Dose-response of five weed species to indaziflam and oxadiazon

Shwetha S. Ramanathan[1] , Travis W. Gannon[2] and Patrick J. Maxwell[1]

[1]Graduate Research Assistant, Department of Crop and Soil Sciences, 101 Derieux Place, North Carolina State University, Raleigh, NC, USA and [2]Associate Professor, Department of Crop and Soil Sciences, 101 Derieux Place, North Carolina State University, Raleigh, NC, USA

Abstract

Indaziflam and oxadiazon are efficacious preemergence herbicides used in warm-season turfgrass because of their persistence and residual activity. It is beneficial to quantify effective concentrations for preemergence control of summer annual weeds and determine whether these concentrations are maintained throughout weed emergence periods. Therefore, greenhouse bioassays were conducted with barnyardgrass, broadleaf signalgrass, doveweed, large crabgrass, and purple nutsedge. Treatments included indaziflam at 0, 4, 8, 12, 17, 21, 25, 29, 33, and 37 g ai ha^{-1} or oxadiazon at 0, 420, 841, 1,260, 1,681, 2,102, 2,354, 2,942, 3,363, and 3,783 g ha^{-1}. Although preemergence herbicides are not used to control perennial weeds, purple nutsedge was included to investigate the effect of selected herbicides on its growth. Herbicide EC$_{50}$, EC$_{80}$, and EC$_{90}$ for seedling emergence inhibition and shoot and root mass reduction were quantified from log-logistic dose–response curves. Herbicide concentration that remains from a preemergence application during the regional species-specific periodicity of emergence was predicted using first-order kinetics equations. Indaziflam and oxadiazon controlled seedling emergence 14 d after treatment (DAT) in the evaluated annual weeds and shoot and root mass in all species 84 DAT. Indaziflam applied in mid-March at 33 g ha^{-1} may provide up to 90% seedling emergence inhibition in large crabgrass and signalgrass; up to 80% in barnyardgrass; and up to 50% in doveweed. Oxadiazon applied in mid-March at 3,363 g ha^{-1} may provide up to 80% seedling emergence inhibition in all species. Indaziflam and oxadiazon may control up to 80% shoot mass and up to 50% root mass, respectively, in purple nutsedge and 80% to 90% shoot or root mass in other species. Such information is useful in evaluating adequacy of herbicide management practices for season-long weed control, and it aids turfgrass managers in applying preemergence herbicides at optimal timing based on target weed species.

Introduction

Weeds decrease the aesthetic value and function of many turfgrass systems including residential and commercial lawns, golf courses, sod farms, athletic fields, and roadsides among many other sites. Weeds adversely affect surface uniformity and wear tolerance, as well as competing with desirable species for nutrients, light, and moisture, thereby reducing turfgrass health and vigor (McElroy and Martins 2013; Watschke et al. 2013). Preemergence herbicides are commonly applied to turfgrass to control susceptible species, and some important factors that dictate the efficacy of preemergence herbicides include geography and related climatic conditions, application timing and rate, site of herbicide placement, formulation, and soil properties such as texture, organic matter content, moisture, and temperature (Knake et al. 1967; McCarty and Murphy 1994). The duration of weed control is contingent on the weed species sensitivity, herbicide persistence as influenced by physicochemical properties, and edaphic and environmental conditions, among other factors. Some of the more commonly researched annual grass and broadleaf weeds that are controlled by preemergence herbicides include annual bluegrass (*Poa annua* L.), crabgrass species (*Digitaria* spp.), goosegrass [*Eleusine indica* (L.) Gaertn.], dandelion (*Taraxacum officinale* Weber), and pigweed species (*Amaranthus* spp.), whereas other species have not been fully evaluated (Leon et al. 2016; McElroy et al. 2017; Unruh and Brecke 2007). Of these herbicides, indaziflam and oxadiazon are of specific interest because of their potential efficacy in consistently controlling annual weeds throughout the emergence period (Brecke et al. 2010; Perry et al. 2011).

Indaziflam is a preemergence herbicide with moderate persistence [half-life ($T_{1/2}$) ≥ 150 d] used in turfgrass systems that provides effective long-term control of many weed species in warm-season turfgrass (Guerra et al. 2014; Jhala et al. 2013; Shaner 2014a). Indaziflam is preferred because of its low use rate of 16 to 55 g ai ha^{-1} compared to other preemergence herbicides, which tend to be applied at higher rates of 500 to 3,000 g ha^{-1} (McElroy and Bhowmik 2013; USEPA 2010). It is an ionizable herbicide [acid dissociation constant

(pK_a) = 3.5; weak acid] with low water solubility [solubility constant (K_s) = 2.04 g L^{-1}; pH 7, 25 C] and moderate sorption to organic carbon [organic carbon water partition coefficient (K_{oc}) = 434 to 1,544 mL g^{-1}], which acts by inhibiting cellulose biosynthesis, thereby representing a unique mode of action for selective and broad-spectrum weed control in select crop areas and turf (Jeffries and Gannon 2016; Sebastian et al. 2017a; Shaner 2014a; USEPA 2010). Oxadiazon is another common preemergence herbicide used in select turfgrass and non-cropland areas (Shaner et al. 2014b). Oxadiazon is a non-ionizable herbicide successful in preemergence weed control as a result of its moderate to long-term field persistence (average $T_{1/2}$ = 60 d), low aqueous solubility (K_s = 0.7 mg L^{-1}; 20 C), and high affinity for soil organic matter (K_{oc} = 1,409 to 3,268 mL g^{-1}) (Lewis et al. 2016; Shaner 2014b; USEPA 2003). Evidence suggests that preemergence applications of indaziflam at up to 55 g ha^{-1} or oxadiazon at up to 4,400 g ha^{-1} before the beginning of spring may provide over 80% control of summer annual weeds such as goosegrass, smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. Ex Muhl.], large crabgrass, annual sedge (*Cyperus compressus* L.), and Florida pusley (*Richardia scabra* L.) (Brosnan et al. 2011, 2012; Brecke et al. 2010; Toler et al. 2003). Perry et al. (2011) showed that indaziflam can provide >90% large-crabgrass control extending 29 wk after treatment (WAT) after a single application at 60 g ha^{-1} whereas Johnson and Murphy (1996) observed 97% control of the same species 24 WAT with a single oxadiazon application at 4,483 g ha^{-1}. However, these studies only evaluated weed injury or control using visual assessment, and pertinent information regarding indaziflam or oxadiazon residue concentration required for acceptable weed suppression throughout the weed emergence period is currently unavailable. In a greenhouse study by McElroy et al. (2017), oxadiazon at 1,120 g ha^{-1} completely prevented goosegrass seedling emergence, and indaziflam at 30 g ha^{-1} prevented seedling emergence and aboveground biomass accumulation 42 DAT. However, as herbicide effective concentrations for seedling emergence inhibition and phytotoxicity in summer annual weeds or control of perennial weed species relevant to southeastern US turf systems remain unknown, managing such weed species common to the region remains challenging.

