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Mitigation Practices to Effectively Overseed into Indaziflam-Treated Turfgrass Areas

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Indaziflam is a PRE herbicide for annual broadleaf and grass control in turfgrass systems and requires a 40-wk minimum interval between application and overseeding perennial ryegrass. Currently, activated-charcoal application is recommended to reduce that interval; however, preliminary evaluations determined activated charcoal alone was not a robust mitigation practice for successful establishment during perennial ryegrass overseeding. Field research was conducted in North Carolina and Tennessee to evaluate various mitigation practices to effectively overseed perennial ryegrass into indaziflam-treated turfgrass areas. Immediately following indaziflam application (53 g ai ha^{-1}), two scenarios were created by delivering 0 or 0.3 cm H_2O before mitigation practice. Irrigated plots were air-dried before conducting mitigation practices. Evaluated mitigation practices included scalping (0.6 cm cut height; debris removed), verticutting (1.25 cm depth; debris removed), and activated-charcoal application (167 kg ha^{-1} applied as an aqueous slurry in 3,180 L ha^{-1}), evaluated individually and in each two-way combination in the order scalp followed by (fb) activated charcoal, scalp fb verticut, or verticut fb activated charcoal. Twenty-four hours after mitigation practice completion, perennial ryegrass was seeded (976 kg ha^{-1}) and maintained as a golf course fairway. Overall, perennial ryegrass cover was reduced $\geq$ 93% at 8 and 20 wk after treatment (WAT) when no mitigation practices were performed. Stand-alone mitigation practices variably improved perennial ryegrass establishment; however, no practice provided acceptable results for end users. Combining mitigation practices improved overseeding establishment, most notably by adding activated charcoal application or verticutting to scalping before irrigation. Across experimental runs and locations, scalp fb activated-charcoal application before irrigation reduced perennial ryegrass cover 22 to 27% at 20 WAT. Results from this research suggest mitigation practices in addition to the currently recommended activated-charcoal application should be performed by turfgrass managers to improve perennial ryegrass overseeding establishment in indaziflam-treated turfgrass areas.

Nomenclature: Indaziflam; bermudagrass, *Cynodon dactylon* (L.) Pers.; hybrid bermudagrass × African dogstooth grass, *Cynodon dactylon* (L.) × *Cynodon transvaalensis* Burtt Davy; perennial ryegrass, *Lolium perenne* L.

Key words: Activated charcoal, best management practice, pesticide remediation, scalp, verticut.

Indaziflam es un herbicida PRE para el control de gramíneas anuales en sistemas de céspedes y que requiere un intervalo mínimo de 40 semanas entre la aplicación y la siembra de *Lolium perenne* sobre césped bermuda establecido. Actualmente, la aplicación de carbón activado está recomendada para reducir este intervalo; sin embargo, evaluaciones preliminares permitieron determinar que el carbón activado solo no fue una práctica robusta para el establecimiento exitoso durante la siembra de *L. perenne* sobre césped establecido. Se realizó una investigación de campo en North Carolina y Tennessee para evaluar varias práctica de mitigación, para poder sembrar efectivamente *L. perenne* en áreas de césped tratadas con indaziflam. Inmediatamente después de la aplicación de indaziflam (53 g ai ha^{-1}), se crearon dos escenarios aplicando 0 ó 0.3 cm H_2O antes de la práctica de mitigación. Las parcelas irrigadas se dejaron secar al aire antes de realizar las prácticas de mitigación. Las prácticas de mitigación evaluadas incluyeron la remoción de la mayoría del tejido foliar (scalp; corte a 0.6 cm de altura y remoción de residuos), corte vertical (verticut; corte a 1.25 cm de profundidad y remoción de residuos), y la aplicación de carbón activado (167 kg ha^{-1} aplicado como una suspensión acuosa en 3,180 L ha^{-1}), evaluados individualmente y en cada una de las posibles combinaciones en pares, en el orden de scalp seguido por (fb) carbón activado, scalp fb verticut, o verticut fb carbón activado. Veinticuatro horas después de terminar la práctica de mitigación, se sembró *L. perenne* (976 kg ha^{-1}) y el área se mantuvo como fairway de un campo de golf. En general, la cobertura de *L. perenne* se redujo ≥93% entre 8 y 20 semanas después del tratamiento (WAT) cuando no había práctica de mitigación. Las

