Spanish Journal of Agricultural Research
15(2), e0203, 10 pages (2017)
eISSN: 2171-9292
https://doi.org/10.5424/sjar/2017152-10668
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)

RESEARCH ARTICLE

OPEN ACCESS

A combined flamer-cultivator for weed control during the harvesting season of asparagus green spears

Luisa Martelloni, Marco Fontanelli, Christian Frasconi, Michele Raffaelli, Michel Pirchio and Andrea Peruzzi
University of Pisa. Dept. Agriculture, Food and Environment (DAFE). Via del Borghetto, 80. 56124 Pisa, Italy

Abstract

Weed competition during spears harvesting reduces asparagus yields. The application of herbicides during this period is illegal, and alternative non-chemical practices are needed. This research tested the effectiveness and efficiency of a custom-built combined flamer-cultivator to control weeds (both in the inter- and intra- spears production bands) during the spears harvest season. It also analysed the effects of various liquefied petroleum gas (LPG) doses on total asparagus yield, mean spear weight, and total number of marketable spears. In both years, the asparagus spears were generally not damaged by flame weeding using LPG doses of between 43 to 87 kg/ha. The same LPG doses were effective in controlling weeds, showing the same total marketable yields as the weed-free control. At high LPG doses (*e.g.* 130 and 260 kg/ha), yields decreased as a consequence of the damage caused to the spears, resulting in a lower number of marketable spears. Flaming did not affect the mean spear weight, and can be applied repeatedly during harvesting to maintain the weeds at a level that does not lead to a yield reduction. The repeated use of the combined flamer-cultivator (every seven days) led to higher yields than plots where weed control was not conducted. The new machine can be used in a period when herbicides are not possible. Flaming could be introduced by asparagus producers as an alternative, or in addition to herbicides applied in the pre-emergence and post-harvest of spears.

Additional key words: *Asparagus officinalis* L.; flaming; heat-tolerance; non-chemical; organic farming

Abbreviations used: CI (Confidence Interval); LPG (Liquefied Petroleum Gas)

Authors' contributions: Conceived and designed the experiments: AP, CF, LM and MR. Performed the experiments: LM, MF, CF and AP. Contributed reagents/materials/analysis tools: LM, CF, AP and MP. Analyzed the data and wrote the paper: LM.

Citation: Martelloni, L.; Fontanelli, M.; Frasconi, C.; Raffaelli, M.; Pirchio, M.; Peruzzi, A. (2017). A combined flamer-cultivator for weed control during the harvesting season of asparagus green spears. Spanish Journal of Agricultural Research, Volume 15, Issue 2, e0203. https://doi.org/10.5424/sjar/2017152-10668

Received: 25 Oct 2016 **Accepted:** 27 Apr 2017

Funding: Centro di Ricerche Agro-Ambientali "E. Avanzi" − University of Pisa

Competing interests: The authors have declared that no competing interests exist. Authors have total access to the data and are responsible for the integrity and accuracy of their analysis.

Correspondence should be addressed to Luisa Martelloni: lmartelloni@agr.unipi.it

Introduction

Asparagus (*Asparagus officinalis* L.) is a perennial high-income horticultural crop that is grown in monoculture. The production of green spears in Italy is usually entirely intended for the fresh market (Falavigna *et al*., 2012).

An effective weed management is essential to promote the healthy growth of the spears and a satisfactory yield and quality (Neeson, 2004). Welker & Brogdon (1972) found that weed competition during the harvesting season seriously reduced asparagus yields. In addition, weeds present during the harvesting season not only reduce the yield for the current season by limiting the availability of water and nutrients, but also restrict the replenishment of carbohydrate reserves in the asparagus plant for the next season's growth (Welker & Brogdon, 1972). Most of the weed flush usually coincides with the beginning of the harvesting season, and the subsequent emergence of weeds continues well into the summer, which makes the selective control of weeds not only difficult but also expensive (Rahman & Sanders, 1996).

Because asparagus is a poor competitor with weeds, it is of prime importance to avoid planting in fields where aggressive perennial weeds have a history of problematical management (Kaiser & Ernst, 2012).

Herbicides are commonly used in commercial asparagus production to increase yields by reducing unwanted plants that compete for space, water and nutrients (Rodríguez-Salamanca *et al.,* 2012). Usually herbicides are applied in the pre-emergence and post-harvest of the spears, because they cannot be used during spear harvesting (Rahman & Sanders, 1996; Pedreros *et al.*, 2002; Araki & Tamura, 2008; Rodríguez-Salamanca *et al.*, 2012; Zandstra *et al.*, 2013). It is recommended that the herbicides (belonging to different chemical families) used in the weed control program should be rotated in order to slow down the shift in weed composition and limit the development of herbicide resistance (Rahman & Sanders, 1996).

Avoiding herbicide applications, and growing asparagus organically, adds further value to this already high-value vegetable crop (Kaiser & Ernst, 2012). Cultivation, mowing, death or living mulch are the weed practices used between the production bands of asparagus organic management. Cultivation within the spear bands during fern production is not possible. Composted wood chips, weed-free hay or straw, or sawdust can be used as a mulch aid in weed suppression within bands. Once mulch has been applied, weeds within bands need to be removed by hand because machine cultivation is not possible (Kaiser & Ernst, 2012). Araki & Tamura (2008) attempted to control weeds with barley living mulch and found a reduction in weeds, but data on spear yields were not reported. Paine *et al*. (1995) found that living mulches were highly effective in weed suppression but also quite competitive with crops, reducing asparagus growth by 50-75%. Ngouajio *et al*. (2014) also found that living mulch can seriously reduce the total yield caused by the competition between cover crop and asparagus.