Barnyardgrass is a summer annual grass commonly found in moist cultivated turfgrass systems that grows prostrate and exhibits prolific reproduction by seed (Uva et al. 1997). Broadleaf signalgrass is a summer annual grass that is competitive in cultivated or disturbed sandy areas and is highly adaptable, making it difficult to suppress (Burke et al. 2003; Johnson and Coble 1986). Doveweed is a summer annual broadleaf that is difficult to control in cultivated turf as it reproduces by seeds and stolons and grows rapidly to form dense stands that compete with desirable turf species for light and nutrients (Atkinson 2014). Large crabgrass is a summer annual that is abundantly stoloniferous and well-adapted to humid and semi-arid south and southeastern United States (Dalrymple et al. 1999). Purple nutsedge is a perennial sedge with a history of invasiveness that most commonly reproduces through tubers and grows in damp or poorly drained soils in the southern United States (USFWS 2015; Uva et al. 1997). The performance of preemergence herbicides in controlling these weed species often depends on the length of their efficacy coordinated with the length of the weed emergence period for consistent weed control throughout the growing season (Johnson and Murphy 1996). Although some preemergence herbicides, including indaziflam and oxadiazon, possess postemergence activity, they should be applied before germination and emergence to obtain acceptable

results in summer annual weeds. Although optimum application time may vary widely with geography, it is generally guided by mean soil temperatures based on temperature optima for specific weed species (Clark and Kenna 2001; Watschke et al. 2013). More research is required to quantify the critical concentrations necessary for preemergence control to assess indaziflam and oxadiazon use parameters for adequate long-term control. Bioassay methods are powerful tools for measuring response to soil herbicide residue, because they capture total residual phytotoxicity and provide qualitative data for effective herbicide concentration estimation (Jeffries and Gannon 2016; Sandín-España et al. 2011; Streibig and Kudsk 1993). Bioassay experiments conducted with winter annual weeds indicate that 0.19 and 0.56 g ha^{-1} indaziflam provide 50% reduction in dry biomass of downy brome (*Centaurea diffusa* Lam.) and feral rye (*Secale cereale* L.), respectively, and 0.06 to 1.33 g ha^{-1} provide 50% dry-biomass reduction in six invasive winter annual grass species 4 to 5 WAT (Sebastian et al. 2016, 2017b). However, a knowledge gap exists for the response of summer annuals common to turfgrass systems to indaziflam and oxadiazon.

The objectives of this research were to (i) quantify indaziflam and oxadiazon effective concentrations for seedling emergence inhibition and control of shoot and root biomass in barnyardgrass, broadleaf signalgrass, doveweed, large crabgrass, and purple nutsedge; (ii) determine the effectiveness of indaziflam and oxadiazon in controlling selected weed species throughout their specific periods of emergence. This research was initiated as the first step toward evaluating whether the current prescribed application timings and rates and number of applications for indaziflam and oxadiazon are adequate for season-long control of the weeds of interest. Generation of such information can help guide the development of preemergence herbicide programs targeted toward emergence periods and optimum soil temperatures for seedling emergence for efficacious long-term, species-specific control.

Materials and Methods

Greenhouse Bioassays

Greenhouse bioassays were conducted using five weed species to quantify the effective indaziflam or oxadiazon concentration required for 50% (EC$_{50}$), 80% (EC$_{80}$), and 90% (EC$_{90}$) inhibition of seedling emergence and shoot and root mass reduction. Bioassays were initiated in the greenhouse (North Carolina State University Method Road Greenhouse Facilities, Raleigh, NC). Barnyardgrass, broadleaf signalgrass, doveweed, and large crabgrass seeds and purple nutsedge tubers were either collected from turfgrass research fields located in North Carolina or purchased (Azlin Seed Service, Leland, MS) and stored in a freezer at −4 C until planting. Based on preliminary laboratory germination tests of each species, 13 seeds of barnyardgrass or doveweed and 14 seeds of large crabgrass or signalgrass were planted at 0.5 cm depth in individual 10 by 10 by 9 cm plastic pots (0.5 L) containing 300 g sand. Seedlings were thinned 1 d after seedling emergence to achieve a target density of 11 plants per pot, and a single tuber of purple nutsedge was planted similarly (100% viability). All species were planted 1 d prior to herbicide application, and the soil surface was smoothed and irrigated after planting.

Herbicide treatments included indaziflam (Specticle® FLO; Bayer Environmental Science, Cary, NC) at 0, 4, 8, 12, 17, 21, 25, 29, 33, and 37 g ha^{-1} or oxadiazon (Ronstar® FLO; Bayer

Environmental Science, Cary, NC) at 0, 420, 841, 1,260, 1,681, 2,102, 2,354, 2,942, 3,363 and 3,783 g ha^{-1}. Indaziflam and oxadiazon rates were selected as 0, 12.5%, 25%, 37.5%, 50%, 62.5%, 75%, 87.5%, 100%, and 112.5% of 33 and 3,363 g ha^{-1}, respectively —the regionally accepted single application rate for summer annual weed control. A single herbicide dose of indaziflam or oxadiazon was applied to replicated pots using a CO_2-pressurized backpack sprayer calibrated to deliver 304 L ha^{-1} and equipped with a XR11003 nozzle (TeeJet®, Spraying Systems Co., Wheaton, IL).

After herbicide application, pots were maintained in the greenhouse with day/night average temperatures of 25/18 C and 60% relative humidity. High-intensity supplemental lighting was provided to extend the photoperiod to 14 h. Each pot was irrigated daily with approximately 30 mL water to maintain optimal soil moisture for growth while caution was taken to prevent herbicide leaching. After seedling emergence, plants were fertilized weekly to provide the equivalent of 12 kg N ha^{-1} (Peters Professional® 20–20–20 Water Soluble Fertilizer; Scotts-Sierra Horticultural Products Co., Marysville, OH). The experiment included nine herbicide treatments and nontreated controls replicated four times and arranged in a completely randomized design and was conducted twice.

Data Collection and Statistical Analyses

Emerged seedling counts of barnyardgrass, broadleaf signalgrass, doveweed, and large crabgrass in treated and nontreated pots were monitored weekly and recorded. Emerging shoot counts from purple nutsedge tubers were monitored similarly. The maximum number of emerged seedlings was observed 14 DAT; therefore, values from this timing were used for analysis. Seedling or tuber emergence data were converted to percent seedling emergence inhibition compared to counts in nontreated pots (where all weed species exhibited 100% seedling emergence) using the following equation:

$$\% \text{ Seedling growth inhibition} = 1 - \left[\frac{\text{Number emerged}}{\text{Total planted}}\right] \times 100 \quad [1]$$

Plants were harvested from pots 84 DAT, and aboveground vegetation (henceforth referred to as shoot) was separated from belowground vegetation (root), washed to eliminate soil debris, weighed, fresh mass recorded, and then was placed into paper bags. Root and shoot vegetation were dried in an oven at 60 C for 96 h, and dry mass was recorded. Fresh and dry mass were converted to percent reduction compared to the nontreated using the equation:

$$\% \text{ Reduction} = \left[\frac{(NT - T)}{NT}\right] \times 100 \quad [2]$$

where *NT* and *T* are from nontreated and treated, respectively.

Percent seedling emergence inhibition and reduction in fresh and dry shoot and root mass were subjected to ANOVA using PROC MIXED in SAS (SAS/STAT 9.4, SAS Institute, Cary, NC) to test for significance of main effects and interactions at the 0.05 level of probability. Experimental run, weed species, and herbicide rate were considered fixed effects, whereas replication was considered a random effect. The main effect of weed species and interactions were significant at $\alpha = 0.05$; therefore, data were sorted by weed species using PROC SORT. Where the effect of herbicide rate was

found to be significant with P values ≤ 0.05, the data were further analyzed using nonlinear regression to describe the response of weed species to indaziflam and oxadiazon. Data were pooled across the two experimental runs where the main effect and interactions of run were not significant ($\alpha = 0.05$).

A four-parameter log-logistic response curve was utilized to describe the relationship between the measured plant response (*y*) and the logarithm of the herbicide dose (*x*) using the equation:

$$y = C + \left[\frac{(D - C)}{1 + 10^{(\log EC_{50} - \log x) \cdot B}}\right] \quad [3]$$

where EC_{50} denotes the dose required for halfway response between the lower limit *C* and upper limit *D*, and *B* represents the Hill slope around the EC_{50} (Motulsky and Christopoulos 2003; Sebastian et al. 2017b). Curve fitting was performed using nonlinear regression in GraphPad Prism (version 8.0.0 for Windows; GraphPad Software, San Diego, CA). The lower limit of the curve was constrained to 0, and upper limit of the curve was constrained to 100 since mean response in nontreated plants was never lower than 0%, and the mean maximum response did not exceed 100% on the scale used. Any one dose-response level can be expressed by a function of the parameters *B* and EC_{50}, in that:

$$EC_{50} = \frac{EC_x}{\left[\frac{x}{100-x}\right]^{\frac{1}{B}}} \quad [4]$$

where EC_x represents the effective dose that elicits *x*% response between the upper and lower limits of the curve (Zhang et al. 1997). This equation was used to calculate the effective herbicide concentration that elicited 80% (EC_{80}) and 90% (EC_{90}) response.

