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Flame Weeding at Archaeological Sites of the Mediterranean Region

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Archaeological sites of the Mediterranean region are widely colonized by weed species causing various problems both to the monuments and the functionality of the sites. Due to recent regulatory restrictions for herbicide use at archaeological sites, flame weeding was studied as an alternative weed management method. The objective of the study was to test two propane doses (99 kg ha^{-1} and 129 kg ha^{-1}) applied two, three, or four times at three archaeological sites of Greece (Kolona, Ancient Messene and Early Christian Amfipolis). Percent weed control and weed heights were significantly affected by flaming treatments. Visual evaluation of percent weed control suggested that the propane dose of 129 kg ha^{-1} applied four times provided excellent weed control (>90%) for over 2 months. Annual broadleaf weeds were controlled better with flaming than grasses and perennial broadleaf species. The high propane dose applied four times reduced average vegetation height to about 10 cm, which was the desirable vegetation height wanted by the managers of the archeological sites suggesting that flame weeding has the potential to be used effectively for weed management in archaeological sites of the Mediterranean region.
Key words: Alternative weed control method, historical sites, integrated weed management, vegetation management

The Mediterranean Basin gave birth to a number of civilizations and is interspersed by a dense network of cultural heritage sites. Archaeological sites are often large scale, open spaces that enclose a variety of monuments, including free spaces between monuments. These spaces are rapidly colonized by herbaceous plants, especially during the rainy season (November to April) (Hatzidakis 1998; Papafotiou et al. 2010). Weed presence between the monuments is not desirable because weeds can 1) conceal the monuments, 2) interfere with regular maintenance and restoration, 3) obstruct site access for visitors, 4) impair the aesthetics of the site (give the appearance of neglect), and 5) increase the risk of fire during the long hot and dry summer season of the Mediterranean region (Lisci et al. 2003; Mishra et al. 1995; Zahos 1998). The typical Mediterranean climate is characterized by mild winters and extended dry periods during the warmest months of the year. The herbaceous vegetation of the archaeological sites in the Mediterranean zone is adapted to such conditions and is dominated by plants with short life cycles (therophytes) that are in a quiescent (dormant) stage during the warm months (summer) (Caneva and Pacini 2008).

Currently, there are no official guidelines for vegetation management around archaeological sites from the pertinent authorities in Greece (Kanellou et al. 2015; Zahos 1998). In addition, Greek national law (8197/90920/B/1883/01.08.2013) prohibits the use of pesticides in and around archaeological sites. Therefore, there is a need to develop alternative tools for vegetation control. Additionally, archaeologists are not in favor of using herbicides as they can cause deterioration of the monuments' building materials. Deterioration caused by herbicide can be attributed to the dissolution of calcium carbonate in the building materials due to the acidity of the herbicide and/or substances originated by

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oxidative degradation of the original herbicide formula (Mouga et al. 1995). The negative effects of herbicide use are well documented in agriculture: evolution of herbicide resistant weeds (Heap 2014), detection of herbicides (or byproducts) in surface and ground water (Albanis et al. 1998), and herbicide residues in food (Tadeo et al. 2000).

Complete eradication of weeds is not the intent at the archaeological sites, but rather the management of vegetation at the desirable level, which can be a challenging task. The most common weed control methods at archaeological sites are string trimming and hand weeding (Catizone 1998; Kanellou et al. 2015), which can be cost prohibitive and labor intensive (Arvanitis 1998; Zahos 1998). Mechanical cultivation, a common weed management method in organic farming systems (Hiltbrunner et al. 2007; Ulloa et al. 2010a), could not be adopted for archaeological sites due to nonuniform landscape and potential for mechanical damage of unexcavated archaeological monuments. Therefore, there is interest in developing alternative vegetation control methods for archaeological sites. One such method might be propane-fueled flame weeding, which is becoming popular in organic crop production (Datta and Knezevic 2013).

Propane-fueled flame weeding is a nonchemical method of weed control used in organic cropping systems (Bond and Grundy 2001) and non-agricultural settings such as city parks and other urban environments (Hansen et al. 2004; Rask et al. 2012). Flame weeding involves exposing plant tissues to heat produced by a propane burner. Flaming differs from burning in that the plant biomass is not incinerated, but rather is heated rapidly causing rupturing of the cell membranes (Lague et al. 2001). Propane burners can generate combustion temperatures of up to 1,900 C (Ascard 1998). At temperatures above 50 C, plant cell integrity is disrupted due to protein denaturation and cell membrane destruction (Lague et al. 2001; Parish 1990; Pelletier et al. 1995; Rifai et al. 1996). Hence, flamed weeds die or their ability to grow is severely reduced.

