EVALUATION OF STEAM APPLICATION FOR WEED MANAGEMENT IN CITRUS

J. J. Abdulridha, R. G. Kanissery, C. E. McAvoy, Y. G. Ampatzidis

ABSTRACT. *In this study, a weed steamer was developed, and several steam treatments were utilized to maintain and control the growth of weeds in a citrus grove. Two factors affecting the steam treatment were studied: (i) tractor speed (low, 1.2 km/h; and high, 1.7 km/h); and (ii) steam flow rate (low, 15 L/h; and high 53 L/h). The weed control treatments included various combinations of steam flows and tractor driving speeds, a post-emergent herbicide (paraquat) treatment, and an untreated check for comparison purposes. Randomized experiments were conducted to evaluate the efficacy of each application. It was found that steam applications at high flow rate provided 93%-97% burndown damage of the weed foliage within 3 days after application. Weed re-growth was observed in steam applications, especially with low flow-rate applications. The combination of low tractor speed and high steam flow-rate was the most effective of the steam treatments tested (84% total weed burndown at 12 days after application). This treatment was found effective in controlling weeds like goatweed and sedges. Florida pusley was the least affected by steam due to its prostrate growth nature that prevents an adequate coverage of steam on the entire plant. Based on the observations from this study, the steam application has the potential to be a non-chemical and sustainable strategy for weed management in citrus tree rows.*

Keywords. *Citrus production, Herbicide, Steam application, Weed control.*

Growers use mainly herbicides and follow conventional application methods for weed control despite the negative environmental impact and the food-related concerns (Gianessi and Reigner, 2007; Luvisi et al., 2016). Conventional sprayers (e.g., hydraulic and hydro-pneumatic) usually have high inefficiencies. For example, chemical spray drift, a common issue of the conventional sprayers, can result in herbicide residues on plant products (Owen and Zelaya, 2005; Markovic et al., 2010) causing damage to the crops and to the consumer health. Additionally, spray drift can contaminate natural resources (Sankhla et al., 2016). Non-chemical weed control, such as steam application, can be utilized as part of an overall weed management program to reduce incidence of weed resistance to specific herbicide chemistries.

Studies have found repeated applications of herbicides over many years result in species evolving to being resistant (Owen and Zelaya, 2005; Rubione and Ward, 2016). In response, increased application rates and tank mixing of multiple chemicals are required to manage weed species which are resistant. This increased use of chemicals increases costs and potentially damages ecosystems. Weed resistance to some chemistries would potentially be reduced if it used less frequently (Busi et al., 2018; Markus et al., 2018). For instance, glyphosate-based herbicides are the most commonly used and have the most well-known incidence of resistant weed species. Herbicides have the potential to damage crops and natural vegetation from off-target movement caused by herbicide drift, leaching through soil profiles and run-off (Ritter, 1990). Most commonly used herbicides have the potential to pollute environments of sensitive inhabitants of rare species which are important to healthy ecosystems (Harris et al., 1998).

Furthermore, most herbicides are applied uniformly, despite the fact that distribution of weeds is typically patchy. New advances in electronics, artificial intelligence (AI), machine vision, and automation have promoted the development of new precision spraying technologies (Ampatzidis et al., 2017; Fernandez-Quintanilla et al., 2018). For example, Partel et al. (2019) developed a low-cost vision-based spraying technology for vegetable crops, utilizing AI, to distinguish a variety of weeds and precisely spray on the desired weed/location. They achieved a more than 90% overall spraying accuracy. Kargar and Shirzadifar (2013) developed a vision-based spot-sprayer to distinguish grass weeds from corn plants with over 90% accuracy. These technologies can

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reduce costs, risk of crop damage, and environmental impact (Balafoutis et al., 2017). Another alternative to herbicide use could be the steam weeding or thermal weed control. Steam weeding applications are unaffected by wind and rain and can be carried out under any conditions at any time. They are non-toxic treatments with no impacts from spray-drift or run-off. Steam weeding can be used within proximity of people, animals, and environmentally sensitive areas.

Thermal technologies such as steam application alleviate environmental and toxicological implications related to chemical weed control. Steam application has been in use for soil disinfestation in agriculture for over 40 years (Runia, 1984). Senner (1934) presented that W. N. Kudd was the first to apply steam in 1893 as sterilization to the soil in the field. Upadhyaya et al. (1993) first demonstrated the use of steam as a potential weed management strategy. Kolberg and Wiles (2002) achieved positive results with controlling lambs quarters and seedling redroot pigweed with steam utilizing several steam rates; they evaluated steam efficacy on various weed species and growth stages. Raffaelli et al. (2016) applied four steam doses (0, 1.11, 1.59, and 2.78 kg/m^2) in mixture with 4000 kg/ha of exothermic compound (CaO) prior to planting the crop. Several factors were monitored and described in this study such weed density, time required for hand weeding, weed dry biomass at harvest, and carrot yield to the band-steaming application. The results were promising in managing weed population in row crops. Melander et al. (2002) applied steam on the soil to reduce weed seedling emergence; they studied the correlation between weed seedling emergence and maximum soil temperature due to the steam application. High temperatures from steam application were found to be effective for scorching and burning the mature weed foliage (Melander et al., 2005).

