THERMAL WEED CONTROL IN *PHOTINIA x FRASERI* "RED ROBIN" CONTAINER NURSERIES

C. Frasconi, L. Martelloni, M. Fontanelli, M. Raffaelli, P. Marzialetti, A. Peruzzi

ABSTRACT. *A near-zero tolerance policy on weeds by markets for nursery crops calls for weed-free container-grown plants, and forces growers to frequently remove weeds. Thermal weed control could represent a novel method to control weeds in shrubs from container nurseries, thus avoiding the use of herbicides and mulches. The aims of this study were to develop custom-built machinery for thermal weed control in container nurseries and to test the weed control efficiency of flame weeding and steaming in Photinia x fraseri "Red Robin" containers. A liquefied petroleum gas (LPG) fed flamer and a steamer with a dedicated diffuser were built. Four treatments were applied for a total period of 24 months: steaming once every four months, steaming once every two months, flame weeding once every two months or once a month. Temperature values measured at different depths in the substrate after thermal applications were recorded and analyzed. Photinia x fraseri features (height, diameter, and dry biomass) and aesthetic parameters as affected by thermal treatments were also evaluated. The trend in temperature values of the substrate over time followed a two-phase exponential decay. All the thermal treatments lead to a continuous near-100% weed control level, which is the level required by growers for aesthetic reasons. No damages caused by heat on Photinia x fraseri were observed. Container nursery producers could thus adopt thermal methods as a substitute for chemical solutions for weed control management.*

Keywords. *Container nurseries, ornamental plant production, Thermal weed control, Flame weeding, Steaming,* Photinia x fraseri *"Red Robin", Two-phase temperature decay model.*

Markets for nursery crops require weed-free container-grown plants, which thus forces growers to frequently remove weeds (Case et al., 2005). Moreover, weed occurrence in containers can cause a growth reduction of nearly 50% in woody ornamentals in a single growing season and decrease the aesthetic value of the plants (Samtani et al., 2007). Weed control in container production is usually preventive and conducted with pre-emergent herbicides, mulches, or hand weeding (Case et al., 2005). There are few post-emergent herbicides registered for selective broadleaf control in ornamental plants. These herbicides do not provide broad-spectrum broadleaf weed control in ornamental production and/or are not registered for use with many ornamental species (Cutulle et al., 2013).

Due to the high cost of labor involved in hand weeding, wherever possible growers use pre-emergent herbicides to control weeds (Mathers, 2003). Pre-emergent herbicides for container-grown plants should be highly effective on weeds, and they have low phytotoxicity on container-grown plants (Case et al., 2005). Pre-emergent herbicides do not prevent germination, but are absorbed by the weed through growing tissue (hypocotyl, shoot tip, root tip) and inhibit the growth of the seedlings (Case et al., 2005). The most common formulation used in container-grown shrubs is granular materials, which begins to degrade very quickly after application. In just days, the barrier already has gaps in which weeds can successfully germinate. Weed seeds can find a gap in the chemical barrier and successfully establish (Gilliam et al., 1992; Derksen et al., 2014). Moreover, the repeated use of one herbicide or herbicides with the same mode of action may lead to some plants in a population developing herbicide resistance, which is "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type", according to the Weed Science Society of America (WSSA, 2016). Many nursery growers apply imidazolinones and sulfonylureas, which have similar mode of action (acetolactate synthase inhibitors). Using one of these two herbicide families repeatedly could lead to the development of biotypes resistant to both herbicide families (cross-resistance) (Case et al., 2005).

Another way to suppress weed growth is to use mulch in the surrounding area of the plant. There are two major classifications of mulches used for weed control in container production: disks (plastic weed lids, coco disks, geotextile disks) and loose fill mulches (sawdust, biotop, bark chips, recycled paper products) (Chong, 2003; Mathers, 2003; Case et al., 2005; Amoroso et al., 2009). Mulches control weeds by inhibiting germination and suppressing weed

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growth. Geotextile disks contain copper hydroxide, which prevents weed seed germination when weed seeds fall onto the container surface with the disk in place (Mathers, 2003). Mulches can be also pre-treated with pre-emergent herbicides, and offer extra advantages for weed control over untreated ones (Mathers, 2003). Mulches have not been extensively used as weed suppressants in container production. Organic mulches can reduce the amount of readily available nitrogen (Billeaud and Zajicek, 1989), whereas plastic and geotextile disks include the size of the opening in the disc for the plant, and wind blowing the disc out of the container (Case et al., 2005).

Generally the level of weed control using loose fill mulches without the addition of pre-emergent herbicides resulted in below commercially acceptable levels (Mathers, 2003; Skroch et al., 1992). The application of pre-emergent herbicide-treated loose-fill mulches resulted in increased and extended herbicide efficacy compared to herbicides or mulches applied alone (Samtani et al., 2007; Ferguson et al., 2008). Mathers and Case (2010) found that bark mulch treated with microencapsulation of herbicides or emulsifiable concentrate formulations provided the least phytotoxicity and greatest extent, consistency, and duration of efficacy (100% weed control up to 110 DAT) compared to herbicides or mulches applied alone. In a study with containers containing willow oak (*Quescus phellos* L.) seedlings, Appleton and French (2000) found that geotextile disks provided complete weed control. Chong et al. (1989) reported an 85% reduction in container weeds using geotextile fabric disks. Appleton and Derr (1990) found that geotextile disks used in combination with pre-emergent herbicides gave superior weed control, leading to a 100% of weed control, observed after 20 weeks since the disks were laid into the containers. Amoroso et al. (2010) used disks made of natural fibres (coconut, agave, and jute) mixed with natural latex, and found that mulches limited weed growth to the same extent as herbicides. Weed dry biomass measured at the end of the experiment ranged from 0.7 to 2.5 g container^{-1} when biodegradable mulching discs were used. Most weeds found in the containers were dicotyledonous, and in higher frequency *Oxalis corniculata* L. (Amoroso et al., 2010). Amoroso et al. (2009) tested five mulching materials and found that the coco disk and a disk comprised of vegetal fiber (90%) and synthetic fiber (10%) led to the best weed control in *Photinia x fraseri* "Red Robin". None of the mulching materials affected the dry biomass and height increase of *Photinia x fraseri* during the growing season (Amoroso et al., 2009).

