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# Quantifying indaziflam soil dissipation and thermal stability

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## Research Article

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## Abstract

Indaziflam is a long-term residual weed control option for Georgia pecan [*Carya illinoinensis* (Wangenh.) K. Koch] growers. As a nonselective cellulose biosynthesis inhibitor, indaziflam has a niche for broad-spectrum weed control with long residual activity in various perennial cropping systems. Indaziflam's soil persistence and chemical behavior at various temperatures have not been fully evaluated; therefore, the objectives of these experiments were to: (1) quantify indaziflam soil dissipation under field conditions in two common Georgia soils and (2) evaluate indaziflam molecular stability as affected by temperature and time using laboratory techniques. Indaziflam soil dissipation followed first-order kinetics and was adequately described by the exponential decay equation. Indaziflam half-life in Greenville sandy clay loam and Faceville loamy sand was 96 and 78 d, respectively. Indaziflam half-life and soil clay content had a direct relationship, while indaziflam half-life and microbial biomass had an inverse relationship. Aqueous solutions of indaziflam were exposed to temperatures that ranged from 20 to 70 C for up to 672 h, with results indicating that temperature had no influence on indaziflam's molecular stability.

## Introduction

Indaziflam is a preemergent, broad-spectrum herbicide that is classified as a cellulose biosynthesis inhibitor (Brabham et al. 2014; Shaner 2014). It controls multiple broadleaf and annual grass weeds in perennial crops, turfgrass, forestry sites, and rangeland, along with non-crop, residential, and non-residential areas (Gonzalez-Delgado et al. 2015). Indaziflam is currently used across the United States in multiple cropping systems, including citrus (*Citrus* L.), apple (*Malus* Mill.), pear (*Pyrus* L.), stone (*Prunus* L.) and pomefruits, grape (*Vitis* L.), olive (*Olea europaea* L. ssp. *europaea*), pistachio (*Pistacia vera* L.), almond [*Prunus dulcis* (Mill.) D.A. Webb.], walnut (*Juglans regia* L.), pecan [*Carya illinoinensis* (Wangenh.) K. Koch], blueberries (*Vaccinium* spp.), blackberries (*Rubus* spp.), and bermudagrass [*Cynodon dactylon* (L.) Pers.] (Brunharo et al. 2020; Grey et al. 2018b, 2021). Indaziflam use in various perennial cropping systems provides long-term, annual weed control with no documented preemergence herbicide resistance (Brabham et al. 2014; Heap 2020). However, there has been a case of postemergence indaziflam resistance in annual bluegrass (*Poa annua* L.) in turf use (Brosnan et al. 2020). This is considered unique, in that most applications for indaziflam are for preemergence weed control situations.

Indaziflam has a niche in Georgia for broad-spectrum grass and broadleaf weed control in various perennial cropping systems, including pecan, blueberry, peaches, and olive to maintain bare ground around the tree rows (Allen 2011; Grey et al. 2018b). Pecan production has remained constant, as there has been a continuous demand for U.S. domestic use and export to foreign markets (API 2025). Pecan production in Georgia increased from 46,266 Mg in 2011 (Grey et al. 2014) to 59,420 Mg in 2022 (USDA-NASS 2020b). Georgia remains on average the largest pecan-producing state in the United States, accounting for more than 30% of all planted hectares (USDA-NASS 2020b; Wells 2014). From 2020 to 2024, the state annually averaged 52,136 Mg with a farm gate value of approximately US$191,421,750 (USDA-NASS 2020b). The fresh-market blueberry industry has also increased in Georgia, with an annual farm gate value of US$123,070,800 (USDA-NASS 2020a). While olive is not a major perennial crop in the Southeast, interest in production as a specialty crop in this region of the United States has increased with demand for locally produced virgin olive oil. Indaziflam can be used for olive trees that have been established for at least 3 yr (Grey et al. 2016; USEPA 2010).

Weed competition can reduce growth in perennial crops by more than 50%. Newly planted trees and bushes are especially sensitive to competition for sunlight, moisture, and nutrients (Smith 2011). Weeds are controlled in perennial cropping systems during establishment and

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throughout the life span of the orchard. In established perennial crop areas, weeds can interfere with cultural practices (Brunharo et al. 2020), irrigation equipment (Belding et al. 2004), and harvesting operations (Company and Gradziel 2017), as well as serving as inoculum for diseases and alternate hosts for insects (Faircloth et al. 2007). Weed control programs for perennial crops typically rely on residual herbicides to provide adequate season-long control by establishing weed-free strips between perennial species (Faircloth et al. 2007; Smith 2011).

