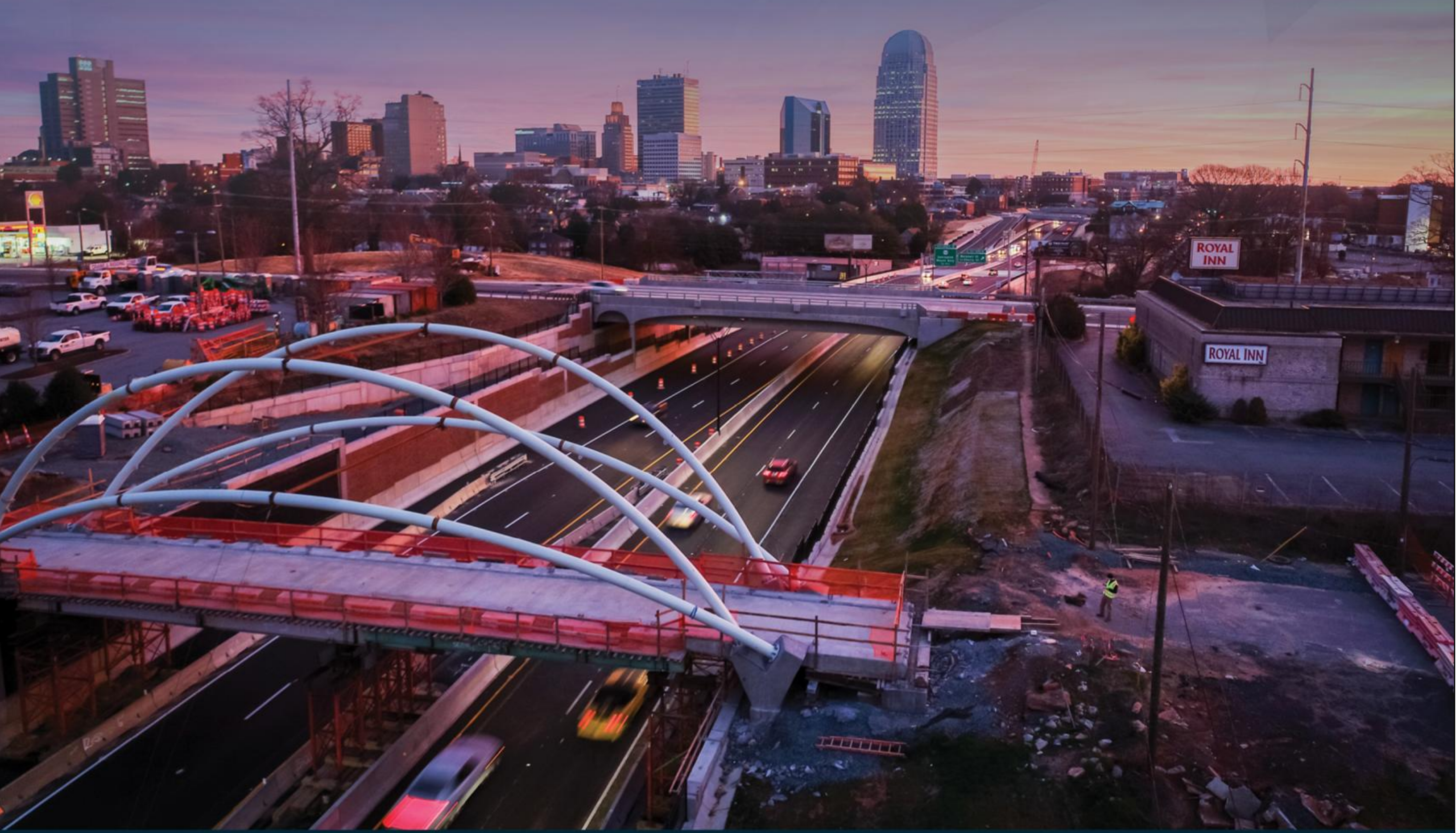
Optimizing Pesticide Applications Along North Carolina



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RESEARCH & DEVELOPMENT

Optimizing Pesticide Applications Along North Carolina

FINAL REPORT

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16. Abstract

Objective I:

This study assessed soybean and tobacco response to simulated drift of five roadside herbicides at four rates (0.01x–1x) and six timings at Sandhills Research Station, NC, in 2022 and 2023. In soybean, sulfometuron-methyl and indaziflam caused 20–33% yield loss at pre-planting and planting, while triclopyr caused 76–80% loss post-planting. In tobacco, sulfometuron-methyl caused 16–24% injury pre-planting and, along with triclopyr, at planting. Post-planting, triclopyr and 2,4-D + dichlorprop caused the highest injury (69–76% and 44–53%, respectively). Damage generally increased with rate but was observed even at the lowest rates.

Objective II:

Herbicide drift from roadside applications can damage nearby crops. This study evaluated the effects of simulated drift of five common roadside herbicides (sulfometuron-methyl, indaziflam, triclopyr, triclopyr + clopyralid, 2,4-D + dichlorprop) at four rates (0.01x–1x field rate) and six timings on corn and cotton at the Upper Coastal Plain Research Station, NC, in 2022 and 2023. In corn, sulfometuron-methyl caused the most damage, with 70% injury and 76% yield loss when applied 4 weeks after planting. In cotton, pre-plant applications caused minimal injury, but yield loss occurred even with early applications. Post-planting, synthetic auxin herbicides were particularly damaging; 2,4-D + dichlorprop, triclopyr, and triclopyr + clopyralid applied 4 weeks after planting caused 54%, 33%, and 30% yield loss, respectively. Crop damage generally increased with rate, though losses occurred even at the lowest rates.

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Executive Summary

This research project addressed two primary objectives: (1) to characterize off-target herbicide movement along North Carolina roadsides, and (2) to evaluate the impact of simulated herbicide drift on key crops in the state to inform best management practices that minimize off-target injury.

For Objective 1, building on preliminary passive air sampling, studies assessed how nozzle type, herbicide formulation, and season influenced vapor and particle drift. Garlon 3A (triclopyr amine) and Vastlan (triclopyr choline) were applied using NC DOT roadside equipment with two boomless spray heads: Norstar's nutating nozzle and UDOR's Boominator nozzle. Applications were structured across four days per seasonal run, rotating nozzle and formulation combinations. Field trials were conducted along Highway 540 in Morrisville, NC. Active air samplers were placed 100 m apart and 3 m from the spray line to collect air samples continuously for 48 hours post-application, with samples taken at 24 and 48 hours. Recovery pads measured ground deposition 10 minutes post-application. The Boominator nozzle was also sent to University of Nebraska-Lincoln for droplet size characterization. Results showed triclopyr choline was less prone to volatilization than triclopyr amine, with most volatilization occurring within 24 hours and increasing under high temperatures. Particle drift deposits and distances were similar across formulations and nozzle types, with drift occurring mainly at short distances from the spray site.

For Objective 2, field research assessed the impact of simulated drift from herbicides on soybean, tobacco, corn, and cotton at Sandhills and Rocky Mount Research Stations. Evaluated herbicides included triclopyr (Garlon 4), 2,4-D + dichlorprop (Patron), triclopyr + clopyralid (Confront), indaziflam (Esplanade), and sulfometuron (Oust). Treatments were applied at 1, 5, 10, and 100% of labeled rates PRE-plant, at planting, and POST-plant using CO_2 backpack sprayers. Crop height, injury, and yield were quantified monthly and at harvest to correlate visual injury with yield loss. Trials ran between January 2022 and July 2023. Sulfometuron-methyl caused the greatest injury, height reduction, and yield loss in corn, especially when applied at or after planting. In cotton, all herbicides caused injury post-planting, with synthetic auxins causing the greatest yield losses. For soybeans, sulfometuron-methyl and indaziflam caused the highest yield losses pre- and at planting, while post-plant synthetic auxins caused the greatest damage. In tobacco, sulfometuron-methyl caused the highest injury pre-planting, with both sulfometuron-methyl and triclopyr causing injury at planting, and triclopyr and 2,4-D + dichlorprop causing the highest injury levels post-planting.

Overall, this research provided critical insights into factors driving off-target herbicide movement and drift impacts on crop injury and yield. These findings inform best practices for nozzle selection, formulation choice, application timing, and drift mitigation to support effective and environmentally responsible roadside vegetation management in North Carolina.

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Introduction

Effective management of roadside vegetation is essential to maintain motorist safety, reduce maintenance needs, and preserve the integrity of transportation infrastructure and surrounding ecosystems. The North Carolina Department of Transportation (NCDOT) manages an extensive network of roads and relies on herbicides as a practical and cost-effective tool for roadside vegetation control. However, because many roadsides are adjacent to agricultural lands, herbicide drift remains a significant concern due to the potential for off-target injury to sensitive crops.

Herbicide drift, defined as the unintentional movement of herbicides away from the target site, can occur as particle drift during or shortly after application or as vapor drift through volatilization over subsequent hours or days. Factors such as droplet size, spray pressure, wind conditions, temperature, and application equipment influence these processes. Triclopyr, a commonly used herbicide for controlling woody and broadleaf weeds in roadside environments, has properties that reduce its environmental mobility, yet studies have demonstrated that even minimal doses can injure sensitive plant species.

North Carolina produces a wide range of crops, including soybean, tobacco, corn, and cotton, which are important to the state's agricultural economy. These crops can be highly susceptible to herbicide drift, resulting in plant injury and yield loss depending on the herbicide, exposure timing, and dose received. While the NCDOT implements measures such as low-drift nozzles and calibrated application equipment to reduce drift risk, roadside applications pose unique challenges due to factors like traffic-induced turbulence, variable environmental conditions, and year-round application schedules.

The purpose of this research was to evaluate herbicide drift from roadside applications and its potential impacts on sensitive crops to inform best management practices for NCDOT vegetation programs. Specifically, the study addressed two objectives. Objective 1 focused on characterizing and quantifying particle and vapor drift of triclopyr under different seasonal conditions, formulations, and nozzle types in roadside settings. Objective 2 assessed the response of soybean, tobacco, corn, and cotton to simulated spray drift of herbicides commonly used along roadsides when applied at pre-planting, planting, and post-planting timings. Together, these objectives aimed to improve understanding of drift dynamics and crop sensitivity to support safer, effective, and environmentally responsible roadside vegetation management.