Plant survival after flaming treatments depends on various factors, such as flaming technique, soil structure, leaf surface moisture, presence of protective hair and wax on leaves, lignification, and water status of the tissue (Ascard 1995). However, plant survival after flaming treatments mainly depends on the plant's capacity to regrow after the treatment (Ascard 1995; Ascard et al. 2007). Weed susceptibility to flaming treatments varies with species and plant size (Cisneros and Zandstra 2008; Sivesind et al. 2009; Ulloa et al. 2010a). In general, grasses are more tolerant to flaming than are broadleaf species (Ulloa et al. 2010a,b; Wszelaki et al. 2007) due to the physical position of the growing point, which in grass species is below ground during early growth stages (Datta and Knezevic 2013). Additionally, perennial species are more tolerant to flaming than are annual species, because flaming does not affect the root structures of perennial weeds (Datta and Knezevic 2013). Tolerance to flaming varies with growth stages; plants are more susceptible to flaming at earlier growth stages than they are at later ones (Ascard 1995; Cisneros and Zandstra 2008; Sivesind et al. 2009). Plants at earlier growth stages have thinner leaves, lower biomass, and more exposed meristems, whereas plants at later growth stages have thicker leaves and increased capacity for regrowth (Ascard 1994, 1995).

Current literature on flame weeding covers the use of the method in crop production systems (Datta and Knezevic 2013; Sivesind et al., 2009; Ulloa et al. 2010a, 2010b, 2011). Although complete kill is not achieved with some species, single flaming treatments can provide early season growth stunting by severely reducing weed growth, thus offsetting weeds' competitiveness against the crop (Knezevic and Ulloa 2007; Ulloa et al. 2010a). However, flaming does not affect subsequent weed emergence (Bond and Grundy 2001), and consequently two successive flamings can be more effective than a single treatment (Bond and Grundy 2001). The repeated flaming should be made after initial regrowth but before regrowing shoots are too large (Ascard 1995).

Given that flaming is a nonchemical method for suppressing weeds, it would be beneficial to study its effectiveness in archaeological sites, particularly in the Mediterranean region. Therefore, the objective of the study was to determine the effects of propane dose and multiple flaming operations on weed control at several archaeological sites in Greece.

Materials and Methods

Site Description. Experiments were conducted over a period of two years (2013 and 2014) at three archaeological sites in Greece (Kolona, Ancient Messene, and Early Christian Amfipolis), representing

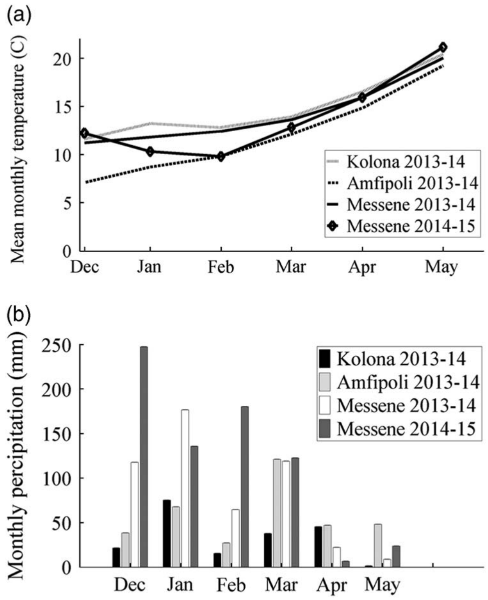

Figure 1. (a) Monthly mean temperature (C) and (b) monthly precipitation (mm), during experimental periods in Kolona (2013–14), Amfipolis (2013–14), and Messene (2013–14, 2014–15).

different bioclimatic types of the Mediterranean climate. Kolona (37°44′N, 23°25′E; altitude 2 m) is located at Aegina Island, 30 km south of Athens, and is characterized by an average rainfall of about 400 mm annually, mild winters, and dry summers. Ancient Messene (37°10′N, 21°55′E; altitude 326 m), situated in southwestern Greece (western Peloponnese), has a wetter climate, with mild winters and cool summers, while the Early Christian Amfipolis site (40°49′N, 23°50′E; altitude 119 m) is located in northern Greece, 100 km east of Thessaloniki, and has cold winters and dry summers. The main growing season for vegetation at archeological sites in this type of climate is typically from November until April. From a practical standpoint, if weeds are managed until the end of April they are not of major concern during the dry, hot summer and fall because there is not enough moisture to promote emergence or growth of new weed flushes, especially for annual species (Kanellou et al. 2014). Meteorological data during experimental periods for all sites are presented in Figure 1.