To the best of our knowledge, no research on weed control within the production bands during the harvesting of the spears has been conducted using thermal means. The aim of this work was to test the effectiveness and efficiency of a custom built combined flamer-cultivator to control weeds (both in the inter- and intra-production bands) during spears harvest season. In addition we analysed the effects of different liquefied petroleum gas (LPG) doses on total asparagus yield, mean spear weight, and total number of marketable spears.

Material and methods

The combined flamer-cultivator machine

The combined flamer-cultivator was designed and built at the University of Pisa by combining a flamer with S-shaped leaf spring tines and two crumbler baskets (Fig. 1). The machine was designed to conduct non-selective mechanical weed control between the production bands, and flame weeding within the bands.

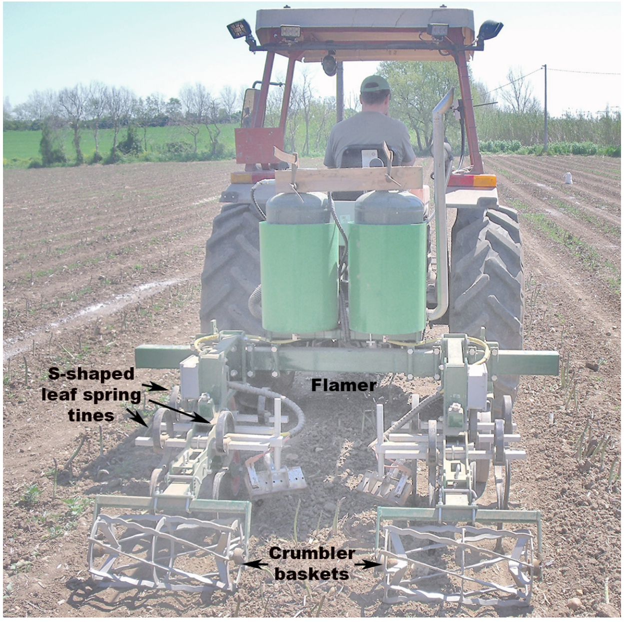

Figure 1. The combined flamer-cultivator conducting weed control in the inter- and intra-bands of asparagus green spears.

Flame weeding is applied by a pair of LPG fed burners, and controls the weeds without damaging emerging spears or crowns, by avoiding tillage.

A steel 1.80 m width frame supports two LPG tanks, each feeding a burner, and two articulated parallelograms. The machine treats one crop band and two inter-bands in one pass. The LPG tanks are inserted into hoppers containing water heated by the exhaust gases from the engine. Each articulated parallelogram is provided with an 0.25 cm wide open flame rod burner, a 0.50 cm wide crumbler basket and four S-shaped leaf spring tines (Fig. 2). The tines control the weeds within the inter bands.

The pair of burners generates a flame which controls weeds in a 0.30 m wide strip where the asparagus spears

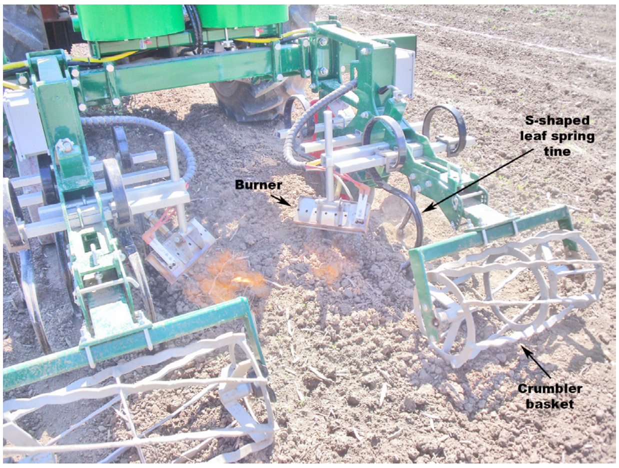

Figure 2. The articulated parallelograms equipped with burners, crumbler baskets and the S-shaped leaf spring tines.

grow (Fig. 1). Burners are placed "cross" to the band where the spears grow. The flame acts directly at the base of the spears. This typology of flaming application is called "cross-flaming" (Martelloni *et al*., 2016a,b). Burners were angled at 45° from the perpendicular to the ground and at 30° from the parallel to the crop row. They were positioned 12 cm above the soil surface. Five LPG doses (43, 52, 87, 130 and 260 kg/ha of flamed surface) were applied combining the working pressures of 0.3 MPa with five forward speeds (1, 2, 3, 5 and 6 km/h). The LPG doses were calculated as intra-band biological doses. The actual doses, computed on the full width of the machine, were lower than the biological doses (10, 12, 19, 29 and 58 kg/ha of flamed plus unflamed surface, respectively).