This report is organized into the following sections. Following this introduction, the Result of Literature Review section summarizes relevant background on herbicide drift processes, triclopyr properties, crop sensitivity, and roadside application practices. The Report Body section details the experimental design, application parameters, sampling methods, and data analysis procedures for both objectives. The Findings and Conclusions section presents and interprets the main findings, including measured drift under different scenarios and crop injury and yield responses to simulated drift, followed by specific recommendations. Finally, the Implementation and Technology Transfer Plan section synthesizes key outcomes and provides guidance for NCDOT and related stakeholders to minimize off-target herbicide movement and optimize roadside vegetation management practices.

OBJECTIVE 1: Characterizing drift and volatility

Result of Literature Review

Management of roadside vegetation is important to provide safety for vehicles and travelers, to reduce cost and need for maintenance, and to preserve the integrity of road system infrastructure, wildlife habitats, and water quality (Johnson, 2008). The North Carolina Department of Transportation (NCDOT) manages the second-largest state-supported transportation network in the nation, which consists of 24,000 km of primary roads, interstates, and highways, and 97,000 km of secondary roads (NCDOT, 2022). Herbicides are considered an effective, low-cost, and practical method to manage vegetation along roadsides (Pellegrini et al. 2016). However, due to the proximity of some roadsides to agricultural lands, crop species can be seriously injured by herbicide drift from roadside applications.

Herbicide drift is the unintentional movement of herbicide via particle or vapor through the air from the target surface to any site other than the intended site (Bish et al., 2021; Klein et al., 2008). Particle drift is affected by several factors, including droplet size, spray pressure, wind speed and direction, and application equipment (Mueller, 2015). Vapor drift, also referred to as volatilization, is primarily affected by herbicide vapor pressure, air temperature and relative humidity, and target surface characteristics (Carbonari et al., 2020). Additionally, while particle drift occurs at application time or shortly thereafter, volatilization can occur in the first hours to several days following application (Gish et al., 2011; Fishel and Ferrel, 2010; Bedos et al., 2002). Triclopyr is a selective herbicide widely used to control woody and broadleaf weeds on crop and non-crop areas such as industrial areas, transmission line rights of way, and roadsides (Ramasahayam, 2014, USEPA, 1998). This herbicide was first introduced in the market as triclopyr triethylamine salt (TEA) in 1979 and is currently available as triclopyr acid, choline salt (CHO), and butoxyethyl ester (BEE) (USEPA, 1998). Triclopyr is a pyridine herbicide that acts by mimicking auxin hormones, which disrupt the normal growth patterns of plants, leading to loss of photosynthesis ability and, ultimately, plant death (Ansari, 2022, Sherwani et al., 2015, Grossmann et al., 2010). Plant symptoms include epinastic twisting and curling of stems and petioles, swelling and elongation of stems, and cupping and curling of leaves (Cessna et al., 2002; Grossmann et al., 2010).

Triclopyr is generally soluble in water, with solubility ranging from 23 mg L^{-1} to 2,100,000 mg L^{-1} (Shaner, 2014). Additionally, other properties of this herbicide include rapid degradation in water through photolysis (10 h at 25°C), moderate soil persistence (10 to 46 days), and low volatility, as evidenced by a vapor pressure of 1.6 10^{-4} Pa at 25°C (Shaner, 2014). These properties suggest that triclopyr is less prone to contaminating the water and atmosphere. Thus, agencies responsible for roadside weed management, such as NCDOT, opt for triclopyr not only due to its effectiveness and versatility but also for its reduced risk of environmental contamination, as well as its low toxicity to humans and wildlife (USEPA, 1998). However, numerous studies have reported that even minimal doses of this herbicide can severely injure sensitive plant species and cause crop yield loss (Marple et al., 2007; Tuffi Santos et al., 2006; Hatterman-Valenti et al., 1995; Jacoby et al., 1990)

North Carolina ranks as the third most crop-diverse state in the United States, boasting over 80 commercial crops (Moore, 2020). The varied climate and geography of the state are attributed to its wide range of crops. To minimize the risk of vapor or particle drift into these crops, it is imperative that applicators, including the NCDOT, exercise caution during applications and implement appropriate mitigation measures. This is particularly important in roadside settings, where turbulence caused by the movement of vehicles can intensify herbicide drift by increasing the dispersion and evaporation rate of droplets and changing the spray trajectory (Belkacem et al., 2020, Dixon et al., 2006). Therefore, the objective of this study was to characterize and quantify particle and vapor drift of triclopyr as influenced by season, formulation, and nozzle type in a roadside setting.

Materials and Methods

Field studies were conducted in 2022 and 2023 along a grassy roadside (25 m × 800 m) on Interstate 540 in Morrisville, NC (35°51'25"N 78°51'29"W) (Figure 1). The site was vegetated with bermudagrass (*Cynodon dactylon*), bahiagrass (*Paspalum notatum*), and centipedegrass (*Eremochloa ophiuroides*). Experiments were arranged in a randomized incomplete block design with three replications and two experimental runs per season.

For the vapor drift study, treatments were arranged in a four-way factorial: two triclopyr formulations × two boomless nozzle types × two collection timings × four seasons. For the particle drift study, treatments were arranged in a three-way factorial: two triclopyr formulations × two nozzle types × six distances from the treated area edge. Due to site and sampler limitations, each experimental run was split across four days with a minimum 72-hour interval between applications to avoid cross-contamination. On each day, four plots (7 m × 30 m) were established, spaced 70 m apart. One plot per day served as a non-treated control. Each plot received only one treatment per run to prevent herbicide interaction effects on volatilization, requiring 16 unique plots per run. Plot lengths were based on nozzle spray reach.

Triclopyr choline (Vastlan®, Corteva Agriscience) and triclopyr amine (Garlon® 3A, Corteva Agriscience) were applied at 3363 g ai ha^{-1} using Nutating® (Norstar Industries) and Boominator® (3750L, Udor USA) nozzles, at 468 L ha^{-1}, 276 kPa, and speeds of 11 and 6 km h^{-1}, respectively. Applications were performed by NCDOT from 8 a.m. to 11 a.m. using their roadside sprayers equipped with boomless nozzles.

For each plot, an active air sampler (CF-5624-WR – 24VDC, HI-Q Environmental) (Figure 2) was centered at 15 m and placed 3 m away from the plot edge in the southeast direction, approximately 10 m from the road. Deposit cards (400 cm^2, Fisher Pure Cellulose Chromatography Paper, Thermo Fisher Scientific) were mounted on wooden supports at six distances (0, 0.75, 1.5, 3, 6, and 12 m) from the plot edge in line with the air sampler. Cards were set out before application and collected 10 minutes post-application. Polyurethane foams (PUFs, 79 cm^2, TE-1010; Tisch Environmental) and filter media (32 cm^2, FPAE-102, HI-Q Environmental) were inserted into air samplers 10 minutes after application. Samplers operated at a constant flow rate of 472 cm^3 s^{-1}. The first PUF and filter were collected 24 hours after application (HAA), after which chambers were cleaned and a second set was installed and collected at 48 HAA. Deposit cards and filter media were stored in sealed plastic bags, while

PUFs were stored in glass jars, all kept on ice until laboratory transfer. Furthermore, triclopyr formulations at 3363 g ai ha^{-1} were delivered to PUFs and filter media stored in open glass jars on the roadside for each 24h of an application day to quantify natural herbicide degradation. These spiked samples were stored and analyzed similarly to other samples. Triclopyr residues were quantified using HPLC-DAD-MS (Agilent 1260 Infinity/MS6120) with an external calibration curve (OpenLAB CDS ChemStation, Version C.01.04).

Meteorological data were recorded at each application timing, including temperature, relative humidity, wind speed and direction, and soil surface temperature, using a Kestrel 5500 weather meter (Nielsen-Kellerman, Boothwyn, PA). Applications were made only under wind speeds between 3 and 16 km h^{-1} to simulate typical roadside operational conditions. Data were subjected to analysis of variance (ANOVA) using SAS software (Cary, NC) version 9.4 with PROC GLIMMIX. Treatment means were separated using Tukey's Honest Significant Difference (HSD) test at $\alpha=0.05$. Formulation, nozzle type, season, and distance were considered fixed effects, while experimental runs and replications were treated as random effects.

Results

Air samplers and deposit cards were placed southeast, opposite the road, which sometimes deviated from the downwind direction (Tables 1 and 2). Applications occurred under varying wind speeds and directions.

Vapor Drift

Sample timing × formulation and sample timing × season interactions were significant at $\alpha=0.05$. Vapor concentrations were 3–4 times higher at 0–24 HAA than at 24–48 HAA, with triclopyr amine 29% higher than choline at 0–24 HAA (Table 3). At 24–48 HAA, both formulations had similar concentrations (~1 x 10^{-9} g ae m^{-3}). Vapor concentrations varied by season at 0–24 HAA (Table 4), with highest values in summer (10.4 x 10^{-9} g ae m^{-3}) and spring (9.3 x 10^{-9} g ae m^{-3}), and lowest in fall (4.3 x 10^{-9} g ae m^{-3}) and winter (5.3 x 10^{-9} g ae m^{-3}). No differences in vapor concentration were observed between Boominator and Nutating nozzles (Table 5).

Particle Drift

Distance significantly influenced deposits ($\alpha=0.05$). The highest triclopyr deposit (1.3% of field rate) occurred at 0.8 m from the spray zone (Table 6). Triclopyr was detected up to 3 m but remained low (<2.0% of field rate), with no differences observed from 1.5 to 12 m. Deposits did not differ across formulations or nozzle types (0.3% of field rate; Tables 7 and 8).

