agronomy

MDPI

Article

Comparative Analysis of the Performance of a Chain Mower and Tools That Perform Under-Row Weed Control with Tillage in the Vineyard

Lorenzo Gagliardi, Sofia Matilde Luglio, Andrea Peruzzi *, Marco Fontanelli, Christian Frasconi and Michele Raffaelli

Department of Agriculture, Food and Environment, University of Pisa, Via del Borghetto 80, 56124 Pisa, Italy; lorenzo.gagliardi@phd.unipi.it (L.G.); sofiamatilde.luglio@phd.unipi.it (S.M.L.); marco.fontanelli@unipi.it (M.F.); christian.frasconi@unipi.it (C.F.); michele.raffaelli@unipi.it (M.R.)

* Correspondence: andrea.peruzzi@unipi.it

Abstract: In the Mediterranean area, vineyard soils are often characterized by a high stone content. In these contexts, where tools commonly adopted for under-row weed control are frequently damaged, the utilization of a chain mower could be a preferable alternative. This research aims to compare a modified mower with chains with other tools commonly employed that control weeds through tillage, such as motorized discs, blade weeder, and rotary star hoe. Weed control effectiveness, effects on weed flora composition, soil compaction, and operative efficiencies were evaluated. The chain mower allowed us to obtain encouraging results of weed biomass reduction (55.4 and 25.4%, between and around vine trunks, respectively), weed height reduction (35.9%), and weed cover reduction (79.2%), comparable to the other tools. All the tools showed a lower weed control efficacy around vine trunks rather than between them (weed biomass reductions of 24.8% and 52.6%, respectively). Results regarding the effect on weed flora composition seem to confirm this trend. Despite the higher chain mower field time (3.78 h ha^{-1}) and fuel consumption (24.24 kg ha^{-1}) compared to the blade weeder and the rotary star hoe, its versatility in stony soil and its lower impact on soil (soil penetration resistances of 1602.42 and 2262.83 kPa in 2022 and 2023, respectively) compared to the other tools make it a potentially advantageous implement for under-row weed management in vineyards. Further studies could be useful to improve chain mower performance, particularly around vine trunks, by evaluating in different planting layouts different dimensions of both the cutting element and feeler, which allows the vine-skipping mechanism.

Keywords: mowing; non-chemical weed control; mechanical weed control; organic farming; soil health; soil compaction; weed flora composition; sustainable vineyard management

check for updates

Citation: Gagliardi, L.; Luglio, S.M.; Peruzzi, A.; Fontanelli, M.; Frasconi, C.; Raffaelli, M. Comparative Analysis of the Performance of a Chain Mower and Tools That Perform Under-Row Weed Control with Tillage in the Vineyard. *Agronomy* **2024**, *14*, 206. https://doi.org/10.3390/agronomy14010206

Academic Editor: Anestis Karkanis

Received: 29 December 2023
Revised: 12 January 2024
Accepted: 15 January 2024
Published: 17 January 2024

1. Introduction

Vineyards are the prevalent crop in various regions over the Mediterranean basin, representing a significant economic pursuit. In particular, Spain, France, and Italy are the European countries with the largest vineyard area and the greatest wine production [1]. Adapting to climate change while maintaining both the quality and sustainability of production poses a significant challenge for viticulture [2]. In recent years, organic farming has been experiencing rapid growth in the vineyards of the southern European Mediterranean region, driven by growing social interest and supportive legislation promoting environmentally friendly and sustainable production systems [3]. However, organic farmers still rely on conventional intensive tillage to carry out various agricultural operations [4]. Among the various challenges, weed presence can substantially impact vineyard performance due to their competitive interaction with the crop for crucial resources like water and nutrients [5]. Regarding inter-row management, there has been a transition from practices involving bare soil management to the adoption of approaches that promote increased plant coverage [6].

However, tillage remains the most traditional weed control strategy in organic farming [7], especially with regard to the management of the area under the rows.

