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RESEARCH ARTICLE

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Mechanical weed control on small-size dry bean and its response to cross-flaming

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Abstract

Dry bean (*Phaseolus vulgaris* L.) can be a profitable crop for farmers; however controlling weeds effectively without a decrease in yield remains a problem. An example where mechanical weed control is difficult to conduct is dry bean 'Toscanello', which is a small sized high-income niche product growing low to the ground. Concerning intra-row weed control, also flame weeding could be an opportunity but the dry bean heat tolerance needs to be studied. The aims of this research were to study the weed control efficacy of a spring-tine harrow and an inter-row cultivator in this bean variety, and to test the tolerance of dry bean cultivated under weed-free conditions to cross-flaming applied with different liquefied petroleum gas (LPG) doses. Flame weeding was applied at BBCH 13 and BBCH 14 bean growth stages by pairs of burners producing direct double flame acting into the intra-row space, with bean plants placed in the middle. The results suggest that the spring-tine harrow used two times at BBCH 13 and 14, respectively, lead to a yield similar to that of the weedy control. The inter-row cultivator could be an opportunity for small-sized dry bean crops producers, enabling them to obtain a similar yield compared to the hand-weeded control. Concerning the bean tolerance to cross-flaming the results showed that bean flamed at BBCH 13 stage had little tolerance to cross-flaming. Bean flamed at BBCH 14 stage was tolerant until an LPG dose of 39 kg/ha, giving yield responses similar to those observed in the non-flamed control.

Additional key words: agricultural engineering; cultivation; flamer; low-competitive crop; organic farming; *Phaseolus vulgaris* L.; physical management.

Abbreviations used: BBCH 13 (first fully developed trifoliolate at the third node); BBCH 14 (second trifoliolate, counted when leaf edges no longer touch); CI (95% confidence interval); DAT (days after treatment); EU (European Union); HW (hand weeding); IRC (inter-row cultivator); LPG (liquefied petroleum gas); STH (spring-tine harrow).

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Introduction

There is increasing awareness of the importance of food legumes in improving the health of humans (Tharanathan & Mahadevamma, 2003). Weeds are a major constraint for legume production both in mechanized farming systems in advanced countries and labour-intensive smallholder farming systems in developing countries (Siddique *et al*., 2012). The scarcity of effective herbicide molecules is one of the most serious constraints to legume production in developed countries, and the increasing diffusion of organic agriculture excludes the use of herbicides. Therefore, there is a clear need for integrated or non-chemical weed management strategies (Siddique *et al*., 2012).

Dry bean (*Phaseolus vulgaris* L.) can be a profitable crop for farmers, however it requires a high level of management due to weed interference which can result in yield losses of up to 85%, since dry beans are poor competitors with weeds (Graham & Ranalli, 1997; Sikkema *et al*., 2008). The effects of mechanical weed control in dry bean vary depending on the year and tillage methods used (Colquhoun *et al*., 1999). Inter-row cultivation controls most weeds located outside the crop rows, but the concern for weed control in dry bean, as well as for other crops, is the growth of plants located within the crop rows (Amador-Ramirez *et al*., 2002). Vangessel *et al*. (1995) observed that rotary hoeing and flex-tine harrowing had a similar efficacy in controlling weeds in dry bean fields. Burnside *et al*. (1998a) found that inter-row cultivation was more effective than rotary hoeing for controlling weeds and increasing dry bean yields whereas Vangessel *et al*. (1998) observed that two mechanical weeding operations using an intra-row cultivator reduced the weed population to the same levels as herbicides. Colquhoun *et al*. (1999) tested five cultivation implements on this crop (two flex-tine cultivators, a brush hoe, and rolling and shovel cultivators) and found that the performance of the cultivators varied according to the year and soil type, however flex-tine cultivators failed to control weeds and to prevent yield reductions. On the contrary, flex-tine harrow was useful preceding the shovel cultivator and the highest levels of weed control and yield were obtained with this combination (Colquhoun *et al*. 1999). Amador-Ramirez *et al*. (2002) evaluated the effect of intra-row cultivation and rotary hoeing on weed seedling emergence throughout the dry bean growing season with unsatisfactory results because, despite the cumulative seedling emergence varied depending on the year and the weeding tools, results were similar to those observed in the untreated control (Amador-Ramirez *et al*., 2002). Stefanic *et al*. (2005) applied inter-row cultivation at the fourth and fifth-sixth weeks after sowing and also found a similar weed density at the end of the dry bean growing season to that of the untreated control. Thus, the varying levels of efficacy highlight the need for further research.

As an alternative to the use of mechanical implements, which show irregular efficacy, flame weeding could be used as an alternative or as a complement for intra-row weed control in heat-tolerant crops both in conventional and organic agriculture (Ascard, 1995). Flame weeding benefits organic growers when wet weather prevents timely mechanical weed control measures (Taylor *et al*., 2012). However, legumes have not been studied much in terms of their tolerance to flame weeding. Knezevic *et al*. (2013) found that soybean can tolerate a maximum of two flaming treatments at unfolded cotyledons and fifth trifoliate growth stages per season without any reduction in yield. These authors compared flame weeding at BBCH 10 bean growth stage to a propane flamer equipped with two torches per row mounted at a 45° angle relative to the ground. An estimated propane dose of 25 kg/ha resulted in a yield reduction of 50% compared to the yield of the non-flamed control. This suggests that dry bean flamed at the BBCH 10 growth stage was not tolerant to flame weeding (Taylor *et al*., 2012). Further studies are needed in order to evaluate whether more advanced growth stages are tolerant to flaming. Taylor *et al*. (2012) compared flaming and rotary hoeing, and the two treatments that achieved the highest level of weed control and bean yields were flaming applied prior to bean emergence, followed by two rotary hoeing and rotary hoeing applied three times without flaming.