Weed Flaming Treatments. During the first study year (2013/2014), flaming treatments were initiated at Kolona on November 29, at Ancient Messene (Messene) on January 23, and at Early Christian Amfipolis (Amfipolis) on March 13. Differences in the treatment starting dates were based on the seasonal differences between the three sites: weeds emerged earliest at Kolona (November) and much later at Amfipolis (February).

Treatments were arranged in a randomized complete block design with seven treatments and three replications (a total of 21 plots) at each of the three sites. Treatments consisted of two propane doses, a low dose of 99 kg ha^{-1} (L) and a high dose of 129 kg ha^{-1} (H), each applied two (2), three (3), or four (4) times at 14 d intervals, and a nontreated control (C) (hereafter referred as 2L, 2H, 3L, 3H, 4L, 4H and C treatments). All plots were 2 by 2 m. Flaming was conducted when weeds reached 10 to 20 cm in height, utilizing a backpack propane flamer (PiroBag One; Maito, Arezzo, Italy), with a single nozzle torch (30 cm wide housing), which provided a flame approximately 40 cm wide. Each plot was uniformly flamed for 52 s, resulting in a propane dose of 99 kg ha^{-1} when using a pressure of 200 kPa, and 129 kg ha^{-1} when using a pressure of 350 kPa. Propane doses were selected based on results of the dose-response study conducted in the previous year (2012/2013, unpublished data) at the Messene site.

Due to labor constraints, the experiment was repeated in the second year only at one site (Messene). The most effective treatments from all three sites in the first year were then repeated the second year, at the newly selected site, in a randomized complete block design consisting of five treatments and three replications. There were a total of 15 plots (2 by 2 m). The treatments included two propane doses (low and high, 99 kg ha^{-1} and 129 kg ha^{-1}, respectively) applied three (3) or four (4) times, at 14 d intervals, and a nontreated control (hereafter referred as 3L, 3H, 4L, 4H, and C treatments). The experimental procedures were same as during the first year of the study.

Weed Species Composition. The most abundant weed species across all sites was sterile oat (*Avena sterilis* L.). The average ground cover with sterile oat was 72.1% at Kolona, 69.3% at Amfipolis, and 55.1% and 74.3% at Messene during the first and second year, respectively. In addition, several broadleaf species were also present, including 11.3% ground cover with buttercup oxalis (*Oxalis pes-caprae* L.) at Kolona, 14.7% with geranium (*Geranium brutium* Gasp.) at Amfipolis, and 42.2% and 13.7% with field marigold (*Calendula arvensis* L.) at Messene during the first and second year, respectively. Other species appeared sporadically at a very low densities, and included: Mediterranean catchfly (*Silene colorata* Poir.), field marigold, black mustard (*Sinapis nigra* L.), high mallow (*Malva sylvestris* L.), and rigid ryegrass (*Lolium rigidum* Gaudin) at Kolona; yellow vetch (*Vicia lutea* L.), annual mercury (*Mercurialis annua* L.), and dill (*Anethum graveolens* L.) the first study year and yellow vetch and geranium the second year at Messene.

Measurements. Weed control, both overall and for each species individually, was evaluated in each plot visually at 1, 14, 28, 42, and 72 d after initial treatment. Visual evaluations (control ratings) were based on a scale of 0 (no plant injury) to 100 (plant death) (Ulloa et al. 2010). On d 72, the height of twenty randomly selected plants (of any species) per plot was measured and aboveground biomass was collected from a 50 by 50 cm area from the center of each plot. Fresh and dry weight was determined, and dry weight reduction was calculated as a percentage of plant biomass collected from the nonflamed (control) plots. Prior to each flaming treatment, visual ratings of species composition (as a percentage of each plot) were assessed. During the second year the same measurement procedures were followed, except that the final day of measurements was moved from 72 d to 100 d from the initial treatment in order to further document the treatments' residual effects.

