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Hot foam: Evaluation of a new, non-chemical weed control option in perennial crops

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ABSTRACT

Hot foam applications represent a new, smart concept in the field of thermal weed control. The aim of this study was to evaluate the efficacy of hot foam and other weed control methods in two olive groves in southern Greece (Pyrgos and Kalamata). The experiment was laid out in a randomized complete block design (RCBD) with six treatments and three replicates. Treatments were applied in the areas between trees, in the row and included mowing with a disc–flail mower, mulching with pruning residues (2.65 kg m^{-2}), glyphosate (at 1,440 g a.e. ha^{-1}), hot foam (13.33 L m^{-2}), pelargonic acid (at 1,088 g a.i. ha^{-1}; twice), and an untreated control. Two experimental runs were conducted at each site using the same treatment list. *Malva parviflora* L. and *Sinapis arvensis* L. were the predominant weeds in Pyrgos, while *Urtica urens* L., *Galium aparine* L., and *Parietaria officinalis* L. dominated in Kalamata. Site–experimental runs and treatments significantly affected NDVI and weed biomass (P–Value $\leq$ 0.001). Hot foam reduced weed biomass by up to 81, 88, 90, and 96% compared to mulching, mowing, pelargonic acid, and the untreated control, respectively. This treatment also reduced *M. parviflora* biomass by 75–88 and 92–93% compared to mowing and pelargonic acid, respectively, in Pyrgos and *P. officinalis* biomass by more than 80% in Kalamata compared to the above treatments. In all site–experimental runs, hot foam and glyphosate resulted in the lowest NDVI and weed biomass. The overall performance of hot foam was comparable to glyphosate, suggesting that this method is an environmentally friendly and effective, alternative method to control weeds in olive groves. Further research is required to optimize the use of hot foam for weed control in more perennial crops and under different soil and climatic conditions.

1. Introduction

Olive (*Olea europaea* L.) is one of the most widely cultivated tree species in Mediterranean countries, bringing environmental, economic, and social benefits to the areas where it is grown [1]. Weeds are an integral element of olive groves and perennial orchards in general. Although the presence of weeds in the orchard is sometimes beneficial, as they increase soil organic matter content, reduce the risk of soil erosion, and provide favourable conditions for many taxa of fauna [2], weed management is a key component in establishing and maintaining a profitable olive grove for several reasons.

First, weeds can compete with trees for water and nutrients when these resources are limited, limiting their yield potential [3]. Especially in newly established olive groves, weeds compete with young trees, resulting in delayed establishment and the onset of fruit production [4]. In addition, weeds serve as hosts for pathogens and insects, infestations of which can affect tree health. In the Mediterranean region, Tatulli et al. [5] reported that the lack of weed control increases the density of weeds that are suitable hosts for *Philaenus spumarius* L. (Hemiptera: Aphrophoridae), the main vector for the spread of *Xylella fastidiosa* subsp. *pauca* (Xfp), a quarantine bacterium for the European Union (EU) that causes the "olive quick decline syndrome" (OQDS). In addition, the presence of weeds under the canopy makes harvesting of fallen olive fruits a very expensive operation that significantly increases labour costs [6]. Severe weed infestations also hinder the check of drippers (in drip–irrigated orchards), the pruning of trees, and the application of pesticides or foliar fertilizers [7]. Another reason for weed control is that weeds in high density lower the air temperature in the orchard and increase the risk of frost damage in winter, while they increase the risk of fire in the dry period of summer [8].

The use of glyphosate throughout the whole field has been by far the most common method of weed control in most olive groves in the Mediterranean region in recent years [9]. However, overuse of this particular herbicide cannot be considered a sustainable agronomic practice for weed control in olive groves and other major perennial crops in the

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near future. The first reason is that the future of glyphosate in Europe is uncertain due to environmental and human health concerns and EU legislation on pesticides [10]. Another reason is that successive applications in orchards and non–crop landscapes over the last two decades have led to the spread of glyphosate–resistant weeds [11–14]. Therefore, there is a growing need to evaluate more alternative practices to build sustainable Integrated Weed Management (IWM) systems [15]. It should be mentioned here that weed management in olive groves typically consists of two management zones, the space between rows of trees, i.e., the inter–row space, and the space between trees in the row, i.e., the intra–row space [16]. While alternative pre–emergence herbicides, contact herbicides, flail–mowing, and cover crops are examples of alternative weed control options with glyphosate that show promising results for the inter–row space [3], more information is needed on the performance of smart alternative options for the intra–row space, including the space under the canopy of olive trees.

Mowing is one of these options to control weeds in these areas, using hydraulic disc flail– mowers that can be connected to the central flail–mower. In these systems, the central flail mower operates in the inter–row area while the disc flail mower works in the intra–row area [17]. Dead organic mulches such as pruning residues can also contribute to important levels of weed suppression by preventing light from reaching weed seeds and creating a physical barrier to germination [16]. Natural, non–selective, contact, burndown herbicides such as pelargonic acid may also be an alternative option to control annual weeds when applied repeatedly at early weed growth stages [18]. Thermal weed control is another attractive alternative to glyphosate that is expected to play an important role in developing effective and environmentally friendly IWM strategies in perennial crops [19]. Flaming, hot water, and steam are the primary methods that have been tested most often but have a major drawback. According to Peerzada and Chauhan [20], the heat escapes to the atmosphere instead of being transferred exclusively to the treated weed. Therefore, there is a growing interest in new relative methods.