The aims of this research were to: (1) study the weed control efficacy on dry bean of a spring-tine harrow and an inter-row cultivator equipped with a manual guidance system, which are low tech and cheap machines already been successfully used in other crops (Peruzzi *et al*., 2007; Fontanelli *et al*., 2013, 2015), to evaluate their applicability in a small-sized dry bean variety, since it is a low-competitive cultivar; and (2) test the tolerance of dry bean cultivated under weed-free conditions to cross-flaming applied with different liquefied petroleum gas (LPG) doses at BBCH 13 and 14. Both mechanical and thermal machines are of fundamental importance in order to meet the EU legislation in terms of reducing the use of chemical herbicides. Their efficacy, related to the possibility of applying them to similar crops and on small farms, needs to be studied and is thus addressed in this paper.

Material and methods

Equipment used for mechanical weed control

An inter-row cultivator and a spring-tine harrow custom-built at the University of Pisa (Italy) were used for the mechanical weed control (Peruzzi *et al*., 2007; Fontanelli *et al*., 2013). The inter-row cultivator removed the weeds in the inter-row space (0.65 m), at about 5 cm from the seeding line, by tilling the soil at a depth of 3 cm. The cultivator was equipped with five elements for a total working width of 3 m. Each element was equipped with one central 22 cm wide rigid goose-foot sweep and two lateral “L-shaped” 21 cm wide rigid sweeps. In test runs, weeds on the seeding line were buried by loose soil near the line without damaging the crop. The machine was equipped with a manual guidance system in order to enable a back-seat operator to adjust the position of the working tools, preventing damage to the crop while working at an operating speed of 1.5 km/h very close to the crop row (Fig. 1). The spring-tine harrow was 3 m width and equipped with 0.36 m long flexible tines (6 mm diameter), which led to weed uprooting, burying and leaf breaking by vibrating in all directions. The machine is designed to exploit the poor anchorage to the soil of small weeds compared to more developed and anchored crop plants. The working depth was 2 cm and operating speed was 5.5 km/h.

Figure 1. Inter-row cultivator equipped with a manual guidance system that enables weeds to be removed very close to the bean row.

Equipment used for bean response to cross-flaming

The cross-flaming machine was designed at the University of Pisa. Cross-flaming consists in applying a direct flame on a soil band corresponding to the line of the crop, to kill weeds from the intra-row space. Flame weeding devitalize weed seedling through the effect of high temperatures that denaturize plant proteins (Fontanelli *et al*., 2013; Raffaelli *et al*., 2013). In this study cross-flaming was not used to control weeds, but to test the tolerance of the crop to the direct flame to evaluate a prospective application of flame weeding in dry bean. The machine was calibrated to deliver the appropriate dose of LPG used as fuel to feed the burners. The calibration procedure was based on combining LPG pressure (0.3 MPa) and operating speed (3, 5, 6 and 8 km/h). The open-flame burners of the machine (0.25 m wide) produced a flat flame and were regulated in order to perform cross-flaming. The burners were angled at 45° from the perpendicular to the ground and parallel to the crop row, and positioned at about 10 cm from each side of the crop row and 12 cm above the soil surface. Cross-flaming was applied by pairs of burners in 0.25 m wide soil strips (the intra-row space), with bean plants placed in the middle (Fig. 2). Four pairs of burners were used for a working width of 3 m.

Experimental set up

Field experiments were conducted in the 2013 and 2014 dry bean growing seasons at the experimental farm of the University of Pisa (+43.7°N +10.3°E) located in San Piero a Grado, close to Pisa, in central Italy. In both years the trials were conducted at the same site following organic agriculture systems. The soil type was loam (38% sand, 44% silt, 18% clay) with 1.4% organic matter, and pH 7.8. The previous crop was fennel harvested in January. Soil tillage included ploughing (0.20 m deep) in March followed by rotary harrowing in April. The false seedbed technique was used three times with the spring-tine harrow before sowing at a distance of 10 days each in April and May, and no fertilization was applied. In the false seedbed technique the preparation of the seedbed is followed by surface tillage to stimulate the germination of the non-dormant weed seeds. The seedlings are subsequently devitalized, before crop planting (Boyd *et al*., 2006). Dry edible bean ‘Toscanello’ was used, which is a popular Tuscan white bean niche product that grows low to the ground, and is characterized by thin skin, small seed size, and generating high-income. Sowing was conducted on 15 May 2013 and on 14 May 2014 using a four-row planter with an inter-row distance of 0.75 m at a density of 250,000 seeds/ha. Broadcast flame weeding was conducted before crop emergence on the whole surface in all plots in order to devitalize any weeds emerging before the crop.

Figure 2. Cross-flaming treatment applied on white dry bean var. ‘Toscanello’.

To test the efficacy of mechanical weed control, the inter-row cultivator and the spring-tine harrow were used twice (on 5 and 13 June in 2013, and on 4 and 12 June in 2014) at the third and fourth week after sowing (8-day interval), according to Burnside *et al*. (1998b) who found that the critical period of weed control for dry bean is 3-5 or 6 weeks after sowing. Treatments were repeated because the application of a single post-emergence mechanical weed control is generally not enough to control weeds in most crops and prevent yield reductions (Peruzzi *et al*., 2007; Fontanelli *et al*., 2013, 2015). The eight days interval is the time needed to control a new weed emergence without damaging crop plants. When mechanical weed control was applied the first time the dry bean was at the BBCH 13 growth stage (first fully developed trifoliolate at the third node), when it was applied the second time dry bean was at the BBCH 14 growth stage (second trifoliolate, counted when leaf edges no longer touch). In the study on bean response to cross-flaming, flame weeding at BBCH 13 bean growth stage was applied on 4 June in 2013 and on 3 June in 2014. Flame weeding at the BBCH 14 bean growth stage was applied on 13 June in 2013 and on 12 June in 2014. Bean growth stage was assessed according to the BBCH scale (Feller *et al*., 1995). In the study on bean response to cross-flaming the BBCH 13 and BBCH 14 growth stages were selected because they corresponded to the time when the weeds were mechanically controlled in the study of the effectiveness of mechanical weed control.

