Technical solutions for under-row weed control in vineyards: Efficacy, costs and environmental aspects analysis

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Abstract

Weed control in vineyards is essential to allow optimal vines development. In this study, three different techniques (hoeing, chemical control, and mulching) used in vineyard's under-row weed control were compared considering their: operative and economic aspects, energy consumptions and environmental impacts. Trials were performed in a vineyard located in Canelli (AT), Italy, characterized by 3 different gradient slopes (<5%, 10-15%, >20%). Each technique has been tested in 3 adjacent rows per each of the 3 vineyard slopes (randomized block test). Two weed control treatments were performed (at 50 days interval) during the peak vegetation growth period (from mid-April to mid-August). Major families of weeds in the test rows were described and scored (%), and weed control efficiency was measured by comparing the weeds cover area projected to the ground vs the test area. Results highlights that the use of mulching machine and the boom sprayer permits to maintain a weed coverage lower than 30% independently of slope gradient. The hoeing, characterized by low operational costs (26 € h^{-1}) and energy requirement (550 MJ ha^{-1}), scored acceptable working performances, but, in case of heavy rains, it can cause a runoff of the soil. The chemical weed control, also if results a valid choice in term of work quality, is not a valid solution from the environmental point of view. The mulching machine, although shows higher operating costs compared to other machines tested (30 € h^{-1}), can be considered as the most viable alternative to chemical weed control because its working efficiency is comparable to that obtained by the sprayer.

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Introduction

In Europe vine cultivation is very spread, especially in Mediterranean area which is the location of three major European wine producers: Italy, France and Spain (OIV, 2018). Only in Italy about 700,000 hectares are dedicates to vineyards accounting for 6.9 million of tons of grapes produced (OIV, 2018).

In order to improve the quality and quantity of grapes production, vineyards require an accurate weed control. In fact, the weed incidence is considered one of the main causes of the grapes production reduction (Cirujeda *et al*., 2012). Generally, in vineyards it is possible to distinguish two different type of weed control: inter-row and under-row. The inter-row weed control can be carried out using conventional implements coming from the agricultural sector adapting their working width to inter-row distance. Differently, the under-row weed control must be performed using specific implements developed for this purpose able to remove weeds near the vine trees without damaging them (Tamagnone *et al*., 2011).

Independent of inter-row or under-row weed control techniques used, the techniques adopted are dependent on morphological area characteristics or vineyard training system. To date, the widespread weed control techniques are fundamentally three: i) chemical control by use of herbicide application; ii) mechanical control trough grass shredding; or iii) soil harrowing (Balsari *et al*., 2006). Herbicides use, even if it is cheaper compared to other techniques, causes some problems linked to environmental contamination and human health (Narayan *et al*., 2017). In the last years, to reduce the pollutant process due to plant protection products application during grow cycle of the vineyards, several direct and indirect measures were proposed. Among direct measures spray drift reducing technologies were proposed as effective to reduce spray drift at source (Grella *et al*., 2017; Miranda-Fuentes *et al*., 2018). Considering the weed control operations, the permanent grassing, soil covered with rock fragments, soil mulching using different plastic and organic materials, were proposed as the main alternatives to the chemical weed control in order to achieve a higher environmental sustainability. In fact, the choice of better weed control technique is based on various criteria like soil erosion, area slope, soil conservation, and environmental impact, not only the efficacy in weed control . Nevertheless, in order to reduce the cultivation costs increasing at the same time crop profitability, some farmers prefer to group different *agricultural activities* in one operation; the growers make the soil tillage combined with the weed control because it aerates the soil with consequent agronomic benefits.

The soil tillage can be made using different implements that generally are chosen considering the following parameters: soil working device, main technical characteristics (mass, power required, working width), working quality (weed control efficiency), soil main characteristics (geomorphology, type, rocks presence), and vineyard layout. A wrong implement choice may produce environmental undesirable effects, such as increasing the soil erosion caused by runoff or wind (De Laune and Sij, 2012), increasing at the same time the grower cost due to tractor high power consumption. The objective of this experimental work was to compare three different vineyard under-row weed control methods, in order to identify the best management options balancing the operative and economic aspects, energy consumption and environmental impacts.

