Weed Technology

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Weed control and highbush blueberry tolerance with indaziflam on sandy soils

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Research Article

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Nomenclature:
Dichlobenil; diuron; indaziflam; mesotrione; oryzalin; American burnweed *Erechtites hieraciifolius* (L.) Raf. ex DC.; carpetweed, *Mollugo verticillata* (L.); horseweed, *Conyza canadensis* (L.) Cronquist; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; narrowleaf goldentop, *Euthamia caroliniana* (L.) Green ex Porter & Britton; Canada toadflax, *Nuttallanthus canadensis* (L.) D.A. Sutton; Pine Barren flatsedge, *Cyperus retrorsus* Chapm; northern highbush blueberry, *Vaccinium corymbosum* L.

Keywords:
Crop safety; residual herbicide; small fruit weed management

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Abstract

Northern highbush blueberry is an important fresh market product in New Jersey where the plant was first domesticated in the early 20th century. Because of the short period for safely and timely applying postemergence (POST) herbicides, reliance on residual herbicides that provide season-long control of weeds is essential for blueberry growers to minimize the detrimental effect of weed competition on berry yield and quality and bush growth. Field studies were conducted from 2018 to 2020 in Chatsworth, New Jersey, on ‘Bluecrop’, ‘Duke’, and ‘Elliott’ blueberry cultivars growing on sandy acidic soil to evaluate weed control and crop tolerance in response to repeated annual applications of indaziflam at 73 or 146 g ai ha^{-1} applied in fall or spring. The efficacy of indaziflam treatments were compared to those of fall-applied dichlobenil at 3,300 g ai ha^{-1} or a spring-applied mix of diuron at 1,800 g ai ha^{-1}, oryzalin at 3,360 g ai ha^{-1}, and mesotrione at 210 g ai ha^{-1}. Indaziflam at the currently labeled rate of 73 g ai ha^{-1} provided ≥85% and season-long control of horseweed, Canadian toadflax, and large crabgrass with fall applications on dormant blueberry, whereas spring applications were less effective. Whereas minor (≤8%) and transient leaf crinkling was noted in response to spring-applied indaziflam at 146 g ai ha^{-1}, a fall application never caused leaf crinkling greater than that observed in the nontreated weedy and weed-free controls, regardless of rate. No negative effects on plant growth or fruit production were observed from indaziflam applied at 73 or 146 g ai ha^{-1} in fall or spring. Findings of this study suggest that indaziflam applied at 73 (1× commercial use rate) and 146 g ai ha^{-1} is safe to use on blueberry grown on New Jersey sandy acidic soils despite restrictions for using this herbicide on such soils.

Introduction

Northern highbush blueberry was first domesticated in New Jersey in the early1920s when Frederick Coville and Elizabeth White released their first controlled crosses (Ehlenfeldt 2009; Mainland and Ehlenfeldt 2017). Since then, more than 38,000 ha of blueberries and 282 million kg of fruits were harvested in the United States in 2022 (USDA-NASS 2022). New Jersey ranked sixth in the United States for highbush blueberry production in 2022, with 3,000 ha harvested, yielding more than 15 million kg of blueberries valued at US$69 million, with 87% of the fruits sold as fresh market produce (USDA-NASS 2022).

New Jersey blueberries are grown in the Pine Barrens region where well-drained sandy acidic soils, high organic matter soil content, and a shallow water table provide ideal conditions for the crop. Blueberries are commonly planted on ridges that are 30 to 50 cm high and 60 cm wide. This prevents root zone flooding that can affect vegetative growth and decrease fruiting potential and fruit quality (Abbott and Gough 1987a, 1987b). Because the blueberry root system is for the most part contained within the ridge, proper management of the ridge is essential so as to reduce weed competition for water or nutrients that could affect productivity of the bushes (NeSmith and Krewer 1995). Furthermore, weed infestations may decrease air circulation around blueberry bushes and interfere with pest and disease management (Gough 1994). New Jersey blueberry growers commonly apply herbicides to control weeds on the ridge, whereas they frequently practice cultivation in the row middles. Growers primarily apply preemergence (PRE) herbicides in late winter or early spring before blueberry budbreak and will eventually complement that with a postemergence (POST) herbicide applied before the row middles close up via canes bending under fruit load. PRE herbicides often used include diuron, simazine, flumioxazin, sulfentrazone, and norflurazon, whereas clethodim and paraquat are the most frequently applied POST herbicides (Besançon et al. 2022). However, efficient control of summer annual weeds such as goosegrass [*Eleusine indica* (L.) Gaertn.], yellow nutsedge (*Cyperus esculentus* L.), or American burnweed is difficult to achieve because early spring PRE herbicides will progressively lose their efficacy. Closure of row middles, harvest operations, and an extended production season also prevent timely applications of POST herbicides, further restricting the control of weeds mentioned above. Application of POST herbicides such as

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paraquat, carfentrazone, or glufosinate has also been linked with necrotic lesions on new canes that can serve as entry ports for *Neofusicoccum* fungal species, which are responsible for blueberry stem blight (Tennakoon et al. 2015). Thus, use of residual herbicides providing season-long weed control would reduce the need for POST herbicides and improve blueberry growth and fruit yield by reducing weed competition at and after harvest.