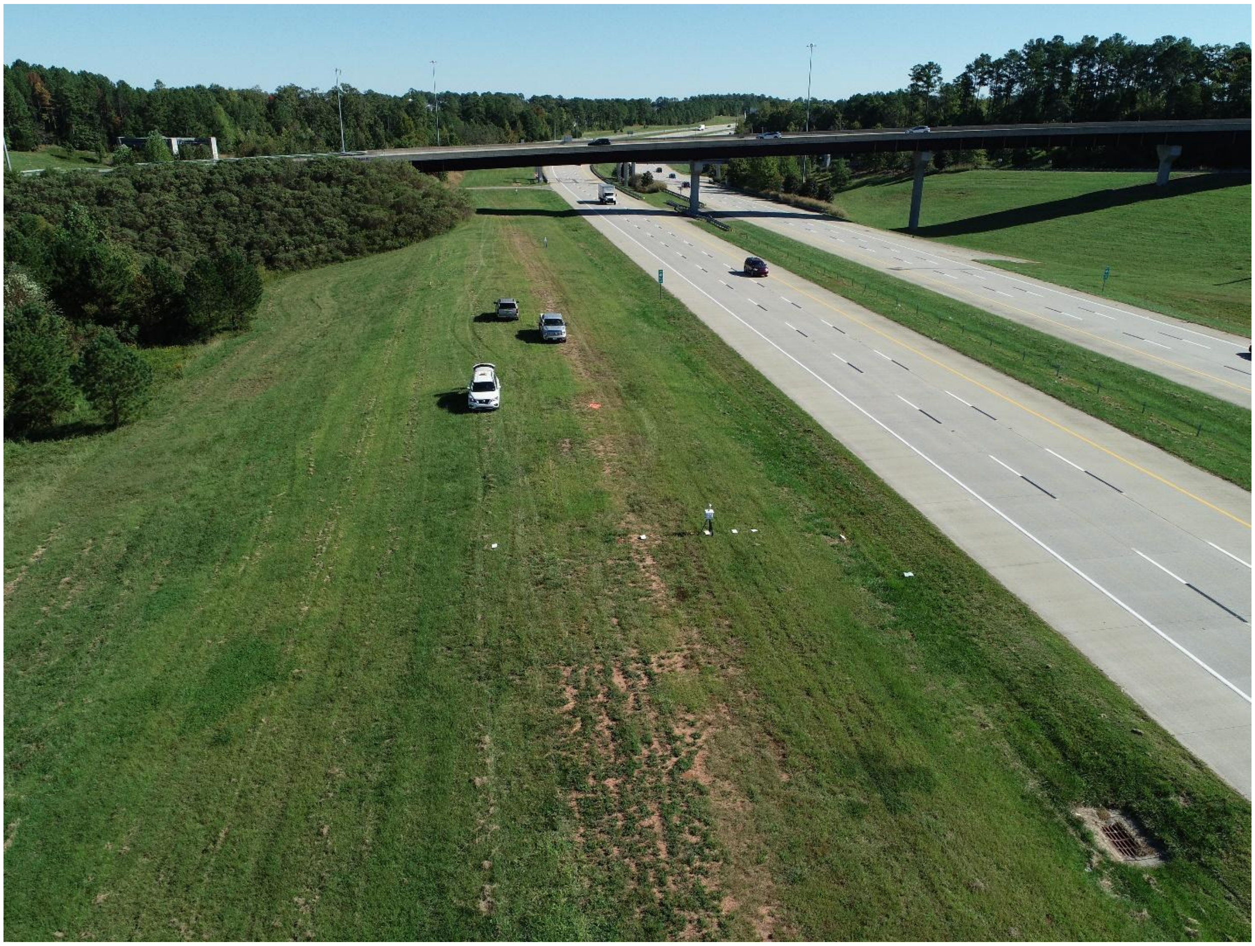

Figure 1. Experimental site located at Interstate 540 in Morrisville, NC (35°51'25"N 78°51'29"W)

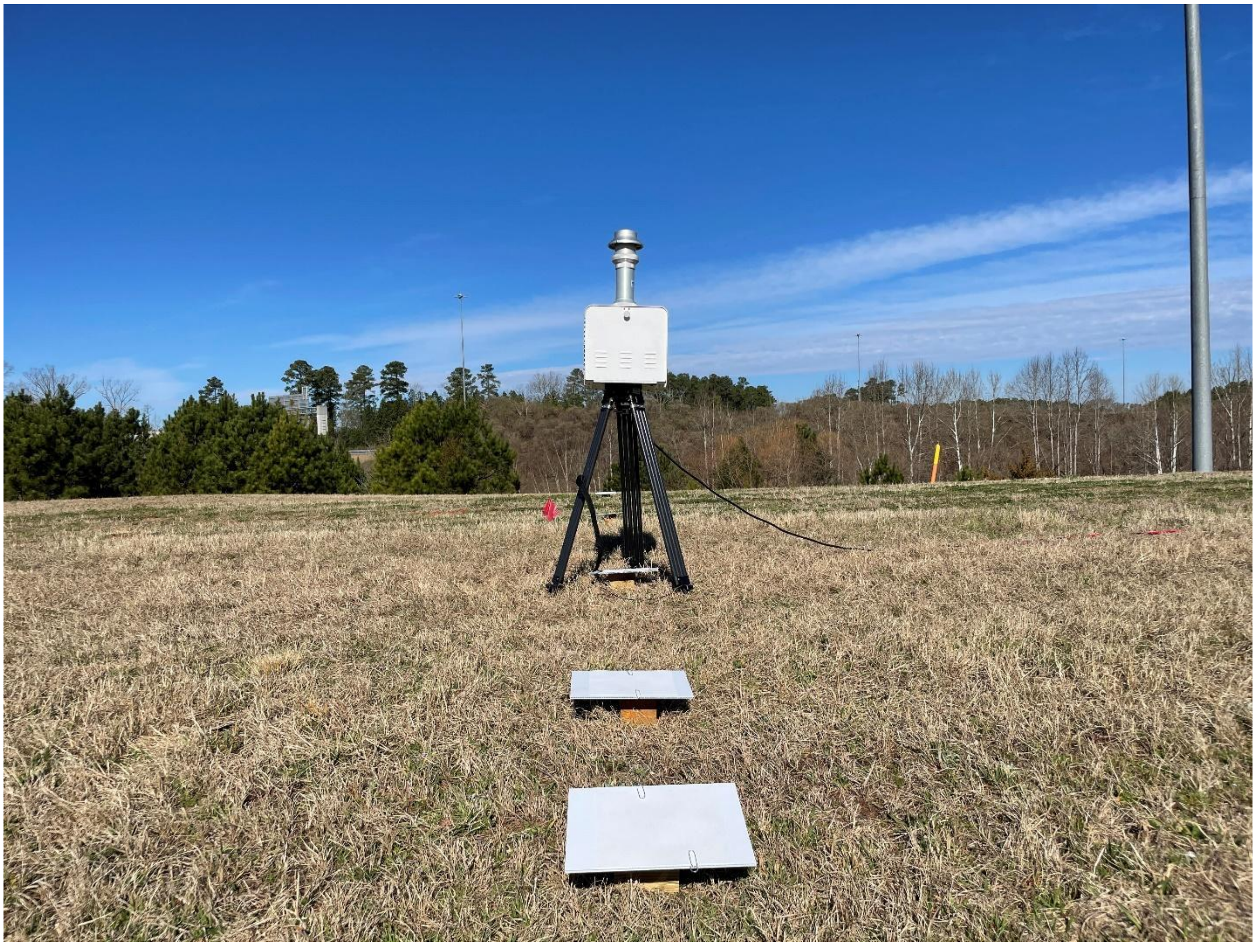

Figure 2. Active air sampler (HI-Q Environmental Products Company, Inc., San Diego, CA, USA) and deposit cards (400 cm2 , Fisher Pure Cellulose Chromatography Paper, Thermo Fisher Scientific, Inc., Pittsburgh, PA, USA) used to collect triclopyr vapor and particle drift, respectively.

Table 1. Weather parameters within 48h after application for each season averaged over experimental run and application day.[a]

Parameter	Winter[b]	Spring[b]	Summer[b]	Fall[b]
Temperature		C°		
Minimum	2	11	16	7
Maximum	29	33	35	28
Average	15	22	25	16
Relative Humidity		%		
Minimum	12	24	27	29
Maximum	96	98	100	100
Average	51	63	71	75
Wind Direction		Frequency (%)[c]		
SE (downwind)	25	0	12	12
NW (upwind)	0	25	0	25
Other directions	75	75	88	63
Wind Speed		km h^{-1}		
Minimum	0	0	0	0
Maximum	30	18	17	14
Average	6	5	6	3

[a] Weather conditions were monitored every 10 min using a weather station positioned at the roadside experimental site, located 10 m away from Interstate 540 in Morrisville, NC, and aligned in the same direction as the air samplers.

[b]Winter experimental runs were conducted from 2/28/2022 to 3/18/2022 and from 2/20/23 to 3/6/2023. Spring experimental runs were conducted from 5/2/2022 to 6/1/2022 and from 5/8/23 to 5/17/2023. Summer experimental runs were conducted from 7/11/2022 to 7/25/2022 and from 7/10/23 to 7/19/2023. Fall experimental runs were conducted from 10/24/2022 to 11/7/2022 and from 10/9/23 to 10/18/2023.

[c] Frequency was determined by calculating the occurrence of a determined wind direction every 10 min within 48h after application across application days for each season.

Table 2. Wind direction and speed at application time averaged over application day and experimental runs [a,b]

Wind direction	Frequency (%) [c]
SE (downwind)	9
NW (upwind)	13
Other directions	78
Wind speed	**km h^{-1}**
Minimum	0
Maximum	22
Average	6

[a] Weather conditions were monitored using a weather station positioned at the roadside experimental site, located 10 m away from Interstate 540 in Morrisville, NC, and aligned in the same direction as the air samplers.

[b] Studies were conducted in the winter, spring, summer, and fall of 2022 and 2023. Winter experimental runs were conducted from 2/28/2022 to 3/18/2022 and from 2/20/23 to 3/6/2023. Spring experimental runs were conducted from 5/2/2022 to 6/1/2022 and from 5/8/23 to 5/17/2023. Summer experimental runs were conducted from 7/11/2022 to 7/25/2022 and from 7/10/23 to 7/19/2023. Fall experimental runs were conducted from 10/24/2022 to 11/7/2022 and from 10/9/23 to 10/18/2023.

[c] Frequency was determined by calculating the occurrence of a determined wind direction at application time across application days and experimental runs.

Table 3. Interaction of collection timing and herbicide formulation averaged over seasons on triclopyr vapor concentration

Collection timing (HAA) [a]	Herbicide formulation	g ae m^{-3} of air [b]	
0-24	Triclopyr amine	$8.3\ 10^{-9}$	a
	Triclopyr choline	$6.4\ 10^{-9}$	b
24-48	Triclopyr amine	$1.1\ 10^{-9}$	c
	Triclopyr choline	$0.9\ 10^{-9}$	c

[a] HAA: Hours after application

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$.