1.1. Under-row Weed Control with Tillage

There are various means available for under-row weed control with tillage. Among these, there are tools such as discs, blade weeders, and rotary star hoes. Discs can be used with motorized plow heads or with filler heads with idle spinning discs. The motorized plow disc head, equipped with a vine-skipping mechanism with a feeler, operates between the vines at a depth of 10–15 cm with a working speed of approximately 2 km·h^{-1}. It controls weeds by loosening the soil, which is partially turned over and moved towards the inter-row. The filler head, not equipped with a feeler, moves the soil toward the row [8]. The blade weeder is a horizontal blade that superficially penetrates the soil, cutting weed roots from their shoots. This tool is equipped with a vine-skipping mechanism by means of a feeler and operates at a speed of approximately 3–7 km·h^{-1} [9,10]. The rotary star hoe is a ground-driven star-shaped hoe not equipped with a vine-skipping mechanism that operates with a working speed of 6–8 km·h^{-1} [10,11]. Despite their effectiveness, tillage practices can lead to various negative effects. They can bring new weed seeds onto the soil surface and tend to boost the mineralization of soil nitrogen, creating favorable conditions for weed flushes [12]. Furthermore, they can favor soil compaction, loss of soil structure, soil erosion, and relevant reductions in soil organic matter and fertility [13]. Vineyards in Mediterranean regions experience considerable soil degradation issues, leading to a growing public concern [14]. This is due, in addition to intensive tillage, to the planting of vineyards on poor soils with coarse texture, high stone content, limited organic matter, steep slopes, and the highly non-uniform rainfall characteristic of the Mediterranean climate, which contributes to promoting further soil degradation [15].

1.2. Under-Row Weed Control with Mowing or Shredding

Mechanical weed control methods also include mowing and shredding weeds. Although this strategy has been shown to be less effective than tillage, requiring a greater number of treatments during the year, it presents positive environmental implications. Indeed, mowing results in minimal soil disruption, contributing to the preservation or enhancement of soil structure and overall health [16]. Moreover, mowing and shredding have been shown to effectively reduce the competitive ability and lifespan of perennial weeds and prevent seed production in various weed species, limiting their spread [17,18]. For this purpose, tools such as a brush weeder can be used. This tool consists of a horizontal rotor equipped with wires usually made of synthetic material such as polypropylene, which allows the cutting of weeds' epigeal portion effectively also around vines [19]. The most recent models of this tool are equipped with a vine-skipping mechanism. To be effective, it must be used when weeds do not exceed a height of 30–40 cm [8]. This tool is usually employed with a working speed of approximately 3 km·h^{-1}. However, brush weeders have the critical disadvantage of being able to damage trunks, thereby promoting the onset of diseases [9,20]. Another tool commonly applied to cut weed is the under-vine mower. This tool, also equipped with a vine-skipping mechanism, consists of a horizontal disc case of various diameters (from 40 to 80 cm) equipped with radial blades. It presents a working speed ranging from 2 to 6 km·h^{-1}. Under-vine mowers enable the cutting of invasive biomass at a specific height while leaving the underlying portion untouched, thereby allowing the preservation of a soil cover that protects against erosive phenomena [9]. However, the control of weeds around trunks can be limited as the disc has a diameter that does not allow the blades to come into contact with trunks [8].

1.3. Impact of Weed Control Methods on Weed Flora Composition

Concerning the impact on biodiversity, plant communities in vineyards can be significantly influenced by the type and intensity of management practices [21,22]. Vineyards managed with tillage exhibit a higher frequency of annual species that reproduce by seed compared to vineyards managed through mowing [23]. Instead, it was observed that mowing was linked to increased biodiversity values and greater ground cover compared to tillage and herbicide use. Furthermore, mowing promoted the growth of shorter plants, potentially less competitive with vines [24]. The higher occurrence of annual species in tillage-managed vineyards is attributed to the substantial soil disturbance caused by tillage, resetting the ecological succession from the soil seed bank [25]. This disturbance triggers extensive weed emergence. On the contrary, mowing tends to favor perennial forms due to incomplete plant destruction, allowing re-sprouting from vegetative organs [21].

In the Mediterranean area, vineyards are often characterized by a high stone content. In these conditions, tools such as brush weeders are subject to wire breakage and, therefore, to frequent replacement, as well as the blades of under-vine mowers. Chain mowers are suitable for stony soils, considering that chains bend over stones [26–28]. Therefore, the utilization of a chain mower could be a preferable alternative for under-row weed management of stony vineyards. In this study, the performance of a modified mower with chains previously successfully tested for under-row weed control in an agroforestry farming system [29] was evaluated in a vineyard. Therefore, this research aims to compare the chain mower with other tools that control weeds under-row through tillage. In the comparison, the performance of the tools is evaluated in terms of weed control effectiveness, effects on weed flora composition, soil compaction, and operative efficiencies.

2. Materials and Methods

2.1. Site Characteristics

A three-year field trial (2021–2023) was conducted at the Ornellaia winery, Castagneto Carducci (Livorno), Italy (43° 14′ 19.1″ N, 10° 37′ 35.3″ E, 129 m a.s.l.). The vineyard (*cv*: Petit Manseng) was planted in 2003 and trained with spurred cordon. The planting layout was 2.00 m between the rows and 0.8 m within the rows. The cordons were 1.00 m in height. The soil texture was sandy clay (54% sand, 16% silt, and 30% clay). Soil organic matter corresponded to 1.3%, and pH was 8.0. Electrical conductivity was 140 $\mu S\ cm^{-1}$, and cation-exchange capacity was 18.93 meq 100 g^{-1}. The soil bulk density in the under-row area before the start of the trial corresponded to 1.36 $g\ cm^{-3}$. The soil penetration resistance in the under-row as an average value between depths from 0 to 25 cm was equal to 1625.82 kPa, with a soil moisture content equal to 13.8%. The weather follows a Mediterranean pattern, featuring seasonal peaks of rainfall in spring and fall. The experimental area's average minimum and maximum air temperatures and total monthly rainfall (mm) during the three-year trial are shown in Figure 1.

