

Research Article

Cite this article: Godara N and Askew SD (2024) Auxin herbicides, halosulfuron, sulfentrazone, and topramezone disparately affect morphology and ultraviolet features of weedy flowers and associated pollinator foraging. *Weed Sci.* **72**: 703–713. doi: [10.1017/wsc.2024.57](https://doi.org/10.1017/wsc.2024.57)

Received: 22 March 2024
Revised: 10 July 2024
Accepted: 15 August 2024
First published online: 30 October 2024

Associate Editor:

Te-Ming Paul Tseng, Mississippi State University

Keywords:

Best management practices; bullseye flowers; integrated pest and pollinator management; pollinator conservation; UV-absorbing inflorescence; UV-reflecting flower

Corresponding author:

Shawn D. Askew; Email: saskew@vt.edu

Auxin herbicides, halosulfuron, sulfentrazone, and topramezone disparately affect morphology and ultraviolet features of weedy flowers and associated pollinator foraging

Navdeep Godara¹  and Shawn D. Askew² 

¹Graduate Assistant, School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA and ²Professor, School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

Abstract

Pollinators risk exposure to insecticide residue when visiting weedy flowers in urban landscapes. Previous research shows that pollinators are routinely exposed to a variety of pesticides, but herbicides have exhibited minimal toxicity and did not contribute to the modeled risk quotients. Herbicides from different modes of action may deter pollinators from visiting turfgrass weeds, but their temporal influence on floral quality and pollinator foraging is unaddressed. Research experiments were conducted at Blacksburg, VA, in 2023 to assess the effect of four herbicides on floral morphology and ultraviolet (UV) reflectance of three different UV floral classes of weeds and associated pollinator foraging visits. Among 1,080 assessments per weed species, honeybees (*Apis mellifera*), bumble bees (*Bombus* spp.), solitary bees (*Chelostoma florissomne*), and flies (*Diptera* spp.) accounted for 94%, 2%, 3%, and 1%, respectively, of the total pollinator visitations on white clover (*Trifolium repens* L.) inflorescences; 71%, 2%, 0%, and 27%, respectively, on dandelion (*Taraxacum officinale* F.H. Wigg.) flowers; and 0%, 0%, 78%, and 22%, respectively, on bulbous buttercup (*Ranunculus bulbosus* L.) flowers. Pollinator visitation and floral quality were temporarily affected by herbicide application, with some herbicides eliminating food resources, while others transiently impacted floral quality and density. The combination of 2,4-D + dicamba + MCPP and topamezone eliminated pollinator foraging visits, but on differing temporal scales of 3 d for auxins and 14 d for topamezone. Halosulfuron and sulfentrazone transiently suppressed floral quality and density, with varying degrees of deterrence on pollinators depending on the weed species. All evaluated herbicides reduced radiometric UV reflectance of *T. officinale* petal apices, but only synthetic auxin and topamezone reduced digitally assessed floral UV-reflecting area. Petal UV reflectance appears to contribute but not solely influence pollinator foraging behavior. UV-absorbing and UV-reflecting flowers differed in UV-reflectance response to herbicides, but pollinators were similarly deterred. Results suggest that herbicides may offer a variety of management solutions to pollinator deterrence in areas slated for insecticide treatment, including long-term or transient deterrence with potential food-resource preservation.

Introduction

The recent decline in pollinator abundance is a cause of concern for sustaining global food production (Koh et al. 2015; USDA 2016), eliciting calls for land management policy (Dicks et al. 2021). Pesticides have been cited as a likely abiotic contributor that negatively interacts with other biotic stressors, adversely affecting pollinator abundance (Goulson et al. 2015). Synthetic insecticides are primarily utilized to prevent damage from foliar- or root-feeding insects in managed turfgrass systems (Held and Potter 2012). The most widely used insecticides in turfgrass pest management are neonicotinoids such as clothianidin, dinotefuran, imidacloprid, and thiamethoxam, which pose a severe threat to pollinators and natural enemies foraging on weedy flowers for floral resources (Larson et al. 2017). Preventive insecticide treatments in turf are applied between March and June, aligning with the periodicity of weedy flower bloom, therefore increasing insecticide-associated risk to pollinators (Larson et al. 2017).

Weeds provide floral resources to pollinators (Bretagnolle and Gaba 2015; Hicks et al. 2016). In urban landscapes, dandelion (*Taraxacum officinale* F.H. Wigg.) and white clover (*Trifolium repens* L.) were visited by 50 different species of pollinators, including 37 species of bees (Larson et al. 2014). This convergence of turfgrass weeds and pollinators in urban landscapes increases the risk of pollinator exposure to toxic insecticide residues (Gels et al. 2002; Larson et al. 2013). Instructions on insecticide labels for pollinator protection mention “Do not apply this product

© The Author(s), 2024. Published by Cambridge University Press on behalf of Weed Science Society of America. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.



while bees are foraging” (Anonymous 2022), which does not provide specific directions to practitioners for the prevention of pollinator exposure. Existing best practices for reducing pollinator exposure include not spraying areas potentially visited by pollinators, spraying in the morning or during times that pollinators are inactive, mowing the area to remove weedy flowers before insecticide treatment, and controlling flowering weeds with herbicides (Godara et al. 2023; Larson et al. 2015; NCIPMC 2019).

Herbicides affect pollinator foraging by reducing weedy flower density and floral resources (King 1964; MacRae et al. 2005; Schmitz et al. 2013). Sublethal drift of synthetic auxin herbicides reduced the floral density and pollinator foraging frequency on alfalfa (*Medicago sativa* L.) and common boneset (*Eupatorium perfoliatum* L.) despite similar pollen protein concentrations in herbicide-treated and nontreated flowers (Bohnenblust et al. 2016). Glyphosate applied at sublethal rates reduced floral density and delayed flowering of common tansy (*Tanacetum vulgare* L.), leading to a decline in insect visitation (Dupont et al. 2018). Herbicides could be utilized in managed turfgrass systems before insecticide applications, as weedy flowers are not typically desired (Godara et al. 2023). However, these management practices may limit future food resources for pollinators for several months, if not years.

Herbicides from different modes of action (MOAs), including acetolactate synthase inhibitors, carotenoid biosynthesis inhibitors, protoporphyrinogen oxidase (PPO) inhibitors, and synthetic auxins were classified as practically nontoxic to honeybee (*Apis mellifera*) (Bunch et al. 2012; Gervais et al. 2008; PMRA 2014; USEPA 2012, 2014). Acute contact and oral toxicity (LD₅₀) to honeybees from the herbicides 2,4-D, dicamba, sulfentrazone, topramezone, and halosulfuron exceed 100,000 and 10,000 ng ai per bee, respectively (APVMA 2011; PMRA 2014; USEPA 2012, 2014). The insecticide imidacloprid, by comparison, has contact and oral LD₅₀ for honeybees of 60 to 243 ng and 4 to 41 ng ai per bee, respectively (Gervais et al. 2010), which are at least 412 and 244 times more toxic than the above-mentioned herbicides following contact or oral exposure, respectively. A statewide study conducted in Maine demonstrated that fungicide and herbicide residues were detected at a higher frequency in pollen of 32 apiaries compared with insecticides, but insecticides constituted the highest risk quotient via contact or oral exposure and herbicides comprised none of the risk quotient (Drummond et al. 2018).

Herbicides pose little risk to pollinators, so their incorporation into efforts to protect pollinators from insecticide exposure through weedy floral suppression should be explored. Herbicides of differing MOAs influence weed physiology differently with regard to temporal plant phytotoxicity and mortality (Duke 1990; Shaner 2014); therefore, one would expect variable degrees of pollinator deterrence and impact on long-term food resources between herbicides. Pollinators vacated auxin-treated turfgrass within 2 d after treatment; however, *T. repens* flower quality persisted up to 5 d after treatment (Godara et al. 2023). This rapid pollinator evacuation from treated lawn weeds suggests a viable practice for preventing the exposure of pollinators to insecticides. However, no literature exists to explain why pollinator evacuation following auxin herbicide treatments to *T. repens* was so rapid despite the persistence of floral quality. Likely causes may include reduced nectar production, as has been observed following some herbicide treatments (Kearns et al. 1998; King 1964), or changes in ultraviolet (UV) floral features that are invisible to humans.

