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Leaching of Indaziflam Compared with Residual Herbicides Commonly Used in Florida Citrus

Amit J. Jhala and Megh Singh*

Soil-applied herbicides are commonly used for broad-spectrum residual weed control in Florida citrus. Groundwater contamination from some soil-applied herbicides has been reported in citrus growing areas in Florida. Indaziflam is a new soil-applied herbicide recently registered for broad-spectrum weed control in Florida citrus. There is no information available on leaching behavior of indaziflam in sandy soil. Experiments were conducted to compare leaching of indaziflam with five commercially used residual herbicides in a Florida Candler soil under simulated rainfall of 5 or 15 cm ha^{-1}. Herbicide movement down soil columns was measured by visually evaluating injury and harvesting aboveground biomass of the bioassay species annual ryegrass. Ryegrass was not injured and plant biomass was not affected beyond 30 cm when indaziflam at a recommended rate of 73 g ai ha^{-1} was leached through the soil column. Leaching of indaziflam increased with increasing amounts of rainfall. For example, indaziflam leached up to 12.2 $\pm$ 0.8 cm (values are expressed $\pm$ SD) and 27.2 $\pm$ 2.6 cm at 5 and 15 cm ha^{-1} rainfall, respectively. The herbicide ranking from high to low mobility at 15 cm ha^{-1} of rainfall was bromacil = norflurazon > indaziflam > simazine = pendimethalin > diuron. Overall results suggested that indaziflam leaching was limited in Florida Candler soil in this study; however, field experiments are required to confirm the leaching of indaziflam under natural rainfall situation.
Nomenclature: Bromacil; diuron; indaziflam {N-[(1R, 2S)-2,3-dihydro-2,6-dimethyl-1H-inden-1-yl]-6-[(1RS)-1fluoroethyl]-1,3,5-triazine-2,4-diamine}; norflurazon; pendimethalin; simazine; annual ryegrass, *Lolium multiflorum* L.
Key words: Contamination, groundwater, herbicide leaching, injury, pollution, soil-applied.

Herbicidas aplicados al suelo son comúnmente usados para el control residual de amplio espectro de malezas en cítricos en Florida. En zonas productoras de cítricos en dicho estado se ha reportado la contaminación de aguas subterráneas con algunos herbicidas aplicados al suelo. Indaziflam es un nuevo herbicida aplicado al suelo recientemente registrado para control de amplio espectro de malezas en cítricos en Florida. No hay información disponible acerca del comportamiento de lixiviación de indaziflam en suelos arenosos. Se realizaron experimentos para comparar la lixiviación de indaziflam con cinco herbicidas residuales usados comercialmente en un suelo Florida Candler bajo lluvia simulada de 5 ó 15 cm ha^{-1}. Se midió el movimiento de herbicidas en columnas de suelo con un bioensayo evaluando visualmente el daño y cosechando la biomasa aérea de la especie *Lolium multiflorum*. Esta especie indicadora no fue dañada y la biomasa no se afectó más abajo de los 30 cm cuando indaziflam, aplicado a la dosis recomendada de 73 g ai ha^{-1}, se lixivió a través de la columna de suelo. La lixiviación de indaziflam incrementó con cantidades crecientes de lluvia. Por ejemplo, indaziflam se lixivió 12.2 $\pm$ 0.8 cm y 27.2 $\pm$ 2.6 cm a 5 y 15 cm ha^{-1}, respectivamente. El ranking de herbicidas de mayor a menor movilidad a 15 cm ha^{-1} de lluvia fue bromacil = norflurazon > indaziflam > simazine = pendimethalin > diuron. Los resultados generales sugieren que la lixiviación de indaziflam fue limitada en el suelo Florida Candler en este estudio. Sin embargo, experimentos de campo son necesarios para confirmar la lixiviación de indaziflam bajo una situación de lluvia natural.

Weeds are undesirable because of their interference during crop production and, in some cases, their toxic properties and negative effects on human and animal health (Hall et al. 2000). There are many methods of weed control; however, use of herbicides is the most important method adopted by crop producers in annual and perennial crops (Cobb and Reade 2010). Despite the obvious advantages of herbicides for weed control in agricultural and noncrop areas, their use has raised concerns relating to human and animal health as well as environmental consequences including potential for surface and groundwater contamination through leaching, runoff, and spray drift (Barbash et al. 2001; Leonard and Knisel 1988; Ritter 1990).