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prácticas de mitigación consideradas en forma independiente, mejoraron el establecimiento de *L. perenne* en forma variable. Sin embargo, ninguna práctica brindó resultados aceptables para los usuarios finales. El combinar las prácticas de mitigación mejoró el establecimiento de *L. perenne*, y esto fue más notable al agregar la aplicación de carbón activado o verticut a áreas con scalp antes del riego. Al analizar en forma conjunta las corridas experimentales y las localidades, scalp fb carbón activado antes del riego redujo la cobertura de *L. perenne* 22 a 27% a 20 WAT. Los resultados de esta investigación sugieren que las prácticas de mitigación, además de las aplicaciones de carbón activado, actualmente recomendadas, deberían ser implementadas por profesionales de manejo de césped para mejorar el proceso de establecimiento en áreas de césped tratadas con indaziflam.

Indaziflam (WSSA group 29) is a cellulose biosynthesis–inhibiting herbicide belonging to the alkylazine chemical family (EPA 2010). In 2010, indaziflam received registration in the United States for PRE annual dicot and monocot weed control in citrus fruit, commercial nurseries, landscape plantings, managed roadsides, noncroplands, and turfgrass (EPA 2010). Injury to susceptible species ranges from chlorosis to necrosis across plant tissue, which is followed by plant death (Anonymous 2015). In addition to providing control of numerous weeds common in turfgrass systems, indaziflam provides an alternative mode of action for PRE control of dinitroaniline-resistant annual, grassy weeds in the southern United States (Brosnan et al. 2011, 2012; Henry et al. 2012; McCullough et al. 2013).

Bermudagrass athletic fields and golf course fairways are commonly overseeded in subtropical climates in fall to provide year-round-green turfgrass cover (Henry et al. 2012; Horgan and Yelverton 2001; McElroy et al. 2011; Turgeon 2011). Further, overseeding may reduce thinning of dormant bermudagrass from equipment and foot traffic and prevent weed encroachment (Mazur and Wagner 1987; Thoms et al. 2011). Overseeding is a process in which a cool-season turfgrass is seeded into bermudagrass typically when air temperatures are consistently < 16 C, and 20 to 30 d before the first killing frost (McElroy et al. 2011; Turgeon 2011). Perennial ryegrass is a common species overseeded into bermudagrass because of its rapid germination (approximately 5 d), dark-green color, and winter hardiness (Horgan and Yelverton 2001; McCarty 2011; McElroy et al. 2011).

Optimum perennial ryegrass establishment comprises sequential cultural practices at the appropriate environmental timing before overseeding (McCarty and Miller 2002). Cultural practices recommended before overseeding include verticutting and scalping. Verticutting is a practice in which an implement with a series of knives vertically mounted on a rotating horizontal shaft slice into the turfgrass canopy to reduce thatch (McCarty 2011; Turgeon 2011). Typically, debris is removed following verticutting. Approximately 10 to 14 d before overseeding, it is recommended that verticutting be combined with scalping or mowing below the one-third maintenance height of cut to promote seed-to-soil contact and reduce light competition (McCarty 2011). As with verticutting, debris produced from scalping is typically collected.