Additionally, 20-yr monthly mean soil temperature at Lake Wheeler Turfgrass Research Lab (North Carolina State University, Raleigh, NC) (35.73001 N, 78.68758 W), representative of the southeastern United States, were compared with the published soil temperature(s) required for germination to identify the periodicity of emergence for barnyardgrass, broadleaf signalgrass, doveweed, large crabgrass, and purple nutsedge. Temperature data were accessed using CRONOS (State Climate Office of North Carolina, NC State University, Raleigh, NC). Assuming an application of indaziflam and oxadiazon at the regionally accepted single application rate (33 or 3,363 g ha^{-1}, respectively) in mid-March before the start of spring (approximately March 20 in the region), distribution in soil up to a depth of 5.1 and 2.5 cm, respectively, and published minimum half-life values of 150 and 60 d, respectively, indaziflam or oxadiazon concentration remaining during the individual species-specific emergence periods was predicted using the following first-order rate of degradation and half-life equations:

$$[A] = [A]_0 e^{-kt} \quad [5]$$

and

$$T_{1/2} = \frac{Ln(2)}{k} \quad [6]$$

where $[A]$ is the herbicide concentration remaining (g ha^{-1}) at time *t* (d), $[A]_0$ is the initial herbicide concentration at the applied rate (g ha^{-1}), *k* is the first-order degradation rate constant, and $T_{1/2}$ is the half-life or time required for 50% of the initial concentration of

herbicide to be degraded (d) (Jhala et al. 2013; Kah et al. 2007; Shaner 2014a, 2014b).

Results and Discussion

Data from the two experimental runs were pooled, because main effect and interactions of run were not significant (P > 0.05). ANOVA revealed significant effect of herbicide rate on percent seedling emergence inhibition (P < 0.001) in barnyardgrass, broadleaf signalgrass, doveweed, and large crabgrass 14 DAT; therefore, percent seedling emergence inhibition for these weed species was further analyzed using nonlinear regression fit to the log-logistic model to describe the response to indaziflam and oxadiazon. Emergence of purple nutsedge tubers was not inhibited by indaziflam or oxadiazon at any evaluated rate throughout the duration of the experiment; therefore, these data were excluded from curve-fitting procedures. The effect of herbicide rate was significant for percent shoot and root mass reduction (P < 0.001) in all evaluated weed species, and these data were further analyzed using nonlinear regression fit to the log-logistic model. Additionally, the Hill slope was constrained for the dose–response curves describing shoot and root mass reduction in doveweed by indaziflam to enable a stable curve-fit (Table 1) (Motulsky and Christopoulos 2003). The results from regression analyses and comparisons to predicted herbicide concentrations are presented and discussed.

Barnyardgrass

Indaziflam EC_{50} and EC_{80} for barnyardgrass seedling emergence inhibition 14 DAT was 6.9 and 20.1 g ha^{-1}, respectively (Table 1). However, EC_{90} (37.7 g ha^{-1}) for a similar response was higher than the prescribed application rate evaluated in this research (33 g ha^{-1}). EC_{50}, EC_{80}, and EC_{90} for fresh shoot and root mass reduction 84 DAT ranged from 1.2 to 10.0 g ha^{-1}, whereas indaziflam concentrations for similar levels of dry shoot and root mass reduction ranged from 1.0 to 7.4 g ha^{-1}, with dry-mass reduction requiring lower concentration. Results from the current study correspond with previous research where indaziflam applied at 36.5 g ha^{-1} resulted in >95% barnyardgrass control 84 DAT in an orchard growth environment (González-Delgado et al. 2016).

Oxadiazon EC_{50}, EC_{80}, and EC_{90} for barnyardgrass seedling emergence inhibition 14 DAT ranged from 766.0 to 2,794.4 g ha^{-1} and were below the prescribed single application rate of 3,363 g ha^{-1} (Table 2). EC_{90} results for dry shoot and root mass reduction were 892.1 and 898.2 g ha^{-1}, respectively, whereas EC_{90} for fresh shoot and root mass reduction was approximately 1,200 g ha^{-1}. Of the evaluated rates, indaziflam >25 g ha^{-1} and oxadiazon >2,942 g ha^{-1} resulted in 100% reduction of above and belowground biomass of emerged barnyardgrass 84 DAT (Figures 1 and 2).

Barnyardgrass seeds germinate from early spring to midsummer when the soil reaches a temperature between 15 and 18 C (Watschke et al. 2013). This soil temperature range corresponds to a periodicity of emergence that ranges from April to mid-July in Raleigh, NC (Figure 3 and Table 3). Indaziflam concentration required for 90% emergence inhibition may not be adequately maintained throughout the period of barnyardgrass emergence when indaziflam is applied before the beginning of spring at 33 g ha^{-1} based on predicted residue concentration (Tables 1 and 3). The indaziflam concentration required for 80% seedling emergence inhibition may not be present by mid-July, when soil temperatures may still be suitable for barnyardgrass germination and emergence. However, it is likely that

indaziflam residue concentration will be maintained during the growing season to control up to 90% root and shoot mass in plants that may have escaped an indaziflam preemergence application.

When oxadiazon is applied before the start of spring at 3,363 g ha^{-1}, the predicted concentration range indicates that 50% to 80% emergence inhibition may be achievable during the period of barnyardgrass emergence, but the concentration for 90% emergence inhibition may not be maintained by mid-July (Tables 2 and 3). Like indaziflam, 50% to 90% control of shoot and root mass may be feasible throughout the emergence season of this species by oxadiazon from a single preemergence application at the prescribed rate and timing. Results from this study also show that barnyardgrass is susceptible to oxadiazon at a normal use rate, as previously indicated in studies conducted in rice systems (Chin 2001).

Broadleaf Signalgrass

Indaziflam and oxadiazon >21 g ha^{-1} and >2,354 g ha^{-1}, respectively, reduced shoot and root mass by 100% in broadleaf signalgrass 84 DAT compared to nontreated (Figures 1 and 2). Indaziflam EC_{50} and EC_{90} for seedling emergence inhibition 14 DAT were 8.8 and 28.0 g ha^{-1}, respectively, and the concentrations for 50% and 80% biomass reduction ranged from 1.2 to 4.8 g ha^{-1} and 5.4 to 15.7 g ha^{-1}, respectively (Table 1). EC_{50} and EC_{90} for seedling emergence inhibition by oxadiazon 14 DAT were 858.8 and 3,348.5 g ha^{-1}, respectively, and the oxadiazon concentration required for similar levels of dry root mass reduction 84 DAT were approximately six times lower (Table 2).

Broadleaf signalgrass is highly propagated by seed, and Burke et al. (2003) found that seed germination occurs between 20 and 35 C. Indaziflam applied in mid-March at the prescribed application rate may likely provide season-long seedling emergence inhibition and biomass control, even though residue concentration may decrease by the end of the emergence season to a concentration that is lower than required for 90% seedling emergence inhibition (Tables 1 and 3). Oxadiazon from a single application in mid-March at a rate of 3,363 g ha^{-1} may be efficacious for only 50% to 80% inhibition of seedling emergence and shoot mass reduction (Tables 2 and 3). Further investigation of management techniques for broadleaf signalgrass is necessary, as this weed is easily adaptable to different growing environments, which enables it to become more prevalent and competitive. Research has elucidated the effects of early-postemergence and postemergence herbicides on broadleaf signalgrass, but it is advantageous to examine the efficacy of preemergence herbicides with alternate modes of action to prevent further development of herbicide tolerance in this species, of which numerous cases are already documented (Burke et al. 2003; Johnston and Coble 1986).

