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Field Testing of a Biomass-Fueled Flamer for In-Row Weed Control in the Vineyard

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Abstract: Concern about the adverse effects of chemicals on the environment and on human health, and increasing restrictions of herbicide use, have led to a renewed interest in non-chemical weed control, particularly under the row of vineyards. A new, biomass-fueled (wood pellet), flaming prototype (CS Thermos, San Vendemiano, TV) was tested in the vineyard during Spring–Summer 2018, and compared with tillage (disc cultivator, weeder blade, and finger blade) and mowing (in-row, vine-skipping mower). Efficacy (in % of weed biomass removed or killed) and re-growth between two applications (in g dry biomass/m^2) were assessed for each treatment at two sampling locations (between the vines, and around the vines). Flaming resulted in greater efficacy of weed removal in comparison to tillage (blade weeder) and mowing, both between the vines (64%–75% versus 44%–68%, and 40%–68%, respectively) and around the vines (56%–78%, 39%–46%, and 37%–48%, respectively). However, five applications of tillage significantly reduced total weed growth until 27 July (by 26%) between vines in comparison to three applications of flaming, while no significant differences were found around vines. Such findings suggest that more frequent applications of flaming may be needed to give average weed control comparable to that of tillage, while improving it close to the vine trunks. Advantages and disadvantages of the prototype versus tillage and mowing, and versus conventional, LPG-fueled flamers are discussed in the paper.

Keywords: vineyard; weed control; flaming; tillage; mowing; agricultural machinery

1. Introduction

Weed control is an important practice in vineyard management. Its primary objective is to reduce weed competition with the crop for water, nutrients, and sunlight (especially in low trellis systems). Additional benefits for weed control are improving air circulation to reduce the incidence of diseases, reducing cover for voles and other rodents, and improving harvest efficiency [1,2].

In rainy climates, such as that of the North-East of Italy, weeds between the rows of vineyards are commonly controlled by mowing or shredding, in order to keep a permanent sod (weed cover) which is fundamental to improve traffic on wet soils (esp. for pesticide application), and to reduce soil erosion in hilly vineyards. Weed control in the row is, however, more critical because of the difficulty of reaching the area under the vines, and the risk of damaging the trunks and roots.

Traditional, mechanical methods, such as tillage and mowing, can be applied with a variety of specialized machines, mostly provided with automatic vine-skipping mechanisms to avoid damage to the crop [3,4]. All of them, however, have several constraints such as: the need of repeated applications (4–6 per year) at low working speeds (2–4 km/h); weed control around vine trunks and posts is never complete, and damage to vine roots and trunks may still occur; limitations on wet soil and weeds; and risk of erosion from tillage in hilly vineyards. Brushes [4] can perform better around trunks and posts, and work faster, but typically damage the vine trunks, causing wounds that can increase the risk of wood diseases. This is why chemical application of pre-emergence and post-emergence herbicides is still the most common technique for in-row weed control: It is cheap, quick, and easy to perform, especially with drift-reducing (shielded, tunnel) sprayers that can avoid phytotoxicity effects on the crop while helping to protect the environment. An additional advantage is that some post-emergence herbicides can control the vine suckers as well, making weed control and suckering possible in a single operation, with substantial cost saving.

However, the future use of chemicals is uncertain, because of several reasons, including: The rising concern about the adverse effects of herbicides on the environment and human health; increasing restrictions to some active substances, particularly post-emergence herbicides (glyphosate, glufosinate-ammonium, diquat); and the importance of organic farming, where "naturality" is perceived by consumers as an added value [5].

This has stimulated the development of non-chemical, alternative methods for weed control, such as flaming, steaming, and hot-foam machines [6–10]. While a thorough description would be outside the scope of the present work, it may be sufficient to say that all these methods require a large energy consumption from typically fossil fuels such as LPG or diesel oil. To avoid this problem, a novel, biomass-fueled, flaming prototype has been recently proposed (CS Thermos, San Vendemiano, TV). Advantages of the biomass-fueled prototype versus conventional, LPG-fueled flamers are: The use of a renewable fuel (with substantial reduction in GHG emissions); lower fuel costs; and the possibility of further savings by using vine wood pellet produced in the farm from pruning residuals.

The objective of this research was to assess the efficacy of the prototype for in-row weed control in the vineyard, in comparison to tillage and mowing.

2. Materials and Methods

A randomized-blocks experiment was performed in the vineyard, with three treatments (Flaming, Tillage and Mowing) and four replicates. Each treatment was applied three times (Flaming and Mowing) or five times (Tillage) between 23 March and 9 July 2018 (Table 1).

