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Original Research Article

Efficiency and Cost-Effectiveness of Weed Flaming in Orchards

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ABSTRACT

The objective of this study was to determine the response and cost of weed flaming in different fruit orchards. Six different propane doses (15, 30, 45, 60, 75 and 90 kg ha^{-1}) were applied to determine the response of 6 dicotyledon and 3 monocotyledon weed species to flaming in apricot, walnut, and mixed fruit orchard. Dose-response relationships were determined using log-logistic model for 50%, 80%, and 90% control rates at 1, 7 and 14 days after treatment (DAT) at 2–4, 6–8 and 10–12 leaf (L) growth stages. Flaming at early stage of weed growth (2–4 L) resulted in 90% control of all dicotyledon weeds at 14 DAT with propane doses ranging from 35.0 to 65.8 kg ha^{-1}, while this range was from 28.6 to 54.9 kg ha^{-1} at 80%, suggesting approximately 15–20% less propane use for 80% weed control compared to 90% control. Monocotyledon weeds were resistant to thermal stress even at 2–4 L stage and could be controlled at 14 DAT with propane dose from 125.7 to 210.9 kg ha^{-1} at 90% control rate and 74.6 to 133.4 kg ha^{-1} at 80% control rate. The cost of weed flaming was compared to the spraying application using partial budgeting method. Flaming costs (30.6 and 34.4 \$ ha^{-1}) for dicotyledon weeds at 80% and 90% weed control rates were comparable to herbicide application at 2-4 L stage, whereas flaming was found costly than chemical spraying at other growth stages for any weed species.

Keywords: Broadcast flaming, dose-response, orchard, weed control, cost

INTRODUCTION

Weeds are accepted as one of the main reasons reducing the quantity and quality of agricultural production (Uludağ *et al.* 2018). Although about half of the losses in crop plants are due to weeds, this loss is estimated to be between 10-50% depending on the variety and weed type (Oerke *et al.* 1994; Uygur 2002; Khanh *et al.* 2005; Thobatsi, 2009). Although the increase in agricultural production depends on many factors, weeds play a big role in obtaining high yields.

The effect of flaming on weed control has been studied for growing different field crops such as corn, cotton, soybeans, and sunflower (Ulloa *et al.* 2010a; Rasmussen *et al.* 2011; Knezevic *et al.* 2012), vegetables (Wszelaki *et al.* 2017; Sivesind (2010)) and berries (Ghantous 2013). Sustainable management of weeds is also important for organic fruit production (Shrestha *et al*. 2012). The major aim of weed flaming is usually to eliminate herbicide use in plant production; however, researchers have also focused on controlling plant diseases (Laguë *et al*. 1997; Mirzakhani and Ehsani 2014)). Weed control is of particular interest in organic production since the use of most chemicals is strictly forbidden. The labor costs are high and hand weeding is time consuming (Kruidhof *et al*. 2008) urging organic producers to adopt alternative weed control methods. Weed control rate of flaming is not as high as mechanical weeding or chemical application; however, 80% weed control is considered acceptable in organic farming (Knezevic and Ulloa 2007).

In addition to the agricultural use, the flamers have urban and suburban use on hard surfaces (Cohen, 2006; Rask et al. 2012). The flamers can be used instead of trimmers in mechanical weed control and may be less costly compared to the ordinary treatments in the urban areas (Raffaelli *et al*. 2012; Rask *et al*. 2012) referred to several studies focusing on flaming on hard surfaces and mentioned equipment designed for footways and verges and handheld/hand-pushed aggregates for weed control around the obstacles or in households. The motivation for flaming in weed control comes from the pollution of ground waters, which led to many European countries limit pesticide use (Rask *et al*. 2012).

The accurate use of weed flamers depends on proper calibration and the factors affecting calibration are pressure and the forward (ground) speed during flaming under field conditions. The calibration of the flamer is done based on the required LPG or propane dose for given weed species. This eventually is determined by using the dose-response curves of weeds. In order to obtain the dose-response curves, varying doses of propane are

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applied in the range from 0 to 90 kg ha^{-1} (Knezevic and Ulloa 2007; Sivesind *et al*. 2009), and can also be relatively high (150–355 kg ha^{-1}) under unusual terrain and application conditions (Kristoffersen *et al*. 2008). The pressures tested for developing or studying different types of burners range from 0.1 to 0.5 MPa (Laguë *et al.* 1997). The burner angles toward the ground should be about 30–45ºC to provide the best efficiency in controlling the weeds.

The ground speed of the flamers is usually low, especially if the propane dose needs to be high. In flame weeding studies, ground speeds of 1.0–7.5 km h^{-1} and higher were reported depending on dose requirements (Wszelaki *et al*. 2007; Cisnenos and Zandsta 2008; Ulloa *et al*. 2010a). However, an acceptable constant ground speed may be chosen in which case the pressure setting needs to be adjusted to provide the desired propane doses (Mutch *et al*. 2008; Ulloa *et al*. 2010a).

Different weed species have varying levels of thermal tolerance during flaming. In general, dicotyledon weeds are more prone to be damaged due to heating. A propane dose of 76 kg ha^{-1} was needed to accomplish 90% reduction in the dry matter of 7-L *Echinochloa crus-galli* (L.) P. Beauv.; however the doses required for 8-L *Convolvulus arvensis* L., 6-L *Kochia prostrata* (L.) *Schrader*, 10-L *Ipomoea purpurea* (L.) Roth., 7-L *Abutilon theophrasti* Medik. and 5-L *Hibiscus trionum* L. were 40, 49, 55, 56 and 51 kg ha^{-1}, respectively (Ulloa *et al.* 2010b). Flame weeding was more effective in controlling dicotyledon weeds than monocotyledon weeds in vegetable crops (Sivesind 2010), and pigweed (*Amaranthus* spp.) weeds were less tolerant than foxtail (*Setaria* spp.) weed species (Ulloa *et al*. 2010a).

Weeds may have different thermal stress behaviors in different areas depending on soil, plant, and whether variations. The response of different weed specie should be determined in different environmental conditions to determine the efficiency and cost effectiveness of weed flaming both at research scale and at the farm level. Therefore, the objectives of this study were to: 1) use a broadcast weed flamer to apply different propane doses to the weeds in an apricot, walnut and mixed fruit orchards, 2) obtain the dose-response curves of the weeds at different growth stages and 3) compare the biological efficiency of flaming on annual and perennial weeds and on monocotyledon and dicotyledon weeds.

MATERIALS AND METHODS

Study area

This study was conducted in three different orchards in Malatya province, Eastern Turkey during 2015 and 2016. Apricot orchard was located in Apricot Research Institute (38˚27'16" N, 38˚21'15" E), while walnut orchard and mixed fruit orchard belonged to the experimental fields of Faculty of Agriculture, İnönü University, Malatya, Turkey (38˚27'34''N, 38˚21'22''E). The institute and the faculty are closely located. The soil type is clay silt loam in the three orchards.