2.2. Experimental Layout

This trial was conducted during the growing seasons 2021, 2022, and 2023 to compare the under-row weed control performance of the modified mower with chains with other tools commonly adopted for this purpose, such as motorized discs, blade weeder, and rotary star hoe. Two under-row weed control interventions were carried out during each growing season. In 2021, the first intervention was performed on 23 April, and the second on 2 July. In 2022, the interventions were performed on 14 April and 5 July. In 2023, the first treatment was performed on 28 April, and the second on 4 July. The implements were compared according to a randomized complete block design with three replications. Twelve rows were selected within the same vineyard, and each row was split into three blocks, each spanning 50 m. Every year, before the first under-row weed control treatment performed with the previously mentioned tools, an intervention was carried out with rotary star hoe in February on the entire vineyard involved in the trial. During the trial, the soil in the inter-row area was maintained with a permanent cover consisting of resident species managed with periodic shredding.

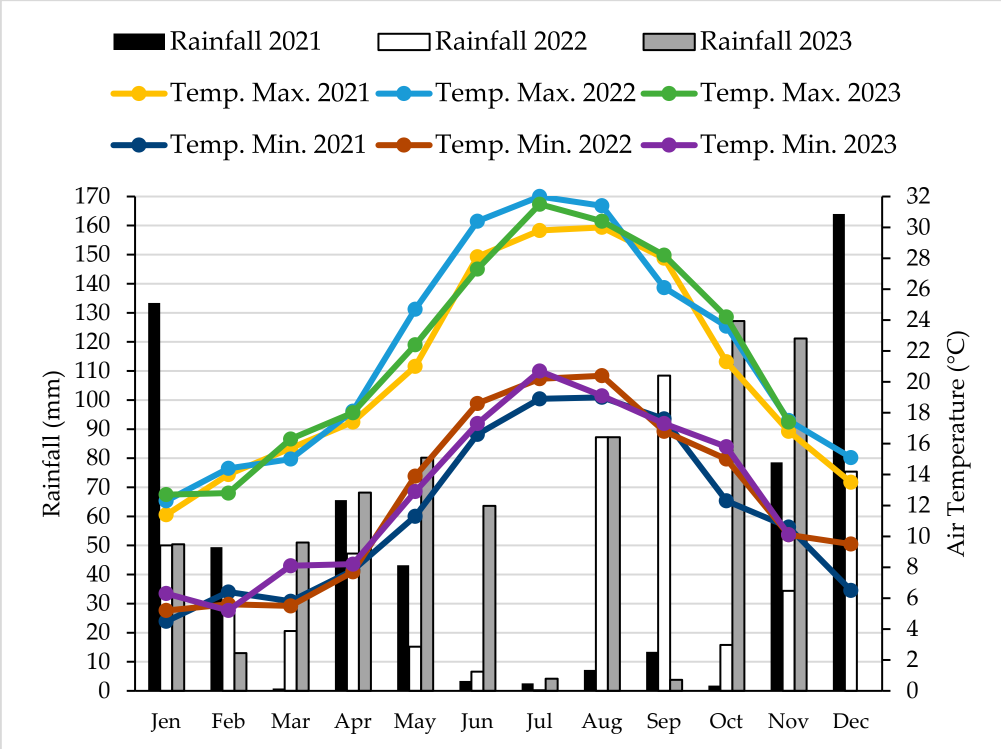

Figure 1. The experimental area's average minimum and maximum air temperatures and total monthly rainfall (mm) during the three-year trial.

2.3. The Tools Employed

The modified mower with chains (Figure 2a) is powered by the power take-off and features a separate hydraulic system. The mowing implement consists of a horizontal disc case (with a diameter of 0.40 m) equipped with grade-8 chains in tempered steel (EN 818-2) driven by a hydraulic motor. The chains mow the weeds by rubbing lightly on the soil surface. The characteristics of the commercial version of the mower (Dondi, Bastia Umbra, Italy) and the modifications made are reported in [29]. The cutting width of the mowing implement equipped with chains was 0.32 m. The machine is equipped with a vine-skipping mechanism; thus, the mowing implement enters the row and exits when the feeler perceives vine trunks. The chain mower was mounted in the rear part of the tractor and is a one-sided type.