The ignition system of the machine is different from the one previously used by Fontanelli *et al*. (2013; 2015a,b), Raffaelli *et al*. (2013 and 2015), Frasconi *et al*., (2016), and Martelloni *et al*. (2016a,b). The ignition system mounted on this machine is almost instantaneous. In fact a bipolar electrode is mounted on the burner, which guarantees a constant electric arc within the burner. The electric arc generates an active flame capable of controlling weeds 0.39 s after the activation of the transformers (Cofi® TRL 12-30C) and the opening of the normally closed electro-valve (Madas® EV6 DN15), which controls the gas flow. Two transformers convert the voltage value of 12V (DC that comes from the electrical outlet of the tractor) into 12 kV (high voltage AC). The power of each transformer (80 W) maintains the electric arc between the two poles of the electrode in the burner, which ignites the LPG/air mixture also at high LPG pressures. Thus, burners can be switched off while the tractor is turning. The almost instantaneous ignition system avoids the use of the pilot flame which is always switched on, and which could cause accidental fires, due to the presence of flammable plant material on the field headland and when the tractor is turning. Each burner contains a K thermocouple, which checks for the presence of the flame and sends a signal to a controller (Pixsys electronics®, ATR 121-141). If the flame accidentally goes out, the electro-valve that controls the gas flow is closed.

Thermal hazards for tractor driver and field operators have to be avoided by adopting preventive measures. The tractor driver and/or other field operators must be qualified person having understood the function of each component of the machine. The hazard of an uncontrolled efflux of the gas is avoided with the presence of the normally closed solenoid electro-valves. The accidental shut down of the flame is avoided by the thermocouple that monitoring the presence of the flame. The electrical system is equipped with fuses to avoid damages caused by short circuit. The functionality of the electrical devices (valves, transformers and electrodes), such us the proper connection of the LPG tanks and the integrity of the LPG feeding system, must be controlled before each use. The contact with the mechanical tools, the flame, the bipolar electrodes and/or burners at high temperature have to be avoided during functioning, and a safety distance of 2 m from the machine must be respected during operation. It is required a person in charge of machine maintenance so as to perform periodic tasks or vehicle inspection. After every 25 h of functioning it is recommended to check accurately the LPG feeding system to verify that there are no leaks. After every 150 h of functioning it is recommended to check and lubricate the mechanical parts of the machine.

Experimental set up, design and treatments

Field experiments were conducted in the 2014 and 2015 asparagus spears harvest seasons at a farm located in Montalto di Castro (+42.32°N +11.60°E), close to Viterbo, in central Italy. The planting of asparagus was established from crowns in 2010. The all-male "Italo" hybrid was used. This hybrid was derived from the Italian breeding programme (Falavigna *et al*., 2012). Crowns were planted at a depth of 0.20 m. The soil, based on the USDA soil classification system, was sandy loam (70% sand, 18% clay, and 12% silt) with 3% organic matter. The spear production band spacing was 0.30 m, and the space between the production bands was 1.05 m. The harvesting season started during the second week of April and stopped at the end of May in both years. The crop water requirement was 150 mm of water for the whole harvesting season and was provided by sub-irrigation. Sub-fertilization was provided by 150 kg actual nitrogen (N), 50 kg actual phosphorus (P) and 50 kg actual potassium (K) per hectare and per year. Weed control was conducted using the combined flamer-cultivator both in the inter- and intra-production bands. No herbicides were applied during the experiment.

The experimental design was a randomized complete-block design with three replications. The size of each plot was 13.5 m^2 (1.35 m × 10 m). Treatments were represented by the application of different LPG flaming doses (43, 52, 87, 130 and 260 kg/ha), plus a weedy and a weed-free control (kept free from weeds by manual weeding throughout the harvesting period). All treatments were repeated every seven days during the harvesting period.

Data collection

Daily yield and number of marketable spears were collected during the harvesting season. The total yield and the total number of spears in the marketable yield were then calculated. Spears were cut at the soil surface once a day, and sorted as marketable (> 7 mm diameter). Spears were manually harvested with a long-handled knife from the second week of April through to the end of May. The harvest was finished as soon as a distinct yield decrease started. The harvesting area consisted of the production band (0.30 m × 10 m of the central area of the plot). Weed density was counted three times starting from the beginning of the harvesting season at a distance of 15-days in a 0.075 m^2 (0.25 m × 0.30 m) area in three randomly-selected sampling points within each plot.

Statistical analysis

All data were analysed separately for each year. The test of normality was performed using the Shapiro-Wilk normality test (Royston, 1995). Total yield and mean spear weight were modelled in a linear mixed model using the extension package *lmerTest* (Kuznetsova *et al*., 2014) of R statistical software (R Core Team, 2013). All count data (total number of unmarketable asparagus spears and weed density) followed a Poisson distribution, and thus were modelled in a generalized linear mixed model using *lmerTest*.

To test the effect of dose on the basis of total yield, the mean spear weight, total number of spears in the marketable yield and weed density were analysed for significance by computing the mixed ANOVA. For the generalized linear mixed models, the extension package *afex* (Analysis of Factorial Experiments) (Singmann *et al.,* 2016) of R was used to compute the ANOVA *p*-values.

The extension package *lsmeans* (Least-squares means) (Russell & Hervé, 2015) of R was used to compute the least squares means and standard errors of dependent variables, and inverse-transformed values of log-transformed data in the generalized mixed model. The comparisons between least squares means were computed considering the 95% confidence interval of the difference between the means of the two groups. If the resulting 95% confidence interval (CI) of the difference between means did not cross the value 0, the null hypothesis that compared means were equal was rejected. The confidence interval for the difference between two group means was computed using Eq. [1] (Knezevic, 2008):

$$CI\ (\text{difference}) = (x_1 - x_2) \pm 1.96\sqrt{\left(SE_{x_1}\right)^2 + \left(SE_{x_2}\right)^2} \quad [1]$$

where *CI* is the confidence interval for the difference, x_1 is the value of the first least squares mean, x_2 is the value

Table 1. Estimated least squares means of total marketable yield and mean spear weight in the marketable yield as affected by LPG dose, in 2014 and 2015, respectively.