Materials

A two-meter-wide hooded broadcast weed flamer was used with a tractor to apply propane doses. The gas burning system comprised a gas tank, pressure regulator, back pressure valve, gas distributer, hoses, and burners. The gas tank was equipped with a pressure release valve, a fuel level gage, and a propane charging inlet.

Methods

The flaming applications were done between the rows of the trees in the second and third week of June in 2015 and 2016, respectively. The ambient air temperatures were between 30–35°C in both years during the flaming applications conducted from 10 am to 1 pm in both years.

Split plot experimental design was used in the study where the growth stage of weed species was the main plot and the applied propane doses was subplot. The flaming experiments were conducted with four replicates in each of the orchards. The spacing between the trees was 6, 8, and 10 meter in the mixed fruit, apricot, and walnut orchards, respectively.

The ground speed of the tractor was determined in the field conditions by measuring a given distance (20 m) and the time (s) needed to travel the distance. The necessary gears and engine speeds were selected to obtain the desired ground speeds so that the preferred propane doses could be applied at the pressure setting of 0.2 MPa

(2 bars). The height of the burners was set to 0.25 m from the ground and the flame angle was adjusted to 30º. The pressure-flow rate characteristics of the gas nozzle and the relationships among the ground speed, gas pressure, and dose were determined in a previous study (Güleç *et al*. 2015). A constant gas pressure (0.2 MPa) was set and forward speed was varied to apply six different propane doses, i.e. 15, 30, 45, 60, 75 and 90 kg ha^{-1}. The corresponding forward speeds ranged from 1.83 to 8.3 km h^{-1} in order to apply the desired propane doses.

Flaming was applied in 50 m long strips for each dose in the walnut and mixed tree orchards, whereas the plot lengths were 150 m in the apricot orchard. Since weeds were not planted in this study, weeds at different growth stages could be found in the experimental plots. The effect of flaming on weed control was determined based on visual observations in 1, 7 and 14 days after treatments (DAT). The weeds in the experimental fields were determined and classified by their growth stages into three categories: 2–4, 6–8 and 10-12 L stages.

In 2015, three monocotyledon weeds and six dicotyledon weed species were found in the experimental fields along with two weed species at flowering stage. In 2016, nine weed species were found common with 2015, six of which were identified in the three growth stages and the remaining species could not be found in 2-4 L stage. Therefore, the control rates of nine common weeds of 2015 and 2016 were evaluated.

Data analysis

Four parameter log-logistic model (eq. 1) was used with non-linear regression analysis to determine the response of weeds to flaming (Streibig *et al.* 1993; Seefeldt *et al.* 1995):

$$Y = C + \frac{D-C}{1+exp\{B[logX-logE]\}} \qquad (1)$$

where Y is the response, C is lower limit of the curve, D is the upper limit, X is propane dose (kg ha^{-1}), E is the dose responsible for 50% control between the lower and upper limits, and B is the slop of the curve at the inflection point. The weed control rates were determined by using ED50 (50% control), ED80 (80% control), and ED90 (90% control) (Knezevic *et al.* 2007).

The cost of flaming was determined for monocotyledon and dicotyledon weeds for 80% and 90% weed control at different growth stages by using the dose requirements determined through dose-response calculations. For this, first average and overall average gas doses were calculated for monocotyledon and dicotyledon weeds for 80% and 90% control rate. Then flaming costs per unit area ($ ha^{-1}) were determined for different weed growth stages. The flaming costs ratios were compared between 2-4 L and 6-8 L, 2-4 L and 10-12 L, and 6-8 L and 10-12 L. Finally, the costs of applying herbicide were calculated per unit area for annual and perennial weeds and the associated costs were compared with flaming costs. Average propane cost of three gas suppliers was 0.81 US$ per liter. Herbicide cost varies depending on the amount of herbicide to be purchased. It is assumed that 5 L bottles would be used for herbicide application instead of 1 L bottles since unit price ($ ha^{-1}) for herbicide is cheaper for 5 L bottles.

The cost of tractor fuel consumption was neglected in the cost assessment, thus the application costs mentioned in the paper refer to solely to the cost of applied gas and pesticides.

RESULTS AND DISCUSSION

Propane dose requirements for weed control

Nine weed species were identified in the orchards, which were common in 2015 and 2016. However, 2–4 L growth stage could not be found for two of the weed species in 2015 and for three of the weed species in 2016.

Weed control rates were different at a given growth stage and given DAT for a selected weed species (Table 1 and Table 2). The propane dose had to be increased as the control rates increased. For instance, in the case of *C. dactylon*, at 6–8 L stage and 7 DAT, the gas doses needed were 47.8, 71.9 and 91.3 kg ha^{-1}, respectively for 50, 80 and 90 % control (Table 1). The data also show that, at a given control rate, the dose of propane needs to be increased as the weeds grow, i.e. as the number of weed leaves increases. In Tables 1-2, some propane doses are greater than 90 kg ha^{-1} that was the highest dose applied during field testing using the weed flamer developed for this study. The data in the tables are the model-predicted propane doses to accomplish different control levels.

Table 1. The propane doses needed at different growth stages for 50, 80 and 90 % control of weeds determined at 1, 7 and 14 days after treatments (DAT) during hooded flaming in 2015.

