Weed Technology

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Research Article

Cite this article: Brankov M, Piskackova T, Rajković M, Vukadinović J, Zarić M (2025) From noncultivated areas to the field: a case of cut-leaved gipsywort (*Lycopus exaltatus* L.) and its response to herbicides in Balkan major crops. Weed Technol. **39**(e90), 1–9. doi: 10.1017/wet.2025.10040

Received: 29 March 2025
Revised: 21 July 2025
Accepted: 23 July 2025

Associate Editor:
Rodrigo Werle, University of Wisconsin

Nomenclature:
Bentazon; dicamba; foramsulfuron; glyphosate; halauxifen-methyl; imazamox; mesotrione; nicosulfuron; tembotrione; thifensulfuron-methyl; tribenuron-methyl; cut-leaved gipsywort; *Lycopus exaltatus* L. LYAEX

Keywords:
Dose-response; *Lamiaceae*; herbicides; rhizomatous species

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From noncultivated areas to the field: a case of cut-leaved gipsywort (*Lycopus exaltatus* L.) and its response to herbicides in Balkan major crops

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Abstract

Certain plant species have the potential to establish themselves in agricultural fields, especially when they are already present nearby. Their spread can be influenced by improper management or intentional and unintentional introduction. Recently, cut-leaved gipsywort (*Lycopus exaltatus* L.) has been increasingly present in some row crops, where it was previously found only along field edges and irrigation channels, with no data about their presence in crops. Currently, no effective control methods for this rhizomatous species have been reported. To address this, 11 herbicides commonly used for weed management in major crops were evaluated in greenhouse studies. These included bentazon, dicamba, foramsulfuron, glyphosate, halauxifen-methyl, imazamox, mesotrione, nicosulfuron, tembotrione, thifensulfuron-methyl, and tribenuron-methyl. A dose-response study was conducted to identify the most effective option for cut-leaved gipsywort control using existing crop protection products. The study evaluated percentage reductions in dry biomass and canopy cover. The results suggest that bentazon, as the only nonsystemic herbicide, was least effective in controlling cut-leaved gipsywort with an effective dose (ED_{90}) estimated at 1.5 × of the recommended labeled rate, or 2,205 g ai ha^{-1}. Plants exposed to dicamba exhibited no regrowth at the field-use rate. Cut-leaved gipsywort may regrow when foramsulfuron, mesotrione, nicosulfuron, and tembotrione are applied at the recommended field-use rates. Halauxifen-methyl and imazamox were most effective, with estimated ED_{90} values of 0.21 × (0.85 g ai ha^{-1}) and 0.4 × (16.14 g ai ha^{-1}), respectively, which are lower than the recommended labeled rates. Although reduced rates are not recommended because good herbicide stewardship practices should aim to prevent the development of herbicide resistance, with both halauxifen-methyl and imazamox, cut-leaved gipsywort exhibited no regrowth when one-half of the recommended labeled rates were applied.

Introduction

Shifts in environmental conditions and land management practices have contributed to an increasing prevalence of some weeds across Europe (Krähmer et al. 2020). Weedy plants are often characterized as generalists, competitors, or ruderals, and they have the greatest potential to adapt rapidly to changes driven by human activities and environmental factors (Franks et al. 2007). In the Balkan nations, several plant species are characterized as invasive, while some that belong to the *Lamiaceae* family have not been yet reported as invasive (Brankov et al. 2024; Sarić-Krsmanović 2020).

Recently, cut-leaved gipsywort (*Lycopus exaltatus* L.) has become more prevalent in some row crops in the region, whereas previously it had been found only along field edges and irrigation channels. This species is a perennial herbaceous plant native to Europe and western Asia, but the plant is more typically found in sand and pebble shallows, river and lake shores, riverside thickets, inundated forests, and canals (Behçet and Cengiz 2023; Moon and Hong 2006). It has also been included in a list of Serbian weed flora (Nestorovic and Konstantinovic 2011); however, it remains a relatively unrecognized species and is not listed on herbicide labels. The species bears resemblance to *Ambrosia* and *Artemisia* species, which are commonly known as ragweeds and mugworts, respectively (Figure 1).

Especially in the vegetative growth stage, cut-leaved gipsywort may appear to be very similar to common ragweed (*Ambrosia artemisiifolia* L.) or a closely related species, western ragweed (*A. psilostachya* DC.). Both common ragweed and cut-leaved gipsywort have deep pinnatisect leaves with opposite leaf orientation (Behçet and Cengiz 2023). At the vegetative stage, the best distinguishing characteristic may be the square stem more typical to *Lamiaceae* family species,

Figure 1. Similarities in the vegetative growth between cut-leaved gipsywort (*Lycopus exaltatus* L.) (A) and western ragweed (*Ambrosia psilostachya* DC.) (B), including the leaf shape, presence of pubescence and opposite leaf orientation. Photo credits: A: Stefan Lefnaer, used under CC BY-SA 4.0 Wikimedia Commons, https://www.knowyourweeds.com/no/weeds/Lycopus_exaltatus; B) aarongunnar, used under CC-BY-4.0/, cropped and compressed from the original, https://www.picturethisai.com/wiki/Ambrosia_psilostachya.html.

whereas at the flowering stage the species may appear very different. While ragweeds and mugworts have flowering panicles of inconspicuous composite flowers at the end of all terminal branches, cut-leaved gipsywort produces clusters of white flowers in compact whorls at each leaf node. The flowering stage of cut-leaved gipsywort ranges from July to September, whereas ragweeds flower from August to October (Pladias 2025). By the time cut-leaved gipsywort begins to flower in July, most herbicides will have already been applied and may or may not have been effective.