With a growing area of more than 223,000 ha, citrus (*Citrus* spp.) is one of the most important crops in Florida agriculture (USDA 2010a). Florida is the largest producer of citrus in the United States with the production of more than 159 million boxes in 2010 (USDA 2010b). Integrated weed management programs in Florida citrus include application of herbicides, various cultivation practices, and naturally occurring weed pathogens. Among different methods of weed control, use of herbicides is the most important in nonbearing and bearing citrus trees (Futch 2005). Some commonly used PRE herbicides in Florida citrus include bromacil, diuron, pendimethalin, and norflurazon (Futch and Singh 2010).

Indaziflam is a new alkylazine herbicide for PRE control of annual grasses and broadleaf weeds in several perennial crops including citrus (Anonymous 2011). It can be applied to the soil as a uniform broadcast or as band application for the prevention of new weed emergence. The labeled rate of indaziflam in Florida citrus ranges from 73 to 95 g ai ha^{-1} in a single application with a maximum cumulative annual amount of 150 g ha^{-1} (Anonymous 2011). In field experiments conducted in Florida, indaziflam provided 3 to 4 mo of residual weed control in citrus depending on weather conditions and weed pressure (Singh et al. 2011). Indaziflam

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may also be applied in tank mixtures with multiple herbicides. When applied with a broad-spectrum herbicide such as glyphosate, the mixture has provided excellent control of emerged weeds in addition to extended residual weed control in California orchards and vineyards (Jhala and Hanson 2011). Thus, indaziflam could be an additional herbicide option for citrus growers for broad-spectrum weed control, and it is predicted that use of indaziflam will be significant in the near future.

During the past two decades, research efforts have been directed toward understanding complex herbicide–soil interactions. The widespread use of soil-applied herbicides in citrus groves in Florida has created concerns about accumulation of herbicide residues in field soils (Tucker 1978). Because of high annual rainfall and sandy soils, groundwater contamination through leaching of soil-applied herbicides is common in the areas where citrus is grown in Florida (Wilson et al. 2011). For example, bromacil, a brominated uracil herbicide, has been used for many years in Florida citrus for control of annual and perennial grasses and annual broadleaf weeds. The application of bromacil to sandy soil in Florida with a water table depth of 4.5 to 6 m has resulted in recovery of bromacil residues in the groundwater 3 mo after application (Hebb and Wheeler 1978). Within 4 mo, its concentration was found to be as high as 1.25 mg L^{-1}. Therefore, bromacil use was prohibited in nonbedded citrus groves located on permeable, well-drained soils (Fishel 2011). A survey conducted in citrus-growing areas in California by the California Department of Food and Agriculture reported that groundwater contamination with simazine, diuron, and bromacil was associated with application of these herbicides in citrus orchards (Pickett et al. 1992).

Groundwater contamination by herbicides is not only limited to sandy soils and citrus crops, but it has been reported in many other soil types and cropping systems as well. For example, atrazine, simazine, alachlor, and metolachlor are commonly used herbicides in maize (*Zea mays* L.) and several other crops, and groundwater contamination by these herbicides has been reported (Heatwole et al. 1997; Huang and Frink 1989; Ritter et al. 1988). Leaching of herbicides is affected by many factors including, but not limited to, soil texture, volume of irrigation or rainfall, adsorption of herbicide to soil colloids, water solubility of herbicide, and in some cases crop management practices (Singh and Tan 1996). Organic carbon distribution in soil determines solute transport in the soil. A mobile organic carbon phase such as colloidal organic carbon dispersed in soil water could act as a carrier of hydrophobic neutral organic compounds, thereby increasing their mobility. Water solubility of indaziflam is 4.4 mg L^{-1} at pH of 4 and temperature of 20 C and an octanol/water partition coefficient (K_{ow}) of 2.0 at pH of 2 (USEPA 2011). The soil organic carbon sorption coefficient (K_{oc}) is used to describe the binding strength of herbicides to soil. Indaziflam is expected to be moderately mobile to mobile in the soil ($K_{oc} < 1{,}000$ mL g^{-1}) (USEPA 2011); however, mobility of herbicides also depends on type of soil and amount of rainfall or irrigation after application.