Steam offers the immense capability for weed control; however, its viability as a weed control option in high-value perennial tree crop production, like citrus, has not been investigated. The relationship between application speed and steam flow rate on the weed control effectiveness of steam was not explored. The main objective of this study is to assess the potential of steam application for ‘in-row’ weed management in citrus orchards by evaluating two tractor driving speeds and two steam flow rates in order to optimize efficacy.

MATERIALS AND METHODS

A weed steamer, attached to a trailer, was developed. It includes (table 1): (i) a boom section (fig. 1) with 12 nozzles (Spraying System Co., 5500 Adjustable Conejet, Glendale Heights, Ill.); (ii) a water tank; (iii) a steamer (Sioux Corporation, #SF-50. Beresford, S. Dak.); (iv) a water pump (Goulds Water Technology, Farmingdale, N.J.); and (v) a generator (DG7000E, DEWALT, Weymouth, Mass.). A tractor (6610 Ford, Atlanta, Ga.) was utilized to pull the trailer containing the weed steamer (fig. 2a).

WEED STEAMER AND BOOM STRUCTURE

The metal boom’s size was 175×57×14 cm. It was comprised of two lines of nozzles (fig. 1); six nozzles in each line (12 nozzles total). The boom section was placed near the trailer (figs. 2a and 2b). Two hot water hoses of 1.5 cm (Parker Hannifin HWR5825, Cleveland, Ohio) were connected to each pipeline to distribute the steam. Two adjustable valves controlled the steam flow rate. For our experiments, the pressure was set to 96.5 kPa (14 psi). Each pipeline was 120 cm long, and the distance between each nozzle was 20 cm. The boom was developed to apply steam with a predetermined flow to burn the weeds canopy (and potential any insects). For more flexibility, rubber curtains were attached to the boom section; so, the total width of the boom section was increased to 105 cm (fig. 1a). The purpose of adding the rubber curtains was to maintain the temperature inside the boom section at the desired level, increase the exposure area, and protect the metal boom section from crashing on ground. Several types of nozzle were evaluated (e.g., cone shape) to develop a uniform steam distribution and increase the temperature inside the boom (results not presented here). A modified nozzle, modified by removing the cap of the nozzle, was chosen to spray in three directions (by three holes) in order to burn the weeds (fig. 3).

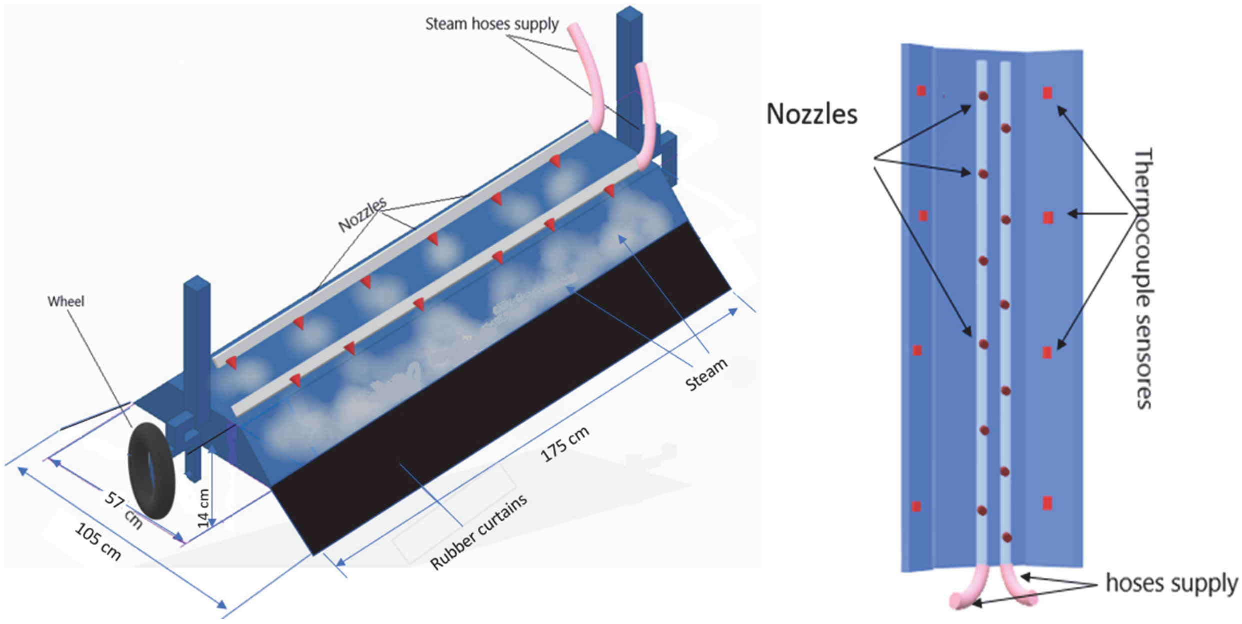
Table 1. Weed steamer components and characteristics.

Component	Characteristics	Commercial Information
Steamer	MAWP Steam: 103.4 kPa Max water temp: 121°C Heating surface: 25.8 m^2 Boiler power: 37.3 kW Steam output 782 kg/h Input: 590 kW Efficiency: 85%	Sioux Corporation, #SF-50 Beresford, S. Dak.
Water pump	Capacity: 8.8 m^3/h Heads: 73 m Pipe connections: 1 × 1¼ NPT Working pressure: 861.9 KPa Maximum temperature: 110°C	Goulds Water Technology Mod HMS, Farmingdale, N.J.
Generator	Voltage: 120/240 VAC Max Output: 7 KVA Power: 9.63 kW Fuel tank capacity: 28.4 L	DG7000E, DEWALT DeWalt, Boston Industrial Tools, Weymouth, Mass.
Tractor	Engine: Ford 4.2 L 4-cyl diesel RPM: 3600 Capacity: 75 L	Ford 6610 Engine Mod WC 10000VE/E, Atlanta, Ga.
Tank	1,987 L	Manufactured by Norwesco, Inc.