Hot foam applications represent a new, smart concept in the area of thermal weed control and are proposed as an evolution of simple hot water or steam applications. The change lies in the additional use of biodegradable foaming agents [21]. The advantage of foam is that it isolates the weed from the ambient air at the time of treatment and transfers all the heat energy to the plant tissues instead of escaping into the atmosphere [22]. Foamstream ® machines (WeedingtechTM Ltd., London, UK) enable the practical implementation of this herbicide–free weed control option that overcomes several of the drawbacks associated with the use of synthetic herbicides and conventional thermal weed control methods and contact bioherbicides [21,23,24]. Regarding the performance of Foamstream ® machines, most research results come from case studies where evaluations were conducted on non–crop areas since hot foam is a non–selective bioherbicide. However, it can be assumed that the application of hot foam can also be a smart, effective weed control method in olive groves and orchards, providing an alternative to glyphosate and being more effective compared to other non–chemical methods.

Therefore, the objective of this study was to evaluate the efficacy of hot foam for weed control in two olive groves in important olive growing areas and to compare it with the corresponding of glyphosate, mowing, mulching and pelargonic acid. The performance of all methods was evaluated in the intra–row spaces, i.e., between the trees in the row including spaces under tree canopy, in field trials repeated in space and time.

2. Materials and methods

2.1. Site description

Different weed control methods were evaluated in olive groves at two sites in the Peloponnese, namely Pyrgos (capital of the administrative district of Elis) and Kalamata (capital of the administrative district of Messinia). One olive grove was studied per site. In Pyrgos, the olive grove was located around 3.5 km southeast outside the city centre of Pyrgos (37.652°N, 21.461°E) and covered an area of 3 ha. In Kalamata, the olive grove was located about 5 km east outside the city centre of Kalamata (37.027°N, 22.151°E) and covered an area of 0.96 ha. At both sites, trees of the olive cultivar '*Koroneiki*', which is predominant in Greece, were planted in north–south (N–S) orientated rows with a spacing of 6 × 6 m, resulting in a stand of 272 trees ha^{-1}. The trees were self–rooted, cup–shaped, 17 years old in Pyrgos and 14 years old in Kalamata, and sprinkler–irrigated in summer. At both sites, the soil type was sandy loam (SL). The soil texture (0 to 30 cm) in Pyrgos was: 19.4% clay, 27.7% silt and 52.9% sand, with a pH of 7.2 and an organic matter content of 1.5%. The soil texture (0 to 30 cm) in Kalamata was: 17.7% clay, 28.8% silt and 53.5% sand, with a pH of 7.1 and an organic matter content of 1.2%. In November and December 2021, precipitation was higher in Pyrgos than in Kalamata. In January 2022, a greater amount of rainfall was observed in Kalamata. The average air temperature was higher in Kalamata throughout the experimental period (Table 1).

In Pyrgos, *Malva parviflora* L. and *Sinapis arvensis* L. were the dominant weed species. According to field history data, weed control in previous years was mainly based on applications of glyphosate in mixtures with fluroxypyr. *Urtica urens* L., *Galium aparine* L., and *Parietaria officinalis* L. were the dominant weeds in Kalamata. At this site, mowing was the main weed management practice carried out in the years preceding the experiment.

2.2. Experimental setup

The experiment was laid out in a randomized complete block design (RCBD) with six weed control treatments repeated three times. Before presenting the weed control treatments, it should be mentioned that the list of treatments was identical at both sites and for both experimental runs conducted at each site. In order to actually repeat the treatments over time, new plots were established at each site to conduct the repeated series of trials. The dates for establishing the plots were different for the two experimental runs conducted at each site (Table 2).

Each plot included the area within the row (intra–row space) between two trees and was extended by another 2 m. Since plot area within the row was 0.6 m wide and the trees in the row were 6 m apart, the plots were 10 m long and 0.6 m wide and had a total size of 6 m^2. In all four site–experimental runs, six plots with two trees per plot were included in each replication, resulting in a total of 12 trees per replication and a replication size of 36 m^2. In both fields, the experimental area consisted of 18 plots and 36 trees and had a total size of 108 m^2. Between adjacent plots in each replication, 2 m were kept weed–free by mowing. The space between the rows (inter–row space) of trees also served as a boundary between the replications. This space was also kept weed–free by mowing. Including the boundaries, the total area used for each experimental run was 864 m^2 at both sites. Considering that different plots were established for each experimental run, a total area of 1728 m^2 was used at each site. An illustration of the experimental plots is given below (Fig. 1).

Weed control treatments included mowing, mulching, a single application of glyphosate, a single application of hot foam, two applications of pelargonic acid, and an untreated control. Mowing was performed with a hydraulic disc flail–mower (UD650, Theoharidis S.A., Thessaloniki, Greece) consisted of a horizontal disc with rubber protection edge and two axial cutting blades. This machinery was attached to a central, tractor–mounted, flail–mower (at a distance of 87.5 cm). The disc flail–mower had a working depth of 0.65 m and mowed the weeds in the intra–row space between the trees at a height of 0.052 m; the working speed was 2–3 km h^{-1}. To skip trunks in the tree row, this kind of machinery has a mechanism consisted in a leverage connected to springs in such a way that the disc is forced to pivot inward by the pressure from tree trunks [17]. The hydraulic capacity (e.g., oil flow) of the disc

Table 1
Climatic conditions prevailed at the two sites during the experimental period.

Month	Site							
	Pyrgos				Kalamata			
	Avg T [2](°C)	Max T(°C)	Min T(°C)	Rainfall(mm)	Avg T(°C)	Max T(°C)	Min T(°C)	Rainfall(mm)
Oct.	19.2	27.6	12.4	312.4	20.0	27.0	13.8	181.4
Nov.	17.3	28.6	9.7	206.0	17.8	26.3	10.5	124.8
Dec.	12.1	19.8	2.8	205.8	13.4	19.6	5.9	179.0
Jan. [2]	10.2	19.0	–1.3	78.6	11.3	20.1	1.4	100.2

[1] Oct.; October, Nov.; November, Dec.; December, Jan.; January.
[2] Avg T; Average temperature, Max T; Maximum temperature, Min T; Minimum temperature.
[3] 2022.