Doveweed

Indaziflam concentrations required for 50%, 80%, and 90% doveweed seedling emergence inhibition 14 DAT ranged from 9.0 to 30.8 g ha^{-1}—lower than the prescribed rate for a single application (Table 1). Indaziflam concentration for shoot and root mass reduction 84 DAT ranged between 0.7 and 2.6 g ha^{-1} for 50% and from 0.8 to 3.5 g ha^{-1} for 90% reduction. Oxadiazon EC_{50} and EC_{80} were 942.8 and 2,322.5 g ha^{-1}, respectively, for seedling emergence inhibition 14 DAT, whereas EC_{90} was 3,935.2 g ha^{-1} and higher than the prescribed application rate (Table 2). Oxadiazon concentrations for 50% fresh shoot mass and root mass reduction 84 DAT were similar, whereas the concentration

Table 1. Coefficient of determination (R^2), Hill slope (B), and indaziflam concentration (g ha^{-1}) that provided 50% (EC$_{50}$), 80% (EC$_{80}$), and 90% (EC$_{90}$) seedling emergence inhibition 14 d after treatment (DAT) and fresh and dry shoot and root mass reduction 84 DAT in five weed species.[a,b]

Weed species	Plant response	R^2	B ($\pm$SE)[c]	EC$_{50}$ ($\pm$SE)	EC$_{80}$ ($\pm$SE)	EC$_{90}$ ($\pm$SE)
					g ha^{-1}	
Barnyardgrass	Seedling emergence	0.80	1.29 (0.15)	6.9 (0.7)	20.1 (2.0)	37.7 (5.8)
	Fresh shoot mass	0.90	1.38 (0.91)	2.0 (1.0)	5.6 (1.9)	10.0 (6.9)
	Dry shoot mass	0.91	1.29 (0.39)	1.4 (0.6)	4.0 (0.8)	7.4 (1.3)
	Fresh root mass	0.97	1.16 (0.41)	1.2 (0.7)	3.9 (1.1)	7.8 (1.8)
	Dry root mass	0.96	1.35 (0.48)	1.0 (0.6)	2.8 (0.8)	5.1 (0.9)
Broadleaf signalgrass	Seedling emergence	0.89	1.89 (0.16)	8.8 (0.5)	18.2 (1.1)	28.0 (2.5)
	Fresh shoot mass	0.91	1.84 (0.50)	4.8 (0.6)	10.1 (2.5)	15.7 (5.6)
	Dry shoot mass	0.95	1.60 (0.23)	2.8 (0.4)	6.7 (0.5)	11.2 (1.3)
	Fresh root mass	0.93	1.61 (0.45)	2.4 (0.7)	5.7 (0.8)	9.4 (1.9)
	Dry root mass	0.98	1.48 (0.96)	1.2 (0.4)	3.1 (0.4)	5.4 (0.5)
Doveweed	Seedling emergence	0.83	1.79 (0.18)	9.0 (0.6)	19.6 (1.5)	30.8 (3.4)
	Fresh shoot mass	0.97	7.21[d]	2.6 (0.1)	3.1 (0.1)	3.5 (0.1)
	Dry shoot mass	0.98	4.76[d]	1.5 (0.7)	2.1 (0.8)	2.6 (1.0)
	Fresh root mass	0.98	5.19[d]	1.8 (1.3)	2.5 (1.3)	2.9 (1.8)
	Dry root mass	0.96	25.04[d]	0.7 (0.2)	0.7 (0.01)	0.8 (0.01)
Large crabgrass	Seedling emergence	0.83	1.58 (0.17)	6.5 (0.6)	15.7 (1.4)	26.3 (3.3)
	Fresh shoot mass	0.96	5.51 (1.20)	5.0 (0.5)	6.4 (0.6)	7.4 (0.9)
	Dry shoot mass	0.95	6.37 (4.75)	4.5 (0.1)	5.6 (0.1)	6.3 (0.2)
	Fresh root mass	0.97	7.19 (1.65)	5.0 (0.5)	6.0 (1.5)	6.7 (1.4)
	Dry root mass	0.95	5.81 (3.09)	3.9 (0.1)	5.0 (0.5)	5.7 (1.0)
Purple nutsedge[e]	Fresh shoot mass	0.90	2.79 (0.70)	7.5 (0.7)	12.3 (2.1)	16.4 (3.8)
	Dry shoot mass	0.92	3.15 (0.49)	6.2 (0.3)	9.6 (0.6)	12.4 (1.1)
	Fresh root mass	0.89	2.05 (0.27)	5.8 (0.5)	11.3 (1.0)	16.8 (2.2)
	Dry root mass	0.93	1.94 (0.25)	4.7 (0.3)	9.6 (0.6)	14.6 (1.3)

[a]Values were calculated from nonlinear regression equations for log-logistic dose–response curves (Equations 3 and 4).
[b]No new emergence was observed beyond 14 d in treated or nontreated pots.
[c]Values in parentheses are standard errors.
[d]Standard errors are absent because Hill slope (B) was constrained to the shown value for the best-fitting curve fit.
[e]R^2 and regression parameters are absent for seedling emergence inhibition in purple nutsedge, as emerging shoot growth from tubers was not inhibited by any evaluated indaziflam rate; therefore, data were excluded from regression analysis.

Table 2. Coefficient of determination (R^2), Hill slope (B), and oxadiazon concentration (g ha^{-1}) that provided 50% (EC$_{50}$), 80% (EC$_{80}$), and 90% (EC$_{90}$) seedling emergence inhibition 14 d after treatment (DAT) and fresh and dry shoot and root mass reduction 84 DAT in five weed species.[a,b]

Weed species	Plant response	R^2	B ($\pm$SE)[c]	EC$_{50}$ ($\pm$SE)	EC$_{80}$ ($\pm$SE)	EC$_{90}$ ($\pm$SE)
					g ha^{-1}	
Barnyardgrass	Seedling emergence	0.89	1.70 (0.17)	766.0 (51.8)	1,733.2 (125.0)	2,794.4 (299.3)
	Fresh shoot mass	0.93	3.24 (0.44)	613.5 (34.9)	940.9 (67.6)	1,208.3 (116.9)
	Dry shoot mass	0.94	3.60 (0.52)	487.9 (20.0)	717.1 (51.4)	898.2 (89.9)
	Fresh root mass	0.96	2.90 (0.36)	561.7 (16.8)	906.2 (35.7)	1,198.7 (64.9)
	Dry root mass	0.95	3.68 (0.68)	490.9 (25.5)	715.6 (75.6)	892.1 (112.5)
Broadleaf signalgrass	Seedling emergence	0.86	1.62 (0.14)	858.8 (53.8)	2,026.5 (141.5)	3,348.5 (346.8)
	Fresh shoot mass	0.93	1.72 (0.33)	365.4 (29.1)	817.3 (50.4)	1,308.9 (121.8)
	Dry shoot mass	0.93	2.01 (0.19)	455.4 (28.1)	906.6 (52.8)	1,356.3 (114.9)
	Fresh root mass	0.96	1.54 (0.50)	241.0 (78.9)	592.9 (67.6)	1,006.0 (105.2)
	Dry root mass	0.96	1.68 (0.39)	151.2 (43.4)	345.6 (41.3)	560.6 (52.3)
Doveweed	Seedling emergence	0.83	1.54 (0.15)	942.8 (64.2)	2,322.5 (187.1)	3,935.2 (483.2)
	Fresh shoot mass	0.88	1.91 (0.20)	591.9 (43.3)	1,224.4 (96.3)	1,873.6 (217.0)
	Dry shoot mass	0.91	2.12 (0.21)	571.4 (34.3)	1,097.9 (75.3)	1,608.7 (155.5)
	Fresh root mass	0.91	2.00 (0.24)	591.8 (33.2)	1,182.1 (725.5)	1,771.9 (154.0)
	Dry root mass	0.95	1.80 (0.21)	319.9 (29.0)	691.6 (43.8)	1,085.7 (104.8)
Large crabgrass	Seedling emergence	0.74	1.27 (0.17)	947.2 (98.6)	2,824.8 (361.9)	5,352.8 (1,070.9)
	Fresh shoot mass	0.95	2.42 (0.68)	336.8 (43.7)	598.6 (31.4)	837.0 (72.2)
	Dry shoot mass	0.95	2.62 (0.43)	324.7 (22.8)	550.9 (28.5)	750.6 (68.3)
	Fresh root mass	0.92	2.36 (0.93)	321.2 (29.2)	577.9 (38.6)	814.7 (93.3)
	Dry root mass	0.92	2.73 (0.57)	358.1 (26.8)	595.1 (45.0)	801.1 (101.6)
Purple nutsedge[d]	Fresh shoot mass	0.66	1.97 (0.40)	2,129.7 (115.7)	4,311.2 (470.3)	6,512.8 (1,053.3)
	Dry shoot mass	0.63	1.51 (0.28)	1,894.9 (201.9)	4,904.2 (1,133.6)	8,553.7 (2,985.3)
	Fresh root mass	0.92	1.71 (0.39)	2,005.9 (126.3)	4,505.9 (571.8)	7,234.0 (1,369.4)
	Dry root mass	0.71	0.97 (0.18)	1,068.2 (110.5)	4,481.8 (750.7)	10,369.9 (2,815.2)