Materials and methods

The experimentation was carried out in the North-West of Italy at the farm '*Ghione Anna*' in Canelli (AT) (44°43'17.2"N; 8°15'38.8"E). Tests were performed in a vineyard of Barbera (*Vitis vinifera* 'Barbera') 15 years old with a layout of 2.5 m × 1 m, espalier trained and Guyot pruned. During the test, weeds showed a BBCH-scale of 25 with a height of about 20 cm.

In the trials, three machines usually used for under-row weed control were employed: a tiller (B.F.M, B1, Cuneo, Italy) with axial hoeing head (tiller) (Figure 1), a short mounted boom sprayer (Abbà, Cuneo, Italy) equipped with a single nozzle XR11004VS (Teejet Technologies, IL, USA) for chemical control (sprayer) (Figure 2), and a mulching machine (Dragone, CR16, Asti, Italy) (mulcher) (Figure 3 and Table 1). All machines were set with a working width of 0.45 meters and they were attached to the three-point hitch and powered by a crawler tractor, featured by a power of 40 kW and with a mass of 2680 kg.

The performance of the different equipments was evaluated on sample areas corresponding to 15-meter long row. Within each of these areas, delimited by two poles, there were 15 plants. All machines were set up to work on a strip of 0.6 m under the row (0.3 m on each side of the vine trees). All tests were performed using a forward speed of 3 km h^{-1} because this is the max forward speed allowed by using the crawler tractor in all working conditions.

During the test, the sprayer applied a volume of 320 l ha^{-1} (at 0.15 MPa pressure) referred to the real sprayed area (this volume correspond to about 75 l ha^{-1} referred to vineyard surface) using glyphosate at a dosage of 0.81 l ha^{-1} of active ingredient.

The tests were performed in three areas characterized by different gradient slopes: i) less than 3%, indicated as Slope A; ii) between 10-15% indicated as Slope B; iii) more than 20% indicated as Slope C. In each vineyard slope area the three machines were tested in three adjacent rows (randomized block test); a portion of each row was left untreated (weeds infested) as control sample (Figure 4). Irrespective of slope, all land plots used for the trials showed similar physical soil characteristics: clay soil with a moisture content from 10 to 12%. Each plot had a length of 20 metres. For each machine, working times and manpower requirement were recorded on the field, according to CIOSTA (*Comité International d'Organisation Scientificue du Travail en Agricolture*) methodology (Manzone and Balsari, 2014). Working rate was estimated using analytic method that considers the worked surface in the unit time and it was expressed as ha h^{-1}.

Figure 1. Under-row tiller with axial hoeing head.

Figure 2. The boom sprayer chose for the trials.

Figure 3. Mulcher machine used in the test.

Table 1. Main technical characteristics and price of the machines used in the trials.

Technique	Machine type	Mass (kg)	Power required (kW)	Working type	Price (€)
Hoeing	Rotary tiller	240	4.8	Hoeing	6120
Chemical control	Sprayer	62	1.7	Herbicide distribution	1200
Mulching	Mulcher	420	12.0	Weed mulching	5900

The required manpower was determined considering the minimum number of operators necessary to the machine and the working time spent per unit surface (ha).

Working quality of each machine tested was determined evaluating the weed control in two different tests performed (at 50 days interval) during the peak vegetation growth period (from mid-April to mid-August, 2016). Families of weeds present in the test rows were described and scored (%), and weed control efficiency was measured by comparing coverage of control parcels (untreated) vs the test area (0.8 × 0.6 m). Every 10 days, in each test row, weeds were visually assessed and scored, always by the same operator throughout the study period. The efficacy of weed control was expressed as % of weeds removed after each treatment, and weeds re-growth was analyzed over the time. Since the weather conditions show a high influence on the weed growth, a weather station Vantage Pro2 GoWeather (Davis Instruments Corporation, CA, USA) was placed near the area used for tests monitoring the air temperature (C°), air relative humidity (%) and rainfall (mm).

