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Propane Flaming as a New Approach to Control Mediterranean Invasive Weeds

Alon Horesh [1,2], Yaakov Goldwasser [1], Karam Igbariya [1], Zvi Peleg [2] and Ran Nisim Lati [1,*]

1 Department of Plant Pathology and Weed Research, Newe Ya'ar Research Center, Agricultural Research Organization, Ramat Yishay 30095, Israel; alon.horesh@mail.huji.ac.il (A.H.); Yaakov.Goldwasser@mail.huji.ac.il (Y.G.); karam@volcani.agri.gov.il (K.I.)

2 The Robert H. Smith Institute of Plant Sciences and Genetics in Agriculture, The Hebrew University of Jerusalem, Rehovot 7610001, Israel; zvi.peleg@mail.huji.ac.il

* Correspondence: ranl@volcani.agri.gov.il; Tel.: +9724-9539529

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Abstract: In recent decades, anthropogenic activity and climate changes have reshaped global weed dispersal and establishment in new territories. This study aimed to evaluate the effectiveness of propane flaming approach in the control of perennial invasive and native Mediterranean broadleaf and grass weeds. The invasive weeds, *Cyperus rotundus*, *Sorghum halepense*, and *Ecballium elaterium*, were treated multiple times with a single propane dose (2.5 kg propane km^{-1}), using the broadcast technique. The local annual weeds, *Sinapis arvensis*, *Lavatera trimestris*, and *Avena sativa*, were treated once at five propane doses (0–2.5 kg propane km^{-1}), using the cross-row technique. Dose-response analysis was performed. Three applications provided effective control (up to >90%) for all tested perennials, and affected seed and flower production in *Sorghum halepense* and *Ecballium elaterium*, respectively. However, the timing of the sequential application had a significant impact on the degree of control, in terms of dry weight reduction and seed production. Weed density had an impact on control efficacy but was only a significant determinant for *Ecballium elaterium*. Cross-row application was effective during early growth stages of broadleaf weeds (ED_{50} < 1.2 kg propane km^{-1}), but was less effective during later growth stages (ED_{50} > 2.6 kg propane km^{-1}). For grass weeds, both early and late application were ineffective (ED_{50} > 4.1 kg propane km^{-1}). More research is needed to optimize this weed control tactic for various cropping systems and weed species. Implementation of this novel approach into integrated weed management programs will increase the control efficacy of invasive weed under the projected climate changes and reduce the evolution of herbicide-resistant weeds.

Keywords: broadcast; broadleaf; cross-row; climate change; grasses; growth-stage; perennial weeds

1. Introduction

Invasive weeds pose a great threat to ecological and agronomical systems throughout the world, by reducing crop productivity, disturbing the ecosystem functions and reducing species biodiversity [1,2]. The economic impact of invasive plant species is estimated at $137 billion per one year only in the U.S., and extreme scenarios may result in irreversible damage to the environment, such as the extinction of native species and abandonment of highly infested fields [3]. While herbicides are the most common tool for invasive weed control [4], in recent years, use of alternative non-chemical weed control practices and/or integration of new weed management strategies have been gaining attention [5,6]. This trend was mainly motivated by the rapid development of herbicide-resistant weeds and the need to conserve viable herbicides and modes of actions. Other catalysts have been increasing environmental awareness and the rising demand for pesticide-free food [7].

One of the non-chemical alternatives for weed control is the use of propane weed flaming, i.e., flaming. This method has become the major thermal weed control tactic in organic cropping systems in the US, such as soybean (*Glycine max*), corn (*Zea mays*), and sorghum (*Sorghum bicolor* (L.) Moench), as it provides effective weed control while minimizing the negative environmental effects associated with herbicide application [8,9]. Flaming kills plants by rupturing plant cell membranes, which eventually causes tissue desiccation [10,11]. The burners can create flame temperatures of up to 1900 °C, which is lethal to the target plant tissues [12].

Broadcast and cross-row are the two major strategies used in weed flaming [13,14]. For broadcast flaming, the burners are mounted parallel to the crop row, and the entire area of the field is covered with overlapping flames [15]. This strategy is suitable for perennial crops (e.g., vineyards) and for some row crops (e.g., corn, and onion (*Allium cepa*)) and can be applied as a sole method before (PRE) and after (POST) crop emergence [16]. In cross-row flaming, the burners are mounted in a staggered position, angled to the crop row, while the flames are targeted exclusively to the intra-row area from both sides of the row, leaving the inter-row area untreated [17]. The cross-row technique is suited for row crops, as it can be adjusted to different crop sizes and row spacings. Most studies that evaluated weed flaming control efficacy of specific species, used the broadcast techniques, and to the best of our knowledge, only one study used the cross-row technique [13].