Granular pre-emergent herbicides are broadcast over container shrubs, typically using hand or air-boom spreaders. Shrub canopies intercept a fraction of the herbicide, while the remainder falls on the substrate surface or in the space between the containers (Derksen et al., 2014). Wehtje et al. (2012) found that the pre-emergent herbicide flumioxazin provided approximately 7 weeks of complete (100%) *Cardamine hirsuta* L. control and 2-4 weeks of complete *Chamaesyce maculata* L. control. Amoroso et al. (2009) found that the granular pre-emergent herbicide oxadiazon was more effective than trifluralin + isoxaben, however trifluralin needed to be re-applied in order to obtain satisfactory weed control throughout the growing season. Many container nurseries conduct three to five granular herbicide applications annually, resulting in significant non-target herbicide losses (Mathers, 2003). Non-target herbicide losses contaminate runoff water, some of which can end up in containment (recirculation) ponds and potentially cause phytotoxicity to crops that are irrigated from these ponds (Mathers and Case, 2010).

With the increasing concerns for the environment, the reduction in new herbicide registrations, and the advent of herbicide-resistant weeds, thermal weed control could represent an innovative method to control weeds in container nurseries. Flame weeding and steaming can be used to devitalize weed seedlings through the effect of high temperatures that denaturize plant proteins. This then results in the loss of cell function, causes intracellular water expansion, ruptures cell membranes, and finally desiccates the weeds, normally within two to three days (Mojžiš, 2002). Shrubs are generally heat tolerant because of the lignified tissues. The main advantages of thermal weed control include the lack of chemical residues in the crop, soil, and water, the lack of herbicide carryover, the very wide spectrum of weeds controlled, and the lack of resistance to flaming and steaming (Mojžiš, 2002; Raffaelli et al., 2013).

The objectives of this study were to customize different equipment for thermal weed control in container nurseries, and test the efficiency of flame weeding and steaming in terms of weeds control in *Photinia x fraseri* "Red Robin" containers. *Photinia x fraseri* features (height, diameter, and dry biomass) and aesthetic parameters as affected by thermal treatments application were evaluated. Temperature values measured at different depths in the substrate after thermal applications were recorded and analysed to verify the heating of the substrate at different depths.

MATERIALS AND METHODS

EQUIPMENTS FOR THERMAL WEED CONTROL

Thermal treatments were applied using a custom-built flamer and a custom-built steamer. A backpack LPG flamer, which required an operator to carry a 5 kg LPG tank (plus 5 kg tare) on the shoulders using a shoulder strap during operation, was designed (fig. 1). The LPG tank is equipped with a pressure regulator, a pressure gauge, and taps for minimum and maximum regulation. The LPG tank is connected to a manual lance provided with an ergonomic handle, a burner, and a trigger for flame generation by a gas pipe 1.5 m long. The burner was developed and built at the University of Pisa (Raffaeli et al., 2013, 2015) and is suitable for working on small areas. It consists of a prismatic open-flame 10 cm wide burner and has an external mixer with an internal nozzle of 0.7 mm diameter. The LPG outflow was 1.16 kg h^{-1}.

The steamer is a 230 V electric steam generator, with a 2.8 L boiler, 2.4 kW boiler power, 0.48 MPa steam pressure, and 3.12 kg h^{-1} steam outflow. The steam extension tube was customized with a purpose-built diffuser constituted by a semi-cylinder carter to avoid steam dispersion (fig. 2). The

Figure 1. Backpack LPG flamer.

shape of the carter enables steam to be applied on the whole semicircle of nursery containers (fig. 3).

Figure 2. Steamer with the custom-built semi-cylinder diffuser.

Figure 3. Application of steam in *Photinia x fraseri* "Red Robin" containers.

EXPERIMENTAL SET UP, DESIGN AND TREATMENTS

The study was conducted from May 2012 to April 2014, at the Department of Agriculture, Food and Environment (DAFE) of the University of Pisa (+43.7°N +10.4°E), in central Italy. *Photinia x fraseri* "Red Robin" plants were potted in 10 dm^3 conical trunk nursery containers (23.5 cm upper diameter and 23.5 cm tall) with peat substrate. At the start of the study, the plants were three years old. Two months before the start of the study, four portions of stolons of *Oxalis corniculata* L. containing 10 buds each were transplanted into the containers in order to create an initial artificial weed infestation. *Oxalis corniculata* L. was chosen because it is one of the most common perennial weeds in Italian container nurseries, and it is considered one of the most troublesome weeds in nursery ornamentals worldwide (Holm et al., 1979). *Oxalis corniculata* L. can be difficult to control because it can spread by stolons, as well as by seeds. Plants must be controlled before seeds are produced because the seeds are ejected with force from their fruit (ballistic dispersal). When this occurs the pods are held beneath the leaf canopy and many seeds are likely to collide with vegetation and drop directly into the containers (Rezvani et al., 2010). Hand weeding is costly and often inadequate in removing all vegetative portions of this weed. Small weeds of *Oxalis corniculata* L. are often missed during hand-weeding and are not controlled with pre-emergent herbicides (Marble et al., 2013). Herbicide failure is likely a result of cultural and environmental factors that either compromise the integrity of the herbicidal barrier over the substrate surface, or accelerate herbicide degradation. Herbicides can also fail because the weed has some tolerance to the herbicide applied (Altland et al., 2004).

During the two years of the study, thermal weed control was conducted both on artificial and natural weed infestation. Fertilization consisted in the application of 40 g container^{-1} of N-P-K (plus trace elements) at 11-4.8-14.9, once year^{-1} at the end of the winter. The fertilizer was applied using the double dibbling technique, consisting in drilling the containers in two diametrically opposed points and applying the total dose of fertilizer into these holes. The average water requirement of the plants was 0.7 dm^3 per day provided by rainfall and/or drip irrigation throughout the study. Before flaming, the plastic irrigation tubes were temporarily removed from the containers to prevent damage.

The experimental unit consisted of one nursery container. The containers were arranged in a randomized complete block design with four replications. The treatments consisted of a weedy control, and four thermal weed control treatments, two with the flamer and two with the steamer. Flaming was applied 6 times year^{-1} (F6 treatment) each at a distance of two months, or 12 times year^{-1} (F12 treatment) each at a distance of one month. Steaming was applied 3 times year^{-1} (S3 treatment) each at a distance of four months, or 6 times year^{-1} (S6 treatment) each at a distance of two months. All treatments were repeated for a total period of two years. The time of application for each container varied from 2 to 4 s with the flame weeding and from 8 to 10 s with the steaming treatment.

DATA COLLECTION

A temperature measurement of the peat in the containers was conducted at 0, 1, 2, and 3 cm depth in supplementary *Photinia x fraseri* containers by simulating the flaming and steaming performed during the weed control tests. Temperatures were measured by a 4-channel digital thermometer (PCE-T 390) equipped with type K thermocouples and SD card datalogger (PCE group, 2015). Treatments were replicated three times. The temperature values were measured and recorded each second for 1 h for steaming and for 0.38 h for flaming. These lapses time were required so that the temperature of the treated substrate reached constant values near to the environmental temperature of 29°C of recorded during this test. This was necessary to estimate the two-phase exponential decay of temperature from the time of application to the re-establishment of environmental conditions.