Indaziflam is a Group 29 herbicide (as categorized by the Weed Science Society of America [WSSA]), a cellulose biosynthesis inhibitor in the alkylazine family (Ahrens 2015). Indaziflam is registered for use on blueberries that have been established for at least 1 yr to provide residual control of annual grasses and broadleaf species (Anonymous 2021). Indaziflam provides season-long residual control of many species due to its long soil persistence with a half-life greater than 150 d, and low water solubility under acidic soil conditions (Shaner 2014). The current indaziflam label prevents its use on soil with ≥20% gravel content or on sandy soil, regardless of soil organic matter content (Anonymous 2021). Thus, indaziflam cannot legally be used on New Jersey blueberries that are primarily planted on sandy soils. However, previous studies did not report injury or stem diameter reduction following repeated applications of indaziflam on young pecan trees, olive trees, blueberry bushes, and blackberry bushes planted on loamy sand with ≥80% sand content (Grey et al. 2016, 2018, 2021). In a study evaluating the leaching potential of indaziflam in Florida sandy soil with <0.5% organic matter content and pH 6.3, Jhala and Singh (2012) reported that indaziflam was not detected beyond 27 cm below the soil surface, whereas norflurazon was detected up to 113 cm deep under a simulated rainfall of 15 cm ha^{-1}. Therefore, the objectives of this research were to determine the effects of repeated indaziflam applications at two different application rates and timings on weed control and crop tolerance for three blueberry cultivars planted in New Jersey soils with >90% sand content.

Table 1. Average monthly rainfall and 30-yr average.[a]

Month	Year 1, 2017–2018	Year 2, 2018–2019	Year 3, 2019–2020	30-yr average, 1991–2020
	mm			
November	56	236	32	89
December	30	152	150	74
January	66	88	69	108
February	162	46	83	91
March	152	88	99	93
April	91	97	104	105
May	127	130	91	124
June	109	119	66	117
July	97	153	203	99
August	176	101	177	101
September	186	60	92	84
October	163	209	115	109
Total	1,414	1,480	1,280	1,195

[a]Measurements were taken at the Rutgers University weather station, located at the P.E. Marucci Center for Blueberry and Cranberry Research and Extension in Chatsworth, NJ.

Materials and Methods

Field trials were conducted from 2018 to 2020 in three different blueberry fields at the Rutgers P.E. Marucci Center for Blueberry and Cranberry Research and Extension (39.42°N, 74.30°W) in Chatsworth, NJ. Soil samples were collected from each field at the start of the study in fall 2018 and analyzed by the Soil Testing Laboratory at Rutgers University (New Brunswick, NJ) to determine soil texture.

Two-year-old 'Duke' northern highbush blueberries were planted in 2016 in Atsion sand (sandy, siliceous, mesic Aeric Alaquods); pH 3.7; 93%, 4%, 3%, and 2.7% sand, silt, clay, and organic matter, respectively. One-year-old 'Elliott' and 'Bluecrop' northern highbush blueberries were planted in 2000 in Lakehurst sand (mesic, coated Aquodic Quartzipsamments); pH 3.6; 92%, 5%, 3%, and 1.7% sand, silt, clay, and organic matter, respectively. Blueberry cultivars were annually maintained using standard practices as advised by the Commercial Blueberry Pest Control Recommendations for New Jersey (Besançon et al. 2022). Annual cumulated rainfall during the study averaged 1,390 mm (Table 1) and exceeded the 30-yr average by 18% in Year 1 (November 2017 to October 2018), 24% in Year 2 (November 2018 to October 2019), and 7% in Year 3 (November 2019 to October 2020).