Several methods have been developed to study leaching of herbicides including soil thin- layer chromatography, solid phase extraction technology, lysimetry, residue monitoring, computer modeling, and packed soil columns (Banks and Markle 1979; James and Lauren 1995; Weber et al. 1986; Wu and Santelman 1975). In spite of rapid developments in analytical methods (Kruger et al. 1996), bioassays remain an important tool for qualitative and quantitative determination of herbicide leaching (Nelson and Penner 2007; Singh and Tan 1996). Bioassay procedures are usually more economical and less difficult to perform; they also take less time and do not require expensive equipment compared with chemical analytical methods (Mueller and Banks 1991). The use of soil columns as a technique to simulate herbicide movement has been reported (Blumhorst 1996; Futch and Singh 1999; Weber et al. 1986).

With its new chemistry and mechanism of action, indaziflam will be applied for broad-spectrum weed control in Florida citrus. However, indaziflam has properties and characteristics associated with chemicals detected in groundwater (USEPA 2011). Hence, there was a compelling need to study leaching of indaziflam in a Florida Candler soil. The objectives of this research were to (1) compare the mobility of indaziflam with other commonly used soil-applied herbicides in Florida citrus and (2) determine the effect of the amount of rainfall (5 or 15 cm ha^{-1}) on leaching of indaziflam in a Florida Candler soil.

Materials and Methods

Soil Collection. The soil used in this study was collected from a citrus grove near Davenport, FL. The site had been a citrus grove and had been free from any agricultural operation or pesticide for at least 15 yr. Soil samples were collected from the top 120 cm profile at different horizons (0 to 30 cm, 31 to 60 cm, 61 to 90 cm, and 91 to 120 cm). The soil was a typical well-drained, fine Candler sand (Hyperthermic, uncoated Typic Quartzipsamments) (Brown 2003) and representative of the majority of Florida's citrus growing region. The soil samples were stored in separate open wooden containers and were air-dried for 2 wk before use. Two representative soil samples of about 100 g each were randomly collected from different soil horizons and sent for soil chemical analysis at the Waters Agricultural Laboratories, Inc., Camilla, GA (Table 1).

Experiment Details. The experiment was conducted using soil leaching columns under greenhouse conditions at the Citrus Research and Education Center, University of Florida, Lake Alfred, FL. Soil columns were 150-cm-long polyvinyl chloride (PVC) pipes with a 10-cm inner diam. The pipes were cut into halves longitudinally. To prevent preferential flow of herbicides along the soil–column interface, silicone ridges were placed cross-sectional at 15-cm intervals along the inner wall with all-purpose adhesive caulk (Plyseamseal®, HCA, Mentor, OH). The halves were sealed using adhesive tape (HVAC tape, Scotch brand, 3M Center, St. Paul, MN) to form a column, and the bottom end was fitted with a PVC cap. A nylon screen with Whatman filter paper no. 4 (Hoffman Manufacturing, Inc., 16541 Green Bridge Road, Jefferson, OR) was placed at the bottom of the PVC cap. The soil columns were filled with soil from the horizons collected from the four incremental depths (0 to 30 cm, 31 to 60 cm,

Table 1. Analysis of soil samples collected from different horizons of a citrus grove near Davenport, FL.[a,b]

Soil depth (cm)	pH	CEC	Sand	Silt	Clay	OM	ENR	P	K	Mg	Ca	B	Zn
		meq 100 g^{-1}	%				kg ha^{-1}						
0–30	6.3	2.9	91.6	4.4	4	0.46	8.74	241	13	57	910	0.45	25
31–60	5.8	1.5	89.2	6.4	4.4	0.24	5.16	91	12	30	254	0.34	4.7
61–90	5.6	1.2	91.2	4.8	4.0	0.18	4.15	86	11	25	233	0.22	3.7
91–120	5.2	1.2	93.2	2.4	4.4	0.15	3.25	81	11	17	169	0.22	1.8

[a] Abbreviations: CEC, cation exchange capacity; OM, organic matter, ENR, estimated nitrogen release.

[b] The analysis of soil samples was done at the Waters Agricultural Laboratories, Inc., Camilla, GA.

61 to 90 cm, and 91 to 120 cm). Soil columns were secured upright and each column was watered to field capacity and allowed to drain for 15 h.