[a]Values were calculated from nonlinear regression equations for log-logistic dose–response curves (Equations 3 and 4).
[b]No new emergence was observed beyond 14 d in treated or nontreated pots.
[c]Values in parentheses are standard errors.
[d]R^2 and regression parameters are absent for seedling emergence inhibition in purple nutsedge, as tuber seedling emergence was not inhibited by any evaluated indaziflam rate; therefore, data were excluded from regression analysis.
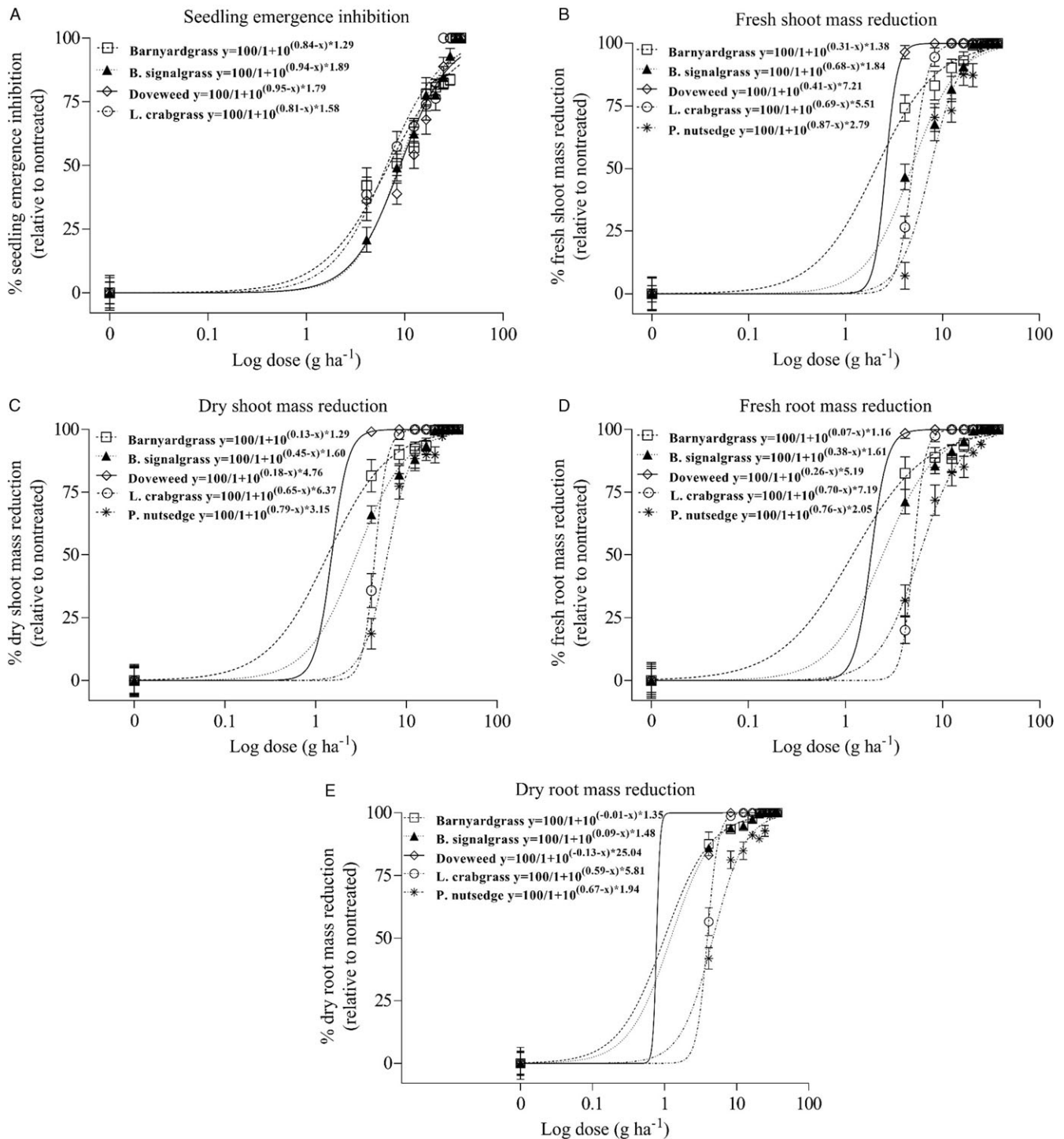
Figure 1. Seedling emergence inhibition (A), fresh shoot mass reduction (B), dry shoot mass reduction (C) fresh root mass reduction (D), and dry root mass reduction (E) in barnyardgrass, broadleaf signalgrass (B. signalgrass), doveweed, large crabgrass (L. crabgrass), and purple nutsedge (P. nutsedge) to indaziflam. Vertical bars represent ± SE of means ($n = 8$). Dose–response curves were fit to a log-logistic model using nonlinear regression (Equation 3).

for dry root mass reduction was lower. Atkinson (2014) reported that 54 g ha^{-1} indaziflam and 3,360 g ha^{-1} oxadiazon in March provide approximately 28% and 24% doveweed control, respectively, 112 DAT. However, we found that indaziflam ≥29 g ha^{-1} and 3,363 g ha^{-1} oxadiazon cause 100% and 88% seedling emergence inhibition, respectively, 14 DAT with no new emergence recorded up to 84 DAT (Figures 1 and 2).