Weeds	**Growth stage**	**DAT (day after treatment)**	**Regression parameters (±SE)***			**ED50 (±SE)**	**ED80 (±SE)**	**ED90 (±SE)**
			B	**C**	**D**			
***Convolvulus arvensis* L.**	2-4 L	1	-3.4 (0.6)	-0.1 (2.9)	93.5 (2)	17.0 (1)	25.7 (2)	32.7 (4)
		7	-3.5 (0.5)	-0.1 (2.7)	95.9 (2)	17.9 (1)	26.7 (2)	33.7 (3)
		14	-3.2 (0.4)	-0.1 (2.8)	95.9 (2)	20.1 (1)	31.1 (2)	40.2 (4)
	6-8 L	1	-2.7 (0.3)	-0.3 (2.8)	95.1 (3)	23.9 (1)	40.1 (4)	54.1 (7)
		7	-2.3 (0.3)	-0.3 (2.9)	96.3 (4)	22.7 (2)	41.1 (5)	58 (10)
		14	-2.2 (0.3)	-1.2 (3.0)	105.4 (7)	31.4 (3)	59.4 (10)	86.2 (18)
	10-12 L	1	-2.9 (0.4)	-1.1 (2.8)	92.4 (3)	25.5 (1)	41.2 (4)	54.6 (7)
		7	-2.2 (0.3)	-0.1 (2.6)	95.1 (5)	25.8 (2)	48.9 (7)	71.2 (13)
		14	-3.3 (0.6)	3.3 (2.4)	94.9 (6)	41.5 (2)	63.6 (8)	81.5 (14)
***Sophora alopecuroides* L.**	2-4 L	1	-4.7 (1.3)	6.0 (2.9)	91.2 (5.2)	39.7 (2)	53.2 (6)	63.3 (10)
		7	-5.2 (1.1)	6.4 (2.6)	89.7 (3.8)	40.2 (2)	52.5 (4)	61.3 (7)
		14	-4.6 (2)	10.0 (3.9)	89.6 (7.8)	40.6 (3)	54.9 (10)	65.6 (16)
	6-8 L	1	-3.2 (1.1)	6.9 (3.6)	106.6 (15)	51.1 (5)	79.3 (19)	102.5 (33)
		7	-2.8 (1.1)	6.0 (3.8)	112.7 (25)	55.6 (10)	91.9 (33)	123.3 (58)
		14	-2.2 (0.5)	2.4 (2.7)	115.0 (21)	55.9 (10)	104.1 (33)	149.7 (60)
	10-12 L	1	-2.7 (1.2)	4.2 (4.4)	102.0 (21)	46.0 (8)	77.1 (30)	104.2 (54)
		7	-2.2 (0.7)	2.5 (3.2)	105.7 (21)	51.0 (10)	95.2 (36)	137.2 (67)
		14	-2.1 (0.7)	2.1 (3.1)	114.9 (34)	60.4 (18)	118 (60)	174.5 (60)
***Chrozophora tinctoria* (L.) A. Juss.**	2-4 L	1	-5.0 (0.8)	-0.2 (3.3)	91.3 (1.9)	20.1 (1)	26.6 (2)	31.3 (3)
		7	-4.2 (0.7)	-0.3 (3.6)	95.6 (2.3)	20.2 (1)	28.1 (2)	34 (4)
		14	-3.8 (0.5)	-0.4 (3.1)	95.5 (2.1)	19.9 (1)	28.6 (2)	35 (4)
	6-8 L	1	-6.8 (1.3)	7.1 (2.8)	89.0 (2.8)	37.1 (1)	45.6 (3)	51.4 (4)
		7	-4.4 (1.4)	6.8 (3.5)	88.8 (4.9)	35.9 (2)	49.3 (6)	59.4 (10)
		14	-4.6 (1)	6.3 (2.7)	91.6 (4.7)	41.1 (2)	55.6 (5)	66.4 (9)
	10-12 L	1	-4.3 (1.3)	7.5 (3.1)	90.6 (6)	40.3 (2)	55.7 (7)	67.3 (12)
		7	-3.0 (1.3)	5.5 (4.4)	95.8 (14)	42.4 (4)	67.6 (20)	88.8 (37)
		14	-6.2 (1.2)	7.2 (2)	87 (4.2)	52.4 (2)	65.6 (4)	74.8 (6)
***Xanthium strumarium* L.**	2-4 L	1	-5.7 (1.0)	5.25 (2.5)	88.9 (2.8)	37.1 (1)	47.2 (3)	54.5 (4)
		7	-6.3 (1.1)	7.0 (2.5)	91.3 (2.7)	37.9 (1)	47.2 (2)	53.7 (4)
		14	-5.4 (1.1)	7.6 (2.7)	92.7 (3.2)	37.2 (1)	48.2 (3)	56.1 (5)
	6-8 L	1	-5.2 (1.9)	8.9 (3.5)	88.1 (4.8)	36.0 (2)	47.1 (6)	55.1 (10)
		7	-6.4 (1.8)	9.3 (3.2)	83.3 (3.5)	36.9 (2)	45. 8 (4)	52 (6)
		14	-4.4 (1)	4.5 (2.4)	84.9 (4)	38.6 (2)	52.7 (5)	63.3 (8)
	10-12 L	1	-6.2 (1.7)	8.5 (3)	81.5 (3.5)	38.2 ((2)	47.8 (4)	54.5 (6)
		7	-4.9 (1.8)	7.1 (3.4)	83.4 (4.8)	36.0 (2)	48.0 (6)	56.7 (10)
		14	-5.3 (1.9)	8.2 (3.1)	79.0 (4.7)	38.6 (2)	50.1 (6)	58.4 (10)
***Lactuca serriola* L.**	6-8 L	1	-4.8 (1.5)	9.5 (3.4)	91.9 (5.6)	39.6 (2)	52.9 (6)	62.6 (11)
		7	-4.2 (1.5)	8.2 (3.4)	88.1 (5.7)	37.9 (2)	52.6 (7)	63.7 (13)
		14	-4.1 (1.2)	7.7 (3.1)	85.4 (5.6)	40.4 (2)	56. 9 (7)	69.4 (13)
	10-12 L	1	-4.4 (1.6)	7.4 (3.5)	89.3 (6.9)	39.6 (2)	54.2 (8)	65.1 (14)
		7	-3.7 (1.8)	6.7 (4.1)	88.1 (10)	39.6 (3)	57.7 (14)	71.9 (24)
		14	-3.2 (1.5)	5.1 (4.1)	89.1 (12)	40 (3)	61.6 (16)	79.3 (30)
***Echinophora* spp.**	6-8 L	1	-2.4 (0.6)	2.3 (3.3)	105.4 (15)	47.9 (6)	84.5 (22)	117.8 (40)
		7	-2.6 (0.6)	2.6 (2.4)	103.3 (14)	53.9 (6)	91.4 (20)	124.5 (36)
		14	-2.9 (0.9)	4 (2.8)	101.9 (10)	59.4 (10)	96.01 (29)	127.2 (49)
	10-12 L	1	-2.6 (2.5)	3.7 (8.7)	97.3 (40)	43.2 (14)	74.3 (16)	102.1 (21)
		7	-2.6 (0.8)	3.2 (3.1)	92.9 (13)	46.1 (6)	78.7 (21)	107.5 (38)
		14	-2.3 (0.7)	2.6 (3.1)	103.7 (24)	54.7 (13)	100.8 (42)	144.0 (76)

Table 1 (continued)