The Radius SL blade weeder (Clemens, Wittlich, Germany) (Figure 2b) is operated by the tractor's hydraulic system. The tool consisted of a horizontal blade designed to be inserted just beneath the soil surface, facilitating the cutting of weed shoots from their root. The blade used in the trial was equipped with clearing shares. Also, in this case, the tool was equipped with a vine-skipping mechanism by means of a feeler. In the trial, the tool holder was mounted on the rear part of the tractor and was a two-sided type; thus, there was a blade weeder on each side of the tool holder. During the trial, the tool holder was equipped with a cage roller. Motorized discs (Figure 2c) are mounted on a tool holder Marte (A. Spedo, Badia Polesine, Italy) and are driven by an independent hydraulic system operated by the tractor power take-off. The tool is represented by a motorized plow head made up of three discs with smooth profiles and concave facing the inter-row that digs the soil under the vine and moves it in the inter-row area. The tool was equipped with a vine-skipping mechanism by means of a feeler. For this trial, the tool holder was mounted in the rear part of the tractor and was equipped with motorized discs on only one side. The rotary star hoe (Braun, Landau in der Pfalz, Germany) (Figure 2d) is a ground-driven rotary hoe with two discs. The tool loosens the soil, eradicating weeds near the row, and redistributes a volume of soil beneath the row, suppressing weeds in that position. The tool was positioned on a vertical hydraulic lifter in the mid-axel area of the tractor. The tractor was equipped with a rotary star hoe on each side. The main parameters of the employed tools are shown in Table 1. During the trial, the different tools used were mounted on 210 v Vario tractors (Fendt, Marktoberdorf, Germany) powered with a 73 kW diesel engine, with the exception of the motorized discs for which a T 4050 N tractor (CNH Industrial Capital, New Holland, Basildon, UK) with a 71 kW diesel engine was used. Figure 3 shows the positioning of tools and their respective tool holders on the tractors.

Figure 2. Tools employed in the trial: chain mower (**a**), blade weeder (**b**), motorized discs (**c**), and rotary star hoe (**d**).

Table 1. Tools' technical parameters.

Tool	Working Elements	Tractor Attachment Configuration	Vine-Skipping Mechanism	Power Transmission	Working Width (cm)
Chain mower	Horizontal disc case with chains	Three-point hitch rear	Feeler	PTO[1]-powered independent hydraulic system	32
Motorized discs	Plow head with three concave discs	Three-point hitch rear	Feeler	PTO-powered independent hydraulic system	45
Blade weeder	Horizontal blade	Three-point hitch rear	Feeler	Tractor hydraulic system	34
Rotary star hoe	Double star-shaped hoe	Mid-mounted	Absent	Ground-driven	36

PTO—power take-off.

2.4. Data Collection

Weed biomass, weed cover, and weed height were evaluated before each treatment and four days later. Measurements before treatments were performed on 23 April and 1 July 2021, 14 April and 4 July 2022, and 27 April and 3 July 2023. Measurements after treatments were carried out on 27 April and 6 July 2021, 18 April and 9 July 2022, and 2 May and 8 July 2023. Weed cover, consisting of soil weed coverage, was assessed by capturing images within a square frame measuring 0.075 m^2 using a Nikon Coolpix 7600 camera (Nikon Corporation, Tokyo, Japan). The Canopeo app was employed for image analysis, wherein the weed cover percentage was determined by evaluating the proportion of green pixels in each image. Weed height was assessed using a folding ruler inside the same square frame. Two measurements and three measurements for each replicate were collected before and after each intervention for weed height and weed cover, respectively. Weed cover was assessed between vine trunks, while weed height was recorded between and around vine trunks. The same square frame was also used to determine weed biomass, where the live above-ground weed biomass was cut and collected. Dry biomass was then determined following oven-drying at 100 °C for 3–4 days until constant weight was achieved. One weed biomass measurement for each replicate was collected both between and around trunks before and after each intervention.

Figure 3. Positioning of tools on the tractor: chain mower (**a**), blade weeder (**b**), motorized discs (**c**), and rotary star hoe (**d**).

The efficacy of the tools tested during each weed control treatment in terms of weed biomass, height, and cover was determined as the percentage of reduction (*R*) of parameters initial values assessed on each plot with the following Equation (1):

$$R\ (\%) = \frac{(x_b\ - x_a)}{x_b} \times 100 \qquad (1)$$

where x_b and x_a represent the parameter amount (weed biomass, weed height, or weed cover) recorded before and after interventions, respectively.