The crop water requirement was 15 mm of water per week provided by rainfall and/or sprinkling irrigation for the whole growing season from May to September. The beans were harvested on 2 September 2013 and on 4 September 2014.

Experimental design and treatments

In the mechanical weed control study (exp. 1), the experimental plot size was 10 × 3 m. The plots were arranged in a randomized complete block design with four replicates. The treatments consisted of (1) a weedy control, (2) a hand-weeded weed-free control conducted as often as necessary, (3) inter-row cultivator and (4) spring-tine harrow.

In the study of bean response to cross-flaming (exp. 2), the experimental plot size was 5 × 3 m. The area was kept weed-free for the entire growing season by manual hoeing as often as necessary. The plots were arranged in a randomized complete block design with three replicates. The treatments consisted of a non-flamed control and four LPG doses, which were applied at two growth stages. Cross-flaming was applied at BBCH 13 with LPG doses of 0, 26, 29, 33 and 39 kg/ha, and at BBCH 14 with LPG doses of 0, 39, 52, 63 and 104 kg/ha. Higher LPG doses were applied at BBCH 14 because the doses used at BBCH 13 did not kill any of the plants and were considered too low to test the tolerance to cross-flaming at a more developed growth stage, *i.e.* BBCH 14. The LPG doses applied at BBCH 13 were obtained by combining the working pressure of 0.2 MPa with the working speeds of 6, 7, 8 and 9 km/h. All the LPG doses applied at BBCH 14 were obtained by combining the working pressure of 0.3 MPa with the working speeds of 3, 5, 6 and 8 km/h. The LPG doses were calculated as intra-row biological doses (*i.e*. the doses applied into the 0.25 m wide soil strips). The actual doses (*i.e*. the doses computed on the full width of the machine) were 67% lower than the biological doses.

Data collection

Bean yield and crop density at harvest were determined by collecting samples from a 4 m^2 area (4 m × 1 m) placed in the middle of two rows of each plot in both studies. Pods were shelled, and the grain was dried at 105 °C up to a constant weight. Weed density was estimated eight days after the end of mechanical weed control applications (8 DAT) in a 0.075 m^2 (0.25 m × 0.30 m) area in three randomly selected sampling points within each plot. Weed dry biomass at harvest was measured after collecting weeds from a 1.5 m^2 (0.25 m × 3 m × 2) area placed in the middle of two intra-rows of each plot. The aerial part of the weeds was cut and dried at 105 °C up to constant weight. In exp. 2, bean dry biomass was measured 14 days after flame weeding application (14 DAT) and at harvest after collecting plants from a 2 m^2 (2 m × 1 m) area placed in the middle of two intra-rows of each plot. Bean plants were cut without roots and dried at 105 °C up to constant weight.

Statistical analysis

The test of normality was performed using the Shapiro-Wilk normality test (Royston, 1995). Yield and dry biomass data, which were normally distributed (*p*-value of the Shapiro-Wilk test > 0.05) were modeled in a linear mixed model using the extension package *lmerTest* (Kuznetsova *et al*., 2014) of the R statistical software (R Core Team, 2013). All density data (bean plants and weeds) were not normally distributed (*p*-value of the Shapiro-Wilk test < 0.05) and followed a Poisson distribution, thus were modeled in a generalized linear mixed model using the extension package *lme4* (Bates *et al*., 2014) that conducted a log transformation. Initial testing of the effect of years, treatments, replications and their interactions on the basis of bean yield, weed and bean density and dry biomass were analysed for significance by computing the mixed ANOVA. Non-significant fixed effects and interactions were excluded from the model. There was no treatment-by-year interaction, thus the data were combined over years. A significant effect of bean growth stage on the flame weeding treatment was observed; therefore the data were presented separately for each growth stage.

The extension package *lsmeans* (Least-squares means) (Russell & Hervé, 2015) of R was chosen to estimate means of dependent variables as affected by the different mechanical weed control methods. Differences between mean values were detected by a ratio test at a 95% confidence level (Wheeler *et al*., 2005). If the resulting 95% confidence interval (CI) for the ratio did not cross the value 1, the null hypothesis that compared values are equal was rejected.

The responses of bean to cross-flaming were analysed using non-linear regression analysis of dose-response curves. The extension package *drc* (dose-response curves) (Ritz & Streibig, 2005) of R was chosen to fit nonlinear regressions, estimate their parameter values, predict values, and plot regression lines. Yield, bean dry biomass and density data were analysed using the four parameter log-logistic model (Seefeldt *et al*., 1995; Knezevic *et al*., 2007) (Eq. [1]):

$$Y = C + \frac{(D - C)}{\{1 + \exp[B(\log X - \log E)]\}} \quad [1]$$

where (Y) is the response, (C) is the lower limit, (D) is the upper limit, (B) is the slope of the line at the inflection point, (X) is the LPG dose, and (E) is the dose providing a 50% response between the upper and the lower limits (also known as the inflection point or ED_{50}) (Seefeldt *et al*., 1995). For bean plants, the density model type=Poisson was set. A test of lack-of-fit at the 95% level was not significant for any of the dose-response curves tested, which means that the non-linear regression model provided an acceptable description of the data.