Atkinson (2014) postulated that the elapsed time between herbicide application (mid-March) and germination in June was "likely too long to provide preemergence control throughout the peak doveweed germination season". Therefore, higher inhibition of emergence may have been exhibited in the present bioassay experiments, because the time between herbicide application and seed planting was 1 d. It may also be hypothesized that herbicide
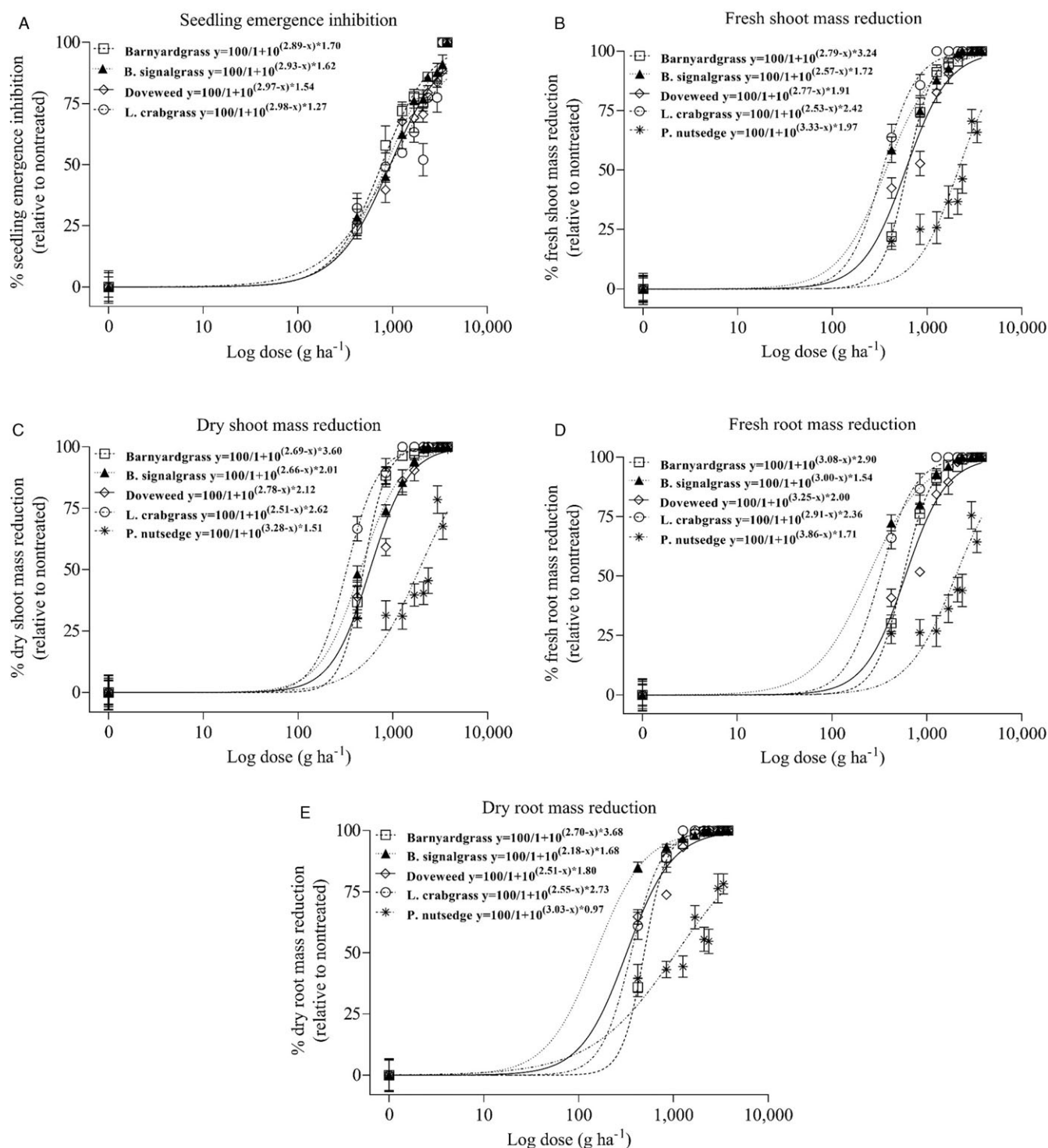
Figure 2. Seedling emergence inhibition (A), fresh shoot mass reduction (B), dry shoot mass reduction (C), fresh root mass reduction (D), and dry root mass reduction (E) in barnyardgrass, broadleaf signalgrass (B. signalgrass), doveweed, large crabgrass (L. crabgrass), and purple nutsedge (P. nutsedge) to oxadiazon. Vertical bars represent ± SE of means (*n* = 8). Dose–response curves were fit to a log-logistic model using nonlinear regression (Equation 3).

persistence may have been shorter under variable conditions of the field environment as per the study by Atkinson (2014) compared to greenhouse conditions utilized in the present research, resulting in higher soil residual activity and efficacy.

Doveweed seeds germinate between 20 and 35 C soil temperature, which aligns with an April to October periodicity of emergence in Raleigh, NC (Figure 3 and Table 3) (Wilson et al.

2006). Indaziflam, when applied as prescribed, may be adequate for 50% seedling emergence inhibition and up to 90% shoot and root mass reduction throughout the growing season (Tables 1 and 3). However, indaziflam concentrations for 80% and 90% seedling emergence inhibition may not be maintained during the emergence period. Oxadiazon applied in early spring at the prescribed rate may provide up to 80% emergence inhibition
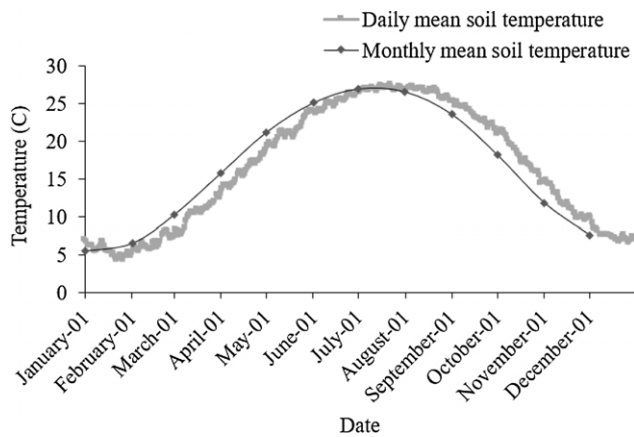
Figure 3. Daily and monthly mean 20-yr (2000–2020) soil temperature profile for Lake Wheeler Turfgrass Field Lab (North Carolina State University, Raleigh, NC), accessed from CRONOS.

during the emergence season, and 80% biomass control (Tables 2 and 3). However, oxadiazon concentration for up to 90% root mass reduction may be adequately maintained, thus suppressing doveweed establishment after emergence.

Large Crabgrass

Complete plant death was observed from indaziflam ≥ 12 g ha^{-1} and oxadiazon $\geq 1,260$ g ha^{-1}, indicating that large crabgrass is sensitive to indaziflam and oxadiazon (Figures 1 and 2). Indaziflam EC$_{80}$ and EC$_{90}$ results for seedling emergence inhibition 14 DAT were 15.7 and 26.3 g ha^{-1}, respectively, and relatively higher concentrations were quantified for similar percentages of fresh or dry shoot and root mass reduction 84 DAT (Table 1). Oxadiazon concentration for 50% to 90% seedling emergence inhibition 14 DAT varied from 947.2 to 5,352.8 g ha^{-1}, and the concentrations for 50%, 80%, and 90% fresh or dry shoot and root mass reduction 84 DAT were ≥ 321.2, 550.9, and 750.6 g ha^{-1}, respectively (Table 2).

The soil temperature reported for crabgrass germination is above 13 C, whereas other reports state that soil temperatures above 18 C support highest germination (Watschke et al. 2013). When applied at the prescribed rate in mid-March, indaziflam may successfully control seedling emergence and shoot and root biomass by up to 90%, and oxadiazon may suppress up to 80% seedling emergence and up to 90% shoot and root accumulation until May (Tables 1 to 3). Most preemergence herbicide research to date has been conducted with other crabgrass species; therefore, future studies utilizing large crabgrass to generate more data regarding effective herbicide concentrations for its control and to test herbicide efficacy under field conditions would be beneficial to develop better chemical management programs for this species.

Purple Nutsedge

Indaziflam >29 g ha^{-1} caused complete plant death in purple nutsedge 84 DAT (Figure 1). Indaziflam was efficacious in reducing purple nutsedge shoot and root mass by 90% at 12.4 and 14.6 g ha^{-1}, respectively, 84 DAT (Table 1). Oxadiazon did not cause complete plant death in purple nutsedge at any evaluated

rate. Up to 8,553.7 and 10,369.9 g ha^{-1} were quantified as necessary for 90% fresh and dry shoot and root mass reduction, respectively, which are >2.5 times the prescribed application rate (Figure 2 and Table 2). Neither indaziflam nor oxadiazon inhibited purple nutsedge emergence during the entirety of the experiment. While S-metolachlor, sulfentrazone, MSMA, halosulfuron, imazaquin, and imazapic have been found to reduce the viability of purple nutsedge tubers by at least 40% in bare-ground sites, sequential or early-postemergence herbicide applications may be necessary, and additional research is required in established turfgrass systems (Blum et al. 2000; Brecke et al. 2005; Webster et al. 2017).