Statistical Analysis. Analysis of variance was performed utilizing Statgraphics Centurion version 15.2.11 (Statpoint Technologies Inc., Warrenton, VA, USA) using MANOVA within each separate sampling date. Three-factor multivariate analysis of variance showed significant interactions between location, dose, and number of applications, which prohibited further multifactorial analysis of the data. Therefore, all data were analyzed for each location and year as a single factor using one-way analysis of variance utilizing Statgraphics Centurion. Due to statistical treatment differences between sites, data are presented separately for each site. Treatment means were separated using Fisher's Protected Least Significant Difference (LSD) at a 0.05 probability level ($P < 0.05$).

Results and Discussion

Overall Weed Control. All flaming treatments reduced weed growth. In general, the highest level of weed control was achieved by multiple applications of the higher propane dose. At Kolona, 4H treatment provided 95% weed control on d 72 (Table 1). Similar trends were observed at Amfipolis and Messene, where the 4H treatment provided 100% control on d 72 (Tables 1 and 2). Results from the second year at Messene also showed that 4H treatment provided 100% control even on d 100 (Table 2). However, fewer applications of the higher dose resulted in lower level of weed control at Kolona and Amfipolis. For example, the 3H treatment at Kolona provided only about 40% weed control at d 72 (Table 1), suggesting that it is critical to have multiple applications of the high dose (at least four applications). In contrast to the results at the Kolona site, the lower propane dose or fewer than four flaming applications resulted in excellent weed control (85% to 95%) at Amfipolis (4L treatment) and Messenne (3H and 4L treatments) (Tables 1 and 2). This is likely attributed to the fact that both sites had a thick dry thatch of dormant bermudagrass [*Cynodon dactylon* (L.) Pers.] that caught on fire during flaming process, which released additional heat and provided better weed control. Additionally, even though rainfall at Messene was much higher during December and February of the second year than it was during the first year (Figure 1b), flaming treatments provided similar weed control as they did the first year.

Table 1. Weed control as percent (%) of total plot area, as influenced by flaming treatments, in Kolona (2013–14) and Amfipolis (2013–14) on d 28 and d 72.

	Weed control[a]			
	Kolona (2013/14)		Amfipolis (2013/14)	
Treatment	d 28	d 72	d 28	d 72
	%			
C	0 e	0 c	0 d	0 c
2L	21.7 d	0 c	22.2 c	0 c
3L	73.3 c	0 c	91.4 a	44.7 b
4L	80.0 bc	25.0 bc	91.6 a	85.0 a
2H	63.3 c	11.7 bc	56.7 b	10.7 c
3H	96.7 ab	36.7 b	100.0 a	53.3 b
4H	100.0 a	95.0 a	100.0 a	100.0 a

[a] Values are the mean of three replicates. Values followed by different letters are significantly ($P < 0.05$) different. C: nontreated control, 2L: 2 applications of 99 kg ha^{-1}, 3L: 3 applications of 99 kg ha^{-1}, 4L: 4 applications of 99 kg ha^{-1}, 2H: 2 applications of 129 kg ha^{-1}, 3H: 3 applications of 129 kg ha^{-1}, 4H: 4 applications of 129 kg ha^{-1}.

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Table 2. Weed control as percent (%) of total plot area, as influenced by flaming treatments, at Messene during 2013–14 on d 28 and d 72, and during 2014–15 on d 28 and d 100.

	Weed control[a]			
	Messene (2013–14)		Messene (2014–15)	
Treatment	d 28	d 72	d 28	d 100
	%			
C	0 c	0 b	0 b	0 b
2L	83.0 b	75.0 a	–	–
3L	97.7 ab	80.0 a	91.0 a	86.0 a
4L	99.3 a	95.0 a	95.0 a	95.0 a
2H	89.0 ab	73.3 a	–	–
3H	100.0 a	93.3 a	100.0 a	100.0 a
4H	100.0 a	100.0 a	100.0 a	100.0 a

[a] Values are the mean of three replicates. Values followed by different letters are significantly ($P < 0.05$) different. C: nontreated control, 2L: 2 applications of 99 kg ha^{-1}, 3L: 3 applications of 99 kg ha^{-1}, 4L: 4 applications of 99 kg ha^{-1}, 2H: 2 applications of 129 kg ha^{-1}, 3H: 3 applications of 129 kg ha^{-1}, 4H: 4 applications of 129 kg ha^{-1}.