Table 1. Treatment dates, growth stages of the vines, implements used and dates of "after" assessments.

Date	BBCH Growth Stage [1]	Treatments			Date of "after" Assessment
		Flaming	Tillage	Mowing	
22 March	00 Dormancy		disc cultivator 4.5 km/h		23 March
10 May	55 Inflorescences swelling	pellet flamer 6.0 km/h			11 May
21 May	57 Inflorescences fully developed		blade weeder 2.6 km/h	mower 2.3 km/h	24 May
28 May	61 Beginning of flowering		finger weeder 5.2 km/h		29 May
11 June	73 Berries groat-sized	pellet flamer 4.3 km/h			14 June
18 June	75 Berries pea-sized		blade weeder 2.8 km/h	mower 2.2 km/h	21 June
9 July	77 Berries beginning to touch	pellet flamer 4.4 km/h	blade weeder 3.2 km/h	mower 2.3 km/h	13 July

[1], [11].

2.1. The Vineyard

The vineyard (cv: Merlot), located in Buttrio (Udine, Italy), was 15 years old and trained to a bi-lateral Guyot, i.e., cane-pruned with two canes per vine, tied to a supporting wire at 1.00 m approx. above the ground. The vines were spaced 1.15 m on the row, and 2.80 m between the rows. Until 2017, the vineyard had been managed using sod alleys (i.e., permanent ground cover between the rows) and a combination of tillage and herbicide applications to control weeds under the vines. Chemicals had been last applied on 11 November 2017 (gliphosate, at 1 L/ha).

2.2. The Implements

Flaming was applied with a prototype biomass-fueled flamer (CS Thermos, San Vendemiano TV, Italy), consisting of a fuel hopper (capacity: 300 dm^3, approx. 200 kg of wood pellet), an auger feeding system, a rotating-grid combustion chamber, and a horizontal chimney delivering the flame laterally onto the ground through a curved outlet (Figure 1). Two centrifugal fans (total flow rate: 950 m^3/h) provided the air for combustion and convection through the chimney and outlet. The prototype was tractor-mounted and one-sided, thus requiring two passes on either side of the row for completing the treatment. It could also use an optional, front-mounted water tank with 500 L capacity, fitted with pump and nozzles to prevent risks of fire from dry weeds or debris, which was, however, never used during the field tests, since no fires were ever observed. Wood pellet (cat. A1, Biopel, Kysucký Lieskovec, Slovakia) was used during the tests (lower calorific value: 16.54 MJ/kg). The flamer required 10 min approx. for ignition and for reaching a stable operating temperature (900 °C at the outlet). Wood pellet consumption was 32.0 kg/h (measured by refilling the hopper after two hours' work). Side tests were conducted in different parts of the same vineyard to assess the field capacity of the flamer under real working conditions. The area covered was 0.49 ha/h and 0.65 ha/h, at working speeds of 4.3 km/h and 6.0 km/h, respectively. The corresponding wood pellet consumption was 65.1 kg/ha and 49.6 kg/ha, respectively.

Figure 1. The biomass flamer in the vineyard on 11 June 2018.

Tillage was performed with a disc cultivator (on 22 March), a weeder blade (on 21 May, 18 June and 9 July), and a finger weeder (on 28 May).

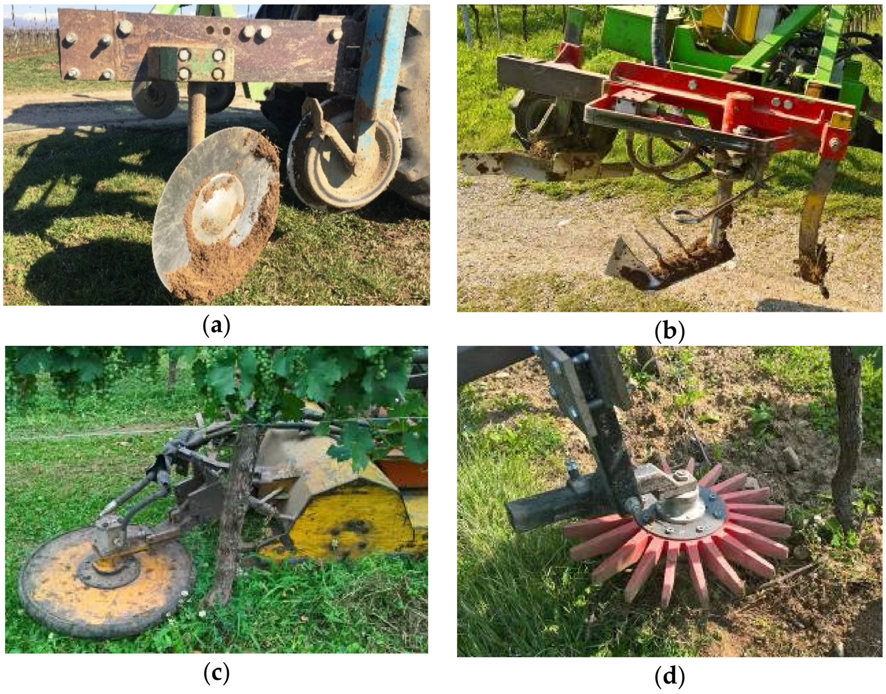
The disc cultivator (RI.ST.IC, Mossa, GO, Italy) (Figure 2a) consisted of a 3-point-hitch mounted frame, a couple of ridged steel wheels, and a concave disc on either side, designed to shuffle an amount of soil onto the row and so suffocate weeds. The resulting small mound of loosen soil was also favorable for the weeder blade (see later) to operate correctly.