Weed cover data were collected 24 times at a distance of one month each in all the experimental plots immediately before treatments application (irrespective of whether or not it recurred), and 4 times after the end of the treatments application, at a distance of 15 days each. Weed cover values were estimated by taking digital images from a 56 cm^2 (7.5 × 7.5 cm) area, in two randomly selected sampling points within each plot. Digital images were analysed using IMAGING Crop Response Analyser (2015). The digital image analysis procedure is described in Rasmussen et al. (2007). The area covered by the individuals of one species was estimated at months 0, 11, and 23 using the Braun-Blanquet Method (Braun-Blanquet, 1932). Weed biomass was collected two months after the final treatments by cutting weeds without roots from the containers area and drying at 105°C to constant weight. The effect of the treatments in terms of the aesthetic parameters of *Photinia x fraseri* plants was visually evaluated two months after final treatments. This evaluation comprised the size of the plants, the amount of foliage, the length of the shoots, and the coloration and appearance of the leaves. Each plant was scored from 1 (worst appearance) to 5 (best appearance). *Photinia x fraseri* height and diameter were measured before the start of the study and two months after the final treatments, after which plants were cut without roots and dried at 105°C to constant weight.

STATISTICAL ANALYSIS

Weed cover data are non-binomial proportions and were logit transformed to normalize the distribution of data (Warton and Hui, 2011). R statistical software (R Core Team, 2013) with the extension package *lmerTest* (tests for random and fixed effects for linear mixed effect models) (Kuznetsova et al., 2014) was used to analyze the linear mixed model of weed cover logit transformed, weed dry biomass and *Photinia x fraseri* features (dry biomass, height, and diameter) two months after the end of the two-year treatments. Weed cover logit transformed was analyzed with the treatment used and the time of observations of weed cover (and their interaction) as fixed effects, and plot, block, and interaction between time of observations of weed cover and block as random effects. Weed dry biomass and *Photinia x fraseri* features (biomass, height and diameter) were analyzed with the treatment used as fixed effect, and block as random effect. In order to omit non-significant factors or factor interaction effects on the dependent variable a likelihood ratio test was performed between more general and restricted models to reduce the complexity in simpler models (Bates, 2015). Means, standard errors and statistical differences between means were estimated with the functions *lsmeans* and *difflsmeans* of the extension package *lmerTest* (Kuznetsova et al., 2014) of R (R Core Team, 2013). Back-transformed values and standard errors were estimated with the function *ref.grid* of the extension package *lsmeans* (Least-squares means) (Russell and Hervé, 2015) of R (R Core Team, 2013). The extension package *sciplot* (scientific graphing functions for factorial designs) (Morales, 2012) of R (R Core Team, 2013) was used to plot the weed cover response in a two-way interaction plot and barplot. The data of the aesthetic parameters of *Photinia x fraseri* were ranked among the blocks (tied values were averaged), and then analyzed using the Friedman test for categorical values of SYSTAT13© (Systat Software, 2009).

A non-linear regression analysis of the temperature values recorded in the substrate at different depths for the two thermal weed control methods was conducted using GraphPad Prism, version 5.0 (GraphPad Software, 2007). A two-phase decay exponential function was adopted for non-linear regression analysis, according to the following model (Motulsky, 2007):

$$\begin{aligned} T = T_{\infty} &+ \left[\left(T_0 - T_{\infty}\right) \cdot PF \cdot 0.01\right] \cdot e^{\left(-K_F \cdot t\right)} \\ &+ \left[\left(T_0 - T_{\infty}\right) \cdot \left(100 - PF\right) \cdot 0.01\right] \cdot e^{\left(-K_S \cdot t\right)} \end{aligned} \tag{1}$$

where

T = the dependent variable, in our case the substrate temperature (°C);

T_{∞} = the value of the temperature at infinite time values, in our case the lowest temperature;

t = time (s);

T_0 = the value of the T when t is equal to 0, in our case the peak temperature (°C);

K_F = the rate constant of the fast decay expressed in reciprocal time units (s^{-1});

K_S = the rate constant of the slow decay expressed in reciprocal time units (s^{-1});
PF = the fraction of the span (from T_0 to T_∞) explained by the fast decay.

The model also includes the estimation of the constants ratio, i.e. the ratio of the two rate constants ($K_F{*}K_S^{-1}$).

The half life, which is the time required for the decaying temperature to fall to one half of its span, was calculated for K_F and K_S. They were computed as:

$$HL_F = \frac{\ln(2)}{K_F} \tag{2}$$

$$HL_S = \frac{\ln(2)}{K_S} \tag{3}$$

where

HL_F = the time required for the decaying temperature to fall to one half of the span explained by the fast decay;
HL_S = the time required for the decaying temperature to fall to one half of the span explained by the slow decay;

When the coefficient of determination was higher than 0.8, the Akaike's information criteria was used to compare two models: the simpler model with all parameters shared between the four different temperature data sets measured at different depths (one global curve for all) and the alternative model with different parameters for the different temperature data sets (separate curves for each depth).

RESULTS

Figures 4 and 5 show the temperature values along the first 40 s, measured at different depths in the substrate for the two weed control methods. Table 1 reports the degrees of freedom, the coefficient of determination, the absolute sum of squares of the distance of the points from the curve, and the standard deviation of the residuals calculated by the non-linear regression.

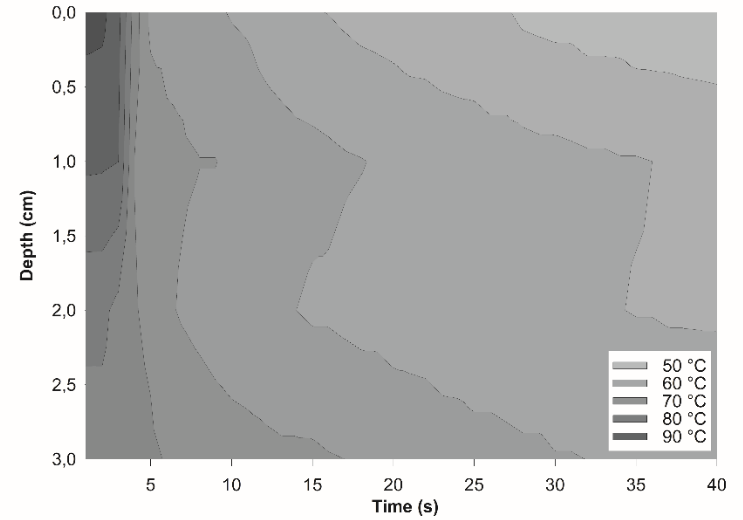

Figure 4. Temperature values along the first 40 s, measured at different depths in the substrate for the steaming method.