Table 2
Dates of key field activities.

Field Activity	Site			
	Pyrgos		Kalamata	
	[1] ER–1	ER–2	ER–1	ER–2
Mulching	05/11/2021	21/11/2021	01/11/2021	20/11/2021
Pelargonic acid (first application)	21/11/2021	02/12/2021	20/11/2021	01/12/2021
Mowing	02/11/2021	15/12/2021	01/12/2021	01/12/2021
Pelargonic acid (second application)	02/12/2021	15/12/2021	01/12/2021	14/12/2021
Glyphosate application	02/12/2021	15/12/2021	01/12/2021	14/12/2021
Hot foam application	02/12/2021	15/12/2021	01/12/2021	14/12/2021
NDVI (first evaluation)	15/12/2021	23/12/2021	14/12/2021	21/12/2021
NDVI (second evaluation)	23/12/2021	31/12/2021	21/12/2021	04/01/2022
Weed biomass (first harvest)	06/01/2022	14/01/2022	04/01/2022	16/01/2022
Weed biomass (second harvest)	19/01/2022	28/01/2022	16/01/2022	31/01/2022

[1] ER; Experimental run.

flail–mower was 30 L min^{-1}. Mowing occurred when most of the weeds were between the 18th and 22nd BBCH growth stages. Mulching was done with tree pruning residues collected from older (40 years or more) trees spaced 8 × 8 m apart in neighbouring olive groves where fruit harvest occurred between late October and early November. Tree pruning residues less than 8 cm in diameter were spread in the corresponding plots at a rate of 15.9 kg per plot. This amount corresponded to the optimal amount of 2.65 kg m^{-2} of tree pruning residues recommended by Repullo et al. [25]. The weeds were mowed before the residues were applied to the corresponding plots.

The hot foam was applied using the Foamstream ® M1200 machine (Weedingtech Ltd., London, UK). The machine was placed on a trailer towed by a tractor in the field. The solution used (Foamstream V4) was a 100% mixture of plant oils and sugars (e.g. alkyl polyglucoside surfactants). The emission class is equivalent to a Euro 5 [26]. The foam was manually applied using a 0.3 m wide hot foam spreader. The flow rate was 12 L min^{-1}, which corresponds to 0.2 L s^{-1} (from 96% water and 4% Foamstream V4). Since the plots were 0.60 m wide, they were divided (with wooden stakes) into two 0.30 cm wide strips. Due to the size of the plots (10 m long and 0.6 m wide) and previous preliminary results where we needed 30 s to adequately cover the 1.5 m long and 0.3 m wide strips, hot foam was applied for 200 s to cover each 0.30 m wide strip of each plot. The last strip of each plot was covered with hot foam using the same method. Foamstream ® M1200 thus worked for 400 s to cover each plot with 80 liters of hot foam. In liters per square metre, 13.33 L m^{-2} of hot foam was applied to all corresponding plots. Most weeds were between the 18th and 22nd BBCH growth stages. Weeds that were at a more advanced growth stage were foot–crimped prior to treatment to ensure adequate coverage with hot foam. This measure was performed only in the hot foam treated plots and was particularly necessary for some individuals of *M. parviflora* in Pyrgos and *P. officinalis* in Kalamata.

Glyphosate (Meteor® TF 36 SL, Alfa Agricultural Supplies S.A., Athens, Greece) was applied once at a rate of 1440 g a.e. ha^{-1} at the same time the hot foam was applied. Pelargonic acid (Beloukha ®, Basf S.A., Athens, Greece) was applied twice at an application rate of 1088 g a.i. ha^{-1} at two–week intervals. At the time of the first application, most weeds had four to eight true leaves (BBCH: 14–18). The second application was made at the same time hot foam and glyphosate were applied. The double application was based on product label recommendations and previous research experience [3]. These two herbicides were applied using an Elettra Venus 5 pressure sprayer calibrated to deliver 300 L ha^{-1} of spray solution through a brass conical nozzle at a constant pressure of 200 kPa for glyphosate and 250 kPa for pelargonic acid.

2.3. Data collection

In all four site–experimental runs, four metallic 0.25 m^2 quadrats were placed in each plot and marked with 1 m–high wooden stakes spaced 0.5 m from the tree trunks and 0.35 m from the plot edges. The Normalized Difference Vegetation Index (NDVI) was evaluated twice on all plots. The first and second NDVI evaluations occurred one and two weeks after the second application of pelargonic acid and the single applications of hot foam and glyphosate. The choice of evaluation timing was based on previous studies in which NDVI had been shown to be a reliable, non–destructive estimate of herbicide efficacy one and two weeks after treatment [27]. Because of the way NDVI is calculated, deterioration in vegetation health can be detected by reduced NDVI values [28]. Assessments were made using a handheld Trimble® GreenSeeker® optoelectronic sensor (Trimble Agriculture Division, Westminster, CO, USA). The sensor unit has self–contained illumination in both the red and near–infrared regions and measures reflectance in the red and near–infrared (NIR) regions of the electromagnetic spectrum [28] ac-