Previous researchers documented that UV floral features affect pollinator foraging behavior (DeMarche et al. 2015; Koski and

Ashman 2014; Papiorek et al. 2016; Rae and Vamosi 2012). A study that investigated 43 taxa of Hymenoptera observed that insects have a trichromatic color vision system with photoreceptors that peak at 340, 430, and 535 nm (Peitsch et al. 1992), emphasizing the importance of UV reflectance in insect vision. Johnson and Andersson (2002) observed that African honeybee (*Apis mellifera scutellata*) foraging on African potato (*Hypoxis hemerocallidea* Fisch. & C.A. Mey.), a UV-reflecting flower, was decreased when the flower surface was coated with sunscreen containing UV-absorbing compounds. Although UV floral features have been characterized by plant species in some ecosystems (Tunes et al. 2021), no studies have reported the effect of herbicides on these features.

Through the exploration of how herbicides of differing MOAs influence floral responses and associated insect foraging behavior, we aim to expand potential best practices for pollinator deterrence in areas that would receive insecticide treatments. Such practices not only protect pollinators, but may reduce regulatory pressure on important insecticide chemistries. We hypothesized that weedy flowers will vary in magnitude and temporal floral periodicity following disparate herbicide treatments, and that insect visitation will likewise vary depending on herbicide. Our first objective was to evaluate the effect of four herbicides from different MOAs on pollinator foraging visits and relate these temporally to floral quality and density metrics. Our second objective was to measure the posttreatment impacts of four herbicides on UV floral features of weedy flowers or inflorescences that can be characterized as UV-absorbing, UV-reflecting at petal apex with bullseye patterns, and UV-reflecting petals with contrasting reproductive parts.

Materials and Methods

Field Assessment of Floral Features and Insect Visitation

Field experiments were conducted as a single-factor, randomized complete block design with four replications and two temporal runs at the Virginia Tech Glade Road Research Facility (37.23°N, 80.43°W), Blacksburg, VA, the Virginia Tech Turfgrass Research Center (37.22°N, 80.41°W), Blacksburg, VA, and a private residence (37.28°N, 80.44°W), Blacksburg, VA. Separate studies were conducted for each of the two floral classifications for a total of 4 site-years (2 per floral class). The floral classifications (Godara and Askew 2023) included “UV-absorbing inflorescence” (represented by *T. repens*) at two sites and “UV-reflecting at petal apex with bullseye-pattern flowers” (represented by *T. officinale* and *R. bulbosus*) at two sites. Studies were initiated on April 21, May 20, May 31, and June 12 of 2023 for UV-reflecting site 1 (37.22°N, 80.41°W), UV-reflecting site 2 (37.28°N, 80.44°W), UV-absorbing site 1 (37.23°N, 80.43°W), and UV-absorbing site 2 (37.23°N, 80.43°W), respectively. Plots were 3.2, 3.2, and 6.5 m² for *T. repens*, *R. bulbosus*, and *T. officinale*, respectively. Plot size was varied to achieve at least 30 inflorescences per plot. The resulting floral density at study initiation was 30, 10, and 5 inflorescences m⁻² for *T. repens*, *R. bulbosus*, and *T. officinale*, respectively. A buffer zone of 3 m between plots and 6 m between blocks ensured that adjacent plots did not serve as the primary insect attractant.

Treatments included a nontreated control; a premix of 2,4-D, dicamba, and MCPP; halosulfuron; sulfentrazone; and topramezone. A detailed list of treatments with product names, manufacturer descriptions, herbicide MOAs, and rates is provided in Table 1. All herbicides were applied using a CO₂-pressurized backpack sprayer equipped with four extended-range

Table 1. List of treatments with trade names, manufacturer details, herbicide modes of action, and rates evaluated in experiments assessing ultraviolet (UV)-absorbing inflorescence, UV-reflecting at petal apex with bullseye-pattern, and UV-reflecting petals with contrasting reproductive part weedy flowers.

Treatment	Trade name	Manufacturer	WSSA mode of action	Rate
Nontreated control	—	—	—	kg ai ha ⁻¹
2,4-D + dicamba + MCPP	Trimec® Classic	PBI Gordon Corporation, Shawnee, KS	Synthetic auxin	1.53
Halosulfuron ^a	Halo 75 WDG Select™	Prime Source LLC, Middlesex, NC	Acetolactate synthase inhibitor	0.07
Sulfentrazone	Dismiss®	FMC Corporation, Philadelphia, PA	Protoporphyrinogen oxidase inhibitor	0.28
Topramezone ^b	Pylex™	BASF Corporation, Research Triangle Park, NC	Carotenoid biosynthesis inhibitor	0.05

^aNonionic surfactant at 0.25% v/v was added.

^bCrop oil concentrate at a rate of 0.5% v/v was added.

(XR11006VS) flat-fan spray nozzles (TeeJet® Technologies, Wheaton, IL), calibrated to deliver 468 L ha⁻¹ at a speed of 4.8 km h⁻¹. Herbicides were applied to weedy flowers at 8:00 AM 1 d after experiment initiation. Mowing and fertilizer applications were withheld throughout the study duration to prevent any alteration to flower density. Baseline floral density and plot size for each study were chosen based on preliminary work to have sufficient pollinator visitation on weedy flowers (data not shown).

Flower density data were collected by counting all flowers in each plot, and three representative flowers in each plot were photographed to assess the flower quality every day at 9:00 AM. Flowers were counted toward the density metric if apparently “healthy” tissue was visually perceived from a standing position. Flower images were batch processed through the object selection tool in Adobe Photoshop (Adobe, San Jose, CA) to select flowers based on color and shape and eliminate background elements before digital analysis. Processed images were analyzed using TurfAnalyzer (Green Research Services, Fayetteville, AR) to quantify flower discoloration. Insect visitation was assessed by counting unique foragers that physically interacted with flowers that were encountered over a 1-min assessment period in each plot three times each day (~10:00 AM, ~12:00 PM, and ~2:00 PM), similar to other researchers (Bohnenblust et al. 2016; Boyle et al. 2020; Larson et al. 2013). Insect foragers were separated into honeybees, bumble bees (*Bombus* spp.), solitary bees (*Osmia* spp.), hoverflies (Syrphidae), wasps (*Vespula* spp.), and butterflies (Hesperiidae, Nymphalidae, Papilionidae, Lycaenidae). Insect visitation, floral density, and flower quality data for all floral species were taken on 1 d before and 0, 1, 2, 3, 4, 7, 10, and 14 d after treatment (DAT).

Floral reflectance via radiometry, UV images, visible-light images, and fluorescent-light images were collected from three random flower samples from each plot at 4, 24, and 72 h after treatment (HAT). Flowers were harvested from experimental sites in test tubes (Falcon™ 15-ml centrifuge tube, Corning, Tewksbury, MA) containing 5 ml L⁻¹ of Miracle-Gro solution for fresh cut flowers (Scotts, Miracle-Gro, Marysville, OH) and moved to an indoor studio with controlled lighting at the Virginia Tech Glade Road Research Facility. UV floral features were captured with an EOS 5D Mark IV camera (Canon, Tokyo, Japan) in which an internal hot mirror was modified with a UV band-pass filter (Life Pixel Infrared, Mukilteo, WA) (Klomberg et al. 2019) and utilizing a non-UV coated Levenoc Helios 44-mm lens and remote digital viewing screen (Shinobi 4K HDMI Monitor, Atomos, Carlton, Australia). Light images and UV-light images were captured with a nonmodified version of a similar camera, Canon EOS 5D Mark IV with a Canon EF 105-mm lens under a UV light (Everbeam®, Surrey, BC, Canada) that emits 315 to 405 nm with a peak at 365 nm or bright white light (Craftsman®, Towson, MD) that emits

400 to 700 nm. Reflectance standards were used for UV photography, including a WS-1 (Ocean Insight, Orlando, FL) diffuse reflectance standard, which reflects >98% of light ranging from 250 to 1,500 nm; a custom-made barium sulfate standard reflecting 100% of UV light; a custom-made barium sulfate and charcoal mixture, uniformly reflecting 50% of incident UV light; and a custom-made charcoal standard absorbing all UV light (Garcia et al. 2014). All images also included a ruler and color standard (DGK-Pro Multifunction Color Chart, DGK Color Tools, Boston, MA). UV photographs were exposure corrected to achieve a uniform hue of UV-reflecting areas by visual evaluation of barium sulfate and charcoal mixture standards. Photographs were subjected to an object selection tool in Adobe Photoshop to select flowers based on color and shape (described earlier) before digital analysis to quantify UV-reflecting area based on hue/saturation-based thresholds using TurfAnalyzer.