Previous research has shown PRE herbicide applications, including indaziflam, may compromise subsequent overseeding establishment (Henry et al. 2012; Johnson and Bundscuh 1993; Keeley and Zhou 2005; Yelverton and McCarty 2001). Keeley and Zhou (2005) reported dithiopyr (WSSA group 3; 0.56 kg ha^{-1}), prodiamine (WSSA group 3; 0.84 kg ha^{-1}), and pendimethalin (WSSA group 3; 3.36 kg ha^{-1}) caused unacceptable Kentucky bluegrass (*Poa pratensis* L.) establishment when broadcast-seeded $<$ 6, 8, and 14 wk after herbicide application. Johnson and Bundscuh (1993) and Yelverton and McCarty (2001) reported $>$ 8 wk intervals were needed between dithiopyr (0.56 kg ha^{-1}) and prodiamine (0.84 kg ha^{-1}) applications and perennial ryegrass seeding. Previous research suggests an overseeding interval following an indaziflam application may exceed the aforementioned herbicides. Henry et al. (2012) reported indaziflam applied in the spring at a rate of 70 fb 35 g ha^{-1} required for $>$ 90% crabgrass (*Digitaria* sp.) control reduced perennial ryegrass establishment (seeded 36 wk after initial application) 65% compared with prodiamine (0.55 kg ha^{-1}) and the nonindaziflam-treated check. This is likely due to long persistence (field half-life $>$ 150 d), moderate soil organic carbon-water partition coefficient (K_{oc}; $K_{oc} = 434$ to 1,544 mL g^{-1}), and perennial ryegrass's inherent sensitivity (50% lethal concentration [LC_{50}]; LC_{50} is approximately equal to 3 g ha^{-1}) (Alonso et al. 2011; EPA 2010; Jhala et al.

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2012). Currently, the indaziflam label requires a minimum overseeding interval of 40 wk for the lowest-labeled, single-application rate (25 g ha^{-1}) (Anonymous 2015).

Turfgrass managers may be unable to predict seeding or sprigging needs under certain circumstances, such as event scheduling or vandalism. Under such circumstances, establishment may be adversely affected if areas were previously treated with indaziflam, either intentionally or unintentionally via misapplication. Ultimately, current seeding and sprigging establishment restrictions in indaziflam-treated areas may limit its use by turfgrass managers (Henry et al. 2012). Therefore, practices should be identified to reduce the interval needed between indaziflam application and perennial ryegrass overseeding. Because of the perennial nature of turfgrass systems, many soil-pesticide residue reduction practices, such as disking or tillage, incineration, and phytoremediation, are not viable options (Gan et al. 2004; Kearney and Roberts 1998). One common mitigation practice in turfgrass systems is to apply activated charcoal to sorb pesticides, making them not bioavailable for uptake (McCarty 2011, 2014). Johnson (1976) reported centipedegrass [*Eremochloa ophiuroides* (Munro) Hack.] establishment was improved when sprigs were dipped into an activated-charcoal solution before planting in herbicide-treated areas. Further, research has shown activated-charcoal applications improve cool-season turfgrass seed establishment in indaziflam-treated areas ($\leq$ 40 g ha^{-1}) (Spak et al. 2011). Currently, the only deactivation practice recommended on the indaziflam label is applying activated charcoal; however, our preliminary evaluations determined that practice alone was nonrobust for successful overseeding establishment (Anonymous 2015). Therefore, it was necessary to evaluate additional turfgrass-management practices designed to remove indaziflam-treated biomass from the system. The objective of this research was to evaluate various mitigation practices to effectively overseed into indaziflam-treated turfgrass.

Materials and Methods

Field research was initiated October 11, 2012, and October 12, 2013, in North Carolina (Lake Wheeler Turfgrass Field Laboratory, Raleigh, NC) to evaluate various mitigation practices to effectively overseed perennial ryegrass into indaziflam-treated turfgrass areas. This experiment was also initiated October 21, 2013, in Tennessee (East Tennessee Research and Education Center–Plant Sciences Unit, Knoxville, TN) to evaluate mitigation practices across a wider geographic region of the southeastern United States. North Carolina experiments were conducted on an established 'Tifway 419' hybrid bermudagrass area maintained at a 1.9-cm cut height. Tennessee experiments were conducted on an established 'Riviera' bermudagrass area maintained at a 1.6-cm cut height. Soil type in North Carolina was a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult), measuring 5.4 and 2.2% weight to weight (w/w) in soil pH and organic matter (OM), respectively. Soil type in Tennessee was a Sequatchie loam soil (fine-loamy, siliceous, semiactive, thermic humic Hapludult), measuring 6.6 and 2.1% w/w in soil pH and OM, respectively. Indaziflam had not been applied to North Carolina and Tennessee trial areas for > 2 yr.