Flaming efficacy varies by the weed species and its growth stage [7,14,18]. Previous studies testing the selectivity of broadcast flaming for some grasses (barnyardgrass (*Echinochloa crus-galli*)) and broadleaf (e.g., bindweed (*Convolvulus arvensia*) and kochia (*Kochia scoparia*)) weeds, at different growth stages (third leaf to flowering) and propane doses (0–87 kg propane ha^{-1}), found that flaming efficacy differs among the different species, their growth stage and applied dose. In general, the grass weeds were more tolerant to flaming than the broadleaf weeds, regardless of the growth stage. However, these studies were performed on local weed species in the northern parts of America (e.g., Nebraska, USA) and in Europe. To the best of our knowledge, there are only a few studies assessing the potential impact of flaming on local Mediterranean weed species [19]. Furthermore, Mediterranean cropping systems (perennial and row crops) are highly infected by perennial and invasive weeds, such as *Cyperus rotundus* (purple nutsedge), *Sorghum halepense* (Johnsongrass) and *Ecballium elaterium* (squirting cucumber). Nonetheless, there is no information about the potential use of flaming in controlling these species. The present study aimed to evaluate the potential use of flaming in perennial and annual weed control and to characterize typical Mediterranean weed species response to such treatment at different phenological stages.

2. Materials and Methods

2.1. Plant Material and Growth Conditions

Annual weed: *Lavatera trimestris* and *Avena sativa* were collected from a naturally infested field near the Newe Ya'ar Research Center in Israel (lat 32°42′, long 35°10′) that had not been treated with herbicides for six years. Seeds were collected between 2016–2018. The seed-bearing parts of the plants were collected in the field and air-dried for one month in a dry-environment greenhouse (~40 °C at noontime) until the seeds separated naturally from the plants. Seeds were cleaned from plant debris and stored at room temperature under dark and dry conditions, until use. Black mustard (*Brassica nigra*) seeds of the common cultivar in Israel were used for the experiments.

Perennials and invasive weeds: The plant material was collected at the same time and place as mentioned for the annual weeds. *Cyperus rotundus* tubers were collected one week before planting, wrapped in damp filter paper and stored at 4 °C until use. Tuber sprouting was 95% under constant-temperature conditions (25 °C). *Ecballium elaterium* seeds were collected into paper bags by touching the fruit capsules and inducing the natural dispersal mechanism. Then, seeds were treated as described for annual species. *Sorghum halepense* was collected and treated as described for annual species.

Experiments were conducted at the Newe Ya'ar Research Center between 2016 and 2018. Two-liter pots were filled with clay soil (57% clay, 23% silt, and 20% sand, on a dry-weight basis and 2% organic matter) and seeded with five weed seeds then thinned to one plant per pot seven days after emergence. When the impact of plant density was evaluated (Section 2.2), higher density was obtained by leaving some of the pots without thinning, resulting in five plants per pot. Plants were placed in a net-house and watered by an automated mini-sprinkler irrigation system as needed. For the flaming treatments, pots were taken from the net-house, placed 50 cm apart on a 10-m-long line, and the flaming was performed in a straight line such that the pots were between the burners. Following treatment, pots were placed back in the net-house and after 14 days, shoots were harvested, and their fresh weight was weighed. Dry weight was measured and recorded after 72 h of drying in a 70 °C oven.

2.2. Flaming Experiments

Some annual weeds can be adequately controlled by a single flaming application, while perennials require multiple applications [7]. Thus, two different flaming strategies, broadcast, and cross-row, were examined across a variety of factors. Broadcast flaming was tested on three perennial weed species at different densities, growth stages, number of applications and timing of the last application. Cross-row flaming was tested on three annual weeds species at different growth stages and propane doses.

Broadcas: Experiments were performed on the perennials and invasive weeds using an un-shielded Red Dragon two-burner system equipped with two liquid-phase torches (LT 1 1/2 × 6; Flame Engineering Inc., LaCrosse, KS, USA). The burners were connected to a 12-kg propane tank mounted on a cart to simulate commercial tractor application. The burners were mounted 30 cm apart, positioned 20 cm above the soil surface, parallel to the crop row and angled 30° to the soil, resulting in a treated bandwidth of 50 cm. The cart was manually pushed over the pots at a speed of 3 km h^{-1}, with a constant pressure of 50 psi. Propane doses were converted to kg propane km^{-1} as described in previous studies [13,17], leading to an application dose of 2.5 kg propane km^{-1}. Each experiment was conducted twice. Experiments were conducted using a complete randomized design with seven replicates.