LPG dose (kg/ha)	Lsmean (±SE)[a]	
	Total yield (kg/ha)	Mean spear weight (g)
2014		
0 (weedy)	7382 (179.9)	33.9 (1.54)
0 (weed-free)	9248 (179.9)	33.4 (1.54)
43	9346 (179.9)	36.0 (1.54)
52	8808 (179.9)	32.3 (1.54)
87	9046 (179.9)	34.5 (1.54)
130	8052 (179.9)	33.0 (1.54)
260	7923 (179.9)	31.0 (1.54)
2015		
0 (weedy)	8633 (134.5)	28.4 (1.49)
0 (weed-free)	10097 (134.5)	26.2 (1.49)
43	9745 (134.5)	25.9 (1.49)
52	10272 (134.5)	25.6 (1.49)
87	9821 (134.5)	25.2 (1.49)
130	9910 (134.5)	26.4 (1.49)
260	9147 (134.5)	24.4 (1.49)

[a]Least squares means and standard errors (SEs) were estimated with the *lsmeans* function of the extension package *lsmeans* (Least-squares means) (Russell & Hervé, 2015) of R (R Core Team, 2013).

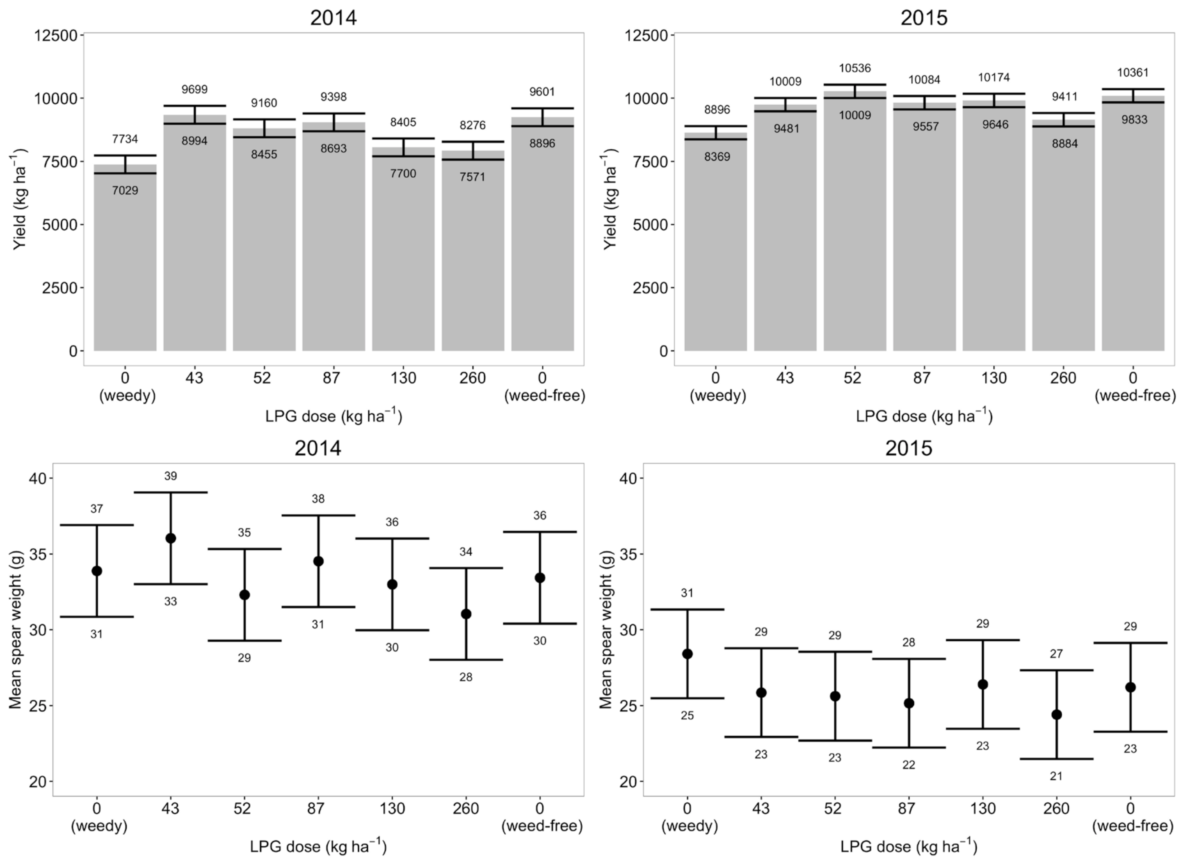

Figure 3. Least squares means and 95% confidence interval bars of total marketable yield (kg/ha) and mean spear weight (g) in 2014 and 2015, respectively.

of the second least squares mean, *SE* is the standard error of x_1 and x_2, respectively, and 1.96 is the critical t-value.

All plots of least squares means and 95% confidence interval bars were graphed using the extension package *ggplot2* (An Implementation of the Grammar of Graphics) (Wickham & Chang, 2016) of R.

Results

The asparagus spears were generally not damaged by flame weeding using LPG doses of between 43 to 87 kg/ha in both years. The same LPG doses were efficient in controlling weeds, showing the same total marketable yields of the weed-free control. The combined flamer-cultivator was suitable for controlling weeds both in the inter-band and in the production spear bands. Mechanical tools (S-shaped leaf spring tines and crumbler baskets), operating in the non-productive inter-bands, maintained 100% weed control throughout the harvesting season, in both years.