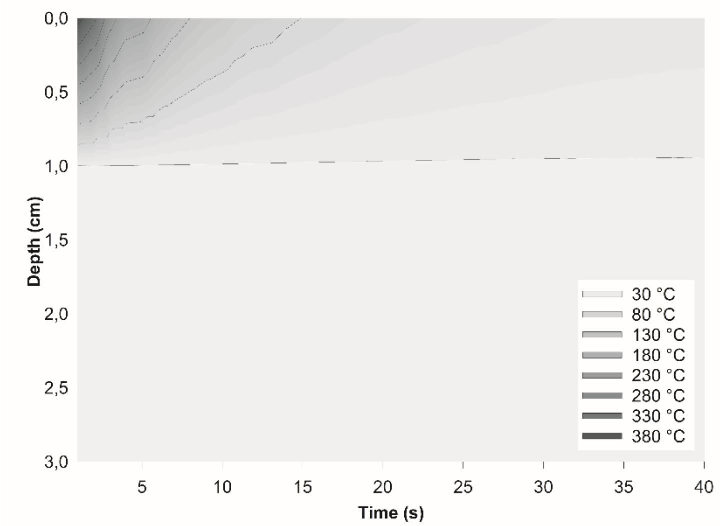

Figure 5. Temperature values along the first 40 s, measured at different depths in the substrate for the flaming method.

Table 1. Results of the non-linear regression conducted on the temperature values measured at different depths in the substrate for the two weed control methods.[a][b]

Thermal Weed Control Method	Depth (cm)	Degree of Freedom	R^2	Sum of Square	Standard Deviation of the Residuals
Steaming	0	10795	0.8814	36136	1.830
	1	10795	0.9433	33771	1.769
	2	10795	0.9343	39562	1.914
	3	10795	0.9142	50536	2.164
Flame weeding	0	4069	0.9002	140613	5.879
	1	4069	0.4596	1134	0.528
	2	4069	0.1910	635	0.395
	3	4069	0.1430	440	0.329

[a] The non-linear regression was conducted using a two-phase exponential decay model.

[b] The temperature was measured at a 1 s interval for a total time of 3600 s and 1368 s when steaming and flame weeding were applied, respectively.

The coefficients of determination of the steaming application reported in table 1 are higher than 0.8, for all the depths taken into account. When flaming was applied, only the data set of temperature values measured at 0 cm resulted in a coefficient of determination higher than 0.8, suggesting that the temperature at 1, 2, and 3 cm depths did not follow a two-phase exponential decay. At 1, 2, and 3 cm depths the maximum temperature measured after flaming was similar to the environmental temperature recorded (29°C). Therefore the parameters of the two-phase exponential decay model were estimated at all the depths when steaming was applied, and only at 0 cm when flaming was applied (figs. 6 and 7, table 2). In order to investigate whether the parameters of the two-phase exponential decay model, when steaming was applied, could be the same for the different temperature values measured at different depths in the peat (i.e., fitting the same curve for all datasets), a comparison with Akaike's information criteria was used. This analysis indicated that the model with different curves for the different temperature values measured at different depths was more suitable compared to the simpler model of one curve for all datasets (>99.99% vs. <0.01%). Table 2 reports the parameter estimations and the standard errors obtained with the non-linear regression analysis.

Temperature decay when flame weeding was applied on the substrate surface was very quick, and after only 28 s the temperature was 54°C (table 3). When steaming was applied the decay was slower and influenced by the depth of application (table 3).

Weed cover is defined as the relative proportion of pixels in the collected digital images determined to be green. When the weed cover observed during the treatments application was the dependent variable, analysis of variance showed that the treatment used, the observation time expressed as months after the start of the treatments application and their interaction were significant ($p=2.2 \times 10^{-16}$ for each). Figure 8 shows the 2-way interaction plot with means and 95% confidence intervals for weed cover logit transformed between different treatments and 23 observation times expressed as months after the start of the application. The effect of the different weed control treatments varied according to the time of observation. For example at month 4, all treatments were applied, and at month 5 the weed cover was smaller when S3 and S6 were used. At month 10, all treatments with the exception of S3 (applied at month 8) were applied, and at month 11 the weed cover was smaller when F12 and S6 were used. At month 16, all treatments were applied again, and at

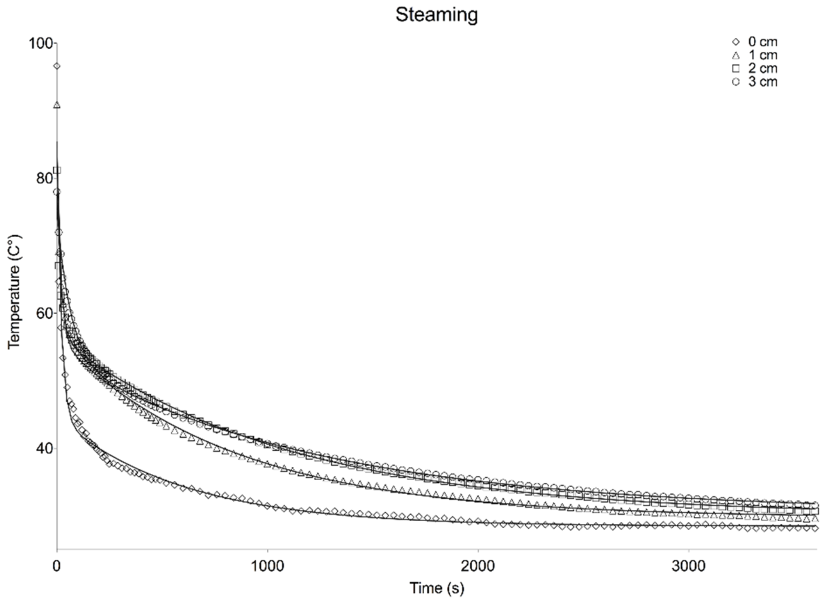

Figure 6. Influence of steaming on temperature decay as affected by time and substrate depth. The regression lines are plotted using equation 1, and the parameters are presented in table 2. The points are the temperature values measured by the thermocouples; solid lines are the non-linear regression curves by modelling with the two-phase decay exponential function.

