table 1). Irrigation was applied to supplement rainfall on all plots. Each experiment was arranged as a randomized complete block design with four replications of 1.5-m^2 plots. Treatments included single applications of imazapic (Plateau®; BASF Corp., Research Triangle Park, NC, USA) at 0, 35, 52, 70, or 105 g·ha^{-1} mixed with methylated seed oil (1.75 L·ha^{-1}). Treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 374 L·ha^{-1} via 8002 nozzles (TeeJet Technologies, Wheaton, IL, USA).

Hybrid bermudagrass injury. Hybrid bermudagrass injury was assessed 3, 10, 14, 21, and 28 DAT via visual injury ratings as well as measurements of the normalized difference vegetation index (NDVI). Turfgrass injury was rated visually on a 0% to 100% scale, where 0 = no turfgrass injury and 100 = complete kill relative to untreated check plots (0 g·ha^{-1} imazapic) in each replication. A handheld NDVI meter (FieldScout TCM 500; Spectrum Technologies Inc., Aurora, IL, USA) was used on each date that visual injury was rated to collect three measurements per plot.

Hybrid bermudagrass growth suppression. Growth suppression was measured by collecting clippings from a single pass with a reel mower (PGM 22, Jacobsen, Ipswich, England, UK, 55.5 cm wide in 2020; Greensmaster® 1021, The Toro Co., Bloomington, MN, USA 55.5 cm wide in 2021) in the center of each plot on each rating date. Plots were not mowed for 48 h before a clipping collection event, and the entire plot was mown after clippings had been collected. Clippings collected for analysis were dried in a forced-air oven at 54 °C for a minimum of 2 d and weighed. Clipping weight data were expressed as a percentage of the untreated check (0 g·ha^{-1} imazapic) to quantify the degree of growth suppression following imazapic treatment.

Statistical analysis. Hybrid bermudagrass injury and growth suppression data from all plots (N = 160) were subjected to repeated-measures ANOVA and a means separation technique (least squares means) using the GLIMMIX procedure in SAS (ver. 9.4; SAS Institute, Cary, NC, USA). For all data, slicing was performed in PROC GLIMMIX to

Table 3. Injury of hybrid bermudagrass (*Cynodon dactylon* × *Cynodon transvaalensis* Burtt Davy) cultivars in 2020 and 2021 in Knoxville, TN, USA, following application of imazapic.

		Hybrid bermudagrass injury[iii]									
		2020					2021				
Cultivar[i]	Rate (g·ha^{-1})[ii]	3 DAT[iv]	10 DAT	14 DAT	21 DAT	28 DAT	3 DAT	10 DAT	14 DAT	21 DAT	28 DAT
Latitude 36	35	10	10 a[v]	35 a	0 a	0	60	45 a	30 a	0 a	0
	52	10	13 a	50 b	3 a	0	63	50 ab	46 b	0 a	0
	70	11	20 b	53 b	10 b	0	58	63 bc	63 c	14 b	0
	105	11	20 b	53 b	18 c	0	65	68 c	71 c	28 c	0
Tahoma 31	35	15	38 a	5 a	0	0	63	48 a	35 a	3	0
	52	13	45 b	15 b	0	0	53	50 ab	45 a	0	0
	70	14	50 b	25 c	0	0	45	68 c	68 c	9	0
	105	16	45 b	50 d	3	0	65	65 bc	65 bc	5	0
TifTuf	35	14	33	23 a	0 a	0 a	0	45 a	40	26 a	0
	52	15	35	33 b	5 a	3 ab	0	63 bc	45	38 a	0
	70	11	33	40 c	15 b	9 b	0	60 b	50	64 b	0
	105	13	33	40 c	25 c	9 b	0	73 c	58	61 b	0
Tifway	35	43 b	33 a	3 a	3	0	55	45 a	33 a	8 a	0
	52	30 a	43 a	6 a	0	0	55	53 ab	36 a	6 a	3
	70	40 b	58 b	20 b	0	0	50	68 c	68 b	25 b	5
	105	38 ab	60 b	33 c	0	0	60	63 bc	69 b	49 c	13

[i] Hybrid bermudagrass cultivars Latitude 36, Tahoma 31, TifTuf, and Tifway are presented by each treatment and experimental year.

[ii] Treatments were applied on 14 Aug 2020 or 6 Aug 2021. All treatments were mixed with methylated seed oil at 316 mL·ha^{-1}.

[iii] Hybrid bermudagrass injury was assessed visually on a 0% (i.e., no injury) to 100% (i.e., complete kill) scale relative to untreated check plots in each replication.