The above results indicate that flaming can be a potential tool for weed management at archaeological sites. The 4H treatment provided a consistently high level (>90%) of weed control. Lower propane rates applied multiple times (4L) at Amfipolis and Messene were also effective in controlling weeds, which is similar to the previous reports of Ascard (1995), who suggested that multiple applications of flaming are more effective than a single application.

Grass and Broadleaf Species Response to Flaming. In general, propane flaming provided better control of broadleaf weeds than it did of grasses. A broadleaf geranium was completely controlled (100%) by 3L treatment, whereas sterile oat required 4H treatment to reach the same level of control at Amfipolis (Table 3). Similarly, at Messene, field marigold was completely controlled (100%) by even 2L treatment, whereas the same treatment resulted in only 72% control for sterile oat, which required 4L treatment to obtain over 90% control (Table 3). Grasses are more tolerant to flaming due to the physical position of the growing point at the time of flaming (below soil surface, and away from the heat) (Datta and Knezevic 2013; Knezevic and Ulloa 2007; Ulloa et al. 2010a).

Datta and Knezevic (2013) also suggested that perennial broadleaf weeds may require multiple applications and higher propane doses than do the annual broadleaf weeds. That was also observed in this experiment. For example, perennial broadleaf oxalis required at least four applications of high dose (4H treatment) to obtain excellent control (100%) at Kolona, compared to only 50% or 25% control with fewer applications (3H) and lower doses (2L), respectively (Table 3).

Previous surveys of vegetation types at seven archaeological sites across Greece, including the three sites of the present study, reported the presence of over 230 different plant species (Kanellou et al. 2014). The presence of such a diverse population of plant species, including many perennial and annual grasses, will likely necessitate the use of higher propane doses and multiple flaming treatments to manage weeds effectively for the duration of the growing period (November-April).

It might be interesting to note that Reyes and Trabaud (2009) reported that increased heat caused by natural fire had variable effects on the germination of Mediterranean plants. Crosti et al. (2006) also reported that the pattern of germination of Mediterranean species in relation to fire-stimulated germination is still not clear. There was no observed evidence of alteration in germination pattern of the species that were present in our experiments.

Vegetation Height. Flaming treatments significantly reduced weed height across all sites and years. In general, average height decreased with increasing propane dose and number of flaming applications. The 4H treatment reduced vegetation height to about 10 cm at Amfipolis, while the vegetation in the nontreated control was 119 cm in height. Similar results were obtained at the other sites and years (Table 4), suggesting that flaming treatments can be utilized effectively to control vegetation height. Vegetation height was identified by the managers of archeological sites as one of the most important factors contributing to the overall enjoyment of the site. A 2014 survey of 34 Regional Services of the Directorate of Antiquities (Ministry of Culture and Sports) across Greece revealed that about 80% of the site managers believed that native vegetation plays a significant part in the enjoyment of the archaeological landscape (Kanellou 2016). Managers agreed that a 5 to 10 cm height is an ideal vegetation height at any historical site. Taller vegetation can interfere with monument restoration projects, and can also visually impair the monuments or obstruct free access to the site.

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Table 3. Weed control (%) on final experimental day for abundant species in Kolona (2013–14), Amfipolis (2013–14), and Messene (2013–14, 2014–15), as influenced by flaming treatments.

	Weed control[a]							
	Kolona (2013–14)		Amfipolis (2013–14)		Messene (2013–14)		Messene (2014–15)	
Treatment	Sterile oat	Oxalis	Sterile oat	Geranium	Sterile oat	Field marigold	Sterile oat	Field marigold
	%							
C	0 c	0 c	0 d	0 b	0 c	0 b	0 b	0 b
2L	0 c	25.0 bc	3.7 d	33.3 b	72.0 ab	100.0 a	–	–
3L	0 c	50.0 b	36.3 c	100.0 a	76.7 ab	100.0 a	65.8 a	100.0 a
4L	23.3 bc	15.0 bc	78.3 b	100.0 a	93.3 a	100.0 a	96.7 a	100.0 a
2H	14.6 bc	29.0 bc	6.0 d	16.7 b	56.7 b	100.0 a	–	–
3H	46.0 b	25.0 bc	45.5 c	100.0 a	90.3 ab	100.0 a	100.0 a	100.0 a
4H	98.0 a	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a	100.0 a

[a] Values are the mean of three replicates. Values followed by different letters are significantly ($P < 0.05$) different. C: nontreated control, 2L: 2 applications of 99 kg ha^{-1}, 3L: 3 applications of 99 kg ha^{-1}, 4L: 4 applications of 99 kg ha^{-1}, 2H: 2 applications of 129 kg ha^{-1}, 3H: 3 applications of 129 kg ha^{-1}, 4H: 4 applications of 129 kg ha^{-1}.