EXPERIMENTAL DESIGN

Preliminary Experiments

The temperature inside the boom section was recorded and monitored by thermocouples (temperature recorder: OMEGA RDXL 12SD, Stamford, Conn.) in order to evaluate the capability of the weed steamer to increase and maintain a desired temperature inside the boom. Three preliminary experiments were designed for this purpose. All experiments were conducted in the Southwest Florida Research and Education Center (SWFREC) in Immokalee, Florida (latitude 26°25′16″N, longitude 81°25′22″W), on 27 September 2018. The minimum ambient temperature was 24.4°C, the mean temperature 27.3°C, and the maximum temperature was 34.9°C.



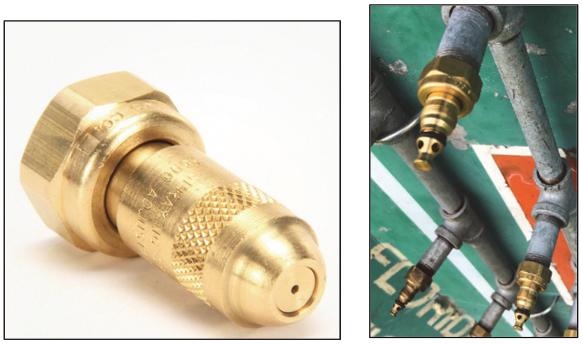
(a) (b)

Figure 1. Frame design of the boom section; (a) top view, (b) bottom view presenting the thermocouples location.

(a) (b)

(c)

Figure 2. (a) side view of the weed steamer. Main components of the weed steamer: (b) right side view (includes the boom section, pressure gauge, pipes etc.); (c) left side view (includes the water tank, water pump, and electric generator).



(a) (b)

Figure 3. (a) Spraying nozzle (Co- 5500 Adjustable Conejet); (b) modified nozzles after removing the caps.

Preliminary Experiment I

This experiment includes two sub-experiments: (a) static and (b) dynamic. In the static sub-experiment (a), the weed steamer was placed in a pre-determined area. Two flow rates were evaluated: (i) low flow rate (LFR) of 15 L/h, using 6 nozzles (one line); (ii) high flow rate (HFR) of 53 L/h, using 12 nozzles (two lines). The tractor did not move in this sub-experiment (static). The flow rate was recorded by a flowmeter (DLJ Meter, Daniel L. Jerman Co., Hackensack, N.J.). Eight thermocouples were placed (mounted) inside the boom section; four of them were placed in the front and the other four in the back of the boom section (fig. 1b). The temperature inside the boom section was recorded for 5 min (the weed steamer did not move in this experiment). The experiment was repeated five times for every case. The temperature measurements were stored in an SD card. For a better understanding on how to maintain the temperature inside the boom section and predict the temperature increase or decrease based on flow rate pressure, a test was conducted to evaluate the steam system based on a variety of six flow rate pressures (2.5, 5, 7.5, 10, 12.5, and 14 psi).

In the dynamic sub-experiment (b), the weed steamer moved (with a speed of ~1.2 km/h) for 5 min, applying steam using the LFR and HFR (as above), and the temperature was recorded (by the same thermocouples as above). This dynamic experiment was repeated five times, for every case, as well.

Preliminary Experiment II

In this experiment, the weed steamer sprayed a pre-determined area (150 m × 1.75 m). In this dynamic experiment, the combination of the two flow rates above and two driving speeds were studied. The tractor's "low speed" was achieved using the 1st gear, at low range and at 1,000 rpm (~1.2 km/h). The tractor's "high speed" was achieved using the 1st gear, at low range and at 1,500 rpm (~1.7 k/h). The "high speed" is considered as the regular speed in spraying herbicide applications. This experiment was repeated three times. Tables 2 and 3 present the actual speed measurements for each repetition. The temperature was recorded placing a 50 cm bar of thermocouples (four sensors) horizontally on the ground (on the desired area). The temperature was recorded in low and high speed and with low flow rate (LFR) (15 L/h) and high flow rate (HFR) (53 L/h), generating four scenarios.

Table 2. High driving speed: 1st gear, low range, 1,500 rpm.

Run	Distance (km)	Time (h)	Speed (km/h)
1	0.183	0.11	1.69
2	0.183	0.11	1.70
3	0.183	0.12	1.58
AVG	0.183	0.11	1.66

Table 3. Low driving speed: 1st gear, low range, 1,000 rpm.

Run	Distance (km)	Time (h)	Speed (km/h)
1	0.183	0.16	1.17
2	0.183	0.16	1.16
3	0.183	0.16	1.15
AVG	0.183	0.16	1.16

Preliminary Experiment III

In this "static" (the weed steamer did not move) experiment three application times (5, 10, 15 s) were evaluated in HFR and LFR, measuring the temperature inside the boom section. A 20 cm bar containing four thermocouples was utilized to record the temperature in four levels: 2.5 cm under the soil surface and 2.5, 7.5, and 12.5 cm above the soil surface (fig. 4). The purpose of this experiment was to identify the optimal steam application time required (with HFR and LFR) to increase the temperature (inside the boom section) on a desired point/area, optimizing the required energy (e.g., steam volume). The 2.5 cm under the ground level was chosen to evaluate the effect (if any) of the steam application on the tree root zone. These experiments were repeated three times.