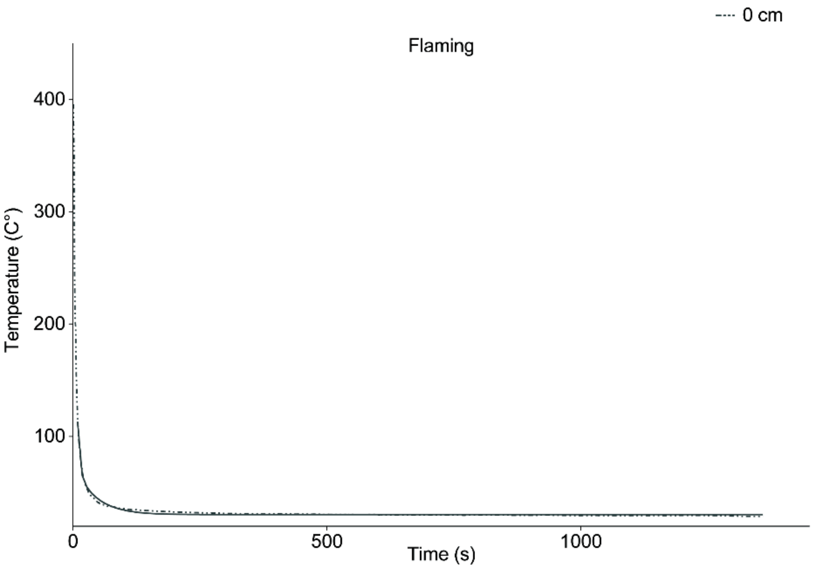

Figure 7. Influence of flaming on temperature decay as affected by time at 0 cm depth. The regression line is plotted using equation 1, and the parameters are presented in table 2. Dotted lines are the points measured by the thermocouples; solid lines are the non-linear regression curves by modelling with the two-phase decay exponential function.

Table 2. Best fit values estimation of the parameters obtained by non-linear regression analysis adopting the two-phase exponential decay model, conducted on the temperature values measured at different depths in the substrate for the two different thermal weed control methods.[a]

		Best Fit Values Estimation of the Parameter (±SE)					
Weed Control Method	Depth (cm)	T_0 (°C)[b]	T_∞ (°C)[c]	PF[d]	K_F (s^{-1}) [e]	K_S (s^{-1}) [f]	$K_F{*}K_S^{-1}$ [g]
Steaming	0	85.44 (0.50)	28.46 (3.03 10^{-2})	71.65 (0.29)	4.85 10^{-2} (9.33 10^{-4})	1.68 10^{-3} (2.02 10^{-5})	28.92 (0.54)
	1	84.61 (0.52)	29.75 (4.02 10^{-2})	51.65 (0.46)	5.52 10^{-2}(1.51 10^{-3})	1.20 10^{-3} (8.58 10^{-6})	45.94 (1.20)
	2	77.75 (0.52)	30.06 (6.22 10^{-2})	44.32 (0.60)	4.89 10^{-2} (1.81 10^{-3})	9.21 10^{-4} (8.03 10^{-6})	53.09 (1.88)
	3	75.15 (0.33)	30.57 (9.57 10^{-2})	48.27 (0.41)	1.55 10^{-2} (4.31 10^{-4})	8.08 10^{-4} (1.23 10^{-5})	19.22 (0.46)
Flame weeding	0	478.90 (4.65)	30.30 (0.10)	89.51 (0.51)	0.24 (4.86 10^{-3})	2.45 10^{-2} (1.23 10^{-3})	9.80 (0.41)

[a] The temperature was measured at 1 s intervals for a total time of 3600 and 1368 s when steaming and flame weeding were applied, respectively.

[b] The peak temperature (°C).

[c] The lowest temperature (°C).

[d] The fraction of the span (from T_0 to T_∞) explained by the fast decay.

[e] The rate constant of the fast decay expressed in reciprocal time units.

[f] The rate constant of the slow decay expressed in reciprocal time units.

[g] The estimation of the constants ratio.

month 17 the weed cover was similar between all weed control methods. At month 23, one month after the application of all treatments with the exception of S3 (applied at month 20), the weed cover was smaller when S6 was used (table 4).

When the weed cover observed 15, 30, 45, and 60 days after the month 23 (the end of the treatments application) was the dependent variable, analysis of variance showed that the treatment used and the time of observation were significant ($p = 3.6 \times 10^{-6}$ and $p = 1.8 \times 10^{-5}$, respectively), whereas their interaction was not significant (p = 0.4). Fifteen and thirty days after the observation at month 23, the weed cover in S6 was similar with that observed in F12 (95% CIs: -0.73, 1.68, and -0.22, 2.19, respectively) and smaller than the other treatments used (95% CIs did not cross the 0 value) (fig. 9). Forty-five days after the observation at month 23, all treatments showed similar weed cover with the exception of F6 which was 4-fold larger than S6 (95% CI: 0.17, 2.59). After the observation at month 23 (60 days later), all treatments showed a similar weed cover (fig. 9, table 5).

The initial weed cover at month 0 was constituted only by *Oxalis corniculata* L. in all plots. Weed presence at month 11 and 23 was reported in table 6.

When weed dry biomass collected two months after the last application of treatments was the dependent variable,

Table 3. Half-life estimated by the fast and slow decay, and corresponding temperature at different depth by using equation 2 and 3.

Weed Control Method	Depth (cm)	HL_F (s)[a]	T (°C)[b]
Steaming	0	14	65
	1	13	70
	2	14	67
	3	45	64
	Depth (cm)	HL_S (s)[c]	T (°C)[b]
	0	414	37
	1	577	43
	2	753	43
	3	858	42
	Depth (cm)	HL_F (s)[a]	T (°C)[b]
Flame weeding	0	3	278
	Depth (cm)	HL_S (s)[c]	T (°C)[b]
	0	28	54

[a] The time required for the decaying temperature to fall to one half of the span explained by the fast decay.

[b] Values of temperature reached at time intervals corresponding to half-life fast and half-life slow.

[c] The time required for the decaying temperature to fall to one half of the span explained by the slow decay.

Table 4. Estimated means logit transformed and back-transformed values for weed cover as influenced by different weed control treatments and four observation times (5, 11, 17, and 23 months) after the start of the treatments application.