Analysis of variance showed the significance of the LPG dose on yield (p=8.4 · 10^{-6} and 7.35 · 10^{-6} in 2014 and 2015, respectively). Least squares means of total annual marketable yields are reported in Table 1. In 2014, when the LPG doses applied were between 43 to 87 kg/ha, the total annual yields were similar to findings in weed-free plots. Yields with LPG doses of 43, 52 and 87 kg/ha were similar, and higher compared with doses of 130 and 260 kg/ha. The yield in weedy plots was lower than the yield when a dose of 260 kg/ha was applied (Fig. 3). In 2015, also with the LPG dose of 130 kg/ha the yield was similar to that observed in the weed-free plots. Using the dose of 260 kg/ha the total yield was lower than the other doses, but higher than the weedy control (Fig. 3). The mean spear weight in the marketable yield was not affected by the dose (p=0.2 and p=0.4 in 2014 and 2015, respectively), suggesting that the flaming did not influence the size of the marketable spears. Least squares means of the mean weight of a spear in the marketable yield are reported in Table 1 and plotted in Fig. 3.

The total number of marketable spears was affected by the LPG dose (p<0.0001 in both years). Least squares means of the total number of marketable spears and comparisons between the weed-free control and other LPG doses are reported in Table 2 and plotted in

Table 2. Estimated least squares means (log-transformed) and inverse-transformed values of total number of marketable spears per hectare as affected by LPG dose, and comparisons between the weed-free control and all the other LPG doses, in 2014 and 2015, respectively.

LPG dose (kg/ha)	Lsmean (±SE)[a] No./ha	Inverse-transformed mean (±SE) [b] No./ha	95% confidence interval for the difference			
			Comparison between doses (kg/ha)	Estimate	Lower CI	Upper CI
2014						
0 (weedy)	12.25 (0.02)	209624 (5014)	0 (weed-free) - 0 (weedy)	0.25	0.18	0.32
0 (weed-free)	12.50 (0.02)	269421 (6442)	0 (weed-free) - 43	-0.01	-0.07	0.06
43	12.41 (0.02)	271370 (6488)	0 (weed-free) - 52	0.00	-0.06	0.07
52	12.50 (0.02)	268656 (6423)	0 (weed-free) - 87	0.02	-0.04	0.09
87	12.48 (0.02)	263476 (6300)	0 (weed-free) - 130	0.11	0.05	0.18
130	12.39 (0.02)	240779 (5758)	0 (weed-free) - 260	0.10	0.03	0.16
260	12.41 (0.02)	244973 (5858)				
2015						
0 (weedy)	12.67 (0.02)	318394 (7813)	0 (weed-free) - 0 (weedy)	0.27	0.20	0.34
0 (weed-free)	12.94 (0.02)	416171 (10210)	0 (weed-free) - 43	0.03	-0.04	0.10
43	12.91 (0.02)	404700 (9929)	0 (weed-free) - 52	0.01	-0.06	0.08
52	12.93 (0.02)	411730 (10101)	0 (weed-free) - 87	0.02	-0.05	0.09
87	12.92 (0.02)	407783 (10005)	0 (weed-free) - 130	0.01	-0.06	0.08
130	12.93 (0.02)	411483 (10095)	0 (weed-free) - 260	0.13	0.06	0.19
260	12.81 (0.02)	367079 (9007)				

[a]Least squares means and standard errors (SEs) were estimated as indicated in Table 1. [b]Inverse transform means and SEs were estimated with the *ref.grid* function of the extension package *lsmeans* (Least-squares means) (Russell & Hervé, 2015) of R (R Core Team, 2013).

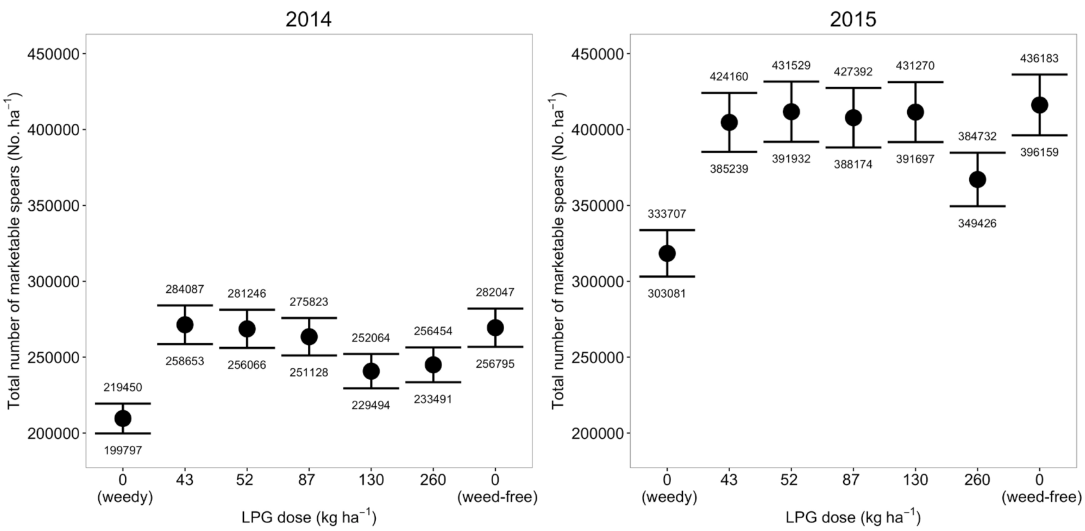

Figure 4. Least squares means and 95% confidence interval bars of total number of marketable spears per hectare in 2014 and 2015, respectively.