In this experiment, the total energy required for each machine was determined by considering the direct energy consumption - the energy input to perform the weed control operation (tractor fuel and lubricant consumption) - and the indirect energy consumption - the energy used for the tractor and implements manufacturing (Manzone, 2016). An energy content of 92.0 MJ kg^{-1} for the tractor and an average value of 69.0 MJ for each kilogram of mass was considered for all of the implements (Mikkola and Ahokas, 2010). The direct energy input was calculated considering an energy content of 37.0 MJ L^{-1} for the diesel and of 83.7 MJ kg^{-1} for the lubricant. Additionally, 1.2 MJ kg^{-1} was added to these values, as energy required in their transportation and distribution.

The fuel consumption for the weed control operation was determined by the *topping-off system* (Manzone, 2015a). This method involves measuring the fuel consumption before and after to have worked a specific surface. The forward speed was determined using two couples of photocells ZOOM Z2E (Nologo S.r.l., Mi, Italy) placed at the distances of 10 m. In order to reduce the eventual effect of the lower forward speed during the manoeuvres in headland on the effective operative forward speed, the photocells were positioned at a distance from headland boundaries of at least 5 m. All distances were measured by a flexible metric ruler (Super active) (Metrica Spa, Mi, Italy) with accuracy of 2 mm. In each testing area (2000 m^2), the forward speed was determined with three replications. Since lubricant consumptions are very low in the unit time spent for test, these were estimated as a function of diesel consumptions according to the ASAE standards (1999).

The environmental impact of the weed control in vineyards was determined through CO_2 emission analysis. The analysis was carried out considering the CO_2 emissions from fuel combustion, lubricant consumed and machines maintenance and repair. Moreover, only for the sprayer, also the CO_2 emission in herbicide production were considered. This parameter was expressed in terms of kg of CO_2 emitted per unit surface worked (ha).

In this study, 2.94 kg of CO_2 for each kg of lubricant and 3.76 kg of CO_2 per litre of fuel emitted into the environment were considered. A value of 0.16 kg CO_2 released into the atmosphere per each MJ of energy content in the machines was assumed for maintenance and repair (Manzone, 2015a). Furthermore, an amount of 6.30 kg CO_2 per each litre of herbicide was considered in the calculation (Khoshnevisan *et al*., 2013).

The procedure used to calculate the machine cost was described by Miyata (1980), considering an annual utilisation of 500 h for the tractor (tractor used also for other operations) and 200 h for all implements tested. The investment costs used in the calculation for implements were reported in the Table 1, while the tractor ones amounted to 22.30 €. The depreciation period was assumed to be six years for implements and ten years for the tractor. Value retention at the end of this period was assumed to 20% of the initial investment. Repair and maintenance costs were considered those incurred directly by the machine owner (average value obtained during 5 years). Labour cost was considered to be 18.50 € h^{-1} (Manzone, 2015b). A value of 1.10 € dm^{-3} and 5.50 € kg^{-1} were assumed for fuel and lubricant, respectively.

All statistical analyses were performed using IBM SPSS Statistics (Statistical Package for the Social Sciences) for Windows. Separate ANOVA models considering slope gradient as a fixed effect for each weed families and weed families as a fixed effect for each slope gradient were made. Moreover, ANOVA models were used for all other parameters considered: Working rate, manpower, and energy consumption. Eventual differences between tests were checked by performing Tukey's multiple comparison test, adopting a significance level of α=0.05. Tukey's test was used because it highlighted a high power with this data distribution.