Perennial weeds are difficult to control due to their deep root systems, strong reproductive capacity, adaptability, and ability to regrow. These plants may have one of several organ modifications: rhizomes (underground stems), stolons (aboveground stems), or bulbs, corms, and tubers (Hatcher 2017). Those modifications make perennial weeds hard to control because their energy storage or protected growing points are not vulnerable to specific mechanical tools and, in some cases, may aid in their spread (Miller 2016). If these weeds also have invasive tendencies, their management becomes even more challenging (Tataridas et al. 2022). Cut-leaved gipsywort has rhizomes, and therefore, its control might be challenging, as has been previously reported for other perennials (Saberi et al. 2022).

Because no data are yet available to determine any effects on crop yield, management of cut-leaved gipsywort should be approached with caution, particularly when aiming to limit its proliferation in row crops. Effective control requires a coordinated approach that integrates multiple tactics within a well-planned integrated pest management strategy (Buckley 2008). The period between a species introduction and its widespread establishment is critical for successful management through education, monitoring, prevention, and containment. Once a species becomes fully established, these efforts remain essential but tend to be less effective than the required effort (Black and Bartlett 2020). Corn (*Zea mays* L.), sunflower (*Helianthus annuus* L.), and soybean [*Glycine max* (L.) Merr] are extensively grown in Serbia, covering nearly two million hectares in recent years (Anonymous 2022). In some cases, herbicide applications to noncultivated areas may also be warranted, provided they are conducted with proper stewardship to prevent environmental disruption. Moreover, a dose-response study to evaluate the efficacy of currently available registered herbicides in crops is necessary to include in farmer handbooks and will be transferable to

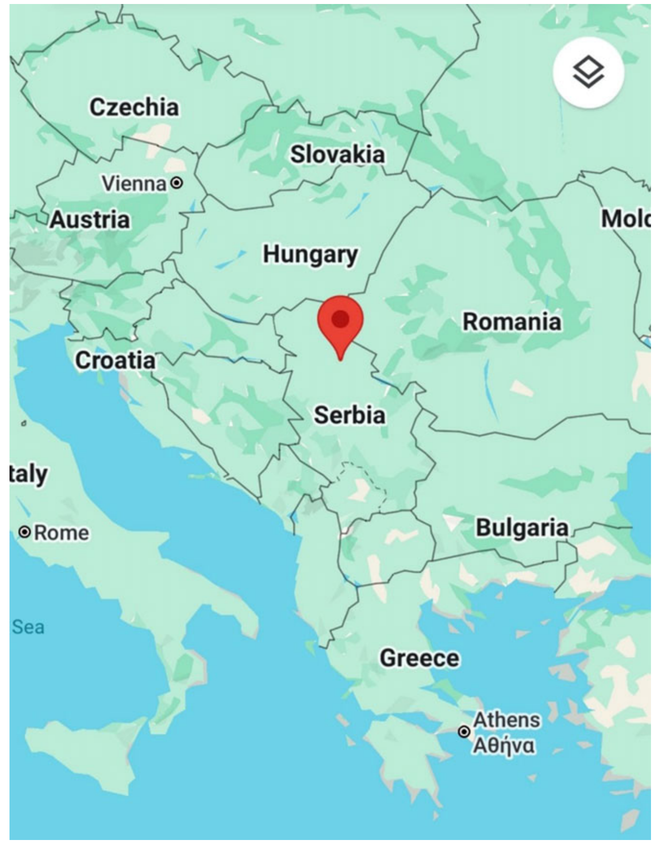

Figure 2. Location of Debeljača, Serbia, where cut-leaved gipsywort plants were obtained. Credit: Google maps.

a broader audience. Therefore, our objective was to evaluate the dose-response of 11 herbicides, selected based on their potential use in major row crops in Serbia. The herbicides included bentazon, dicamba, foramsulfuron, mesotrione, nicosulfuron, and tembotrione, which are used on corn; halauxifen-methyl, imazamox, and tribenuron-methyl used on sunflower; and bentazon, imazamox, and thifensulfuron-methyl used on soybean. Glyphosate was included because it is used to control cut-leaved gipsywort along rights-of-way, including roads and irrigation channels. Moreover, glyphosate may be used between crop seasons on stubble fields, where cut-leaved gipsywort may emerge following the harvest of small grain crops such as wheat (*Triticum vulgare* L.), barley (*Hordeum vulgare* L.), or oat (*Avena sativa* L.).

Materials and Methods

The population of cut-leaved gipsywort evaluated in the dose-response study was identified in July 2022 around Debeljača municipality in the Republic of Serbia (Figures 2 and 3) on several fields, mostly row crops, close to each other (45.0219°N 20.3351° E). Rhizomes from the vegetative reproduction stage of cut-leaved gipsywort were collected in spring 2023 and incubated for emergence in 10-L plastic containers filled with a commercial substrate (Floragard; Oldenburg, Germany). Before planting, rhizomes were cut into 5- to 10-cm segments. Therefore, only one population of the species was evaluated in this study. When seedlings were 5 cm tall they were transplanted, together with the rhizome part, into plastic cones 6.9 cm diam, 35.6 cm depth, and a volume of 983 mL (Stuewe and Sons, Inc., Corvallis, OR) filled with the same substrate and kept

https://doi.org/10.1017/wet.2025.10040 Published online by Cambridge University Press

Figure 3. Evidence of the presence of cut-leaved gipsywort near an irrigation channel (A), in a field of corn (B), and among soybean (C). Photo: Miloš Rajković, September 2022.