The most common and troublesome weeds for Georgia pecan include Palmer amaranth (*Amaranthus palmeri* S. Watson), Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], crabgrass species (*Digitaria* spp.), and Benghal dayflower (*Commelina benghalensis* L.) (Grey et al. 2014). Herbicide-tolerant (e.g., *C. benghalensis*) and herbicide-resistant (e.g., *A. palmeri*) weeds have been reported throughout the region by Georgia pecan growers (Culpepper et al. 2006; Monquero et al. 2004). Indaziflam controls a variety of these weed species, including *L. perenne* ssp. *multiflorum*, *Digitaria* spp., and *Amaranthus* spp., along with other weeds common to the region (Brosnan et al. 2011). Previous research reports residual control from indaziflam for 28 wk in turfgrass (McCullough et al. 2013; Perry et al. 2011), 3 to 4 mo in Florida citrus (Singh et al. 2011), and up to 6 mo in pistachio, pome fruit, and stone fruit (Allen 2011). In California orchards and vineyards, chemical weed management programs that relied on indaziflam as a preemergence herbicide application provided adequate residual control, including control of glyphosate-resistant weeds (Brunharo et al. 2020; Grey et al. 2016; Jhala and Hanson 2011).

In 2012, indaziflam was registered for use in pecan orchards in the United States. Several months after application, growers in New Mexico and Arizona began to report varying herbicide injury symptoms on trees where indaziflam was applied (Gonzalez-Delgado et al. 2015). These injury symptoms were attributed to variations in the soil physical properties, and it was estimated that pecan roots were being exposed to indaziflam concentrations above the recommended field rate (Gonzalez-Delgado et al. 2015). Injury was further attributed to indaziflam movement with water, consistent with the flood-irrigation practices used in those states (Gonzalez-Delgado et al. 2016). Pecan trees are known to be highly sensitive to poor soil drainage, and their productivity decreases in areas under prolonged flooding conditions (Sparks 2005). In Georgia, newly planted pecan trees, watered through microjet irrigation, were tolerant to indaziflam applied in the spring (Grey et al. 2018b). Other perennial crops, such as olive (Grey et al. 2016) and woody ornamentals (Parker and Myers 2011), were also found to be tolerant to indaziflam.

Herbicide dissipation varies greatly among soils, compounds, and environments. Microbial degradation is a large factor in understanding herbicide dissipation and is the major mechanism of degradation for many herbicides, including indaziflam (Shaner 2014; USEPA 2010). Microbial degradation is influenced by soil temperature, moisture, and microbial biomass. As soil temperature and moisture decrease below certain levels (cold, dry soil), microbial degradation virtually stops (Nash 1988). As soil temperatures and moisture increase above certain levels (very hot, saturated soil), microbial biomasses cannot complete their breakdown processes, also ceasing degradation (Nash 1988).

Sorption kinetics are also useful in understanding and quantifying the biological availability of certain herbicides. The main physiochemical properties that impact indaziflam soil movement and availability are the dissociation constant (3.5; weak acid), an average half-life of 30 to 150 d (>2 yr in cold, dry areas of the U.S. Midwest), and low water solubility (Gonzalez-Delgado et al. 2015, 2017; Sebastian et al. 2017; Shaner 2014; USEPA 2010). Indaziflam sorption is moderate for most soil types, increasing as soil organic matter increases (Sebastian et al. 2017), while desorption shows hysteresis, indicating a lower potential for mobility in the soil profile (Alonso et al. 2015). Indaziflam is relatively immobile; however, its long residual half-life and moderate sorption properties suggest the potential to move into the root zone of perennial crops (Jefferies and Gannon 2016).

**Table 1.** Soil characteristics for both Webster and Sumter County orchards.

| Location | Sand | Silt | Clay | Organic matter | pH[a] | Microbial biomass carbon[b] |
|---|---|---|---|---|---|---|
| | % | | | | | |
| Webster County[c] | 61.9 | 16.1 | 22.0 | 2.1 | 5.3 | 266 |
| Sumter County[d] | 77.9 | 16.1 | 6.0 | 3.9 | 5.9 | 686 |

[a]Water:soil = 2:1.
[b]Microbial biomass carbon based on 2% of the soil carbon levels (McGonigle and Turner 2017; Sparling 1985).
[c]Greenville sandy clay loam (fine, kaolinitic, and thermic Rhodic Kandiudults).
[d]Faceville loamy sand (fine, kaolinitic, and thermic Typic Kandiudults).

