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Effects of Preemergence Herbicides on the Establishment Rate and Tensile Strength of Hybrid Bermudagrass Sod

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Use of PRE herbicides for control of annual grassy weeds during commercial sod production has been limited. Research was conducted from 2010 to 2013 evaluating the effects of pendimethalin (3.36 kg ai ha^{-1}), dithiopyr (0.56 kg ai ha^{-1}), prodiamine (0.6 kg ai ha^{-1}), oxadiazon (3.36 kg ai ha^{-1}), prodiamine + sulfentrazone (0.84 + 0.41 kg ai ha^{-1}), dimethenamid-*P* (1.68 kg ai ha^{-1}), and indaziflam (0.03 and 0.05 kg ai ha^{-1}) applications at sprigging on the establishment rate and tensile strength of 'Tifway' hybrid bermudagrass sod at harvest (377 d after sprigging). All herbicides increased the days required to reach 50% hybrid bermudagrass cover compared with the nontreated control. Days required to reach 50% hybrid bermudagrass cover were lowest for oxadiazon and prodiamine (39 to 44 d), greatest for both rates of indaziflam (65 to 141 d), with dimethenamid-*P*, prodiamine plus sulfentrazone, pendimethalin, and dithiopyr ranking intermediate (45 to 63 d). Both rates of indaziflam reduced sod tensile strength at harvest compared with the nontreated control during a single year of the study; no other differences in sod strength due to herbicide treatment were detected at any time.

Nomenclature: Dimethenamid-*P*; dithiopyr; indaziflam; oxadiazon; pendimethalin; prodiamine; sulfentrazone; hybrid bermudagrass, *Cynodon dactylon* (L) Pers. × *Cynodon transvaalensis* Burtt Davy.
Key words: Athletic field, golf course, lawn, sod production, turf, turfgrass.

El uso de herbicidas PRE para el control de malezas gramíneas anuales durante la producción comercial de césped para corta ha sido limitado. Se realizó una investigación desde 2010 a 2013 evaluando los efectos de aplicaciones al momento de la siembra de fragmentos de estolones enraizados de pendimethalin (3.36 kg ai ha^{-1}), dithiopyr (0.56 kg ai ha^{-1}), prodiamine (0.6 kg ai ha^{-1}), oxadiazon (3.36 kg ai ha^{-1}), prodiamine + sulfentrazone (0.84 + 0.41 kg ai ha^{-1}), dimethenamid-*P* (1.68 kg ai ha^{-1}), e indaziflam (0.03 y 0.05 kg ai ha^{-1}) sobre la tasa de establecimiento y la resistencia al tiro del híbrido 'Tifway' del césped bermuda para corta al momento de la cosecha (377 d después de la siembra). Todos los herbicidas incrementaron los días requeridos para alcanzar 50% de cobertura del césped bermuda híbrido al compararse con el testigo sin tratamiento. El menor número de días requeridos para alcanzar 50% de cobertura del césped bermuda híbrido se obtuvo con oxadiazon y prodiamine (39 a 44 d), y el mayor número de días se observó con las dos dosis de indaziflam (65 a 141 d), los valores intermedios se observaron con dimethenamid-*P*, prodiamine más sulfentrazone, pendimethalin, y dithiopyr (45 a 63 d). Ambas dosis de indaziflam redujeron la resistencia al tiro al momento de la cosecha en comparación con el testigo sin tratamiento durante uno de los años del estudio; pero en ningún otro momento se detectó diferencia alguna en la fortaleza del césped después de la cosecha debido a los tratamientos de herbicidas.

Bermudagrass (*Cynodon* spp.) is the major turfgrass species commercially grown for sod throughout the southern United States, with most growers using vegetatively propagated hybrid bermudagrass varieties, such as 'Tifway'(McCalla et al. 2008). The quality of a turfgrass sod is not only a function of its aesthetic appearance, but also the ease with which it can be handled during harvest and installation (Sharpe et al. 1989). Infestations of annual grassy weeds, such as smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.], during grow-in can reduce sod quality (Fishel and Coats 1994).