The weeder blade cultivator (Arrizza, Fossacesia, CH, Italy) (Figure 2b) was a semi-mounted frame with a horizontal blade on either side, designed to being slightly inserted below the soil's surface so as to sever weed shoots from their roots. Each blade was provided with a vine-skipping mechanism, composed of a horizontal feeler rod and a single-acting hydraulic cylinder, designed to keep the blade in working position while allowing it to rotate back any time the feeler was pushed by sufficient pressure from trunks or posts.

The finger weeder cultivator (K.U.L.T. Kress, Vaihingen an der Enz, Germany) (Figure 2c) was a mounted, two-sided implement carrying on either side a semi-horizontal disc, or "finger weeder", fitted with 20 radial, rubber spikes (diameter: 540 mm), entrained by the soil's reaction so as to rotate and eradicate small weeds, while bending slightly close to posts and vine trunks to avoid damage to the crop.

Mowing was performed with an under-vine mower (Aedes, Andriano BZ, Italy) (Figure 2d), designed as an attachment to a standard flail mower for between-rows floor management. The under-vine tool itself consisted of a horizontal disc (diameter: 60 cm) with rubber protection edge and two axial cutting blades, driven by a hydraulic motor and provided with a mechanical vine-skipping mechanism. This consisted in a leverage connected to springs in such a way that the disc was forced to pivot inward by the pressure from vine trunks and posts.

All these implements were operated by a 4WD, 58-kW tractor (Fendt 280P, Agri Ravagnolo, Codroipo, UD, Italy).



(a) (b) (c) (d)

Figure 2. (**a**) The disc cultivator; (**b**) the blade weeder; (**c**) the mower; and (**d**) the finger weeder.

2.3. Experiment Layout and Measurements

The experimental area included 12 test rows (i.e., three main treatments × 4 replicates) and 13 border rows, i.e., one on each side of the area, three between the blocks, and one on each side of the Tillage rows. In fact, all tillage implements were two-sided, and this required two passes to till a complete row, leaving the two adjacent rows tilled on one side only; these rows were considered as borders. Other 15 rows in the same vineyard were available and were used to test and adjust each implement before application in the experimental area.

Tillage was first applied on 22 March 2018 with the disc cultivator. Flaming was applied on 10 May and 11 June, when most of weeds had reached a height of approx. 15 cm and 35 cm, respectively. Tillage (with the blade weeder) and Mowing had been planned for 11 May, but were delayed by rain and/or wet soil until 21 May; this caused a delay in the second application as well (18 June). After Tillage on 21 May, and based on insufficient weed control results obtained with the blade cultivator, particularly around vines (see comments in the Results section), an additional Tillage application with the finger weeder was made. All treatments were then applied again on 9 July. This resulted in three applications of both Flaming and Mowing, and five applications of Tillage (Table 1). Weed control on border rows was performed or completed with the flaming machine, generally on the same day of the experiment application.

Standard vineyard management was performed during the season, including: Suckering (i.e., the removal of shoots arising from below the cordon; on 28 May and 28 June, with a mechanical sucker remover, AVA Tordable ECOLO; AVA, Bègles, France), side and top trimming, vertical shoot positioning, and inter-row mowing (on 5 May, 13 June, and 14 July; between Flaming and Tillage rows only). Assessment of aboveground weed biomass was performed both before and after each treatment, with four measurements per row, using a square frame (Figure 3) of 50 cm × 50 cm, consisting in two plastic tubes held together by two portions of rope, so that it could be opened to place it around vine trunks when needed.

(**a**) (**b**)

Figure 3. The frames used for measurements: (**a**) Around a vine; (**b**) between two vines.