Two days before experiment initiation, trial areas were mown, debris was removed, and the plots were irrigated to field capacity. At initiation, indaziflam (Specticle FLO, Bayer Environmental Science, Research Triangle Park, NC) was applied (53 g ha^{-1}; maximum labeled rate for annual bluegrass [*Poa annua* L.] control at experiment initiation) to 1.1- by 3.4-m experimental units with a CO_2-propelled boom comprising three 8002 XR VS flat-fan nozzles (TeeJet Flat-Fan Nozzles, Spraying Systems Co., Wheaton, IL) calibrated to deliver 304 L ha^{-1} at 179 kPa (Anonymous 2010). One hour after initiation, two indaziflam application scenarios were developed by manipulating irrigation inputs. Previous research, as well as the current indaziflam label, states irrigation following application is required for acceptable weed control (Anonymous 2015; Brosnan and Breeden 2012). Therefore, 0 or 0.3 cm of H_2O was delivered to half of the block immediately after indaziflam application and before beginning mitigation practice to mimic a misapplication scenario (0 cm H_2O) or to comply with current recommendations (0.3 cm H_2O). After plots dried from irrigation, evaluated mitigation practices were initiated and included scalping (Toro ReelMaster 1000 Mower, The Toro Company, Bloomington, MN), verticutting (GS04 Verticutter, Graden USA, Richmond, VA), and activated charcoal application (BL Powdered Activated Carbon, Calgon Carbon Corporation, Pittsburgh, PA). Scalping was completed by mowing the plot six times at a 0.6-cm cut height (collecting debris) to remove all aboveground green vegetation. Verticutting was completed by making two side-by-side passes (38-cm width per pass) at a 1.25-cm depth. Debris was collected with hand tools after a 30-min drying time. Activated charcoal was applied in accordance with general pesticide deactivation recommendations (167 kg ha^{-1}) as an aqueous slurry with a CO_2-propelled boom comprising three 8008 XR VS flat-fan nozzles calibrated to deliver 3,180 L ha^{-1} at 137 kPa (McCarty 2011, 2014). The slurry was applied in a manner to prevent foot-tracking to adjacent plots. Nonindaziflam-treated plots were subjected to a mitigation practice or practices before indaziflam-treated plots to prevent indaziflam contamination. All mitigation practices were evaluated individually, as well as in each two-way combination in the order scalp followed by (fb) activated charcoal, scalp fb verticut, or verticut fb activated charcoal. Finally, nonmitigated plots were included as baselines to quantify perennial ryegrass establishment success following the evaluated indaziflam mitigation practices.

Twenty-four hours after the completion of mitigation practices, perennial ryegrass ('Carly') was broadcast-seeded (976 kg ha^{-1}) and irrigated to supplement rainfall and promote germination; however, irrigation or rainfall > 1.25 cm H_2O d^{-1} was not delivered to plots for 1 wk. This measure was taken to minimally affect POST application irrigation inputs (0 or 0.3 cm H_2O) and mitigation practices. The selected perennial ryegrass seed timing was based on previous research that determined indaziflam soil–solution equilibrium was reached in < 24 h across two loam soils (Alonso et al. 2011). Following perennial ryegrass overseeding, research areas were maintained as a golf course fairway for fungicide and insecticide applications, fertility (49 kg N ha^{-1} mo^{-1}), irrigation (provided to supplement rainfall), and mowing (1.9 cm cut height; three events per weeks; clippings returned) (McCarty 2011). Herbicides and plant growth regulators were not applied to experimental areas throughout the research.

Perennial ryegrass cover was visually estimated on a 0 (no cover) to 100% (complete cover) scale at 4, 8, 12, 16, and 20 wk after treatment (WAT). Perennial ryegrass cover data were converted to a percentage of reduction relative to the respective nonindaziflam-treated mitigation practice within a replicate using the following equation:

$$\%\ reduction = \{[(NT - T)/NT] \times 100\} \quad (1)$$

where NT and T equaled perennial ryegrass cover data from a nonindaziflam-treated and indaziflam-treated plot, respectively. At the aforementioned rating dates, digital image analysis (DIA) was conducted to determine the percentage of perennial ryegrass cover within an image using a macro for ImageJ 64 software (National Institutes of Health, Bethesda, MD), similar to that used by Campillo et al. (2008). Three images (1,936 by 1,296 pixels) were captured at random over 1,200-cm^2 areas within each plot using a digital camera (Canon PowerShot SD750, Canon Inc., Lake Success, NY) mounted to a portable light box (NexGen Light Box, NexGen Turf Research, Albany, OR) equipped with four fluorescent light bulbs (TCP T2, 9 W, 6,500 K SpringLamp, Technical Consumer Products, Aurora, OH) to quantify average green cover per plot.