Weed Management Evaluation in the Field

An experiment was conducted to evaluate the efficacy of steam application on managing weeds in a citrus production system. The experimental design was a randomized complete block design (RCBD) with four replications. Each plot consisted of three citrus trees, and one tree was placed as a buffer area between each treatment. Irrigation, fertilization and other crop maintenance were conducted according to UF recommendations (Kadyampakeni et al., 2018; Morgan et al., 2018). Steam was applied by the weed steamer as described earlier in this section using the boom structure attached to the tractor. The steam treatments included various combinations of steam flow and tractor speed. An herbicide with 'contact' mode of action, paraquat, was included in the treatment for comparison purposes. Herbicide was applied to utilize a tractor mounted boom sprayer. Moreover, untreated checks of no herbicide or steam applications were included in the experiment. A summary of treatments tested in

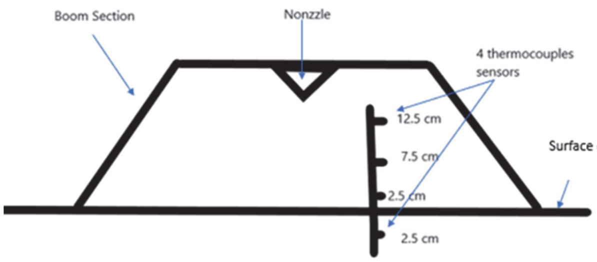


Figure 4. The position of a bar to measure the temperature in different height levels (-2.5 cm, 2.5 cm, 7.5 cm, 12.5 cm).

this experiment is described in table 4. The weed control efficacy evaluation of the application was done at 3 and 12 days after the treatment (DAT). The variables collected during the experiment were a visual rating (0-100) of post-emergent burndown of weeds expressed as % weed control (0% indicates no burn-down and 100% indicates complete burn-down of the weed foliage). The spectrum of citrus weed species in this field study was a mix of annual broadleaves, perennial grasses, and sedges. All weeds were in their early growth stage. Broadleaves included Florida pusley (*Richardia scabbra)* and goatweed (*Scoparia dulcis*), grasses were mostly Guinea grass (*Panicum maximum*) and sedges were identified as yellow nutsedge (*Cyperus rotundus*).

Statistical Analysis

The weed control efficacy data were checked for normality and analyzed using PROC GLM in SAS (SAS v 9.4, SAS Institute Inc., Cary, N.C.). Means were separated by Tukey's multiple range test (P<0.05).

RESULT AND DISCUSSION

PRELIMINARY EXPERIMENTS

Preliminary Experiment I

In the static experiment (a), the maximum temperature inside the boom section using the LFR (15 L/h) was 76°C and using the HFR (53 L/h) was 92°C. Figure 5a presents the temperature (average of five repetitions) inside the boom during this 5 min experiment, for both flow rates. The HFR achieved and maintained a higher temperature (~90°C for 5 min) than the LFR (from 60°C-76°C) (fig. 5a). The stability of the system in order to maintain a high temperature during treatments is very critical; the HFR obviously achieved better stability than the LFR. It must be mentioned that the performance of the weed steamer heavily relies on the environmental conditions (e.g., air temperature and humidity).

In the dynamic experiment (b), the HFR achieved a maximum temperature of 78°C, significantly higher than the LFR (52°C). Figure 5b presents the temperature profiles (average of five repetitions) for both rates. Obviously, the HFR generates much higher temperatures as expected.

The mean temperature values (during steam treatment) of both preliminary experiments (static and dynamic; for both LFR and HFR) are presented in table 5. Analyses of variance (ANOVA) was implemented to identify significant differences among the mean temperature values of all preliminary experiments in SAS (version 9.1.3 for Windows; SAS Institute, Cary, N.C.) using Duncan comparison test at $P < 0.05$. The HFR of the static experiment was achieved the highest temperature value (82°C), significantly higher than all other experiments. Significant differences were observed when comparing the two flow rates (LFR and HFR) in both static and dynamic experiments.

The relationship between the flow rate pressure and temperature is presented in figure 6 (with a coefficient of determination of R^2=0.93, and standard error with 95% confidence interval).

Table 4. Treatment list for the experiment.