		Estimated Mean Logit Transformed ± SE[c]				Back-transformed Value ± SE[d]			
	Weed Control	Month after the First Application				Month after the First Application			
Variable	Treatment[b]	5	11	17	23	5	11	17	23
Weed cover	Control	0.3 (0.4)	1.2 (0.4)	1.8 (0.4)	1.7 (0.4)	$5.8\ 10^{-1}$ ($2.4\ 10^{-1}$)	$7.7\ 10^{-1}$ ($3.1\ 10^{-1}$)	$8.5\ 10^{-1}$ ($3.5\ 10^{-1}$)	$8.5\ 10^{-1}$ ($3.4\ 10^{-1}$)
	S3	-8.0 (0.4)	-5.9 (0.4)	-4.4 (0.4)	-4.9 (0.4)	$3.4\ 10^{-4}$ ($1.4\ 10^{-4}$)	$2.8\ 10^{-3}$ ($1.2\ 10^{-3}$)	$1.3\ 10^{-2}$ ($5.1\ 10^{-3}$)	$7.5\ 10^{-3}$ ($3.0\ 10^{-3}$)
	S6	-7.0 (0.4)	-8.0 (0.4)	-4.9 (0.4)	-8.3 (0.4)	$8.9\ 10^{-4}$ ($3.6\ 10^{-4}$)	$3.3\ 10^{-4}$ ($1.4\ 10^{-4}$)	$7.5\ 10^{-3}$ ($3.0\ 10^{-3}$)	$2.5\ 10^{-4}$ ($1.0\ 10^{-4}$)
	F6	-4.2 (0.4)	-6.3 (0.4)	-3.9 (0.4)	-5.4 (0.4)	$1.4\ 10^{-2}$ ($5.7\ 10^{-3}$)	$1.7\ 10^{-3}$ ($7.1\ 10^{-4}$)	$1.9\ 10^{-2}$ ($7.8\ 10^{-3}$)	$4.7\ 10^{-3}$ ($1.9\ 10^{-3}$)
	F12	-6.1 (0.4)	-7.6 (0.4)	-4.3 (0.4)	-6.0 (0.4)	$2.2\ 10^{-3}$ ($8.8\ 10^{-4}$)	$5.1\ 10^{-4}$ ($2.1\ 10^{-4}$)	$1.3\ 10^{-2}$ ($5.3\ 10^{-3}$)	$2.6\ 10^{-3}$ ($1.0\ 10^{-3}$)

[a] Weed cover is defined as the relative proportion of pixels in the collected digital images determined to be green. Weed cover percentages are obtainable by multiplying back transformed values by 100.

[b] S3: steaming applied three times year^{-1} at month 0, 4, 8, 12, 16, and 20; F6 and S6: flaming and steaming applied six times year^{-1}, respectively, at month 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, and 22; F12: flaming applied 12 times year^{-1}, at all months.

[c] Means and standard errors (SEs) were estimated with the function *lsmeans* of the extension package *lmerTest* (tests for random and fixed effects for linear mixed effect models) (Kuznetsova et al., 2014) of R (R Core Team, 2013).

[d] Back-transformed values and standard errors (SEs) were estimated with the *ref.grid* function of the extension package *lsmeans* (Least-squares means) (Russell and Hervé, 2015) of R (R Core Team, 2013).

analysis of variance showed that the treatment used was significant ($p=1.3 \times 10^{-9}$). Estimated means were 0.1 g for F12, S3 and S6, 0.2 g for F6, and 19.8 g for the control (standard error=1.0), suggesting that there were no differences between the treatments used, and that in the control containers weed dry biomass was statistically larger than in the containers where thermal weed control was applied. The similar weed dry biomass observed into the treated containers suggests that after the end of the application of the thermal treatments the regrowth of weeds was independent of the type of treatment applied, and suggests that all thermal treatments were effective mainly on the epigeal part of the weeds.

The Friedman test of the aesthetical parameters of *Photinia x fraseri* (size of plants, amount of foliage, length of the shoots, coloration, and appearance of the leaves visually rated) did not show significant statistical differences between the weed control treatments used (Friedman statistic test = 3.522, p = 0.474 assuming χ^2 with 4° of freedom). The sum of ranks calculated was 15.0 for S3, 14.5 for F12, 11.0 for the control and S6, and 8.5 for F6.

Analysis of variance showed that *Photinia x fraseri* features (height and diameter), measured before the start of the study, were not statistically different (p=0.89 and p=0.92, respectively). The relationship between *Photinia x fraseri* features (dry biomass, height, and diameter), measured two months after the last treatments' application, and the treatment used is shown by the boxplots (fig. 10). The large boxes show how inconsistent the weed control treatment was on plant features. Analysis of variance showed that the weed control treatment used did not affect the features of *Photinia*