The experimental design was a randomized complete block with four replications and six herbicide treatments applied to the same plot each year. Treatments included indaziflam (Alion®; Bayer CropScience LP, St Louis, MO) applied at 73 and 146 g ai ha^{-1} in fall or spring; dichlobenil (Casoron® CS; MacDermid Agricultural Solutions, Inc., Waterbury, CT) at 3,300 g ai ha^{-1} applied in fall; and a mix of diuron (Karmex® DF; ADAMA, Raleigh, NC) at 1,800 g ai ha^{-1}, oryzalin (Surflan® AS; UPL Inc., King of Prussia, PA) at 3,360 g ai ha^{-1}, and mesotrione (Callisto®; Syngenta Crop Protection LLC, Greensboro, NC) at 210 g ai ha^{-1} applied in spring. Indaziflam at 73 and 146 g ai ha^{-1} represent the maximum rate per application and per year, respectively, for use on highbush blueberry grown on non-sandy soil with organic matter content ≥1% (Anonymous 2021). The dichlobenil and diuron plus oryzalin plus mesotrione treatments were selected to represent residual herbicides commonly applied by New Jersey blueberry growers in fall and spring, respectively. Dichlobenil was not used as a standard for spring application because of volatility associated with the encapsulated liquid formulation used in this study when temperatures exceed 20 C (Anonymous 2016). Glufosinate (Rely® 280 SL; Bayer CropScience LP) at 1,310 g ai ha^{-1} was added to indaziflam and dichlobenil treatments to control emerged weeds. Since the diuron plus oryzalin plus mesotrione treatment also provides POST weed control, glufosinate was not added to this treatment. Nontreated weedy and weed-free controls were included for evaluation of herbicide weed control efficacy and crop tolerance. Herbicides were applied to the vegetation-free ridge beneath the planted blueberry row using a CO_2pressurized backpack sprayer equipped with two AIUB 85025 air induction nozzles (Teejet® Technologies, Glendale Heights, IL) calibrated to deliver 210 L ha^{-1} of spray solution at 206 kPa. AIUB 85025 nozzles with an off-center spray pattern instead of standard flat-fan nozzles were selected to improve herbicide coverage of the ridge. Each treatment was applied to both sides of the vegetation-free ridge and included an inert blue dye to reduce application overlap. All autumn treatments were applied after blueberry bushes reached the 50% leaf drop stage on November 16, November 19, and November 15 in 2017, 2018, and 2019, respectively. Spring treatments were applied before blueberry budbreak on March 15, March 25, and March 9 in 2018, 2019, and 2020, respectively. Individual plots were 4.6 m long and 2.4 m wide, totaling five bushes per plot for each blueberry cultivar.

Data Collection

Weed control for the predominant weed species present at each site was visually assessed 5, 8, and 17 wk after the spring treatment

Table 2. Horseweed (n = 16), Canada toadflax (n = 28), and large crabgrass (n = 36) control in response to fall- or spring-applied residual herbicides in highbush blueberry at Chatsworth, NJ.[a,b,c]

			ERICA			LINCA			DIGSA	
Herbicide	Time	Rate	5 WST	8 WST	17 WST	5 WST	8 WST	17 WST	8 WST	17 WST
		g ai ha^{-1}	%							
Indaziflam	Fall	73	99 ab	99 a	98 a	100 a	98 b	86 b	97 a	92 b
Indaziflam	Fall	146	100 a	100 a	98 a	100 a	100 a	100 a	100 a	100 a
Dichlobenil	Fall	3,300	97 b	99 a	100 a	98 b	100 a	100 a	56 c	37 d
Indaziflam	Spring	73	100 a	91 b	73 b	98 b	95 c	89 b	89 b	78 c
Indaziflam	Spring	146	100 a	98 a	97 a	100 a	99 ab	99 a	99 a	98 ab
DIU + ORY + MES	Spring	1,800 + 3,360 +210	99 ab	99 a	99 a	99 ab	99 ab	99 a	97 a	97 ab

[a]Abbreviations: DIGSA, large crabgrass; DIU, diuron; ERICA, horseweed; LINCA, Canada toadflax; MES, mesotrione; ORY, oryzalin; WST, weeks after spring treatment.
[b]Weed control ratings were visually estimated on a 0% (no control) to 100% (complete plant death) scale and were pooled across site-years.
[c]Means followed by the same letter in a column are not significantly different at the $P \le 0.05$ level according to the Fisher's protected least significant difference test for multiple means comparisons.

(WST) on a scale of 0% (no control) to 100% (death of all plants), based on a composite estimation of weed density reduction, growth inhibition, and foliar injury (Frans et al. 1986). All visual assessments were conducted by the same person for the entire duration of the study. The predominant weed species included horseweed in Bluecrop and Elliott fields in 2018 and 2019; Canada toadflax and Pine Barren flatsedge in Duke fields every year and in Bluecrop and Elliott fields in 2018 and 2019; narrowleaf goldentop [*Euthamia caroliniana* (L.) Green ex Porter & Britton] in Duke in 2020 and in Bluecrop and Elliott fields in 2019 and 2020; large crabgrass in all fields every year; carpetweed in all fields in 2019 and 2020; and American burnweed in Bluecrop fields in 2018 and 2019 and in Elliott fields in 2018. Because of later emergence, large crabgrass and Pine Barren flatsedge were rated only 8 and 17 WST, whereas carpetweed and American burnweed were rated only 17 WST. Blueberry tolerance was evaluated by scoring bush canopy for leaf necrosis, chlorosis, and distortion as well as plant stunting compared with the nontreated, weed-free control on a scale of 0% (no injury or growth reduction) to 100% (all leaves injured or complete stunting) at 8, 11, and 17 WST. Blueberry growth was measured from the three central bushes within each plot by tape marking and measuring three branches per plant at the time of the spring application (Aldridge et al. 2019). The length of the selected branches was measured again in late September each year to determine annual growth. A new set of branches was marked each year. To evaluate the impact of treatments on berry production, a total of 15 clusters were collected from the three central bushes within each plot when at least 50% of the berries were considered ripe (≥80% blue surface). After harvesting, individual cluster weight was recorded and berries were separated into ripe or unripe (green) berry, and then counted and weighed separately.