Table 1. Herbicides evaluated for cut-leaved gipsywort control[a].

Active ingredient	Group[b]	Trade name	Labeled crops[c]	Manufacturer	Rate[d]
					g ai ha^{-1}
Bentazon	6	Bentamark 480 SC	corn, soybean	Ningbo Sunjoy Agroscience	1,440
Dicamba	4	Plamen SC	corn	Galenika-Fitofarmacija	289
Foramsulfuron	2	Equip	corn	BASF	45
Glyphosate	9	Bingo 480	N/A[e]	Agroarm	960
Halauxifen-methyl	4	Viballa EC	sunflower	Corteva	4
Imazamox	2	Pulsar® SL	sunflower, soybean	BASF	40
Mesotrione	27	Intermezzo	corn	Agrosava	120
Nicosulfuron	2	Motivell Extra 6 OD	corn	Belchim	45
Tembotrione	27	Laudis OD	corn	BASF	88
Thifensulfuron-methyl	2	Harmony 75 WG	soybean	Corteva	8
Tribenuron-methyl	2	Express 75 WG	sunflower	Corteva	30

[a]Abbreviations: EC, emulsifiable concentrate; OD, oil dispersion; SC, suspension concentrate; SL, soluble concentrates; WG, water-dispersible granules.
[b]Herbicides are grouped according to criteria established by the Weed Science Society of America and the Herbicide Resistance Action Committee.
[c]Serbia and other countries in Europe do not grow genetically modified crops, and all herbicides are labeled for certain crops.
[d]Recommended field-use rate (1×).
[e]Not labeled for use on any crop in Serbia and other countries in Europe.

in the greenhouse. One plant was gown per cone. Plants were top-watered as needed. Plants were maintained in a greenhouse at the Maize Research Institute Zemun Polje in Belgrade, Serbia (44.52° N 20.20° E) with a temperature of 30/20 C day/night, under a 16-h photoperiod (LED growth lights 520 μmol s^{-1}; Philips Lighting, Somerset, NJ). Plants that grew to have 4 to 6 true leaves (10 to 15 cm-tall) were treated using a single-nozzle research-grade spray chamber (Avico Praha, Prague, Czech Republic). After application, plants were returned to the greenhouse and maintained for another 21 d. All applications used an AI95015EVS nozzle calibrated to deliver 93.5 L ha^{-1} at 414 kPa.

The dose-response study was conducted as a completely random design with four replications and two experimental runs (the first run was June to September 2023; the second run was September to November 2023). One plant was considered as one replication. Eleven herbicides were tested in the study (Table 1). Each herbicide was applied in the following doses: 0.125×, 0.25×, 0.5×, 1×, 2×, 4×, and 8×, where 1 × represents the labeled rate for each herbicide evaluated hereby (Table 1). The experiment included a nontreated control, wherein plants were grown under the same conditions. All evaluations were conducted by comparing herbicide-treated plants with the nontreated control.

Data Measurements and Statistical Analysis

Canopy cover was collected 21 d after treatment (DAT) using the CANOPEO cell phone application (Oklahoma State University, Norman, OK). CANOPEO is an image-based application used to accurately determine the percent of green canopy cover by classifying and counting the pixels representing green canopy in the image (Patrignani and Ochsner 2015). Fractional green canopy cover ranges from 0% (no green canopy cover) to 100% (complete green canopy cover). One photograph per plant was taken using a mobile telephone at 1 m from the base, using a tripod at an angle of 90°.

On Day 21, just before plant harvesting, visible observation on surviving (regrowth) was evaluated at all doses of each herbicide (yes vs. no regrowth). Regrowth assessments were evaluated using the treated parts. After canopy cover measurement, plants were harvested (cut at the soil surface) and dried at 60 C to constant mass. All canopy cover and dry biomass data were converted into a percentage of reduction compared with the nontreated control. Canopy cover and biomass reduction (y) were calculated using Equation 1:

$$y = 100 - \left[\left(\frac{X_{(treated)}}{\bar{X}_{(nontreated\ control)}} \right) * 100 \right] \qquad [1]$$

The *mselect* function in R software (R Foundation for Statistical Computing, Vienna, Austria) was used to compare models, and the four-parameter Weibull (type 2) was selected as the best-fit model based on Akaike information criterion (unpublished data). Cut-leaved gipsywort biomass and canopy cover reduction were analyzed using the DRC package in R software (Ritz et al. 2015) following Equation 2:

$$y = c + (d - c)\exp(-\exp(b(\log(x) - \log(e)))) \qquad [2]$$

where y represents biomass or canopy reduction (%), b is the slope at the inflection point, c is the lower limit (fixed at 0% for both

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Table 2. Model parameter estimates and standard errors for cut-leaved gipsywort biomass reduction 21 d after herbicide application.