Even though indaziflam is already a commonly used residual herbicide in Georgia pecan orchards for preemergence control of grass and broadleaf weeds (Shaner 2014), its soil persistence and behavior at various temperatures have not been fully evaluated. Therefore, the objectives of this research were to: (1) quantify indaziflam soil persistence in Georgia pecan orchards under field conditions and (2) evaluate indaziflam stability as affected by temperature and time using laboratory techniques.

## Materials and Methods

Field and thermal gradient table experiments were conducted in conjunction with research reported by Eason et al., 2022), therefore the following methods are similar in language to the published article but describe treatments related only to indaziflam.

### Field Experiments

Experiments were conducted at two pecan orchards in Georgia, located in Webster (31.943, −84.573) and Sumter (31.948, −83.981) counties with the cultivars 'Byrd' and 'Pawnee', respectively. The soil characteristics for both locations are described in Table 1. The Webster County trial began in April 2016 and concluded 603 d after application, while the Sumter County trial began in March 2017 and concluded 478 d after application (Table 2). Indaziflam (formulated as Alion®, Bayer CropScience, Research Triangle Park, NC) was applied at 73.2 g ai $ha^{-1}$ (3,460 µmol kg $soil^{-1}$) using a four-nozzle (1.8-m) tractor-mounted boom, calibrated to deliver 140 L $ha^{-1}$ to either side of the tree row. All management practices were common to all trees during the growing seasons and directed by the growers.

Soil sampling and preparation procedures outlined by Grey et al. (2007) were followed. One soil core was taken from each replication at each sample date (three soil samples per location per sample date) (Table 2). Soil cores were collected using an aluminum cylinder (7.62-cm diameter by 7.62-cm height) that was hammered into the soil until flush with the soil surface. The

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**Table 2.** Sample dates and environmental measures recorded during the course of the experiment from the University of Georgia weather station[a].

| Application[b] | Sample date | DAA[c] | R | SR | ST (10 cm) |
|---|---|---|---|---|---|
| | | | mm | MJ m$^{-2}$ | C |
| Webster | 4/19/2016 | 0 | 0 | 26 | 23 |
| | 4/22/2016 | 3 | 20 | 74 | 22 |
| | 4/26/2016 | 7 | 20 | 171 | 27 |
| | 5/5/2016 | 16 | 23 | 360 | 24 |
| | 5/13/2016 | 24 | 23 | 555 | 29 |
| | 5/19/2016 | 30 | 33 | 676 | 26 |
| | 6/1/2016 | 43 | 43 | 1,001 | 34 |
| | 7/7/2016 | 79 | 146 | 1,821 | 33 |
| | 8/3/2016 | 106 | 204 | 2,417 | 29 |
| | 9/23/2016 | 157 | 359 | 3,423 | 31 |
| | 12/12/2016 | 237 | 479 | 4,593 | 14 |
| | 3/14/2017 | 329 | 897 | 5,624 | 11 |
| | 3/27/2017 | 342 | 898 | 5,646 | 23 |
| | 4/11/2017 | 357 | 994 | 5,782 | 24 |
| | 5/15/2017 | 391 | 1,093 | 6,233 | 29 |
| | 6/19/2017 | 426 | 1,293 | 7,468 | 30 |
| | 7/21/2017 | 459 | 1,475 | 9,412 | 33 |
| | 8/29/2017 | 498 | 1,569 | 12,007 | 31 |
| | 12/13/2017 | 603 | 1,890 | 15,407 | 9 |
| Sumter | 3/6/2017 | 0 | 0 | 15 | 17 |
| | 3/9/2017 | 3 | 4 | 63 | 18 |
| | 3/13/2017 | 7 | 20 | 125 | 11 |
| | 3/20/2017 | 14 | 22 | 244 | 17 |
| | 4/4/2017 | 29 | 52 | 529 | 22 |
| | 5/4/2017 | 45 | 181 | 1,219 | 24 |
| | 5/24/2017 | 65 | 301 | 1,674 | 24 |
| | 6/19/2017 | 90 | 418 | 2,189 | 30 |
| | 7/21/2017 | 122 | 600 | 2,840 | 33 |
| | 8/22/2017 | 154 | 694 | 3,493 | 33 |
| | 12/13/2017 | 267 | 1,015 | 5,142 | 9 |
| | 2/28/2018 | 344 | 1,203 | 5,149 | 18 |
| | 3/7/2018 | 351 | 1,228 | 5,257 | 15 |
| | 3/20/2018 | 364 | 1,264 | 5,582 | 21 |
| | 4/26/2018 | 397 | 1,421 | 6,589 | 21 |
| | 5/24/2018 | 428 | 1,522 | 8,186 | 27 |
| | 7/13/2018 | 478 | 1,785 | 10,799 | 34 |