Data Analysis

All data were subjected to ANOVA using the generalized linear mixed model (GLIMMIX) procedure with SAS software (version 9.4; SAS Institute, Cary, NC). Cultivar and year were combined into site-year sampled from a population (Carmer et al. 1989) for analysis of weed control data, whereas crop tolerance data were analyzed separately for each cultivar. Herbicides, year, and site-year were considered fixed effects, whereas replication (nested within year for crop tolerance data or within site-year for weed control data) was designed to be random in the model. Weedy and weed-free controls were excluded from the weed control ANOVA because values were 0% and 100%, respectively. Because of unequal variance, weed control and crop injury data were converted using the arcsine square root transformation prior to ANOVA and backtransformed for presentation purposes (Grafen and Hails 2002). Means were separated using Fisher's protected least significant difference test ($\alpha = 0.05$), and orthogonal contrast were defined for analyzing various groups of treatments ($\alpha = 0.05$).

Results and Discussion

In the absence of a significant site-years by herbicide treatment interaction ($P > 0.05$), weed control ratings were pooled across site-years for horseweed, Canada toadflax, and large crabgrass (Table 2) and for narrowleaf goldentop, Pine Barren flatsedge, carpetweed, and American burnweed (Table 3).

Horseweed

Fall application of indaziflam at 73 and 146 g ai ha^{-1} provided ≥98% and season-long control of horseweed, which is equivalent to results obtained with the dichlobenil standard (Table 2). Horseweed control 8 WST with indaziflam at 73 g ai ha^{-1} in spring was lower (91%) than it was with the 146 g ai ha^{-1} rate or the diuron plus oryzalin plus mesotrione standard (≥98%). Further evidence of reduced control (73%) with the low rate of indaziflam in spring was noted 17 WST compared to ≥97% with other treatments. By the end of the cropping season and pooled across herbicides, greater horseweed control was achieved with a fall rather than a spring application (Table 4). In spring, the diuron plus oryzalin plus mesotrione mix provided better control than the average of indaziflam rates. Previous studies also showed excellent efficacy of indaziflam at controlling horseweed. Aulakh (2020) reported that indaziflam applied at bud break in a Canaan fir (*Abies balsamea* var. *phanerolepis* Fernald) nursey provided 56% and 87% horseweed control 16 wk after treatment (WAT) at the 20 and 41 g ai ha^{-1} rates, respectively. Complete inhibition of horseweed germination was noted in Ohio nursery fields where indaziflam was applied at 84 g ai ha^{-1} in fall, whereas a spring application at the same rate reduced horseweed germination by only 80% (Valles-Ramirez and Atland 2018). Lower indaziflam efficacy in spring can be caused by lower rainfall accumulation following spring applications compared to fall applications, which may reduce indaziflam bioavailability for root absorption of emerging weed seedlings. Over the course of our study, rainfall

Table 3. Narrowleaf goldentop (n = 20), Pine Barren flatsedge (n = 28), carpetweed (n = 24), and American burnweed (n = 12) control in response to fall- or spring-applied residual herbicides in highbush blueberry at Chatsworth, NJ.[a,b,c]

			ETITE			CYPRT		MOLVE	ERAHI
Herbicide	Time	Rate	5 WST	8 WST	17 WST	8 WST	17 WST	17 WST	
		g ai ha^{-1}	%						
Indaziflam	Fall	73	83 b	89 b	84 b	89 c	62 d	41 c	81 bc
Indaziflam	Fall	146	100 a	100 a	95 a	99 ab	92 b	82 b	100 a
Dichlobenil	Fall	3,300	92 ab	84 bc	74 bc	100 a	97 ab	34 c	99 a
Indaziflam	Spring	73	87 b	67 c	54 c	89 c	65 cd	31 c	31 d
Indaziflam	Spring	146	86 b	69 c	57 c	93 bc	78 c	80 b	96 ab
DIU + ORY + MES	Spring	1,800 + 3,360 +210	91 ab	93 ab	81 b	100 a	99 a	99 a	74 c

[a]Abbreviations: CYPRT, Pine Barren flatsedge; DIU, diuron; EREHI, American burnweed; ETITE, narrowleaf goldentop; MES, mesotrione; MOLVE, carpetweed; ORY, oryzalin; WST, weeks after spring treatment.
[b]Weed control ratings were visually estimated on a 0% (no control) to 100% (complete plant death) scale and were pooled across site-years.
[c]Means followed by the same letter in a column are not significantly different at the P ≤ 0.05 level according to the Fisher's protected least significant difference test for multiple means comparisons.