Purple nutsedge tubers tend to break dormancy when soil temperature is above 15 C, with optimum sprouting between 25 and 35 C (Nishimoto 2001). Therefore, the periodicity of purple nutsedge emergence in Raleigh, NC, is likely to extend from mid-May to October (Figure 3 and Table 3). Based on the predicted indaziflam concentration during this period under select assumptions, 50% to 80% control of purple nutsedge may be achieved during the peak germination and emergence season, and 90% biomass control may be achieved until the end of August (Tables 1 and 3). Up to 50% control of shoot and root mass may be feasible by oxadiazon at the prescribed application rate and timing (Tables 2 and 3).

In conclusion, indaziflam and oxadiazon are successful in controlling summer annual weed emergence, likely owing to innate species sensitivity and specific herbicide persistence. Factors that influence herbicide efficacy include herbicide rate, application timing, and bioavailability in soil, soil texture, organic matter content and pH, temperature, moisture, microbial populations, and climatic conditions (Cox et al. 1995; Jeffries and Gannon 2016; Swanton and Weise 1991). Though findings of this research are limited to the specific soil type and annual and perennial weeds investigated in this study, further research should include field efficacy trials with weed species relevant to southeastern United States to fully evaluate the extent of weed control by indaziflam and oxadiazon in turfgrass systems.

Practical Implications

These research findings show that seedling emergence inhibition may require a higher indaziflam or oxadiazon concentration than shoot or root biomass reduction among the evaluated weed species. This indicates that application timing and rate are critical for effective preemergence control of seedling emergence. Turfgrass managers may opt for a split application of indaziflam or oxadiazon during the periodicity of weed emergence at appropriately adjusted application rates and timings to provide a higher level of control, especially for controlling weeds that may escape a single preemergence application. Split applications that better correspond with the optimum soil temperature for germination of specific species could ensure that emerging weeds are exposed to lethal herbicide residue throughout their respective optimal germination periods. Turfgrass managers can select application timings and rates based on weed emergence periods and herbicide efficacy that correspond to region-specific soil temperature variations and soil type and texture. Future research under field conditions in varying soil types can further evaluate indaziflam and oxadiazon efficacy and optimal application rates for adequate control of diverse weed species throughout their emergence and growth periods.

Table 3. Predicted indaziflam and oxadiazon concentrations (g ha^{-1} and mg kg^{-1}) during periodicity of emergence of selected weed species.

Weed species	Soil temperature for germination[a]	Periodicity of emergence[b]	Predicted indaziflam concentration remaining[c]		Predicted oxadiazon concentration remaining	
	C		g ha^{-1}	mg kg^{-1}	g ha^{-1}	mg kg^{-1}
Barnyardgrass	15 to 18	April to mid-July	30.5 to 18.8	0.045 to 0.028	3,108.9 to 1,913.7	9.33 to 5.74
Broadleaf signalgrass	20 to 35	Early April to October	29.7 to 13.0	0.044 to 0.019	3,023.9 to 1,334.6	9.07 to 4.00
Doveweed	20 to 35	April to October	30.5 to 13.0	0.045 to 0.019	3,108.9 to 1,334.6	9.33 to 4.00
Large crabgrass	13 to >18	Mid-March to May	33.0 to 26.6	0.049 to 0.039	3,363.0 to 2,760.4	10.10 to 8.28
Purple nutsedge	25 to 35	Mid-May to October	24.9 to 13.0	0.036 to 0.019	2,536.9 to 1,334.6	7.61 to 4.00

[a]Soil temperature values from published literature: Burke et al. 2003; Nishimoto 2001; Watschke et al. 2013; and Wilson et al. 2006.
[b]Periodicity of emergence in Raleigh, NC, identified by comparing soil temperatures for germination with 20-yr monthly mean soil temperatures at Lake Wheeler Turfgrass Field Lab, Raleigh, NC, accessed from CRONOS (State Climate Office of North Carolina, NC State University, Raleigh, NC).
[c]Predicted indaziflam and oxadiazon concentrations during respective periodicity of emergence of each weed species calculated using Equations 5 and 6. Assumptions include indaziflam and oxadiazon applied on March 15 (i.e., before March 20—beginning of spring) at the regionally accepted single application rate of 33 or 3,363 g ha^{-1}, respectively, distribution in soil up to a depth of 5.1 and 2.5 cm, respectively, and half-life of 150 and 60 d, respectively, as per published literature (Anonymous 2016, 2020; Shaner 2014a, 2014b).

References

Anonymous (2016) Ronstar® Flo herbicide label. Bayer Environmental Science Publication No. 432-1465. Cary, NC: Bayer CropScience. 25 p

Anonymous (2020) Specticle® Flo herbicide label. Bayer Environmental Science Publication No. 432-1608. Cary, NC: Bayer CropScience. 25 p

Atkinson J (2014) Biology, Ecology, and Control of Doveweed [*Murdannia nudiflora* (L.) Brenan]. Ph.D. dissertation. Clemson, SC: Clemson University. 102 p

Blum RR, Isgrigg J, Yelverton FH (2000) Purple (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*) control in bermudagrass (*Cynodon dactylon*) turf. Weed Technol 14:357–365. https://www.jstor.org/stable/3988842. Accessed: June 28, 2023

Brecke BJ, Stephenson DO, Unruh BJ (2005) Control of Purple Nutsedge (*Cyperus rotundus*) with herbicides and mowing. Weed Technol 19:809–814. https://www.jstor.org/stable/3989253. Accessed: June 28, 2023

Brecke BJ, Stephenson DO, Unruh JB (2010) Timing of oxadiazon and quinclorac application on newly sprigged turfgrass species. Weed Technol 24:28–32. http://www.jstor.org/stable/40587147. Accessed: June 28, 2023

Brosnan JT, Breeden GK, McCullough PE, Henry GM (2012) PRE and POST control of annual bluegrass (*Poa annua*) with indaziflam. Weed Technol 26:48–53. https://doi.org/10.1614/WT-D-11-00088.1. Accessed: June 28, 2023

Brosnan JT, McCullough PE, Breedan GK (2011) Smooth crabgrass control with indaziflam at various spring timings. Weed Technol 25:363–366. https://doi.org/10.1614/WT-D-11-00005.1. Accessed: June 28, 2023

Burke IC, Thomas WE, Spears JF, Wilcut JW (2003) Influence of environmental factors on germination of barnyardgrass, red sprangletop (*Bracharia platyphylla*) germination. Weed Sci 51:683–689. https://doi.org/10.1614/0043-1745(2003)051[0683:IOEFOB]2.0.CO;2. Accessed: June 28, 2023

Chin DV (2001) Biology and management of barnyardgrass, red sprangletop and weedy rice. Weed Biol Manag 1:37–41. https://doi.org/10.1046/j.1445-6664.2001.00009.x. Accessed: June 28, 2023

Clark JM, Kenna MP (2001) Lawn and Turf: Management and Environmental Issues of Turfgrass Pesticides. Pages 203–241 *in* Krieger RI, Krieger WC, eds. Handbook of Pesticide Toxicology. 2nd edn. San Diego, CA: Academic Press

Cox L, Hermosin MC, Cornejo J (1995) Adsorption and desorption of the herbicide thiazafluron as a function of soil properties. Int J Environ Anal Chem 58:305–314. https://doi.org/10.1080/03067319508033132. Accessed: June 28, 2023

Dalrymple RL, Mitchell R, Flatt B, Dobbs W, Ingram S, Coleman S (1999) Crabgrass for forage: management from the 1990s. Ardmore, OK: Noble Foundation, Agric. Division

González-Delgado AM, Shukla M, Ashigh J, Perkins R (2016) Effect of application rate and irrigation on the movement and dissipation of indaziflam. J Environ Sci 51:111–119. https://doi.org/10.1016/j.jes.2016.09.002. Accessed: June 28, 2023