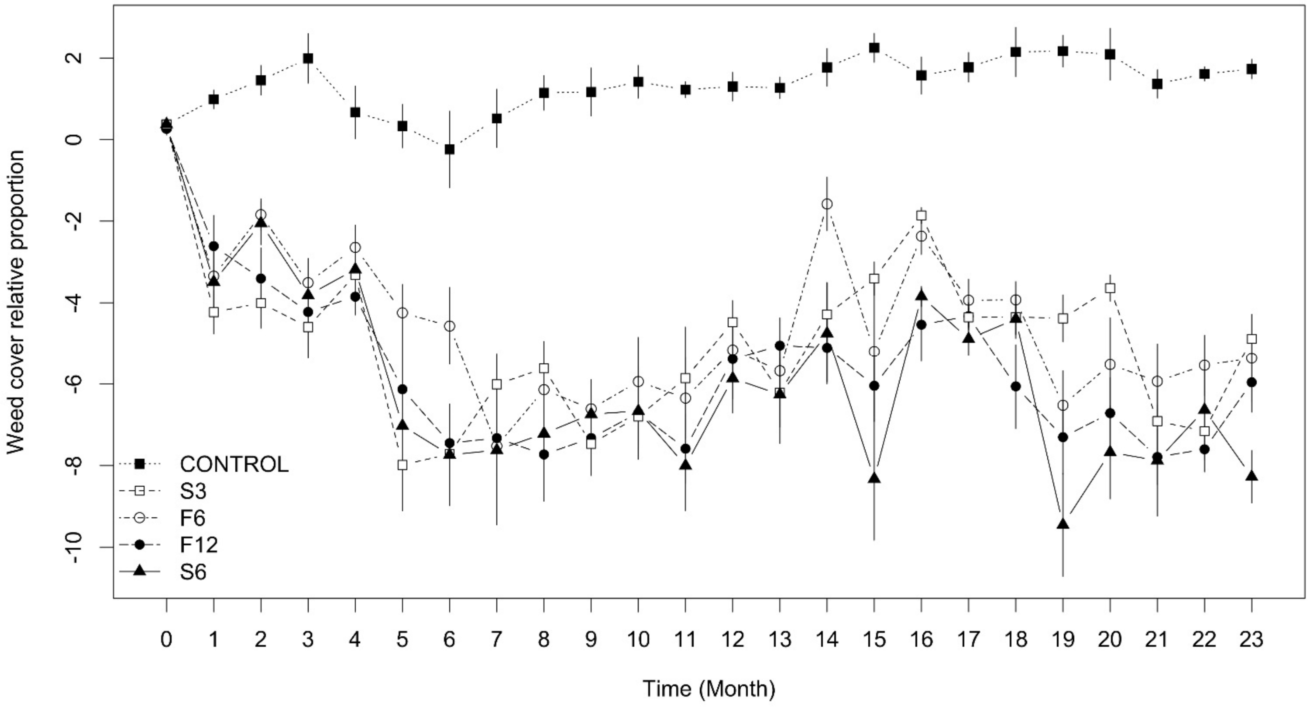

Figure 8. Two-way interaction plot with means and 95% confidence intervals of weed cover, logit transformed, between different weed control treatments and 23 observation times expressed as months after the start of the treatments application. S3: steaming applied three times year^{-1} at month 0, 4, 8, 12, 16, and 20; F6 and S6: flaming and steaming applied six times year^{-1}, respectively, at month 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, and 22; F12: flaming applied 12 times year^{-1}, at all months. Weed cover is defined as the relative proportion of pixels in the collected digital images determined to be green. Weed cover data were collected before treatments application.

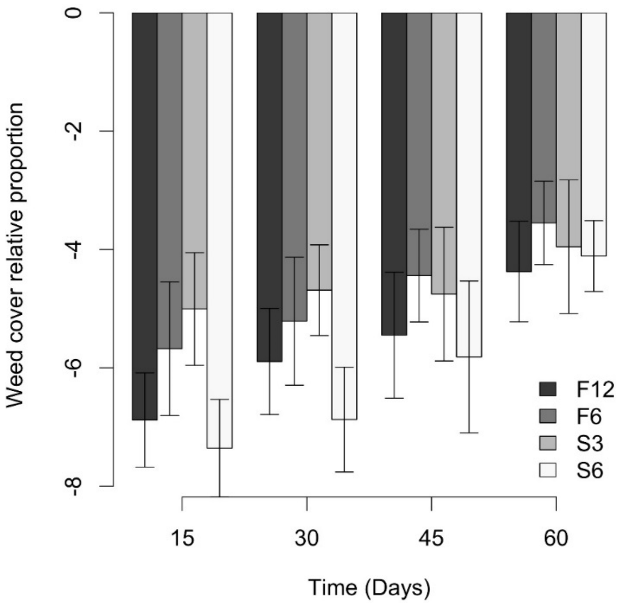

Figure 9. Barplot of the mean and 95% confidence intervals of weed cover, logit transformed, for different weed control treatments and four observation times expressed as days after the end of all treatments application. S3: steaming applied three times year^{-1}; F6 and S6: flaming and steaming applied six times year^{-1}, respectively; F12: flaming applied 12 times year^{-1}. Weed cover is defined as the relative proportion of pixels in the collected digital images determined to be green.

x fraseri ($p = 0.66$, $p = 0.20$, $p = 0.88$, respectively for dry biomass, height and diameter). Table 5 shows estimated mean values and standard errors of dry biomass, height and diameter. No differences between treatments were observed for *Photinia x fraseri* features.

Table 5. Estimated means for *Photinia x fraseri* features (dry biomass, height and diameter) as influenced by different weed control treatments at two months after the final application.

Variable	Weed Control Treatment[a]	Estimated Mean ± SE[b]
Biomass (g)	CONTROL	735.9 (70.56)
	S3	721.3 (70.56)
	S6	620.2 (70.56)
	F6	755.3 (70.56)
	F12	668.5 (70.56)
Height (m)	CONTROL	1.6 (0.06)
	S3	1.7 (0.06)
	S6	1.6 (0.06)
	F6	1.5 (0.06)
	F12	1.5 (0.06)
Diameter (cm)	CONTROL	3.5 (0.14)
	S3	3.5 (0.14)
	S6	3.5 (0.14)
	F6	3.6 (0.14)
	F12	3.6 (0.14)

[a] S3: steaming applied three times year^{-1}; F6 and S6: flaming and steaming applied six times year^{-1}, respectively; F12: flaming applied 12 times year^{-1}.

[b] Means and standard errors (SEs) were estimated with the *lsmeans* function of the extension package *lmerTest* (Tests for random and fixed effects for linear mixed effect models) (Kuznetsova et al., 2014) of R (R Core Team, 2013).

DISCUSSION

Our analysis suggests that the temperature measured at different depths in the substrate of the container after steaming application, decreased over time following a two-phase exponential model. The adopted model seems adequate in explaining the decrease in the temperature also after the flaming application, but only on the surface of the substrate (0 cm depth), in this case the highest value of T_0 was observed. The parameter T_0 of the model represents the peak in temperature values after the thermal weed control was applied. In the case of flaming, a significant effect on temperature values of the substrate was not observed at depths equal and higher than 1 cm (fig. 5). This probably suggest that small flame exposure times on the substrate surface did not lead to an increase in temperatures at a depth greater than 1 cm. Ascard et al. (2007) reported that exposure times to flame below 1 s are enough to kill the leaf tissue of weeds. In our study the temperature estimated on the surface was 278°C after 3 s, suggesting that the temperatures reached were effective in controlling weed seedlings. The lack of high temperatures in deeper layers of the substrate (> 0 cm) suggests that flaming is not adequate to kill the buried seeds and probably neither the stolons of *Oxalis corniculata* L., species observed in small part at the end of the study (0.1% and 2.5 10^{-2} in F6 and F12 plots, respectively).

In the case of steaming, an influence on temperature values measured at different depths in the substrate was observed (fig. 4). The decrease in temperature over time followed a two-phase exponential decay model (eq. 1). The parameters of the model, in most cases, varied according to the depth of the substrate where the temperatures were measured. The highest peak temperature values (T_0) were observed at the substrate surface (0 cm) and at a depth of 1 cm.

All thermal treatments controlled the epigeal part of the weeds, and probably steaming treatments, thanks to temperatures higher than 64°C persisting for at least 45 s at 3 cm depth, were also able to control the stolons of *Oxalis corniculata* L., which were not observed at the end of the study in the containers where steaming was applied. A study of weed seeds devitalisation was not take into account in this experiment, and it is difficult to gauge a steaming controlling effect also on the seeds. As a matter of fact, van Loenen et al. (2003) found that steam treatments at 50-60°C for 11 min destroy most weed seeds and reduce problems of phytotoxicity and re-infestation which may persist after steaming at higher temperatures. In our study a mean temperature of 55°C was estimated after 64, 96, and 125 s at the depth of 1, 2, and 3 cm, respectively. These time values are largely lower compared with that reported in van Loenen et al. (2003). Raffaelli et al. (2016) found that a temperature decay from 63°C to 50°C estimated in 17 minutes resulted in a significant decrease of weed emergence observed after steaming application. Melander and Jørgensen (2005) applied steaming in the laboratory on a limited soil volume collected from the top 10 cm of the soil, and studied the relationship between maximum soil temperature and effects on weed seedling emergence. They found that maximum temperatures slightly above 60°C were necessary to reduce the emergence of natural weed seedlings by at least

Table 6. Weed composition (expressed as percentage of presence) observed 11 and 23 months after the start of the experiment under different weed control treatments.