Table 4. Interaction of collection timing and season averaged over herbicide formulations on triclopyr vapor concentration

Collection timing (HAA) [a]	Season	g ae m^{-3} of air [b]	
0-24	Winter	$5.3\ 10^{-9}$	b
	Spring	$9.3\ 10^{-9}$	a
	Summer	$10.4\ 10^{-9}$	a
	Fall	$4.3\ 10^{-9}$	b
24-48	Winter	$0.6\ 10^{-9}$	c
	Spring	$1.6\ 10^{-9}$	c
	Summer	$1.6\ 10^{-9}$	c
	Fall	$0.1\ 10^{-9}$	c

[a] HAA: Hours after application

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$.

Table 5. Main effect of nozzle type averaged over herbicide formulations and drift distances on triclopyr vapor concentration

Nozzle type	g ae m^{-3} of air [a]	
Boominator	$4.4\ 10^{-9}$	a
Nutating	$3.9\ 10^{-9}$	a

[a] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$.

Table 6. Main effect of distance averaged over herbicide formulations and nozzle types on triclopyr particle deposit

Distance (m)	g ae ha^{-1} [a]		% of field rate [b]
0.8	42.8	a	1.3 %
1.5	5.6	b	0.2 %
3.0	0.2	b	0.006 %
6.0	0.0	b	0.0 %
12.0	0.0	b	0.0 %

[a] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$.
[b] Field application rate: 3363 g ae ha^{-1}

Table 7. Main effect of herbicide formulation averaged over distances and nozzle types on triclopyr particle deposit

Herbicide formulation	g ae ha^{-1} [a]		% of field rate [b]
Triclopyr amine	10.0	a	0.3 %
Triclopyr choline	9.4	a	0.3 %

[a] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$.

[b] Field application rate: 3363 g ae ha^{-1}

Table 8. Main effect of nozzle type averaged over distances and herbicide formulations on triclopyr particle deposit

Nozzle type	g ae ha^{-1} [a]		% of field rate [b]
Boominator	10.7	a	0.3%
Nutating	8.8	a	0.3%

[a] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$.

[b] Field application rate: 3363 g ae ha^{-1}

Findings and Conclusions

The findings of this study underscore the importance of understanding vapor and particle drift dynamics to effectively mitigate herbicide vapor and particle drift risk in roadside settings. Herbicide formulation and weather conditions, particularly within the first 24 h post-application, were primary factors affecting triclopyr vapor concentration in the air. Consequently, opting for lower vapor pressure formulations and considering alternative approaches, such as mechanical methods, during warmer seasons are recommended strategies to mitigate vapor drift risk. Moreover, very low amounts of triclopyr particle deposits were detected at short distances from the application zone under varying wind direction and speed conditions. Both Boominator and Nutating nozzles, classified as low-drift nozzle types, produce a reduced amount of driftable fines. Thus, nozzle selection is critical for mitigating particle drift. Moreover, given that agricultural lands commonly align parallel to roads, some applications along roadsides may inadvertently be directed towards these lands. In roadside systems, adjusting the application based on wind direction poses challenges since application vehicles are usually limited to roadways. Additionally, road-induced turbulence can unpredictably alter particle and vapor trajectory. Therefore, the establishment of buffer zones is a crucial strategy for safeguarding nearby sensitive crop species.

Recommendations

To mitigate herbicide vapor and particle drift risks in roadside applications, it is recommended to prioritize formulations with lower vapor pressures, such as triclopyr choline, particularly during warmer seasons when volatilization risk is higher. Both Boominator and Nutating nozzles produced minimal driftable fines, indicating that nozzle selection is critical for minimizing particle drift. However, due to the challenges of adjusting application direction in roadside systems and unpredictable turbulence caused by traffic, establishing buffer zones remains essential for protecting nearby sensitive crops.

Implementation and Technology Transfer Plan

To reduce herbicide vapor and particle drift risks along roadsides, prioritize formulations with lower vapor pressures such as triclopyr choline, especially during warmer seasons when volatilization is highest. Utilize low-drift nozzles like Boominator and Nutating to minimize particle drift. Due to challenges in adjusting spray direction in roadside applications and unpredictable turbulence from traffic, establishing buffer zones between treated areas and sensitive crops is essential. Applications should be scheduled during cooler times of the day and under favorable wind conditions to further minimize drift. These findings should be incorporated into pesticide applicator trainings by emphasizing formulation selection, nozzle choice, weather considerations, and buffer zone implementation to ensure safe and compliant roadside applications.

OBJECTIVE 2: Quantifying crop injury and yield

Result of Literature Review

Soybean (*Glycine max*), tobacco (*Nicotiana tabacum*), corn (*Zea mays*), and cotton (*Gossypium hirsutum*) are economically important crops in North Carolina. Soybean is the state's largest crop by planted area, with approximately 688,000 hectares and an annual production value of $1 billion (USDA, 2022). Tobacco, while planted on a smaller area of about 47,000 hectares, has a significant production value of $524 million, ranking it as the third most valuable crop behind soybean and corn (USDA, 2022). Corn and cotton are also major commodities, with corn and cotton covering approximately 385,000 and 154,000 hectares, respectively, and generating a combined revenue of $1 billion (USDA, 2024). The diverse climate and geography of North Carolina support the cultivation of these crops (Moore, 2020). However, these species are susceptible to injury and yield loss from herbicide drift. Studies have reported severe damage to soybean and tobacco from exposure to sub-lethal herbicide doses (Jeffries et al., 2014; Lewis et al., 2011; Burke et al., 2005; Ellis & Griffin, 2002; Al-Khatib & Peterson, 1999), while corn and cotton have also shown high sensitivity to certain herbicides. For example, Felisberto et al. (2007) documented corn yield losses ranging from 25% to 100% following exposure to sulfometuron at only 3% to 12% of the field rate during vegetative growth stages. In cotton, Jeffries et al. (2017) observed 30% injury from indaziflam at 5% of the field rate, and Egan et al. (2014) reported cotton yield losses of up to 49% and 33% when exposed to 2,4-D drift during vegetative and pre-flowering squaring stages, respectively. Additionally, Marple et al. (2007) noted up to 40% injury in pre-flowering cotton sprayed with triclopyr at 1% of the field rate.

Spray drift, defined as the unintended airborne movement of herbicide particles from the target surface to other areas during or shortly after application, is a primary cause of off-target injury (Bish et al., 2021; Klein et al., 2008). Drift can occur via particle drift or vapor drift, with particle drift influenced by factors such as droplet size, spray pressure, wind speed and direction, and equipment type (Mueller, 2015; Butts et al., 2018; Al Heidary et al., 2014). Vapor drift, or volatilization, is affected by herbicide vapor pressure, temperature, relative humidity, and target surface characteristics (Carbonari et al., 2020). Although drift is commonly associated with agricultural spray applications, it can also originate from lawn care, aquatic, forest, industrial, and roadside applications. This is of particular concern in North Carolina, where the Department of Transportation (NCDOT) manages over 130,000 km of roads, making it the second-largest state-maintained highway system in the United States (NCDOT, 2022). To manage roadside vegetation effectively and safely, NCDOT employs integrated methods, including herbicide use, which remains a primary tool due to its efficacy and practicality (Pellegrini et al., 2016).

NCDOT utilizes herbicides with varying modes of action depending on season and target vegetation, such as sulfometuron-methyl (ALS inhibitor, Group 2) for pre- and post-emergence control of broadleaf and grass weeds (BAYER, 2024a; Zahnow, 1985); triclopyr, clopyralid, and 2,4-D + dichlorprop (synthetic auxins, Group 4) for post-emergence broadleaf control (Todd et al., 2020; Solomon & Bradley, 2014); and indaziflam (cellulose biosynthesis inhibitor, Group 29) for pre-emergence control of broadleaf and grass species (BAYER, 2024b; Courkamp et al., 2022; Sebastian et al., 2017). To reduce drift risk, NCDOT employs low-drift nozzles, such as ultra coarse and multiple stream nozzles, which generate fewer fine droplets prone to drift

(Kruger et al., 2019). Equipment is calibrated to label recommendations; however, drift remains a challenge due to environmental factors, application timing, and unique roadside conditions. Vehicle-induced turbulence can increase drift by dispersing droplets further, accelerating evaporation, and altering spray trajectory (Belkacem et al., 2020; Shi et al., 2020; Dixon et al., 2006; Cape et al., 2004).

In North Carolina, the growing seasons for soybean, tobacco, corn, and cotton generally extend from April through October, a period when these crops are most susceptible to drift of post-emergence herbicides, though pre-emergence herbicide drift can also affect subsequent crop cycles. Given the extensive use of both pre- and post-emergence herbicides in roadside programs, including products with long residual activity, it is important to understand potential off-target impacts. Therefore, the objective of this research was to investigate the response of soybean, tobacco, corn, and cotton to simulated spray drift of commonly used roadside herbicides applied at six different timings, including pre-, at-, and post-planting.

Materials and Methods

Field studies for soybean and tobacco were conducted from January to October of 2022 and 2023 at the Sandhills Research Station in Jackson Springs, NC (35°11'25"N 79°33'01"W), on a Candor sand soil (pH 5.8, organic matter 0.66%) (Fisk et al., 2018). Soybean (AG69XFO, Bayer) was planted at 33 seeds m^{-1} and 2.5 cm depth on May 18, 2022, and May 19, 2023. Experimental plots measured 3 x 5 m with four rows spaced 1 m apart; two central rows were treated, border rows served as buffers, and 1 x 2 m alleys separated plots. Tobacco (NC196) transplants from Ahoskie, NC were planted on the same days at 0.6 m spacing and 6 cm depth in 2 x 5 m plots consisting of one treated row and one border row, spaced 1 m apart with similar alleys. Fields were maintained weed-free and irrigated as needed.

Field studies for corn and cotton were conducted in 2022 and 2023 at the Upper Coastal Plain Research Station in Rocky Mount, NC (35°53'33"N 77°44'20"W), on Norfolk sandy loam soil (pH 6.1, organic matter 1.8%) (York et al., 2005). Glufosinate-glyphosate resistant corn (DKC62-08, Bayer) was planted at 7 seeds m^{-1} and 5 cm depth, and cotton (ST4550GLTP, BASF) at 13 seeds m^{-1} and 1.3 cm depth, on May 19, 2022, and May 20, 2023. Experimental plots measured 3.7 x 7.6 m with four rows spaced 0.9 m apart; two central rows were treated, border rows served as buffers, and 2 m alleys separated plots. Fields were maintained weed-free without irrigation.