[a]Cumulative values are reported from initial herbicide application date for days after application (DAA), solar radiation (SR), and R (rainfall). Soil temperature (ST 10 cm) values are reported for each sample date. UGA weather station is approximately 20 km from field sites.
[b]Application dates: Webster, 4/19/2016; Sumter, 3/6/2017.

cylinder was removed from the soil and the contents were individually wrapped in aluminum foil. Individual samples were placed into a sealable plastic bag, which was subsequently placed into cold storage for transportation and then frozen at −10 C until analysis. Rainfall, solar radiation, soil temperature (10 cm), and daily maximum and minimum air temperature data were collected at a University of Georgia Weather Monitoring Network station, located 20 km from the sites (Table 2).

## Thermal Stability Experiments

To further understand the implications of long-term residual herbicides such as indaziflam, stability as affected by temperature and time was evaluated using a thermal gradient table. The thermal gradient table (Grey et al. 2018a) is constructed from solid aluminum blocks (2.4 m by 0.9 m by 7.6 cm) with a warming or cooling unit (Anova Model A40, Anova Industries, Stafford, TX) on each side, pushing a 1:10 ethylene glycol:water solution across the table at a rate of 3.8 L min$^{-1}$. Thermocouples (Omega Engineering, Stamford, CT) are within 5 mm of the table surface in 10-cm intervals, recording temperatures every 30 min using a Graphtec data logger (Micro*DAQ*, Concord, NH).

**Table 3.** ETHOS X microwave extraction program parameters.

| Step | Time | Temperature | Power limit | Comments |
|---|---|---|---|---|
| | min | C | W | |
| 1 | 10 | 60 | <350 | Ramp from ambient to 60 C |
| 2 | 10 | 60 | <350 | Maintain at 60 C |
| 3 | 5 | — | — | Cool down to ambient |

A solution of indaziflam (0.33 µmol L$^{-1}$ [100 ppb]) was prepared using formulated product (Alion®) in high-performance liquid chromatography (HPLC) water, followed by stirring with a stir bar until all indaziflam was dissolved. This solution was transferred to flasks (100 ml flask$^{-1}$) that were sealed with Parafilm® and placed onto the thermal gradient table. Flasks were placed on cells across 11 temperatures, ranging from 20 to 70 C, with three replications per temperature, and then the experiment was repeated in time. All samples were kept in complete darkness for the duration of each experiment. Duplicate 1-ml aliquots were transferred from the flasks to HPLC vials at 0, 1, 6, 12, 24, 48, 72, 96, 168, 240, 336, 408, 504, 576, and 672 h after trial initiation. These vials were then placed into storage and frozen immediately after sampling at −10 C until analysis.

## Analytical Method

Soil samples were prepared for extraction by allowing them to acclimate to room temperature, sieving to homogenize while removing foreign material (>2 mm), and then weighing out a 15-g subsample into a microwave glass tube (Milestone Srl, Sorisole, Italy). Then 30 ml of an 80:20 (v/v) acetonitrile:water solution was added to each tube, which was then capped with a rubber stopper and vigorously shaken on a vortex mixer to break up any soil aggregates. The rubber stoppers were removed, and glass tubes were placed into slots evenly spaced on the microwave carousel assembly. Samples were subjected to microwave-assisted extraction (Mao et al. 2012) using an ETHOS X (Milestone Srl) following the parameters listed in Table 3. After microwave extraction, a 1.5-ml supernatant aliquot was pipetted into a 2.0-ml microcentrifuge tube (Fisher Scientific International, Waltham, MA) and then centrifuged for 5 min (12,500 rpm) using an Eppendorf MiniSpin® (Eppendorf, Hamburg, Germany). Then, 1.0 ml of the aliquot from each sample was transferred into HPLC vials (Fisher Scientific International) for analysis.