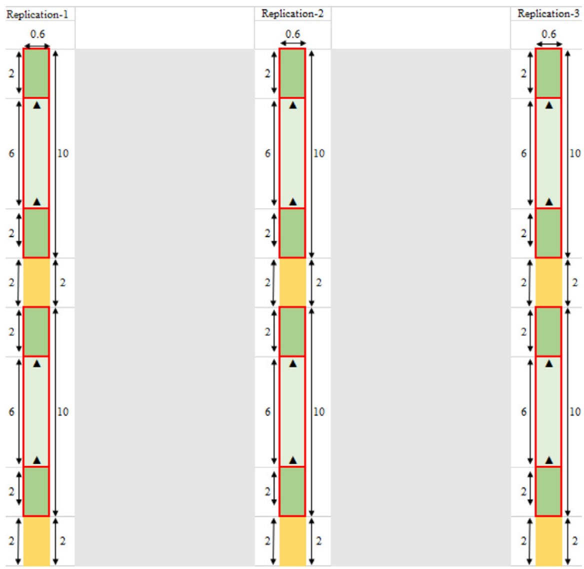

Fig. 1. Illustration of the experimental plots. "▲"; tree presence. Numbers accompanied with double–sided arrows; plot length and width (both expressed in meters). Light green; plot area between two consecutive trees of each separate plot in each replication. Intense green; plot area in the back and front of each one of the two trees included in each separate plot in each replication. Red outline; total area of each separate plot (6 m^2) in each replication. Yellow; boundary between plots in each replication. Grey; boundary between replications.

cording to Eq. (1):

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

As shown in previous studies, this sensor quite precisely measures the green area of the treated plot giving lower values when the effect of treatment on weeds is more significant [3,27].

On days without precipitation, measurements were made at midday (12:00–14:00) by passing the sensor over the quadrats at a height of 0.5 m above the weed canopy. Weed biomass was evaluated four and six weeks after the second application of pelargonic acid and the single applications of hot foam and glyphosate. Total weed biomass and biomass of the predominant weed species were measured in both evaluations. In the first evaluation, weeds were harvested by cutting plants with scissors to a height of 0.02 m, separating them by species, and placing them in numbered plastic bags. Weed samples were then weighed to determine fresh weed biomass per unit area using a KF–H2 digital balance (Zenith S.A., Athens, Greece). The first weed harvest was conducted in two quadrats of each plot. Weeds were allowed to grow in the remaining two quadrats of each plot to redetermine weed biomass using the method described above and in previous studies [29].

2.4. Statistical analysis

Data from each evaluation of NDVI and total weed biomass were subjected to a two–way Analysis of Variance (ANOVA) at a significance level of $a = 0.05$. A general linear model was constructed in which site–experimental runs and weed control treatments were considered fixed effects and blocks (replications) were considered random effects. This was possible because the list of treatments was the same in all four site–experimental runs. Because the effects of the site–experimental runs on the parameters studied were significant (P–Value ≤ 0.05), the data for each site–experimental run were further analysed separately using the one–way ANOVA procedure. In these analyses, the means were separated according to the Fischer's LSD (Least Significance Difference) test ($a = 0.05$).

We then analysed the biomass of the predominant weed species, which varied by site. To perform these analyses, data from each evaluation were first subjected to a two–way ANOVA ($a = 0.05$) in which experimental runs and treatments were considered fixed effects and blocks were considered random effects. For all evaluations, the effects of experimental runs on weed biomass were not significant (P value ≥ 0.05). Therefore, for each site, data from the two experimental runs were combined and further analysed by one–way ANOVA to compare means between treatments using Fischer's LSD procedure ($a = 0.05$). Statgraphics Centurion XVI (Statgraphics Technologies, Inc., P.O. Box 134, The Plains, VA 20,198, USA) was the statistical package used for all data analyses.

Table 3
NDVI as affected by site–experimental runs and weed control treatments.

Factors	Df [1]	NDVI First evaluation *P*–Value	NDVI First evaluation *F*–Ratio	NDVI Second evaluation *P*–Value	NDVI Second evaluation *F*–Ratio
Site–ER [2]	3	*** [3]	55.58	***	39.19
error (a) [4]	6	*ns*	0.21	*ns*	0.61
Treatments	5	***	1140.30	***	734.99
Site–ER * Treatments	15	*ns*	1.33	**	2.66
Error (b) [5]	40				
Blocks	2	*ns*	12.87	*ns*	0.60
Total	71				

[1] Df; Degrees of freedom.
[2] ER; Experimental runs.
[3] ***; *P*–Value ≤ 0.001, *ns*; *P*–Value ≤ 0.05, **;*P*–Value ≤ 0.01.
[4] error (a); Site–ER * Blocks.
[5] error (b); Treatment(Site–ER) * Blocks.

3. Results

3.1. NDVI

In the first evaluation, site–experimental runs and treatments significantly affected NDVI (P–Value ≤ 0.001). In the second evaluation, NDVI was influenced by site–experimental runs and treatments (P–*Value* ≤ 0.001) and also by the interaction between site–experimental runs and treatments (P–*Value* ≤ 0.01; Table 3).

Because the effects of the site–experimental runs on NDVI were significant, data were analysed separately for each site–experimental run. In the first NDVI evaluation in Pyrgos–ER1, pelargonic acid, glyphosate, and mowing resulted in some reduction in NDVI compared to the untreated control. Compared to the above treatments, an even lower NDVI was observed in plots mulched with pruning residues. Similar results were obtained in Pyrgos–ER2. In both experimental runs, the application of hot foam resulted in the lowest NDVI values. In the first NDVI evaluation in Kalamata–ER1, mowing and pelargonic acid reduced NDVI compared to the untreated control while mulching and glyphosate resulted in further NDVI reductions. Glyphosate caused a significant reduction in NDVI compared to mowing and pelargonic acid in both Kalamata–ER 1 and Kalamata–ER 2. In both Kalamata–ER1 and Kalamata–ER2, the lowest NDVI values were observed in plots that were treated with hot foam (Table 4).