The experimental design was a split-plot, randomized complete block with four and three replicates in North Carolina and Tennessee, respectively. Whole-plot factor was irrigation, and subplots were mitigation practices. Data were subjected to ANOVA ($P = 0.05$) using general linear models in SAS software (version 9.2, SAS Institute, Cary, NC). Significant main effects and their interactions are presented accordingly, with precedent given to interactions of increasing magnitude (Steel et al. 1997). Means were separated according to Fisher's protected LSD test ($P < 0.05$) when F tests were statistically significant. Finally, Pearson correlation coefficients ($P = 0.05$) were calculated to quantify the relationship between visual perennial ryegrass cover estimates and cover determined by DIA.

Results and Discussion

The first evaluation date when perennial ryegrass cover in nonindaziflam-treated plots was consistently $> 80\%$, which was our baseline for successful overseeding establishment, was 8 WAT. Final perennial ryegrass cover evaluations were conducted at 20 WAT because of bermudagrass transitioning

Table 1. Effect of irrigation and mitigation practices following indaziflam application on perennial ryegrass cover 8 wk after seeding.[a–d]

Practice	North Carolina 2012–2013 Irrigated[e]	North Carolina 2012–2013 Nonirrigated	North Carolina 2013–2014 Irrigated	North Carolina 2013–2014 Nonirrigated	Tennessee 2013–2014 Irrigated	Tennessee 2013–2014 Nonirrigated
	% cover reduction[f]					
AC	54	98	100	100	90	90
SC	90	49	99	54	100	95
VC	95	95	100	100	98	100
SC fb AC	36	25	43	19	87	48
SC fb VC	60	26	92	19	100	94
VC fb AC	63	86	93	100	96	98
Nonmitigated	93	100	100	100	100	96
$LSD_{0.05}$	22		15		14	

[a] Abbreviations: AC, activated charcoal; SC, scalp; VC, verticut; fb, followed by.

[b] Visual cover rated on a scale of 0 (no ryegrass cover) to 100% (complete ryegrass cover).

[c] Indaziflam applications made October 11, 2012 (North Carolina); October 12, 2013 (North Carolina); and October 21, 2013 (Tennessee).

[d] Perennial ryegrass cover evaluations conducted December 7, 2012 (North Carolina); December 10, 2013 (North Carolina); and December 16, 2013 (Tennessee).

[e] Irrigation = 0.3 cm H_2O delivered to plots immediately after application and before mitigation practices.

[f] *% cover reduction* = $\{[(NT - T)/NT] \times 100\}$, where *NT* and *T* were cover estimated in nonindazilfam-treated and indaziflam-treated plots, respectively, within a mitigation practice and replicate.

out of dormancy at later evaluation dates. Further, indaziflam-treated plots had maximum perennial ryegrass cover at 20 WAT. At both 8 and 20 WAT, a significant experimental run-by-irrigation-by-mitigation practice interaction was detected in North Carolina data collected in 2012 to 2013 and 2013 to 2014. Further, a significant location-by-irrigation-by-mitigation practice interaction was detected between 2013 to 2014 data collected in North Carolina and Tennessee at 8 and 20 WAT. In both cases, data were separated by experimental run and location and are presented accordingly. Data from 8 and 20 WAT are presented to (1) discuss the effect of POST application irrigation on mitigation practices, (2) compare mitigation practices within an indaziflam-application scenario, and (3) highlight mitigation practices providing ≤ 30% perennial ryegrass cover reduction.