	Month 11 (%)					Month 23 (%)				
Weed Specie	Control	S3[a]	S6[b]	F6[c]	F12[d]	Control	S3[a]	S6[b]	F6[c]	F12[d]
Conyza canadensis L.	19.0	-	-	-	-	56.0	1.3	-	-	1.3
Digitaria sanguinalis L.	36.0	-	-	-	-	-	-	-	-	-
Fumaria officinalis L.	-	-		0.1	$2.5\ 10^{-2}$	-	-	-	-	-
Oxalis corniculata L.	15.0	2.5	-	0.5	-	1.3	-	-	0.1	$2.5\ 10^{-2}$
Parietaria officinalis, L.	-	$2.5\ 10^{-2}$	-	-	-	-	-	-	-	-
Picris hieracioides L.	44.0	1.3	-	1.3	-	-	-	-	-	-
Sonchus oleraceus L.	1.0	2.5	$2.5\ 10^{-2}$	2.5	-	5.0	8.0	6.0	13.0	6.0
Graminaceous species	-	-	-	-	-	8.0	5.0	4.0	9.0	5.0

[a] Steaming applied three times year^{-1}.

[b] Steaming applied six times year^{-1}.

[c] Flaming applied six times year^{-1}.

[d] Flaming applied 12 times year^{-1}.

90% compared with non-steamed soil samples. In our experiment the maximum temperatures were higher than 75°C at all depths measured.

Thermal weed control led to a satisfactory level of weed control (near-100% weed control) during the two-year growing seasons of *Photinia x fraseri*. At the end of the study, steaming applied once every two months (S6 treatment) resulted in completely weed free containers (0% weed cover), and other treatments (F6, F12, and S3) gave a maximum weed cover of 1%. This suggest that when flaming was applied, a temperature comprised from 479°C (T_0) to 278°C lasting for at least three seconds is enough for controlling the aerial part of weeds (table 3). The same near-100% weed control level can be obtained by applying steaming at temperatures comprised from 85°C (T_0) to 65°C for at least 14 s. These weed control levels are comparable to those found by other researchers using preemergent granular herbicides, mulch plus herbicides or some type of mulch disks.

A certain persistence of the thermal weed control effect was observed over time. Two months after the end of treatments application, weed cover was on average 2% and weed dry biomass 0.1 g in all containers, 160-fold smaller than the control containers. Some deterioration to the plastic containers was observed after two years of treatments only in flaming plots [data not shown]. The high temperatures reached applying the thermal treatments did not affect *Photinia x fraseri "Red Robin"* features and aesthetical parameters.

Flame weeding and steaming in container nurseries is effective and reduces the environmental impact compared with the use of pre-emergent herbicides or mulches treated with herbicides. All treatments lead to a continuous near-100% weed control without damaging *Photinia x fraseri*, which is the aim of nursery growers.

CONCLUSION

The temperatures in the profile of the substrate followed a non-linear two-phase decay model when steaming was applied at a different depth, whereas flaming followed the same model only on the surface of the substrate because the deeper layers resulted not heated. The temperatures reached at the surface of the substrate were able to control weed seedlings when both steaming and flaming thermal treatments were applied. As a consequence of the ineffectiveness of flaming to heat the deeper layers of the substrate, a devitalisation effect on buried weed seeds into the container has to be excluded. Regarding steaming application, future specific studies are needed to understand how the temperature and time of exposure affects the devitalization of weed seeds inside the substrate. *Oxalis corniculata* L., which is a weed difficult to remove in container nursery, was completely controlled with all the applications. Thermal weed control did not affect *Photinia x fraseri* dry biomass, height, and diameter compared with the non-treated control. The higher weed control effect determined by the steaming during the two years' study did

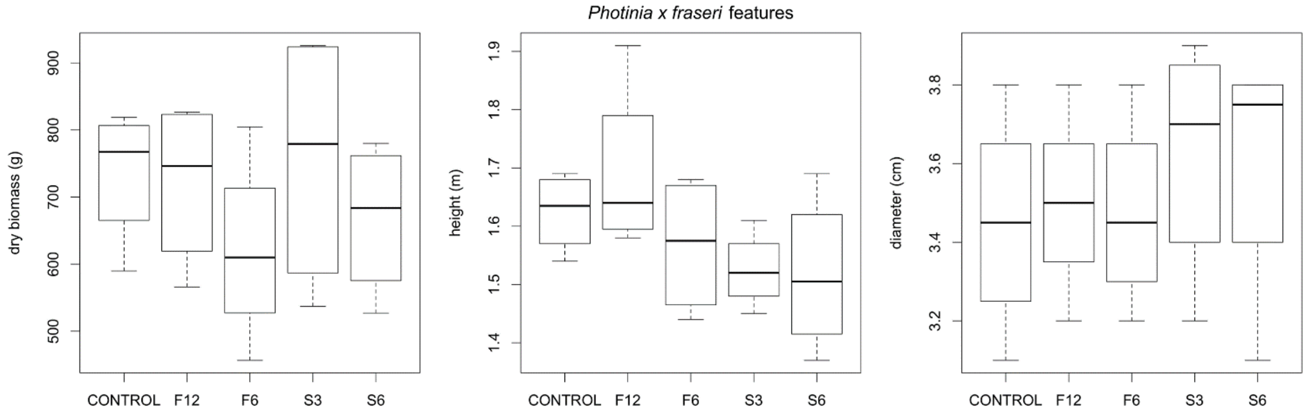

Figure 10. Boxplots of the relationship between *Photinia x fraseri* features (dry biomass, height, and diameter) measured two months after the final application and the weed control treatment used. S3: steaming applied three times year^{-1}; F6 and S6: flaming and steaming applied six times year^{-1}, respectively; F12: flaming applied 12 times year^{-1}.

not persist after the end of the steaming applications. Indeed, two months after the end of the study, the weed regrowth similar for all the thermal treatments applied.

Maintaining the containers at a weed control level near to 100% is the aim of container nursery producers. In accordance with the results of this study, thermal equipment tested could be introduced in container nursery production, where weed management is still entrusted to chemical solutions. Physical weed control in container nursery productions is less mechanized than other agricultural sectors, and it still linked too closely to costly hand weeding.

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