All samples were analyzed using a Waters Acquity Ultra-High Performance Liquid Chromatography (LC) coupled with a Waters 2998 PDA and Waters QDa Mass Spectrometry (MS) Detector (LC/MS) (Waters, Milford, MA). The LC separation was performed on a C18 reversed-phase column (Symmetry C18, 4.6 by 75 mm, 3.5 µm). A water and methanol gradient was used (Table 4). Table 4 summarizes the LC/MS instrument parameters used for quantification. Indaziflam concentrations (µmol L$^{-1}$) were quantified by correlating peak area detected to those of analytical grade standard solutions (Fisher Scientific International) of various known concentrations (0.1 to 1.0 µmol L$^{-1}$ [30 to 300 ppb]).

## Kinetic Evaluation of Herbicide Dissipation

Soil dissipation data were initially analyzed separately for each experiment, to account for trees at different locations having varying planting dates and multiple measures taken over time.

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**Table 4.** Chromatographic and mass spectrometer instrument parameters.

| | | | |
|---|---|---|---|
| Instrumentation | Waters ACQUITY Arc LC system<br>Waters QDa MS system Waters<br>Empower 3 data software | | |
| Column | Symmetry C18<br>4.6 × 75 mm, 3.5 µm | | |
| Column temperature | Ambient | | |
| Injection volume | 50 µl | | |
| Run time | 7.0 min | | |
| Mobile phase[a] | A: LC/MS water + 0.05% formic acid<br>B: LC/MS methanol + 0.05% formic acid | | |
| Flow rate | 0.8 ml min$^{-1}$ | | |
| Gradient | Time | A | B |
| | min | — % — | |
| | 0.00 | 60 | 40 |
| | 0.08 | 60 | 40 |
| | 0.40 | 35 | 65 |
| | 1.59 | 30 | 70 |
| | 2.38 | 20 | 80 |
| | 2.58 | 5 | 95 |
| | 3.93 | 5 | 95 |
| | 3.97 | 60 | 40 |
| Scan type | Multiple reaction monitoring | | |
| Polarity | Positive | | |
| Cone voltage | 17 V | | |

[a]LC/MS, liquid chromatography coupled with mass spectrometry.

Indaziflam dissipation data from the field experiment were subjected to regression analysis using SAS (SAS Institute, Cary, NC) nonlinear regression (PROC NLIN) to determine whether the response could be described by the following exponential decay equation (Grey et al. 2018a):

$$y = B_0 e^{-B1(t)} \quad [1]$$

where $y$ is the measured indaziflam concentration (µmol L$^{-1}$), $B_0$ is the initial indaziflam concentration (µmol L$^{-1}$) when time $t$ is 0, $B_1$ is the indaziflam dissipation rate (slope), and $t$ is time or energy elapsed after indaziflam application (day). After regression against time or energy, the output included the first-order dissipation rate constant ($k$) (Ohmes et al. 2000). Indaziflam field persistence was then determined using the half-life equation (Grey et al. 2018a):

$$t_{1/2} = ln(2)/k \quad [2]$$

where $t_{1/2}$ is the indaziflam half-life (in days) and $k$ is the first-order dissipation rate constant. Data were then graphed in SigmaPlot v. 14.0 (Systat Software, San Jose, CA).

***Kinetic Evaluation of Herbicide Thermal Stability in Solution***

Samples from the thermal gradient table were analyzed for indaziflam concentrations over temperature and time. Data were subjected to linear regression (PROC REG) using SAS v. 9.4 to determine whether there were any temperature effects over time on indaziflam concentration. Data were then graphed in SigmaPlot v. 14.0.