The first experiment aimed to determine the impact of weed density and growth stage on control efficacy. To this end, the weeds were planted at two densities, one or five plants per pot, and treated 23 or 33 days after planting (DAP). These timings represent well-established growth stages at which weed control poses a challenge. Additionally, during the main growth season of these weeds (between May and September), a 10-day interval is significant in terms of biomass accumulation and reproductive growth (Horesh, personal observation). Efficacy was evaluated by measuring the dry weight of the above-ground plant parts.

The second experiment aimed to determine the impact of sequential propane applications on control efficacy. To this end, weeds were treated once, twice or three times, with two days interval between applications. For *E. elaterium*, the first application was performed at 33 DAP, while for *C. rotundus* and *S. halepense*, treatment was applied at 23 DAP. These timings were selected according to results from the first experiment, where treatment was not always effective.

The third experiment evaluated the impact of the timing of the last application on control efficacy. *Cyperus rotundus* and *S. halepense* were each treated three times and *E. elaterium* was treated twice. However, the last application of all three species was performed at two different stages, 1 or 10 days after previous treatment (DAPT). Table 1 summarizes the weed species, application timings and growth parameters evaluated in this experiment.

Table 1. Weed species, application timings (days after planting (DAP)) and evaluated growth parameters following the second\third application on the perennial and invasive weeds.

Weed Species	Applications (DAP)			Growth Parameters
	First	Second	Third	
Ecballium elaterium	33	34/43		Above-ground dry weight, number of flowers
Cyperus rotundus	23	25	26/35	Above-ground dry weight, roots dry weight, number of tubers
Sorghum halepense	23	25	26/35	Above-ground dry weight, roots dry weight, number of rhizomes, seeds weight

Cross-row: Experiments were performed on the annual weeds using an unshielded Red Dragon two-burner system equipped with two liquid-phase torches (LT 1 1/2 × 8; Flame Engineering Inc., LaCrosse, KS, USA), that were both connected to the same cart. Burners were set in a cross-row design, at a 45° angle with respect to the zenith, and 20 cm from the crop line, resulting in a 30-cm treated bandwidth. Burners were mounted in a staggered position to avoid intersecting flames. The same driving speed was used, however, different propane doses were tested by using a gas-valve regulator connected to the gas system and adjusted to pressures between 6.5–50 psi, resulting in doses between 0.9–2.5 kg propane km^{-1}. Table 2 summarizes the weed species, growth stages and propane doses used in this experiment. Each experiment was conducted twice, using a complete randomized design, with five replicates for each dose.

Table 2. Weed species, growth stages and propane doses used in the cross flaming experiment.

Weed Species	Growth Stage	Propane Doses (kg propane km^{-1})
Sinapis arvensis	4 and 8–10 leaves	0.95, 1.45, 1.8 and 2.5
Lavatera trimestris	3 and 6 leaves	0.95, 1.45, 1.8 and 2.5
Avena sativa	3 and 6 leaves	0.95, 1.45, 1.8 and 2.5

2.3. Data Analysis

Broadcast: For the first experiment, weed dry weights were analyzed by ANOVA, and a two-way analysis was performed to determine the interaction between weed density (one and five plants per pot) and growth stage (23 and 33 DAP) on control efficacy. For the second and third experiments, the evaluated growth parameters were analyzed by ANOVA, and means were separated using the Tukey–HSD test, $p \leq 0.05$ and t-test, respectively.

Cross-row: Dry weight data were analyzed using a three-parameter log-logistic function [20]:

$$y = \frac{m}{1 + (\frac{x}{x_{50}})^b} \quad (1)$$

where y is the shoot dry weight of the weeds (g), m is the upper asymptote value (maximum), x is the propane dose (kg propane km^{-1}), x_{50} is the propane dose when y is 50% of the maximum (also known as ED_{50}), and b is the slope at x_{50} [21].