Herbicide[b]	Model parameter[a]							
	b		*d*		*e*		BR_{90}	
			%		g ai ha^{-1}			
Bentazon	0.67	±0.10	83.10	±3.04	638.41	±101.16	2,205.44	±644.22
Dicamba	1.64	±0.15	84.78	±1.49	172.47	±8.45	286.57	±22.94
Foramsulfuron	0.48	±0.08	89.07	±2.48	8.09	±1.20	46.72	±15.47
Glyphosate	2.36	±0.32	89.39	±1.30	212.00	±8.02	301.92	±20.47
Halauxifen-methyl	2.11	±0.24	93.00	±0.79	0.58	±0.02	0.85	±0.05
Imazamox	0.46	±0.11	87.61	±1.53	2.62	±0.64	16.14	±4.30
Mesotrione	0.16	±0.04	95.86	±2.55	0.84	±0.43	122.29	±22.88
Nicosulfuron	0.88	±0.06	94.10	±1.27	15.75	±0.86	40.65	±4.10
Tembotrione	0.28	±0.06	94.43	±2.63	3.09	±0.92	62.87	±32.26
Thifensulfuron-methyl	1.00	±0.13	91.30	±1.81	2.32	±0.19	5.34	±0.92
Tribenuron-methyl	0.65	±0.15	89.21	±2.14	4.49	±0.51	17.91	±5.79

[a]The *b* parameter corresponds to the slope at the inflection point, *e* represents the inflection point, *c* is the lower limit (fixed to 0%), *d* corresponds to the upper limit, BR_{90} corresponds to the dose in g ai ha^{-1} required to achieve a 90% biomass reduction.
[b]Herbicide trade names, manufacturers, and application doses are presented in Table 1.

Table 3. Model parameter estimates and standard errors for cut-leaved gipsywort canopy cover reduction 21 d after herbicide application.

Herbicide[b]	Model parameter[a]							
	b		*e*		CR_{90}		CR_{95}	
			g ai ha^{-1}					
Foramsulfuron	0.82	±0.03	6.54	±0.14	17.99	±0.65	24.76	±1.18
Glyphosate	1.59	±0.06	152.49	±1.77	257.86	±304.34	304.34	±8.53
Halauxifen-methyl	1.76	±0.57	0.39	±0.03	0.63	±0.04	0.74	±0.09
Imazamox	0.41	±0.03	0.51	±0.09	3.97	±0.18	7.57	±0.25
Mesotrione	0.67	±0.08	3.98	±0.68	13.86	±0.48	20.54	±0.80
Nicosulfuron	0.92	±0.03	7.95	±0.12	19.61	±0.53	26.08	±0.89
Tembotrione	0.27	±0.02	0.11	±0.03	2.33	±0.24	6.17	±0.42
Thifensulfuron-methyl	0.93	±0.05	1.98	±0.08	4.87	±0.31	6.46	±0.51
Tribenuron-methyl	0.98	±0.13	2.29	±0.18	5.36	±0.22	7.01	±0.50

[a]The *b* parameter corresponds to the slope at the inflection point, *e* represents the inflection point, *c* is the lower limit (fixed to 0%), d is the upper limit (fixed to 100%), CR_{90} and CR_{95} correspond to the dose in g ai ha^{-1} required to achieve 90% and 95% reductions in canopy cover, respectively.
[b]Trade names, manufacturers, and application doses are presented in Table 1.

responses unless otherwise noted), *d* is the upper limit (fixed at 100% only for canopy reduction), and *e* is the inflection point. The model structure was simplified based on the biological behavior of the response variable. For biomass reduction, a three-parameter model was used by fixing the variable *c* at 0% (no injury baseline) and allowing the variable *d* to vary. For canopy reduction, a different three-parameter form was used by fixing *d* at 100% (complete canopy loss). At the same time, *c* was left unrestricted to capture instances of negative reduction (i.e., increased canopy relative to the untreated check, observed only in response to bentazon and dicamba). For all other treatments, *c* was fixed at 0%. Data from the two experimental runs were combined with at least three replications, and experimental runs were considered random effects. To evaluate whether data from Run 1 and Run 2 (for both biomass and canopy reduction) could be pooled for each active ingredient, run-by-dose interactions were tested by comparing a model with a separate dose-response curve to a model with pooled curves for each run using the analysis of variance function in the DRC package.

Results and Discussion

Among all tested herbicides labeled for use on corn, dicamba, foramsulfuron, mesotrione, nicosulfuron, and tembotrione provided acceptable control (efficacy >90%) of cut-leaf gipsywort at labeled field-use rates (FLR) (Tables 2 and 3). Biomass and canopy cover were reduced by 90% (ED_{90}) when tembotrione was applied at less than its FLR of 62.9 g ai ha^{-1} (0.71 × FLR) and 2.3 g ai ha^{-1} (0.02 × FLR). When mesotrione was applied the ED_{90} for biomass reduction was close to the FLR with an application of 122.29 g ai ha^{-1} and an ED_{90} for canopy coverage with 13.9 g ai ha^{-1} (0.12 × FLR). Nicosulfuron, dicamba, and foramsulfuron provided a 90% reduction in biomass, which was close to the FLRs of 0.99×, 0.90×, and 1.04 × for the three herbicides, respectively. However, when observing a 90% reduction in canopy cover, lower rates of 0.43×, 0.53×, and 0.4 × were required for nicosulfuron, dicamba, and foramsulfuron, respectively,. Bentazon required more than the FLR to provide a 90% reduction in biomass and canopy cover: 2,205.4 g ai ha^{-1} (1.53 × FLR), or 3,206 g ai ha^{-1} (2.2 × FLR), respectively (Tables 3 and 4). Based on visible estimates, cut-leaved gipsywort did not survive and had no regrowth after dicamba was applied at the FLR or higher (Table 5). However, regrowth was observed after foramsulfuron, mesotrione, and tembotrione were applied at their FLR, after 2 × FLR of nicosulfuron, and even up to the 8 × FLR of bentazon. Biomass and canopy cover reduction and their corresponding model parameters are shown in Figures 4 and 5.