PRE herbicides, such as dithiopyr, indaziflam, prodiamine, pendimethalin, and oxadiazon, can be used effectively to control annual grassy weeds, such as smooth crabgrass, which may facilitate hybrid bermudagrass establishment from sprigs by reducing weed competition (Bhowmik and Bingham 1990; Brosnan et al. 2010a, 2011; Ferrell et al. 2003). However, use of certain PRE herbicides has been shown to negatively affect bermudagrass

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establishment and root development, resulting in growers delaying planting for 12 to 20 wk after a PRE herbicide application (McCarty and Weinbrecht 1997). For example, applications of prodiamine at 0.8 kg ai ha^{-1} and dithiopyr at 0.6 kg ai ha^{-1} at sprigging reduced Tifway hybrid bermudagrass cover compared with the nontreated control for 12 wk after treatment (WAT) (McCarty and Weinbrecht 1997). In Arkansas and Oklahoma, at sprigging applications of dithiopyr at 0.6 kg ha^{-1}, prodiamine at 0.8 kg ha^{-1}, and pendimethalin at 1.7 kg ai ha^{-1} reduced 'Midlawn' hybrid bermudagrass establishment compared with the nontreated control at 28 d after treatment (DAT); however, bermudagrass cover was not significantly different from the nontreated control by $\sim$ 10 WAT (Boyd and Baird 1997). Fagerness et al. (2002) also observed reductions in Tifway cover with spring applications of dithiopyr and prodiamine 9 wk after sprigging in North Carolina but observed no reductions in Tifway cover with pendimethalin at 1.7 kg ha^{-1} or oxadiazon at 3.4 kg ai ha^{-1}. Bingham and Hall (1985) observed Tifway tolerance at sprigging to applications of oxadiazon up to 4.5 kg ha^{-1}. Brecke et al. (2010) reported moderate injury (20%) with oxadiazon at 2.2 kg ha^{-1} at sprigging, but turfgrass cover measured 90% of the nontreated at 13 WAT. McCullough et al. (2012) observed that dimethenamid-*P* (0.85 and 1.70 kg ai ha^{-1}) and oxadiazon (1.1, 2.2, and 4.4 kg ha^{-1}) applications at TifEagle hybrid bermudagrass sprigging did not reduce cover compared with a nontreated control after 8 wk. Moreover, these treatments controlled green kyllinga (*Kyllinga brevifolia* Rottb.) as well.

In addition to affecting bermudagrass establishment rate, reductions in bermudagrass root development have been reported with certain PRE herbicides used for smooth crabgrass control. Prodiamine and pendimethalin have been shown to reduce root growth of mature bermudagrass sod (Bhowmik and Bingham 1990). Fishel and Coats (1994) reported that dithiopyr (0.56 and 1.1 kg ha^{-1}) and prodiamine at 1.1 kg ha^{-1} reduced the total number of roots growing from bermudagrass sod 8 WAT. However, reductions in root weight were less pronounced because of increases in the number of abnormal (i.e., $<$ 2.5 cm long, lack of secondary root formation, root swelling) roots observed at 2 to 8 WAT with dithiopyr and prodiamine. In a separate study, Fishel and Coats (1993) reported substantial reductions in root weight at a 0 to 2.5 cm depth 2 to 8 WAT with prodiamine and dithiopyr to 'Tifgreen' bermudagrass grown on sandy clay loam and very fine sandy loam soils. In minirhizotrons, indaziflam (35 g ai ha^{-1}) and prodiamine (840 g ha^{-1}) reduced Tifway root length density 68 to 89% when applied to plants with roots ranging from 5 to 15 cm in a sand-based root zone with no organic matter. However, in silt loam soils, reductions with those treatments were less pronounced (Jones et al. 2013). Neither oxadiazon (1.7 and 3.4 kg ha^{-1}) nor pendimethalin (1.7 and 3.4 kg ha^{-1}) reduced the total number of bermudagrass roots or root weight at 8 WAT in Mississippi (Fishel and Coats 1994).

Reductions in bermudagrass root growth could compromise sod strength; however, data describing the effects of PRE herbicide applications on bermudagrass sod strength are limited. Bingham and Schmidt (1983) reported that prosulfalin and siduron reduced the force to lift 'Tifway' bermudagrass sod from soil compared with the nontreated; however, no reductions were observed with oxadiazon at 1.7 and 3.4 kg ha^{-1}. Similarly, Sharpe et al. (1989) reported no reduction in the tensile strength of Tifway sod at 8 WAT with oxadiazon (2.2 and 4.5 kg ha^{-1}) or pendimethalin (1.7 and 3.4 kg ha^{-1}).