Field studies at both locations were organized as strip-plot designs in a randomized complete block design (RCBD) with three replications and two experimental runs per crop. For all crops, strip-plots comprised six application timings: 18, 12, and 6 weeks before planting, at planting, and 4 and 8 weeks after planting. Sub-plots were a two-level factorial of five herbicides [sulfometuron-methyl, triclopyr, triclopyr + clopyralid, 2,4-D + dichlorprop, and indaziflam] at four rates (0.01x, 0.05x, 0.1x, and 1x of the field rate) (Table 9). Untreated controls were included within each block and application timing for comparison.

Herbicide applications were conducted using a CO_2-pressurized backpack sprayer with a 3-nozzle boom. For sulfometuron-methyl, triclopyr + clopyralid, and indaziflam, DG80015 nozzles were used to deliver 140 L ha^{-1} at 138 PSI. For triclopyr and 2,4-D + dichlorprop, XR8006 nozzles delivered 935 L ha^{-1} at 145 PSI. Carrier volumes followed the North Carolina Department of Transportation (NCDOT) recommendations.

Visual estimations of crop injury and plant height were recorded 12 weeks after planting (WAP) for all crops by assessing three arbitrary plants within treated rows. Plant height data were converted to percent height reduction (HR) relative to untreated controls using Equation (1):

$$HR = 100 - \frac{(X*100)}{Y} \qquad (1)$$

Where HR is the height reduction (%), X is the height (cm) of an individual experimental unit after being treated, and Y is the mean height (cm) of the untreated control replicates.

Soybean was harvested on October 28, 2022, and October 29, 2023; corn on September 27, 2022, and September 29, 2023; and cotton on October 11, 2022, and October 12, 2023. Yield data were recorded and converted to percent yield loss (YL) relative to untreated controls using Equation (2):

$$YL = 100 - \frac{(X*100)}{Y} \qquad (2)$$

Where YL is the yield loss (%), X is the yield of an individual experimental unit after being treated, and Y is the mean yield (kg ha^{-1}) of the untreated control replicates.

Tobacco was harvested on August 17, 2022, and August 19, 2023. Three arbitrary plants per treated row were cut above the soil surface, fresh biomass was recorded, and dry biomass was estimated by multiplying by 85% (Mason et al., 2018; Vann et al., 2017). Biomass reduction (BR) was calculated relative to untreated controls using Equation (3):

$$BR = 100 - \frac{(X*100)}{Y} \qquad (3)$$

Where BR is the biomass reduction (%), X is the biomass (g) of an individual experimental unit after being treated, and Y is the mean biomass (g) of the untreated control replicates.

Data were subjected to analysis of variance (ANOVA) in SAS version 9.4 using PROC GLIMMIX, with treatment means compared via Tukey's Honest Significant Difference (HSD) test at α=0.05. Treatments were considered fixed effects, and experimental runs and replications were treated as random effects.

Results

The three-way interaction of herbicide, rate, and application timing was significant at α=0.05 for visual estimation of injury, height reduction, and yield loss or biomass reduction. However, to facilitate data interpretation, results are presented through the two-way interactions between those factors.

Soybean

Indaziflam caused the highest injury (26-35%) and height reduction (20-28%) in pre-planting application timings (18 to 6 WBP) (Table 10). However, the greatest injury and height reduction at planting (0 WBP) were observed with sulfometuron-methyl, 39% and 28%, respectively. For post-planting application timings (4 WAP and 8 WAP), triclopyr resulted in the highest injury and height reduction, 79% and 72%, respectively. Additionally, except for sulfometuron-methyl and indaziflam, herbicides caused greater injury when applied post-planting compared to pre- or at planting.

Regarding yield loss, sulfometuron-methyl and indaziflam caused the greatest reduction in pre- and at planting application timings, with losses ranging from 20% to 29% for sulfometuron-methyl and from 24% to 33% for indaziflam (Table 10). For post-planting application timings, the highest yield loss was observed with triclopyr (78%), followed by triclopyr + clopyralid (45%) and 2,4-D + dichlorprop (34%). Furthermore, sulfometuron-methyl caused similar yield loss across all application timings (20-29%). In contrast, the other herbicides caused higher yield losses when applied either pre- and at planting (indaziflam) or post-planting (triclopyr + clopyralid , triclopyr , and 2,4-D + dichlorprop).

Herbicide x Rate

Injury mostly increased as the rate increased for all herbicides (Table 11). However, while this trend held true for height reduction and yield loss in most cases, there were exceptions. For instance, no differences in height reduction (5%) and yield loss (3-9%) were observed between 0.05x and 0.1x rates for 2,4-D + dichlorprop.

Rate x Application Time

Regardless of rate, injury, height reduction, and yield loss were generally higher in the post-planting timings compared to at and pre-planting application timings (Table 12). Moreover, differences between the smallest rates (0.01x, 0.05x, and 0.1x) were more pronounced in the post-application timings. For example, there were no differences in injury, height reduction, and yield loss between 0.01x, 0.05x, and 0.1x rates at 18 WBP. However, while at 4 WAP and 8 WAP, differences were observed between these rates.

Tobacco

Herbicide x Application Timing

The highest injury was caused by sulfometuron-methyl in pre-planting application timings, with values ranging from 16% to 22%, while at planting, sulfometuron-methyl and triclopyr caused the highest injury, 40% and 38%, respectively (Table 13). However, in post-planting application timings, the highest injuries were observed with triclopyr (69-76%) and 2,4-D + dichlorprop (44-53%). Overall, all herbicides resulted in greater injury when applied at and post-planting, with low injury of $\leq$ 21% observed with indaziflam across application timings.

Sulfometuron-methyl, triclopyr + clopyralid, and 2,4-D + dichlorprop caused the greatest height reductions in pre-planting application timings, with values ranging from 4% to 14% (Table 13). Additionally, sulfometuron-methyl reduced height by 21% at planting. Height reductions were more pronounced when herbicides were applied post-planting compared to at or pre-planting. For instance, the average height reduction for triclopyr and 2,4-D + dichlorprop was 6% across pre- and at planting applications timings, compared to 49% and 47%, respectively, at 4 WAP. Low height reductions of ≤ 10% were observed with indaziflam across application timings.

The greatest biomass reductions in pre-planting application timings were observed with sulfometuron-methyl, triclopyr + clopyralid, triclopyr, and 2,4-D + dichlorprop (Table 13). Sulfometuron-methyl was the only herbicide that consistently promoted the highest biomass reduction from 18 to 6 WBP, with values ranging from 14% to 21%. At planting, sulfometuron-methyl continued to cause the greatest biomass reduction (37%), while triclopyr (58-79%) and 2,4-D + dichlorprop (62-37%) promoted the greatest biomass reductions in post-planting application timings. Additionally, indaziflam resulted in a biomass reduction of ≤ 18% across application timings.

Herbicide x Rate

Overall, higher rates led to increased injury, yield loss, and biomass reduction (Table 14). However, in several cases, differences between rates were not observed. For instance, sulfometuron-methyl at 0.01x and 0.05x rates caused similar injuries of 18% and 20%, respectively. Moreover, similar height reductions of 10% and 11% were observed with 2,4-D + dichlorprop at 0.1x and 0.05x rates. Furthermore, no differences in biomass reduction were observed with indaziflam across rates.

Rate x Application Time

Injury was generally higher in the post-planting application timings compared to the at and pre-planting application timings (Table 15). While height and biomass reduction presented a similar tendency, in some cases, values were comparable to at or pre-planting application timings. For example, height and biomass reduction did not differ between 0 WBP and 4 WAP at 1x rate. Additionally, differences between the smallest rates (0.01x, 0.05x, and 0.1x) within application timings were more pronounced in the latest application timings.

Corn

The three-way interaction of herbicide, rate, and application timing was significant at $\alpha=0.05$ for visual estimation of injury, height reduction, and yield loss. However, to facilitate interpretation, results are presented through the two-way interactions between these factors.

Herbicide x Application Timing

Sulfometuron-methyl resulted in the highest levels of injury across all application timings, except at 8 weeks after planting (Table 16). For pre-planting applications, injury ranged from 14% to 23% with sulfometuron-methyl, followed by indaziflam (6% to 10%), while synthetic auxin herbicides caused minimal injury (0% to 2%). At planting, sulfometuron-methyl caused 50% injury, higher than triclopyr (11%), 2,4-D + dichlorprop (9%), indaziflam (9%), and triclopyr + clopyralid (0%). At 4 weeks after planting, injury from sulfometuron-methyl increased to 70%, followed by triclopyr (29%) and 2,4-D + dichlorprop (14%). However, at 8 weeks after planting, injury across all herbicides was notably low, at or below 8%, with 2,4-D + dichlorprop and indaziflam resulting in only 1% injury.

Height reduction followed a pattern similar to injury, with sulfometuron-methyl causing the highest reduction across most application timings. When applied pre-planting, this herbicide reduced height by 7% to 11%, while other herbicides reduced height by no more than 3%. At 0 planting and 4 after planting, height reduction from sulfometuron-methyl reached 32% and 49%, respectively, while other herbicides did not exceed 12%. At 8 weeks after planting, height reduction was low or absent across herbicides.

In terms of yield loss, sulfometuron-methyl consistently resulted in the highest losses across application timings. At 18 and 12 weeks before planting, this herbicide led to 31% and 32% yield loss, respectively, with other herbicides ranging from 0% to 12%. At 6 weeks before planting, sulfometuron-methyl further reduced yield by 44%, followed by indaziflam (24%), triclopyr + clopyralid (18%), 2,4-D + dichlorprop (16%), and triclopyr (8%). At planting, yield losses from triclopyr, indaziflam, 2,4-D + dichlorprop, and triclopyr + clopyralid increased (32%, 26%, 20%, and 15%, respectively). At 4 weeks after planting, yield loss from sulfometuron-methyl reached 76%, followed by triclopyr (61%), triclopyr + clopyralid and 2,4-D + dichlorprop (29%), and then indaziflam (13%). Lastly, at 8 weeks after planting, sulfometuron-methyl still exhibited the highest yield loss (51%), followed by triclopyr (33%), triclopyr + clopyralid (20%), 2,4-D + dichlorprop (21%), and indaziflam (20%).