3. Results

3.1. Broadcast Flaming is an Effective Means to Control Invasive Mediterranean Weeds

The experiments in this section evaluated the impact of growth stage and weed density on the control efficacy of invasive Mediterranean weeds by flaming and examined how sequential propane applications affected the control level and phenology of these weeds. The weed growth stage at application had a significant impact on the weed above-ground dry weight measured at the end of the experiment (Table 3, $p \leq 0.026$ for all tested species). For example, *S. halepense* treated at early

(23 DAP) and late (33 DAP) growth stages, showed an above-ground dry weight of 20% and 47% of the non-treated control, respectively. *Sorghum halepense* and *C. rotundus* weed density did not have a significant impact on the above-ground dry weight, and for both species, the flaming treatment resulted in an above-ground dry weight of ~35% of the non-treated control at both tested densities. However, an interaction between the main factors (weed density and growth stage) was observed in *E. elaterium* ($p < 0.0001$), and the mean separation of the above-ground dry weights revealed that the low-density weeds (one plant pot^{-1}) treated at early (23 DAP) versus late (33 DAP) growth stages, resulted in the lowest (3%) versus highest (81%) above-ground dry weight values, respectively. In contrast, when treating the high-density weeds (five plants pot^{-1}) at the early or late growth stages, above-ground dry weight values were not significantly different (40% and 36%, respectively; Table 3).

Table 3. Interaction between weed density (seeds pots^{-1}) or growth stage (days after planting (DAP)) and weed dry weight (% of non-treated control). Values with different letters are significantly different according to Tukey–HSD test.

		Dry Weight (% of Non-Treated Control)		
Main Effect		***Sorghum halepense***	***Cyperus rotundus***	***Ecballium elaterium*** [a]
DAP				
23		20 B	29 B	
33		47 A	41 A	
Density (DS)				
1 plant pot^{-1}		34 A	36 A	
5 plant pot^{-1}		34 A	33 A	
Source of variance	d.f.	Sum of squares		
DAP	1	5814 ***	962 *	10342 ***
DS	1	1.33	68	97
DAP × DS	1	0.22	101	12833 ***
Total				

[a] Mean separation by Tukey–HSD test for *Ecballium elaterium*: 33 DAP and one plant pot^{-1}: 81 A; 23 DAP and five plant pot^{-1}: 40 B; 33 DAP and five plant pot^{-1}: 36 B; 23 DAP and one plant pot^{-1}: 3 C.* and *** indicates a significant difference of $p < 0.05$ and $p < 0.0001$, respectively.

Sequential propane applications using the broadcast technique revealed that any additional treatment contributed significantly ($p < 0.0001$) to the control of *C. rotundus* and *S. halepense* (Figure 1). The mean above-ground dry weights of *C. rotundus* dropped from 66% of the non-treated control (range of 20–100 %) after a single treatment, to 25% of the non-treated control (range of 7–51 %) and 10% of the non-treated control (range of 2–38 %) after two and three applications, respectively (Figure 1). Overall, the percent of plants with high (> 90%) level of control increased from 0% to 56% following a single versus triple application, respectively (Table 4). *Sorghum halepense* was more resistant to the flaming treatments, with only 12% of the plants showing high (>90%) weed control following three applications (Table 4). In contrast, the number of treatments had no significant impact on *E. elaterium* ($p = 0.217$). However, the dry weights following a single application varied from 0 to 81% of control, compared to 0% of control for all plants following a triple application (Figure 1). Correspondingly, the percent of plants exhibiting high (> 90%) control levels increased from 31% to 100% following a single versus triple applications, respectively (Table 4).