## Results and Discussion

### Tree Injury

The previously described injury from indaziflam in New Mexico and Arizona pecan orchards was attributed to various soil properties (Gonzalez-Delgado et al. 2016) and flood-irrigation practices (Gonzalez-Delgado et al. 2016). When indaziflam was applied to Greenville sandy clay loam and Faceville loamy sand soils, no visual phytotoxic injury was recorded, and no trees died during the entirety of these studies (data not shown). Rainfall amounts received in these studies were sufficient to leach indaziflam into pecan tree rooting zones and were similar to values reported in previous literature, where there were no visual injury symptoms on newly planted pecan trees (Grey et al. 2018b). Even though similar rates of indaziflam were used in these studies and the New Mexico and Arizona pecan orchards, no tree injury occurred in the Georgia soils. This can be attributed to differences in irrigation practices, with flood irrigation used in New Mexico and Arizona, while microjet irrigation practices are common in Georgia.

### Dissipation of Indaziflam in Soil

Soil dissipation parameter estimates were separated by soil type and tested for variances, with the regression coefficient differing between location ($P = 0.039$). Therefore, indaziflam soil dissipation was separated by soil type, with the exponential decay equation (Equation 2) adequately describing indaziflam dissipation at both locations, with $R^2$ values of 0.56 to 0.62. Half-life values for Greenville sandy clay loam and Faceville loamy sand were 96 d (Figure 1A) and 78 d (Figure 1B), respectively.

Indaziflam typically persists in soil for a longer time period compared with other residual herbicides. Pendimethalin is recommended for use with indaziflam in sequential application herbicide programs for California tree nut crops (Grey et al. 2018b). Pendimethalin has a shorter half-life (24 d) compared with indaziflam (Dinelli et al. 1998). In a similar Georgia soil (Tifton loamy sand), halosulfuron and flumioxazin soil dissipation were rapid with an average half-life of 9 d (Sparling 1985) and 13 to 14 d (Ferrel and Vencill 2003), respectively. Most of the determined indaziflam half-lives in field research are shorter than the 150 d reported by the registrant (Gonzalez-Delgado and Shukla 2020; Singh et al. 2011; USEPA 2010). This difference suggests indaziflam dissipation is influenced by soil type, experimental and environmental conditions, and herbicide movement with irrigation or rainfall.

Indaziflam $t_{1/2}$ in a sandy loam soil (field study) was reported at 53 to 63 d (0 to 15 cm of soil) and was consistently detected at 135 d after application (Singh et al. 2011), while $t_{1/2}$ values of 63 to 99 d were reported in greenhouse experiments using the same soil type (Gonzalez-Delgado and Shukla 2020). Shorter half-life values from field studies than those from greenhouse studies could be the result of greater degradation from microbial biomass or additional routes of dissipation, such as leaching, under field conditions (Gonzalez-Delgado and Shukla 2020). Indaziflam $t_{1/2}$ was shorter in Faceville loamy sand, which had 158% greater microbial biomass (mg kg$^{-1}$) than the Greenville sandy clay loam. The degradation of another herbicide, alachlor, is also reported to be positively correlated to soil microbial biomass (Walker et al. 1992). Similarly, atrazine indicated faster dissipation rates in warmer years, which was attributed to increased microbial degradation (Clay et al. 2000; Walker et al. 1992). This could be expected with indaziflam, due to microbial metabolism being a major degradation pathway (Shaner 2014), although other soil properties may have a greater impact on indaziflam's dissipation rate.

Positive correlations between indaziflam sorption and clay content have been previously reported (Alonso et al. 2011), with

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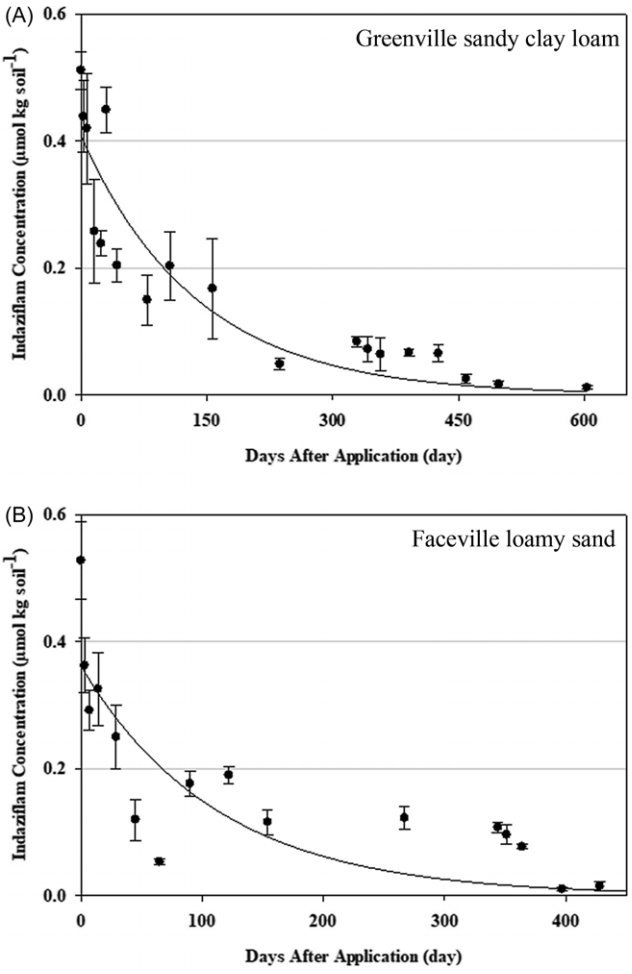