Herbicide x Rate

Sulfometuron-methyl resulted in the highest injury, height reduction, and yield loss across all application rates (Table 17). Generally, increased sulfometuron-methyl rates correlated with increased injury, plant reduction, and yield loss. For instance, at 0.01x rate, sulfometuron-methyl resulted in 8% injury, 3% height reduction, and 20% yield loss. In contrast, at 1x rate, these values increased to 64%, 42%, and 84%, respectively. For triclopyr, triclopyr + clopyralid, 2,4-D + dichlorprop, and indaziflam, differences in injury and height reduction across rates were less pronounced. At 0.01x, 0.05x, and 0.1x rates, these herbicides exhibited minimal injury and height reduction, with injury ranging from 0% to 5% and height reductions from 0% to 4%. However, even at the lowest rates, yield losses were observed, with triclopyr + clopyralid ranging from 9% to 18%, triclopyr alone from 7% to 44%, 2,4-D + dichlorprop from 11% to 29%, and indaziflam from 9% to 39%.

Rate x Application Timing

The highest levels of injury, plant height reduction, and yield loss were recorded at the full dose (1x) across all application timings (Table 18). Notably, except at planting and 4 weeks after planting, no differences in injury were observed among the lowest application rates (0.01x, 0.05x, and 0.1x), with values ranging from 0% to 3%. Similarly, height reduction did not differ among these application rates, except at 6 weeks after planting, planting, and 4 weeks after planting, where reductions ranged from 0% to 9%. However, differences in yield loss among the lowest rates were observed at all application timings, except at 18 weeks before planting.

Cotton

The three-way interaction of herbicide, rate, and application timing was significant at α=0.05 for visual estimation of injury and height reduction. However, to facilitate data interpretation, results are presented through the two-way interactions between these factors. For yield loss, only the two-way interaction of herbicide and application timing and the main effect of rate were significant at α=0.05.

Herbicide x Application Timing

Pre-planting applications resulted in minimal injury overall. Among herbicides, sulfometuron-methyl was the most damaging, with 8% to 10% injury, while other herbicides caused minimal injury (≤ 4%) (Table 19). At planting, sulfometuron-methyl and triclopyr caused the highest injury (23% and 21%, respectively), followed by 2,4-D + dichlorprop (20%), indaziflam (7%), and triclopyr + clopyralid (2%). Furthermore, high injury occurred with post-planting applications, especially four weeks after planting, where 2,4-D + dichlorprop and triclopyr resulted in 81% and 52% injury, compared to sulfometuron-methyl (31%), triclopyr + clopyralid (24%), and indaziflam (17%). At 8 weeks after planting, injury remained highest with 2,4-D + dichlorprop (48%) and triclopyr (45%). Similarly to injury, minimal height reductions were observed with pre-planting applications. Sulfometuron-methyl was again the most harmful, with a reduction ranging from 1% to 7%. At planting, this herbicide led to 16% height reduction, followed by 2,4-D + dichlorprop (13%) and triclopyr (11%), with no reductions for triclopyr + clopyralid and indaziflam. Post-planting application, particularly at 4 weeks after planting, resulted in high height reduction. As with injury, 2,4-D + dichlorprop and triclopyr also caused the greatest height reduction.

Yield loss was minimal (≤ 7%) across herbicides at 18 and 12 weeks before planting, except for sulfometuron-methyl at 12 weeks before planting. At 6 weeks before planting, herbicides caused similar yield losses (11% to 16%). At planting, 2,4-D + dichlorprop caused the highest yield loss (21%), followed by triclopyr + clopyralid (17%), triclopyr (11%), indaziflam (11%), and sulfometuron-methyl (8%). Post-planting applications resulted in further increases in yield loss, consistent with their effects on injury and height reduction. At 4 weeks after planting, 2,4-D + dichlorprop caused the greatest yield loss (54%), followed by triclopyr (33%), triclopyr + clopyralid (30%), sulfometuron-methyl (24%), and lastly indaziflam (8%). At 8 weeks after planting, the yield loss with indaziflam increased to 41%. However, synthetic auxin herbicides continued to cause the highest yield losses at this timing, ranging from 44% to 50%.

Herbicide x Rate

Application rates as low as 0.01x led to injury (Table 20). Among herbicides, 2,4-D + dichlorprop and triclopyr caused the most damage across 0.01x, 0.05x, and 0.1x rates. At 0.01x rate, this herbicide resulted in 18% of injury, while other herbicides caused 7% or less. At 0.05x rate, 2,4-D + dichlorprop led to 19% injury, followed by triclopyr (15%), indaziflam (9%), sulfometuron-methyl (7%), and triclopyr + clopyralid (3%). At 0.1x rate, 2,4-D + dichlorprop remained the most damaging, causing 24% injury, followed by triclopyr (20%), sulfometuron-methyl (13%), indaziflam (7%), and triclopyr-clopyralid (3%). However, at full rate, triclopyr caused the highest injury (45%), closely followed by 2,4-D + dichlorprop (42%), sulfometuron-methyl (35%), triclopyr + clopyralid (19%), and indaziflam (14%).

Height reductions were observed at rates as low as 0.01x, except for triclopyr + clopyralid. At both 0.01x and 0.05x rates, minimal height reductions (0% to 5%) were observed across herbicides. At 0.1x rate, both 2,4-D + dichlorprop and triclopyr caused the highest height reduction (11%), followed by sulfometuron-methyl (8%), triclopyr + clopyralid (2%), with no reduction observed with indaziflam. At 0.1 x rate, triclopyr, 2,4-D + dichlorprop, and sulfometuron-methyl caused the greatest height reductions (26% to 30%), followed by triclopyr + clopyralid (11%), and lastly, indaziflam (2%).

Rate

Yield losses were similar between 0.01x and 0.05x, with both resulting in 7% yield loss (Table 21). However, yield loss increased at the 0.1x and 1x rates, reaching 13% and 35%, respectively.

Application Timing x Rate

The full dose consistently caused the highest injury across application timings (Table 22). Pre-planting applications led to minimal injury at the lower rates, ranging from 1% to 3%, compared to 7% to 11% at 1x rate. At planting, 1x rate caused 38% injury, followed by 10% at 0.1x, 6% at 0.05x, and only 3% at 0.01x. Post-planting applications resulted in greater injury, especially 4 weeks after planting, where 1x rate caused 66% injury, followed by 28% at 0.1x, 20% at 0.05x, and 22% at 0.01x. At 8 weeks after planting, injuries ranged from 11% to 54%. For height reduction, pre-planting applications led to minimal reductions, 0% to 4%, across rates. At 0 WAP, only 1x rate caused a notable 28% reduction, with all other rates resulting in reductions of 2% or less. Consistent with injury levels, height reductions increased post-planting, especially at 4 weeks after planting, where 1x rate reduced height by 56%, followed by 25% at 0.1x, 19% at 0.05x, and 9% at 0.01x. At 8 weeks after planting, height reductions ranged from 7% to 27% across rates.

Table 9. Herbicide treatment information

Herbicide	Commercial Name	Field Rate	SOA Group [d]	Timing [d]	Field Half-life [e]
		g ai ha^{-1}			days
Sulfometuron-methyl	Oust® XP [a]	78	2	PRE + POST	20-28
Triclopyr + clopyralid	Confront® [b]	378 + 126	4	POST	20-28	40
Triclopyr	Garlon® 4 [b]	8967	4	POST	30
2,4-D + dichlorprop	Patron® 170 [c]	1917 + 975	4	POST	6	10
Indaziflam	Esplanade® 200 SC [a]	103	29	PRE	> 150

[a] Bayer Environmental Science, Cary, NC
[b] Corteva Agriscience, Indianapolis, IN
[c] Nufarm Americas, Inc., Alsip, IL
[d] Abbreviation: SOA (site-of-action), PRE (pre-emergence) and POST (post-emergence).
[e] Information retrieved from the Herbicide Handbook (Weed Science Society of America), Tenth Edition (2014).

Table 10. Effect of the interaction between herbicide and application timing averaged over rate on injury, height reduction, and yield loss of soybean at 84 days after planting [a,b]

Application Timing [c]	Sulfometuron-methyl	Triclopyr + clopyralid	Triclopyr	2,4-D + dichlorprop	Indaziflam
			Injury (%)		
18WBP	14 D b	5 D c	4 D c	3 C c	26 C a
12WBP	17 CD b	5 D c	4 D c	4 BC c	30 B a
6WBP	19 C b	15 C c	10 C d	7 B e	35 A a
0WBP	39 A a	16 C d	29 B c	6 BC e	32 AB b
4WAP	33 B c	54 A b	78 A a	35 A c	21 D d
8 WAP	36 AB c	49 B b	81 A a	32 A d	23 CD e
			Height Reduction (%)		
18WBP	10 C b	5 D c	4 C c	6 C c	20 B a
12WBP	10 C b	0 E c	2 C c	0 D c	25 A a
6WBP	10 C b	5 CD c	3 C cd	1 D d	28 A a
0WBP	28 A a	9 C c	23 B b	3 CD d	28 A a
4WAP	23 B d	47 A b	72 A a	32 A c	10 C e
8 WAP	23 B c	36 B b	71 A a	26 B c	9 C d
			Yield Loss (%)		
18WBP	21 A b	14 B c	12 BC c	12 B d	33 A a
12WBP	20 A a	4 B b	5 C b	5 B b	24 Ab a
6WBP	20 A ab	16 B b	2 C c	2 B c	24 AB a
0WBP	29 A a	1 B c	23 B b	23 B c	25 Ab ab
4WAP	21 A d	48 A b	80 A a	80 A a	14 B e
8 WAP	29 A c	42 A b	76 A a	76 A	5 C d

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Uppercase letters represent mean comparison of the main effect of application timing within columns and lowercase letters the main effect of herbicide within rows.

[c] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

Table 11. Effect of the interaction between herbicide and rate averaged over application timing on injury, height reduction, and yield loss of soybean at 84 days after planting [a,b]

Rate [c]	Sulfometuron-methyl	Triclopyr + Clopyralid	Triclopyr	2,4-D + dichlorprop	Indaziflam
			Injury (%)		
0.01x	6 D c	8 D b	13 D a	4 D c	5 D c
0.05x	12 C c	17 C b	32 C a	8 C c	9 C c
0.1x	26 B b	24 B b	36 B a	10 B d	16 B c
1x	62 A b	47 A d	56 A c	37 A e	82 A a
			Height Reduction (%)		
0.01x	2 D bc	4 D b	8 D a	2 C bc	1 C c
0.05x	8 C bc	11 C b	26 C a	5 B c	3 C c
0.1x	14 B b	13 B b	32 B a	5 B c	8 B c
1x	44 A c	39 A d	51 A b	32 A e	69 A a
			Yield Loss (%)		
0.01x	3 D b	2 D b	11 C a	0 C b	1 C b
0.05x	9 C bc	14 C b	32 B a	3 B cd	0 C d
0.1x	22 B b	19 B b	36 B a	9 B c	8 B c
1x	60 A b	49 A c	53 A c	33 A d	74 A a

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of rate practice within columns, and lowercase letters represent the main effect of herbicide within rows.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1}).