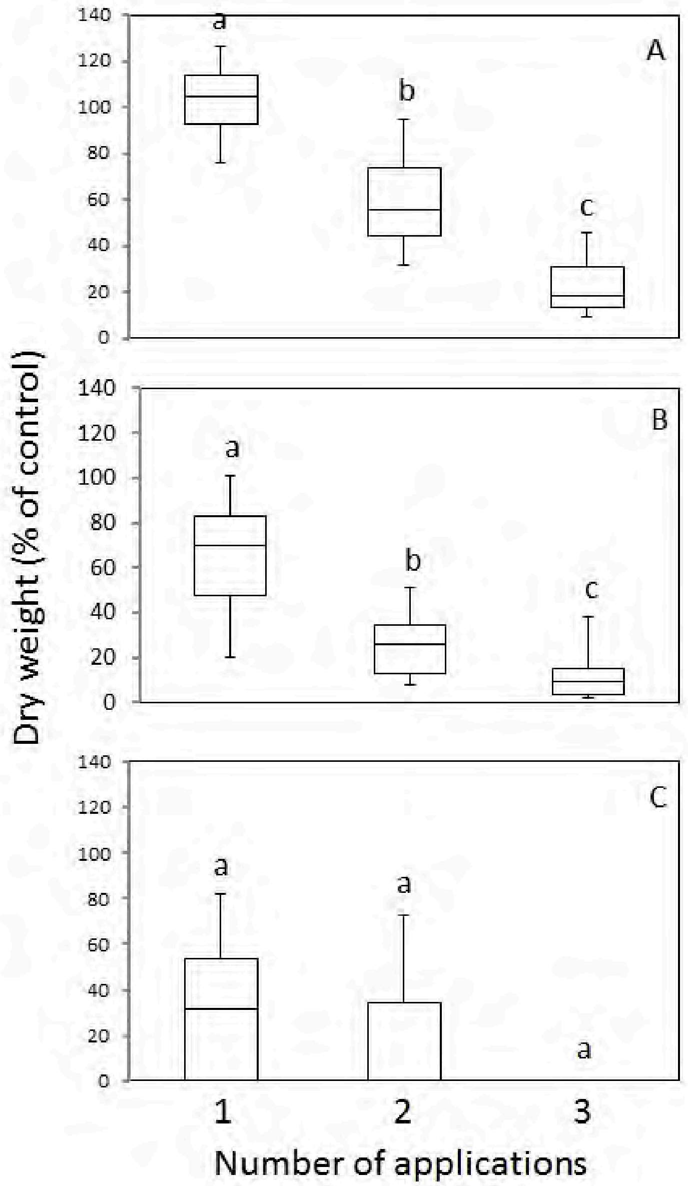

Figure 1. The impact of sequential flaming applications on the dry weight (% of control) of *Sorghum halepense* (**A**), *Cyperus rotundus* (**B**) and *Ecballium elaterium* (**C**). Different letters indicate significant differences, as determined by Tukey LSD test ($p \leq 0.05$). Values are means ± SD ($n = 7$).

Table 4. Plants (%) with >90% dry weight reduction following one, two or three applications of flaming ($n = 7$).

	Plants (%) with >90% Dry Weight Reduction		
Number of Applications	**#1**	**#2**	**#3**
Sorghum halepense	0	0	12
Cyperus rotundus	0	6	56
Ecballium elaterium	31	68	100

The timing of the second/third application had a significant impact on the degree of weed control, and for all tested species, the later application (10 DAPT) was more effective compared to the earlier one (1 DAPT). Nevertheless, not all morphological parameters were equally affected by the timing of the last treatment. More specifically, for *S. halepense*, the above-ground, roots, rhizome and seed weights following the later (10 DAPT) treatment were 48%, 59%, 73%, and 59%, respectively, lower compared to after the earlier treatment (1 DAPT). For example, the mean rhizome dry weight was 42% (range 0–81 %) and 11% (range 0–35 %) of the non-treated control following the early and later applications, respectively (Figure 2). *Cyperus rotundus* was less affected by the timing of the last treatment. The mean above-ground dry weight was reduced from 66% (range 53–91 %) to 43% (range 29–75 % control) of the non-treated control following the early and late applications, respectively, while no significant difference in root dry weights was observed between the treatments ($p = 0.063$, Figure 3). *Ecballium elaterium* was the most sensitive species to the flaming treatments and to their timings. The mean above-ground dry weight was reduced from 44% (range 9–69 %) to 10% (range 0–33 %) of the non-treated control following the early and later applications, respectively (Figure 4). The number of flowers was even more markedly affected by the timing of the last treatment, with a mean reduction in flower number from 10% (range of 0–36 %) to 0% of non-treated control following the early and later applications, respectively (Figure 4).