Since the short vegetation presence is very important to provide a ground cover, the results from this study are encouraging as they suggest that multiple flaming with the dose of 129 kg ha^{-1} has the potential not only to keep vegetation suppressed for the first 2 to 3 months of the growing season, but also to keep the vegetation at the desirable height (e.g., 10 cm).

Weed Biomass Reduction. The largest biomass reduction was observed with the high propane dose and multiple flaming treatments. For example, at Kolona and Amfipolis, the 4H treatment provided over 94% dry matter reduction. Similar effects were observed at Messene in both study years (Table 5). These results are encouraging from the practical standpoint, as the presence of dry biomass during the summer months is not desirable at archeological sites because of fire risk. In fact, a survey of archaeological site managers suggested that over 76% believe that fire is an extremely serious threat to monuments during the summertime (Kanellou 2016). The damage caused by fire to a monument is irreversible, as the stones get covered by black soot, become calcified, develop cracks, and get exfoliated. Most archaeological sites are not equipped with fire extinguishing systems (Zahos 1998).

Table 4. Average plot height (cm) on final experimental day in Kolona (2013–14), Amfipolis (2013–14), and Messene (2013–14, 2014–15), as influenced by flaming treatments.

	Average plot height[a]			
Treatment	Kolona (2013–14)	Amfipolis (2013–14)	Messene (2013–14)	Messene (2014–15)
	cm			
C	52.3 a	119.7 a	46.7 a	34.2 a
2L	37.6 b	70.0 b	22.6 b	–
3L	28.3 bc	31.3 c	15.0 bc	7.8 b
4L	25.1 bc	18.3 cd	10.9 c	6.3 b
2H	34.2 bc	69.3 b	15.3 bc	–
3H	22.0 cd	28.3 c	9.15 c	5.0 b
4H	9.1 d	10.3 d	7.5 c	5.3 b

[a] Values are the mean of three replicates. Values followed by different letters are significantly ($P < 0.05$) different. C: nontreated control, 2L: 2 applications of 99 kg ha^{-1}, 3L: 3 applications of 99 kg ha^{-1}, 4L: 4 applications of 99 kg ha^{-1}, 2H: 2 applications of 129 kg ha^{-1}, 3H: 3 applications of 129 kg ha^{-1}, 4H: 4 applications of 129 kg ha^{-1}.

Results from our study suggest that propane flaming can be utilized to suppress vegetation at archaeological sites. It is evident that flaming can control vegetation for the first 100 d of the growing season, which is when vegetation must be controlled in the Mediterranean climate. Flaming can maintain the desirable vegetation height, and provide a pleasant visual appearance at the site, as well as protection of the monument from fire due to significant reduction of dry plant biomass. However, it is important to design flaming treatments based on the site-specific growing conditions and weed species. In particular, the weed height at the first flaming application is critical for the overall success of the control. Datta and Knezevic (2013) suggested that smaller weeds (2 to 10 cm tall) are much easier to control than larger ones (20 to 50 cm tall). Therefore, we believe that flaming-based weed

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Table 5. Dry weight reduction (%) on final experimental day in Kolona (2013–14), Amfipolis (2013–14), and Messene (2013–14, 2014–15), as influenced by flaming treatments.

	Dry weight reduction[a]			
Treatment	Kolona (2013–14)	Amfipolis (2013–14)	Messene (2013–14)	Messene (2014–15)
	%			
C	0 e	0 e	0 c	0b
2L	33.2 d	40.3 d	42.0 b	–
3L	61.5 bc	79.3 b	66.8 ab	59.8 a
4L	64.3 bc	91.3 a	75.7 a	88.8 a
2H	53.4 cd	60.0 c	63.3 ab	–
3H	79.1 ab	88.3 a	76.5 a	97.6 a
4H	95.0 a	94.7 a	82.3 a	98.6 a

[a] Values are the mean of three replicates and values followed by different letters are significantly ($P < 0.05$) different. C: nontreated control, 2L: 2 applications of 99 kg ha^{-1}, 3L: 3 applications of 99 kg ha^{-1}, 4L: 4 applications of 99 kg ha^{-1}, 2H: 2 applications of 129 kg ha^{-1}, 3H: 3 applications of 129 kg ha^{-1}, 4H: 4 applications of 129 kg ha^{-1}.

management programs should be initiated when vegetation height is at approximately 10 cm and should be repeated at least four times at 2 to 3 week intervals (at 10 to 15 cm regrowth height), which should provide at least 3 months of vegetation control.