Table 12. Effect of the interaction between rate and application timing averaged over herbicide on injury, height reduction, and yield loss of soybean at 84 days after planting. [a,b,c]

Application Timing [d]	0.01x	0.05x	0.1x	1x
		Injury (%)		
18WBP	3 B b	3 C b	4 D b	31 E a
12WBP	4 B c	5 C c	8 C b	32 E a
6WBP	6 B c	8 BC c	13 B b	42 D a
0WBP	4 B d	10 B c	16 B b	68 C a
4WAP	11 A d	32 A c	46 A b	88 A a
8 WAP	15 A d	35 A c	47 A b	80 B a
		Height Reduction (%)		
18WBP	5 A b	3 BC b	4 C b	21 E a
12WBP	-2 B c	1 C b	4 C b	23 E a
6WBP	-1 B c	1 C c	4 C b	31 D a
0WBP	0 B c	5 B b	5 C b	60 C a
4WAP	6 A d	23 A c	36 A b	80 A a
8 WAP	9 A d	27 A c	31 B b	64 B a
		Yield Loss (%)		
18WBP	14 A b	14 AB b	13 B b	33 C a
12WBP	4 A c	-1 B c	12 B b	27 C a
6WBP	0 A c	6 B b	4 B bc	35 C a
0WBP	-3 B c	-5 B c	6 B b	62 B a
4WAP	-5 B d	28 A c	42 A b	91 A a
8 WAP	9 A d	30 A c	37 A b	76 AB a

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of application timing practice within columns, and lowercase letters represent the main effect of rate within rows.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1}).

[d] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

Table 13. Effect of the interaction between herbicide and application timing averaged over rate on injury, height reduction, and biomass reduction of tobacco at 84 days after planting [a,b]

Application Timing [c]	Sulfometuron-methyl		Triclopyr + clopyralid		Triclopyr		2,4-D + dichlorprop		Indaziflam	
					Injury (%)					
18WBP	22	B a	8	C c	13	DE b	9	D c	12	BC bc
12WBP	24	B a	14	B c	16	D b	17	C b	14	B c
6WBP	16	C a	12	C b	11	E bc	10	D bc	8	C c
0WBP	40	A a	17	B b	38	C a	19	C b	11	BC c
4WAP	40	A c	33	A d	76	A a	53	A b	14	B e
8 WAP	39	A c	33	A d	69	B a	44	B b	21	A e
					Height Reduction (%)					
18WBP	14	C a	1	C c	4	D b	4	C b	2	B bc
12WBP	4	E b	7	B a	2	D b	4	C ab	3	B b
6WBP	8	D a	5	B b	6	D ab	4	C b	3	B b
0WBP	21	B a	5	B c	12	C b	11	B b	6	B c
4WAP	25	A c	19	A d	49	A a	35	A b	10	A e
8 WAP	7	DE c	4	BC d	27	B a	13	B b	7	AB cd
					Biomass reduction (%)					
18WBP	19	B a	5	B c	10	D bc	15	C ab	13	AB b
12WBP	21	B a	15	B b	14	D b	11	C b	16	AB b
6WBP	14	B ab	17	AB a	13	D ab	14	C ab	9	AB b
0WBP	37	A a	14	B c	30	C b	11	C c	4	B d
4WAP	33	A c	26	A d	79	A a	62	A b	7	B e
8 WAP	31	AB c	17	AB d	58	B a	37	B b	18	A e

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letter represent mean comparison of the main effect of application timing within columns and lowercase letters the main effect of herbicide within rows.

[c] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

Table 14. Effect of the interaction between herbicide and rate averaged over application timings on injury, height reduction, and biomass reduction of tobacco at 84 days after planting [a,b]

Rate [c]	Sulfometuron-methyl	Triclopyr + clopyralid	Triclopyr	2,4-D + dichlorprop	Indaziflam
			Injury (%)		
0.01x	18 C b	10 C c	23 D a	12 C c	12 B c
0.05x	20 C c	13 C d	34 C a	25 B b	13 B d
0.1x	25 B b	19 B c	38 B a	25 B b	11 B d
1x	58 A a	35 A c	54 A b	38 A c	17 A d
			Height Reduction (%)		
0.01x	4 C ab	2 D b	6 D a	5 C a	4 A ab
0.05x	6 BC b	6 C b	12 C a	11 B a	6 A b
0.1x	7 B bc	9 A b	17 B a	10 B b	5 A c
1x	35 A a	11 A d	32 A b	20 A c	7 A e
			Biomass reduction (%)		
0.01x	20 B a	7 C b	19 C a	8 C b	10 A b
0.05x	15 B b	9 C c	32 B a	28 B a	12 A bc
0.1x	16 B c	19 B bc	32 B a	24 B b	11 A c
1x	54 A a	29 A c	54 A a	40 A b	11 A d

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at α = 0.05. Uppercase letters represent mean comparison of the main effect of rate practice within columns, and lowercase letters the main effect of herbicide within rows.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1}).

Table 15. Effect of the interaction between rate and application timing averaged over herbicides on injury, height reduction, and biomass reduction of tobacco at 84 days after planting [a,b,c]

Application Timing [d]	0.01x	0.05x	0.1x	1x
			Injury (%)	
18WBP	9 B b	12 C b	11 C b	19 D a
12WBP	13 B b	19 B a	18 B a	17 D a
6WBP	9 B b	7 D b	9 C b	20 D a
0WBP	14 B c	15 BC c	23 B b	49 C a
4WAP	22 A c	37 A b	39 A b	74 A a
8 WAP	22 A d	36 A c	42 A b	65 B a
			Height Reduction (%)	
18WBP	1 C c	5 CD b	2 C bc	12 C a
12WBP	1 C b	5 CD a	6 C a	4 D a
6WBP	5 B b	2 D c	3 C bc	11 C a
0WBP	2 BC d	6 C c	11 B b	25 B a
4WAP	12 A d	21 A c	28 A b	49 A a
8 WAP	3 BC c	10 B b	9 B b	25 B a
			Biomass reduction (%)	
18WBP	5 B b	13 BC a	17 B a	14 C a
12WBP	13 AB b	19 B a	12 B b	18 C ab
6WBP	13 AB b	7 C c	15 B ab	20 C a
0WBP	8 B b	10 BC b	9 B b	49 B a
4WAP	22 A c	36 A b	39 A b	67 A a
8 WAP	20 AB c	29 AB b	30 A b	53 B a

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Sandhills Research Station in Jackson Springs, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent the mean comparison of the main effect of application timing practice within columns, and lowercase letters the main effect of rate within rows.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1}).

[d] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

Table 16. Effect of the interaction between herbicide and application timing averaged over rate on injury, height reduction, and yield loss of corn at 84 days after planting [a,b]

Application Timing [c]	Sulfometuron-methyl	Triclopyr + clopyralid	Triclopyr	2,4-D + dichlorprop	Indaziflam
			Injury (%)		
18WBP	14 E a	1 B c	0 D c	1 C c	10 A b
12WBP	18 D a	2 B c	0 D c	1 C c	5 B b
6WBP	23 C a	0 B c	0 D c	0 C c	6 B b
0WBP	50 B a	0 B	11 B b	9 B b	9 AB b
4WAP	70 A a	7 A d	29 A b	14 A c	8 AB d
8 WAP	8 F a	3 B b	7 C a	1 C b	1 C b
			Height Reduction (%)		
18WBP	7 D a	0 A c	1 B bc	2 C bc	3 AB b
12WBP	11 C a	1 A b	0 B b	0 C b	0 B b
6WBP	10 CD a	2 A c	1 B c	2 C c	7 A b
0WBP	32 B a	0 A d	7 A b	5 B bc	3 B c
4WAP	49 A a	0 A d	5 AB c	12 A b	0 B d
8 WAP	1 E a	0 A a	0 B a	1 C a	0 B a
			Yield Loss (%)		
18WBP	31 C a	0 B c	4 C c	5 B c	13 A b
12WBP	32 C a	9 B b	1 C c	12 AB b	13 A b
6WBP	44 BC a	18 AB c	8 C d	16 AB c	24 A b
0WBP	70 A a	15 AB d	32 B b	20 AB cd	26 A c
4WAP	76 A a	29 A c	61 A b	29 A c	13 A d
8 WAP	51 B a	20 AB c	33 B b	21 AB c	20 A c

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Upper Coastal Plain Research Station in Rocky Mount, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of application timing within columns, and lowercase letters represent the main effect of herbicide within rows.

[c] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

Table 17. Effect of the interaction between herbicide and rate averaged over application timing on injury, height reduction, and yield loss of corn at 84 days after planting [a,b]

Rate [c]	Sulfometuron-methyl	Triclopyr + Clopyralid	Triclopyr	2,4-D + dichlorprop	Indaziflam
			Injury (%)		
0.01x	8 D a	1 A b	0 B b	3 BC b	2 B b
0.05x	21 C a	2 A bc	4 B b	0 C bc	0 B c
0.1x	28 B a	3 A bc	4 B bc	5 B b	1 B c
1x	64 A a	3 A d	24 A b	10 A c	22 A b
			Height Reduction (%)		
0.01x	3 C a	0 A a	0 B a	1 C a	0 B a
0.05x	13 B a	0 A b	0 B b	0 C b	0 B b
0.1x	16 B a	0 A bc	0 B c	4 B b	0 B c
1x	42 A a	0 A c	12 A b	9 A b	10 A b
			Yield Loss (%)		
0.01x	20 D a	9 B b	7 C b	11 C b	9 B b
0.05x	42 C a	7 B c	23 B b	7 C c	13 B c
0.1x	56 B a	21 A b	19 B b	21 B b	13 B c
1x	84 A a	18 A e	44 A b	29 A d	39 A c

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Upper Coastal Plain Research Station in Rocky Mount, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of rate practice within columns, and lowercase letters represent the main effect of herbicide within rows.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1}).