The results of the second evaluation showed that NDVI in Pyrgos–ER1 was highest in the untreated plots and lowest in the hot foam treated plots. Pelargonic acid and mowing reduced NDVI compared to the untreated control. Mulching and glyphosate resulted in even lower NDVI. These results were consistent with the corresponding assessments in Pyrgos–ER2. In Kalamata–ER1 and Kalamata–ER2, the application of hot foam resulted in the lowest NDVI values. The next lowest NDVI values were measured in plots treated with glyphosate and in plots mulched with pruning residues. Mowing and pelargonic acid also resulted in some reduction in NDVI compared to the untreated control.

Table 4
NDVI as affected by weed control treatments in four site–experimental runs. The results of the first and the second evaluations are presented for each site–experimental run. In each column, different lowercase letters indicate significant differences between treatments.

Treatments	NDVI – First Evaluation Site–ER Pyrgos–ER1	 Pyrgos–ER2	 Kalamata–ER1	 Kalamata–ER2
Control	0.84 a	0.85 a	0.81 a	0.79 a
Mowing	0.61 b	0.62 b	0.58 b	0.57 b
Mulching	0.34 c	0.33 c	0.33 c	0.33 c
Hot foam	0.19 d	0.18 d	0.18 d	0.17 d
Glyphosate	0.65 b	0.59 b	0.57 b	0.55 b
Pelargonic acid	0.62 b	0.60 b	0.59 b	0.59 b
P–Value	***	***	***	***
LSD	0.05	0.04	0.03	0.04

Treatments	NDVI – Second Evaluation Site–ER Pyrgos–ER1	 Pyrgos–ER2	 Kalamata–ER1	 Kalamata–ER2
Control	0.86 a	0.86 a	0.82 a	0.81 a
Mowing	0.67 b	0.67 b	0.6 b	0.58 b
Mulching	0.40 c	0.39 c	0.36 c	0.34 c
Hot foam	0.27 d	0.19 d	0.18 d	0.18 d
Glyphosate	0.42 c	0.40 c	0.35 c	0.3 c
Pelargonic acid	0.66 b	0.63 b	0.64 b	0.59 b
P–Value	*** [2]	***	***	***
LSD	0.06	0.05	0.04	0.05

[1] ER; Experimental runs.
[2] ***; *P*–Value ≤ 0.001.

Table 5
Total weed biomass as affected by site–experimental runs and weed control treatments.

Factors	Df [1]	Total weed biomass First evaluation P–Value	 F–Ratio	 Second evaluation P–Value	 F–Ratio
Site–ER [2]	3	*** [3]	54.91	***	59.68
error (a)	6	*ns*	1.08	*ns*	1.18
Treatment	5	***	267.85	***	220.65
Site–ER * Treatment	15	***	8.31	***	8.95
error (b)	40				
Blocks	2	*ns*	8.66	*ns*	6.87
Total	71				

[1] Df; Degrees of freedom.
[2] ER; Experimental runs.
[3] ***; *P*–Value ≤ 0.001, *ns*; *P*–Value ≤ 0.05.
[4] error (a); Site–ER * Blocks.
[5] error (b); Treatment(Site–ER) * Blocks.

3.2. Total weed biomass

Site–experimental runs, treatments and the interaction between site–experimental runs and treatments affected total weed biomass at a significant point in the first and second evaluations (*P–Value* ≤ 0.001; Table 5).

In Pyrgos–ER1, the results of the first evaluation showed that mowing reduced weed biomass by 40–45% compared to pelargonic acid and the untreated control. Glyphosate and mulching further reduced weed biomass compared to mowing. Hot foam application resulted in 70 and 78% lower weed biomass than glyphosate and mulching, respectively. These results were consistent with those obtained in Pyrgos–ER2. However, no significant difference was found between hot foam and glyphosate at this site–experimental run. In Kalamata–ER1, mowing and pelargonic acid reduced total weed biomass by more than 60% compared to the untreated. In addition, the use of pruning residues as mulch suppressed weed biomass by 40, 46, and 79% compared to mowing, pelargonic acid, and the untreated control, respectively. The lowest levels of weed biomass were obtained in plots treated with either glyphosate or hot foam; no significant differences were found between these two treatments. Hot foam performance was also excellent and tended to be better than glyphosate in Kalamata–ER2. Specifically, this treatment reduced total weed biomass by 81, 88, 90, and 96% compared to mulching, mowing, pelargonic acid, and the untreated control, respectively (Table 6).

In Pyrgos–ER1, the results of the second evaluation showed that weed biomass in plots that were mowed was 40% lower than the corresponding values in plots treated with pelargonic acid. No significant differences were found between pelargonic acid and the untreated control. Glyphosate and mulching further reduced weed biomass compared to mowing. Hot foam application resulted in 76% less weed biomass than mulching. Although the differences were not significant, hot foam tended to result in lower weed biomass than glyphosate. Similar results are reported for Pyrgos–ER2. Specifically, weed biomass was lowest in plots treated with hot foam and glyphosate and highest in plots treated with pelargonic acid and in plots left untreated. The intermediate values correspond to the mowing and mulching treatments; however, mulching resulted in a significant reduction in total weed biomass than mowing. In the second assessment of weed biomass in Kalamata–ER1, pelargonic acid and mowing reduced weed fresh weight per unit area by 60 and 65%, respectively, compared to the untreated control. Mulching resulted in lower weed biomass than the above treatments. In addition, weed biomass was lowest in plots treated with hot foam and glyphosate. In the second experimental run conducted in Kalamata (Kalamata–ER2), hot foam and glyphosate remained the most effective treatments, resulting in the lowest levels of weed biomass. Mulching reduced weed fresh weight by 38 and 44% compared to mowing and pelargonic acid, respectively. Mowing and pelargonic acid also caused significant reductions in weed biomass compared to the untreated control.