***Cynodon dactylon* (L.)Pers.**	2-4 L	1	-2.3 (0.3)	0.6 (2.9)	99.1 (6)	32.4 (2)	59.6 (8)	85.2 (16)
		7	-2.1 (0.4)	0.5 (2.8)	101.5 (11)	41.6 (5)	82 (20)	122 (39)
		14	-1.9 (0.5)	1.2 (2.9)	115.3 (24)	55.7 (13)	115.6 (47)	177.3 (90)
	6-8 L	1	-3.9 (1.6)	7.7 (4.1)	90.4 (11)	46.5 (4)	66.4 (13)	81.8 (23)
		7	-3.4 (1.5)	6.3 (4.3)	90.4 (14)	47.8 (5)	71.9 (19)	91.3 (34)
		14	-2.2 (1.3)	4.0 (5.1)	118.2 (60)	63.1 (31)	118.9 (10)	172.4 (19)
	10-12 L	1	-3.2 (2.7)	5.9 (6.6)	91.0 (25)	42.5 (8)	65.6 (35)	84.6 (63)
		7	-2.3 (0.6)	2.7 (3)	101.8 (15)	47.9 (7)	88.6 (26)	126.9 (49)
		14	-1.8 (0.6)	1.4 (3.4)	111.5 (32)	56.5 (19)	121.7 (69)	190.6 (134)
***Phragmites australis* (Cav.) Trin. Ex. Steud.**	2-4 L	1	-4.0 (1.1)	5.6 (3)	90.8 (7)	40.1 (2)	56.8 (8)	69.7 (14)
		7	-2.9 (0.8)	1.9 (3)	99.7 (13)	46.5 (5)	74.6 (17)	98.4 (29)
		14	-2.6 (0.6)	1.2 (2.4)	107.3 (17)	54.4 (8)	93.2 (23)	127.7 (40)
	6-8 L	1	-1.7 (0.2)	0.2 (1.9)	112.1 (8)	40.2 (4)	89.1 (16)	141.9 (33)
		7	-1.9 (0.2)	-0.1 (1.9)	99.2 (7)	39.8 (4)	82.3 (14)	125.9 (27)
		14	-1.8 (0.2)	-0.4 (1.8)	122 (10)	58.2 (10)	127.9 (33)	202.5 (65)
	10-12 L	1	-2.1 (0.9)	2.8 (4.9)	109.5 (29)	47.7 (13)	91.5 (49)	133.8 (49)
		7	-2.4 (1.4)	4.8 (5.1)	106.9 (40)	54.3 (18)	96 (64)	133.9 (115)
		14	-2.0 (0.7)	1.6 (3.1)	135.6 (32)	73.7 (32)	146.8 (97)	219.7 (174)
***Sorghum halepense* (L.) Pers.**	2-4 L	1	-4.5 (0.9)	6.2 (2.6)	91.8 (4)	39.1 (2)	53.1 (4)	63.5 (8)
		7	-3.1 (0.8)	3.1 (3)	95.7 (10)	44.7 (4)	70 (14)	90.9 (24)
		14	-2.3 (0.6)	0.8 (2.9)	103.6 (17)	50 (9)	92.5 (29)	132.4 (52)
	6-8 L	1	-4.0 (1.2)	7.2 (3.3)	97.3 (7)	39.7 (2)	56 (8)	68.5 (13)
		7	-2.1 (0.8)	3 (5.2)	105.3 (31)	41.8 (8)	81.2 (36)	119.8 (71)
		14	-1.8 (0.7)	2.2 (4.8)	105.8 (22)	42.4 (10)	90.9 (45)	142.2 (93)
	10-12 L	1	-3.3 (1.4)	5.4 (3.9)	90.6 (11)	40.3 (3)	61.2 (14)	78.2 (26)
		7	-2.4 (0.9)	2.7 (4.2)	102 (21)	46.9 (9)	83.8 (34)	117.6 (62)
		14	-2.1 (0.7)	1.8 (3.4)	105.1 (25)	53.1 (13)	102.1 (45)	149.8 (84)

* SE: standard error, B: the slope of the dose-response curve at the inflection point, C: the lower limit of the curve, D: upper limit, E is the dose responsible for 50% control between the lower and upper limits, X is propane dose (kg ha^{-1}), ED50: 50% control, ED8: 80% control, ED90: 90% control.

Table 2. The propane doses needed at different growth stages for 50, 80 and 90 % control of weeds determined at 1, 7 and 14 days after treatments (DAT) during hooded flaming in 2016.

Weeds	Growth stage	DAT (day after treatment)	Regression parameters (±SE)*			ED50 (±SE)	ED80 (±SE)	ED90 (±SE)
			B	C	D			
***Convolvulus arvensis* L.**	2-4 L	1	-3.7 (0.3)	-0.1 (2.0)	94.3 (1)	19.7 (1)	28.7 (2)	35.9 (2)
		7	-3.6 (0.4)	-0.1 (2.6)	89.6 (2)	20.9 (1)	30.9 (2)	38.8 (4)
		14	-3.1 (0.5)	-0.1 (3.0)	86.2 (3)	21.9 (1)	34.2 (4)	44.4 (6)
	6-8 L	1	-3.3 (0.5)	2.3 (2.3)	96.7 (3)	31.9 (1)	48.7 (3)	62.4 (6)
		7	-3.3 (0.7)	2.3 (3.1)	91.9 (4)	31.4 (1)	47.9 (5)	61.3 (9)
		14	-3.2 (0.6)	1.6 (2.9)	91.8 (4)	32.4 (2)	50.1 (5)	64.7 (9)
	10-12 L	1	-2.6 (0.2)	-0.3 (1.8)	95.1 (2)	25.2 (1)	42.7 (3)	58.2 (5)
		7	-2.6 (0.3)	-0.1 (2.4)	92.0 (3)	26.7 (1)	45.9 (4)	63.0 (8)
		14	-2.6 (0.6)	1.2 (3.7)	96.2 (9)	36.1 (3)	62.1 (12)	85.4 (23)
***Sophora alopecuroides* L.**	2-4 L	1	-5.8 (1.5)	8.3 (3.0)	86.9 (3.6)	37.4 (2)	47.5 (4)	54.6 (6)
		7	-4.7 (1.4)	6.9 (3.0)	88.2 (5.1)	39.1 (2)	52.6 (6)	62.6 (10)
		14	-4.5 (1.3)	6.0 (2.6)	88.3 (4.7)	40.2 (2)	54.9 (6)	65.8 (9)
	6-8 L	1	3.5 (1.1)	7.8 (3.3)	105.1 (14)	52.8 (5)	78.3 (16)	98.6 (54)
		7	-3.5 (1.2)	7.9 (3.2)	105.6 (17)	55.8 (6)	83.0 (19)	104.7 (32)
		14	-3.2 (0.9)	5.6 (2.8)	105.2 (16)	56.5 (6)	87.5 (20)	113.0 (33)
	10-12 L	1	-3.0 (1.1)	6.6 (3.8)	110.5 (20)	53.4 (7)	84.8 (25)	111.2 (43)
		7	-2.6 (1.1)	5.6 (4.1)	120.2 (35)	59.6 (15)	102.2 (48)	140.2 (84)
		14	-2.2 (0.5)	2.8 (2.7)	118.8 (23)	58.8 (11)	109.3 (37)	157.1 (66)

Table 2 (continued)