In 2022 and 2023, weed species were recognized and counted, and the ground cover of each one was visually estimated both between and around vine trunks before and four days after the weed control intervention. Species richness, Shannon diversity index, evenness, and annual and perennial species coverage were then determined. The estimate of the Shannon diversity index was carried out using the following Formula (2):

$$H = -\sum_{i=l}^{S} p_i \times ln(p_i) \qquad (2)$$

where H is the Shannon diversity index, p_i is the proportion of individuals belonging to the ith species, and S is the total number of species (species richness). For the estimation of evenness, the following formula was used (3):

$$E = \frac{H}{ln(S)} \tag{3}$$

where H is the Shannon diversity index, and S is species richness. One measurement of the aforementioned parameters for each replicate was carried out. Soil penetration resistance was assessed between vine trunks using a Fieldscout SC 900 Soil Compaction Meter (Spectrum Technologies Inc., Aurora, IL, USA) before weed control treatments on 14 April 2022 and 27 April 2023, and during the harvest period; thus, after the weed control interventions, on 8 September 2022, and 27 September 2023. Data on soil penetration resistance were collected between depths of 0 and 25 cm at 2.5 cm intervals. Operative parameters, such as working speed, theoretical field times, and turning times, were taken into account. Theoretical field times represent the period during which the tools operate at an optimal working speed, covering their entire width of action. To determine the working speeds of the tractors equipped with the different tools, the time taken to travel a straight section of 50 m within the experimental area was measured. The time required to perform the turning at the end of the rows was timed. Working speed, theoretical field time, and turning time were used to measure the total field time per unit area for the tractor equipped with each tool. The estimation of the total field time was carried out by referring to the single tool, therefore considering the tractor equipped with only one tool for each type. Fuel consumption per unit area was calculated using the formula for hourly consumption:

$$Ch = W \times d \times Cs \tag{4}$$

where Ch denotes the tractor's hourly fuel consumption (kg fuel h^{-1}); W is the tractor power (kW); d is the engine effort percentage of the tractor, which varies based on the tool employed; and Cs stands for the tractor's energy efficiency (kg fuel kWh^{-1}). In this investigation, the tractor's energetic efficiency (Cs) was assumed to be 0.25 kg fuel kWh^{-1}. Working speed, turning time, total field time, and fuel consumption per unit area collected over the three years of the trial during the treatments for each tool tested were then averaged.

2.5. Statistical Analyses

Data analysis was carried out using the statistical software R version 4.3.2. [30]. The Shapiro–Wilk test and Bartlett test were performed to assess data normality and homoscedasticity, respectively. Data underwent arcsine or square root transformations when necessary to meet the normality assumption. Weed biomass and weed height reduction were modeled with a linear mixed effect model, and data were processed with a four-way ANOVA using the R software extension package 'lme4' [31]. For these parameters, tool, position, year, and the treatment of the year (whether the first or second treatment) were fixed factors, while blocks were randomized effect factors. Weed cover reduction data were processed with a linear mixed effect model three-way ANOVA, with tool, year, and treatment of the year as fixed factors and blocks as randomized effect factors. Species richness, the Shannon diversity index, evenness, and annual and perennial weed species coverage were modeled with a linear mixed effect model, and data were processed with a five-way ANOVA. Tool, position, year, time of the survey (if performed before or after the treatment), and treatment of the year were considered as fixed factors, while blocks were treated as randomized effect factors. Soil penetration resistances were modeled with a linear mixed effect model, and data were processed with a four-way ANOVA. Tool, depth, time of the survey (if performed at the beginning of the vine growing season before the treatments or after the treatments), and year were considered as fixed factors, while blocks were treated as randomized effect factors. Mean comparisons were performed using Tukey's HSD (honestly significant difference) post hoc test ($p < 0.05$). The "ggplot2" extension package was used to generate graphs [32].

3. Results

3.1. Tools' Under-Row Weed Control Performance

Four-way ANOVA revealed that the tool employed ($p < 0.001$), the position ($p < 0.05$), and their interaction ($p < 0.05$) had a significant effect on weed biomass reduction, while the year and the treatment of the year did not affect the parameter. Weed height reduction was affected by the tool employed ($p < 0.001$) and position ($p < 0.001$), while neither their interaction nor the year and the treatment of the year had a significant effect on the parameter. Three-way ANOVA highlighted that the tool employed ($p < 0.001$) and year ($p < 0.001$) affected weed cover, while the treatment of the year did not affect the parameter. The interaction between toll employed and year had no significant effect on weed cover reduction ($p = 0.053$). Results of the four-way and three-way ANOVAs conducted regarding the weed biomass, weed height, and weed cover reduction are reported in Table 2.

Table 2. Results of the four-way ANOVA analysis assessing the effect of tool, position, year, treatment of the year, and the interaction between tool and position on weed biomass and weed height reduction. Results of the three-way ANOVA analysis evaluating the effect of tool, year, and treatment of the year on weed cover reduction.