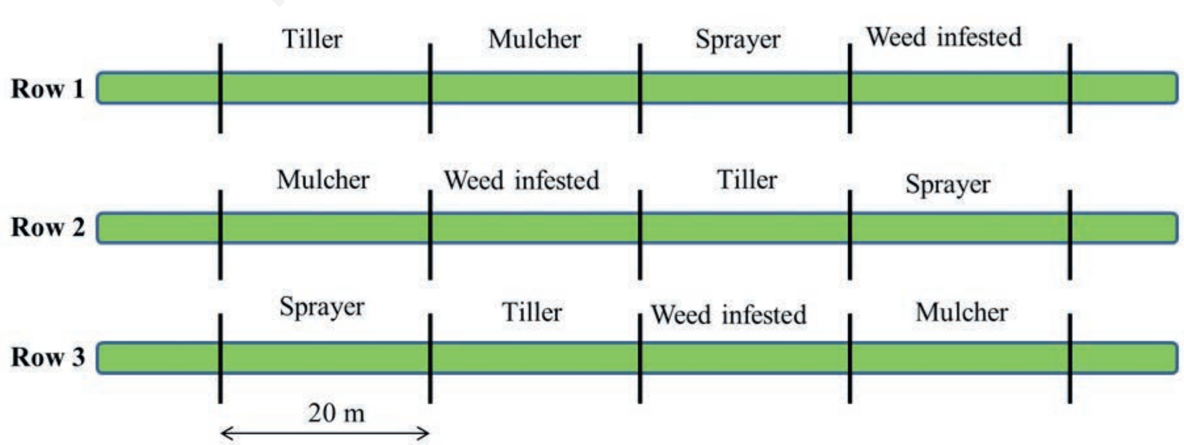

Figure 4. Plots disposition.

Results

Weather conditions

Air temperature during the test period ranged between 3 and 27°C (daily average of 17°C), while the monthly average air humidity varied between 64% and 72%. During the experimental period (50 days before the first treatment and 50 days after the second treatment), 158 mm of rain were measured. Each rain event contributed up to 22 mm and these were mainly concentrated between the first and the second treatment (Figure 5). All values of these parameters were in line with those recorded by the same weather station in the last five years. In this period, in fact, the daily average air temperature was 18°C, the monthly average air humidity varied between 60% and 74% and the average amount of water precipitations was 143 mm.

Weed analysis

Weeds present in the tested area was a mix of different species belonging to different botanic families, among them two were the predominant: Poaceae about 65% and Asteraceae about 25%. Two way ANOVA showed no difference between the botanic families composing the weed coverage in all plots sited in the three different vineyards slope gradients (Table 2).

Working times

During the trials all machines have guaranteed a good level of work efficiency showing a high productive working time (94%). No difference in splitting working time were highlighted. Unproductive time, mainly due to workers' break, were limited (1%) for all implements and the 5% remaining was attributable to time required in headland for maneuvers.

The higher working rate was obtained by sprayer and rotary tiller with values of about 0.41 ha per working hour. Statistical analysis showed no difference between different slope gradient for all tested machines (Table 3).

Similar values trend was found regarding the manpower requirements; the better performance was obtained by sprayer and rotary tiller (2.49 h ha^{-1}). Also this parameter resulted not influenced by the slope gradient (Table 3).

Working quality

Data processing highlighted that after the second treatment the weed growth was lower (about 30%) compared to the first treatment (Table 4). The difference could be attributable to different weather conditions, in fact, the second treatment was performed in summer where the climate was dry while the first treatment was carried out in spring when the rain events were more frequent. The statistical analysis showed significant difference between all machines tested, slope gradients, and treatments (Table 5).

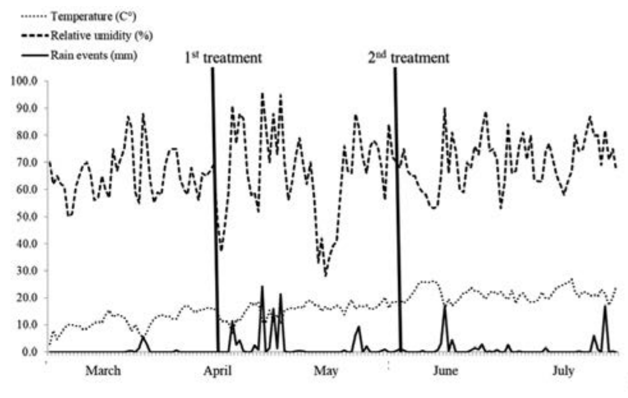

Figure 5. Weather data recorded during the experiment.