The experiment was set up in a randomized complete block design with three replications. There was a total of seven treatments including six herbicides: indaziflam (Alion herbicide, Bayer CropScience, 2 T.W. Alexander Drive, Research Triangle Park, NC), simazine (Princep 4L herbicide, Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC.), norflurazon (Solicam herbicide, Syngenta Crop Protection), bromacil (Hyvar X herbicide; E. I. du Pont de Nemours and Company, 1007 Market St., Wilmington, DE), diuron (Direx 4L herbicide, E. I. du Pont de Nemours and Company), and pendimethalin (Prowl H_2O herbicide, BASF, Research Triangle Park, NC) at rates recommended for use in Florida citrus; an nontreated control was the seventh treatment (Table 2). Two separate experiments were conducted for the 5 and 15 cm ha^{-1} rainfall. Herbicide solutions were prepared in a 5-ml solution in a 20-ml vial, and shaken vigorously prior to application in the soil column. Herbicide solutions were applied with a small dropper to the soil surface in the soil column. Whatman filter paper no. 4 was placed on the surface of the soil column (after application of herbicide inside the column), and then a 1.25-cm layer of silanized-grade glass wool was placed on the surface to ensure proper spread and uniform flow of water through the soil column.

To simulate rainfall of 5 and 15 cm ha^{-1}, deionized water was dripped from a siphon system attached to a 1,000-ml Erlenmeyer flask mounted above each soil column over the glass wool. The volume of water to be applied in each soil column was calculated as

$$\text{Volume of water for 5 cm ha}^{-1}\text{ rainfall} = \pi r^2 h$$

where $\pi = 3.1428$, r = radius of the column (5 cm), and h = height of rainfall (cm).

For example, the volume of water required per soil column to simulate a rainfall of 5 cm ha^{-1} was 392.8 ml.

The intensity of rainfall, that is, the amount falling in any 24-h period varies from a trace (less than 0.025 cm) to as much as 41 cm; however, it is very common to have a rainfall of 2.0 cm h^{-1} in the citrus-growing areas in central Florida (Jackson and Davies 2009). Preliminary experiments were conducted to determine the flow of water (droplets) in 15 min to establish a simulated rainfall of 2.0 cm h^{-1}. During the experiment, the flow rate of water (droplets) was visually monitored with a stopwatch to ensure uniform leaching at a preestablished rate of 2.0 cm h^{-1}. The soil columns remained intact for 18 h after herbicide and rainfall treatments in specially prepared wooden stands. The PVC cap at the end of the soil column was then removed and columns were split longitudinally by removing the duct tape from one side and slicing the soil along the center. Using a 1-m ruler, three shallow furrows were made on the soil surface with a distance of 2.5 cm between each furrow.

Annual ryegrass was used as a bio-indicator species and the seeds were planted in a thick stand in previously prepared furrows, and finally the seeds were covered with adjacent soil (Futch and Singh 1999; Lavy and Santelman 1986; Sharma and Singh 2007). In a previous study, we determined the sensitivity of ryegrass to indaziflam concentration and the results suggested that an indaziflam dose as low as 29.2 g ha^{-1} was sufficient to prevent germination of ryegrass (Jhala et al. 2012). The split soil columns were arranged on a wooden bench in the greenhouse and mist-irrigated three times each day. The greenhouse was maintained at day/night

Table 2. Physico-chemical properties of the residual herbicides used in this study.[a,b]

Herbicide	MOA	Water solubility[d] (mg L^{-1})	Vapor pressure[d] (Pa)	pK_a	K_{ow}	K_{oc} (ml g^{-1})	Half-life in soil (d)	Mobility
Indaziflam[c]	Inhibits cellulose biosynthesis	4.4	6.92×10^{-8}	3.5	2.8	$< 1{,}000$	> 150	Moderate
Simazine	Inhibits photosynthesis at PS II	3.5	2.9×10^{-6}	1.62	122	130	149	Low to moderate
Norflurazon	Inhibits phytoene desaturase enzyme	28	3.87×10^{-6}	Nonionizable	280 ± 15	700	45–180	Low
Bromacil	Inhibits photosynthesis at PS II	815	4.1×10^{-5}	9.1	NA	32	60–365	High
Diuron	Inhibits photosynthesis at PS II	42	9.2×10^{-6}	Nonionizable	589	480	90–365	Moderate
Pendimethalin	Inhibits microtubule protein tubulin	0.275	1.25×10^{-3}	Nonionizable	152,000	17,200	44	Low

[a] Abbreviations: MOA, mechanism of action; pK_a, dissociation constant; K_{ow}, octanol-water partition coefficient; K_{oc}, adsorption coefficient; PS, photosystem; NA, not applicable.