Fig. 4. Comparisons showed that in 2014, the number of marketable spears in the weed-free plots was similar to that observed when LPG doses of between 43 to 87 kg/ha were used. In 2015, the dose of 130 kg/ha also led to a similar number of marketable spears to that of the weed-free control. In 2015, the dose of 260 kg/ha resulted in a lower number of marketable spears than the other doses, whereas in 2014 both the doses of 130 and 260 kg/ha led to a lower number of marketable spears.

Weed composition was constituted mainly by *Chenopodium album* (L.), *Solanum nigrum* (L.), *Anagal-*

lis arvensis (L.), *Sonchus oleraceus* (L.), *Amaranthus retroflexus* (L.) and *Crepis biennis* (L.) throughout the harvesting season in both years.

The weed density collected during the spears harvest season in the production bands was affected by the dose ($p≤0.0001$), the date of sampling ($p≤0.0001$), and their interaction ($p≤0.0001$), both in 2014 and 2015. Least squares means of weed density are reported in Table 3. Inverse-transformed least squares means and 95% confidence intervals bars are graphed in Fig. 5. In 2014, the weed density of the non-flamed control was significantly higher than the weed density in the flamed plots. Weed density decreased by increasing the LPG dose, except for 16/05/2014 when the dose of 87 kg/ha controlled the same number of weeds as the dose of 52 kg/ha. In 2015 the weed density was generally lower than in 2014 in all plots. When flame weeding was conducted, the weed density observed was significantly lower than the non-flamed control. The LPG doses of 260 and 130 kg/ha controlled a higher number of weed plants compared with the doses of 87, 52 and 43 kg/ha, which instead had the same weed reduction effect (Fig. 5). On 22/04/2015 and 27/05/2015, the LPG dose of 260 kg/haled to a higher level of weed control compared with the dose of 130 kg/ha (95% CIs: -0.72; -0.04 and -0.86; -0.18, respectively). Throughout the entire harvesting period, the use of the combined flamer-cultivator allow maintained the weeds emerging in all plots at early growth stages, with the observed plants showing a maximum 5-leaf growth stage irrespective of the species.

Discussion

The asparagus spears were heat-tolerant up to the LPG dose level of 87 kg/ha in both years. This seems to indicate that flame weeding is an efficient tool to control weeds within the production spears band during the harvest season. The combined flamer-cultivator was able to control weeds effectively in a period of time when the high presence of weeds can determine a decrease in yield. The critical period of weed competition in asparagus is six or more weeks in the spring/early summer. Weed competition during this period reduces the fern growth and spear yield significantly (Rahman & Sanders, 1996). Flame weeding can be applied repeatedly during this period to maintain the weed presence at a level that does not lead to yield reduction. The repeated use of the combined flamer-cultivator led to higher yields than those measured when weed control was not conducted during the spears harvesting period.

The reduction in yields compared with the weed-free control, when doses higher than 87 and 130 kg/ha were used respectively in 2014 and 2015, was caused by damage to the spears, which made them unmarketable. Flaming at all doses, indeed, did not lead a reduction in the size of the treated spears. Thus, total yields were influenced by the number of marketable spears. This suggests that when the highest LPG doses were used (130 and 260 kg/ha in 2014, and 260 kg/ha in 2015), some spears were damaged and became unmarketable, leading to a significant decrease in yields, although their use also obtained the highest weed control. However,

Table 3. Estimated least squares means (log-transformed) of weed density (plants/m^2) as affected by the LPG dose, and collected on different dates within the production bands during the spears harvest season in 2014 and 2015, respectively.

LPG dose (kg/ha)	Lsmean (±SE)[a]		
	Date of sampling		
2014	**16/04/2014**	**30/04/2014**	**16/05/2014**
0 (weedy)	6.28 (0.02)	6.23 (0.02)	6.25 (0.02)
43	5.60 (0.02)	5.71 (0.02)	5.63 (0.02)
52	5.52 (0.02)	5.59 (0.02)	5.53 (0.02)
87	5.10 (0.03)	5.38 (0.02)	5.52 (0.02)
130	4.91 (0.03)	5.27 (0.02)	4.73 (0.03)
260	4.10 (0.04)	4.36 (0.04)	3.43 (0.06)
2015	**22/04/2015**	**06/05/2015**	**27/05/2015**
0 (weedy)	5.59 (0.11)	5.43 (0.11)	5.35 (0.11)
43	4.67 (0.11)	4.80 (0.11)	4.61 (0.13)
52	4.65 (0.11)	4.65 (0.11)	4.52 (0.12)
87	4.45 (0.11)	4.57 (0.11)	4.47 (0.11)
130	3.78 (0.12)	3.73 (0.12)	3.91 (0.11)
260	3.40 (0.13)	3.78 (0.12)	3.39 (0.11)

[a]Least squares means and standard errors (SEs) were estimated as indicated in Table 1. [b]Inverse transform means and SEs were estimated as indicated in Table 2.