***Chrozophora Tinctoria* (L.) A. Juss.**	2-4 L	1	-4.5 (0.4)	-0.3 (2.1)	89.6 (1.3)	20.7 (1)	28.2 (1)	33.9 (2)
		7	-4.1 (0.5)	-0.1 (2.4)	87.8 (1.6)	21.1 (1)	29.7 (2)	36.2 (3)
		14	-3.4 (0.4)	-0.6 (2.5)	87.1 (2.0)	21.3 (1)	32.0 (2)	40.5 (4)
	6-8 L	1	-5.3 (1.1)	6.6 (2.5)	90.3 (3.3)	38.8 (1)	50.4 (3)	58.7 (6)
		7	-3.4 (1.5)	5.1 (4.4)	92.5 (8.7)	36.3 (2)	54.6 (11)	69.3 (21)
		14	-4.1 (1.3)	5.9 (3.2)	90.0 (7.0)	41.4 (3)	58.0 (8)	70.6 (14
	10-12 L	1	-4.5 (1.0)	6.2 (2.6)	92.5 (5)	40.1 (2)	54.5 (5)	65.2 (8)
		7	-3.0 (1.2)	4.0 (4.6)	96.5 (10)	37.4 (3)	59.7 (14)	78.5 (26)
		14	-3.7 (1.2)	5.5 (3.4)	93.3 (9.1)	43.2 (2)	63.0 (11)	78.5 (19)
***Xanthium Strumarium* L.**	2-4 L	1	-6.5 (1.5)	7.0 (2.8)	86.0 (3)	36.3 (2)	45.0 (3)	51.0 (5)
		7	-4.9 (1.3)	5.4 (2.8)	86.2 (4)	38.0 (2)	50.5 (5)	59.6 (9)
		14	-4.8 (1.4)	5.4 (2.8)	88.1 (5)	38.5 (2)	51.4 (6)	60.8 (10)
	6-8 L	1	-5.5 (1.8)	6.5 (3.2)	86.5 (5)	36.9 (2)	47.5 (5)	55.0 (9)
		7	-3.6 (1.3)	4.2 (3.5)	90.9 (9)	39.7 (3)	58.2 (11)	72.8 (20)
		14	-3.4 (1.4)	3.9 (3.7)	88.9 (11)	40.7 (4)	60.9 (14)	77.0 (25)
	10-12 L	1	-4.2 (0.9)	6.0 (2.4)	87.5 (4.2)	39.3 ((2)	54.9 (5)	66.7 (9)
		7	-4.4 (0.9)	5.4 (2.3)	85.1 (3.7)	39.5 (2)	54.2 (5)	65.3 (8)
		14	-4.1 (0.7)	4.5 (2.0)	84.6 (3.8)	40.6 (2)	57.0 (5)	69.5 (8)
***Lactuca serriola* L.**	6-8 L	1	-4.1 (1.4)	8.9 (3.5)	94.8 (7)	41.0 (2)	57.4 (9)	69.8 (15)
		7	-4.4 (1.5)	8.2 (3.4)	87.2 (7)	40.3 (2)	55.4 (8)	66.7 (14)
		14	-4.1 (1.3)	7.5 (3.0)	86.7 (6)	40.6 (2)	56. 8 (8)	69.2 (13)
	10-12 L	1	-3.9 (1.4)	8.7 (3.7)	96.4 (9)	41.8 (3)	59.8 (10)	73.6 (18)
		7	-4.0 (1.5)	8.0 (3.5)	91.5 (8)	41.2 (3)	58.1 (10)	71.2 (17)
		14	-3.9 (1.2)	7.4 (3.1)	88.1 (7)	41.5 (2)	59.2 (9)	72.8 (15)
Echinophora. spp.	6-8 L	1	-2.7 (0.7)	2.6 (3.2)	99.0 (11)	44.2 (4)	73.9 (15)	99.9 (27)
		7	-3.3 (0.6)	3.6 (2.2)	90.9 (7)	46.8 (3)	71.5 (9)	91.7 (16)
		14	-3.3 (0.7)	4 (2.3)	90.1 (9)	50.5 (4)	77.3 (12)	99.2 (21)
	10-12 L	1	-2.4 (0.5)	1.9 (2.8)	104.6 (12)	46.8 (5)	83.8 (18)	117.8 (33)
		7	-2.8 (0.5)	2.8 (2.2)	96.8 (10)	49.6 (4)	81.1 (14)	108.2 (24)
		14	-2.8 (0.6)	3.3 (2.3)	98.3 (14)	54.8 (6)	90.3 (20)	121.1 (34)
C. dactylon	2-4 L	1	-2.2 (0.3)	1.3 (2.5)	95.4 (6)	33.6 (2)	62.4 (9)	89.7 (17)
		7	-2.0 (0.4)	1.5 (2.8)	101.9 (12)	43.0 (6)	86.3 (22)	129.6 (44)
		14	-1.9 (0.5)	1.9 (2.6)	118.3 (26)	59.3 (14)	123.3 (51)	189.3 (96)
	6-8 L	1	-3.6 (1.1)	7.0 (2.9)	89.3 (10)	48.2 (4)	70.9 (13)	88.9 (22)
		7	-2.9 (0.8)	4.7 (2.4)	92.2 (13)	52.4 (6)	83.9 (19)	110.5 (32)
		14	-2.5 (0.8)	3.6 (3)	105 (30)	63.6 (16)	111.6 (47)	155.1 (81)
	10-12 L	1	-3.7 (1.1)	7.1 (2.7)	88.7 (10)	49.3 (4)	71.7 (13)	89.2 (21)
		7	-3.6 (0.8)	5.3 (2.1)	86.2 (8)	50.9 (4)	75.2 (11)	94.6 (19)
		14	-2.4 (0.8)	2.9 (2.8)	105.9 (33)	64.1 (18)	113.1 (53)	157.8 (92)
P. australis	6-8 L	1	-2.0 (0.2)	0.3 (1.9)	100.2 (8)	41.1 (4)	83.6 (14)	126.7 (28)
		7	-1.7 (0.2)	-0.1 (1.9)	114.5 (9)	41.8 (4)	92.7 (18)	147.8 (36)
		14	-1.8 (0.3)	-0.1 (2.6)	125.8 (26)	61.0 (15)	133.4 (51)	210.9 (98)
	10-12 L	1	-1.8 (0.2)	0.1 (1.6)	104.5 (8)	43.8 (4)	94.2 (16)	147.4 (32)
		7	-1.6 (0.2)	-0.1 (1.8)	119.4 (11)	44.9 (6)	105.1 (23)	172.9 (47)
		14	-1.6 (0.3)	-0.3 (2.3)	141.4 (34)	71.5 (22)	167.7 (74)	276.3 (146)
S. halepense	2-4 L	1	-3.9 (1.8)	4.4 (4.0)	89.6 (9)	37.5 (3)	53.5 (11)	65.8 (20)
		7	-2.6 (0.8)	1.8 (3.6)	99.4 (14)	43.1 (5)	73.3 (20)	100.0 (36)
		14	-2.3 (0.6)	1.1 (2.9)	107.0 (16)	49.3 (7)	89.0 (24)	125.7 (44)
	6-8 L	1	-3.4 (1.2)	6.2 (3.8)	101.4 (10)	41.0 (3)	61.9 (12)	78.7 (22)
		7	-1.9 (0.2)	-0.1 (1.9)	96.2 (7)	36.7 (3)	74.4 (12)	113.5 (25)
		14	-1.9 (0.4)	-0.4 (2.6)	98.9 (15)	45.9 (9)	96.0 (31)	147.8 (60)
	10-12 L	1	-3.0 (1.0)	5.5 (3.9)	106.2 (13)	43.1 (3.8)	68.6 (16)	90.0 (28)
		7	-1.8 (0.2)	-0.2 (1.6)	102.4 (8)	39.9 (3.9)	88.1 (15)	140.0 (31)
		14	-1.9 (0.3)	-0.1 (2.1)	103.5 (13)	48.0 (6.9)	98.7 (24)	150.5 (47)