Efficacy (in % of weed biomass removed or killed) and re-growth between two applications (in g dry biomass /m^2) were calculated for each treatment.

Prior to assessment, four sample vines were randomly chosen along one row, spaced at least 15 m from each other, and labelled to avoid repeating the assessment in the same position. Each measurement consisted of: placing the frame on the ground, around the sample vine; cutting with scissors at ground level and manually collecting all weeds present within the frame; placing the sample in a plastic bag; placing the frame between the same vine and the nearest one in South direction; repeating the procedure. All samples were then weighed, dried in the oven at 103 °C for 24 h, and weighed again to determine the dry matter.

All "before" measurements were performed immediately before each application. "After" measurements were performed within four days from application. Such delay was necessary. In fact, "flamed" weeds visibly changed color within 10 min, wilted within 30 to 120 min (weeds exposed to sunlight wilted faster), and dried in one to two days. After tillage, some of the weeds, although damaged, still retained part of their roots and were so connected to the soil or to loose clods, and it was difficult to judge whether they could survive, unless they were let to dry completely. Although it was always managed to perform all "after" measurements on sunny days, they were to some extent affected by subjective judgement. Anyway, it was tried to include only "living" weeds or parts of weeds in the samples, both during the "after" and (especially for the Flaming treatments) even the "before" assessments.

Additional, complete assessments were performed: On 8 May, to evaluate the effect of the disc cultivator application versus untreated rows (Flaming and Mowing treatments); and on 27 July.

Living aboveground biomass samples were then expressed in g dry matter per m^2 ground (including the portion occupied by the vine trunk, in the "around" measurement).

The efficacy of an application (E, %) was calculated as:

$$E = 100\left(1 - \frac{Y_a}{Y_b}\right) \tag{1}$$

where Y_b and Y_a are the living aboveground biomasses before and after application, respectively.

Biomass growth between two consecutive application (G, g d.m./m^2) was defined as:

$$G = Y_{a,i-1} - Y_{b,i} \tag{2}$$

were $Y_{b,i}$ and $Y_{a,i-1}$ are the living aboveground biomasses before application i and after the previous application $i-1$, respectively.

Average efficacy and biomass growth were estimated for the whole under-vine area as weighed means, taking the respective lengths as weights, i.e.: 0.5 m around the vine, and 0.65 m between vines. Total weed biomass growth was finally calculated, including both the re-growth after applications until 27 July, and the growth since the last application of a chemical herbicide on November 2017.

Analysis of variance and Student–Newman–Keuls test for mean comparison were performed using the statistical package CoStat version 6.400 (Copyright 1998-2008, CoHort Software, Monterey, CA, 93940, USA).

3. Results

3.1. Efficacy of Weed Removal

The efficacy of the disc cultivator application on 22 March was uniformly rated 100%, since no weeds were visible on the day following application. In the later applications, the efficacy of Flaming was generally superior to that of Tillage or Mowing (Table 2). Average efficacy (i.e., the weighed mean of around-vines and between-vines sampling locations) was higher (76.1%) on 10 May than in later applications (66.3% on 11 June, and 64.4% on 9 July), probably owing to the lower weed biomass before treatment (59.9 g d.m./m^2, vs. 85.6 and 79.5 g d.m./m^2, respectively), and despite the higher forward speed (6 km/h vs. 4.3 and 4.4 km/h, respectively, Table 1). Efficacy of weed removal was also similar both around vines and between vines (56.4 to 77.7% and 64.3 to 75.0%, respectively).

Table 2. Weed biomass before application, and efficacy of weed removal (mean and standard deviation).

Treatment	Date	Biomass before, g d.m./m^2			Efficacy (%)					
		between	around	Average	between		around		Average	
		Mean	Mean	Mean	Mean	st.dev.	Mean	st.dev.	Mean	st.dev.
flamer	10 May	62.9	55.9	59.9	75.0	3.5	77.7	1.7	76.1	2.7
blade	21 May	90.8	71.3	82.3	68.3	5.5	45.8	5.6	59.9	4.2
mower	21 May	119.1	105.6	113.2	68.0	3.6	47.6	7.6	59.7	5.0
finger w.	28 May	28.6	38.6	33.0	33.1	15.2	44.1	6.2	39.0	9.8
combined [1]					79.1	4.4	69.8	3.7	75.6	4.0
flamer	11 June	94.8	73.7	85.6	64.3	4.7	69.5	5.7	66.3	5.1
blade	18 June	59.4	59.6	59.5	66.1	5.7	38.6	14.0	54.3	8.6
mower	18 June	122.4	98.9	112.2	51.7	3.2	37.0	10.0	46.1	2.8
flamer	09 July	93.0	61.9	79.5	68.6	1.3	56.4	1.4	64.4	1.1
blade	09 July	46.0	46.8	46.4	44.4	9.6	41.7	9.4	43.2	9.2
mower	09 July	102.3	94.5	98.9	40.3	5.5	41.2	3.1	40.7	3.2

[1], Combined effect of the blade weeder and finger weeder.