Spectral reflectance data ranging from 200 to 950 nm with 1.6-nm optical resolution were collected from each of the three random flower samples harvested from each plot with a QEPRO-XR spectrometer (Ocean Insight). The QEPRO-XR spectrometer was equipped with a UV-sensitive fiber-optic probe (QR400-7-SR, Ocean Insight) and connected to a PX-2 Pulsed Xenon light source (Ocean Insight) having a 200- to 750-nm light output. The fiber-optic probe was fixed at 45° and 2 cm above the target for collecting reflectance data. As established by previous researchers (Camargo et al. 2019; Tunes et al. 2021), reflectance data were collected on each flower at the petal apex, petal base, and reproductive structures. Pollinator visitation and floral quality data over time were converted to the area under progress curve (AUPC) using

$$\partial = \sum_{i=1}^{n_i-1} \left(\frac{(y_i + y_{(i-1)})}{2} (t_{(i+1)} - t_{(i)}) \right) \quad [1]$$

where ∂ is the AUPC of floral quality or pollinator visitation, i is the ordered sampling date, n_i is the number of sampling dates, y is pollinator visitation or floral quality expressed as a percent of the nontreated control at a given assessment date, and t is the time in days. AUPC data were subjected to ANOVA using PROC GLM in SAS v. 9.3 (SAS Institute, Cary, NC). Means were separated using Fisher's protected LSD ($\alpha = 0.05$). Based on the significance of experimental run by treatment or treatment effect, data were subjected to nonlinear regression (Table 2) using SigmaPlot software (v. 13.0, Systat software, San Jose, CA). Other response variables were also subjected to ANOVA using the same procedure, and means were separated using Fisher's protected LSD ($\alpha = 0.05$).

Table 2. Nonlinear and polynomial regression equations with parameters utilized for pollinator visitation and floral quality of ultraviolet (UV)-absorbing inflorescence and UV-reflecting at petal apex with bullseye-pattern flowers.

Flower	Herbicide	Response	Equation name	Equation	Parameters	R ²
Absorbing	2,4-D; dicamba; MCPP	Pollinator	Exponential decay	$y = a + be^{(-cx)}$	$a = -0.2, b = 92, c = 2.3$	0.99
Absorbing	2,4-D; dicamba; MCPP	Flower	Sigmoidal 3P	$y = a/1 + e^{-(x-x_0)/b}$	$a = 127, b = 1.0, x_0 = 1.5$	0.99
Absorbing	Halosulfuron	Pollinator	Cubic polynomial	$y = y_0 + ax + bx^2 + cx^3$	$a = 5.8, b = -2.4, c = 0.1, y_0 = 100$	0.99
Absorbing	Halosulfuron	Flower	Sigmoidal 4P	$y = y_0 + a/(1 + e^{-(x-x_0)/b})$	$a = 68, b = -0.9, x_0 = 6.5, y_0 = 34$	0.99
Absorbing	Sulfentrazone	Pollinator	Gaussian	$y = y_0 + ae^{-0.5(x-x_0)^2/b^2}$	$a = -270, b = 9.1, x_0 = 7.3, y_0 = 295$	0.99
Absorbing	Sulfentrazone	Flower	Gaussian	$y = y_0 + ae^{-0.5(x-x_0)^2/b^2}$	$a = -156, b = 6.6, x_0 = 7.9, y_0 = 177$	0.94
Absorbing	Topramezone	Pollinator	Gompertz	$y = ae^{-e^{-(x-x_0)/b}}$	$a = 99, b = -3.4, x_0 = 16$	0.97
Absorbing	Topramezone	Flower	Sigmoidal 4P	$y = y_0 + a/(1 + e^{-(x-x_0)/b})$	$a = 114, b = -2.5, x_0 = 6.9, y_0 = -5.3$	0.99
Bullseye	2,4-D; dicamba; MCPP	Pollinator	Exponential decay	$y = a + be^{(-cx)}$	$a = 93, b = 1.7, c = 0.7$	0.99
Bullseye	2,4-D; dicamba; MCPP	Flower	Sigmoidal 3P	$y = a/1 + e^{-(x-x_0)/b}$	$a = 202, b = -1.8, x_0 = -0.3$	0.98
Bullseye	Halosulfuron	Pollinator	Sigmoidal 4P	$y = y_0 + a/(1 + e^{-(x-x_0)/b})$	$a = 130, b = -2.0, x_0 = 3.9, y_0 = -2.4$	0.99
Bullseye	Halosulfuron	Flower	Sigmoidal 3P	$y = a/1 + e^{-(x-x_0)/b}$	$a = 130, b = -4.7, x_0 = 6.1$	0.99
Bullseye	Sulfentrazone	Pollinator	Sigmoidal 4P	$y = y_0 + a/(1 + e^{-(x-x_0)/b})$	$a = 83, b = -0.2, x_0 = 1.6, y_0 = 20$	0.99
Bullseye	Sulfentrazone	Flower	Cubic polynomial	$y = y_0 + ax + bx^2 + cx^3$	$a = -22, b = 2.8, c = -0.1, y_0 = 108$	0.92
Bullseye	Topramezone	Pollinator	Sigmoidal 4P	$y = y_0 + a/(1 + e^{-(x-x_0)/b})$	$a = 226, b = -7.1, x_0 = 10, y_0 = -84$	0.99
Bullseye	Topramezone	Flower	Sigmoidal 3P	$y = a/1 + e^{-(x-x_0)/b}$	$a = 98, b = -2.4, x_0 = 14$	0.96
Descriptions of equations used						
Cubic polynomial		$y = y_0 + ax + bx^2 + cx^3$, where y is the pollinator visitation or floral quality, a is the coefficient of linear term, b is the coefficient of quadratic term, c is the coefficient of cubic term, x is the number of days after treatment, and y_0 is the constant.				
Exponential decay		$y = a + be^{(-cx)}$, where y is pollinator visitation or floral quality, a is the lower asymptote, b is the amplitude, c is the decay rate parameter, and x is days after treatment.				
Gaussian		$y = y_0 + ae^{-0.5(x-x_0)^2/b^2}$, where y is the pollinator visitation or floral quality, a is the peak height, b is the width of the peak, x is the days after treatment, x_0 is the center or mean of the peak, and y_0 is the offset.				
Gompertz		$y = ae^{-e^{-(x-x_0)/b}}$, where y is pollinator visitation or floral quality, a is the upper asymptote, b is the growth rate parameter, x is the number of days after treatment, and x_0 is the inflection point.				
Sigmoidal 3 parameter		$y = a/1 + e^{-(x-x_0)/b}$, where y is the pollinator visitation or floral quality, a is the upper asymptote, b is the slope, x is the number of days after treatment, and x_0 is the inflection point				
Sigmoidal 4 parameter		$y = y_0 + a/(1 + e^{-(x-x_0)/b})$, where y is the pollinator visitation or floral quality, a is the amplitude, b is the slope, x is the number of days after treatment, x_0 is the inflection point, and y_0 is the lower asymptote				