3.3. Biomass of dominant weed species

In Pyrgos, *M. parviflora* and *S. arvensis* were the dominant weeds. Averaged over two experimental runs, mowing reduced *M. parviflora* biomass compared to the untreated control and pelargonic acid in both

Table 6
Total weed biomass as affected by weed control treatments in four site–experimental runs. The results of the first and second evaluations are presented for each site–experimental run. In each column, different lowercase letters indicate significant differences between treatments.

Treatments	Total weed biomass (g m^{-2}) – First Evaluation Site–ER [1] Pyrgos–ER1	 Pyrgos–ER2	 Kalamata–ER1	 Kalamata–ER2
Control	428.2 a	450.4 a	386.1 a	348.5 a
Mowing	232.7 b	248.8 b	131.7 b	108.0 b
Mulching	131.9 c	139.6 c	79.9 c	67.3 c
Hot foam	29.1 d	23.0 d	16.3 d	12.4 d
Glyphosate	99.8 c	64.2 d	41.1 cd	31.3 cd
Pelargonic acid	392.5 a	384.7 a	149.3 b	121.2 b
P–Value	*** [2]	***	***	***
LSD	61.0	68.4	48.3	37.1

Treatments	Total weed biomass (g m^{-2}) – Second Evaluation Site–ER Pyrgos–ER1	 Pyrgos–ER2	 Kalamata–ER1	 Kalamata–ER2
Control	593.9 a	631.6 a	499.1 a	451.3 a
Mowing	337.4 b	361.0 b	174.4 b	140.5 b
Mulching	188.8 c	203.4 c	105.3 c	87.7 c
Hot foam	44.3 d	53.8 d	21.7 d	16.4 d
Glyphosate	136.6 cd	88.3 d	55.5 cd	41.9 cd
Pelargonic acid	567.7 a	586.5 a	197.7 b	156.7 b
P–Value	***	***	***	***
LSD	93.3	110.9	62.6	46.7

[1] ER; Experimental runs.
[2] ***;*P*–Value ≤ 0.001.

evaluations. Mulching further reduced fresh weight per unit area of this species; this observation was common in both the first and second assessments. In the first evaluation, glyphosate resulted in 62, 72, and 76% lower biomass of *M. parviflora* compared to mowing, the untreated control, and pelargonic acid, respectively. Similar results were obtained in the second evaluation. The application of hot foam reduced the fresh weight of this species by 75–88 and 92–93% compared to mowing and pelargonic acid, respectively. This treatment tended to be more effective than glyphosate in controlling *M. parviflora*, but the differences between these two treatments were not statistically significant. Pelargonic acid, mowing, and mulching resulted in a significant reduction in fresh weight of *S. arvensis* in both evaluations compared to the untreated control. In the first evaluation, no *S. arvensis* plants survived the application of hot foam and glyphosate. In the second evaluation, hot foam reduced *S. arvensis* biomass by 90, 94, 96, and 98% compared to mulching, mowing, pelargonic acid, and the untreated control, respectively. The performance of hot foam was similar to glyphosate (Fig. 2).

In Kalamata, *U. urens, G. aparine*, and *P. officinalis* were the dominant weed species. *U. urens* biomass was lower in plots treated with pelargonic acid, mowed, and mulched with pruning residues than in plots left untreated. These observations were common in both evaluations. No plants had survived treatment with glyphosate and hot foam in either the first or second evaluation. Pelargonic acid, mowing, and mulching resulted in more than 85% reduction in fresh weight of *G. aparine* per unit area compared to the untreated control. Glyphosate and hot foam applications completely eliminated all plants of this species in both the first and second assessments (Fig. 3).

In the first evaluation, glyphosate and mulching resulted in a significant reduction in *P. officinalis* biomass compared to pelargonic acid, mowing, and the untreated control. Similar observations were made in the second evaluation. The application of hot foam resulted in 66–71% reductions in fresh weight of *P. officinalis* per unit area compared to mulching. In addition, this treatment resulted in more than an 80% reduction in biomass of this species compared to mowing, pelargonic acid, and the untreated control in both evaluations. Hot foam appeared to be superior to glyphosate in controlling *P. officinalis* in both the first and second evaluations. However, the differences between these two specific treatments could not be characterized as statistically significant.

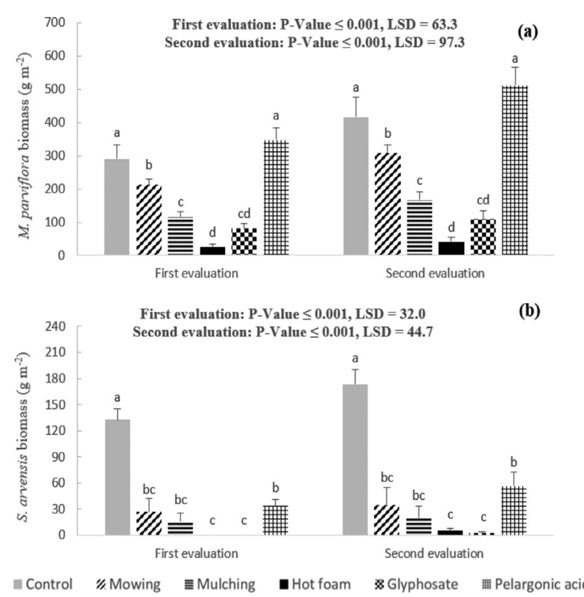

Fig. 2. (a) *M. parviflora*, and (b) *S. arvensis* biomass (g m^{-2}) in Pyrgos. Data were pooled over the experimental runs conducted at this site for each separate evaluation. Different lowercase letters indicate significant differences between treatments. Vertical bars indicate standard errors.