Table 2. Coverage percentage of different weed families in the different vineyard slope gradient (A<5%, B=10-15%, C>20%).

Weed families	Slope gradient A Mean	A SD	B Mean	B SD	C Mean	C SD
Poaceae	64^{aA}	2.44	62^{aA}	2.06	66^{aA}	1.91
Asteraceae	24^{bA}	1.29	27^{bA}	1.29	22^{bA}	1.29
Others	12^{cA}	0.57	11^{cA}	0.81	12^{cA}	1.41

Slope: F=0.103; df=2, 35; P=0.903; weed families: F=3700.985; df=2, 35; P<0.0001; Slope × weed families: F=7529; df=4, 35; P<0.0001). SD, standard deviation; values in table is a mean of 3 test replications; lower case letters indicate significant differences between percentage of different coverage families weed for each slope gradient separately; upper case letters indicate the statistical difference among slope gradients.

Table 3. Working rate and manpower of the tested machines as a function of gradient slope.

Working rate	Slope gradient A Mean	A SD	B Mean	B SD	C Mean	C SD
Hoeing	0.40^{bA}	0.0048	0.39^{bA}	0.0100	0.39^{bA}	0.0076
Chemical control	0.41^{bA}	0.0061	0.39^{bA}	0.0055	0.40^{bA}	0.0053
Mulching	0.35^{aA}	0.0072	0.33^{aA}	0.0091	0.33^{aA}	0.0100
Manpower	**Slope gradient A Mean**	**A SD**	**B Mean**	**B SD**	**C Mean**	**C SD**
Hoeing	2.49^{aA}	0.035	2.55^{aA}	0.031	2.51^{aA}	0.028
Chemical control	2.43^{aA}	0.062	2.58^{aA}	0.075	2.44^{aA}	0.083
Mulching	2.84^{bA}	0.085	3.03^{bA}	0.061	2.89^{bA}	0.076

Working rate: Slope: F=9.332; df=2, 26; P<0.0001; machines: F=288.222; df=2, 26; P<0.0001; Slope × machines: F=3.454; df=4, 26; P<0.0001. *Manpower*: Slope: F=12.432; df=2, 26; P<0.0001; machines: F=372.792; df=2, 26; P<0.0001; Slope × machines: F=5.701; df=4, 26; P<0.0001. SD, standard deviation; values in table is a mean of 3 test replications; lower case letters indicate significant differences between machine type for each slope gradient separately; upper case letters indicate the statistical difference among slope gradients.

Table 4. Weed coverage after 50 days from the first and the second treatment.

Slope gradient	Treatment 1 A Mean	SD	B Mean	SD	C Mean	SD	Treatment 2 A Mean	SD	B Mean	SD	C Mean	SD
Hoeing	41.7	22.5	61.7	37.5	51.7	23.6	28.3	10.4	20.0	13.2	13.3	2.9
Chemical control	16.7	20.2	3.3	2.9	5.3	5.0	13.3	23.1	5.9	5.8	0.0	0.0
Mulching	23.3	14.4	13.3	2.9	10.0	2.9	28.3	23.1	6.7	5.8	8.3	2.9

SD, standard deviation; values in table is a mean of 3 test replications and they are a percentage value of the initial weed coverage relative to each treatment.

In general, all machines have guaranteed a good work quality with an initial weed control higher than 95%. Nevertheless, the chemical control needs a period of 10 days after the spray application to achieve the maximum efficiency (Figure 6). Differently from other machines tested, the rotary tiller showed a remarkable efficiency reduction on the weed control after 30 days from the treatment; in fact, the working efficiency resulted only 56% after 40 days and it reduced to 38% at the 50th days from the first treatment (Figure 6).