Table 4. Orthogonal contrast for weed control ratings pooled across site-years and collected 17 wk after the spring herbicide application in highbush blueberry at Chatsworth, NJ.[a,b]

Contrast	ERICA	LINCA	DIGSA	ETITE	CYPRT	MOLVE	ERAHI
Fall vs. spring application	**[b]	NS	***	**	NS	***	***
Indaziflam vs. standard fall applied	NS	**	***	*	***	**	NS
Indaziflam vs. standard spring applied	**	**	NS	***	***	***	NS

[a]Abbreviations: CYPRT, Pine Barren flatsedge; DIGSA, large crabgrass; ERAHI, American burnweed; ERICA, horseweed; ETITE, slender goldentop; LINCA, Canada toadflax; MOLVE, carpetweed.
[b]Significance levels: *P = 0.05 to 0.01, **P = 0.01 to 0.001, ***P < 0.001. Horseweed, n = 16; Canada toadflax, n = 28; large crabgrass, n =36; narrowleaf goldentop, n = 20; Pine Barren flatsedge, n = 28; carpetweed, n = 24; and American burnweed, n = 12.

accumulation between the fall and the spring application averaged 390 mm, whereas rainfall accumulation within 8 WST was 210 mm (Table 1). Greater rainfall accumulation may increase indaziflam bioavailability because its water solubility is only 4 mg L^{-1} at pH 4 at a temperature of 20 C (USEPA 2010).

Canada Toadflax

Excellent control (≥98%) was observed 5 WST, regardless of treatment or application timing (Table 2). By 8 WST, toadflax control provided by indaziflam, regardless of rate or timing, remained ≥95%. However, toadflax control 17 WST with indaziflam at the 73 g ai ha^{-1} rate dropped below 90% regardless of application timing, whereas indaziflam at 146 g ai ha^{-1}; dichlobenil applied in fall; or the spring mix of diuron, oryzalin, and mesotrione still provided ≥99% toadflax control. By the end of the season, there was no significant difference between fall and spring residual herbicide placement for toadflax control (Table 4). However, standard treatments in fall or spring tended to better perform than either indaziflam rate. Indaziflam efficacy for controlling toadflax has previously been reported by Sebastian et al. (2017) who observed >80% control of invasive Dalmatian toadflax [*Linaria dalmatica* (L.) Mill.] 4 yr after treatment with indaziflam at 58 g ai ha^{-1} as compared to <70% control with aminocyclopyrachlor or picloram applied alone.

Large Crabgrass

Following a fall or spring application of indaziflam at 146 g ai ha^{-1}, large crabgrass was controlled ≥98% 8 and 17 WST, a result that was similar to that provided by the spring-applied mix of diuron, oryzalin, and mesotrione (Table 2). In contrast, large crabgrass control was only 56% 8 WSP and 37% 17 WSP with fall-applied dichlobenil. Although efficacy by 17 WSP remained >90% with a fall application, indaziflam at 73 g ai ha^{-1} applied in spring was less effective (78%). Pooled across treatments, greater large crabgrass control was reported by the end of the season with a spring rather than a fall application (Table 4). Previous studies reported similar indaziflam efficacy with 84% to 100% control of goosegrass [*Eleusine indica* (L.) Gaertn.] (McCullough et al. 2013), large crabgrass (Perry et al. 2011), smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] (Brosnan et al. 2011), and annual bluegrass (Brosnan et al. 2012) following PRE applications of indaziflam at 35 to 70 g ai ha^{-1}.

Narrowleaf Goldentop

Control ≥95% was observed throughout the season with indaziflam at 146 g ai ha^{-1} applied in fall (Table 3). Lower control was observed following a fall application at 73 g ai ha^{-1} but remained >80% throughout the season and was equivalent to goldentop control provided by the dichlobenil standard. Following a spring application, indaziflam at 73 or 146 g ai ha^{-1} performed similarly with <70% control 8 WST and <60% control 17 WST. Conversely, >80% control throughout the season was achieved with the spring mix of diuron, oryzalin, and mesotrione. Pooled across herbicides, a fall application of indaziflam provided significantly better control of narrowleaf goldentop 17 WST than a spring application (Table 4).

Pine Barren Flatsedge

Regardless of rates or timing of application, indaziflam controlled flatsedge ≥89% 8 WST (Table 3). Control declined to <70% 17 WST with indaziflam at 73 g ai ha^{-1} applied in fall or spring, whereas dichlobenil applied in fall or the mix of diuron, oryzalin,

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and mesotrione in spring still provided ≥97% control. Increasing the indaziflam rate to 146 g ai ha^{-1} maintained ≥90% control when applied in fall but only 78% in spring. Overall, application times pooled across herbicides did not influence flatsedge control by the end of the season (Table 4). Nevertheless, when averaged over application rate, indaziflam control of Pine Barren flatsedge was less than fall or spring standards for other herbicides tested in this study.