Table 1. Significance levels (5% level) in the mixed ANOVA of the effect of mechanical weed control (MWC) methods, year (Y), and their interaction on weed density observed eight days after the second treatment (DAT), weed dry biomass at harvest, crop density observed at harvest and yield.

Variable	Terms	*p* value
Weed density 8 DAT (plants/m^2)	MWC	<0.0001
	Y	0.45
	MWC × Y	0.23
Weed dry biomass at harvest (g/m^2)	MWC	<0.0001
	Y	0.09
	MWC × Y	0.75
Crop density at harvest (plants/m^2)	MWC	0.31
	Y	0.82
	MWC × Y	0.95
Yield (t/ha)	MWC	<0.0001
	Y	0.87
	MWC × Y	0.76

Results

Mechanical weed control

In general, the mechanical weed control method used affected the response of weed density observed eight days after the second treatment (8 DAT), weed dry biomass at harvest, and yield (Table 1). No effects of year and of the interaction year and weed control method were observed. Weed control method did not affect the crop density observed at harvest (Table 1).

Initial weed composition consisted of 78% *Cynodon dactylon* L., 12% *Convolvulus arvensis* L., 10% *Equisetum arvense* L. and an occasional presence of *Solanum nigrum* L. All these species, with the exception of *Solanum nigrum* L., are perennials, and thus difficult to control (Table 2). Weed density observed 8 days after the second treatment was lower after using the inter-row cultivator than in plots treated with the spring-tine harrow and in the untreated control (Tables 3, 4). The use of the spring-tine harrow did not lead to a statistically significant difference in terms of weed density compared to the control (Tables 3, 4), however the large data interval (Fig. 3a) shows that the machine worked inconsistently. Both tools controlled weed species differently. Inter-row cultivator was more efficient on *Cynodon dactylon* L. and *Solanum nigrum* L., while

Table 2. Weed composition observed 8 days after the first and the second mechanical weed control application, expressed as percentage of presence.

	Weed presence after the first treatment (%)			Weed presence after the second treatment (%)		
	Control	Inter-row cultivator	Spring-tine harrow	Control	Inter-row cultivator	Spring-tine harrow
Cynodon dactylon L.	79	45	70	85	20	55
Convolvulus arvensis L.	11	<1	9	7	40	18
Equisetum arvense L.	10	33	13	5	25	16
Solanum nigrum L.	<1	22	8	2	-	11
Amaranthus retroflexus L.	–	–	–	1	15	–

Initial weed composition consisted of 78% *Cynodon dactylon* L., 12% *Convolvulus arvensis* L., 10% *Equisetum arvense* L. and *Solanum nigrum* L. (mean of all plots).

Table 3. Estimated mean values and standard errors (SE) of weed density observed 8 days after the second treatment (DAT), weed dry biomass at harvest, crop density observed at harvest and yield as affected by the two mechanical weed control methods.

Variable	Weed control method	Estimated mean ± SE[a]
Weed density 8 at DAT (plants/m^2) [b]	Inter-row cultivator	78.6 (10.86)
	Spring-tine harrow	174.2 (23.82)
	Control	168.5 (23.05)
Weed dry biomass at harvest (g/m^2)	Inter-row cultivator	182.9 (7.84)
	Spring-tine harrow	249.8 (7.84)
	Control	289.2 (7.84)
Crop density at harvest (plants/m^2) [b]	Hand weeding	20.5 (1.85)
	Inter-row cultivator	19.3 (1.80)
	Spring-tine harrow	16.5 (1.66)
	Control	20.7 (1.86)
Yield (t/ha)	Hand weeding	1.70 (0.08)
	Inter-row cultivator	1.52 (0.08)
	Spring-tine harrow	1.05 (0.08)
	Control	1.03 (0.08)

[a] Means and SE were estimated with the extension package *lsmeans* (least-squares means) (Russell & Hervé, 2015) of R (R Core Team, 2013). [b] Weed density at 8 DAT and crop density at harvest are back-transformed values and were estimated with the function *update* of the extension package *lsmeans*.

Table 4. Estimate, lower and upper limit of the ratio between means of each dependent variable under the two mechanical weed control methods.

Variable	Comparison of weed control methods	Estimated ratio[a]		
		Estimate	Lower	Upper
Weed density after the second treatment (8 DAT) [b]	Spring-tine harrow/Inter-row cultivator	1.2	1.09	1.29
	Spring-tine harrow/Control	1.0	0.93	1.08
	Control/Inter-row cultivator	1.2	1.08	1.27
Weed dry biomass at harvest	Control/Spring-tine harrow	1.2	1.06	1.25
	Control/Inter-row cultivator	1.6	1.42	1.74
	Spring-tine harrow/Inter-row cultivator	1.4	1.22	1.51
Crop density at harvest	Control/Spring-tine harrow	1.1	0.98	1.18
	Control/Inter-row cultivator	1.0	0.94	1.11
	Control/Hand weeding	1.0	0.92	1.09
	Hand weeding/Inter-row cultivator	1.0	0.93	1.11
	Hand weeding/Spring-tine harrow	1.1	0.98	1.18
	Inter-row cultivator/Spring-tine harrow	1.1	0.96	1.16
Yield	Hand weeding/Inter-row cultivator	1.1	0.98	1.27
	Hand weeding/Spring-tine harrow	1.6	1.35	1.89
	Hand weeding/Control	1.6	1.37	1.92
	Inter-row cultivator/Spring-tine harrow	1.4	1.20	1.69
	Inter-row cultivator/Control	1.5	1.21	1.72
	Spring-tine harrow/Control	1.0	0.81	1.22

[a] Confidence level used: 0.95. If the resulting 95% confidence interval for the ratio test does not cross the value 1, the null hypothesis that the weed control methods compared are equal was rejected. [b] DAT: days after the second treatment.

the spring-tine harrow controlled better *Convolvulus arvensis* L. (Table 2). Weed dry biomass at harvest was higher for the spring-tine harrow than for the inter-row cultivator. Compared to the control, a significant weed decrease of 40% was observed when the inter-row cultivator was used, whereas the decrease with the spring-tine harrow was 14% (Fig. 3b; Tables 3, 4). These results show a considerable ability of the weed species found in the field to regrow after mechanical weed control application.