**Figure 1.** Indaziflam persistence ($t$ = day) using the exponential decay equation in (A) Greenville sandy clay loam and (B) Faceville loamy sand in Georgia from 2017 to 2020. Nonlinear regression was applied. Model shows that data can be described by first-order kinetics. Lines represent the first-order regression equation. Data points indicate the means of replications. Error bars represent the standard error of each mean (SEM). Parameter estimates: (A) Greenville sandy clay loam: $y = 0.4080e^{(-0.0072 \cdot t)}$, $k = 0.0072$, $t_{1/2} = 96.3$ d, $R^2 = 0.62$; (B) Faceville loamy sand: $y = 0.3612e^{(-0.0089 \cdot t)}$, $k = 0.0089$, $t_{1/2} = 77.9$ d $R^2 = 0.56$.

faster dissipation rates of indaziflam occurring in soils with lower clay content (Gonzalez-Delgado et al. 2015). Similar to indaziflam, atrazine is known to remain for a longer time period in soils with greater clay content (Clay et al. 2000). When tested in similar Georgia soils, flumioxazin $t_{1/2}$ in Greenville sandy clay loam soil (with higher clay content) was longer (16 to 18 d) when compared with Tifton loamy sand soil (13 to 14 d) (Ferrell and Vencill 2003). A more rapid dissipation rate of indaziflam in soil with higher sand content (77%) and drainage capacity has been previously reported (Gonzalez-Delgado et al. 2015). Trends in our results indicate that indaziflam dissipation was faster in Faceville loamy sand, which had higher sand content (78%) than the Greenville sandy clay loam soil (62%). The downward movement of indaziflam in the soil profile has been attributed to sand content, with plant injury increasing with increasing soil coarseness (Sebastian et al. 2017).

Indaziflam sorption is also positively correlated with increasing organic matter content (Gonzalez-Delgado et al. 2015; Schneider et al. 2015). Various studies support this, reporting indaziflam injury to bermudagrass decreasing (Jones et al. 2013) and higher mass recovery (%) of indaziflam (Singh et al. 2011) occurring in areas with higher organic matter content. Sorption of simazine, which is similar in solubility to indaziflam, follows the same trend (Flores et al. 2009). Sulfonylurea herbicides, which are staple herbicides used in Georgia pecan production, are also noted to have increasing herbicide sorption with increasing soil organic matter content (Grey and McCullough 2012). Inversely, alachlor half-life and soil organic matter are reported to be negatively correlated (Walker et al. 1992). Trends in indaziflam dissipation at the two locations could be attributed to the various soil properties, with organic matter content being 1.8% greater, clay content being 73% lower, and microbial biomass being 158% greater in the Faceville loamy sand soil compared with the Greenville sandy clay loam soil. However, to form more definitive conclusions, further research including several soil types with similar and varying soil characteristics is needed.

Soil tillage practices influence soil hydraulic properties, with higher macropore flow expected in no-tillage situations (Shipilato et al. 2000), which is the most common practice for Georgia pecan orchards. Macropores play an important role in the movement and distribution of water through the soil profile (Shipilato et al. 2000). Faster movement of solutes and water in soil is influenced by macropores that promote their preferential flow, ultimately leading to increased herbicide injury (Gonzalez-Delgado and Shukla 2020). Previously, indaziflam was ranked as transitional to leacher, with groundwater ubiquity score (GUS) index values of 1.84 to 3.00 in oxisol and 2.66 to 2.83 in mollisol soils from Brazil and the United States (Alonso et al. 2011). While indaziflam does have a transitional potential to leach, no downward movement of indaziflam beyond 30 cm has been reported (Gonzalez-Delgado and Shukla 2020; Jhala and Singh 2012), further indicating the limited mobility of the herbicide (Gustafson 1989).