Carpetweed

Indaziflam at 73 g ai ha^{-1}, regardless of application timing, or dichlobenil, did not control carpetweed 17 WSP (Table 3). Increasing the indaziflam rate to 146 g ai ha^{-1} improved carpetweed control for both fall (82%) and spring (80%) applications, but not as effectively as the spring-applied mix of diuron, oryzalin, and mesotrione that almost completely controlled carpetweed. Overall, spring applications performed better than fall applications (Table 4). Pooled across rates, fall-applied indaziflam provided greater control than the dichlobenil standard, but lower control than the diuron, oryzalin, and mesotrione mix when applied in spring. Despite the indaziflam label mentioning control of carpetweed at 50 to 95 g ai ha^{-1} (Anonymous 2021), our data suggest that only partial control would be achieved at those rates, regardless of application timing.

American Burnweed

Control was 81% with fall-applied indaziflam at 73 g ai ha^{-1}, but only 31% with a spring application (Table 3). At the 146 g ai ha^{-1} rate, no difference was noted between fall and spring applications with ≥95% control. At this rate, indaziflam was as effective as fall-applied dichlobenil and more effective than the spring-applied mix of diuron, oryzalin, and mesotrione. Pooled across herbicides, a fall application provided greater control of American burnweed than a spring application, regardless of herbicide active ingredient (Table 4).

Crop Injury

No leaf chlorosis was recorded over the course of the study, regardless of blueberry cultivar. Leaf necrosis not exceeding 3% 11 WST was reported only in Elliott fields in 2018 and was not associated with treatments (data not shown). Leaf necrosis affected the terminal leaves of blueberry new growth and was most liked caused by larvae of obliquebanded (*Choristoneura rosaceana* Harris) or red-banded (*Argyrotaenia velutinana* Walker) leafroller based on leaf webbing of injured shoots. Transient crop injury in the form of leaf crinkling affecting young emerging leaves was apparent at 8 and 11 WST but vanished by 17 WST. Bluecrop and Elliot fields were minimally affected with <2% injury 8 WST, respectively, without any significant herbicide effect (date not shown). Leaf crinkling was no longer visible 11 WST for these two cultivars. Leaf crinkling was more noticeable on Duke plants (Figure 1), and the year by herbicide interaction was significant for injury 8 WST ($P = 0.0019$) and 11 WST ($P = 0.0007$) (Table 5). Greater leaf crinkling 8 WST was noted in 2018 with spring-applied indaziflam at 146 g ai ha^{-1} (8%) compared to a fall application, regardless of rate, or a spring application at 73 g ai ha^{-1} (≤3%). To a lesser extent, similar results were noted again 8 WSP in 2019 and 2020 with higher leaf crinkling associated with spring-applied indaziflam at 146 g ai ha^{-1}. Leaf crinkling 11 WST was still higher in 2018 after spring-applied indaziflam at 146 g ai ha^{-1} (8%)

Figure 1. Leaf crinkling associated with indaziflam applied in spring at 146 g ai ha^{-1} on Duke highbush blueberry at Chatsworth, NJ.

compared to all other treatments (≤4%), but no differences between treatments were reported in 2019 and 2020 (Table 5). No visible leaf crinkling was reported 17 WST (data not shown). We hypothesize that higher leaf crinkling symptoms observed on Duke plants following a spring application of indaziflam at 146 g ai ha^{-1} may result from higher sensitivity of newly established highbush blueberry to a high rate of indaziflam, especially when applied around the time blueberry bushes are coming out of dormancy. Similar injury described as "puckered" foliage has been reported in knockout rose (*Rosa* × 'Radrazz') sprayed over-the-top with indaziflam (Neal et al. 2015). Injury observed with indaziflam on grape was associated with fields characterized as gravel or cobbles in California, whereas damage to pecan trees in Arizona and New Mexico were associated with sandy fields with a high pH that were flooded for irrigation (B. Hanson, personal communication). The indaziflam label recommends using this herbicide in established highbush blueberry plantings at least 1 yr after the bushes have been planted except in California, where the period is extended to 3 yr (Anonymous 2021).

Blueberry Growth

In the absence of significant year by herbicide interaction, visual stunting data and growth measurements were pooled across years for each cultivar. Bush stunting was noticeable starting 8 WAT for Duke and 11 WAT for Bluecrop and Elliott cultivars. In response to severe weed competition (Figure 2), bush stunting of the weedy control 8 and 17 WSP averaged 4%, 9%, and 5% for Bluecrop, Duke, and Elliott cultivars, respectively (data not shown). Regardless of blueberry cultivar or herbicide rate, bush stunting

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Table 5. Interaction effect of year and residual herbicide treatment on leaf crinkling (n = 4) for Duke highbush blueberry at Chatsworth, NJ.[a,b,c]