The crop density observed at harvest was similar to that observed within the hand-weeded plots (Fig. 3c; Tables 3, 4). Yield in the plots treated with the inter-row cultivator was similar in the hand-weeded plots, and

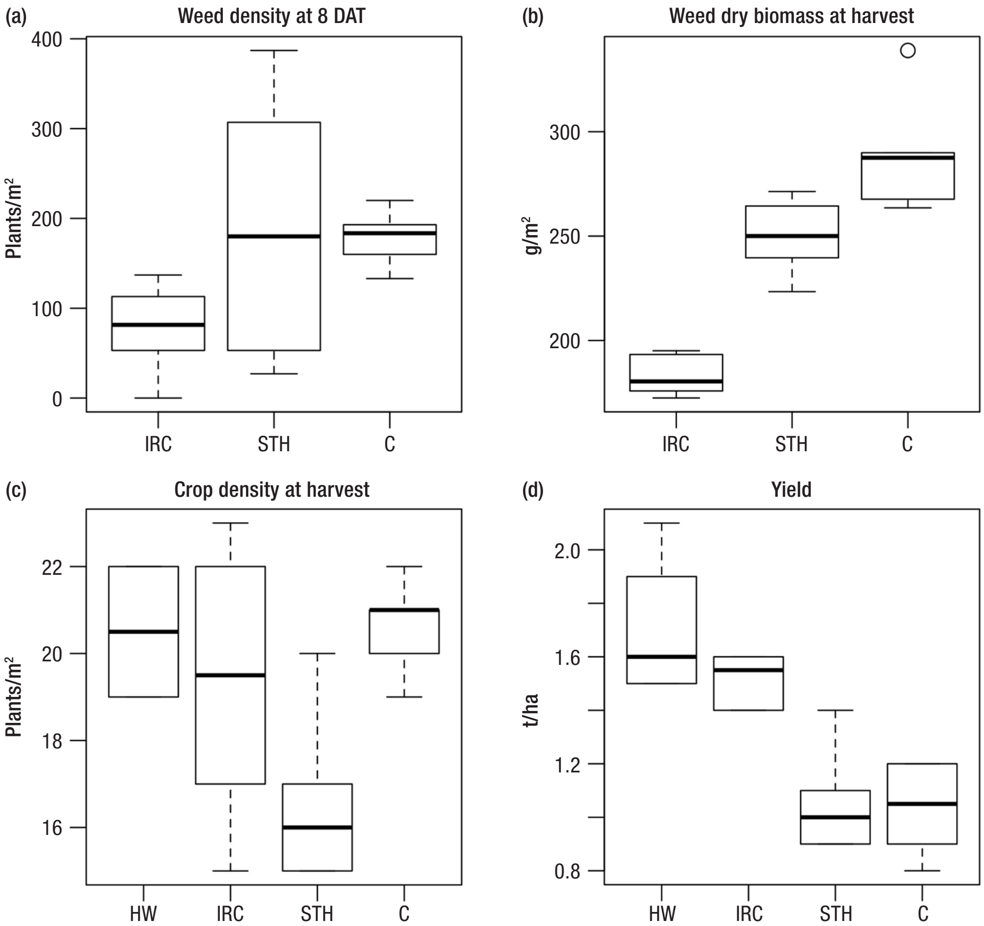

Figure 3. Boxplots of the relationship between the mechanical weed control method used and: the weed density 8 days after the second treatment application (a), the weed dry biomass at harvest (b), the crop density at harvest (c), and the yield (d). Combined data of both years. IRC, inter-row cultivator, STH, spring-tine harrow, C, control, HW, hand weeding.

higher than in the spring-tine harrowed and the untreated control (Fig. 3d; Tables 3, 4). When the spring-tine harrow was used a 1.2-fold and 1.4-fold larger weed density and biomass, respectively, lead to 1.4-fold smaller yields compared to the inter-row cultivator (Table 4).

Bean response to cross-flaming

Bean plants dry biomass measured 14 days after the application of cross-flaming (14 DAT) and at harvest, and yield were all influenced by the LPG dose, the bean growth stage and their interaction (Table 5). The crop density counted at harvest was influenced only by the LPG dose applied (Table 5). In general, bean plants flamed at BBCH 14 showed a higher tolerance to cross-flaming.

Bean dry biomass collected 14 DAT decreased by increasing the LPG dose (Fig. 4a). When an LPG dose of 39 kg/ha was applied, the dry biomass of BBCH 13 was half than for the non-flamed control, whereas the dry biomass of BBCH 14 was similar to of the non-flamed control, suggesting that beans flamed at BBCH 13 showed less tolerance to cross-flaming than at BBCH 14 (Table 6). Bean flamed at BBCH 13 and collected at harvest showed a small recovery in terms of dry biomass, which was 1.5-fold lower than the non-flamed control when the LPG dose of 39 kg/ha was applied. Beans flamed at BBCH 14 with LPG doses larger than 39 kg/ha were not able to recover, and showed a smaller dry biomass at harvest compared to the non-flamed control (Fig. 4b; Table 6).