Figure 1 shows the effect of low and high levels of propane doses applied with the 2 m wide broadcast flamer in the walnut orchard in plots infested heavily with *S. halepense*. Increased dose from 30 to 90 kg ha^{-1} improved the control rate of *S. halepense* as seen with less green monocotyledon left in the flamed strip in Figure 1b compared to Figure 1a. The weeds at 10–12 L stage were barely affected at low propane dose, which can be seen in Figure 1a clearly. Some monocotyledons could not be killed properly, thus remaining greenish even after high level of propane dose application (Fig. 1b). On the other hand, 90 kg propane ha^{-1} showed improvement in weed killing when the plot was infested with a mixture of dicotyledon and monocotyledon weeds (Figure 1c).

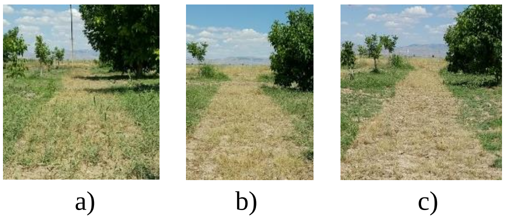

Figure 1. The response of weeds to flaming at 1 DAT in the walnut orchard: a) a plot heavily infested with *S. halepense* – applied dose of 30 kg ha^{-1}, b) a plot heavily infested with *S. halepense* – applied dose of 90 kg ha^{-1}, c) a plot infested with dicotyledon weeds and some monocotyledon weeds – applied dose of 90 kg ha^{-1}

Although low and medium level of doses were generally needed to control the dicotyledon weeds compared to monocotyledon weeds (*C. dactylon, P. australis* and *S. halepense*) at the same leaf growth stage, exceptions could be found in the results. The propane dose requirement of *S. alopecuroides* and *Echinophora* spp. were similar to the monocotyledon weeds more than dicotyledon weeds, resulting in higher dose requirements for a given control rate. As an example, *S. alopecuroides* and *Echinophora spp.* needed 104.1 and 96.01 kg ha^{-1}, and 87.5 and 77.3 kg ha^{-1}, respectively in 2015 and 2016 at 14 DAT, 80% control, and 6–8 L stage, while other three dicotyledon weeds needed a substantially low dose range of 50–61 kg ha^{-1}. The same weed control rate (80%) for monocotyledon weeds was achieved by applying gas doses from 90.9 to 133 kg ha^{-1} in both years.

Fifty percent control for monocotyledon weeds required propane doses from 32.4 to 73.7 kg ha^{-1} and 33.6 to 71.5 kg ha^{-1}, respectively in 2015 and 2016, depending on weed growth level. At 2–4 and 6–8 L stages, propane doses of 30–60 kg ha^{-1} were sufficient, whereas at 10–12 L stage the applied propane doses were much greater. However, there were distinct differences among the monocotyledon weed species. Maximum propane dose for *S. halepense* at 10–12 L stage and 14 DAT was about 50 kg ha^{-1} whereas maximum dose for *P. australis* was about 70–75 kg ha^{-1}, suggesting approximately 50% more dose application to achieve the same level of control. When data from 2015 and 2016 evaluated together for dicotyledon weeds, 50% control level was accomplished with doses from 17.0 to 60.4 kg ha^{-1}. Among the dicotyledon weeds, the minimum and maximum doses were needed for *C. arvensis* and *S. alopecuroides*, respectively with 17.0–41.5 kg ha^{-1} and 37.4–60.4 kg ha^{-1}, depending on leaf growth stage.

The weed control is expected to be at 90% level so that the control rate is considered efficient in chemical spraying applications for field crops production. When the effect of flaming was evaluated for dicotyledon specie, *C. arvensis*, *C. tinctoria*, *X. strumarium* and *L. serriola* were controlled at 14 DAT and 10-12 L stage with propane doses of 81.5, 74.8, 54.8 and 79.3 kg ha^{-1} in 2015 (Table 1) and 85.4, 78.5, 69.5 and 72.8 kg ha^{-1} in 2016 (Table 2). Thus, for a given weed specie, the dose level was similar in both years and it was possible to obtain 90% control with propane doses from about 55 to 85 kg ha^{-1} at 10–12 L stage. At 6–8 L stage, the doses were 86.2, 66.4, 63.3 and 69.4 kg ha^{-1} in 2015 and 64.7, 113.0, 70.6 and 69.2 kg ha^{-1} in 2016 for the same dicotyledon weeds, respectively.

The weeds develop resistance towards thermal stress as they grow and it becomes more difficult to control them, similar to the weed behavior in chemical spraying. For example, *C. arvensis* needed 44.4, 64.7 and 85.4 kg ha^{-1}, respectively for 2–4, 6–8 and 10–12 L stages for 90% control (Table 2). These findings are similar to the results of previous research (Knezevic and Ulloa 2007; Doninges *et al.* 2008). At a given control rate for a given weed specie, the need for propane dose increased with time after the treatments. For instance, *P. australis* needed 69.7, 98.4 and 127.7 kg ha^{-1}, respectively at 1, 7 and 14 DAT for 90% control rate (Table 1). Although exceptions might be found in the data, the explained trends were valid for all weeds and cases evaluated in the study. Therefore, weed response to flaming was affected by the weed specie, growth stages, and applied doses.

The efficiency in weed control usually rose sharply as the propane dose increased from 20 to 50 kg ha^{-1}. Small increments in applied propane dose resulted in significant rises in the control level. As a result, the propane dose needs to be increased significantly when the control rate needs to be increased. For a small increase in control rate, for instance from 80% to 90%, the increase in dose demand was substantial as seen in Tables 1–2. When 14 DAT is considered, the greatest applied propane dose (90 kg ha^{-1}) in the orchards was not sufficient to reach 90% control rate for most weeds.

It could be argued that some of the dicotyledon weeds present “monocotyledon like” behavior and could be almost as resistant as monocotyledon weeds to thermal stress. This behavior might be due to the strong root systems of these perennial weeds. It may be concluded that dicotyledon weeds are easier to control but exceptions exist that should be studied in agronomic fields and orchards to identify more resistant weed specie so that efficient control strategies could be developed to manage the dominant weed specie within a specific field.