Considering that commercially grown bermudagrass sod is traditionally harvested 10 to 12 mo after planting (Hall et al. 1988; White et al. 1991), PRE herbicides may be able to provide effective control of annual grassy weeds such as smooth crabgrass during grow-in without negatively affecting sod strength at harvest. However, PRE herbicides are not commonly applied by growers, in part because data describing the effects of PRE herbicides on bermudagrass establishment and sod tensile strength at harvest are limited, with few studies reporting data beyond 8 to 14 wk after sprigging. Therefore, the objective of this research was to evaluate the effects of various PRE herbicides applied at sprigging on the establishment rate and tensile strength of 'Tifway' hybrid bermudagrass sod.

Materials and Methods

Research was conducted on two bermudagrass fields at the East Tennessee Research and Education

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Figure 1. Apparatus used to measure hybrid bermudagrass *(C. dactylon* × *C. transvaalensis* Burtt-Davy, cv. 'Tifway') sod tensile strength at harvest during (377 d after sprigging) during field experiments conducted in Knoxville, TN during 2010 to 2011 and 2012 to 2013.

Center-Plant Sciences Unit (Knoxville, TN) from June 2010 to June 2011 and repeated from May 2012 to May 2013. Each field was a Sequatchie loam soil (fine-loamy, siliceous, semiactive, thermic humic Hapludult), with 6.2 soil pH and 2.1% organic matter content. Before initiating this research, each site received two rounds of broadcast glyphosate (Roundup ProMax, Monsanto, St. Louis, MO) applications (28 d interval) at 2.2 kg ha^{-1} to kill existing vegetation. Two weeks after the second application, each site was tilled and leveled with a heavy-duty reverse rototiller (STECAVATOR, Sandy Springs, SC). Sprigs of Tifway hybrid bermudagrass were hand-broadcast across each site on June 10, 2010, and May 16, 2012, at a rate of 78 m^3 ha^{-1} and were rolled to promote sprig-to-soil contact. Nutrients were applied weekly at 49 kg nitrogen (N) ha^{-1} from ammonium nitrate (34–0–0 [N–P–K]) for 12 wk. Once mature, turf was mowed with a reel mower at 22 mm with clippings returned.

Experimental design each year was a randomized complete block with six replications. Plot size was 1.5 by 1.5 m. Treatments included pendimethalin (Pendulum AquaCap, BASF Corporation, Research Triangle Park, NC) at 3.36 kg ha^{-1}, dithiopyr (Dimension 40 WP, Dow AgroSciences, Indianapolis, IN) at 0.56 kg ha^{-1}, prodiamine (Barricade 4FL, Syngenta Professional Products, Greensboro, NC) at 0.60 kg ha^{-1}, oxadiazon (Ronstar G, Bayer Environmental Sciences, Research Triangle Park, NC) at 3.36 kg ha^{-1}, prodiamine + sulfentrazone (Echelon 4SC, FMC Corporation, Philadelphia, PA) at 0.84 + 0.41 kg ai ha^{-1}, dimethenamid-*P* (Tower, BASF Corporation, Research Triangle Park, NC) at 1.68 kg ha^{-1}, and indaziflam (Specticle 20WSP, Bayer Environmental Sciences, Research Triangle Park, NC) at 0.03 and 0.05 kg ha^{-1}. A nontreated control was included for comparison. Treatments were applied immediately before sprigging with a CO_2-powered boom sprayer calibrated to deliver 281 L ha^{-1} using 8002 flat-fan nozzles (TeeJet, Spraying Systems Co., Roswell, GA) and watered in with ~ 6 mm of irrigation from an in-ground irrigation system within 30 min of treatment. After application, all plots were irrigated 5 times daily using an in-ground irrigation system to facilitate establishment (McCarty and Miller 2002).