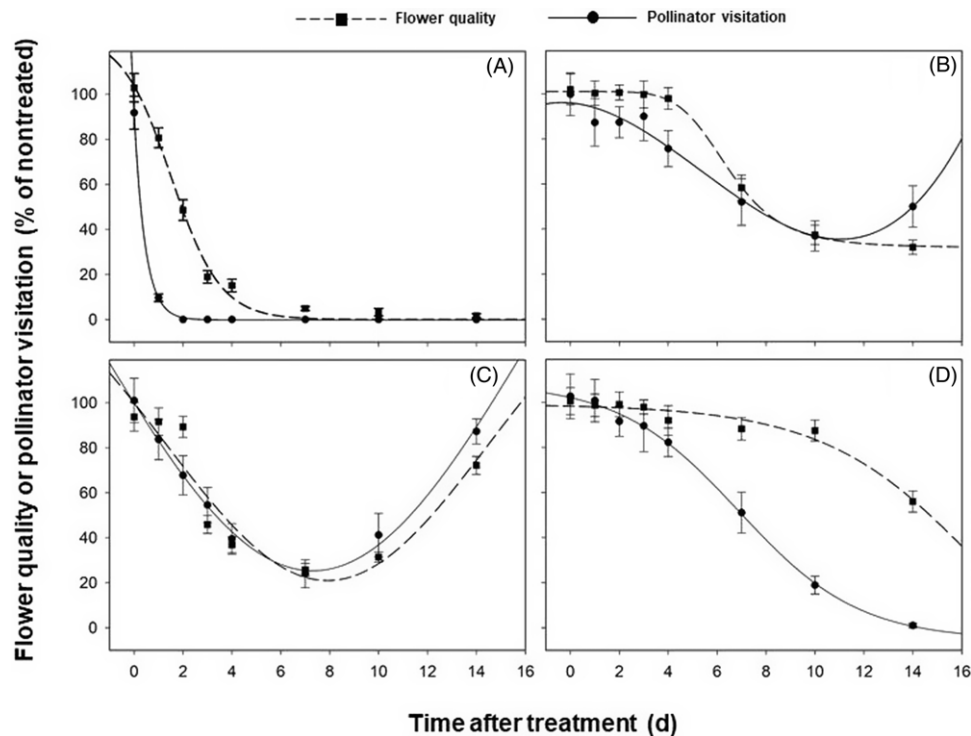


Figure 1. Effect of herbicides 2,4-D + dicamba + MCPP (A); halosulfuron (B); sulfentrazone (C); and topramezone (D) on floral quality of ultraviolet (UV)-absorbing inflorescence and pollinator visitation.

Additional UV-Reflectance Assessment

Two additional experiments were conducted to evaluate the effect of herbicides on an alternate floral UV-reflectance class that reflects more UV than “bullseye”-type flowers. Foxglove beard-tongue (*Penstemon digitalis* Nutt. ex Sims) flowers reflect UV throughout the petals, but have contrasting reproductive organs that absorb UV (Godara and Askew 2023). *Penstemon digitalis* flowers were collected from the Virginia Tech Glade Road Research Facility (37.23°N, 80.43°W), Blacksburg, VA, on June 20, 2023, and July 6, 2023. The experiment was conducted as a randomized block design with two temporal runs and four replications. Each experimental unit had three subsample flowers for a total of 12 flowers per treatment for each experimental run. Flowers were collected from volunteer plants growing in a 4-yr-old pollinator garden and moved to test tubes, as previously described. These studies differed from the aforementioned field studies in that flowers were treated with herbicides on June 20 and July 6, 2023, after being separated from plants rather than spraying plants in situ. Similar to these previous studies, flowers were subjected to digital photography and radiometric reflectance analysis at 4 HAT. Thus, these studies only evaluated floral reflectance metrics soon after treatment and did not assess the impact of herbicide treatments on pollinator visitation, floral density, and floral quality. Our goal was to compare an alternate class of UV-reflecting flowers for impact on UV reflectance soon after herbicide treatment. Previous research demonstrated that *P. digitalis* plant height was 76 cm and 13 cm for inflorescence (Parachnowitsch and Kessler 2010), so it is unlikely to occur in managed turfgrass situations, but is found in managed beds and reduced management sites in urban settings. *Penstemon digitalis* offers floral rewards to a broad diversity of pollinators (Clinebell and Bernhardt 1998) and is an important component of pollinator gardens (Anonymous

2024). Because its inflorescences could be subjected to insecticide drift in urban settings, it was deemed a viable candidate for this research despite its differences from *R. bulbosus*, *T. officinale*, and *T. repens*. Reflectance and UV-reflecting area data were subjected to ANOVA using PROC GLM in SAS v. 9.3, and means were separated using Fisher’s protected LSD ($\alpha = 0.05$).

Results and Discussion

UV-absorbing Inflorescence and Pollinator Response to Herbicides

Honeybees comprised 94% over the total pollinator visitations on *T. repens* inflorescences followed by bumble bees (2%), solitary bees (3%), and flies (1%) when averaged over 1,080 assessments comprising 27 assessment times, 5 treatments, 4 replicates, and 2 experimental runs (data not shown). Honeybees have been documented as primary insect visitors on *T. repens* blooms (Goodman and Williams 1994; Larson et al. 2014; Wolfin et al. 2023). Temporal response of UV-absorbing floral quality and pollinator visitation averaged over experimental runs exhibited mostly nonlinear trends (Table 2). Visual association of the temporal trends (Figure 1) and correlations ranging from 0.56 for synthetic auxins to 0.86 for sulfentrazone (data not shown) suggested that the dependency between these two variables varies with herbicide. In the case of auxin herbicides, pollinator visitation declined more rapidly than floral quality (Figure 1A). Pollinator visitation was eliminated at 2 DAT, while floral quality took 7 d to decline by 95% (Figure 1A). Pollinator vacancy in advance of *T. repens* floral quality decline following auxin herbicide treatment has occurred in other studies (Godara et al. 2023).

Halosulfuron similarly reduced pollinator foraging more rapidly than floral quality, but approximately 35% of pollinators

Table 3. Effect of herbicides on area under progress curve (AUPC) for pollinator visitation and flower quality of ultraviolet (UV)-absorbing inflorescence and UV-reflecting at petal apex with bullseye-pattern flowers.^a

Treatment	UV-absorbing inflorescence				UV-reflecting at petal apex with bullseye pattern			
	Pollinator visitation		Flower quality		Pollinator visitation		Flower quality	
Nontreated control	14	a	14	a	13	a	14	a
2,4-D + dicamba + MCPP	0.5	d	3.5	d	0.7	d	3.3	d
Halosulfuron	8.7	b	9.6	b	5.2	c	8.4	c
Sulfentrazone	7.4	bc	6.9	c	4.4	c	9.4	c
Topramezone	7.2	c	13.4	a	7.6	b	12	b
P-value	<0.0001		0.0003		0.0009		0.0161	

^aMeans followed by the same letter within each column are not significantly different based on Fisher's protected LSD ($\alpha = 0.05$).

were undeterred (Figure 1B). Sulfentrazone decreased pollinator foraging visits to approximately 25% of nontreated plots in step with floral quality decline (Figure 1C). Both halosulfuron and sulfentrazone exhibited a trend of recovery in pollinator visitation during the assessment, with near-complete recovery following sulfentrazone treatment at 14 DAT (Figure 1B and 1C). These trends suggest that some herbicides may be viable methods to transiently deter pollinator visitation without causing long-term loss of food resources. MacRae et al. (2008) found that halosulfuron injured watermelon 34% at 2 wk after treatment (WAT), but did not affect fruit production at a later stage, showing that plants recovered from herbicidal injury. Halosulfuron injured broadleaf weeds at 7 to 14 DAT (Anonymous 2018), but McCurdy et al. (2016) observed that *T. repens* floral density increased by 65% at 28 DAT. Transient pollinator deterrence could be attributed to the residual attractiveness of halosulfuron-treated flowers or temporary suppression of nectar production in *T. repens*. Topramezone floral quality persisted for more than 1 WAT and declined sharply thereafter (Figure 1D). Pollinator foraging following topramezone decreased more rapidly than floral quality but required 2 wk to reach peak decline, which completely eliminated pollinator visitation, similar to auxin herbicides (Figure 1D). Thus, if topramezone is to be used as a deterrent to pollinator foraging, insecticide treatment must be delayed for at least 2 WAT of herbicide. Larson et al. (2015) demonstrated that imidacloprid residues were >99% lower in the nectar of newly formed *T. repens* blooms at 1 WAT, which suggests that translocation of insecticide residue to new blooms is practically nontoxic to pollinators after eliminating the existing blooms with herbicides.