Herbicide	Time	Rate	Leaf crinkling					
			8 WST			11 WST		
			2018	2019	2020	2018	2019	2020
		g ai ha^{-1}	%					
None, weedy	–	0	2 b X	0 b X	1 b X	2 b X	1 X	1 X
None, weed-free	–	0	2 b X	1 b X	0 b X	2 b X	1 X	1 X
Indaziflam	Fall	73	2 b X	2 b X	0 b X	2 b X	2 X	0 X
Indaziflam	Fall	146	1 b X	2 b Y	0 b Y	2 b X	2 X	0 Y
Dichlobenil	Fall	3,300	2 b X	2 b X	0 b X	1 b X	1 X	0 X
Indaziflam	Spring	73	3 ab X	2 b Y	1 b Z	3 b X	1 XY	0 Y
Indaziflam	Spring	146	8 a X	4 a Y	2 a Z	8 a X	3 Y	1 Z
DIU + ORY + MES	Spring	1,800 + 3,360 +210	4 ab X	3 ab X	1 b Y	4 b X	2 XY	1 Y

[a]Abbreviations: DIU, diuron, MES, mesotrione; ORY, oryzalin; WST, weeks after spring treatment.
[b]Injury rated on a scale from 0% to 100%, with 100% corresponding to complete leaf crinkling.
[c]Means followed by the same letter in a column (a–c) or a row (X–Z) are not significantly different at the P ≤ 0.05 level according to the Fisher's protected least significant difference test for multiple means comparisons.

Figure 2. Weed control 16 wk after treatment with indaziflam at 146 g ai ha^{-1} applied in fall (A) compared to a nontreated weedy control (B) in Duke highbush blueberry at Chatsworth, NJ, in 2020.

did not exceed 2% where indaziflam was applied in fall or spring and did not differ from the weed-free control. Poor control of large crabgrass and narrowleaf goldentop following a fall application of dichlobenil caused 5% stunting on average to Duke crops, but <2% to Bluecrop and Elliott crops, where weed competition was less severe (data not shown). Growth measurements indicated that fall- or spring-applied indaziflam at 73 or 146 g ai ha^{-1} did not negatively affect blueberry growth compared with the weed free control, regardless of blueberry cultivar (Table 6). Conversely, compared with the nontreated weed-free control, annual growth decreased by 46% in Duke, 64% in Bluecrop, and 43% in Elliott crops when weeds were allowed to compete all season long. Reduced grass control with fall-applied dichlobenil in Duke crops or goldentop control with a spring-applied mix of diuron, oryzalin, and mesotrione in Elliott crops led to 29% and 38% growth reduction, respectively, compared with the weed-free control. Annual growth was less pronounced in Bluecrop crops, which may have concealed the effect of treatments on plant development.

Cluster Fruit Density and Weight

The year by herbicide interaction for cluster fruit density was significant for the Duke cultivar (P = 0.0003) but not for Bluecrop and Elliott cultivars. Thus, data for the latter were pooled across years (Table 7). Treatments had no effect on the number of berries per cluster for Bluecrop (data not shown). Weed competition in the weedy control caused the number of berries per cluster for Duke to drop by 52% on average in 2019 and 2020 compared with the nontreated weed-free control. Regardless of cultivar, fall- or spring-applied indaziflam at either 73 or 146 g ai ha^{-1} did not result in fewer berries per cluster throughout the study. Duke berry density decreased by 43% on average following fall application of dichlobenil in 2019 and 2020 in comparison with the weed-free control, which is likely the result of poor weed control observed with this herbicide. Duke berry density of all treatments dropped in 2019 and 2020 compared with 2018 as a result of rainy conditions in 2019 and low temperatures in 2020 during bloom. For the Elliott variety, and compared with the weed-free control, increased weed competition reduced berry density by 20% and 15% from the weedy control and spring-applied indaziflam at 73 g ai ha^{-1} treatments, respectively.

In the absence of a significant year by herbicide interaction, berry weight data were pooled across years. Berry weight of Elliott was not affected by herbicides and averaged 1.07 g (data not shown). Individual berry weight of Duke and Bluecrop dropped by 18% on average as a result of weed competition and compared with

Table 6. Crop annual growth (n = 12) for three highbush blueberry cultivars in response to fall- or spring-applied residual herbicides in Chatsworth, NJ.[a,b,c]

Herbicide	Time	Rate	Average yearly growth		
			Bluecrop	Duke	Elliott
		g ai ha^{-1}	cm		
None, weedy	–	0	5 b	13 c	12 c
None, weed-free	–	0	14 a	24 a	21 a
Indaziflam	Fall	73	12 a	21 ab	18 a
Indaziflam	Fall	146	13 a	23 a	18 a
Dichlobenil	Fall	3,300	15 a	17 b	20 a
Indaziflam	Spring	73	15 a	25 a	15 ab
Indaziflam	Spring	146	13 a	25 a	17 a
DIU + ORY + MES	Spring	1,800 + 3,360 +210	14 a	26 a	13 bc

[a]Abbreviations: DIU, diuron; MESO, mesotrione; ORY, oryzalin.
[b]Growth measurements data were pooled across years for each cultivar.
[c]Means followed by the same letter in a column (a–c) or row within cultivars (X–Z) are not significantly different at the P ≤ 0.05 level according to the Fisher's protected least significant difference test for multiple means comparisons.