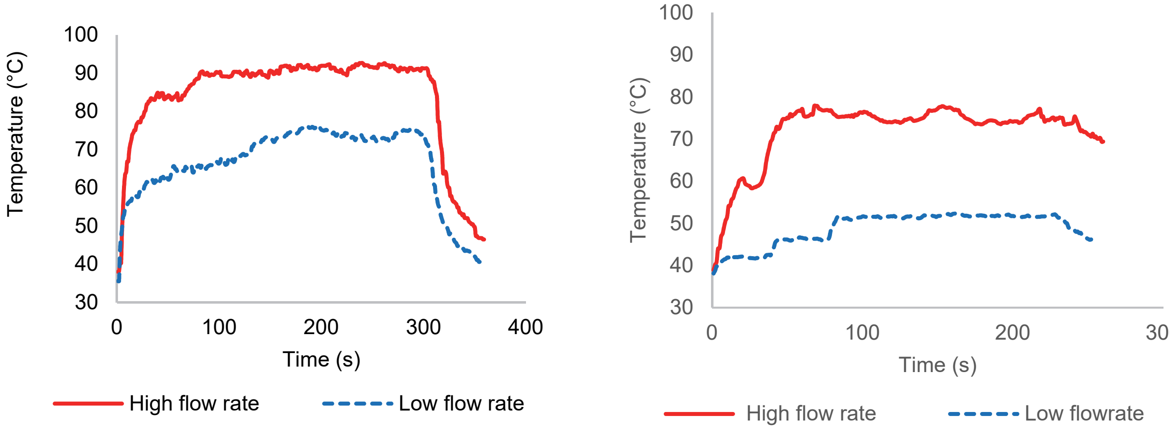
Treatment	Steam Flow (L/h)	Tractor Speed (km/h)
Untreated control	n/a	n/a
Herbicide (Paraquat)[a]	n/a	n/a
Steam Treatment 1	53	1.70
Steam Treatment 2	53	1.20
Steam Treatment 3	15	1.70
Steam Treatment 4	15	1.20

[a] Herbicide (Paraquat) was applied at 0.33 kg a.i /acre using a CO_2 powered backpack sprayer at the rate of 280.6 L/ha (30 gal/acre) (GPA) and pressure of 30 psi.

Table 5. Average temperature values of the Preliminary Experiment I.

Preliminary Experiment I	Steam Flow Rate	Mean Temperature (°C)	Standard Deviation
Static Experiment	HFR	82 a	13.4
	LFR	65 b	10.1
Dynamic Experiment	HFR	72 b	7.4
	LFR	49 c	3.8

[a] Values that share the same letter indicate no significant differences according to ANOVA analyses of variance (ρ < 0.0001).



(a) (b)

Figure 5. Temperature measurements (average of five repetitions) inside the boom section in low (15 L/h) and high (53 L/h) flow rate: (a) in a static experiment (b) in a dynamic experiment. Thermocouples sensors are mounted inside the boom section.

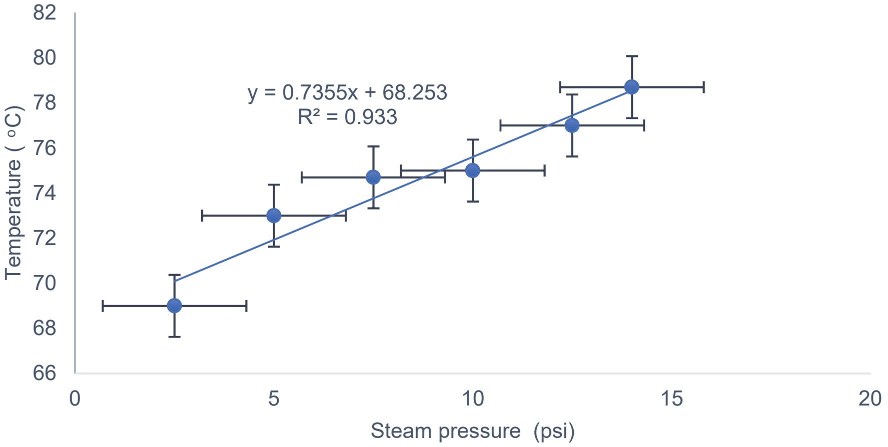


Figure 6. The relationship between the flow rate pressure of steam and temperature.