The herbicidal treatment effect was significant for AUPC of pollinator visitation ($P < 0.0001$) and floral quality ($P = 0.0003$) of UV-absorbing inflorescence and did not interact with the experimental run, so data were pooled over both experimental runs (Table 3). It should be noted that AUPC is a unitless, relative comparison that reflects the quantity of pollinator foraging visits over the assessment period from 1 to 14 DAT. Thus, in a scenario in which an herbicide was applied to serve as a deterrent to pollinator foraging and an insecticide was applied concurrently, greater AUPC is predictive of greater potential insecticide exposure. The herbicides 2,4-D + dicamba + MCPP reduced the AUPC of pollinator visitation to 0.5 from the nontreated value of 14 (Table 3). Thus, 2,4-D + dicamba + MCPP would allow for insecticide treatment to occur more rapidly with respect to herbicide treatment and effectively eliminate pollinator foraging visits for the 2-wk, posttreatment duration (Table 3). Only one other study has evaluated the temporal trend of pollinator

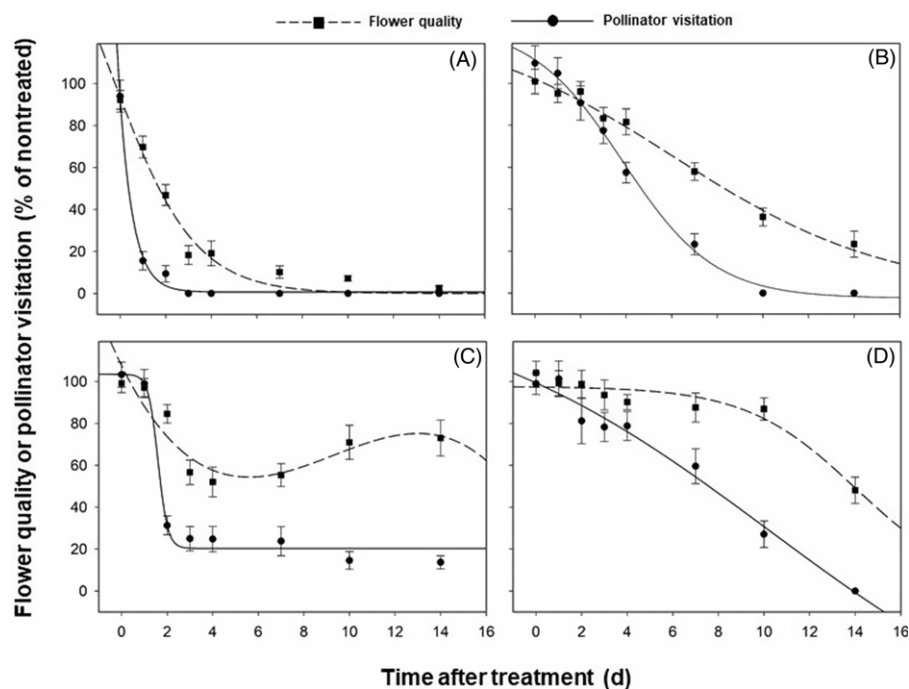
deterrence following herbicide treatment (Godara et al. 2023), wherein pollinator decline following *T. repens* treatment with 2,4-D + dicamba + MCPP was similar to the current study (Figure 1A). Halosulfuron, sulfentrazone, and topramezone reduced pollinator visitation AUPC to 8.7, 7.4, and 7.2, respectively, which were more than the auxin herbicides AUPC for pollinator visitation (Table 3). These values of pollinator visitation AUPC appear to imply that these herbicides only reduced pollinator visitation by approximately 50% compared with the nontreated control (Table 3), but the temporal trends show that the maximum reduction in pollinator decline was 35%, 25%, and 0% of the nontreated control for halosulfuron, sulfentrazone, and topramezone, respectively (Figure 1B–D). Trends in AUPC of flower quality generally mirrored those of pollinator visitation AUPC (Table 3). During the duration of the experiment, total reduction in floral quality differed between each herbicide and can be ordered greatest to least floral quality reduction based on AUPC for 2,4-D + dicamba + MCPP, sulfentrazone, halosulfuron, and topramezone (Table 3). As with insect visitation AUPC, floral quality AUPC numbers reflect cumulative quality over the entire period and do not necessarily reflect peak floral quality reduction. Herbicides from similar MOAs evaluated in other studies also reduced floral quality. Clopyralid, halosulfuron, and mesotrione caused 73%, 88%, and 45% phytotoxicity to garden coreopsis (*Coreopsis lanceolata* L.) flowers (Henry et al. 2023).

In turfgrass systems, floral density changes over time and is transiently reduced by mowing (Fetridge et al. 2008; Lerman et al. 2018), typically declining over time when mowing is withheld (Körösi et al. 2014). Such was the case in our study, where mowing was withheld from a turf sward infested with *T. repens* for approximately 21 d starting 7 d before herbicide treatment. The nontreated control lost 1% and 7% *T. repens* floral density at 7 and 14 DAT, respectively (Table 4). Zaleski (1964) also documented a 14% natural decline in *T. repens* floral density, which was attributed to retarded vegetative and reproductive growth due to lower levels of light intensity at the base of high-density *T. repens*. Another possible cause of the decline in *T. repens* floral density is that several inflorescences present in the subcanopy (<5 cm) were not subjected to mowing, and maximum *T. repens* bloom occurred ~4 wk after the mowing event, which suggests unmowed blooms reached floral longevity (SAREP 2024). Herbicides may reduce floral density by phytotoxic effect on the whole inflorescence or by delaying the production of new inflorescences (Carpenter et al. 2020). Furthermore, synthetic auxin herbicide triggers the biosynthesis of ethylene, a known hormone that influences floral induction and evocation (Askew 2017). These herbicides also cause epinasty, tissue swelling, and inhibition of auxin transport, which

Table 4. Effect of herbicides on weedy floral density at 7 and 14 d after treatment (DAT).^a

Treatment	UV-absorbing inflorescence				UV-reflecting at petal apex with bullseye pattern							
	<i>Trifolium repens</i> density 7 DAT		<i>Trifolium repens</i> density 14 DAT		<i>Taraxacum officinale</i> density 7 DAT		<i>Ranunculus bulbosus</i> density 7 DAT		<i>Taraxacum officinale</i> density 14 DAT		<i>Ranunculus bulbosus</i> density 14 DAT	
Nontreated control	1	d	7	c	3	c	35	b	22	b	75	b
2,4-D + dicamba + MCP	100	a	100	a	100	a	78	a	100	a	100	a
Halosulfuron	41	c	61	b	45	b	46	b	100	a	100	a
Sulfentrazone	57	b	6	c	46	b	74	a	73	a	100	a
Topramezone	2	d	54	b	26	bc	47	b	90	a	93	a
P-value	0.0003		0.001		0.0087		0.0054					

^aFloral density is expressed as a percent reduction of initial flower density. Means followed by the same letter within each column are not different based on Fisher's protected LSD ($\alpha = 0.05$).

**Figure 2.** Effect of herbicides 2,4-D + dicamba + MCP (A); halosulfuron (B); sulfentrazone (C); and topramezone (D) on floral quality of ultraviolet (UV)-reflecting at petal apex with bullseye-pattern flower and pollinator visitation.

delays flowering time and reduces floral display (Ramos et al. 2023). For all herbicides, *T. repens* floral density at 7 and 14 DAT (Table 4) generally mirrored trends in floral quality (Figure 1), and only the 2,4-D + dicamba + MCP treatment reduced floral density 100% at 14 DAT (Table 4). MacRae et al. (2005) also found that synthetic auxins reduced *T. repens* floral density 100% and suggested herbicides as a measure of pollinator protection from insecticide treatment in apple (*Malus* spp.) orchards.

UV-reflecting at Petal Apex with “Bullseye” Pattern Flower and Pollinator Response to Herbicides

Honeybees, bumblebees, and hoverflies (Syrphidae) accounted for 71%, 2%, and 27%, respectively, of total pollinator foraging visits on *T. officinale* flowers, while solitary bees (*Chelostoma florissomne*) and flies (Diptera) accounted for 78% and 22%, respectively, of total insect visitors on *R. bulbosus* flowers (data not shown).