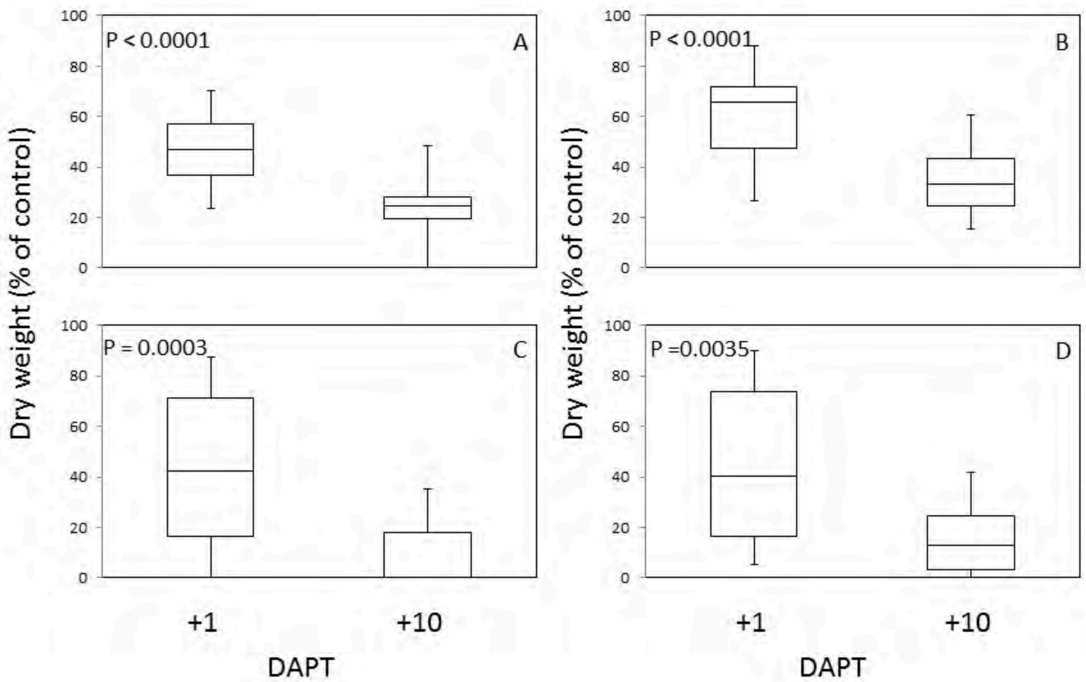

Figure 2. The impact of third treatment timing (1 or 10 days after previous treatment (DAPT)) on the above-ground dry weight (**A**), root dry weight (**B**), number of rhizomes (**C**), and seed weight (**D**) (% of untreated control) of *Sorghum halepense*. *p*-values were determined by Student's *t*-test. Values are mean ± SE ($n = 7$).

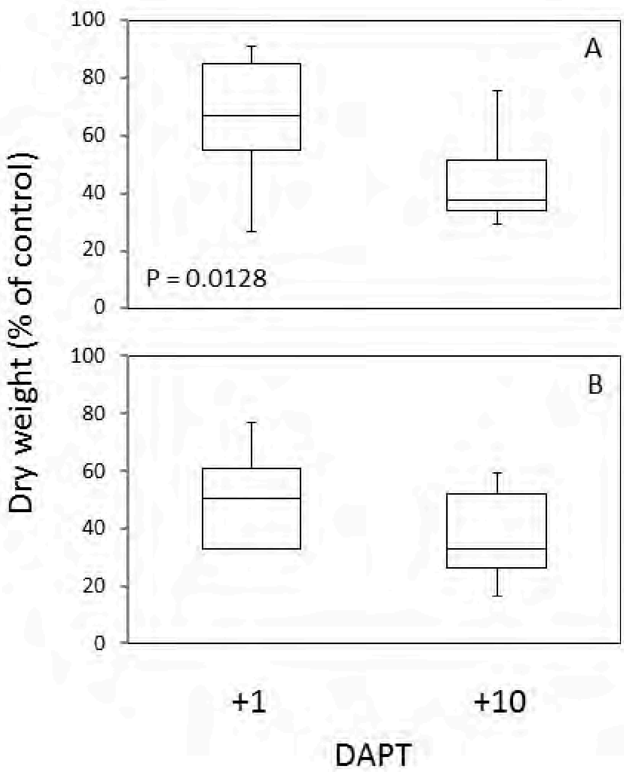

Figure 3. The impact of third treatment timing (1 or 10 days after previous treatment (DAPT)) on the above-ground dry weight (**A**) and root dry weight (**B**) (% of control) of *Cyperus rotundus*. *p*-values were determined by Student's *t*-test. Values are mean ± SE (n = 7).

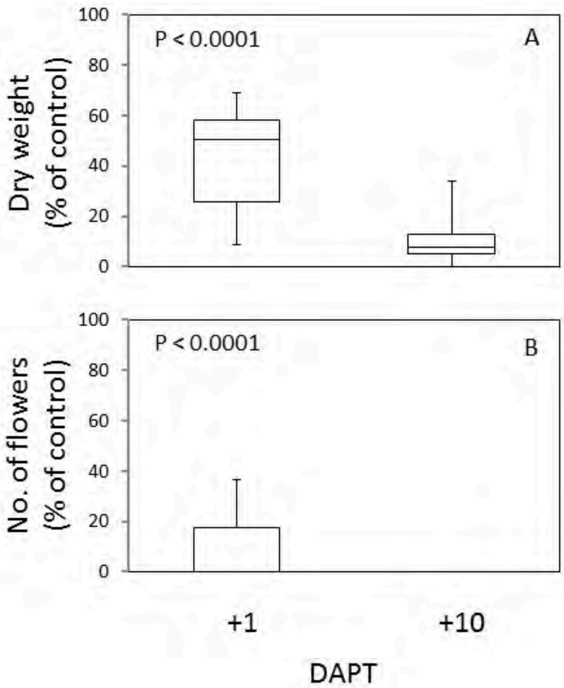

Figure 4. The impact of second treatment timing (1 or 10 days after previous treatment (DAPT)) on the above-ground dry weight (**A**) and the number of flowers (**B**) (% of control) of *Ecballium elaterium*. *p*-values were determined by Student's *t*-test. Values are mean ± SE (n = 7).