Preliminary Experiment II

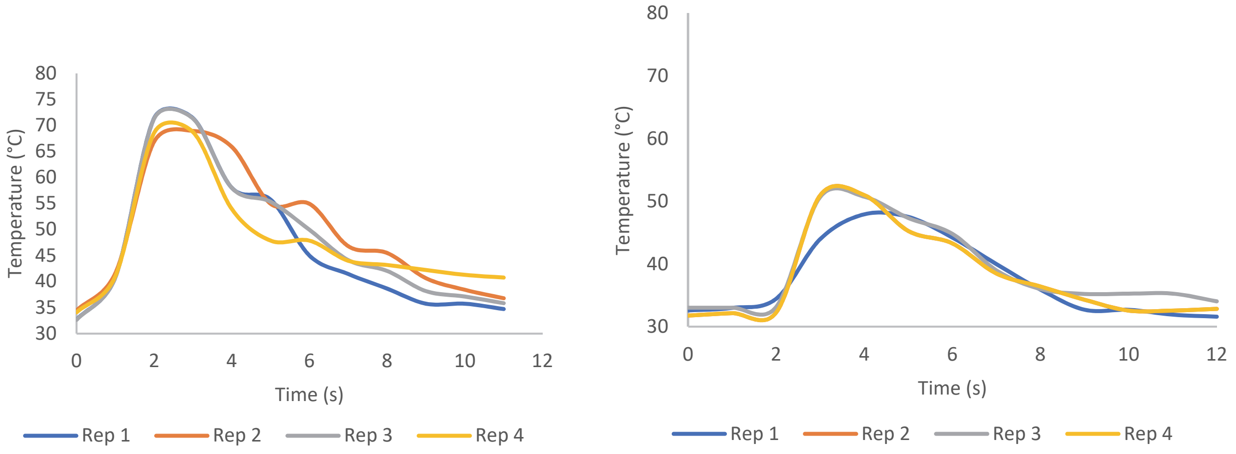
HFR in High and Low Speed

Figures 7a and 7b present the temperature profiles of the HFR with low and high (1.2 and 1.7 km/h) tractor driving speeds. The sensing system recorded lower temperatures with the high speed in most trails. The average of the temperature for four sensors and four replicates reached up to 70°C with the low speed, and 50°C with the high speed. In this experiment, a 50 cm bar of thermocouples (four sensors) placed horizontally on the ground (and not mounted inside the boom section as the Experiment I) to record the temperature when the steamer passes through a specific area. That explains the temperature differences between figure 5b (thermocouples sensors mounted inside the boom section) and figure 7 (bar of thermocouples sensors placed on the ground), so the bar represents the area was exposed to heat. Herein, we studied the effect of single factors (e.g., HFR vs. LFR, or low vs. high speed) and the relative differences on temperature for each experiment separately.

LFR in High and Low Speed

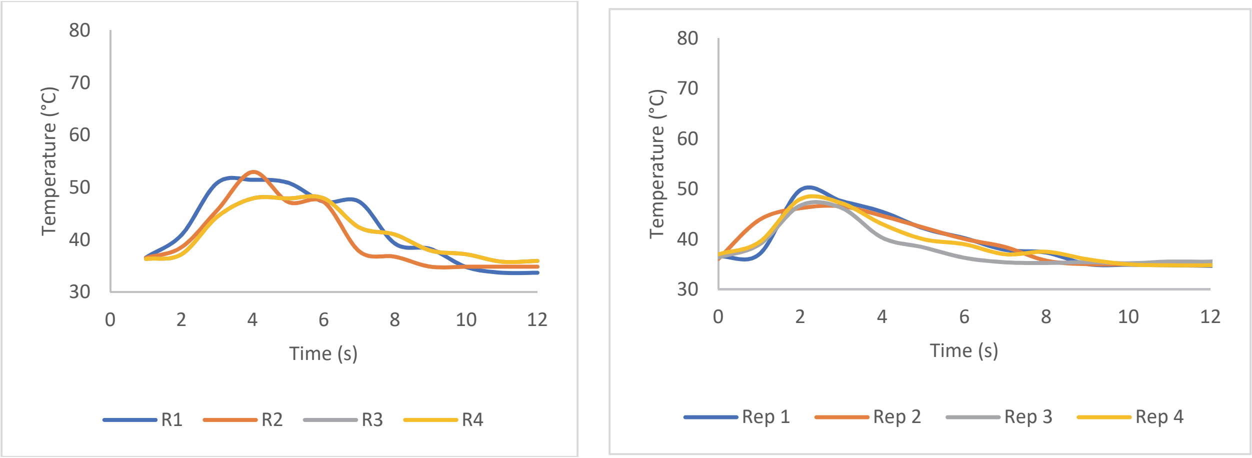
Four repetitions were tested to evaluate the LFR with two different tractor speeds. Figures 8a and 8b present the temperature profiles in both cases. The highest temperature was recorded when the tractor speed was at low (1.2 km/h). The average of the highest temperature for the four sensors, recorded at the low tractor speed trial, was 50°C (table 6).

Comparing HFR (fig. 7) and LFR (fig. 8), the temperatures in HFR were at least 20°C higher than the LFR in low speed and 3°C in high speed (table 6). The HFR achieved higher temperatures of around 69°C-71°C, than the LFR (45°C-51°C). In low speed, the area of interest is exposed to steam for longer time increasing the duration of the steam treatments and it has more uniformity of heat distribution.



(a) **(b)**

Figure 7. Temperature profile (the area exposed to heat) using (a) high flow rate and low speed (1.2 km/h) and (b) high flow rate and high (1.7 km/h) speed. 50 cm bars of thermocouples (four sensors) placed horizontally on the ground (represent the area exposed to heat). The experiments repeated four times (4 repetitions).



(a) **(b)**

Figure 8. Temperature profile (inside the boom section) using (a) low flow rate and low speed (1.2 km/h) and (b) low flow rate and high (1.7 km/h) speed. 50 cm bars of thermocouples (four sensors) placed horizontally on the ground.

Based on the current design, rubber curtains were attached to the boom section; the total width of the boom section (with the curtains) was increased from 75 to ~105 cm. Hence, a specific point/weed will be treated for around 3.2 s with the low speed (~1.2 km/h = 33 cm/s; the ~105 cm width will be covered in ~3.2 s) and around 2.2 s with the high speed (~1.7 km/h = 47 cm/s; the ~105 cm width will be covered in ~2.2 s). With the HFR the weed will be treated with much higher temperature (~78-81°C) than the LFR (~57°C-63°C) during the above times. Furthermore, steam can explode the cells of the weeds, by denaturing the proteins and bursting cell walls (Peerzada and Chauhan, 2018), and potential instantly kill the weeds.

Preliminary Experiment III

The Temperature under the Soil Surface

The goal of the proposed system was to kill weeds using (saturated) steam without affecting beneficial organisms in the soil and harming tree or plant roots. From figure 9, the temperature increase at 2.5 cm under the soil (-2.5 cm) is about 0°C (0°C in the first trail of 5 s treatment for HFR and LFR; ~1°C in the second and third trials, with 10 and 15 s application times, for HFR). Hence, it was found that steam does not penetrate (significantly) beyond few centimeters of soil and it does not affect the root zone, microbes, worms, and other beneficial organisms.