Previous research also documented honeybees and hoverflies as primary visitors on *T. officinale* flowers (Larson et al. 2014), and solitary bees on *R. bulbosus* flowers (Westrich 1996). The temporal response of UV reflecting at petal apex with “bullseye” pattern floral quality and associated pollinator visitation averaged over experimental runs exhibited nonlinear trends (Table 2). Response variables differed by herbicidal effect, and floral quality persisted longer after herbicide treatment compared with pollinator visitation, which declined rapidly (Figure 2).

Pollinators completely evacuated bullseye flowers 3 d after auxin herbicide treatment but complete floral quality decline required 14 d (Figure 2A). Halosulfuron-treated flower quality declined at each assessment timing such that 25% of floral quality persisted at 14 DAT and 4 d later than complete pollinator evacuation, which occurred by 10 DAT (Figure 2B). Sulfentrazone reduced the quality of bullseye flowers by half at 4 DAT, but floral quality rebounded by 14 DAT (Figure 2C). Sulfentrazone applied

Table 5. Effect of herbicides on ultraviolet (UV) reflectance from petal apex of weedy flowers assessed via radiometry at 4 h after treatment.^a

Treatment	UV-reflecting petals with contrasting reproductive parts		UV-reflecting at petal apex with bullseye pattern					
	<i>Penstemon digitalis</i>		<i>Taraxacum officinale</i>		<i>Ranunculus bulbosus</i>	<i>Taraxacum officinale</i>		<i>Ranunculus bulbosus</i>
	UV-A ^b				%	UV-B ^c		
Nontreated control	29	a	14	a	NS	13	a	NS
2,4-D + dicamba + MCPP	25	bc	9	bc	NS	9	bc	NS
Halosulfuron	22	c	8	c	NS	8	c	NS
Sulfentrazone	22	c	10	b	NS	10	b	NS
Topramezone	26	ab	9	bc	NS	9	bc	NS
P-value	0.0194				0.0015			0.0087

^aValues followed by the same letter within each column do not differ based on Fisher's protected LSD ($\alpha = 0.05$).
^bUV-A = 315–400 nm.
^cUV-B = 280–315 nm.

at 280 g ha⁻¹ transiently injured cranberry (*Vaccinium macrocarpon* Aiton) but no differences in reproductive structures were observed at 8 WAT (Besançon et al. 2021). Sulfentrazone causes rapid necrosis (Shaner 2014) of herbicide-exposed floral tissues but likely does not inhibit new blooms that develop after treatment. Similarly, pollinator visitation on sulfentrazone-treated flowers also exhibited a rapid decline to as low as 25% of visits on nontreated flowers (Figure 2C) but did not recover over time, as observed in the case of *T. repens* (Figure 1C). Pollinator visitation on topramezone-treated bullseye flowers declined at each evaluation timing, with no visitors observed at 14 DAT (Figure 2D). Bullseye floral quality also declined, but 48% of floral quality still persisted at 14 d after topramezone treatment (Figure 2D). Previous research conducted in New Jersey, USA, did not measure floral quality but showed that herbicides reduced floral density, resulting in lower abundance, richness, and diversity of pollinator visitation (McDougall et al. 2021). The treatment effect was significant for AUPC of pollinator visitation ($P = 0.0009$) and floral quality ($P = 0.0161$) and not dependent on the experimental run (Table 3). Both response variables were pooled over experimental runs that included *R. bulbosus* and *T. officinale* sites (Table 3). Synthetic auxin herbicide reduced the AUPC of pollinator visitation to 0.7, but other assessed herbicides had ≥ 4.4 AUPC (Table 3). All evaluated herbicides reduced the AUPC of bullseye floral quality, but the severity of damage varied with herbicide (Table 3).

The experimental run by treatment effect was significant for floral density reduction of bullseye species at 7 DAT ($P = 0.0087$) and 14 DAT ($P = 0.0054$), so data are presented by *R. bulbosus* and *T. officinale* sites (Table 4). 2,4-D + MCPP + dicamba reduced *T. officinale* density 100% at 7 DAT, but other assessed herbicides reduced floral density <50% (Table 4). However, synthetic auxins and topramezone reduced *R. bulbosus* floral density by at least 74% at 7 DAT (Table 4). At 14 DAT, herbicides reduced *T. officinale* floral density by at least 73%, with a complete reduction in floral density after 2,4-D + MCPP + dicamba and halosulfuron treatment (Table 4). Similarly, herbicide treatment reduced *R. bulbosus* floral density $\geq 93\%$ at 14 DAT, but nontreated control plots also had a 75% reduction in floral density at 14 DAT (Table 4). Schmitz et al. (2013) also observed that sulfonylurea herbicide reduced *Ranunculus* spp. floral density by 85% at 2

WAT. *Ranunculus bulbosus* peak flowering occurs in early June (Sarukhan 1974), which explains the 75% reduction in nontreated *R. bulbosus* flowers in late June, as no new flowers were produced.

Response of Petal UV Reflectance and UV-reflecting Area of Flowers to Herbicides

The treatment effect ($P = 0.0194$) was significant for UV-A reflectance from the petal apex of *P. digitalis* at 4 HAT and was not dependent on treatment by experimental run interaction (Table 5). All herbicide treatments reduced UV-A reflectance from the petal apex of *P. digitalis* flowers to at least 25%, except topramezone (Table 5), which exhibited UV-A reflectance (29%) similar to the nontreated flowers (Table 5). The experimental run by treatment effect was significant for UV-A ($P = 0.0015$) and UV-B ($P = 0.0087$) reflectance from petal apex of bullseye flowers at 4 HAT, so data are shown by *R. bulbosus* and *T. officinale* flowers (Table 5). Herbicide-treated *T. officinale* flowers reflected $\leq 10\%$ of UV-A and UV-B from petal apex at 4 HAT, but nontreated flowers reflected 14% and 13% of UV-A and UV-B, respectively (Table 5). Herbicide treatment did not affect UV-A and UV-B reflectance from the petal apex of the *R. bulbosus* (Table 5), which could be attributed to the upper epidermal layer of the flower (van der Kooi et al. 2017). *Ranunculus* spp. flowers reflect the incident light to the center of the flower to heat the reproductive parts, which enhances seed and pollen maturation to attract pollinators (van der Kooi et al. 2017).

Digitally assessed UV-reflecting area at 4 HAT was insignificant for UV-absorbing *T. repens* flowers ($P > 0.05$; data not shown), exhibited a treatment main effect for the UV-reflecting petals with contrasting reproductive organs of *P. digitalis* ($P = 0.0419$), and exhibited an experimental run by treatment interaction for UV-reflecting petal apex with bullseye-pattern flowers of *T. officinale* and *R. bulbosus* ($P = 0.0114$) (Table 6). Herbicide treatment reduced the UV-reflecting area of *P. digitalis* to ≤ 0.56 cm², except for topramezone-treated flowers (Table 5). Previous research also showed that the floral disk diameter of *T. vulgare* and oxeye daisy (*Leucanthemum vulgare* Lam.) was reduced after glyphosate application (Strandberg et al. 2017), and this physical change in floral size can also reduce UV-reflecting area compared with nontreated petals. Herbicides did not affect the UV-reflecting area

Table 6. Effect of herbicides on digitally assessed ultraviolet (UV)-reflecting area of weedy flowers at 4 hours after treatment.^a

Treatment	UV-reflecting petals with contrasting reproductive parts		UV-reflecting at petal apex with bullseye pattern		
	<i>Penstemon digitalis</i>		<i>Taraxacum officinale</i>		<i>Ranunculus bulbosus</i>
			cm ²		
Nontreated control	0.75	a	1.92	a	NS
2,4-D + dicamba + MCP	0.56	b	0.76	c	NS
Halosulfuron	0.55	b	1.65	ab	NS
Sulfentrazone	0.52	b	1.41	ab	NS
Topramezone	0.62	ab	1.14	bc	NS
P-value	0.0419		0.0114		

^aMeans within each column followed by the same letter are not significantly different based on Fisher's protected LSD ($\alpha = 0.05$).

of *R. bulbosus* (Table 6), but physically altered *T. officinale* flowers, such that UV-reflecting area was reduced by 2,4-D + dicamba + MCP and topramezone (Table 6).