Guerra N, Oliveira Neto AM, Oliveira JR RS, Constantin J, Takano HK (2014) Sensibility of plant species to herbicides aminocyclopyrachlor and indaziflam. Planta Daninha 32(3):609–617. https://doi.org/10.1590/S0100-83582014000300017. Accessed: June 28, 2023

Jeffries MD, Gannon TW (2016) Soil organic matter content and volumetric water content affect indaziflam–soil bioavailability. Weed Sci 64:757–765. https://doi.org/10.1614/WS-D-16-00039.1. Accessed: June 28, 2023

Jhala A, Ramirez A, Singh M (2013) Tank mixing saflufenacil, glufosinate, and indaziflam improved burndown and residual weed control. Weed Technol 27:422–429. https://doi.org/10.1614/WT-D-12-00141.1. Accessed: June 28, 2023

Johnson BJ, Murphy TR (1996) Efficacy of preemergence herbicides in turfgrasses. Athens, GA: Georgia Agricultural Experiment Stations, College of Agricultural and Environmental Sciences, University of Georgia. 29 p

Johnson WC III, Coble HD (1986) Crop rotation and herbicide effects on the population dynamics of two annual grasses. Weed Sci 34:452–456. https://doi.org/10.1017/S0043174500067187. Accessed: June 28, 2023

Kah M, Beulke S, Brown, CD (2007) Factors influencing degradation of pesticides in soil. J Agric Food Chem 55:4487–4492. https://doi.org/10.1021/jf0635356. Accessed: June 28, 2023

Knake EL, Appleby AP, Furtick WR (1967) Soil incorporation and site of uptake of preemergence herbicides. Weeds 15:228–232. https://doi.org/10.2307/4041210. Accessed: June 28, 2023

Leon R, Unruh J, Brecke B (2016) Relative lateral movement in surface soil of amicarbazone and indaziflam compared with other preemergence herbicides for turfgrass. Weed Technol 30:229–237. https://doi.org/10.1614/WT-D-15-00126.1. Accessed: June 28, 2023

Lewis KA, Tzilivakis J, Warner D, Green A (2016) An international database for pesticide risk assessments and management. Human and Ecological Risk Assessment: An International Journal 22:1050–1064. https://doi.org/10.1080/10807039.2015.1133242. Accessed: June 28, 2023

McCarty LB, Murphy TR (1994) Control of Turf Grass Weeds. Pages 209–248 *in* Turgeon AJ, ed. Turf Weeds and Their Control. Madison, WI: American Society of Agronomy & Crop Science Society of America

McElroy JS, Bhowmik PC (2013) Turfgrass Weed Management. Pages 777–809 *in* Stier JC, Horgan BP, Bonos SA, eds. Turfgrass: Biology, Use, and Management. Madison, WI: American Society of Agronomy

McElroy JS, Head WB, Wehtje GR, Spak D (2017) Identification of goosegrass (*Eleusine indica*) biotypes resistant to preemergence-applied oxadiazon. Weed Technol 31:675–681. https://doi.org/10.1017/wet.2017.41. Accessed: June 28, 2023

McElroy JS, Martins D (2013) Use of herbicides on turfgrass. Planta Daninha 31:455–467. https://doi.org/10.1590/S0100-83582013000200024. Accessed: June 28, 2023

Motulsky HJ, Christopoulos A (2003) Fitting Models to Biological Data using Linear and Nonlinear Regression. A Practical Guide to Curve Fitting. San Diego, CA: GraphPad Software Inc.

Nishimoto RK (2001) Purple nutsedge tuber sprouting. Weed Biol Manag 1:203–208. https://doi.org/10.1046/j.1445-6664.2001.00037.x. Accessed: June 28, 2023

Perry DH, McElroy JS, Doroh CM, Walker RH (2011) Indaziflam utilization for controlling problematic turfgrass weeds. Appl Turf Sci 8:1–7. https://doi.org/10.1094/ATS-2011-0428-01-RS. Accessed: June 28, 2023

Sandín-España P, Loureiro I, Concepcion E, Cristina C, Santìn-Montanya I (2011) The bioassay technique in the study of herbicide effects. Pages 431–454 in Soloneski S, Larramendy ML eds. Herbicides Theory and Applications. Rijeka, Croatia: InTech

Sebastian DJ, Fleming MB, Patterson EL, Sebastiaon JR, Nissen SJ (2017a) Indaziflam: a new cellulose-biosynthesis-inhibiting herbicide provides long-term control of invasive winter annual grasses. Pest Manag Sci 73:2149–2162. https://doi.org/10.1002/ps.4594. Accessed: June 28, 2023

Sebastian DJ, Nissen DJ, Scott J, De Souza Rodrigues J (2016) Pre-emergence growth control of six invasive winter annual grasses with imazapic and indaziflam. Invasive Plant Manag Sci 9:308–316. https://doi.org/10.1614/IPSM-D-16-00045.1

Sebastian DJ, Nissen SJ, Sebastian JR, Meiman PJ, Beck KG (2017b) Preemergence growth control of nine invasive weeds with aminocyclopyrachlor, aminopyralid, and indaziflam. Invasive Plant Sci Manag 10:99–109. https://doi.org/10.1017/inp.2017.7. Accessed: June 28, 2023

Shaner DL, ed (2014a) Herbicide Handbook. 10th edn. Champaign, IL: Weed Science Society of America. Pp 267–268

Shaner DL, ed (2014b) Herbicide Handbook. 10th edn. Champaign, IL: Weed Science Society of America. Pp 332–334

Streibig JC, Kudsk P, eds (1993) Herbicide Bioassays. Boca Raton, FL: CRC Press

Swanton CJ, Weise F (1991) Integrated weed management: the rationale and approach. Weed Technol 5:657–663. https://doi.org/10.1017/S0890037X00027512. Accessed: June 28, 2023

Toler JE, McCarty LB, Higingbottom JK (2003) New options for annual bluegrass control in overseeded bermudagrass putting greens. Hort Sci 38:1232–1234. https://doi.org/10.21273/HORTSCI.38.6.1232. Accessed: June 28, 2023

Unruh J, Brecke B (2007) Response of turfgrass and turfgrass weeds to herbicides. Institute of Food and Agriculture Services, EDIS. Gainesville, FL: University of Florida Cooperative Extension Service. 10 p

[USEPA] US Environmental Protection Agency (2003) Reregistration Eligibility Decision for Oxadiazon. Washington, DC: US Environmental Protection Agency. 56 p

[USEPA] US Environmental Protection Agency (2010) Pesticide Fact Sheet for Indaziflam. Washington, DC: US Environmental Protection Agency. 108 p

[USFWS] US Fish & Wildlife Service (2015) Purple Nutsedge (Cyperus rotundus) Ecological Risk Screening Summary. Washington, DC: US Fish & Wildlife Service. 26 p

Uva RH, Neal JC, DiTomaso JM eds. (1997) Weeds of the Northeast. Ithaca, NY: Cornell University Press

Watschke TL, Dernoeden PH, Shetlar DJ, eds (2013) Managing Turfgrass Pests. Baton Rouge, LA: CRC Press. Pp 1–68

Webster TM, Grey TL, Ferrell JA (2017) Purple Nutsedge (Cyperus rotundus) tuber production and viability are reduced by imazapic. Weed Sci 65:97–106. https://doi.org/10.1614/WS-D-16-00088.1. Accessed: June 28, 2023

Wilson DG, Burton MG, Spears JF, York AC (2006). Doveweed (Murdannia nudiflora) germination and emergence as affected by temperature and seed burial depth. Weed Sci 54:1000–1003. https://doi.org/10.1614/WS-06-091.1. Accessed: June 28, 2023

Zhang WM, McGiffen ME Jr, Becker JO, Ohr HD, Sims JJ, Kallenbach RL (1997) Dose-response of weeds to methyl iodide and methyl bromide. Weed Res 37:181–189. https://doi.org/10.1046/j.1365-3180.1997.d01-15.x. Accessed: June 28, 2023