Temperature in Different Height Level Inside the Boom Section

In this static experiment the temperature was recorded in four different height level: -2.5 cm under the soil surface, 2.5 cm, 7.5 cm, and 12.5 cm above the surface, and in three different application times (5, 10, and 15 s), with HFR and LFR. Figure 9 presents the temperature profiles (average of five repetitions) for each scenario. In all scenarios, the HLR produced higher temperatures than the LFR. The HFR-15 s (fig. 9e) recorded the highest temperatures in all scenarios, with a maximum of 77°C. At the beginning of each treatment (steam application) the temperature increases rapidly. After the treatment (no steam is applied, and the boom is removed for the pre-determined area), the temperature decreases with a high rate (in most cases). In figure 11f (HFR-15 s), the temperature decreases with a low rate though, for all height levels (above ground). In all cases, the higher height levels recorded the highest temperatures. The height levels 7.5 cm and 12.5 cm recorded similar temperatures (in most cases). The temperatures of the 2.5 cm level were about 7°C-15°C lower than the 12.5 cm level in all LFR treatments, while the temperature in 2.5 cm level in HFR was 2°C-6°C lower than the 12.5 cm level.

Table 6. Average highest temperature values and standard deviation (four repetitions for each experiment) of the Preliminary Experiment II.

Speed of Tractor	Flow Rate	Mean Highest Temperature (°C)	Standard Deviation
Low speed (LS)	HFR	70	1.5
	LFR	50	2.6
High speed (HS)	HFR	50	1.5
	LFR	47	6.2

WEED MANAGEMENT EVALUATION IN THE FIELD

The initial signs of the steam treatments were a change of foliage color, and subsequently wilting of the whole plant. Shortly following the application of treatments on 3 DAT, a burn-down of weed foliage up to 97% was observed with the high rate of steam flow (53 L/h) (fig. 10). When observed on 12 DAT, substantial regrowth was observed from the steam applications for low flow rate steam applications (steam treatments 3 and 4). However, high rate steam flow treatments, when applied at slow tractor driving speeds of 1.2 km/h (steam treatment 2), maintained the weed suppression efficacy.

The post-emergent burndown effectiveness of the treatments on specific weed species is depicted in table 7. The steam treatments were found to be effective on certain weed species like goatweed and sedges despite their hardy nature. Similar ‘species specificity’ of steam treatments in weed management has been suggested previously (Lacko-Bartosova and Rifai, 2008). However, Florida pusley was least affected by the steam application, probably because of its prostrate (creeping) growth nature, that prevents an adequate coverage of steam on the entire plant. A thorough canopy and stem penetration is a critical factor towards the success