Average efficacy of the blade cultivator was 59.9% on 21 May, 54.3% on 18 June, and 43.2% on 9 July (Table 2). Such decrease was not related to an increase in weed biomass present before application, which actually decreased as well (from 82.3 to 59.5 and 46.4 g d.m./m^2, respectively). In general, the weeder blade removed weeds completely, severing them from their roots, unless prevented to do so by the vine trunks, or particularly thick weeds, or uneven ground (any lowering of the soil level preventing the blade from reaching the roots). At such locations, weeds remained difficult to eliminate, and this may account for decreased efficiency throughout the season. Efficacy was better between vines (44.4 to 68.3%) than around vines (38.6 to 45.8%).

Application of the finger weeder on 28 May, one week after the blade weeder, resulted in 39.0% average efficacy (44.1% around vines, 33.1% between vines; Table 2). Combined efficacy of the blade and finger weeders (75.6%, i.e., 69.8% around vines and 79.1% between vines) was similar to that of Flaming on 10 May.

The efficacy of Mowing was generally lower in comparison to either Flaming or Tillage; in fact, weeds were cut at 5 cm height approximately, so that any parts of weeds below this level remained untouched. Average efficacy decreased during the season (from 59.7 to 46.1% and 40.7%, on 21 May, 18 June and 9 July, respectively; Table 2), probably owing to the increase in thickness of the biomass layer under the cutting level. As in the Tillage treatments, efficacy was better between vines (40.3 to 68.0%) than around vines (37.0 to 47.6%).

3.2. Effect of the Disc Cultivator on Weed Re-Growth

The effect of the disc cultivator application can be analyzed based on the weed biomass assessment of 8 May, i.e., after 47 days (Table 3). Tillage reduced aboveground weed biomass by 50.3% in comparison to untreated plots (average of Flaming and Mowing treatments), i.e., by 52.2% between vines, and 47.7% around vines. All these differences were statistically significant. Biomass water content was not statistically different. However, Tillage resulted in slightly higher water content (85.4% versus 81.7%), owing to different weeds: mostly *Chenopodium album*, *Echinocloa crus-galli*, *Sorghum halepense* in Tillage, while *Stellaria media* was the predominant species in Flaming and Mowing.

Table 3. Effect of the disc cultivator: aboveground biomass (g d.m./m^2) on 8 May.

Treatment	between Vines			around Vines			Average		
	Mean	**st.dev.**	**([1])**	**Mean**	**st.dev.**	**([1])**	**Mean**	**st.dev.**	**([1])**
Flaming	62.9	7.6	a	55.9	5.4	a	59.9	3.8	a
Tillage	30.3	8.1	b	30.6	5.5	b	30.4	6.6	b
Mowing	63.7	9.0	a	61.0	8.3	a	62.5	8.3	a

([1]), Means in the same column denoted by the same letter do not differ significantly at $p < 0.05$ (Student–Newman–Keuls Test).

3.3. Total Growth of Weed Biomass until 27 July

Weed re-growth after application can be assumed as a measure of weed competition with the crop for water and nutrients. Such evaluation is necessary, since considering efficacy of weed removal alone [12] would not be sufficient for a correct comparison. In fact, none of the tested techniques was able to remove weeds completely; some of the weeds, or parts of them, remained in place and, although disturbed, were able to continue or to resume growth.

As expected, total growth of weed biomass until 27 July was maximum for the Mowing treatment (Table 4). Growth was better controlled by Tillage than by Flaming, with reductions in total weed biomass production until 27 July of 34% and 18%, respectively, versus Mowing. This was because the blade's action was more lasting than the flamer's. In fact, the former was able to completely extirpate most weeds, or to cut them from their roots, and apparently any re-growth from new seedlings was not sufficient to replace the biomass removed. On the contrary, Flaming never removed weeds completely, particularly grasses such as *Echinocloa crus-galli*, *Digitaria* spp., and *Sorghum halepense*, which remained generally alive in the first 3–5 cm from the ground with their growing points undisturbed, and so were able to resume growth.