4. Discussion

4.1. NDVI

NDVI has been proposed as a non–destructive tool to detect changes in vegetation health caused by the use of synthetic herbicides and bio-

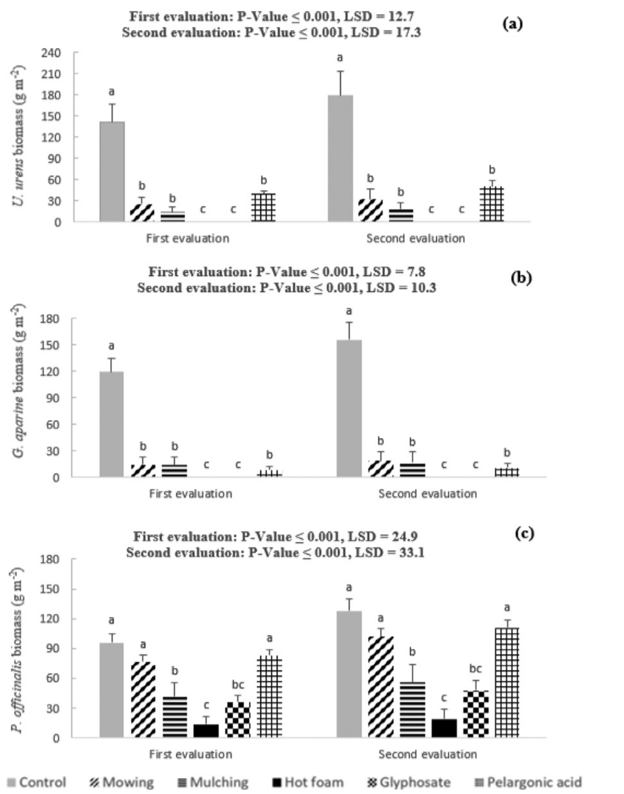

Fig. 3. (a) *U. urens*, (b) *G. aparine*, and (c) *P. officinalis* biomass (g m^{-2}) in Kalamata. Data were pooled over the experimental runs conducted at this site for each separate evaluation. Different lowercase letters indicate significant differences between treatments. Vertical bars indicate standard errors.

herbicides [3,27]. This was confirmed in our study, where the application of hot foam resulted in NDVI values between 0.17 and 0.27, while values above 0.80 were recorded in the untreated plots. The foam acted very quickly and the weeds looked stunted within an hour after treatment and showed signs of complete breakdown 2 days after treatment (visual observations). These changes in the health of the treated weeds were confirmed by measuring NDVI, as the process of absorption of red light and subsequent energy reflection in the NIR range is a characteristic of healthy vegetation. Thus, the lower the NDVI of weeds, the higher the efficacy of a particular weed control treatment [28]. Glyphosate resulted in higher NDVI than hot foam in the initial evaluations at all site–experimental runs. This was due to the fact that although injury symptoms were visible after one week in the glyphosate–treated plots, they were not as intense as in the hot foam–treated plots. Based on the second NDVI evaluations, glyphosate injury symptoms increased significantly about two weeks after treatment. These observations are consistent with other researchers who indicate that glyphosate symptoms are visible four to seven days after treatment and symptoms peak three to four weeks after treatment [30,31].

Pelargonic acid, mowing, and mulching also provided some reduction in NDVI. This suggests that pelargonic acid controlled annual weeds at early growth stages. Although larger plants survived, the treatments caused some chlorotic symptoms in their leaf tissue that reduced NDVI compared to the untreated control. Mowing may also have controlled some weeds. Weeds that exhibited regrowth were at an earlier growth stage and had fewer leaves at the time of evaluation, so they had lower NDVI values than plants left untreated in the control plots. The lower NDVI values in the plots mulched with pruning residues were due to the fact that mulching suppressed and delayed the emergence of weeds and, consequently, the sensor detected the presence of fewer plants that were in earlier growth stages at the time of the measurements. These results were the same for most of the site–experimental runs in both evaluations and are consistent with previous studies reporting that pelargonic acid, mowing, and mulching can cause some reductions in the NDVI of weeds [3].

4.2. Total weed biomass

Hot foam and glyphosate were the most effective treatments for weed control, resulting in the lowest levels of total weed biomass. At an application rate of 13.33 L m^{-2}, hot foam reduced weed biomass by more than 90% at all four site–experimental runs, compared to the untreated. The satisfactory performance of hot foam is consistent with other studies in which hot foam at an application rate of 8.33 L m^{-2} reduced weed biomass by up to 84% [21]. Moreover, in some cases, the performance of hot foam was more satisfactory than that of glyphosate. This may be attributed to the presence of certain weed species in the olive groves studied, which are less sensitive to glyphosate. Further explanations are provided in 4.3. In any case, our results agree with those of Martelloni et al. [23], who also suggested that hot foam should be recognized as a potential alternative to glyphosate weed control option. These authors also found that hot foam is a much more effective method of weed control than pelargonic acid, an observation that was common in all four site–experimental runs in the current study. The explanation lies in the fact that pelargonic acid is a contact herbicide that lacks any systemic activity [18]. Contact herbicides act only on the aboveground parts of weeds that are actually treated by destroying the cuticular layer of the foliage, resulting in rapid burn–down of the young tissues [32]. Therefore, although pelargonic acid and similar natural herbicides can be effective on broadleaf weeds in early growth stages, they only injure larger annual weeds that recover treatments and exhibit regrowth [33].

In contrast, foam allows complete coverage of all above–ground parts of treated weeds, which are exposed to very high temperatures for a considerable time after treatment because foam prevents heat energy from escaping to the atmosphere [22]. The low efficacy of pelargonic acid and the slight (albeit significant) reductions it caused compared to the untreated control in most cases can be explained by the fact that most weeds already had four to six leaves at the time of treatment. Research has shown that the performance of pelargonic acid is maximized when applications target young weed seedlings early in the season [34].