Also, the presence of dry biomass (e.g., thatch of dormant grasses or dry vegetation from the previous year) should be taken into account before applying the flaming protocol, in order to avoid a potential fire hazard. For this reason, it is often recommended that land managers conduct flaming after a rainfall, as long as the moisture is not present on the leaves. Datta and Knezevic (2013) reported that any kind of moisture, including heavy dew and rain droplets on weed leaves, can reduce the effectiveness of flame weeding treatments, or require higher propane doses to be successful. Flame weeding can be also combined with other weed control tools (hand weeding or trimming) as part of an integrated weed management program, especially in those years when weather conditions may not be favorable for flaming (e.g., rainy or extremely wet or dry periods). The cost of propane may make flaming cost prohibitive. For example, the cost of flaming (propane plus labor) can range from €213 to €329 ha^{-1}, compared to the cost of string trimming at €450 ha^{-1} or hand weeding at €1.800 ha^{-1}.

This is the first time that flame weeding has been tested in Greece, and we believe that flame weeding could also become an alternative tool for weed management in cropping systems across Greece. More research is needed to test this hypothesis.

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Literature Cited

Albanis TA, Hela DG, Sakellarrides TM, Konstantinou IK (1998) Monitoring of pesticide residues and their metabolites in surface and underground waters of Imathis (N. Greece) by means of solid-phase extraction disks and gas chromatography. J Chromatog A 823:59–71

Arvanitis P (1998) Flora and fauna management in the archaeological sites of second Ephorate of Prehistorical and Classical Antiquities. Pages 45–47 *in* Proceedings of Symposium on Spontaneous vegetation in Archaeological sites. Athens: Acropolis Friends Association

Ascard J (1994) Dose response models for flame weeding in relation to plant size and density. Weed Res 34:377–385

Ascard J (1995) Effects of flame weeding on weed species at different developmental stages. Weed Res 35:397–411

Ascard J (1998) Comparison of flaming and infrared radiation techniques for thermal weed control. Weed Res 38:69–76

Ascard J, Hatcher PE, Melander B, Upadhyaya MK (2007) Thermal weed control. Pages 155–175 *in* Upadhyaya M.K. & Blackshaw RE, ed. Nonchemical Weed Management. Wallingford, UK: CAB International

Bond W, Grundy AC (2001) Nonchemical weed management in organic farming systems. Weed Res 41:383–405

Caneva G, Pacini A (2008) Biodeterioration problems in relation to geographical and climatic contexts. Mediterranean climates. Pages 227–230 *in* Caneva G, Nugari MP & Salvadori O. Plant Biology for Cultural Heritage – Biodeterioration and Conservation. Los Angeles: The Getty Conservation Institute

Catizone P (1998) Pompeii and Selinunte: Two examples of vegetation management in Mediterranean archaeological sites. Pages 48–53 *in* Proceedings of Symposium on Spontaneous Vegetation in Archaeological Sites. Athens: Acropolis Friends Association

Cisneros JJ, Zandstra BH (2008) Flame weeding effects on several weeds species. Weed Technol 22:290–295

Crosti R, Ladd PG, Dixon KW, Piotto B (2006) Post-fire germination: the effect of smoke on seeds of selected species from the central Mediterranean basin. Forest Ecol Manage 221:306–312

Datta A, Knezevic SZ (2013) Flaming as an alternative weed control method for conventional and organic agronomic crop production systems: a review. Adv Agron 118:399–428

Hansen PK, Kristoffersen P, Kristensen K (2004) Strategies for nonchemical weed control on public paved areas in Denmark. Pest Manag Sci 60:600–604

Hatzidakis P (1998) Archaeological sites and spontaneous vegetation. Pages 34–44 *in* Proceedings of Symposium on Spontaneous Vegetation in Archaeological Sites. Athens: Acropolis Friends Association

Heap I (2014) Herbicide resistant weeds. Pages 281–301 *in* Pimentel D & Peshin R. Integrated Pest Management, Pesticide Problems. Vol 3. London: Springer