Other researchers found propane doses of 40–51 kg ha^{-1} for dicotyledon weeds with 8 leaves and less, which were less compared to our study (Ulloa *et al.* 2010b). *S. alopecuroides* and *Echinophora* spp. behaved differently requiring greater doses compared to other dicotyledon weeds at 14 DAT with 175.5 and 144 kg ha^{-1}, and 157.1 and 121.1 kg ha^{-1}, respectively in 2015 and 2016 at 10–12 L stage. Damage from flaming was less in 7 and 14 days from the treatment, compared to 1 DAT because the weeds recovered from the thermal stress to varying degrees with time after the flaming. Despite this recovery from damage, the dicotyledon weeds could be controlled at 90% level at 7 and 14 DAT. However, it was not possible to obtain 90% control at 7 or 14 DAT for two of the three monocotyledon weeds (*P. australis* and *S. halepense*) even at the early growth stage (2–4 L) with the greatest propane dose (90 kg ha^{-1}) applied during the experiments. Ulloa *et al.* (2010a) found 90% reduction in dry weight of dicotyledon weeds with propane doses of 30–60 kg ha^{-1} at 3 L to 14 L stages, confirming that relatively low levels of propane doses are sufficient to kill dicotyledon weeds (Ulloa *et al.* 2010b).

Particularly, the monocotyledon weeds have the ability to recover from thermal stress and start re-growing after the flaming application since they have disguised meristems (Ulloa et al. 2010b). *C. dactlyon* could be controlled at 90% with a propane dose of 85.2 kg ha^{-1}. Therefore, assuming 90% weed control is targeted, the required doses for effective weed control will be high for 7 or 14 DAT for monocotyledon weeds. At 7 DAT, the propane dose ranged from 91.3 to 172.9 kg ha^{-1} whereas at 14 DAT the range was from 125.7 to 276.3 kg ha^{-1}. Knezevic and Ulloa (2007) found that 182 and 153 kg ha^{-1} propane dose was needed to obtain 90% control in barnyard grass (*E. crus-galli*) and green foxtail (*Setaria* spp.), respectively (Knezevic and Ulloa, 2007). Other research also suggests doses up to 150–355 kg ha^{-1} under undesired terrain and application conditions (Kristoffersen *et al.* 2008). It was explained that 80% dry weight reduction was possible in barnyard grass at 4 to 7 L compared to 90% reduction in broadleaf weed species using the same propane dose (Ulloa *et al.* 2010b). A propane dose of 80 kg ha^{-1} could kill all weeds provided that flaming is done repeatedly (10 treatments) in a growing season (Rask *et al.*, 2012). It was also noted that six applications in a season with a total dose of 631–674 kg ha^{-1} could reduce dry weight of *L. perenne* by 90%. This finding suggests that repeated treatments may be necessary to control some of the weeds that are very difficult to control.

Due to difficulties in obtaining 90% weed control in organic production practices, 80% control could be considered acceptable (Knezevic and Ulloa 2007). If 80% control is targeted for organic production, applied propane dose can be reduced profoundly, compared to conventional production that aims a control rate of 90%. A monocotyledon weed, *S. halepense*, required 92.5, 90.9 and 102.1 kg ha^{-1} for 2–4, 6–8 and 10–12 L stages in 2015 for 80% control whereas the propane doses for 90% control were 132.4, 142.2 and 149.8 kg ha^{-1}, suggesting approximately 50% reduction in propane use. The saving in propane consumption was similar for *S. halepense* in 2016, too. Dicotyledon weed *C. tinctoria* needed propane doses of 32.0, 58.0 and 63.0 kg ha^{-1} for 80% control at 2–4, 6–8 and 10–12 L, respectively compared to 40.5, 70.6 and 78.5 kg ha^{-1} at 90% weed control rate. Thus, the fuel use was approximately 20% less in 80% control rate. *S. alopecuroides* and *Echinophora* spp., while requiring greater doses compared to other dicotyledon weeds, also suggested an approximate range of 15–30% propane dose reductions for 80% control level compared to traditional target of 90% weed control. Since weed flaming attracts more attention for organic production of agricultural products, 80% control rate would be preferred by the producers, which should reduce the propane use substantially compared to 90% control rate.

The propane dose requirements of *S. alopecuroides*, *C. tinctoria*, *X. strumarium*, *L. serriola*, *Echinophora spp.*, *C. dactylon*, *P. australis* and *S. halepense* were found, which, were not generally reported in the literature previously. The propane dose requirement behavior of *C. arvensis* was similar to the findings in literature (Knezevic *et al*. 2007). Therefore, it was not likely to compare all our findings to other published research. In this study, the flaming was used at a pressure of 0.20 MPa with burner angle of 30º. The pressure could not be increased because of the technical characteristics of the gas nozzles used in the burners, i.e. domestic low pressure gas nozzles were used to develop the weed flamer to conduct the field tests. Decreasing the pressure level resulted in insufficient flame length and width. Due to the restrictions in the flame length and width, the calibration of the flamer was done at a single pressure setting by varying the forward speed of the tractor. At low doses, i.e. high ground speeds, the heat exposure time gets shorter compared to lower ground speed flame applications.

Cost of flaming and comparison to spraying

Table 3 summarizes simple statistics of propane doses needed to accomplish 80% and 90% weed control at different growth stages, referring to the combined data of the two-year experiments. The ranges of gas doses for the weed growth stages of 2-4, 6-8, and 10-12 L were 37.6-110.5, 56.3-152.0, and 67.1-174.1 kg ha^{-1}, respectively, depending on the weed types and the targeted weed control rate.

Table 3. Some statistics of monocotyledon weeds and dicotyledon weeds on gas doses (kg ha^{-1}) needed for 80% and 90% control at different growth stages.

		%80		**90%**	
Growth stage	**Statistical value**	**Monocotyledon weeds**	**Dicotyledon weeds**	**Monocotyledon weeds**	**Dicotyledon weeds**
2-4 Leaf	Average	77.9	37.6	110.5	42.5
	Min	46.3	30.3	65.7	28.1
	Max	119.5	49.8	158.5	61.7
	Std. Dev	33.8	10.6	51.7	14.1
6-8 Leaf	Average	104.4	56.3	152.0	72.3
	Min	86.7	53.5	113.2	68.5
	Max	115.3	58.7	178.8	77.6
	Std. Dev	32.9	20.5	49.1	26.5
10-12 Leaf	Average	116.9	67.1	174.1	75.0
	Min	95.6	54.7	132.6	64.0
	Max	134.9	90.5	247.9	83.5
	Std. Dev	16.1	16.0	48.8	8.1

The propane costs per ha were given in Table 4. Both dicotyledon and monocotyledon weeds at different growth stages may be found in a given field and the gas dose may be dictated by specific weed species. The overall averages of herbicide application costs for 80% and 90% control rate were also shown in Table 4.

Table 4. Flaming costs per unit area ($ ha^{-1}) at different weed growth stages for %80 and %90 control for monocotyledon and dicotyledon weeds.