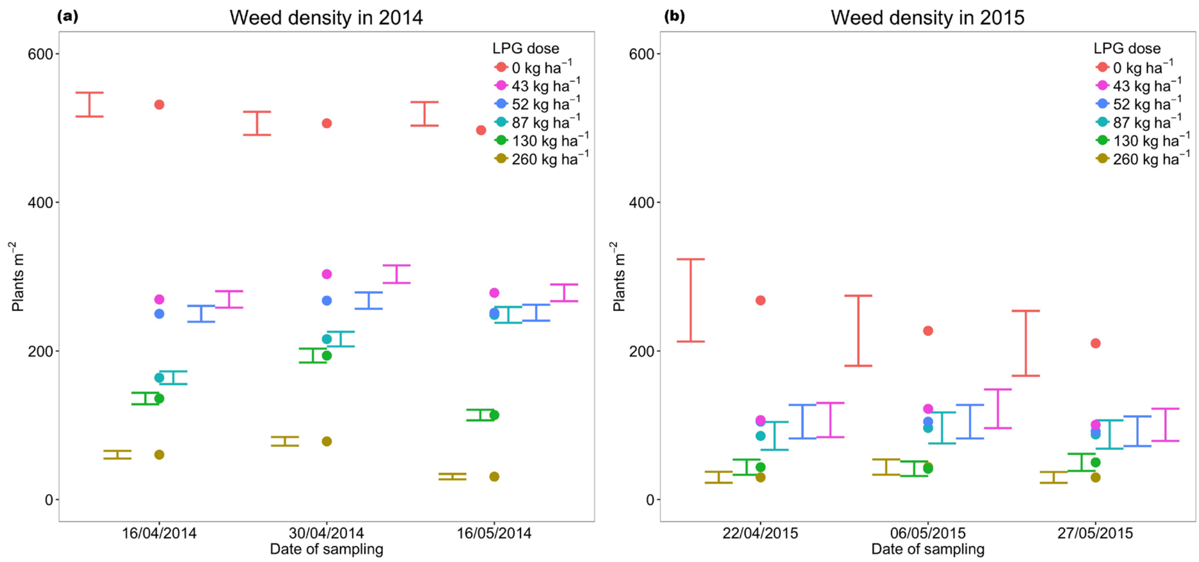

Figure 5. Estimated inverse-transformed least squares means and 95% confidence interval bars of weed density (plants/m^2) measured on different dates within the production bands during the spears harvest season in 2014 (a) and 2015 (b).

although the highest flaming dose (260 kg/ha) caused significant damage to the spears, the yields were higher when compared with those measured in the weedy plots (95% CIs: 42; 1040 and 141; 887, respectively in 2014 and 2015), where yield reduction was due to weed competition. This suggests that during the spears harvest season, the total number of marketable spears is influenced by the presence of weeds, which compete for nutrients. In terms of total yields, the damage caused by weeds is higher than that caused by flaming. Welker & Brogdon (1972) also found that weed competition during the harvesting period seriously reduced yields. The combined flamer-cultivator is a non-chemical alternative to the use of herbicides with long residual activity and broad-spectrum weed control, which are generally applied before the spear growing season to reduce the number of weeds during the harvesting (Rahman & Sanders, 1996; Pedreros *et al*., 2002; Araki & Tamura, 2008; Rodríguez-Salamanca *at al*., 2012; Zandstra *et al*., 2013). A combined flamer-cultivator could be adopted to increase the asparagus yields by controlling weeds in a period where herbicides are commonly prohibited. In fact, the results of this study indicating that weeds growing during the spears harvesting season led to lower yields. The machine can be used both in organic and conventional production systems, where the repeated application of pre-emergence herbicides could have an adverse effect on spear quality. It could also in some cases reduce yields if the herbicides leach into the crop root zone after heavy rainfall or flooding (Welker & Brogdon, 1972; Zandstra *et al*., 2013). Rodríguez-Salamanca *et al*. (2012) found that certain herbicide applications could compromise fern growth, and consequently negatively influence yields.

The results of this research showed that to obtain high total yields it is preferable to use doses of between 43 to 87 kg/ha in fact these guaranteed an adequate level of weed control in both years. These doses prevent yield losses due to weed competition, and at the same time save spears from the damage caused by flaming. The application of flame weeding should be repeated about every seven days, based on the growth stage of the weeds, and ensuring that weeds do not grow too large, because flaming works with the maximum efficiency when weeds are small (Ascard, 1994; Martelloni *et al*., 2016b).

The combined flamer-cultivator could be adopted in asparagus spear cultivation systems (both organic or conventional) that also use mechanical harvesting. Asparagus is traditionally harvested by hand, however there are now several mechanical asparagus harvesters on the market (Brandenberger *et al*., 2016). The mechanization of the harvesting process is essential to reduce the amount of labour used in production and to stabilize the production costs (Cembali & Hood, 2009). To facilitate this it is essential that the weed density in asparagus fields is low and that weeds are at the early growing stages throughout the entire harvesting period. This good level of weed control was achieved in this research by using the combined flamer-cultivator.

In conclusion, the new machine for weed control during the spears harvest season showed a high potential to increase yields in a period when herbicides cannot be used. Flame weeding could be introduced by asparagus producers as an alternative, or in addition to the herbicides commonly applied in spears pre-emergence and post-harvest. Finally, to obtain a sufficient level of weed control, the combined flamer-cultivator must be used when weeds are at the early growth stages, preferably at the cotyledonary stage.

Acknowledgments

The authors would like to acknowledge the asparagus producer Giulio Ciampana who hosted the experiment on his farm in Montalto di Castro, Viterbo, Italy.

References

Araki H, Tamura H, 2008. Weed control and field management with barley living mulch in asparagus production. Acta Hort 776: 51-54. https://doi.org/10.17660/ActaHortic.2008.776.4

Ascard J, 1994. Dose-response models for flame weeding in relation to plant size and density. Weed Res 34 (5): 377-385. https://doi.org/10.1111/j.1365-3180.1994.tb02007.x

Brandenberger L, Shrefler J, Rebek E, Damicone J, 2016. Asparagus production. http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-1101/HLA-6018web.pdf [27 May 2016].