3.2. Cross-Row Flaming is Effective for Broadleaf Weeds

The experiments in this section used the dose response assay to evaluate the efficacy of cross-row flaming for Mediterranean annuals and evaluated the impact of weed species and growth stage on the outcomes. The dose-response analysis revealed a significant log-logistic relationship between propane dose and above-ground dry weight for all tested species and growth stages (except *S. arvensis* at the eighth leaf), indicating the positive impact of propane dose on control efficacy (Table 5). Computed ED_{50} was significantly lower in all species at the early as compared to the later growth stage (Table 5), demonstrating the negative impact of application at late growth stages on weed control efficacy. For example, the ED_{50} of *L. trimestris* was 1.2 ± 0.1 kg propane km^{-1} and 2.6 ± 0.8 kg propane km^{-1} in the early versus later growth stages, respectively (Table 5). The ED_{50} was higher in *A. sativa* compared to *S. arvensis* and *L. trimestris*, regardless of growth stage. In the early growth stage, the computed values of these weeds were 1.4, 0.6 and 1.2 kg propane km^{-1}, respectively (Table 5), with no significant difference measured between *L. trimestris* and *A. sativa*. At the later application, ED_{50} of *L. trimestris* and *A. sativa* increased to 2.6 ± 0.8 and 5.9 ± 1.3 kg propane km^{-1}, respectively, suggesting higher tolerance of grasses compared to broadleaf weeds to flaming treatment.

Table 5. Equation coefficient of the three-parameter log-logistic regression[1] between propane dose (kg propane km^{-1}) and dry weight (% of non-treated control), with 95% confidence interval (CI) of the X_{50} coefficient and the regression computed *p*-values, probability (*p*), and root mean square error (RMSE) values.

Weed Species	Growth Stage	Coefficients								P	RMSE
		A	p (a)	b	p (b)	X_{50}	95% Lower CI	95% Higher CI	p (X_{50})		
Sinapis arvensis	4 leaf	99.8	0.006	1.39	0.164	0.6	0.1	1.1	0.116	0.026	8.2
	8–10 leaf	101.9	0.001	1.94	0.148	4.1	1.9	6.3	0.065	0.086	4.6
Lavatera trimestris	2–3 leaf	100.1	0.0005	1.58	0.007	1.2	1.1	1.4	0.002	0.002	2.2
	5–6 leaf	109.8	0.0002	0.35	0.042	2.6	1.8	3.4	0.023	0.002	1.5
Avena sativa	2 leaf	100	<0.0001	0.41	0.006	1.4	1.3	1.5	0.001	0.0004	0.6
	6 leaf	99.9	<0.0001	0.66	0.006	5.9	4.6	7.1	0.011	0.001	0.7

[1] $y = \frac{m}{1+(\frac{x}{x_{50}})^b}$.

4. Discussion

Controlling perennial invasive weeds by flaming is a challenging task, as the flames do not penetrate the soil surface to affect the root-system nor have residual activity in the soil [22]. Our findings demonstrated that repeat flaming treatments can be useful for controlling such weeds, including *C. rotundus* and *S. halepense*, which are considered highly invasive and among the most noxious weeds in the Mediterranean region (Figure 1). Furthermore, it is possible that earlier applications than those used in this study (e.g., 23 DAP for *C. rotundus*) would result in a higher degree of control with fewer applications. Our findings are in agreement with previous flaming studies aimed to control perennial weeds in apple orchards and urban hard surfaces [22–24], which emphasized the necessity for multiple applications, up to 10 treatments in the case of *Lolium perenne*, and the importance of the timing of sequential applications. These applications should be timed after regrowth initiation but before weeds are too developed. The fact that the number of applications had no significant impact on *E. elaterium* control and the high range of above ground dry weight values following the first treatment (0–81%), suggests a higher sensitivity of this weed and wide phenotypic diversity at application timings. For smaller plants, one treatment was sufficient to reach full control (Figure 1 and Table 4).