Pollinator visitation and floral quality are temporarily dependent on herbicide chemistry, with some herbicides eliminating food resources and others transiently impacting floral quality and density, thus supporting our hypothesis. Weedy floral quality and density reductions generally lag behind insect evacuation from herbicide-treated sites. Petal UV reflectance exhibited characteristics that suggest this factor contributes to but does not solely influence pollinator foraging behavior after herbicide treatment. Herbicides did not affect UV reflectance of *T. repens* and *R. bulbosus* flowers in contrast to effects on *T. officinale* flowers that mirror pollinator deterrence. Pollinator deterrence by these four herbicides was consistent across both UV-absorbing and UV-reflecting floral classifications in contrast with herbicidal effects on UV reflectance, which were dependent on floral UV-reflectance classification and even varied between species within UV-reflecting bullseye floral types. These data suggest that herbicides of differing MOAs may offer a variety of management solutions to pollinator deterrence in areas slated for insecticide treatment, as recommended by other researchers (Godara et al. 2023; MacRae et al. 2005; McDougall et al. 2021). These solutions range from long-term removal of food resources in areas that receive frequent insecticide treatments to transient floral suppression and sustained food resources in areas that rarely need insecticides. Nectar depletion after herbicide treatment (Kearns et al. 1998; King 1964) is speculated to be a major driver in reducing pollinator visitation. Future research will assess the effect of different herbicides on the temporal response of nectar production of weedy flowers and in situ bee exposure to pesticide and UV tracer dye following deterrent treatments.

Acknowledgments. The authors want to acknowledge Daewon Koo and Juan R. Cubas for their technical support. We also want to thank Annu Kumari for her assistance in making figures.

Funding. The authors thank the PBI Gordon Corporation for partially funding this study under the 2022 PBI-Gordan Turfgrass Pest Management Research Grant Program and also Virginia's Agricultural Council for partial funding.

Competing interests. The authors declare no conflicts of interest.

References

- Anonymous (2018) Halo 75 WDG Select™ specimen label. Middlesex, NC: Prime Source, LLC. 6 p

- Anonymous (2022) Imidacloprid 2F Turf & Ornamental Insecticide specimen label. Pasadena, TX: Control Solutions, Inc. 32 p
- Anonymous (2024) *Penstemon digitalis*. North Carolina Extension Gardener Plant Toolbox. <https://plants.ces.ncsu.edu/plants/penstemon-digitalis>. Accessed: February 14, 2024
- Askew SD (2017) Plant growth regulators applied in winter improve annual bluegrass (*Poa annua*) seedhead suppression on golf greens. *Weed Technol* 31:701–713
- [APVMA] Australian Pesticides and Veterinary Medicines Authority (2011) Public Release Summary of the Evaluation by the NRA of the New Active Constituent Halosulfuron-Methyl. Sydney NSW, Australia: APVMA. 169 p. <https://www.apvma.gov.au/sites/default/files/publication/13806-prs-halosulfuron-methyl.pdf>
- Besançon TE, Ghantous KM, Sandler HA (2021) Cranberry response to sulfentrazone rate, timing, and application volume. *Weed Technol* 35: 574–581
- Bohnenblust EW, Vaudo AD, Egan JF, Mortensen DA, Tooker JF (2016) Effects of the herbicide dicamba on nontarget plants and pollinator visitation. *Environ Toxicol Chem* 35:144–151
- Boyle PE, Wisdom MM, Richardson MD (2020) Testing flowering plants in a bermudagrass (*Cynodon* spp.) lawn. *HortScience* 55:1642–1646
- Bretagnolle V, Gaba S (2015) Weeds for bees? A review. *Agron Sustain Dev* 35:891–909
- Bunch TR, Gervais JA, Buhl K, Stone D (2012) Dicamba Technical Fact Sheet. Corvallis: National Pesticide Information Center, Oregon State University Extension Services
- Camargo MGG, Lunau K, Batalha MA, Brings S, de Brito VLG, Morelato LPC (2019) How flower colour signals allure bees and hummingbirds: a community-level test of the bee avoidance hypothesis. *New Phytol* 222:1112–1122
- Carpenter DJ, Mathiassen SK, Boutin C, Strandberg B, Casey CS, Damgaard C (2020) Effects of herbicides on flowering. *Environ Toxicol Chem* 39:1244–1256
- Clinebell RR, Bernhardt P (1998) The pollination ecology of five species of *Penstemon* (Scrophulariaceae) in the tallgrass prairie. *Ann Mo Bot Garden* 85:126–136
- DeMarche ML, Miller TJ, Kay KM (2015) An ultraviolet floral polymorphism associated with life history drives pollinator discrimination in *Mimulus guttatus*. *Am J Bot* 102:396–406
- Dicks LV, Breeze TD, Ngo HT, Senapathi D, An J, Aizen MA, Basu P, Buchori D, Galetto L, Garibaldi LA, Gemmill-Herren B, Howlett BG, Imperatriz-Fonseca VL, Johnson SD, Kovacs-Hostyanszki A, et al. (2021) A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nat Ecol Eval* 5:1453–1461
- Drummond FA, Ballman ES, Eitzer BD, Du Clos B, Dill J (2018) Exposure of honey bee (*Apis mellifera* L.) colonies to pesticides in pollen, a statewide assessment in Maine. *Environ Entomol* 47:378–387
- Duke SO (1990) Overview of herbicide mechanisms of action. *Environ Health Perspect* 87:263–271
- Dupont YL, Strandberg B, Damgaard C (2018) Effects of herbicide and nitrogen fertilizer on non-target plant reproduction and indirect effects