Some broad-leaf weeds (especially *Chenopodium album*, *Sonchus arvensis*, and *Erigeron canadensis*) were difficult to control after they reached a height of 20 cm or more. At the time of the second flaming (11 June), nearly 25% of the sampling locations had weeds taller than 0.5 m; these were scarcely affected by the flame, having just their bottom leaves dried, while the upper leaves and the stem were mostly still green and turgid. *Chenopodium album* seemed particularly resistant, and able to recover even when most of its leaves had been desiccated or at least had severely withered.

Such tall weeds were, however, later controlled during mechanical sucker removal performed along all test rows on 28 June, so that no weeds taller than 25 cm were present in any of the sampling locations at the time of the third flaming on 9 July.

No significant differences were observed around the vines. In general, weed biomass growth was smaller here in comparison with the between-vines locations, owing in part to the presence of the trunk, which reduced by some extent the actual sampling area, but more probably to the vine's competition for water, nutrients and light. Considering that weed removal by tillage or mowing is typically difficult around the trunks and posts, because of the need of keeping a minimum safety distance, it was expected that Flaming might give better weed control at this location; but this seems not confirmed by the data in Table 4.

Table 4. Total aboveground biomass growth until 27 July 2018 (g d.m./m^2).

Treatment	between Vines			around Vines			Average		
	Mean	**st.dev.**	**(1)**	**Mean**	**st.dev.**	**(1)**	**Mean**	**st.dev.**	**(1)**
Flaming	261.0	17.5	b	200.5	16.3	a	234.7	6.5	b
Tillage	193.2	25.6	c	181.8	32.4	a	188.2	24.1	c
Mowing	317.4	37.3	a	241.8	48.6	a	284.5	26.9	a

(1), Means in the same column denoted by the same letter do not differ significantly at $p < 0.05$ (Student–Newman–Keuls Test).

3.4. Aboveground Biomass on 27 July

The final effect of the applied treatments can be evaluated based on weed biomass present on 27 July, i.e., 18 days after the last treatment on 9 July (Table 5). Tillage significantly reduced aboveground biomass by 41.3% in comparison to mowing, particularly between vines (53.5% less), while only to a limited extent (23.3% less) around vines. In comparison to Flaming, however, Tillage did not significantly reduce average biomass (9.7% less; not significant at $p < 0$ 0.05, Student–Newman–Keuls test); this was owing to a statistically significant reduction by 31.1% between vines, combined with an actual increase around vines (by 25.2%; not statistically significant). The data in Table 5 thus suggest that Flaming can indeed give a relatively better weed control around vine trunks at the end of the season. Even if total growth is not reduced, repeated applications can give a cumulative effect in this sense.

Table 5. Aboveground biomass (g d.m./m^2) on 27 July.

Treatment	between Vines			around Vines			Average		
	Mean	**st.dev.**	**(1)**	**Mean**	**st.dev.**	**(1)**	**Mean**	**st.dev.**	**(1)**
Flaming	88.9	16.0	b	70.7	16.2	b	81.0	14.8	b
Tillage	61.2	6.0	c	88.5	14.6	b	73.1	9.2	b
Mowing	131.6	25.3	a	115.4	10.1	a	124.5	16.2	a

(1), Means in the same column denoted by the same letter do not differ significantly at $p < 0.05$ (Student–Newman–Keuls Test).

4. Discussion

4.1. The Field Tests

The field tests showed that Flaming generally resulted in greater efficacy of weed removal in comparison to Tillage (blade weeder) and Mowing, both between the vines (64%–75% versus 44%–68%, and 40%–68%, respectively) and around the vines (56%–78%, 39%–46%, and 37%–48%, respectively). Only the combined effect of the blade weeder and the finger weeder resulted in better efficacy (80% between vines and 70% around vines), compared to Flaming (Table 2).

However, five applications of Tillage significantly reduced (by 26%) total weed growth until July 27 versus three applications of Flaming in the "between vines" sampling locations, while no significant differences were found in the "around vines" locations (Table 4). Similar results were found after assessing aboveground weed biomass at the end of the experiment on 27 July (Table 5). Such findings suggest that more frequent applications of Flaming (e.g., four per season, from spring to summer) may be needed to give comparable average weed control, while improving it close to the vine trunks.

Additional research is needed to optimize the timing and frequency of flaming, as well as to assess its efficacy against the most resistant weeds, particularly broadleaves such as *Chenopodium*, *Sonchus*, and *Erigeron* spp. In such tests, a different methodology for weed biomass assessment might be recommended. The method used in this study and in previous research [9,13] has the disadvantages of being destructive, thus increasing data variability, and time-consuming. Visual assessment of ground covered by the weeds, coupled with digital image analysis [10,14], while appropriate to assess treatments aiming at a complete removal of the weeds, as in most field crops experiments, seems hardly suited for permanent crops, when the purpose is just to reduce weed competition, because of the difficulty of establish a correlation between the ground area covered by the weeds and their actual biomass. Hence, a combination of the two methods, i.e., visual rating coupled with destructive sample weighing, as suggested by some studies [15], might be recommended for further field tests.