To the best of our knowledge, this study was one of the first to evaluate the efficacy of flaming using several phenological parameters and not exclusively biomass. A significant impact of the flaming treatment on flower and seed production of *E. elaterium* and *S. halepense* and on the sub-soil development of *S. halepense* was observed, suggesting a potential reductive effect on the seed bank by repeated flaming treatments. This effect on the seedbank may be of value for the long term control of invasive weeds in agricultural and ecological systems. The lack of impact on *C. rotundus* sub-soil development may be due to its propagules (tubers) and their resilience following various control treatments, including cultivation and hoeing [25,26]. In the current study, plants from *S. halepense* seeds were used, which may have introduced reduced baseline resistance and recovery compared to rhizome-originated plants. However, the fact that broadcast flaming covers the entire weed canopy and *S. halepense* seeds develop above the soil surface, may result in seed bank reduction of this weed. In recent years, climatic changes have resulted in a wider distribution of *S. halepense* and changes in the growing season. For example, it can now germinate during the Mediterranean winter and infect wheat and other winter crops. Thus, efficient control of seedlings has become highly important.

A previous weed flaming study suggested that weed density has only a minor impact on control efficacy [16]. The highly significant interaction ($p < 0.0001$) between weed density and growth stage demonstrated in *E. elaterium* indicates a potential impact of this factor. Other species (e.g., *C. rotundus*) showed high sensitivity for intra-species competition during some growth stages that resulted in higher control efficacy following herbicide treatments [27]. It can be assumed that a similar phenomenon occurred here. However, our findings showed that for some species, weed density is a determinant of successful flaming treatment.

In general, the efficacy of flaming for both annual and perennial invasive weeds varied dramatically among different species. The two tested kinds of grass (*A. sativa* and *S. halepense*) showed higher tolerance to flaming as compared to the broadleaf species (*E. elaterium* and *S. arvensis*). The higher tolerance of grasses can be ascribed to differences in the anatomy and morphology of these weeds, primarily to the meristems of young grass weeds, which are located below the soil surface and are protected by the leaves during flaming [7,28]. Previous studies that compared the tolerance of various weed species to flaming, observed similar trends for other grasses, like yellow foxtail (*Setaria pumila*) and barnyard grass (*Echinochloa crus-galli*) [10,13,14]. Weed growth stage was also shown to significantly influence weed control efficacy. Early growth stages of both annual and perennial invasive weeds were more susceptible compared to the later stages (Tables 3 and 5). Likewise, previous studies reported lower ED_{50} values in early growth stages compared to later ones in various weed species, such as common lambsquarters (*Chenopodium album*) and tansy mustard (*Descurainia pinnata*) [14,29]. These authors argued that the thin leaves of young plants are highly sensitive to the heat of flaming treatment, which results in higher control efficacy following treatments at early growth stages.

The ED_{50} values reflect the difficulty in controlling grass weeds ($ED_{50} \geq 1.4$ kg propane km^{-1}) and developed broadleaf weeds ($ED_{50} \geq 2.6$ kg propane km^{-1}) when using a single treatment of the cross-row technique. It is possible that our burner positioning, which directed treatment to the plant bases from the row sides, rather than across the entire weed canopy, may have been unsuitable for treatment of developed weeds, with shoot apexes that can avoid the flames. It is also possible that the un-shielded burners resulted in lower temperatures and reduced control efficacy. Nonetheless, our results emphasize the need for early and multiple applications in order to achieve effective and long-term control of grass weeds while using the cross-row technique.

5. Conclusions and Future Perspectives

The threat of invasive weeds coupled with over-reliance on herbicides call for adoption of new weed control practices. Flaming offers an effective novel approach that may address these needs. Perennial and invasive weeds can be effectively treated by broadcast flaming, but multiple applications are required, with the timing of the sequential applications and/or weed density being key determinants of control efficacy. Phenological development is affected by sequential flaming treatments, and the number of flower and seeds of treated weeds, such as *E. elaterium* and *S. halepense*, can be reduced. This may affect their seed bank and improve long-term control. Flaming with the cross-row technique is effective for broadleaf weeds, but application timing must be targeted for early growth stages. Grass weeds are more tolerant of this technique, and a single application does not provide suitable control levels. While further research is needed to optimize the number of applications for different cropping systems and environments, our findings demonstrate the potential of flaming for perennial invasive and annual weed control in row and perennial crops. Thus, the implementation of this novel approach into integrated weed management practices will facilitate control of invasive weeds and slow the development of herbicide resistance.

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