Other tested herbicides are currently labeled for weed control in crops of either soybean (thifensulfuron-methyl) or sunflower (halauxifen-methyl and tribenuron-methyl), while imazamox can be used on both crops. Halauxifen-methyl provided 90% biomass reduction at 0.2 × FLR (0.8 g ai ha^{-1}), but all four herbicides

Table 4. Model parameter estimates and standard errors for cut-leaved gipsywort canopy cover reduction 21 d after herbicide application.

Herbicide[b]	Model parameter[a]									
	b		c		e		CR_{90}		CR_{95}	
			%		g ai ha^{-1}					
Bentazon	−1.03	±0.06	−17.68	±7.69	360.36	±48.23	3,158.65	±243.60	6,325.03	±637.24
Dicamba	1.41	±0.14	−40.45	±14.01	79.21	±5.51	143.11	±4.29	172.46	±6.38

[a]The *b* parameter corresponds to the slope at the inflection point, *e* represents the inflection point, *c* is the lower limit, *d* is the upper limit (fixed to 100%), CR_{90} and CR_{95} correspond to the dose in g ai ha^{-1} required to achieve 90% and 95% canopy reduction.
[b]Trade names, manufacturers, and application doses are presented in Table 1.

Table 5. Visible observations of cut-leaved gipsywort regrowth 21 d after herbicide application[a,b].

Herbicide	Rate						
	⅛×	¼×	½×	1×	2×	4×	8×
Bentazon	n/a	n/a	n/a	yes	yes	yes	yes
Dicamba	n/a	n/a	n/a	no	no	no	no
Foramsulfuron	n/a	n/a	yes	yes	no	no	no
Glyphosate	n/a	yes	yes	yes	yes	no	no
Halauxifen-methyl	n/a	yes	no	no	no	no	no
Imazamox	yes	yes	no	no	no	no	no
Mesotrione	n/a	n/a	yes	yes	no	no	no
Nicosulfuron	n/a	n/a	n/a	yes	yes	no	no
Tembotrione	n/a	n/a	yes	yes	no	no	no
Thifensulfuron-methyl	n/a	n/a	yes	yes	no	no	no
Tribenuron-methyl	n/a	yes	yes	no	no	no	no

[a]Key: Yes means that cut-leaved gipsywort plants survived the herbicide at the applied rate, no means they did not survive at that rate, and n/a indicates that plants survived that rate of herbicide but did not exhibit regrowth.
[b]Trade name, manufacturer, and application doses are presented in Table 1.

achieved 90% reduction at less than FLR: imazamox at 16.1 g ai ha^{-1} (0.40 × FLR), thifensulfuron-methyl at (0.59 × FLR), and tribenuron-methyl at 5.3 g ai ha^{-1} (0.66 × FLR). Once again, a 90% reduction in biomass did not occur at the same rates at which a 90% reduction in canopy cover occurred, and was estimated at lower rates: imazamox at 0.02 × FLR; halauxifen-methyl at 0.1 × FLR; thifensulfuron-methyl at 0.25 × FLR; and tribenuron-methyl at 0.08 × FLR. Glyphosate was also very effective at lower than FLR, achieving a 90% biomass reduction at 212 g ai ha^{-1} (0.22 × FLR) and a 90% canopy cover reduction at 152.5 g ai ha^{-1} (0.16 × FLR). Regrowth was not observed with imazamox or halauxifen-methyl at rates above 0.5 × FLR, whereas regrowth did occur with tribenuron-methyl up to 0.5 × FLR, thifensulfuron-methyl at 1 × FLR, and with glyphosate at up to 2 × FLR.

Because cut-leaved gipsywort has only recently been reported in row crops and vegetable fields, research on its control remains limited. This study aimed to evaluate the efficacy of postemergence herbicides as potential solutions for weed management in major crops. Given the challenges that some of the other rhizomatous species such as quackgrass (*Agropyron repens* [L.] Beauv.) or johnsongrass (*Sorghum halepense* [L.] Pers.) (Johnson and Norsworthy 2017), can cause in similar cropping systems, evaluating herbicide options for controlling cut-leaved gipsywort is particularly urgent. As previously described, perennial weeds are difficult to control and because they can regenerate from remaining roots or rhizomes. This regeneration can occur even after multiple attempts to control them, especially when ineffective methods are used, such application of contact herbicides alone or suboptimal herbicide rates are applied relative to plant size (Miller 2016). Likewise, Saberi et al. (2022) reported challenges in controlling western ragweed, also a rhizomatous broadleaf species. Identifying effective control strategies for this newly reported weed is particularly important not only due to its rhizomatous growth habit, which contributes to its persistence and spread, but also its morphological similarity to common annual species, which increases the risk for misidentification by farmers, potentially leading to inadequate management. Therefore, a key objective of this study is to raise awareness of this perennial species and its visible similarity to other annual species. For example, what may be perceived as a herbicide failure to control presumed populations of ragweed (*Ambrosia* spp.) or mugwort (*Artemisia* spp.), may actually involve misidentification of this perennial species of a completely different plant family.