Hiltbrunner J, Liedgens M, Boch L, Stamp P, Streit B (2007) Legume cover crops as living mulches for organic wheat: components of biomass and the control of weeds. Eur J Agron 26:21–29

Kanellou E (2016) Development of Native Vegetation Management Methods Based on Indicative Recording of Vegetation and Associated Problems, as Well as Investigation of Vegetation Design Principles Aiming to Protect the Monument and Enhance the Historical Landscape. Ph.D. dissertation. Athens: Agricultural University of Athens

Kanellou E, Papafotiou M, Economou F, Dogani I, Galanos A (2015) Unwanted vegetation management in archaeological sites. Pages 87–89 *in* Book of Abstracts of the 4th Panhellenic Conference on Restoration. Thessaloniki, Greece: Association for Research and Promotion of Restoration of Monuments

Kanellou E, Papafotiou M, Economou G, Lyra D, Ntoulas N (2014) Integrated weed management in archaeological sites – Thalis project. Page 109 *in* Book of Abstracts of the 9th International Symposium on the Conservation of Monuments in the Mediterranean Basin. Ankara, Turkey: Department of Architecture, METU

Knezevic S, Ulloa S (2007) Potential new tool for weed control in organically grown agronomic crops. J Agric Sci 52:95–104

Lague C, Gill J, Peloquin G (2001) Thermal control in plant protection. Pages 35–46 *in* Vincent C, Panneton B & Fleurat-Lessard F, eds. Physical Control Methods in Plant Protection. Berlin, Germany: Springer-Verlag

Lisci M, Monte M, Pacini E (2003) Lichens and higher plants on stone: a review. Int Biodet Biode 51:1–17

Mishra AK, Jain KK, Garg KL (1995) Role of higher plants in the deterioration of historic buildings. Sci Total Environ 167:375–392

Mouga TM, Almeida MT, Rosa PJ (1995) Chemical control of wall vegetation. Neutralization of herbicides. Pages 293–301 *in* Proceedings of the LCP Congress on Preservation and Restoration of Cultural Heritage. Montreux, Switzerland: Ecole Polytechnique Federale de Lausanne

Papafotiou M, Kanellou E, Economou G (2010) Alternative practices for vegetation management in archaeological sites – the case of Eleusis. Acta Horticulturae 881:879–883

Parish S (1990) A review of nonchemical weed control techniques. Biol Agric Hort 7:117–137

Pelletier Y, McLeod CD, Bernard G (1995) Description of sub-lethal injuries caused to the Colorado potato beetle by propane flamer treatment. J Econ Entomol 88:1203–1205

Rask AM, Kristoffersen P, Andreasen C (2012) Controlling grass weeds on hard surfaces: effect of time intervals between flame treatments. Weed Technol 26:83–88

Reyes O, Trabaud L (2009) Germination behavior of 14 Mediterranean species in relation to fire factors: smoke and heat. Plant Ecol 202:113–121

Rifai MN, Zilka T, Mojzis M (1996) Flame and mechanical cultivation for weed control. Zemedelska Technika 42: 109–113

Sivesind EC, Leblanc ML, Cloutier DC, Seguin P, Stweart KA (2009) Weed response to flame weeding at different developemental stages. Weed Technol 23:438–443

Tadeo JL, Sanchez-Brunete C, Perez RA, Fernandez MD (2000) Analysis of herbicide residues in cereals, fruits and vegetables. J Chromatog A 882:175–191

Ulloa SM, Datta A, Knezevic S (2010a) Tolerance of selected weed species to broadcast flaming at different growth stages. Crop Prot 29:1381–1388

Ulloa SM, Datta A, Cavalieri SD, Lesvik M, Knezevic S (2010b) Popcorn (Zea mays L. var everta) yield and yield components as influenced by the timing of broadcast flaming. Crop Prot 29:1496–1501

Ulloa SM, Datta A, Knezevic S (2011) Growth stage influenced sorghum response to broadcast flaming: effects on yield and its components. Agron J 103:7–12

Wszelaki AL, Doohan DJ, Alexandrou A (2007) Weed control and crop quality in cagabe [*Brassica oleraceae* (capitata group)] and tomato (*Lycopersicon lycopersicum*) using a propane flamer. Crop Prot 26:134–144

Zahos K (1998) The spontaneous flora in archaeological sites. The Greek experience. Pages 9–17 *in* Proceedings of Symposium on Spontaneous Vegetation in Archaeological Sites. Athens: Acropolis Friends Association

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