In most evaluations, mulching was characterized by intermediate efficacy, reducing weed biomass compared to mowing, pelargonic acid, and the untreated control, but resulting in higher weed fresh weight per unit area compared to hot foam and glyphosate. Based on these results, it can be concluded that mulching with tree pruning residues is a practice that can suppress and delay weed emergence in olive groves. Similar results are reported by Verdú and Mas [35] in citrus orchards. However, additional weed control measures may be needed to achieve optimal results later in the season [36]. In addition, pruning residues should come from healthy trees to avoid the spread of diseases in the olive grove [37]. Application rates should also be chosen carefully, as the high carbon content and high carbon–to–nitrogen ratio (C:N) of tree pruning residues can lead to immobilization of nitrogen in the soil and reduce its availability to trees [16].

Mowing also resulted in some reduction in weed biomass, suggesting that smart disc flail– mowers operating in the tree row may contribute to solutions in weed control in the intra–row spaces and near tree trunks in olive groves and orchards. It is certain that weed regrowth later in the season will require more weed control measures to achieve sufficient levels of weed control [38]. However, the potential of mowing as part of mixed IWM systems that include both chemical and non–chemical practices in orchards should not be underestimated [3].

4.3. Biomass of dominant weed species

Pelargonic acid effectively controlled *G. aparine* in Kalamata, as also shown in previous studies [18]. This natural herbicide also showed some efficacy on *U. urens* at the same site and on *S. arvensis* in Pyrgos, but plants of both species that were at more advanced growth stages survived the applications [33]. Glyphosate controlled the annual weeds infesting both sites, i.e., *S. arvensis* in Pyrgos, *U. urens* and *G. aparine* in Kalamata. This was an expected result since glyphosate is a systemic herbicide characterized by excellent uptake and translocation [39]. Hot foam also provided excellent control of these annual broadleaf weeds. These results suggest that annual broadlead weeds are unlikely to survive applications if adequate coverage is provided [20]. Mulching and mowing also suppressed weed growth in the respective plots to some extent, but without achieving optimal control of the aforementioned weeds when applied as single treatments, as also observed in previous field trials in olive groves and citrus orchards [3].

For *M. parviflora* and *P. officinalis*, the results were different. Notably, all treatments except hot foam and glyphosate failed to control these weeds. *M. parviflora* is a very common weed species in the olive groves of Elis and in the Peloponnese in general, which is quite difficult to control. It is a winter, occasionally biennial or annual broadleaf weed with a deep taproot that cannot be controlled by mowing, since the plants can regrow after cutting [40]. It was also expected that mulching would not be effective because seeds do not require light to germinate. Nevertheless, some plants managed to emerge and make their way through the mulch layer of pruning residues [41]. Pelargonic acid only injured leaves that came into contact with the natural herbicide, but failed to control *M. parviflora*. In plots treated with hot foam, regrowth still occurred, with plants accumulating as much as 50 g m^{-2} biomass by the second assessment, but it appears that hot foam applications can control plants that are in early growth stages or delay their regrowth to some extent. A necessary step is to crimp the plants to adequately cover them with hot foam. In addition, glyphosate at an application rate of 1440 g a.e. ha^{-1} did not achieve adequate control of *M. parviflora*. Our results confirm that this species has some tolerance to glyphosate, as also observed by Chorbadjian and Kogan [42], who reported that glyphosate should be tank–mixed with fluroxypyr to achieve better results.

Similar results are reported for the performance of the various weed control methods tested on *P. officinalis*. Mowing, mulching, and pelargonic acid were not effective, and glyphosate was not as effective as against other species. These results are consistent with previous studies in which researchers reported that glyphosate eliminates most weed populations but cannot achieve complete control of this species (with populations that include annual and perennial plants), and excessive use of this herbicide can lead to its dominance in orchards; similar early reports exist on a closely related species, *Parietaria judaica* L. [43,44]. Although differences were not found to be significant, hot foam controlled several plants of this species and tended to reduce their biomass per unit area to a greater extent than glyphosate. The good performance of hot foam against *P. officinalis* is consistent with Raffaelli et al. [45], who also observed good control of this species using thermal weed control methods. These researchers also found that thermal weed control was superior to mowing, as in the current study, and attributed these results to the fact that thermal methods, unlike mowing, control weeds that grow on the soil surface or whose vegetation is very close to the ground.

5. Conclusions

Hot foam applications represent a new, smart concept in the field of thermal weed control. The overall efficacy of hot foam was comparable to that of glyphosate as observed in four site-experimental runs. Hot foam performance was satisfactory on a wide range of broadleaf weeds, including species that are difficult to control by conventional methods. Our results suggest that the use of hot foam is an environmentally friendly, effective and alternative to glyphosate method to control weeds in olive groves in the spaces between trees in the row. In addition, the use of hot foam appears to outperform other non-chemical methods that provide only a moderate level of weed control. However, the contribution of practices such as mowing, mulching and bioherbicides in developing IWM strategies in perennial crops should not be underestimated [3]. In any case, further research is needed to optimize the use of hot foam for weed control in olive groves, orchards and vineyards under different soil and climatic conditions.

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CRediT authorship contribution statement

Nikolaos Antonopoulos: Methodology, Resources, Writing – original draft. **Panagiotis Kanatas:** Conceptualization, Methodology, Validation. **Ioannis Gazoulis:** Software, Formal analysis, Writing – original draft. **Alexandros Tataridas:** Validation, Investigation, Data curation. **Dimitris Ntovakos:** Validation, Investigation. **Vasilis–Nektarios Ntaoulis:** Validation, Investigation. **Spyridoula-Marina Zavra:** Validation, Investigation. **Ilias Travlos:** Conceptualization, Supervision, Project administration, Resources.

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