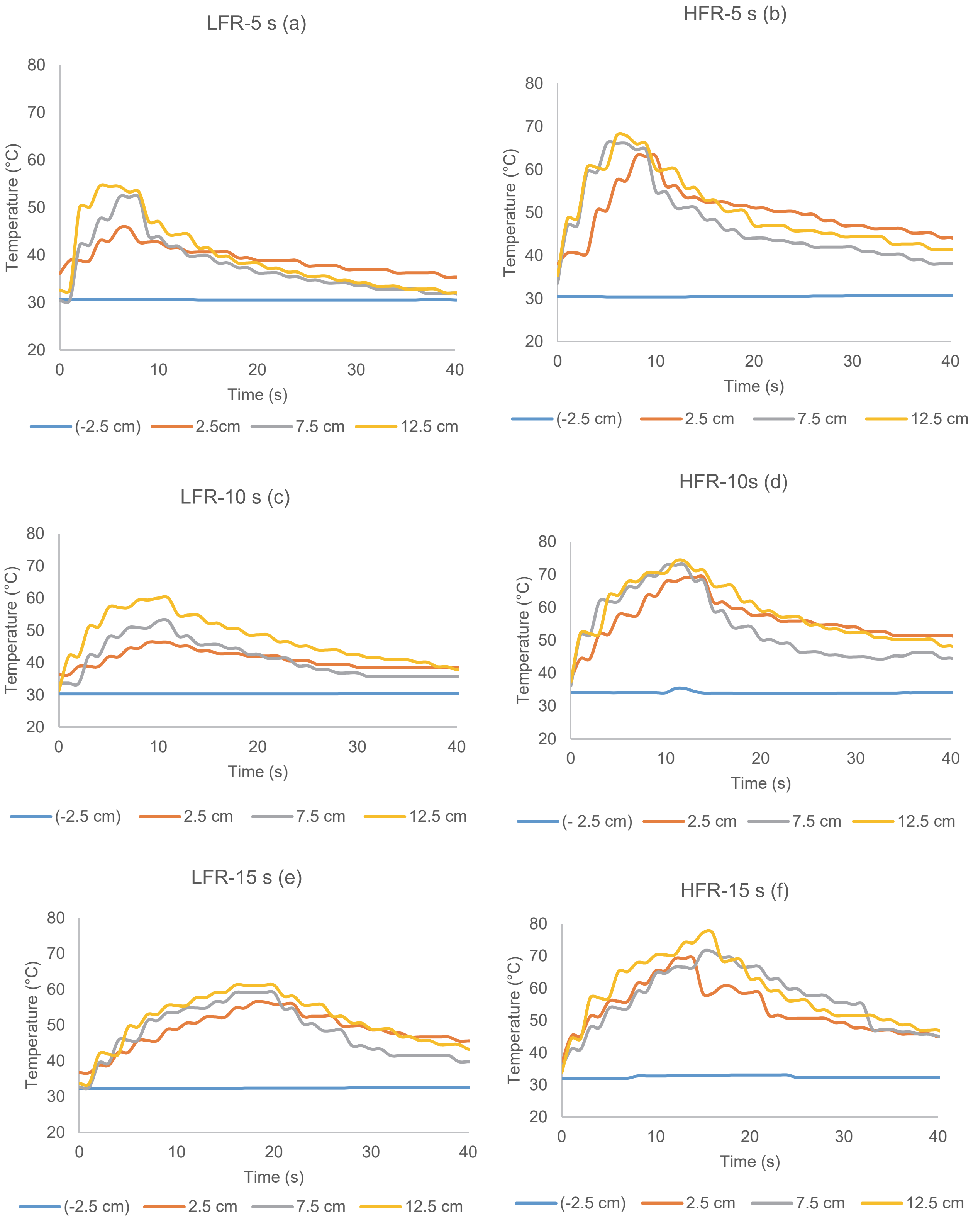


Figure 9. Temperature profiles (average of five repetitions) for the static experiment III. The temperature was recorded in four different height level (2.5, 7.5, and 12.5 cm), and in three application times (5, 10, and 15 s), with HFR and LFR.

of weed 'burndown' from the steam application experiment (fig. 10 and table 7). Negligible regrowth of the weed species was observed from the application of herbicide.

The herbicide (paraquat) treatment provided more than 95% post-emergence burn-down control of weeds. How-

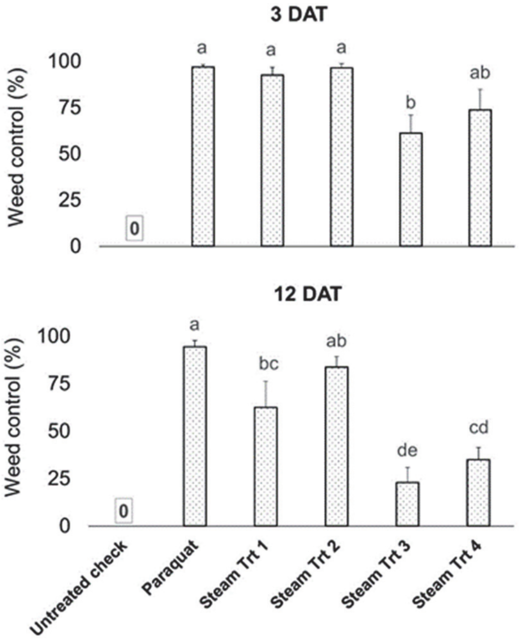


Figure 10. Weed control efficacy of treatment methods tested in the study, observed at 3 and 12 days after treatment (DAT). Scale: 0-100% where 0% indicates no burn-down and 100% indicates complete burn-down of the weed foliage. Error bars represent standard error (n=4). Bars with the same letters do not significantly differ (Tukey's HSD, P<0.05).

ever, when steam was applied for weed management, a noticeable regrowth of the weeds was observed. Therefore, follow up steam applications are required to manage weed with steam alone. This observation is in line with Shrestha et al. (2013) who also found regrowth in weeds, weeks after initial steam treatment. When regrowth has been observed, it was primarily in the lateral regrowth of broadleaf weed species after steam applications, and potentially due to the main growing axis being damaged (Leon and Ferreira, 2008). Such regrowth potentially could be managed with additional applications (Kurfess and Kleisinger, 2000) or an in conjunction with a chemical weed control method. With multiple applications, steam treatment has the potential to be an alternative for control weeds in citrus.

CONCLUSION

A weed steamer was developed, and steam application treatments were tested in this study for their potential for weed control in a citrus grove. Two tractor driving speeds (1.2 and 1.7 km/h) and two flow rates (high flow rate of 53 L/h and a low flow rate of 15 L/h) were evaluated. The most efficacious steam application was obtained by combining a low tractor speed with high steam flow rate (1.2 km/h and 51 L/h, respectively), where citrus weeds like goatweed and sedges were burned and did not regrow back significantly. With repeated applications, steam treatment has the potential to be an alternative strategy for weed management in citrus. Moreover, the prospects of testing steam application in conjunction with chemical control strategies to prolong the window of weed control need to be evaluated in the near future.

Table 7. Weed control efficacy of treatment methods on selected weed species in citrus grove, observed at 12 days after treatment (DAT).

	Weed Control (%)[a] – 12 DAT			
Treatment	Florida Pusley[b]	Goatweed	Guinea grass	Sedge
Untreated control	0.00b	0.00d	0.00b	0.00c
Herbicide (Paraquat)	95.00a	97.50a	97.67a	97.50a
Steam Treatment 1	12.50b	75.00abc	48.33ab	83.75ab
Steam Treatment 2	36.67b	83.75abc	27.50b	72.50ab
Steam Treatment 3	10.00b	51.25bc	28.33b	32.50bc
Steam Treatment 4	5.00b	48.75c	0.00b	35.00bc

[a] Average weed control n=4; Scale: 0-100% where 0% indicates no burn-down and 100% indicates complete burn-down of the weed foliage.

[b] Percentages followed by the same letter do not significantly differ (Tukey's HSD, P<0.05).

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