[iv] Days after treatment (DAT) represents the time between experiment initiation and rating date.

[v] Within each column and for each cultivar, means with the same letter are not significantly different according to Fisher's least significant difference ($\alpha = 0.05$).

identify rating dates (DAT) on which treatments were significantly different. Data were tested for experimental year, cultivar, rating date, and treatment main effects and interactions. Treatment means for significant effects were separated using Fisher's protected least significant difference test ($\alpha = 0.05$). Pearson's correlation coefficients were calculated for turfgrass injury and NDVI data using the correlation function in Prism (ver. 9.5.1; GraphPad Prism, La Jolla, CA, USA).

Results and Discussion

Hybrid bermudagrass injury. ANOVA revealed a treatment-by-cultivar-by-year-by-DAT interaction in hybrid bermudagrass injury data; therefore, data are presented separately by cultivar and year (Table 2). Turfgrass visual injury data correlated significantly with NDVI assessments ($r = -0.53$; $P \leq 0.000$), similar to previous reports outlining the relationship between qualitative and quantitative measures of herbicide performance (Carroll et al. 2021; Hoyle et al. 2013). Therefore, only visually rated injury data are presented for clarity.

Hybrid bermudagrass injury means are presented based on treatment, cultivar, year, and DAT in Table 3. Hybrid bermudagrass injury increased with imazapic rate for all cultivars in both years; however, injury was less pronounced in 2020 compared with 2021. For example, 10 DAT in 2020, no cultivar was injured > 38% with imazapic at 35 g·ha^{-1}, whereas in 2021 this treatment resulted in upward of 48% hybrid bermudagrass injury (Table 3). Peak hybrid bermudagrass injury following imazapic treatment (regardless of rate) occurred within 14 DAT for all cultivars each year; however, the degree of injury varied by year, which may be related to environmental conditions, particularly increased precipitation during the data collection period in 2021 compared with 2020 (Table 4). The activity of imidazolinone herbicides (such as imazapic) in the soil is greater when moisture is nonlimiting (Mangels 1991) and can lead to crop injury. For example, increased rainfall leading to greater imazapic availability in soil solution has been identified as a cause of exacerbated imazapic injury in rice (*Oryza sativa*) (Marchesan et al. 2010). In our study, peak injury of 'Latitude 36' was 35% following treatment with imazapic at 35 g·ha^{-1} in 2020 compared with 60% in 2021 when precipitation was nearly double (Tables 3 and 4). Similar responses were also observed for 'Tahoma 31', 'TifTuf', and 'Tifway' in 2020 and 2021. All cultivars recovered (0% injury) by 28 DAT each year following treatment with imazapic at 35 g·ha^{-1}.

These findings suggest hybrid bermudagrass is less tolerant to imazapic applications for growth suppression than common bermudagrass. Brosnan et al. (2011) reported 15% and 17% common bermudagrass peak injury year over year with imazapic at 52 g·ha^{-1} at the same research location as our study. Comparatively, hybrid bermudagrass peak injury was ≥ 35% between 10 and 14 DAT (across cultivars and years) with imazapic at 52 g·ha^{-1} in our study. Hybrid bermudagrass injury reported herein is greater than that observed for other warm-season grass species (Marques et al. 2021a, 2021b) and may be a function of mowing height. Turfgrass was maintained at ≤ 1.6 cm in our study compared with a 3- to 5-cm range in work conducted on bahiagrass and St. Augustinegrass (Marques et al. 2021a).

Table 4. Environmental conditions at the East Tennessee Research and Education Center–Plant Sciences Unit (Knoxville, TN, USA) during field experiments conducted in 2020 and 2021.[i]

Data	2020 (11 Aug–11 Sep)	2021 (3 Aug–3 Sep)
Average surface temperature (°C)	24.6	24.6
Precipitation (cm)	12.7	23
Relative humidity (%)	78	77
Average soil temperature at 5 cm (°C)	25.4	25.1

[i] All data obtained from the mesur.io Earthstream® platform (mesur.io, Yanceyville, NC, USA).

Table 5. Analysis of variance of hybrid bermudagrass (*Cynodon dactylon* × *Cynodon transvaalensis* Burtt Davy) growth suppression data[i] following application of imazapic (Plateau®) in 2020 and 2021.

	Latitude 36 Run B		Tahoma 31		TifTuf		Tifway	
Source of variation	2020	2021	2020	2021	2020	2021	2020	2021
Imazapic rate[ii]	NS[iii]	*	*	NS	NS	NS	NS	NS
DAT[iv]	***	***	***	***	***	*	***	**
Imazapic rate × DAT	NS	NS	*	NS	*	NS	*	NS

[i] Turfgrass growth suppression was assessed by collecting clippings using a reel mower. Clippings were then placed in a forced-air oven for 72 h. When dried, they were weighed and made a percentage of the untreated control plots.