[b] The data regarding physico-chemical properties of herbicides (except indaziflam) were taken from the 9th edition of the *Herbicide Handbook* (Senseman, 2007).

[c] The data of indaziflam were taken from USEPA (2011).

[d] Water solubility and vapor pressure at 25 C (20 C for indaziflam).

Table 3. Injury and biomass of ryegrass affected by herbicide leaching in different horizons at 5 cm ha^{-1} rainfall.

Herbicide	Rate (kg ai ha^{-1})	Ryegrass injury[a,b]				Ryegrass biomass[b]			
		0–30 cm	31–60 cm	61–90 cm	91–120 cm	0–30 cm	31–60 cm	61–90 cm	91–120 cm
		%				g			
Nontreated control	—	0 f	0 a	0 a	0 a	12.7 a	13.2 a	13.0 a	13.4 a
Indaziflam	0.073	21 b	0 a	0 a	0 a	6.6 d	13.0 a	13.4 a	13.2 a
Simazine	4.5	5 e	0 a	0 a	0 a	11.5 b	12.9 a	13.6 a	13.4 a
Norflurazon	3.52	39 c	0 a	0 a	0 a	10.03 c	13.3 a	13.5 a	13.2 a
Bromacil	4.48	72 a	0 a	0 a	0 a	4.0 e	13.0 a	13.4 a	13.0 a
Diuron	3.36	5 e	0 a	0 a	0 a	11.5 b	13.4 a	13.2 a	13.3 a
Pendimethalin	4.8	11 d	0 a	0 a	0 a	10.8 bc	13.2 a	13.1 a	13.1 a

[a] The data for percentage of injury to ryegrass were arcsine transformed for homogenous variance prior to analysis; however, data presented are the means of actual values for comparison.

[b] Means within columns with no common letters are significantly different according to Fisher's Protected LSD test where $P \leq 0.05$.

temperatures of 25/16 C (± 0.5 C), 70% (± 5%) relative humidity, and normal photoperiod.

Data Collection. Annual ryegrass plants were evaluated visually in each horizon (0 to 30 cm, 31 to 60 cm, 61 to 90 cm, and 91 to 120 cm) for injury on a 0 to 100% scale with 0% = healthy plants and 100% = complete plant death, 14 d after planting. Ryegrass from each 30-cm horizon (0 to 30 cm, 31 to 60 cm, 61 to 90 cm, and 91 to 120 cm) was harvested and dried at 60 C for 72 h; dry weights were recorded. The depth of herbicide leaching was recorded by measuring the distance from the top of soil surface to the area where ryegrass plants showed no signs of injury. The experiment was repeated to confirm the results.

Statistical Analysis. Data were subjected to ANOVA using SAS version 9.2 (SAS Institute Inc, Cary, NC). The experiments for two rainfall rates (5 and 15 cm ha^{-1}) were conducted separately, so they were analyzed separately. Normality and homogeneity of variance were tested. In this study, treatment by experiment interaction was nonsignificant; therefore, data from the two experiments were pooled and the combined data were presented. Depth-of-leaching data were $\log_{10}(x + 1)$ transformed and the percent ryegrass injury data were arcsine transformed prior to analysis in order to meet assumptions. However, nontransformed percentages were presented with mean separation based on transformed data. Where the ANOVA indicated that treatment effects were significant, means were separated at $P \leq 0.05$ and adjusted with Fisher's Protected LSD test.

Results and Discussion

Chemical analysis of the soil samples from the different horizons (0 to 30 cm, 31 to 60 cm, 61 to 90 cm, and 91 to 120 cm) used for these experiments indicated that the soil contained > 89% sand, < 7% silt, < 5% clay, and < 0.5% organic matter (Table 1). These characteristics are typical of the Candler fine sand found in Florida's citrus growing region (Brown 2003). The physicochemical characteristics of herbicides used in this study suggest that indaziflam has less water solubility compared to bromacil, norflurazon, and diuron and that its adsorption coefficient is higher compared with other herbicides used in this study, except pendimethalin (Table 2).