**Table 5.** Parameter estimates for indaziflam stability in aqueous solution at various temperatures over time when evaluated on a thermal gradient table[a].

| Temperature C | $k$[b] | SE (±) | $DT_{50}$[c] |
|---|---|---|---|
| 20 | $2.1 \times 10^{-5}$ A | $5.2 \times 10^{-6}$ | Stable |
| 25 | $1.7 \times 10^{-5}$ A | $5.7 \times 10^{-6}$ | Stable |
| 30 | $2.2 \times 10^{-5}$ A | $5.7 \times 10^{-6}$ | Stable |
| 35 | $2.1 \times 10^{-5}$ A | $5.2 \times 10^{-6}$ | Stable |
| 40 | $1.6 \times 10^{-5}$ A | $5.9 \times 10^{-6}$ | Stable |
| 45 | $2.1 \times 10^{-5}$ A | $5.4 \times 10^{-6}$ | Stable |
| 50 | $1.6 \times 10^{-5}$ A | $5.6 \times 10^{-6}$ | Stable |
| 55 | $1.7 \times 10^{-5}$ A | $5.3 \times 10^{-6}$ | Stable |
| 60 | $1.9 \times 10^{-5}$ A | $5.4 \times 10^{-6}$ | Stable |
| 65 | $1.8 \times 10^{-5}$ A | $5.4 \times 10^{-6}$ | Stable |
| 70 | $1.6 \times 10^{-5}$ A | $5.6 \times 10^{-6}$ | Stable |

[a]Each value is the average of three replicates per experiment, with experiments conducted twice over time and combined for presentation. Values for each rate constant within a column followed by the same letter are not significantly different at $P < 0.05$ probability level.
[b]Degradation rate constants ($k$) were calculated by linear regression of the herbicide quantity with respect to time (0–672 h).
[c]Half-lives ($t_{1/2}$) were determined using the $k$-values and the equation: $t_{1/2} = \ln(2)/k$.
(A) Greenville sandy clay loam.
(B) Faceville loamy sand.

## Thermal Stability of Indaziflam

Determining the influence of temperature on indaziflam degradation was one objective of this research. Over the temperature range of 20 to 70 C, there was no impact of temperature on indaziflam degradation (Table 5). Indaziflam is known to be stable in anerobic aquatic environments (USEPA 2010), and data from the thermal gradient table indicated that indaziflam is hydrolytically stable at various temperatures (Table 5). The parameter estimates did not

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differ between time and indaziflam concentration across all temperatures ($P = 0.4563$); therefore, half-life information could not be determined for any specific temperature.

### Overall Behavior of Indaziflam

Indaziflam soil dissipation followed first-order kinetics and was adequately described by the exponential decay equation at both locations. Indaziflam half-life values in Greenville sandy clay loam and Faceville loamy sand were 96 and 78 d, respectively.

There was no indaziflam degradation by hydrolysis at any temperature. Relating indaziflam molecular stability laboratory experiments to the field dissipation studies indicates that indaziflam degradation in soil over time is not directly influenced by diurnal and seasonal changes in soil temperature. However, indaziflam dissipation did slightly slow down between approximately 240 to 340 d after application, which corresponded to decreasing soil temperatures, indicating that changes in soil temperature directly affected microbial activity, which in turn affected indaziflam dissipation. This is a unique and important aspect, as there have been no previous reports relating how temperature is not a direct factor concerning indaziflam degradation. This has many positive implications for providing extended residual weed control, as indaziflam is used in multiple facets, including perennial crops, forages, industrial sites, and turf.

As a nonselective cellulose biosynthesis inhibitor, indaziflam has a niche for broad-spectrum weed control with long residual activity in Georgia pecan orchards to maintain bare ground in the tree row. Because Webster and Sumter counties are the largest pecan-growing counties in Georgia, most growers can expect their indaziflam to provide long-term residual weed control with a half-life of 78 to 96 d. Georgia growers utilizing indaziflam in their residual weed control programs can now better understand the longevity of this chemistry in their specific soil types.

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