Perennial Ryegrass Cover. Irrigation-by-mitigation practice interactions were detected 8 WAT across all three experiments ($P < 0.0001$; Table 1). Perennial ryegrass cover in nonindaziflam-treated plots was ≥ 80%, whereas cover was ≤ 4% when no mitigation practice was performed after indaziflam treatment across all three experiments (data not shown). Irrigation before applying activated charcoal reduced perennial ryegrass cover 54% in North Carolina during 2012 to 2013; however, this was not observed in either location during 2013 to 2014 (≥ 90% perennial ryegrass cover reduction). Perennial ryegrass cover was reduced 49 and 54% in 2012 to 2013 and 2013 to 2014, respectively, when irrigation was not applied before scalping; however, this was not observed, regardless of irrigation inputs, in Tennessee (≥ 95% perennial ryegrass cover reduction). Verticutting was an ineffective stand-alone mitigation practice across both indaziflam-application scenarios because perennial ryegrass cover was reduced ≥ 95% in all three experiments. In general, combining mitigation practices improved perennial ryegrass cover at 8 WAT. In both North Carolina experiments, the addition of activated charcoal or verticutting to nonirrigated scalping (19 to 26% perennial ryegrass cover reduction) improved perennial ryegrass cover compared with activated charcoal application (≥ 98% reduction), scalping (49 to 54% reduction), or verticutting (95 to 100% reduction) independently. These mitigation practices in tandem were the only evaluated treatments that

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Table 2. Effect of irrigation and mitigation practices following indaziflam application on perennial ryegrass cover 20 wk after seeding.[a–d]

	North Carolina				Tennessee	
	2012–2013		2013–2014		2013–2014	
Practice	Irrigated[e]	Nonirrigated	Irrigated	Nonirrigated	Irrigated	Nonirrigated
	% cover reduction[f]					
AC	66	90	83	94	94	89
SC	93	50	97	37	100	89
VC	91	97	99	100	98	100
SC fb AC	38	27	29	22	67	23
SC fb VC	55	35	86	7	100	95
VC fb AC	60	79	74	89	100	100
Nonmitigated	100	100	100	100	100	96
$LSD_{0.05}$	13		12		8	

[a] Abbreviations: AC, activated charcoal; SC, scalp; VC, verticut; fb, followed by.

[b] Visual cover rated on a scale of 0 (no ryegrass cover) to 100% (complete ryegrass cover).

[c] Indaziflam applications made October 11, 2012 (North Carolina); October 12, 2013 (North Carolina); and October 21, 2013 (Tennessee).

[d] Perennial ryegrass cover evaluations conducted March 4, 2013 (North Carolina); March 2, 2014 (North Carolina); and March 10, 2014 (Tennessee).

[e] Irrigation = 0.3 cm H_2O delivered to plots immediately after application and before mitigation practices.

[f] % *cover reduction* = $\{[(NT - T)/NT] \times 100\}$, where NT and T were cover estimated in nonindaziflam-treated and indaziflam-treated plots, respectively, within a mitigation practice and replicate.

provided ≤ 30% perennial ryegrass cover reduction. In general, Tennessee mitigation practices were less effective on perennial ryegrass cover at 8 WAT because only scalping fb activated charcoal application before irrigation (48% perennial ryegrass cover reduction) differed from plots receiving no mitigation practice after indaziflam application and seeding (96% perennial ryegrass cover reduction). Although no evaluated mitigation practice provided < 10% perennial ryegrass cover reduction, data suggest the interval required between indaziflam application and perennial ryegrass overseeding can be reduced via mitigation practices. Perennial ryegrass cover was reduced > 93% when no mitigation practice was performed in areas irrigated and nonirrigated after indaziflam application, regardless of location or experimental run.

Irrigation-by-mitigation practice interactions were also detected at 20 WAT across all three experiments ($P < 0.0001$; Table 2). In general, results from 20 WAT aligned with 8 WAT. Across all three experiments, when no mitigation practice was performed following indaziflam treatment, perennial ryegrass cover in nonindaziflam-treated plots was ≥ 88%, whereas cover was ≤ 2% (data not shown). Activated charcoal application and verticutting performed before irrigation reduced perennial ryegrass cover > 89%. Although unacceptable, when scalping occurred before irrigation, perennial ryegrass cover was reduced 50 and 37% in 2012 to 2013 and 2013 to 2014 (North Carolina), respectively. All stand-alone mitigation practices performed after irrigation caused perennial ryegrass cover to be reduced > 65%. Perennial ryegrass cover was reduced 89 to 100% following all Tennessee stand-alone practices. Similar to 8 WAT, combining mitigation practices generally improved perennial ryegrass cover at 20 WAT. Averaged across both North Carolina experiments, scalping fb verticutting before irrigation improved perennial ryegrass cover 52 and 79% compared with scalping and verticutting, respectively, when averaged across both North Carolina experiments. Improvements were also observed across all experiments when comparing scalping fb activated charcoal application (irrigated and nonirrigated) to scalping and activated charcoal application alone. Further, scalping fb activated charcoal application before irrigation was the only practice in which perennial ryegrass cover reductions were < 30% across all three experiments at 20