Hybrid bermudagrass cover was measured weekly using digital image analysis (DIA) similar to the methods of Brosnan et al. (2010b). Digital images of each plot were captured using a 0.28-m^2 light box equipped with four TCP 40-W Spring Lamps (Lighthouse Supply Co., Bristol, VA) connected to an external power source (Xantrex 600 HD Power Pack, Xantrex Technology, Burnaby, BC, Canada). Images were taken with a digital camera (Cannon G5, Cannon USA, Lake Success, NY) capable of capturing 5 million pixels per image. Total image size measured 307,200 pixels. SigmaScan Pro software (Systat Software, San Jose, CA) was used to express image pixilation as measurements of turfgrass cover similar to the methods of Richardson et al. (2001). Pixels defined as green turf exhibited a hue range of 45° to 120° and saturation values between 0% and 100%. To calculate hybrid bermudagrass cover, the number of green turf pixels in each image was divided by the total number of pixels in the image (307,200 pixels).

Sod tensile strength was measured 377 d after sprigging, using a device similar to that designed at Michigan State University by Sorochan et al. (2001). This instrument is pictured in Figure 1. Two slabs of sod (~ 2,000 cm^2) were harvested from the center of each plot using a walk-behind sod harvester (Ryan Jr. Sod Cutter, CGC Inc., Johnson Creek, WI) set to a 2 cm depth. Each slab was fastened to the measuring device using four metal bars (10 cm width) equipped with 29 metal golf spikes (8 mm length). During testing,

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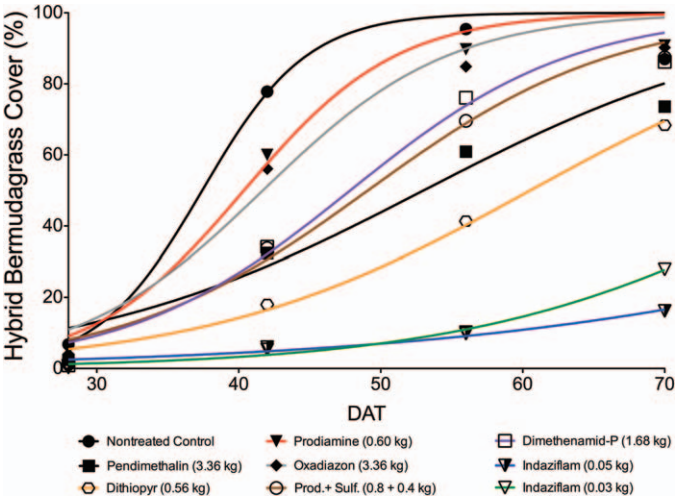

Figure 2. Predicted turfgrass cover increase over time following applications of various PRE herbicides on the day of hybrid bermudagrass *(C. dactylon* × *C. transvaalensis* Burtt-Davy, cv. 'Tifway') sprigging in Knoxville, TN, during 2010 and 2012.

hydraulically driven pulleys directed one set of fasteners away from the other and the maximum lateral pulling force (N) required to tear the sod was recorded using a load cell (Chatillon Digital Force Load Cell, AMETEK US Gauge Division, Largo, FL). Similar devices have been used by other researchers to measure sod strength (McCalla et al. 2008). Sod strength means, in this study, represent the average of two subsamples per plot. Sod strength data were collected on June 22, 2011, and May 28, 2013.

Statistical Analysis. Hybrid bermudagrass cover and sod tensile strength data were subjected to ANOVA in SAS, with main effects and all possible interactions tested using the appropriate expected mean square values described by McIntosh (1983).

Hybrid bermudagrass cover data were fit to a sigmoid variable slope model similar to Karcher et al. (2008) where,

$$\text{Hybrid bermudagrass cover}\,(\%) = 100/\left\{1 + 10^{\left[(\text{days}_{50} - \text{DAT})\text{slope}\right]}\right\} \qquad [1]$$

where DAT is days after treatment, and days_{50} and slope are estimated regression parameters. Days_{50} is an estimate of the days required to reach 50% hybrid bermudagrass cover, whereas the slope provides an indication of how rapidly hybrid bermudagrass cover changes over time; larger positive or negative values indicate steeper slopes on each sigmoid curve. A sums of squares reduction *F* test was conducted to compare sums of squares from a global model (all treatments share days_{50} and slope values) to a cumulative model where unique days_{50} and slope values were calculated for each treatment. Confidence intervals (95%) were used to determine whether herbicide treatments varied in the days required to reach 50% hybrid bermudagrass cover. All nonlinear regression analyses were conducted using GraphPad Prism 6 for Mac OS X (GraphPad Software, San Diego, CA.) Sod strength means were separated using Fisher's protected LSD test at the $\alpha = 0.05$ level.