Although our study was carried out in a greenhouse and it entailed testing a single population rather than in a field setting of growing crops, our findings can be beneficial for cut-leaved gipsywort control in the most commonly planted row crops, such as corn, soybean, or sunflower. The findings from our study indicate that effective options are available in each of these cropping systems. Among the herbicides we evaluated that can be applied to corn, mesotrione and tembotrione demonstrated the greatest efficacy, achieving a 90% reduction in biomass at rates of 0.28 × and 1.02 × of the FLR (Table 2). However, caution is needed because plants showed regrowth at 21 DAT. Furthermore, cut-leaved gipsywort survived an 8 × rate of the contact herbicide bentazon, suggesting it may not be a reliable option for control. Given that perennial species often recover from nonsystemic herbicides, these products are generally less suitable for effective management of cut-leaved gipsywort (Kaya-Altop et al. 2016). For other available herbicides for weed control in corn, only plants treated with dicamba exhibited no regrowth at the FLR (Table 4), whereas survival was observed when other herbicides (foramsulfuron and nicosulfuron) were applied at the same rate. This would raise concerns about the potential development of nontarget site resistance in surviving plants, although more populations will need to be evaluated before such conclusions can be drawn (Rey-Caballero et al. 2017; Vieira et al. 2019). Among acetolactate synthase inhibitors, foramsulfuron and nicosulfuron achieved 90% biomass reduction at rates closely aligned with their respective field-use rates (46.72 and 40.65 g ai ha^{-1}, respectively). However, regrowth was observed at the FLR for foramsulfuron and at 0.5 × FLR for nicosulfuron, emphasizing the need for attention.

Among the evaluated herbicides labeled for use on soybean and sunflower, halauxifen-methyl and imazamox were the most effective at controlling cut-leaved gipsywort, achieving a 90% reduction in biomass at doses of 0.21 × and 0.4 × of the FLR, respectively (Table 2). Moreover, plants did not survive either herbicide, even at 0.5 × FLR. These results, along with previous research on halauxifen-methyl and imazamox (Malidža et al. 2023), suggest that these herbicides may provide excellent control

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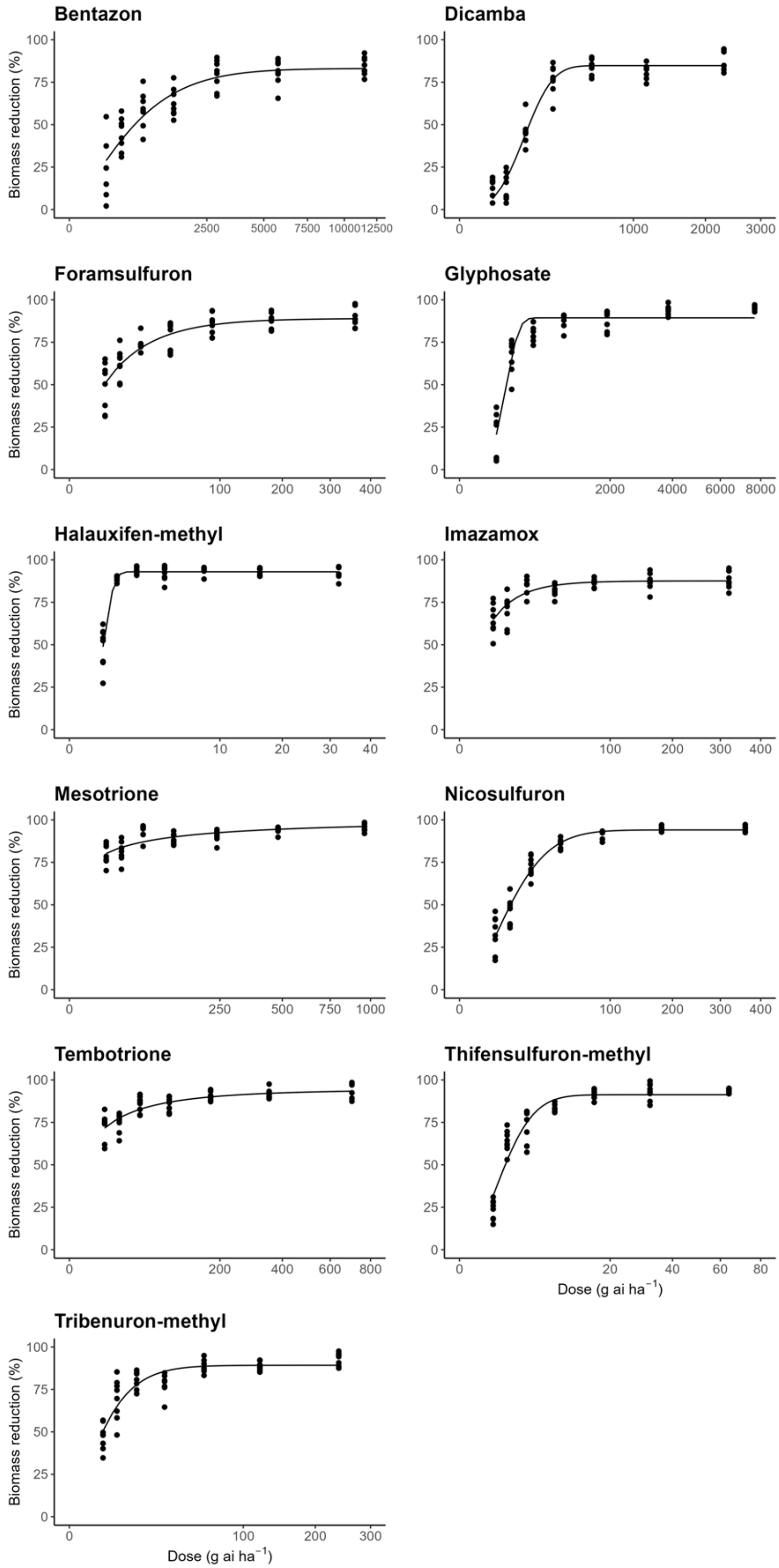