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WAT. When no mitigation practice was performed, regardless of irrigation scenario, perennial ryegrass cover was reduced > 96%.

Previous research has shown perennial ryegrass germination is adversely affected when indaziflam is applied at < 29.2 g ha^{-1}, with an LC_{50} estimated at 3 g ha^{-1} (Jhala et al. 2012). Based on that report, < 45% of applied indaziflam (53 g ha^{-1}) was neutralized or removed in our research because germination was adversely affected following all mitigation practices in both indaziflam-application scenarios. However, data from this research suggests perennial ryegrass establishment in indaziflam-treated bermudagrass can be improved by incorporating scalping before activated charcoal application. The differing effect of irrigation on stand-alone mitigation practices in North Carolina is likely because of indaziflam's persistence coupled with a moderate to high organic carbon sorption coefficient ($K_{oc} = 434$ to 1,544 mL g^{-1}), which has previously been attributed to indaziflam movement from application origin (Alonso et al. 2011; EPA 2010; Jhala et al. 2012). Perennial ryegrass establishment was improved after irrigation following activated charcoal application because it likely washed indaziflam from treated vegetation into the soil surface/thatch layer. This could have increased activated charcoal-indaziflam sorption and reduced indaziflam bioavailability. Indaziflam wash-off following irrigation also helps explain why perennial ryegrass establishment was reduced when scalping followed irrigation because appreciable amounts of indaziflam had likely moved below the mowing cut height. Verticutting was an ineffective stand-alone mitigation practice; however, it did improve perennial ryegrass establishment when coupled with scalping before irrigation in both North Carolina experiments. Further, improvements were also observed with scalping fb verticutting following irrigation in 2013 to 2014 (North Carolina).

The significant experimental run-by-irrigation-by-mitigation practice interaction detected between North Carolina experiments is largely due to varying results from activated charcoal application following irrigation. Reduced perennial ryegrass establishment in 2013 to 2014 is attributed in part to comparatively superior germination conditions coupled with suboptimal time for activated charcoal–indaziflam sorption before seeding. Previous research has shown perennial ryegrass germination rate increases as air and soil temperatures increase up to 20 C (Larsen and Bibby 2005; Rogers and Lush 1989). Average daily air and soil temperatures in the first 5 d after seeding in 2012 to 2013 were 12.9 and 16.9 C, respectively, whereas, in 2013 to 2014, they were 17.7 and 19.1 C. Further, average hourly photosynthetically active radiation (from 8:00 A.M. to 4:00 P.M. eastern standard time) during this period was 370 and 562 μmol m^{-2} s^{-1} in 2012 to 2013 and 2013 to 2014, respectively. Although data were not collected in this research quantifying indaziflam–soil residues or bioavailability, the authors think more-favorable conditions for perennial ryegrass germination in 2013 to 2014, compared with 2012 to 2013, which was observed in nonindaziflam-treated plots, may have reduced the time for activated charcoal–indaziflam sorption (personal observation). Consequently, decreased perennial ryegrass cover may have been attributed to increased indaziflam–soil bioavailability. Future research should evaluate activated charcoal-indaziflam sorption in more detail to determine optimal seeding or sprigging timings because Bai and Li (2013) reported perennial ryegrass establishment in diesel-contaminated soils increased 83% as the seeding interval increased from 0 to 2 wk after activated charcoal application.