Energetic evaluation

The energy consumption of the tested implements ranged between 469.2 and 848.3 MJ ha^{-1} as a function of the differences in their mass, fuel consumption and field capacity. The sprayer showed the lowest value (469.2 MJ ha^{-1}), while the rotary tiller showed the highest value (588.7 MJ ha^{-1}). The incidence of the indirect energy always resulted lower than 1% of the total energy required to perform the weed control operation (Table 6).

CO_2 emission analysis

The amount of CO_2 eq emitted during the weed control ranged between 49.70 kg ha^{-1} and 57.40 kg ha^{-1}. The higher value (57.40 kg ha^{-1}) was obtained by the rotary tiller, instead the lower value was observed with the mulcher use: fuel consumptions showed the mainly incidence (98%) on the total CO_2 emissions in both machines. On the other hand, although the sprayer has recorded a low value of CO_2 emissions on fuel consumptions, intermediate value was highlighted (50.86 kg ha^{-1}) due to CO_2 emission related to herbicide used (5.10 kg ha^{-1}). Lubricant consumption and maintenance and repair showed an incidence on total emissions always under 1% for all machines tested (Table 7).

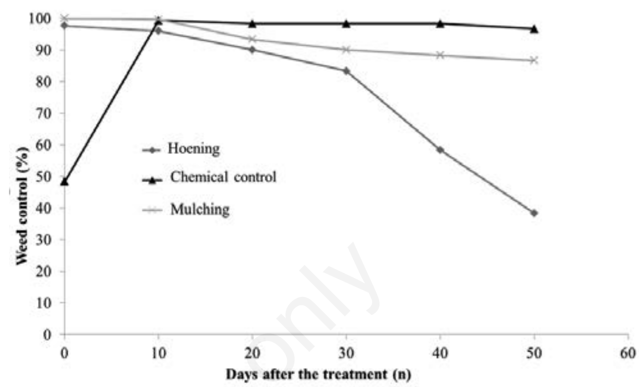

Figure 6. Weed control efficiency of the machines tested.

Table 5. ANOVA results referred to weed coverage.

	SS	df	F value	P value
Correct model	15,029.213	17	88.706	<0.001
Intercept	20,542.471	1	2061.18	<0.001
Treatment	1768.51	1	177.448	<0.001
Slope	1018.175	2	51.081	<0.001
Technique	7966.765	2	399.683	<0.001
Treatment × Slope	381.722	2	19.151	<0.001
Treatment × technique	2618.427	2	131.363	<0.001
Slope × technique	784.324	4	19.674	<0.001
Treatment × Slope × technique	491.291	4	12.324	<0.001
Error	358.789	36		
Total correct	15,388.002	53		

SS, sum of squares; df, degree of freedom.

Table 6. Energy consumption (MJ ha^{-1}) and hourly costs of the tested machines.

Machine type	Direct energy	Indirect energy	Total energy	Hourly cost (€ h^{-1})	Cost for unit surface (€ ha^{-1})
Hoeing	585.4	3.3	588.7	26.89	68.29
Chemical control	466.5	2.7	469.2	32.41	80.52
Mulching	506.4	3.1	509.5	29.38	86.09

Table 7. CO_2 emitted during the weed control.

	CO_2 emitted (kg ha^{-1})				
	Fuel	Lubricant	Repair	Material	Total
Hoeing	56.47	0.41	0.52		57.40
Chemical control	45.00	0.33	0.43	5.10	50.86
Mulching	48.85	0.36	0.49		49.70

Economic evaluation

The economic analysis showed that the weed control cost ranged from 68.29 to 86.09 Euro per hectare. Lower values were achieved by rotary tiller, instead the highest value was observed for mulcher. Middle value (80.52 € ha^{-1}) was obtained by sprayer used for herbicide application (Table 6). The low value achieved by the rotary tiller can be attributed to the low power required and the non-use of additional material like plastic wire (mulcher) and chemical products (Sprayer).