The crop density observed at harvest when plants were flamed at BBCH 13 was similar to the non-flamed control for all the range of LPG doses used, so that by applying doses equal to or lower than 39 kg/ha, none of the bean plants died. When the plants at BBCH 14 were flamed with the highest LPG dose (104 kg/ha), 37% of plants died, suggesting that bean is not tolerant to high LPG doses (Fig. 4c; Table 6). When beans were flamed at BBCH 14, the maximum estimated LPG dose that did not result in a decrease of the crop density at harvest was 78 kg/ha, resulting in a predicted crop

Table 5. Significance levels (5% level) in the mixed ANOVA of the effect of liquefied petroleum gas (LPG) dose, dry bean growth stage (GS), year (Y), and their interactions on bean dry biomass observed 14 days after treatment (DAT) and at harvest, crop density observed at harvest, and yield.

Variable	Terms	*p* value
Dry biomass 14 DAT (g/m^2)	LPG dose	<0.0001
	GS	<0.0001
	Y	>0.99
	LPG dose × Y	0.87
	GS × Y	0.12
	LPG dose × GS	<0.0001
	LPG dose × GS × Y	0.19
Dry biomass at harvest (g/m^2)	LPG dose	<0.0001
	GS	<0.0001
	Y	0.65
	LPG dose × Y	0.51
	GS × Y	0.84
	LPG dose × GS	<0.0001
	LPG dose × GS × Y	0.99
Crop density at harvest ($plants/m^2$)	LPG dose	0.01
	GS	0.14
	Y	0.69
	LPG dose × Y	0.72
	GS × Y	>0.99
	LPG dose × GS	0.96
	LPG dose × GS × Y	>0.99
Yield (t/ha)	LPG dose	<0.0001
	GS	<0.0001
	Y	0.70
	LPG dose × Y	0.05
	GS × Y	0.70
	LPG dose × GS	<0.0001
	LPG dose × GS × Y	0.99

density at harvest of 15.19 ± 1.78 $plants/m^2$. However, with the maximum LPG dose of 39 kg/ha applied at BBCH 13 it was not possible to estimate the LPG dose needed to cause a predicted reduction of the crop density at harvest.

Bean yield decreased by increasing the LPG dose (Fig. 4d). When bean was flamed at BBCH 13 with an LPG dose of 39 kg/ha, the yield was 1.3-fold smaller than the yield of the non-flamed control. Bean flamed at BBCH 13 showed poor tolerance to cross-flaming, with a minimum yield reduction of 5% compared to the weed-free control when the LPG dose of 26 kg/ha was applied (estimated yield of 1.62 ± 0.01 t/ha). Plants flamed at BBCH 13, despite showing a certain growth recovery (26%) from 14 DAT to harvest (dry biomass reduction from 62% to 36%), did not result in satisfactory yields, probably due to the plants size (36% smaller than plants in the weed-free control) (Table 6). When bean was flamed at BBCH 14 with an LPG dose of 39 kg/ha, the yield was similar to the non-flamed control. This suggests that when bean was flamed at BBCH 14 with an LPG dose of 39 kg/ha, no differences in terms of plant size (dry biomass at harvest similar to the non-flamed control) allowed to avoid yield losses (Table 6).

Discussion

Mechanical weed control applied at BBCH 13 and 14 with both machines did not damage bean plants, which resulted in a crop density at harvest similar to that of the hand-weeded control. Vangessel *et al.* (1995) observed a damage to dry bean hypocotyls and stems when the flex-tine harrow was used at both crook and trifoliolate stages (BBCH 10 and 13, respectively).

The weed flora composition observed in all plots was constituted by very aggressive species which are difficult to control. The inter-row cultivator was more effective than the spring-tine harrow in controlling these weeds both in terms of density counted at the fifth week after sowing (55% lower) and dry biomass measured at harvest (27% lower). This suggests that when the inter-row cultivator was used, some weed control effect persisted until harvest, and weeds were effectively controlled in a period of the crop growth cycle