Factors	Weed Biomass Reduction	Weed Height Reduction	Weed Cover Reduction
	p-value	*p*-value	*p*-value
Year	0.248	0.200	***
Treatment [1]	0.242	0.155	0.132
Tool	***	***	***
Position	*	***	-
Tool × Position	*	0.109	-

[1] Treatment of the year, i.e., whether the first or second treatment of the year; *** $p < 0.001$, * $p < 0.05$.

As the data are presented as a percentage of the reduction from the initial values of the parameters rather than in absolute values, Table 3 displays the average weed biomass, height, and cover values recorded prior to each under-row weed control intervention performed during the trial.

Table 3. Average values of weed biomass, height, and cover recorded prior to each under-row weed control intervention performed during the trial (standard error).

Year	Data	Weed Biomass	Weed Height	Weed Cover
			Values (SE)	
		g d.m.·m^{-2}	**cm**	**%**
2021	23 April	244.11 (3.91)	55.49 (0.31)	47.3 (0.45)
	1 July	97.42 (3.50)	19.19 (0.21)	15.1 (0.27)
2022	14 April	144.3 (3.56)	26.33 (0.19)	42.9 (0.54)
	4 July	82.51 (3.0)	19.37 (0.17)	20.6 (0.30)
2023	27 April	304.34 (4.94)	32.54 (0.22)	52.2 (0.50)
	3 July	62.79 (2.38)	18.04 (0.13)	21.4 (0.33)

Concerning weed biomass reduction, lower values of reduction were recorded around vine trunks (24.8%) rather than between vine trunks (52.6%). The rotary star hoe obtained a significantly lower reduction between vine trunks (23.4%) compared to the blade weeder (70.2%) ($p < 0.05$) and, in absolute values, compared to motorized discs (61.2%) and chain mower (55.4%), even if there were no statistically significant differences. No significant differences in terms of weed biomass reduction between trunks emerged between the chain mower, the motorized discs, and the blade weeder. No significant differences emerged even in the comparison between the tools tested in terms of weed biomass reduction around vine trunks, with values in the range from 18.5 to 31.1% (Figure 4).

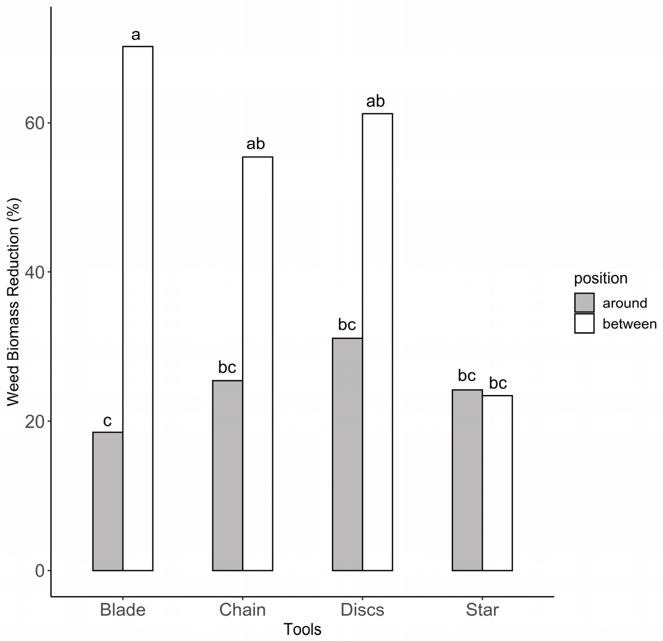

Figure 4. Effects of the interaction between tool employed and position on weed biomass reduction. Means distinguished by different letters indicate statistically significant differences at $p < 0.05$ (HSD test). Blade—blade weeder; chain—chain mower; discs—motorized discs; star—rotary star hoe.

Overall, the chain mower (40.4%) achieved similar results compared to the other tools employed, while the rotary star hoe (23.8%) achieved lower values compared to the motorized discs (46.1%) and the blade weeder (44.4%) ($p < 0.05$) (Figure 5).