[ii] Treatments were applied 14 Aug 2020 and 6 Aug 2021. All treatments were mixed with methylated seed oil at 316 mL·ha^{-1}.

[iii] NS, ***, **, *Nonsignificant or significant at $P \leq 0.000$, 0.01, and 0.05 level, respectively.

[iv] DAT = days after treatment.

Hybrid bermudagrass growth suppression. ANOVA revealed a significant year-by-cultivar-by-DAT interaction (Table 5); therefore, growth suppression data are presented separately for each cultivar and year (Table 6). A significant imazapic rate-by-DAT interaction was present for growth suppression data collected for 'Tahoma 31', 'TifTuf', and 'Tifway' in 2020. However, significant differences among treatments were present only for select assessment dates (Supplemental Figs. S1–S3). A significant imazapic rate main effect was present in growth suppression data collected for 'Latitude 36' in 2021; however, this response was not present in growth suppression data collected for other cultivars (Supplemental Table S1).

Differences in growth suppression were detected among cultivars each year (Table 6). In 2020, across all cultivars, imazapic reduced dry clipping weight 37% to 56% compared with the untreated check. In 2021, dry clipping weight was reduced 39% to 78% across all cultivars by 21 DAT; however, rebound growth occurred, with dry clipping weight measuring 64% to 122% of the untreated check by 28 DAT. Interestingly, dry clipping weight for all cultivars other than 'Tifway' was ≥ 100% of the untreated check by 28 DAT in 2021. Similar to our turfgrass

Table 6. Growth suppression of hybrid bermudagrass (*Cynodon dactylon* × *Cynodon transvaalensis* Burtt Davy) cultivars in 2020 and 2021 in Knoxville, TN, USA.

		Growth suppression[ii]				
Cultivar[i]	Year	3 DAT[iii]	10 DAT[iv]	14 DAT	21 DAT	28 DAT
Latitude 36	2020	52 a[v]	26 b	13 c	42 a	50 a
	2021	62 b	ND	15 c	75 b	109 a
Tahoma 31	2020	66 a	5 d	34 c	78 a	50 b
	2021	57 b	ND	19 c	76 b	122 a
TifTuf	2020	56 a	17 c	18 c	20 c	37 b
	2021	90 ab	ND	68 b	78 b	107 a
Tifway	2020	43 c	4 e	22 d	77 a	56 b
	2021	74 a	ND	ND	39 b	64 a

[i] Hybrid bermudagrass cultivars Latitude 36, Tahoma 31, TifTuf, and Tifway are presented by each experimental year.

[ii] Growth suppression was determined by collecting and weighing clippings in each experimental unit. Data were used to calculate growth suppression as a percentage relative to the untreated control.

[iii] DAT = days after treatment.

[iv] No data (ND) for 10 DAT in 2021 are presented because extreme weather prevented clipping yield collections.

[v] Means with the same letter within each row are not significantly different according to Fisher's protected least significant difference ($\alpha = 0.05$).

injury assessments, greater growth suppression in 2021 could be related to increased precipitation (Table 4). Peak growth suppression following imazapic treatment occurred 10 to 14 DAT for all cultivars in both years, with the exception of 'Tifway' in 2021. Imazapic reduced hybrid bermudagrass dry clipping weight effectively for all cultivars each year. For example, at 10 DAT in 2020, dry clipping weights were 4% to 26% of the untreated check regardless of cultivar. In 2021, similar reductions were observed at 14 DAT for 'Latitude 36' and 'Tahoma 31'. Growth suppression with imazapic in our study was similar to that reported for other warm-season turfgrass species (Marques et al. 2021a, 2021b).

Imazapic (35 $g \cdot ha^{-1}$) could be used to suppress hybrid bermudagrass growth on golf courses if commercially unacceptable (albeit transient) injury (> 30%) is tolerable for up to 28 d. This is particularly important given that the species constitutes 32% of all maintained turfgrass hectarage on golf courses. Our study was limited in that imazapic was applied only singly to cultivars maintained at mowing heights $\leq$ 1.6 cm on a single soil type. Moreover, we did not compare directly the effects of imazapic to other PGRs used commercially in turfgrass, including trinexapac-ethyl, paclobutrazol, and Flurprimidol. Future research to understand these limiting factors more fully is warranted, given that turfgrass tolerance to imidazolinone herbicides can be affected by climatic zone (Brosnan et al. 2012).

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