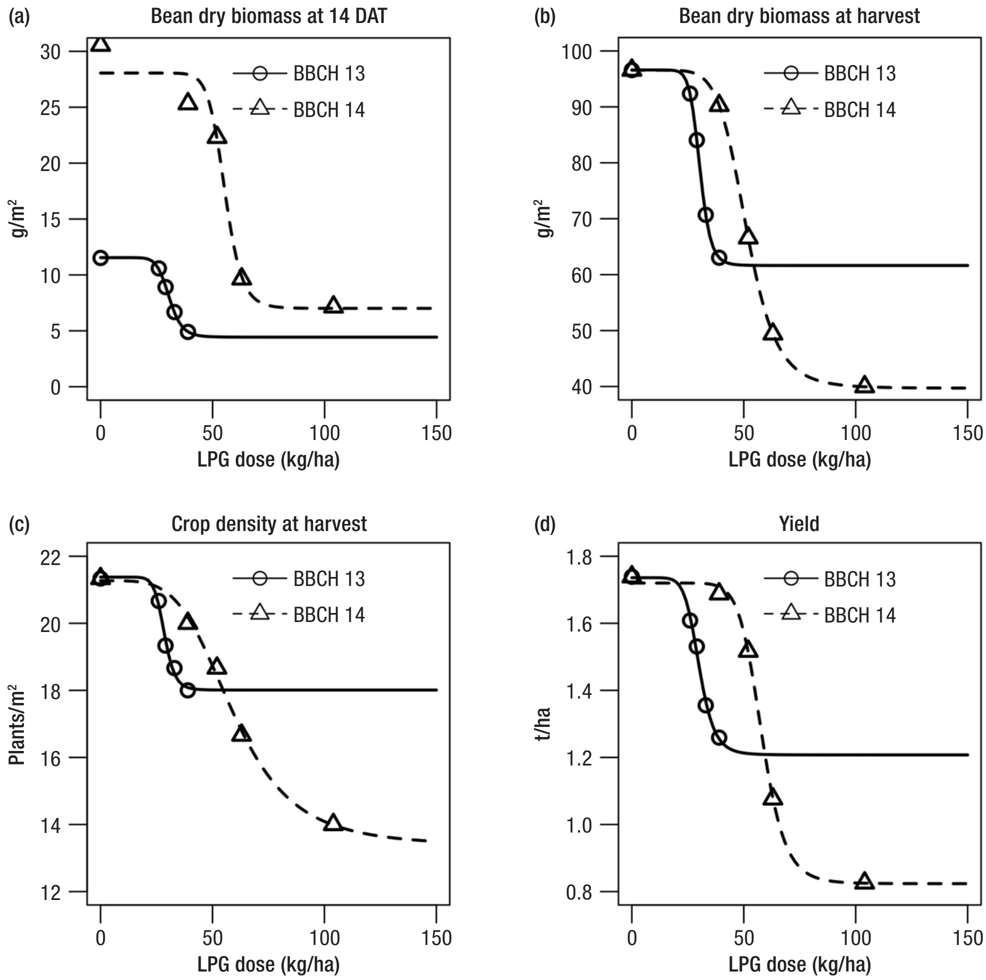

Figure 4. Influence of cross-flaming on bean dry biomass at 14 DAT (a) and at harvest (b), crop density at harvest (c) and yield (d) as affected by LPG dose and bean growth stage (BBCH 13: first fully developed trifoliolate at the third node; BBCH 14: second trifoliolate, counted when leaf edges no longer touch). Each data point represents the mean of two years. The regression lines are plotted using Eq. [1], and the parameters are presented in Table 6.

useful to prevent yield losses. Burnside *et al.* (1998b) found that the critical period of weed control for dry bean is 3-5 or 6 weeks after sowing. In our study we observed that when weeds were controlled with the inter-row cultivator at the third and fourth week after sowing, a weed density of about 80 plants/m^2 observed at the fifth week after sowing did not reduce the yield compared to the hand-weeded control. This suggests that the inter-row cultivator killed weeds difficult to control such as *Cynodon dactylon* L., *Convolvulus arvensis* L. and *Equisetum arvense* L. or suppressed them long enough for the crop to gain a competitive advantage. The significant reduction in the competitive effects of these weeds emphasizes the usability of the machine on a broad spectrum of weed species. Compared to the inter-row cultivator, the spring-tine harrow seemed more effective in controlling *Convolvulus arvensis* L., and less effective on *Cynodon dactylon* L.. However, the significant higher weed density persisting for all the growing season in plots treated with the spring-tine harrow causing yields 1.4-fold and 1.6-fold smaller compared to the yields obtained in the plots treated with the inter-row cultivator and the hand-weeded control, respectively.

The inter-row cultivator equipped with the manual guidance system could be beneficial for dry bean producers, since it produced a similar yield to that obtained in the hand-weeded control and had a reasonably positive effect on those perennial weeds that are normally difficult to control. The integration of repeated inter-row cultivations in a weed management system which comprise the stale-seedbed technique was expected to be a non-chemical as well as an economic low-tech opportunity for weed control (Peruzzi *et al.*, 2007; Fontanelli *et al.*, 2013, 2015), and the effectiveness of the tactic was confirmed also in the low-competitive dry bean 'Toscanello'. The results are similar to those found in the literature for other legume crop.

Table 6. Regression parameters for bean dry biomass 14 DAT and at harvest (g/m^2), crop density at harvest and yield (t/ha) as affected by LPG dose and dry bean growth stage, and predicted values at the common LPG doses of 39 kg/ha at the two growth stages.

Variable	Growth stage	Regression parameters (±SE)				Predicted value (±SE) at the dose of 39 kg/ha
		B[a]	C[b]	D[c]	E[d]	
Dry biomass 14 DAT (g/m^2)	BBCH 13[e]	10.8 (3.76)	4.4 (0.98)	11.5 (0.50)	30.6 (1.28)	4.9 (0.52)
	BBCH 14[f]	14.6 (1.70)	7.0 (0.52)	28.1 (0.38)	55.4 (0.53)	27.9 (0.36)
Dry biomass at harvest (g/m^2)	BBCH 13	12.7 (0.41)	61.6 (0.37)	96.6 (0.24)	30.4 (0.10)	63.0 (0.25)
	BBCH 14	7.6 (0.14)	39.7 (0.26)	96.6 (0.24)	51.2 (0.15)	90.3 (0.22)
Crop density at harvest (plants/m^2)	BBCH 13	12.1 (32.8)	18.0 (2.49)	21.4 (1.83)	28.5 (6.80)	18.1 (1.78)
	BBCH 14	4.4 (6.13)	13.4 (1.51)	21.3 (1.91)	59.3 (17.44)	20.2 (1.62)
Yield (t/ha)	BBCH 13	8.9 (1.06)	1.2 (0.03)	1.7 (0.01)	30.0 (0.48)	1.3 (0.01)
	BBCH 14	11.1 (0.58)	0.8 (0.01)	1.7 (0.01)	58.0 (0.33)	1.7 (0.01)

[a] B = slope of the curve at the inflection point. [b] C = lower limit. The value of C is the response when the highest LPG dose was applied. [c] D = upper limit. The value of D is the response of the non-flamed weed-free control. [d] E = dose of LPG resulting in a 50% response between the upper and the lower limit. [e] BBCH 13= first fully developed trifoliolate at the third node. [f] BBCH 14 = second trifoliolate, counted when leaf edges no longer touch.