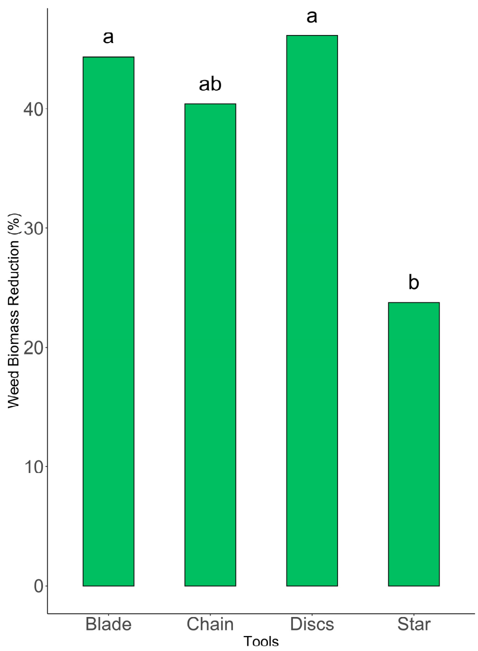

Figure 5. Effects of the tools employed on weed biomass reduction. Means distinguished by different letters indicate statistically significant differences at $p < 0.05$ (HSD test). Blade—blade weeder; chain—chain mower; discs—motorized discs; star—rotary star hoe.

A lower weed height reduction was observed around vine trunks (25.5%) compared to between vine trunks (46.7%). The blade weeder achieved the best results in terms of weed height reduction (50.6%), while the chain mower (35.9%), the motorized discs (33.6%), and the rotary star hoe (24.1%) obtained lower results and similar to each other ($p < 0.05$) (Figure 6).

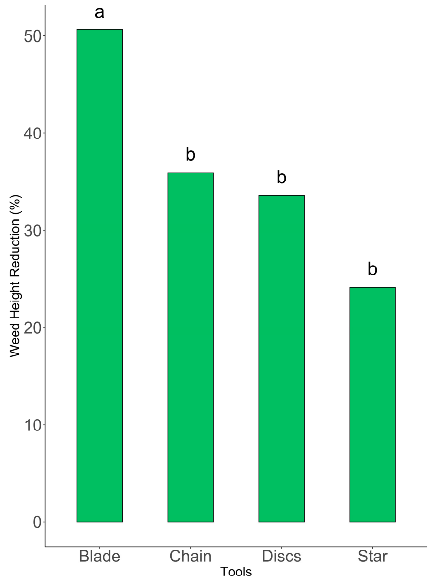

Figure 6. Effects of the tools employed on weed height reduction. Means distinguished by different letters indicate statistically significant differences at $p < 0.05$ (HSD test). Blade—blade weeder; chain—chain mower; discs—motorized discs; star—rotary star hoe.

Higher weed cover reduction values were recorded in 2021 (79.7%) and 2022 (78.7%) rather than in 2023 (56.7%) ($p < 0.05$). The rotary star hoe achieved lower weed cover reduction (53.0%) compared to the blade weeder (79.2%), the chain mower (79.2%), and the motorized discs (75.6%), which yielded similar results ($p < 0.05$) (Figure 7).

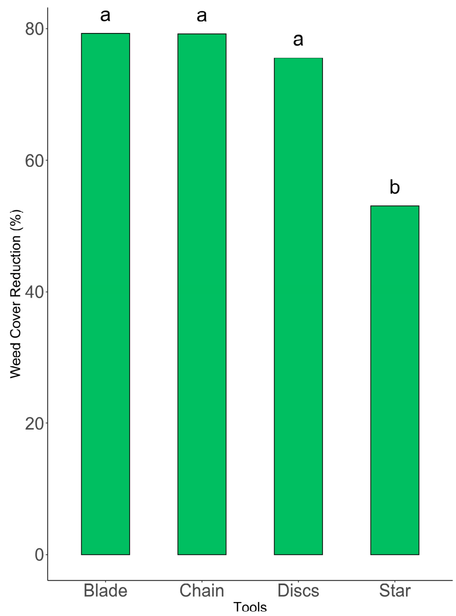

Figure 7. Effects of the tools employed on weed cover reduction. Means distinguished by different letters indicate statistically significant differences at $p < 0.05$ (HSD test). Blade—blade weeder; chain—chain mower; discs—motorized discs; star—rotary star hoe.

3.2. Effect of the Under-Row Weed Control Treatments on Weed Flora Composition

Five-way ANOVA analysis revealed that year ($p < 0.01$), time of the survey ($p < 0.001$), and the treatment of the year ($p < 0.001$) had a significant effect on species richness, while the tool, the position, and their interaction had no significant effect on the parameter. The interaction between machine and year ($p = 0.887$) and between position and year ($p = 0.123$) had no significant effect on the parameter. The Shannon diversity index was affected by position ($p < 0.05$) and treatment of the year ($p < 0.001$). The tool employed, year, time of the survey, and the interaction between tool and position had no significant effect on the parameter. None of the factors evaluated nor their interaction significantly influenced evenness. Annual species coverage was significantly affected by position ($p < 0.05$) and time of the survey ($p < 0.05$), while tool employed, year, treatment of the year, and the interaction between tool and position did not affect the parameter. Perennial species coverage was affected by position ($p < 0.05$), year ($p < 0.001$), time of the survey ($p < 0.001$), and treatment of the year ($p < 0.001$), while tool and the interaction between tool and position did not affect the parameter. The interaction between machine and year ($p = 0.496$) and between position and year ($p = 0.867$) had no significant effect on the parameter. Results of the five-way ANOVA performed regarding species richness, the Shannon diversity index, evenness, and annual and perennial species coverage are shown in Table 4.