- on pollination in *Tanacetum vulgare* (Asteraceae). *Agric Ecosyst Environ* 262:76–82
- Fetridge ED, Ascher JS, Langellotto GA (2008) The bee fauna of residential gardens in a suburb of New York City (Hymenoptera: Apoidea). *Ann Entomol Soc Am* 101:1067–1077
- Garcia JE, Greentree AD, Shrestha M, Dorin A, Dyer AG (2014) Flower colours through the lens: quantitative measurement with visible and ultraviolet digital photography. *PLoS ONE* 9:e96646
- Gels JA, Held DW, Potter DA (2002) Hazards of insecticides to the bumble bees *Bombus impatiens* (Hymenoptera: Apidae) foraging on flowering white clover in turf. *J Econ Entomol* 95:722–728
- Gervais J, Luukinen B, Buhl K, Stone D (2008) 2,4-D Technical Fact Sheet. Corvallis: National Pesticide Information Center, Oregon State University Extension Services
- Gervais J, Luukinen B, Buhl K, Stone D (2010) Imidacloprid Technical Fact Sheet. Corvallis: National Pesticide Information Center, Oregon State University Extension Services
- Godara N, Askew SD (2023) Ultraviolet floral characteristics of volunteer plants in urban landscapes. In ASA, CSSA, SSSA International Annual Meeting, St Louis, MO, October 29 to November 1, 2023. <https://scisoc.confex.com/scisoc/2023am/meetingapp.cgi/Paper/150081>. Accessed: March 2, 2024
- Godara N, Williamson RC, Koo D, Askew SD (2023) Effect of herbicides on pollinator foraging behavior and floral morphology in white clover (*Trifolium repens* L.)-infested turfgrass. *Weed Technol* 37:221–225
- Goodman RD, Williams AE (1994) Honeybee pollination of white clover (*Trifolium repens* L.) cv. Haifa. *Aust J Exp Agric* 34:1121–1123
- Goulson D, Nicholls E, Botias C, Rotheray EL (2015) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347:1255957
- Held DW, Potter DA (2012) Prospects for managing turfgrass pests with reduced chemical inputs. *Annu Rev Entomol* 57:329–354
- Henry G, Tucker K, McCurdy J (2023) Response of common wildflower species to postemergence herbicides. *HortScience* 58:660–665
- Hicks DM, Ouvrard P, Baldock KCR, Baude M, Goddard MA, Kunin WE (2016) Food for pollinators: quantifying the nectar and pollen resources of urban flower meadows. *PLoS ONE* 11:e0158117
- Johnson SD, Andersson S (2002) A simple field method for manipulating ultraviolet reflectance of flowers. *Can J Bot* 80:1325–1328
- Kearns CA, Inouye DW, Waser NM (1998) Endangered mutualisms: the conservation of plant–pollinator interactions. *Annu Rev Ecol Syst* 29: 83–112
- King CC (1964) Effects of herbicides on nectar secretion. *J Apic Res* 3:5–9
- Klomborg Y, Dywou Kouede R, Bartos M, Mertens JE, Tropek R, Fokam EB, Janecek S (2019) The role of ultraviolet reflectance and pattern in the pollination system of *Hypoxis camerooniana* (Hypoxidaceae). *AoB Plants* 11: lz057
- Koh I, Lonsdorf EV, Williams NM, Brittain C, Isaacs R, Gibbs J, Ricketts TH (2015) Modeling the status, trends, and impacts of wild bee abundance in the United States. *Proc Natl Acad Sci USA* 113:140–145
- Kőrösi Á, Szentirmai I, Batáry P, Kövér S, Örvössy N, Peregovits L (2014) Effects of timing and frequency of mowing on the threatened scarce large blue butterfly—a fine-scale experiment. *Agric Ecosyst Environ* 196:24–33
- Koski MH, Ashman TL (2014) Dissecting pollinator responses to ubiquitous ultraviolet floral pattern in the wild. *Func Ecol* 28:868–877
- Larson JL, Dale A, Held D, McGraw B, Richmond DS, Wickings K, Williamson RC (2017) Optimizing pest management practices to conserve pollinators in turf landscapes: current practices and future research needs. *J Integr Pest Manag* 8:1–10
- Larson JL, Kesheimer AJ, Potter DA (2014) Pollinator assemblages on dandelions and white clover in urban and suburban lawns. *J Insect Conserv* 18:863–873
- Larson JL, Redmond CT, Potter DA (2013) Assessing insecticide hazard to bumble bees foraging on flowering weeds in treated lawns. *PLoS ONE* 8: e66375
- Larson JL, Redmond CT, Potter DA (2015) Mowing mitigates bioactivity of neonicotinoid insecticides in nectar of flowering lawn weeds and turfgrass guttation. *Environ Toxicol Chem* 34:127–132
- Lerman SB, Contosta AR, Milam J, Bang C (2018) To mow or to mow less: lawn mowing frequency affects bee abundance and diversity in suburban yards. *Biol Conserv* 221:160–174
- MacRae AW, Culpepper AS, Batts RB, Lewis KL (2008) Seeded watermelon and weed response to halosulfuron applied preemergence and postemergence. *Weed Technol* 22:86–90
- MacRae AW, Mitchem WE, Monks DW, Parker ML (2005) White clover (*Trifolium repens*) control and flower head suppression in apple orchards. *Weed Technol* 19:219–233
- McCurdy JD, McElroy JS, Flessner ML, Hoyle JA, Parker ET (2016) Tolerance of three clovers (*Trifolium* spp.) to common herbicides. *Weed Technol* 30:478–485
- McDougall R, DiPaola A, Blaauw B, Nielsen AL (2021) Managing orchard groundcover to reduce pollinator foraging post-bloom. *Pest Manag Sci* 77:3554–3560
- [NCIPMC] North Central Integrated Pest Management Center (2019) Best Management Practices for Turf Care and Pollinator Conservation. <https://www.ncipmc.org/2019-pollinators-bmp-booklet>. Accessed: January 30, 2024
- Papiorek S, Junker RR, Alves-Dos-Santos I, Melo GA, Amaral-Neto LP, Sazime M, Wolowski M, Freitas L, Lunau K (2016) Bees, birds and yellow flowers: pollinator-dependent convergent evolution of UV patterns. *Plant Biol* 18:46–55
- Parachnowitsch AL, Kessler A (2010) Pollinators exert natural selection on flower size and floral display in *Penstemon digitalis*. *New Phytol* 188:393–402
- Peitsch D, Fietz A, Hertel H, de Souza J, Ventura DF, Menzel R (1992) The spectral input systems of hymenopteran insects and their receptor-based colour vision. *J Comp Physiol A* 170:23–40
- [PMRA] Pest Management Regulatory Agency (2014) Registration Decision For Halosulfuron, Present as Methyl Ester. Ontario, Canada: PMRA. 7 p. https://www.canada.ca/content/dam/hc-sc/migration/hc-sc/cps-spc/alt_fmats/pdf/pubs/pest/_decisions/rd2014-20/rd2014-20-eng.pdf. Accessed: December 12, 2023
- Rae JM, Vamosi JC (2012) Ultraviolet reflectance mediates pollinator visitation in *Mimulus guttatus*. *Plant Species Biol* 28:177–184
- Ramos SE, Bakhtiari M, Castañeda-Zárate M, Iriart V, Ashman TL (2023) Herbicides and their potential to disrupt plant-insect chemical communication. *J Syst Evol* 61:550–560
- Sarukhan J (1974) Studies on plant demography: *Ranunculus repens* L., *R. bulbosus* L. and *R. acris* L. II. Reproductive strategies and seed population dynamics. *J Ecol* 62:151–177
- Schmitz J, Schafer K, Bruhl CA (2013) Agrochemicals in field margins—assessing the impacts of herbicides, insecticides, and fertilizer on the common buttercup (*Ranunculus acris*). *Environ Toxicol Chem* 32:1124–1131
- Shaner DL, ed (2014) *Herbicide Handbook*. 10th ed. Lawrence, KS: Weed Science Society of America
- Strandberg B, Boutin C, Mathiassen SK, Damgaard C, Dupont YL, Carpenter DJ, Kudsk P (2017) Effects of herbicides on non-target terrestrial plants. Pages 149–166 in Duke SO, Kudsk P, Solomon K, eds. *Pesticide Dose: Effects on the Environment and Target and Non-target Organisms*. Washington, DC: American Chemical Society
- [SAREP] Sustainable Agriculture Research & Education Program (2024) White Clover. Davis: University of California Agriculture & Natural Resources. <https://sarep.ucdavis.edu/covercrop/whiteclover>. Accessed: June 30, 2024
- Tunes P, Camargo MGG, Guimaraes E (2021) Floral UV features of plant species from a neotropical savanna. *Front Plant Sci* 12:618028
- [USDA] U.S. Department of Agriculture (2016) Reversing Pollinator Decline Is Key to Feeding the Future. <https://www.usda.gov/media/blog/2016/06/24/reversing-pollinator-decline-key-feeding-future>. Accessed: January 28, 2024
- [USEPA] U.S. Environmental Protection Agency (2012) Environmental Fate and Ecological Risk Assessment for First Residential Uses of Topramezone. Washington, DC: USEPA. 26 p. <https://www.regulations.gov/document/EPA-HQ-OPP-2012-0310-0006>. Accessed: November 14, 2023

- [USEPA] U.S. Environmental Protection Agency (2014) Preliminary Ecological Risk Assessment for the Registration Review of Sulfentrazone and Proposed New Uses on Apples, Sinclair, Barrett. Washington, DC: USEPA. 145 p. <https://www.regulations.gov/document/EPA-HQ-OPP-2009-0624-0017>. Accessed: December 17, 2023
- van der Kooi CJ, Elzenga JT, Dijksterhuis J, Stavenga DG (2017) Functional optics of glossy buttercup flowers. *J R Soc Interface* 14:20160933
- Westrich P (1996) Habitat requirements of central European bees and the problems of partial habitats. Pages 1–16 *in* Matheson A, Buchmann SL, O'Toole C, Westrich P, Williams IH, eds. *The Conservation of Bees*, London: Academic Press
- Wolfin J, Watkins E, Lane I, Portman ZM, Spivak M (2023) Floral enhancement of turfgrass lawns benefits wild bees and honey bees (*Apis mellifera*). *Urban Ecosyst* 26:361–375
- Zaleski A (1964) Effect of density of plant population, photoperiod, temperature and light intensity on inflorescence formation in white clover. *Grass Forage Sci* 19:237–247