The significant location-by-irrigation-by-mitigation practice interaction detected between 2013 to 2014 experiments may be due, in part, to varying turfgrass canopy dynamics and their effect on indaziflam spray interception. Experiments in North Carolina were conducted on Tifway 419 hybrid bermudagrass, maintained at a 1.9-cm cut height, whereas Tennessee conducted the experiment on Riviera bermudagrass, maintained at a 1.6-cm cut height. Tifway 419 is finer-textured than Riviera is and has superior summer and fall canopy density (NTEP 2012). Previous research has shown herbicide–soil deposition increases as plant canopy coverage decreases (Kim et al. 2011). Further, White et al. (2010) reported light penetration, which is positively correlated with herbicide–soil deposition, increases in turfgrass canopies as mowing height decreases (Kim et al. 2011). The authors think the comparatively denser canopy of Tifway 419 maintained at a higher cut height intercepted more of the applied indaziflam. This could have affected all mitigation practices, most notably, the overall most effective stand-alone mitigation practice, scalping, before irrigation by

Table 3. Pearson correlation coefficients for the relationship between visual estimates of perennial ryegrass green foliage cover with cover determined by DIA.[a–d]

	North Carolina				Tennessee	
	2012–2013		2013–2014		2013–2014	
	8 WAT	20 WAT	8 WAT	20 WAT	8 WAT	20 WAT
	DIA					
Cover	0.87	0.91	0.94	0.93	0.93	0.83
P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a] Abbreviations: DIA, digital image analysis; WAT, weeks after treatment.

[b] Data pooled over irrigation and mitigation practices.

[c] DIA cover determined with ImageJ on a 0 (no green ryegrass) to 100% (complete green ryegrass) scale.

[d] Visual cover rated on a scale of 0 (no green ryegrass) to 100% (complete green ryegrass).

increasing the total indaziflam removed via clipping collection and removal.

Correlation of Perennial Ryegrass Cover Ratings. Pearson correlation coefficients were calculated at 8 and 20 WAT to quantify the relationship between visual perennial ryegrass cover estimates and cover determined by DIA (Table 3). Across all experiments, visual cover estimates showed a strong positive relationship with DIA cover at 8 ($r =$ 0.87 to 0.94; $P < 0.0001$) and at 20 ($r = 0.83$ to 0.93; $P < 0.0001$) WAT, indicating visual perennial ryegrass cover estimates increased with perennial ryegrass cover by DIA. These findings agree with previous research by Hoyle et al. (2013) and Richardson et al. (2001) that correlations between visual turfgrass cover estimates and DIA cover were $r = 0.88$ to 0.95 and $r^2 = 0.99$, respectively. The strong correlations from our research further support visual ratings and nonsubjective measurements compliment each other and, when used appropriately, both have utility in turfgrass research (Hoyle et al. 2013).

Research Implications. Results from this research indicate mitigation practices to overseed into indaziflam-treated turfgrass areas variably improved perennial ryegrass overseeding establishment. Variations between results from experiments were likely due, in part, to climatic conditions and turfgrass canopy dynamics, coupled with inherent variability associated with small-plot research. Overall, all stand-alone mitigation practices reduced perennial ryegrass cover > 37% at 8 and 20 WAT. Irrigation before mitigation practices affected perennial ryegrass establishment differently because it increased perennial ryegrass cover after activated charcoal application, whereas it detrimentally affected scalping and had no effect on verticutting. Combining mitigation practices, most notably by adding activated charcoal application or verticutting with scalping before irrigation, improved perennial ryegrass establishment. Results from this research suggest turfgrass managers should use mitigation practices in addition to the currently recommended activated charcoal application to improve perennial ryegrass establishment in indaziflam-treated turfgrass areas.

Finally, this research evaluated a worst-case scenario for overseeding into indaziflam-treated turfgrass because of the selected application rate and interval between indaziflam application and perennial ryegrass seeding. Aside from time inherently reducing soil–indaziflam residue concentrations following application, the 24-h period from mitigation practice commencement to perennial ryegrass seeding may have not been sufficient for indaziflam–soil or thatch equilibration. This would have had the most notable effect on activated charcoal–indaziflam sorption and inherent reduction in bioavailability. Future research should evaluate additional irrigation-timing and mitigation-practice combinations, later mitigation practice initiation intervals after indaziflam application, and overseeding intervals and rates after mitigation practice completion.

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