Table 7. Cluster fruit density and individual berry weight for three highbush blueberry cultivars in response to fall- or spring-applied residual herbicides in Chatsworth, NJ.[a,b,c]

Herbicide	Time	Rate	Berry/cluster				Berry weight	
			Duke, n = 4					
			2018	2019	2020	Elliott	Bluecrop	Duke
		g ai ha^{-1}	count				g	
None, weedy	–	0	6.1 X	1.9 d Y	1.8 b Y	5.0 d	1.09 c	1.25 d
None, weed-free	–	0	6.0 X	3.8 bc Y	3.9 a Y	6.2 ab	1.33 a	1.53 bc
Indaziflam	Fall	73	5.8 X	3.4 c Y	3.4 a Y	6.3 ab	1.22 a-c	1.37 cd
Indaziflam	Fall	146	6.1 X	3.5 bc Y	3.4 a Y	6.7 a	1.28 ab	1.52 bc
Dichlobenil	Fall	3,300	5.9 X	2.5 d Y	1.5 b Z	4.9 d	1.37 a	1.42 c
Indaziflam	Spring	73	6.1 X	4.4 ab Y	3.1 a Z	5.3 cd	1.30 a	1.44 bc
Indaziflam	Spring	146	6.1 X	4.2 ab Y	4.0 a Y	5.9 a-c	1.24 ab	1.63 ab
DIU + ORY + MES	Spring	1,800 + 3,360 +210	5.8 X	4.5 a Y	3.0 a Y	5.8 bc	1.14 bc	1.67 a

[a]Abbreviations: DIU, diuron; MESO, mesotrione; ORY, oryzalin.
[b]Means followed by the same letter in a column (a–c) or row within cultivars (X–Z) are not significantly different at the P ≤ 0.05 level according to the Fisher's protected least significant difference test for multiple means comparisons.
[c]Cluster fruit density data for Elliott and average berry weight data for Bluecrop and Duke cultivars (n = 12) were pooled across years.

the weed-free control (Table 7). For both cultivars, indaziflam at 73 or 146 g ai ha^{-1} applied in fall or spring had no effect on individual berry weight compared with the weed-free control. As a result of excellent control of large crabgrass and Pine Barren flatsedge following spring application of a diuron, oryzalin, and mesotrione mix, Duke berry weight was 13% higher than it was when indaziflam at 73 g ai ha^{-1} was applied in the fall or spring.

By the final year of this study, the cumulated amount of indaziflam was 219 and 438 g ai ha^{-1}, for each rate of indaziflam, respectively, over 34 mo. If transient leaf crinkling was noted on newly planted Duke bushes, no injury was noted in established Elliott or Bluecrop plantations. Ultimately, none of the minor injuries observed on Duke reduced blueberry bush development or fruit quantity and size. Similarly, Grey et al. (2021) did not observe growth reduction on 2-yr-old 'Alapaha' rabbiteye (*Vaccinium ashei* Rade) exposed to a cumulated amount of 725 g ai ha^{-1} indaziflam over 30 mo. A fall application of indaziflam mixed with a WSSA Group 9, 10, 22, or 27 burndown herbicide would provide season-long residual control of many annual weeds, and help suppress the development of perennial Asteraceae and annual Cyperaceae species in New Jersey without requiring additional spring application, as was previously reported for other perennial crops (Basinger et al. 2019; Brunharo et al. 2020; Grey et al. 2021; Jhala et al. 2013). Even though rainfall exceed the 30-yr average by 16% during the study, highbush blueberry grown on sandy acidic soils showed excellent tolerance to repeated annual applications of indaziflam at the maximum labeled use rate (73 g ai ha^{-1}).

Practical Implications

Results of this study demonstrate that repeated fall or early spring applications of indaziflam at the 73 g ai ha^{-1} labeled rate did not cause injury or reduce commercial yield of blueberry grown on sandy acidic soil in New Jersey. Data generated through this research will help to support a request by New Jersey blueberry growers for a Special Local Need label under §24(c) of the Federal Insecticide, Fungicide, and Rodenticide Act to be granted for application of Alion® herbicide in New Jersey blueberry plantations established on sandy soil. Fall application of indaziflam more than spring applications provided better control of some species such as horseweed, large crabgrass, or narrowleaf goldentop. This suggests that a Special Local Need label to use Alion® on New Jersey blueberries could restrict application of this herbicide to dormant bushes during the fall season to maximize weed control effectiveness while maintaining the highest level of crop safety as compared to spring application.

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