Cembali T, Hood M, 2009. Evaluation of an electrical harvester for asparagus. Int J Veg Sci 15: 158-167. https://doi.org/10.1080/19315260802611202

Falavigna A, Casali PA, Valente MT, 2012. Recent progress of asparagus breeding in Italy. Acta Hort 950: 133-142. https://doi.org/10.17660/ActaHortic.2012.950.14

Fontanelli M, Raffaelli M, Martelloni L, Frasconi C, Ginanni M, Peruzzi A, 2013. The influence of non-living mulch, mechanical and thermal treatments on weed population and yield of rainfed fresh-market tomato (Solanum lycopersicum L.). Span J Agric Res 11 (3): 593-602. https://doi.org/10.5424/sjar/2013113-3394

Fontanelli M, Frasconi C, Martelloni L, Pirchio M, Raffaelli M, Peruzzi A, 2015a. Innovative strategies and machines for physical weed control in organic and integrated vegetable crops. Chem Eng T 44: 211-216.

Fontanelli M, Martelloni L, Raffaelli M, Frasconi C, Ginanni M, Peruzzi A, 2015b. Weed management in autumn fresh market spinach: A nonchemical alternative. HortTechnol 25 (2): 177-184.

Frasconi C, Fontanelli M, Martelloni L, Pirchio M, Raffaelli M, Peruzzi A, 2016. Thermal weed control on horizontal and vertical surfaces in archaeological sites as an alternative to herbicides. Int J Conserv Sci 7(S1): 301-310.

Kaiser C, Ernst M, 2012. Organic asparagus. https://www.uky.edu/Ag/CCD/introsheets/organicasparagus.pdf [27 May 2016].

Knezevic A, 2008. Overlapping confidence intervals and statistical significance. https://www.cscu.cornell.edu/news/statnews/stnews73.pdf [16 May 2016].

Kuznetsova A, Brockhoff PB, Christensen RHB, 2014. lmerTest: Tests for random and fixed effects for linear mixed effect models. http://CRAN.R-project.org/package=lmerTest [16 May 2016].

Martelloni L, Frasconi C, Fontanelli M, Raffaelli M, Peruzzi A, 2016a. Mechanical weed control on small-size dry bean and its response to cross-flaming. Span J Agric Res 14 (1): e0203. https://doi.org/10.5424/sjar/2016141-7976

Martelloni L, Fontanelli M, Frasconi C, Raffaelli M, Peruzzi A, 2016b. Cross-flaming application for intra-row weed control in maize. Appl Eng Agric 32 (5): 569-578. https://doi.org/10.13031/aea.32.11114

Neeson R, 2004. Organic asparagus production. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0017/113417/organic-asparagus-production.pdf [16 May 2016].

Ngouajio M, Counts JW, Clark D, 2014. Effect of compost and Brassica cover crops on soil biomass and asparagus performance. Acta Hort 1018: 175-180. https://doi.org/10.17660/ActaHortic.2014.1018.16

Paine L, Harrison HC, Newenhouse AC, 1995. Establishment of asparagus with living mulch. J Prod Agr 8: 1-2. https://doi.org/10.2134/jpa1995.0035

Pedreros A, González MI, Guadamud C, 2002. Weed control during asparagus establishment year in a volcanic soil of Chile. Acta Hort 589: 155-158. https://doi.org/10.17660/ActaHortic.2002.589.21

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Raffaelli M, Martelloni L, Frasconi C, Fontanelli M, Peruzzi A, 2013. Development of machines for flaming weed control on hard surfaces. Appl Eng Agric 29 (5): 663-673.

Raffaelli M, Frasconi C, Fontanelli M, Martelloni L, Peruzzi A, 2015. LPG burners for weed control. Appl Eng Agric 31 (5): 717-731.

Rahman A, Sanders P, 1996. Succession of weed flora in some New Zeland asparagus. Acta Hort 415: 279-284. https://doi.org/10.17660/ActaHortic.1996.415.39

Rodríguez-Salamanca LM, Foster JM, Hausbeck MK, 2012. Greenhouse and field herbicide evaluation on asparagus plants. Acta Hort 950: 101-107. https://doi.org/10.17660/ActaHortic.2012.950.10

Royston P, 1995. Remark AS R94: A remark on Algorithm AS 181: The W test for normality. Appl Stat 44: 547-551. https://doi.org/10.2307/2986146

Russell VL, Hervé M, 2015. lsmeans: Least-Squares Means. R package version 2.16. http://CRAN.R-project.org/package=lsmeans [16 May 2016].

Singmann H, Bolker B, Westfall J, Aust F, Højsgaard S, Fox J, Lawrence MA, Mertens U, 2016. Analysis of Factorial Experiments. https://cran.rproject.org/web/packages/afex/afex.pdf [16 May 2016].

Welker WV, Brogdon JL, 1972. Effects of continued use of herbicides in asparagus planting. Weed Sci 20: 428-432.

Wickham H, Chang W, 2016. An implementation of the grammar of graphics. http://ggplot2.org, https://github.com/hadley/ggplot2 [09 September 2016].

Zandstra BH, Morse S, Tocco RV, Morrice JJ, 2013. Response of asparagus to repeated application of residual herbicides. HortTechnol 23 (1): 109-113.