Injury of ryegrass from different horizons at 5 cm ha^{-1} rainfall suggested that the highest injury was recorded in bromacil-treated soil columns (72%) followed by norflurazon (39%) and indaziflam (21%) in the first horizon (0 to 30 cm) (Table 3). However, there was no injury of ryegrass beyond the first horizon (> 30 cm) in any herbicide treatment at 5 cm ha^{-1} rainfall. Similar results were reflected in ryegrass biomass (Table 3). For example, the least biomass was observed in bromacil-treated soil columns (4.0 g) followed by indaziflam (6.6 g) in the first horizon (0 to 30 cm) at 5 cm ha^{-1} rainfall; however, beyond this horizon, ryegrass

Table 4. Injury and biomass of ryegrass affected by herbicide leaching in different horizons at 15 cm ha^{-1} rainfall.

Herbicide	Rate (kg ai ha^{-1})	Ryegrass injury[a,b]				Ryegrass biomass[a,b]			
		0–30 cm	31–60 cm	61–90 cm	91–120 cm	0–30 cm	31–60 cm	61–90 cm	91–120 cm
		%				g			
Nontreated control	—	0 g	0 a	0 a	0 a	11.8 a	12.9 a	12.0 a	13.0 a
Indaziflam	0.073	95 b	0 a	0 a	0 a	0.1 d	12.8 a	12.4 a	12.9 a
Simazine	4.5	21 e	0 a	0 a	0 a	8.9 b	12.7 a	12.6 a	13.1 a
Norflurazon	3.52	50 c	35 b	15 b	15 a	6.5 c	8.5 b	9.1 b	8.5 b
Bromacil	4.48	98 a	95 c	96 c	89 b	0.1 d	1.0 c	2.5 c	3.0 c
Diuron	3.36	14 f	0 a	0 a	0 a	10.1 b	12.8 a	12.5 a	13.4 a
Pendimethalin	4.8	26 d	0 a	0 a	0 a	9.5 b	12.5 a	12.7 a	13.2 a

[a] The data for percentage of injury to ryegrass were arcsine transformed for homogenous variance prior to analysis; however, data presented are the means of actual values for comparison.

[b] Means within columns with no common letters are significantly different according to Fisher's Protected LSD test where $P \leq 0.05$.

Table 5. Leaching of soil-applied herbicides under simulated rainfall of 5 and 15 cm ha^{-1} in Florida Candler soil.

Treatment	Rate	Depth of herbicide leaching[a,b] Amount of rainfall 5 cm ha^{-1}	15 cm ha^{-1}
	(kg ai ha^{-1})	cm	
Nontreated control	—	0 ± 0.0 f	0 ± 0.0 e
Indaziflam	0.073	12.2 ± 0.8 b	27.2 ± 2.6 b
Simazine	4.5	4.2 ± 1.1 c	7.9 ± 1.0 c
Norflurazon	3.52	14.5 ± 1.0 b	112.5 ± 5.8 a
Bromacil	4.48	19.9 ± 1.0 a	120 ± 1.2 a
Diuron	3.36	1.9 ± 0.3 e	3.5 ± 0.5 d
Pendimethalin	4.8	2.5 ± 0.3 d	5.9 ± 1.0 c

[a] Mean distance of herbicide moved ± SD; The data were $\log_{10}$ (x + 1) transformed for homogenous variance prior to analysis; however, data presented are the means of actual values for comparison.

[b] Means within columns with no common letters are significantly different according to Fisher's Protected LSD test where $P \leq 0.05$.

biomass in all the herbicide-treated columns was comparable with the nontreated control (Table 3).

Leaching of herbicides may increase with a higher amount of rainfall or irrigation (Futch and Singh 1999). This was reflected in the results of this study because the injury of ryegrass in the 0 to 30–cm horizon was higher at 15 cm ha^{-1} rainfall compared to that at 5 cm ha^{-1} (Table 3 and 4). The highest injury of ryegrass (98%) was observed in bromacil-treated soil columns, followed by indaziflam (95%) and norflurazon (50%) in the first horizon (0 to 30 cm) (Table 4). Bromacil leaching was highest and recorded up to the bottom of the soil columns (120 cm) at 15 cm ha^{-1} rainfall. Similarly, Sharma and Singh (2001) reported that leaching of norflurazon increased from 19.6 to 105.4 cm with increasing amount of rainfall from 6.25 to 12.5 cm ha^{-1}. Primary soil factors that influence herbicide leaching to the groundwater system are organic matter content and texture (Leonard and Knisel 1988). Bromacil is more strongly adsorbed by organic matter and thus it is more persistent and less mobile in soils with high organic matter content (Gerstl and Yaron 1983a,b). The Florida Candler soil is very poor in organic matter (< 0.5%) (Table 1), so bromacil would be less adsorbed and resulted in more leaching.