Figure 4. Biomass reduction in cut-leaved gipsywort 21 d after applications of bentazon, dicamba, foramsulfuron, glyphosate, halauxifen-methyl, imazamox, mesotrione, nicosulfuron, tembotrione, thifensulfuron-methyl, and tribenuron-methyl. Trade names, manufacturers, and application doses are listed in Table 1. Model parameter estimates are presented in Table 2.

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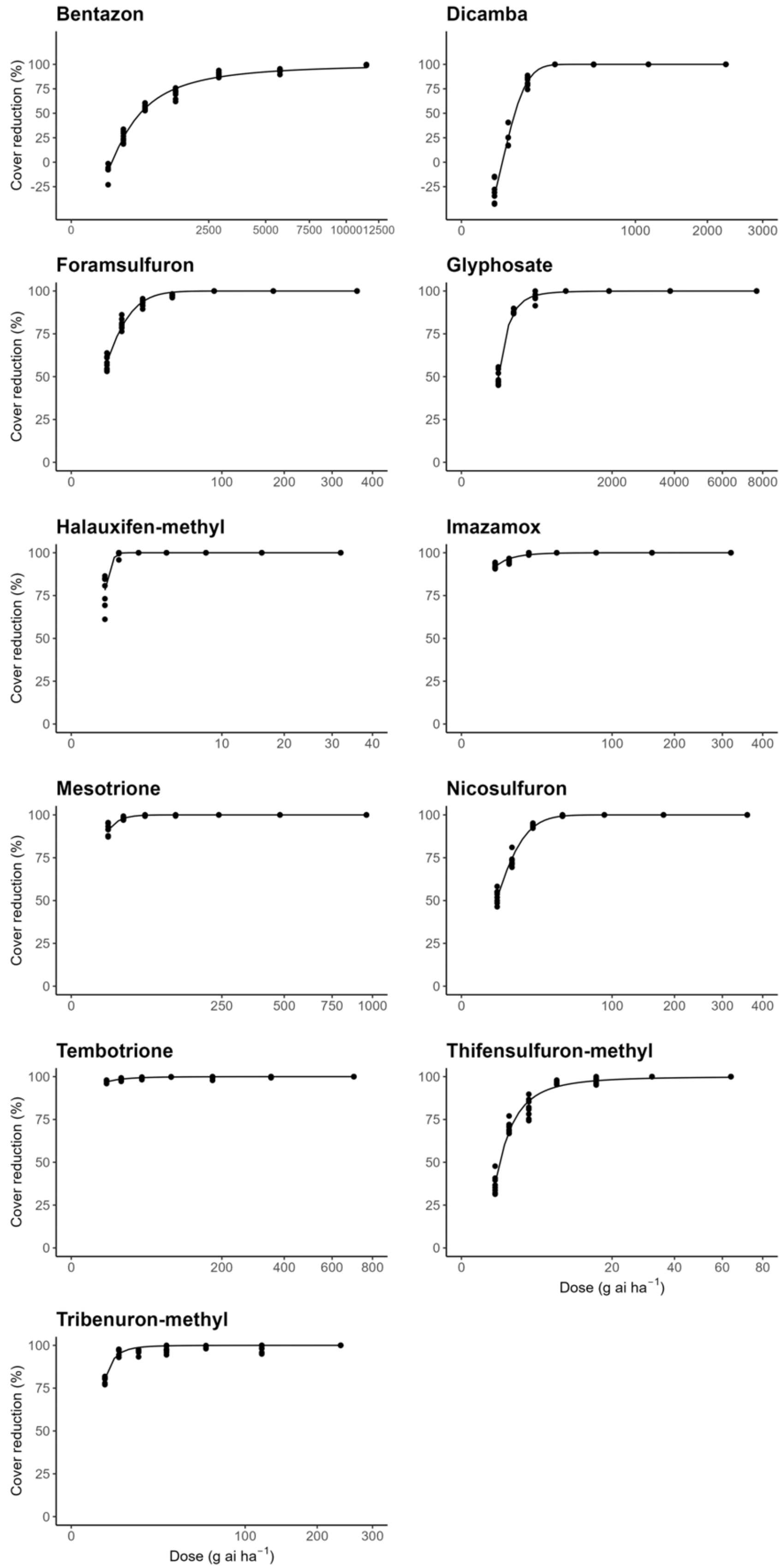

Figure 5. Cover reduction in cut-leaved gipsywort 21 d after applications of foramsulfuron, glyphosate, halauxifen-methyl, imazamox, mesotrione, nicosulfuron, tembotrione, thifensulfuron-methyl, tribenuron-methyl, bentazon, and dicamba. Trade names, manufacturers, and application doses are presented in Table 1. Model parameter estimates are presented in Tables 3 and 4.

https://doi.org/10.1017/wet.2025.10040 Published online by Cambridge University Press

of cut-leaved gipsywort. Similarly, plants treated with tribenuron-methyl did not survive the FLR, further supporting its potential effectiveness.