4.2. Biomass Flaming: Still Open Issues and Further Perspectives

Possible disadvantages of flaming, such as the risks of damaging the vines or triggering uncontrolled fires, should be further investigated. No damage to the vines, or even to shelters or other accessories, was however visually assessed during or after the tests. In order to prevent fires from dry weeds or debris, the flaming prototype can use an optional, front-mounted water tank with 500 L capacity, fitted with pump and nozzles, which was, however, never used during the field tests, since fires were never observed. In general, fires are unlikely to represent a serious problem in such rainy climates as that of Friuli Venezia Giulia: in fact, weeds grow faster when rainy day alternate with hot, sunny days, when it is generally possible to perform flaming with moist soil and vegetation, and so avoid any risks of fire; on the other hand, weed control is hardly needed during dry periods, because of the slower growth rate of the weeds. Nevertheless, also because of the importance of accident prevention in agricultural farms [16], an additional safety system is under study, in order to automatically exclude the flame and to prevent risks even in the case of unpredictable events, such as accidents or forced stops of the machine. Finally, the flue emissions of the flamer should be assessed, along with possible ways [17,18] to reduce them if necessary.

Biomass flaming is also an interesting alternative to other thermal methods, including LPG-fueled flamers, since the use of a renewable fuel can reduce net greenhouse gases (GHG) emissions and fuel costs, particularly if vine wood pellet, produced in the farm from pruning residuals, could be used. The wood pellet consumption recorded during the field tests (50 to 65 kg/ha approx.) can be compared with fossil fuel (propane) consumption (20 to 24 kg/ha) reported by various sources [8,19]. These figures imply a fuel cost of 17.5 to 22.8 €/ha for the wood pellet (at 0.35 €/kg), versus 46.0 to 55.2 €/ha for propane (at 2.3 €/kg). Additional savings are possible by using vine wood pellet produced in the farm from pruning residuals. Vineyards can produce 1 to 2.5 t of dried vineyard residual per hectare [20], so that flaming for weed control would use just a portion of it. However, while harvesting of pruning residuals is a well-established technique [21], further research is still needed to optimize biomass processing and vine wood pellet production [22].

5. Conclusions

The field tests confirmed that flaming may be an interesting alternative to tillage and mowing, particularly in such rainy climates as that of the North-East of Italy, because of advantages including: the wider application timeframe, since flaming can be applied even on moist soil and wet weeds; the higher working speeds (4 to 6 km/h); no damage is caused to the roots or vine trunks, thus avoiding the cost for replacement of damaged vines; better weed control around trunks and posts is possible, which eliminates the need of additional manual hoeing or weeding. Additionally, in comparison to tillage, a permanent sod is maintained under the vines, which helps prevent soil erosion in hilly vineyards.

The biomass-fueled flamer, on the other hand, is an interesting alternative to LPG-fueled flamers, because of advantages such as the reduction in net GHG emissions from the use of a renewable fuel, the lower fuel costs, and the possibility of further savings by using vine wood pellet produced in the farm from pruning residuals.