Discussion and conclusions

The data collected would provide a set of useful information to be used in the selection of machine for under-row weed control in slope vineyards. Results showed that the slope gradient influences the weed regrowth independently of the machine types tested. Data suggests that weeds regrowth was limited on areas with a higher slope gradient. This result is not affected only by machines performances, but it could be related also to the lower water availability in the slope soil. The rainfall events in slope area generate the soil erosion but also limit the water penetration into the soil (Luo *et al*., 2018).

The use of mulchers and sprayers (chemical control) have allowed to maintain a weed coverage lower than 30% independently from the slope gradient. This weed coverage value could be considered the limit over which the weeds must be removed. Although this value can be considered as a fairly low threshold index, it must be considered that the rotary tiller cannot guarantee a weed coverage below 60%.

In order to select the most suitable machine it is needed to consider also other parameters (energy required, economic cost, and environmental impact).

Although the rotary tiller used guaranteed an acceptable weed control during the tests, maintaining at the same time low hourly costs (about 26 € h^{-1}) and energy requirement (550 MJ ha^{-1}), it can generate runoff in case of heavy rains (De Laune and Sij, 2012). Nevertheless, this machine type is preferred to other weed control systems because with a single pass it is possible to perform more operations in simultaneous: weed control, soil aeration, and organic matter burying. In addition, fragmentation of the underground storage organs (*e.g*., thickened roots or rhizomes) of perennial species is an important aspect of the mechanical weed control (Ringselle *et al*., 2018). In fact, in these weed species, the clonal integration is beneficial to the clonal network as a whole thanks to its resources and information content (Lopp and Sammul, 2016). Fragmenting the storage organs can decrease their intraspecific competitions because dividing the resources of the underground network, it is possible to reduce the amount available to each fragment. Moreover, the plant parts damaged are more susceptible to infections (Imathiu *et al*., 2009).

The chemical weed control through the use of boom sprayer was the best choice in terms of work quality, but it is not the best environmental choice. The toxic effects of herbicide applied (glyphosate), especially if combined to heavy metals, can be persistent in soil until 120 days from the application (Domine *et al*., 1993). In general, herbicides are toxic not only to humans, but they are very dangerous for terrestrial organisms and microorganisms, plants and earthworms (Uwizeyimana *et al*., 2017). In the last years, chemical substances have contaminated also urban and suburban surface water around the world: in America (Smith, 2013), in Vietnam (Chau *et al*., 2015) and in China (Kong *et al*., 2015). In addition, the overuse of chemical products for weed control can select herbicides-resistant weeds; globally 208 resistant weed species have been individuated (Heap, 2013).

The mulcher, although showing higher operating costs compared to other machines tested mainly due to high power required (30 € h^{-1}), can be considered as the most viable alternative because its working efficiency is comparable to that obtained by the sprayer. In addition, weed mulched and left at the soil surface can provide several advantages to the vineyard in terms of: reduction of surface runoff and soil erosion regulation of the soil surface temperature, capture of rainfall water, reduction of the water evaporation from the soil surface translated in soil water content increase, weeds control, and increasing of the total organic matter in the top soil (Castellanos-Navarrete *et al*., 2012).

From the environmental side impact, limited to CO_2 emissions released in atmosphere, the under-row weed control showed values (49.70 kg ha^{-1} - 57.40 kg ha^{-1}) in line with those obtained during other agricultural activities: e.g. tree planting (31 kg ha^{-1} - 92 kg ha^{-1}) (Manzone, 2016).

Although the mulcher highlighted higher CO_2 emissions due to fuel consumptions, compared to the boom sprayer weed control system, it achieved the best environmental results because does not require the use of chemical compounds.

In conclusion, the mulcher can be considered the best environmental friendly alternative to chemical under-row weed control in vineyard, for its good performances in weed control despite high operative costs and energy requirement.

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