Results and Discussion

Hybrid Bermudagrass Cover. No significant year-by-treatment interactions were detected; therefore, data from each year were combined for regression analysis. Variable-slope sigmoid models fit hybrid bermudagrass cover data (Figure 2). A sum of squares reduction *F* test determined that days_{50} and slope values were not shared among treatments ($P < 0.0001$). Therefore, days_{50} and slope values for each treatment are presented in Table 1, along with R^2 values for each sigmoid-variable slope model.

Confidence intervals surrounding the predicted number of days required to reach 50% hybrid bermudagrass cover revealed significant differences between treatments (Figure 3). All herbicides increased the days required to reach 50% hybrid bermudagrass cover compared with the nontreated control. Furthermore, the slope of the sigmoid model used to fit hybrid bermudagrass cover data for the nontreated control exceeded all other herbicide treatments indicating that changes in cover were most rapid when no herbicides were applied (Table 1). This research site had been maintained weed-free for 3 yr before initiating this study; thus, weed pressure across the experimental area was low. Weed control efficacy with dimethenamid-*P* and oxadiazon can facilitate establishment compared with nontreated areas when weed pressure is significant (Brecke et al. 2010; McCarty and Weinbrecht 1997; McCullough et al. 2012).

Among herbicide treatments, days required to reach 50% hybrid bermudagrass cover were lowest for oxadiazon and prodiamine (39 to 44 d), greatest for both rates of indaziflam (65 to 141 d), with

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Table 1. Parameters for predicting hybrid bermudagrass (*C. dactylon* × *C. transvaalensis* Burtt-Davy, cv. 'Tifway') cover following treatment with various PRE herbicides applied at sprigging in Knoxville, TN, during 2010 and 2012. Larger slope values translate to more-rapid changes in hybrid bermudagrass cover over time. $Days_{50}$ is the predicted number of days to reach 50% hybrid bermudagrass cover. Standard error values for each parameter are listed in parentheses.

Treatment	Rate	Slope	$Days_{50}$	R^2
	kg ha^{-1}	°	Mean d (SE)	
Dimethenamid-*P*	1.68	0.05 (0.008)	47.8 (1.3)	0.78
Dithiopyr	0.56	0.04 (0.005)	60.5 (1.5)	0.73
Indaziflam	0.03	0.03 (0.007)	81.8 (3.6)	0.54
Indaziflam	0.05	0.02 (0.009)	103.1 (18.7)	0.16
Oxadiazon	3.36	0.07 (0.012)	41.7 (1.2)	0.78
Pendimethalin	3.36	0.04 (0.006)	53.0 (2.1)	0.61
Prodiamine	0.60	0.08 (0.011)	40.4 (0.7)	0.90
prodiamine + sulfentrazone	0.84 + 0.41	0.05 (0.007)	49.1 (1.4)	0.79
Nontreated control	—	0.12 (0.015)	37.4 (0.7)	0.92

dimethenamid-*P*, prodiamine plus sulfentrazone, pendimethalin, and dithiopyr ranking intermediate (Figure 3). Dimethenamid-*P*, prodiamine plus sulfentrazone, and pendimethalin were similar to one another, requiring 45 to 57 d to reach 50% hybrid bermudagrass cover. Days required for dithiopyr-treated plots to reach 50% hybrid bermudagrass cover were similar to that of pendimethalin (58 to 63 d) but greater than that of dimethenamid-*P* and prodiamine plus sulfentrazone.

Increases in the days required to reach 50% hybrid bermudagrass cover following treatment with dimethenamid-*P*, oxadiazon, and prodiamine were minor; these treatments required 39 to 50 d to reach 50% cover compared with ~ 37 d for the nontreated control. This supports previous work