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References

1. Fregoni, M. *Viticoltura di Qualità*, 3rd ed.; Tecniche Nuove: Milano, Italy, 2013.
2. Hanson, B.D.; Roncoroni, J.; Hembree, K.J.; Molinar, R.; Elmore, C.L. Weed Control in Orchards and Vineyards. In *Encyclopedia of Applied Plant Sciences*, 3rd ed.; Academic Press: New York, NY, USA, 2016; pp. 479–484.
3. Gaviglio, C. Intérêt et limites des solutions alternatives au désherbage chimique sur le rang. *Prog. Agric. Vitic.* **2007**, *124*, 423–427.
4. Lanini, W.T.; McGourty, G.T.; Thrupp, L.A. Weed management for organic vineyards. In *Organic Winegrowing Manual*; McGourty, G., Ed.; University of California, Agriculture and Natural Resources: Davis, CA, USA, 2011; pp. 69–82.
5. Centner, T.J.; Russell, L.; Mays, M. Viewing evidence of harm accompanying uses of glyphosate-based herbicides under US legal requirements. *Sci. Total Environ.* **2019**, *648*, 609–617. [CrossRef] [PubMed]
6. Bekkers, T. Weed control options for commercial organic vineyards. *Wine Vitic. J.* **2011**, *6–7*, 62–64.
7. Hammermeister, A.M. Organic weed management in perennial fruits. *Sci. Hortic.* **2016**, *208*, 28–42. [CrossRef]
8. Martelloni, L.; Raffaelli, M.; Frasconi, C.; Fontanelli, M.; Peruzzi, A.; D'Onofrio, C. Using Flaming as an Alternative Method to Vine Suckering. *Agronomy* **2019**, *9*, 147. [CrossRef]
9. Horesh, A.; Goldwasser, Y.; Igbariya, K.; Peleg, Z.; Lati, R.N. Propane Flaming as a New Approach to Control Mediterranean Invasive Weeds. *Agronomy* **2019**, *9*, 187. [CrossRef]
10. Martelloni, L.; Frasconi, C.; Sportelli, M.; Fontanelli, M.; Raffaelli, M.; Peruzzi, A. The Use of Different Hot Foam Doses for Weed Control. *Agronomy* **2019**, *9*, 490. [CrossRef]
11. Lorenz, D.; Eichorn, D.; Bleiholder, H.; Klose, R.; Meier, U.; Weber, E. Phänologische Entwicklungsstadien der Weinrebe (*Vitis vinifera* L. ssp. vinifera). Codierung und Beschreibung nach der erweiterten BBCH-Skala. *Vitic. Enol. Sci.* **1994**, *49*, 66–70.
12. Saglam, C.; Kiran, T. Comparison of flame weeding with other methods in vineyard weed control. *Tarım Makinaları Bilimi Dergisi* **2010**, *6*, 181–184.
13. Shrestha, A.; Kurtural, S.K.; Fidelibus, M.W.; Dervishian, G.; Konduru, S. Efficacy and Cost of Cultivators, Steam, or an Organic Herbicide for Weed Control in Organic Vineyards in the San Joaquin Valley of California. *HortTechnology* **2013**, *23*, 99–108. [CrossRef]

14. Rasmussen, J.; Norremark, M.; Bibby, B.M. Assessment of leaf cover and crop soil cover in weed harrowing research using digital images. *Weed Res.* **2007**, *47*, 299–310. [CrossRef]
15. Domingues, A.C.; Ulloa, S.M.; Datta, A.; Knezevic, S.Z. Weed Response to Broadcast Flaming. *RURALS* **2008**, *3*, 2. Available online: http://digitalcommons.unl.edu/rurals/vol3/iss1/2 (accessed on 16 September 2019).
16. Cividino, S.R.S.; Pergher, G.; Zucchiatti, N.; Gubiani, R. Agricultural health and safety survey in Friuli Venezia Giulia. *Agriculture* **2018**, *8*, 9. [CrossRef]
17. Dell'antonia, D.; Pergher, G.; Cividino, S.R.S.; Gubiani, R.; Cecchini, M.; Marucci, A. Characterization of biomass emissions and potential reduction in small-scale pellet boiler. *Lect. Notes Comput. Sci.* **2013**, *7972*, 192–206. [CrossRef]
18. Pizzi, A.; Foppa Pedretti, E.; Duca, D.; Rossini, G.; Mengarelli, C.; Ilari, A.; Mancini, M.; Toscano, G. Emissions of heating appliances fuelled with agropellet produced from vine pruning residues and environmental aspects. *Renew. Energy* **2018**, *121*, 513–520. [CrossRef]
19. Officine Mingozzi. Technical Info. Available online: http://www.pirodiserbo.it/wp-content/uploads/2011/10/PFV-Disciplinare-Vigneto-rev1.pdf (accessed on 16 September 2019).
20. Zanetti, M.; Brandelet, B.; Marini, D.; Sgarbossa, A.; Giorio, C.; Badocco, D.; Tapparo, A.; Grigolato, S.; Rogaume, C.; Rogaume, Y.; et al. Vineyard pruning residues pellets for use in domestic appliances: A quality assessment according to the EN ISO 17225. *J. Agric. Eng.* **2017**, *XLVIII*, 612. [CrossRef]
21. Spinelli, R.; Nati, C.; Pari, L.; Mescalchin, E.; Magagnotti, N. Production and quality of biomass fuels from mechanized collection and processing of vineyard pruning residues. *Appl. Energy* **2012**, *89*, 374–379. [CrossRef]
22. Toscano, G.; Alfano, V.; Scarfone, A.; Pari, L. Pelleting Vineyard Pruning at Low Cost with a Mobile Technology. *Energies* **2018**, *11*, 2477. [CrossRef]