	80%		**90%**	
Growth stage	**Monocotyledon weeds**	**Dicotyledon weeds**	**Monocotyledon weeds**	**Dicotyledon weeds**
2-4 leaf	63.3	30.6	89.7	34.4
6-8 leaf	84.7	45.6	123.3	58.6
10-12 leaf	94.7	54.4	141.1	60.8
Average	80.8	43.6	118.1	51.4
Overall average	62.2		84.7	

The growth stage of weeds and the targeted control rate had effect on flaming costs (Table 4). The flaming cost was 63.3 \$ ha^{-1} to control 80% of monocotyledon weeds at an early weed growth stage (2-4 L) while the cost increased to 94.7 \$ ha^{-1} at 10-12 Leaf stage. Similarly, when 90% control rate was targeted, in case of dicotyledon weeds for instance, the application cost increased from 45.6 to 58.6 \$ ha^{-1} for 6-8 L stage, suggesting at least 20% increased cost compared to 2-4 L stage.

Table 4 reveals that flaming cost for 80% control was 29.5, 31.3, and 32.9% less, respectively for 2-4, 6-8, and 10-12 L stages compared to 90% control for monocotyledon weeds whereas the cost savings were 11.5%, 22.1%, and 10.6% for dicotyledon weeds, respectively. When higher control rate (90%) was considered, the flaming application cost of monocotyledon weeds and dicotyledon weeds would be approximately 30% and 11% more compared to 80% control.

Cost ratios of flaming among different growth stages (2-4/6-8, 2-4/10-12, and 6-8/10-12 L) show the importance of early flaming during the weed growth (Table 5). For instance, cost ratio of 2-4/6-8 L was 0.75 for monocotyledon weeds for 80% control rate, demonstrating 25% less application cost when flaming was done at 2-4 L stage compared with 6-8 L. Compared to 10-12 L, flaming at 2-4 L stage significantly decreased the costs with ratios from 0.56 to 0.67 depending on the weed type and control rate, suggesting 33 to 44% reduction in gas dose requirement.

Table 5. Cost rates among weed growth stages at different control percentages.

	80% control		**90% control**	
Growth stage/growth stage	**Monocotyledon weeds**	**Dicotyledon weeds**	**Monocotyledon weeds**	**Dicotyledon weeds**
2-4/6-8 leaf	0.75	0.67	0.73	0.59
2-4/10-12 leaf	0.67	0.56	0.63	0.57
6-8/10-12 leaf	0.89	0.84	0.87	0.96

As a result, the calculated savings were greater for dicotyledon weeds both at 80% and 90% control rates when 2-4 L stage was compared to 6-8 L and 10-12 L stages, with a range of 25% to 44%. On the other hand, the savings in flaming applications was lower with a range from 4% to 16% when 6-8 L was compared to 10-12 L. These findings showed that earliest stage possible should be targeted for weed control during flaming.

The unit price of propane is independent of the amount of gas purchased for flaming purposes. However, the herbicide cost varies depending on the brand and volume purchased for chemical application. Herbicide cost varies from 5.0 \$ L^{-1} to 9.72 \$ L^{-1} currently in Turkey. The application rates of 300 mL da^{-1} and 600 mL da^{-1} are recommended for annual and perennial weeds by the herbicide producers. The herbicide application dose was chosen to be 6 L ha^{-1} and the total herbicide costs were calculated (Table 6).

The cost of chemical application for weed control varied from 15.0 \$ ha^{-1} to 58.3 \$ ha^{-1} depending on herbicide unit price and weed specie. Table 4 showed that flaming costs for 80% and 90% control for dicotyledon weeds were 30.6-54.4 \$ ha^{-1} and 34.4-60.8 \$ ha^{-1}, respectively.

Table 6. Herbicide application costs per unit area for annual and perennial weeds (\$ ha^{-1}).

	Herbicide cost per unit volume	
Weed type	**9.72 \$ L^{-1}**	**5.0 \$ L^{-1}**
Annual	29.2	15.0
Perennial	58.3	30.0
Average	43.8	22.5

It was determined that flaming was not comparable to low cost herbicide application. On the other hand, flaming was found to be comparable to high cost herbicide applications for dicotyledon weeds. However, the application strategy will be based on monocotyledon weeds in a field in the presence of a mixture of both monocotyledon and dicotyledon weeds. It may be suggested that flaming can be an alternative method to chemical application only if the herbicide costs are relatively high in the market.

The cost evaluations were made using required propane gas doses and herbicide application rates and partially present the costs in weed control. Herbicide application would be done by using sprayers wider than 2.0

m swath width since the spacing between the rows of trees could be 6 to 10 m in orchards. Therefore, the effective capacity of a sprayer would be at least 2.5 ha h^{-1} even with a small field sprayer whereas the area that can be flamed would be one third of this area even under the maximum ground speed at the minimum propane gas dose to be applied. Consequently, the fuel costs of the tractor itself would be about threefold compared with chemical spraying for weed control.

CONCLUSIONS

Monocotyledon weeds were generally more resistant to heat stress caused by the flaming, resulting in more dose demand compared to dicotyledon weeds. However, there were large differences in the gas doses that had to be applied for the same level of control among the monocotyledon weeds. The propane dose needed for 90% control at 14 DAT for *C. dactylon*, *P. australis* and *S. halepense* were 190.6, 219.7, and 149.8 kg ha^{-1} in the year 2015 and 157.8, 276.3 and 150.5 kg ha^{-1} in 2016, respectively. The propane dose had to be greater than 120 kg ha^{-1} for all monocotyledon weeds for 90% control at 2–4 L stage. It was concluded that the dose may be reduced at early weed growth stages but the amount of propane gas use will still be substantial for monocotyledon weeds compared to dicotyledon weeds. Choosing 80% control compared to 90% resulted in approximately 50% and 20% less gas use, respectively for a dicotyledonweed (*C. tinctoria*) and a monocotyledon weed (*S. halepense*) at 10–12 L. Gas dose requirement reduced significantly at 2-4 L stages of the weeds compared to 6-8 L and 10-12 L stages. For a target of 90% weed control rate, the cost of flaming application at 2-4 L stage was 27% and 41% less, compared to 6-7 L stage of monocotyledon weeds and dicotyledon weeds, respectively. The cost of flaming application for monocotyledon weeds and dicotyledon weeds for 90% control would be approximately 30% and 11% more compared to 80% weed control rate.

It was concluded that flaming was comparable to high cost herbicide applications for dicotyledon weeds, but not for monocotyledon weeds under the current market prices. Based on the results of this study, it may be suggested that, technically, weed flaming was an efficient weed control method since 90% of the weeds could be controlled using this method. The required gas dose depended on the weed type (monocotyledon/dicotyledon), the growth stage of the weeds, the targeted weed-free days after treatment, and the control rate of weeds. In terms of cost effectiveness, it was found that flaming could be used as an alternative weed control method for dicotyledon weeds at early stages under the current market prices for the herbicides and propane.

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