Because cut-leaved gipsywort often establishes along field boundaries, irrigation channels, and noncultivated areas, targeted management in these locations is crucial to prevent the weed's further spread (Fogliatto et al. 2020). Glyphosate is registered for weed control in noncultivated areas and on stubble in Europe, including Serbia, where its approval was recently extended for another 10 yr (EU Commission December 2023). Given its role in spot treatments in high-risk areas, assessing glyphosate efficacy against cut-leaved gipsywort was particularly important. Although a 90% reduction in biomass (ED_{90}) was achieved at one-third of the FLR, regrowth was observed even at twice the field rate (Table 3), raising concerns about the potential for nontarget site resistance as well as ineffective control and further species spread. Because glyphosate remains one of the most cost-effective herbicides (Clapp 2021), it should not be used alone but rather in combination with other herbicides with effective modes of action to mitigate resistance risks. It is worth mentioning a notable discrepancy between biomass reduction and canopy reduction using herbicides that inhibit4-hydroxphenylpyruvate dioxygenase. Because those herbicides provided acceptable biomass reduction, canopy cover was even more influenced. However, dry biomass would be the parameter practitioners should rely on, because it is the best parameter for dose-response studies (Knezevic et al. 2007).

This study focused exclusively on evaluating chemical control options for cut-leaved gipsywort, but additional strategies may enhance its management. Saberi et al. (2022) reported that mowing just before flowering can improve control of rhizomatous species (perennial ragweed), though this approach is often impractical within the crop season when most plants are emerging and flowering. A fully integrated approach to weed management will be necessary to prevent the further spread of this species. This includes diversifying cropping systems, rotating and combining herbicide modes of action (Brankov et al. 2021), and applying herbicide mixtures to reduce selection pressure for resistance (Beckie and Harker 2017). Additionally, optimizing herbicide efficacy will require comprehensive adjuvant screening to enhance control of cut-leaved gipsywort. Furthermore, as reported by Brankov et al. (2023), adding adjuvants to nicosulfuron is beneficial in johnsongrass control, another rhizomatous species that is prevalent in this region.

Based on the present research, the herbicides tested here can be a part of available options for cut-leaved gipsywort control. These herbicides are labeled for use on the three most frequently planted crops in the region in rotation with small grain crops (Brankov et al. 2021); therefore, opportunities exist for cut-leaved gipsywort control. Mesotrione and tembotrione may be the most suitable option in corn crops, whereas herbicides that inhibit acetolactate synthase require caution due to possible regrowth. Dicamba may also be a satisfactory option, but bentazon will not be an effective choice after cut-leaved gipsywort has become established. Halauxifen-methyl and imazamox present excellent options for use on sunflower and soybean crops since no regrowth was observed at even 1/2 × of the FLR. As always, effective use of herbicides should be just part of a comprehensive management strategy against newly in-field species, but if a large area of potential habitat is already under herbicide management, growers have an opportunity to base their herbicide choice on known efficacy if they identify this weed in their fields.

Practical implications

Although this species is not a primary alarm for growers, it has the potential to become problematic in the future. The research presented here shows that it is possible to control cut-leaved gipsywort with available herbicides, and hopefully this species can be added to some herbicide labels in the future. Having 10 out of 11 evaluated herbicides provide more than a 90% reduction in biomass will help growers find the best herbicide option for cut-leaved gipsywort control in either corn, sunflower, or soybean. However, potential regrowth should be closely monitored after application to track the possible spread of the species. If a grower practices a 2- or 3-yr crop rotation that includes corn, soybean, or sunflower with a small grain crop, they may achieve great efficacy against cut-leaved gipsywort. Together with herbicide monitoring, it is essential to control weeds in edges and channels close to fields because they can be reservoirs of noxious weeds (Vieira et al. 2020). An understanding of the field history will be beneficial for selecting preventive measures and for rotating specialty crops with row crops for a few years to clean up the field.

Testing a single population of cut-leaved gipsywort presents a limitation to the broader applicability of the findings. The response we observed may reflect localized adaptation shaped by specific management practices and selection pressures in the study area. Consequently, other populations exposed to different herbicide regimes, dominant crop rotations, or environmental conditions may exhibit varying levels of tolerance. Future studies incorporating multiple geographically and agronomically diverse populations are necessary to more fully understand the variability in species-wide responses and inform regionally relevant management strategies.

Acknowledgments. We thank Dr. Goran Malidža, president of the Weed Science Society of Serbia, for his help in species identification.

Funding. This research received support from the Serbian Ministry of Science, Innovations, and Technological Development via Grants 451-03-136/2025-03/200040 and 451-03-136/2025-03/200003.

Competing interests. The authors declare they have no competing interests.

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