Table 18. Effect of the interaction between rate and application timing averaged over herbicide on injury, height reduction, and yield loss of corn at 84 days after planting [a,b,c]

Application Timing [d]	0.01x		0.05x		0.1x		1x	
	Injury (%)							
18WBP	0	B b	1	C b	1	C b	19	D a
12WBP	2	B b	0	C b	2	C b	17	D a
6WBP	0	B b	0	C b	1	C b	23	C a
0WBP	3	B c	6	B c	18	B b	36	B a
4WAP	10	A c	23	A b	26	A b	43	A a
8 WAP	3	B b	1	C b	1	C b	11	E a
	Height Reduction (%)							
18WBP	0	A b	1	B b	1	B b	8	C a
12WBP	0	A b	0	B b	1	B b	10	C a
6WBP	0	A c	1	B bc	3	B b	14	B a
0WBP	1	A c	1	B c	9	A b	27	A a
4WAP	0	A c	13	A b	12	A b	26	A a
8 WAP	0	A a	0	B a	0	B a	0	D a
	Yield Loss (%)							
18WBP	2	B b	2	B b	4	B b	32	B a
12WBP	4	AB c	7	B c	14	B b	28	B a
6WBP	9	AB d	16	B c	24	B b	39	B a
0WBP	16	AB c	17	B c	43	A b	54	A a
4WAP	22	A c	40	A b	43	A b	62	A a
8 WAP	20	A c	27	AB b	27	AB b	41	B a

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Upper Coastal Plain Research Station in Rocky Mount, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of application timing practice within columns, and lowercase letters represent the main effect of rate within rows.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1})

[d] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

Table 19. Effect of the interaction between herbicide and application timing averaged over rate on injury, height reduction, and yield loss of cotton at 84 days after planting [a,b]

Application Timing [c]	Sulfometuron-methyl	Triclopyr + clopyralid	Triclopyr	2,4-D + dichlorprop	Indaziflam
			Injury (%)		
18WBP	10 CD a	1 C bc	2 D bc	0 Dc	4 BCb
12WBP	8 D a	2 C bc	4 D b	2 Dbc	0 Cc
6WBP	9 D a	1 C b	4 D b	2 Db	2 Cb
0WBP	23 B a	2 C d	21 C ab	20 Cb	7 Bc
4WAP	31 A c	24 A d	52 A b	81 Aa	17 Ae
8 WAP	13 C d	15 B d	45 B b	48 Ba	19 Ac
			Height Reduction (%)		
18WBP	3 D a	0 B a	0 D b	0 Db	2 BCa
12WBP	1 D a	0 B b	0 D ab	0 Db	0 Cb
6WBP	7 CD a	0 B b	0 D bc	0 Dc	0 Cbc
0WBP	16 B a	0 B d	11 C c	13 Cbc	0 Cd
4WAP	23 A b	15 A c	46 A a	43 Aa	9 Ad
8 WAP	8 C cd	10 A c	22 B b	27 Ba	5 ABd
			Yield Loss (%) [d]		
18WBP	2 D a	1 D a	2 CD a	0 E a	5 B a
12WBP	13 C a	0 D b	0 D b	0 E b	7 B a
6WBP	16 BC a	11 CD a	11 C a	14 D a	14 B a
0WBP	8 CD b	17 C ab	11 C b	21 C a	11 B b
4WAP	24 B c	30 B b	33 B b	54 A a	8 B d
8 WAP	39 A b	44 A ab	50 A a	44 B ab	41 A b

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Upper Coastal Plain Research Station in Rocky Mount, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of application timing within columns, and lowercase letters represent the main effect of herbicide within rows.

[c] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

[d] Lint yield.

Table 20. Effect of the interaction between herbicide and rate averaged over application timing on injury and height reduction of cotton at 84 days after planting [a,b]

Rate [c]	Sulfometuron-methyl		Triclopyr + clopyralid		Triclopyr		2,4-D + dichlorprop		Indaziflam	
					Injury (%)					
0.01x	7	C b	3	B c	4	D bc	18	C a	3	C c
0.05x	7	C cd	4	B d	15	C b	19	C a	9	B c
0.1x	13	B c	3	B e	20	B b	24	B a	7	B d
1x	35	A c	19	A d	45	A a	42	A b	14	A e
					Height Reduction (%)					
0.01x	1	C b	0	B b	2	D b	5	C a	0	B b
0.05x	3	C ab	1	B b	5	C a	4	C ab	2	B ab
0.1x	8	B b	2	B c	11	B a	11	B ab	0	B c
1x	26	A a	11	A b	30	A a	27	A a	5	A c

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Upper Coastal Plain Research Station in Rocky Mount, NC.
[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of rate practice within columns, and lowercase letters the main effect of herbicide within rows.
[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1}).

Table 21. Main effect of rate averaged over herbicide and application timing on yield loss of cotton at 84 days after planting [a,b]

Rate [c]	Yield Loss (%) [d]	
0.01x	7	C
0.05x	7	C
0.1x	13	B
1x	35	A

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Upper Coastal Plain Research Station in Rocky Mount, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1}).

[d] Lint yield.

Table 22. Effect of the interaction between rate and application timing averaged over herbicide on injury and height reduction of cotton at 84 days after planting [a,b,c]

Application Timing [d]	0.01x	0.05x	0.1x	1x
	Injury (%)			
18WBP	2 C b	1 D b	1 D b	10 D a
12WBP	3 C b	1 D b	2 D b	7 D a
6WBP	1 C b	2 D b	1 D b	11 D a
0WBP	3 C c	6 C c	10 C b	38 C a
4WAP	22 A c	36 A b	39 A b	66 A a
8 WAP	11 B d	20 B c	28 B b	54 B a
	Height Reduction (%)			
18WBP	0 B b	0 C b	0 C b	4 C a
12WBP	0 B a	0 C a	0 C a	0 C a
6WBP	0 B a	0 C a	0 C a	2 C a
0WBP	1 B b	0 C b	2 C b	28 B a
4WAP	9 A d	19 A c	25 A b	56 A a
8 WAP	7 A c	7 B c	17 B b	27 B a

[a] Data from experimental runs 1 and 2 conducted in 2022 and 2023, respectively, at Upper Coastal Plain Research Station in Rocky Mount, NC.

[b] Means followed by the same letter in the column do not differ using Tukey's test at $\alpha = 0.05$. Uppercase letters represent mean comparison of the main effect of application timing practice within columns, and lowercase letters represent the main effect of rate within rows.

[c] Field rates (1x): sulfometuron-methyl (78 g ai ha^{-1}), triclopyr + clopyralid (378 + 126 g ai ha^{-1}), triclopyr (8967 g ai ha^{-1}), 2,4-D + dichlorprop (1917 + 975 g ai ha^{-1}), indaziflam (103 g ai ha^{-1})

[d] Abbreviations: WBP (weeks before planting) and WAP (weeks after planting).

Findings and Conclusions

The findings of this study can guide the development of herbicide programs for managing roadside vegetation near soybean, tobacco, corn, and cotton fields, focusing on preventing crop injury from spray drift. Assuming an acceptable yield loss and injury threshold of ≤10% for soybean, corn, and cotton, and ≤5% injury for tobacco due to regulatory residue limits, recommendations vary by crop and timing.

For soybean, 2,4-D + dichlorprop is the safest option when applied from 18 weeks before planting until planting. None of the herbicides tested is considered safe when sprayed between 4 and 8 weeks after planting, except indaziflam at 8 weeks after planting. However, indaziflam has very long residual activity, potentially damaging crops in subsequent seasons.
For tobacco, none of the tested herbicides are considered safe at any application timing within the parameters of this study. For corn, synthetic auxin herbicides are the safest option when sprayed 18 weeks before planting. By 12 weeks before planting, triclopyr and triclopyr + clopyralid are also safe. Except for triclopyr at 6 weeks before planting, yield losses exceeded 10% for all herbicides tested from 6 weeks before planting to 8 weeks after planting. For cotton, sulfometuron-methyl, indaziflam, and synthetic auxin herbicides are safe options when applied 18 weeks before planting, while only synthetic auxin herbicides remain safe by 12 weeks before planting. Between 6 weeks before planting and 8 weeks after planting, none of the herbicides tested met the safety threshold.

Recommendations

For managing roadside vegetation near soybean, tobacco, corn, and cotton fields while minimizing crop injury, herbicide program selections should consider crop-specific sensitivities and application timing. For soybean, 2,4-D + dichlorprop is the safest when applied up to planting, though indaziflam applied 8 weeks after planting is also safe but may pose residual risks to subsequent crops. No herbicide tested was safe for tobacco within the study parameters. For corn, synthetic auxin herbicides are safe when applied 18 weeks before planting, with triclopyr and triclopyr + clopyralid also safe by 12 weeks before planting. For cotton, sulfometuron-methyl, indaziflam, and synthetic auxin herbicides are safe 18 weeks before planting, but only synthetic auxin herbicides remain safe by 12 weeks before planting. None of the herbicides met safety thresholds for cotton between 6 weeks before planting and 8 weeks after planting.

Tested herbicides that are not considered safe should be avoided to prevent potential crop damage. Optimal results can be achieved by combining herbicide programs with mechanical and cultural vegetation management practices. Additionally, using drift-reducing adjuvants and low-drift nozzles is an important strategy to minimize spray drift. Lastly, it is noteworthy that simulated drift in this study included 1x the field rate. In practical scenarios, herbicide amounts reaching non-target plants typically range from 0.01x to 0.1x of the field rate; therefore, these results can be considered conservative for operational decision-making.

Implementation and Technology Transfer Plan

When managing vegetation near soybean, tobacco, corn, and cotton fields, select herbicides based on crop-specific safety and application timing. For soybean, 2,4-D + dichlorprop is safest up to planting, while indaziflam is safe at eight weeks after planting but may pose residual risks to subsequent crops. No herbicide tested was safe for tobacco. For corn, synthetic auxin herbicides are safe when applied 18 weeks before planting, with triclopyr and triclopyr + clopyralid also safe by 12 weeks before planting. For cotton, sulfometuron-methyl, indaziflam, and synthetic auxin herbicides are safe 18 weeks before planting, but only synthetic auxin herbicides remain safe by 12 weeks before planting. No herbicide was safe for cotton between six weeks before planting and eight weeks after planting. Unsafe herbicides should be avoided to prevent crop damage. Integrate mechanical and cultural control methods with herbicide programs, and use drift-reducing adjuvants and low-drift nozzles to minimize spray drift. These recommendations should be included in applicator trainings and standard operating procedures to comply with good application and vegetation management plans while protecting nearby crops and reducing liability.

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