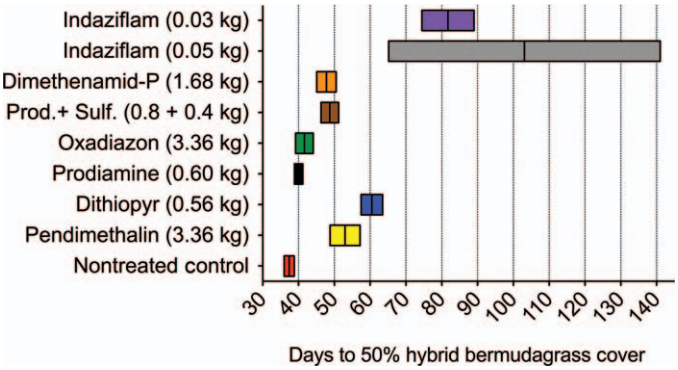

Figure 3. Confidence intervals (95%) for the number of days to reach 50% hybrid bermudagrass *(C. dactylon* × *C. transvaalensis* Burtt-Davy, cv. 'Tifway') cover following treatment with various PRE herbicides applied at sprigging in 2010 and 2012 in Knoxville, TN. Entries with overlapping bars are not significantly different from one another.

reporting no significant reductions in hybrid bermudagrass cover 8 to 13 WAT with applications of dimethenamid-*P* and oxadiazon at sprigging (Brecke et al. 2010; McCullough et al. 2012). Responses with prodiamine in the current study differ from those reported by other researchers (Boyd and Baird 1997; Fagerness et al. 2002; McCarty and Weinbrecht 1997), likely because of application rate. Prodiamine was applied at 0.6 kg ha^{-1}, compared with 0.8 to 1.1 kg ha^{-1}, in previous research. This reduced rate was selected in accordance with current prodiamine label directions for use in newly sprigged hybrid bermudagrass turf (Anonymous 2012a). Responses observed with dithiopyr and pendimethalin applications at sprigging in this study support previous reports of reduced establishment rates with these herbicides (Boyd and Baird 1997; Fagerness et al. 2002; McCarty and Weinbrecht 1997). Delays in the number of days to reach 50% hybrid bermudagrass cover with indaziflam support current labeling that restricts use for 16 mo after sprigging (Anonymous 2012b).

Sod Tensile Strength. Significant differences in sod tensile strength due to herbicide treatment were only detected in a single year of this study (Table 2). In the first year of the study, both rates of indaziflam evaluated reduced hybrid bermudagrass sod strength at harvest compared with the nontreated control, again supporting current label directions pertaining to use during sprigged establishment of turfgrass. No other herbicide treatment reduced sod strength compared with the nontreated control, with tensile strength values ranging from

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Table 2. Effects of various PRE herbicide treatments applied at sprigging on hybrid bermudagrass (*C. dactylon* × *C. transvaalensis* Burtt-Davy, cv. 'Tifway') sod tensile strength at harvest (377 d after sprigging). Experiments were conducted in Knoxville, TN, during 2010 to 2011 and 2012 to 2013.

		Tensile strength	
Treatment[a]	Rate	2010	2013
	kg ha^{-1}	N	
Dimethenamid-*P*	1.68	890	642
Dithiopyr	0.56	853	617
Indaziflam	0.03	473	686
Indaziflam	0.05	433	546
Oxadiazon	3.36	890	808
Pendimethalin	3.36	834	703
Prodiamine	0.60	795	705
Prodiamine + sulfentrazone	0.84 + 0.41	890	791
Nontreated control	—	789	586
$LSD_{0.05}$		129	NS[b]

[a] Herbicides applied on the day of sprigging. Each location was sprigged at 78 m^3 ha^{-1} on June 10, 2010, and May 16, 2012.
[b] Abbreviation: NS, not significant.

789 to 890 N. In the second year of the study, no significant differences in sod strength were detected due to herbicide treatment, with values ranging from 546 to 808 N. Responses with oxadiazon and pendimethalin in the current study support previous reports by Sharpe et al. (1989).

Our research was limited because evaluations were made on sites that had been maintained weed free for several years before initiating research. Reductions in hybrid bermudagrass establishment because of weed pressure were not captured in these studies. Moreover, weed control with PRE herbicide use during establishment could facilitate hybrid bermudagrass establishment rates compared with nontreated plots. Nevertheless, our findings indicate that pendimethalin, dithiopyr, prodiamine, oxadiazon, prodiamine + sulfentrazone, and dimethenamid-*P* may slow the establishment rate of hybrid bermudagrass sod up to 28 d but do not negatively affect sod tensile strength at harvest. Future research should evaluate effects of PRE herbicide applications on the establishment rate and tensile strength of other warm-season turfgrasses produced as sod, particularly zoysiagrass (*Zoysia* spp.)

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