Compared with the nontreated control, all herbicide treatments reduced biomass in the 0 to 30–cm horizon at 15 cm ha^{-1} rainfall (Table 4). For certain herbicides, such as bromacil and norflurazon, there was a reduction in biomass in the second (31 to 60 cm), third (61 to 90 cm), and fourth horizons (91 to 120 cm) compared to other herbicide treatments. This was due to mobility of these herbicides in the lower depth of the soil columns, which reduced germination of ryegrass. There was some injury of ryegrass in norflurazon-treated soil columns beyond 30 cm. Bleaching of ryegrass foliage was observed in all the horizons in norflurazon-treated soil columns; this is a typical symptom associated with the mode of action of this herbicide (Vencill 2002). There was no reduction in ryegrass biomass in indaziflam-treated soil columns beyond 30 cm and it was comparable with the nontreated control suggesting that leaching was limited to the top 30 cm of the soil column.

Compared with the nontreated control, leaching was observed in all herbicide treatments ($P < 0.0001$) (Table 5). Indaziflam leached up to 12.2 ± 0.8 cm and 27.2 ± 2.6 cm at 5 and 15 cm ha^{-1}, respectively. These results were in accordance with the previous studies indicating that herbicide leaching increased with increasing amount of rainfall (Alva and Singh 1990; Reddy and Singh 1993; Tan and Singh 1995). The highest leaching was observed in bromacil-treated soil columns regardless of rate of rainfall compared to other herbicide treatments, suggesting that bromacil was highly mobile (Table 5). Similarly, Futch and Singh (1999) concluded that bromacil was highly mobile and leached up to 79 and 107 cm at 6.4 and 12.8 cm ha^{-1} rainfall, respectively.

In this study, bromacil and norflurazon leaching was higher than that of indaziflam, whereas leaching of simazine (< 10 cm), pendimethalin (< 7 cm), and diuron (< 5 cm) was less than that of indaziflam (Table 5). Therefore, herbicide ranking from high to low mobility at 5 cm ha^{-1} was as follows: bromacil > norflurazon = indaziflam > simazine > pendimethalin > diuron; herbicide ranking at 15 cm ha^{-1} was bromacil = norflurazon > indaziflam > simazine = pendimethalin > diuron (Table 5). The results of this study were similar to those of a study by Futch and Singh (1999), who ranked herbicides based on mobility along the soil columns in the order of least to most mobile herbicide as oryzalin, thiazopyr, oxyfluorfen, diuron, norflurazon, simazine, and bromacil.

Indaziflam dissipates in the environment primarily through degradation and leaching. Indaziflam metabolites are more mobile than the parent material ($K_{oc} < 1{,}000$ ml g^{-1}), and were detected in field studies at the deepest depths sampled (105 to 120 cm) (USEPA 2011). Therefore, indaziflam metabolites have the potential to persist and leach to groundwater. A recent study to evaluate sorption–desorption of indaziflam in selected soils from different countries suggested that based on sorption coefficients, indaziflam was classified as a moderate to low-mobility herbicide (Alonso et al. 2012). Herbicide leaching can be reduced with the use of various herbicide formulations (Nelson and Penner 2007) and adjuvants (Sharma and Singh 2007). For example, leaching of alachlor in a sandy soil was reduced with microencapsulation compared with the commercial emulsifiable concentrate (Fleming et al. 1992). Therefore, more research is required in this direction, which may reduce indaziflam leaching.

This is the first report of comparing leaching of indaziflam with several soil-applied herbicides commonly used in Florida citrus. There was no leaching of indaziflam beyond 30 cm even under a high-rainfall situation (15 cm ha^{-1}) indicating that the mobility of indaziflam is limited. Although the research conducted in this study concerns comparison of indaziflam leaching with other herbicides under a closely defined set of experimental conditions, the basic principle involved can be applied in a variety of environmental conditions. The limitation of this study is that comparison of mobility among the herbicides was under the conditions of the experiment (sandy soil in soil columns); therefore, field studies at multiple locations would be needed to determine potential for leaching under natural field and rainfall conditions.

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