Stefanic *et al*. (2003) combined herbicides with mechanical control in dry bean and found that one single inter-row cultivation treatment did not provide the expected weed control. Burnside *et al*. (1998a) found that increasing from one to two cultivations resulted in a significant dry bean yield increase. Inter-row cultivation performed twice following a soil-applied herbicide resulted in improved control of *Amaranthus retroflexus* L. and *Setaria viridis* (L.) Beauv. (Sikkema *et al*., 2008). Avola *et al*. (2008) found that chemical weed control in *Vicia faba* L and *Cicer arietinum* L. can be avoided by adopting an inter-row cultivator.

The results obtained in this study also suggest that the spring-tine harrow was not effective for weed management in dry bean, producing a yield similar to that obtained in the weedy control. Also Colquhoun *et al*. (1999) found that the spring-tine harrow failed to control weeds and to prevent dry bean yield reductions.

The results of the study of the dry bean tolerance to cross-flaming opens up the possibilities to control weeds within the row space of dry bean by applying this method used at BBCH 14. Bean flamed at this stage showed tolerance up to an LPG dose of 39 kg/ha, giving similar yields to that observed in the weed-free control. This suggests that when dry bean is flamed at BBCH 14 with LPG doses equal to or lower than 39 kg/ha, cross-flaming should not lead to yield losses. Taylor *et al*. (2012) applied flame weeding at the unfolded cotyledons bean growth stage (BBCH 10) with a propane dose of 25 kg/ha and found that bean was not tolerant, which is in accordance with our findings. In our study bean flamed at BBCH 13 showed poor tolerance to cross-flaming, with an yield decrease of 23% when an LPG dose of 39 kg/ha was applied. Further studies are needed to evaluate whether an LPG dose of 39 kg/ha applied at BBCH 14 (alone or in combination with inter-row cultivation) would be effective in controlling weeds and thus could avoid yield losses due to weed competition.

Assuming that the LPG dose tolerated by the dry bean can be effective in controlling weeds, cross-flaming could be used for intra-row weed control, thus avoiding problems connected to mechanical intra-row weeding that is highly influenced by selectivity factors (Rueda-Ayala *et al*., 2010). Cirujeda *et al*. (2003) found that probably mechanical weed control efficacy was much more influenced by uprooting, removal and burial of plants. Flame weeding is not influenced by soil type, resistance and moisture because the weeding mechanism is not based on tilling the soil and uprooting weeds, but to the effect of high temperatures that denaturize plant proteins and thus desiccate the weeds, normally within two to three days (Mojžiš, 2002). Flaming in the intra-row space could be a valid alternative to mechanical tools working in the rows and could be integrated with inter-row cultivators for weed management in dry bean. Frasconi *et al*. (2014) built an automatic machine able to perform the application of flame weeding within the row space of maize, and cultivation in the inter-row. The application of the machine in maize resulted in a weed control reduction ranging from 95% to 99% (Pérez-Ruiz *et al*., 2015). This machine, such us other intelligent camera-based systems capable of guiding mechanical weeding devices (Melander *et al*., 2015), is effective but still too expensive to be transferred at the small farms, which generally still search for low-tech and low-cost solutions.

Available and effective low-tech solutions for physical weed control are economically accessible for all farmers, who need to become less dependent on herbicides, according to the strict European legislation

(EU Regulation 1107/EC and EU Directive 128/EC; OJ, 2009a,b). Non-chemical weed control is also crucial in minor crops such as vegetables, where there is a lack of registered and effective herbicides (Melander *et al*., 2005). Results of this study on dry bean shown that the inter-row cultivator equipped with manual guidance could be the starting point for controlling weeds in other small-sized summer crops with little competitive ability. The manual guidance provides a high level of accuracy when operating close to individual crop plants. Flame weeding can be adopted for controlling weeds in all heat-tolerant and low-competitive crops such as *Allium cepa* L. (Sivesind *et al*., 2012). Cross-flaming can be used in crops with narrow space between the individual crop plants in the row, which represents the major obstacle for the selective use of high-tech automatic machines for mechanical weed control. Another limitation of mechanical weed control application is that in order to achieve good results, the soil structure should be fine and easy to work with; however lumpy or stony soils may often be the situation in practice (van der Weide *et al*., 2008). Flame weeding is not bound by the quality of soil, although the excessive presence of lumps or stones could screen weeds from the flame.

Manual intra-row weeding can be expensive and time consuming, particularly in slow-growing crops with poor weed competitiveness (van der Weide *et al*., 2008). The use of the inter-row cultivator can drastically reduce the direct costs for hand-weeding in small-sized low-competitive crops, such as *Daucus carota* L. and *Spinacia oleracea* L. (Peruzzi *et al*., 2007; Fontanelli *et al*., 2015).

In Europe, high-income niche crops rarely can benefit from registered herbicides, and the economic value of organic products is higher than that of conventionally-grown products. Often, these crops are cultivated in small farms and farmers cannot invest in high-tech solutions. Our findings highlight that a low-tech and low-cost machine such as the inter-row cultivator equipped with manual guidance, which in our study was effective in controlling weeds, could be exploited in other small-sized legumes crops, characterized by little competitive ability and high-income, such as certain cultivars of *Lens culinaris* Medik. or *Cicer arietinum* L., highly appreciated by consumers in terms of protein intake, or other summer crops. Further studies on the applicability of the flaming machine for intra-row weed control in post-emergence are required because each crop has its own threshold of heat tolerance at different growth stages that has to be identified and made known. It is also fundamental to conduct studies to evaluate if the doses tolerated by crops are sufficient to control weeds. Both mechanical and thermal machines have wide applicability especially due to the increasingly strict legislation on chemical herbicides. In addition, they have benefits both in terms of environmental and human health.

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