Table 4. Results of the five-way ANOVA evaluating the effect of tool employed, position, year, time of the survey, treatment of the year, and the interaction between tool and position on species richness, Shannon diversity index, evenness, annual and perennial species coverage.

Factors	SR	SDI	Evenness	Annual Species Coverage	Perennial Species Coverage
	p-value	*p*-value	*p*-value	*p*-value	*p*-value
Tool	0.083	0.440	0.617	0.338	0.641
Position	0.082	*	0.282	*	*
Year	**	0.559	0.393	0.265	***
Time of the Survey [1]	***	0.991	0.051	*	***
Treatment [2]	***	***	0.394	0.229	***
Tool × Position	0.132	0.227	0.351	0.523	0.132

[1] Time of the survey, i.e., performed before or after the treatment; [2] treatment of the year, i.e., whether the first or second treatment of the year. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. SR—species richness; SDI—Shannon diversity index.

Regarding species richness, higher values were observed in 2023 (2.35) rather than in 2022 (1.87). Lower values of species richness were observed after the treatment (1.77) compared to before treatment (2.46) and during the second treatment of the year (1.28) compared to the first one (2.95). Concerning the Shannon diversity index, higher values were observed between vine trunks (0.32) rather than around them (0.25) and during the first treatment (0.35) compared to the second one (0.22). Annual species coverage was higher around vine trunks (18.8%) rather than between vine trunks (9.8%) and before the weed control intervention (2.5%) compared to after the intervention (1.8%). Perennial species coverage was higher around vine trunks (19.8%) than between vine trunks (13.8%) and in 2023 (27.0%) compared to 2022 (6.6%). Higher values of the parameter were observed before the weed control treatment (22.6%) compared to after (11.0%) and during the first treatment (23.9%) compared to during the second one (9.7%).

3.3. Effect of the Under-Row Weed Control Treatments on Soil Penetration Resistance

Soil penetration resistance was affected by the tool ($p < 0.001$), the depth ($p < 0.001$), and the year ($p < 0.001$), while the time of the survey (if performed at the beginning of the vine growing season before the treatments, or after the treatments) had no significant effect on the parameter ($p = 0.522$). The interaction between tool and year also had a significant effect on the parameter ($p < 0.001$). Therefore, the three-way ANOVA analysis was conducted separately for the data collected in 2022 and 2023. In 2022, soil penetration resistance was affected by the tool ($p < 0.05$), the depth ($p < 0.001$), and the time of the survey ($p < 0.001$). In 2023, the tool ($p < 0.001$), the depth ($p < 0.001$), and the time of the survey ($p < 0.001$) had significant effects on the parameter. Results relating to soil penetration resistance analysis for 2022 and 2023 are shown in Table 5.

Table 5. Results of the three-way ANOVA analysis evaluating the effect of tool, depth, and time of the survey on soil penetration resistance in 2022 and 2023.

Factors	Soil Penetration Resistance	
	2022	2023
	p-value	*p*-value
Tool	*	***
Depth	***	***
Time of the Survey [1]	***	***

[1] Time of the survey, i.e., if performed at the beginning of the vine growing season before the treatments or after the treatments; *** $p < 0.001$, * $p < 0.05$.

The values of the soil water content percentage at the times of the analysis carried out with the penetrometer are reported in Table 6.

Table 6. Soil water content percentage at the times of the assessments carried out with the penetrometer.

Date		Soil Water Content (%)
14 April 2022	Chain Mower	11.9
	Motorized Discs	12.9
	Blade Weeder	12.5
	Rotary Star Hoe	12.7
8 September 2022	Chain Mower	15.9
	Motorized Discs	16.7
	Blade Weeder	16.3
	Rotary Star Hoe	14.5
27 April 2023	Chain Mower	8.8
	Motorized Discs	9.4
	Blade Weeder	9.3
	Rotary Star Hoe	9.2
27 September 2023	Chain Mower	7.9
	Motorized Discs	6.2
	Blade Weeder	8.7
	Rotary Star Hoe	7.5

In 2022, a lower soil penetration resistance was recorded on plots managed with the chain mower (1602.42 kPa) and the rotary star hoe (1573.38 kPa) compared to plots managed by the blade weeder (1920.21 kPa) ($p < 0.05$). No difference emerged in the comparison of the chain mower, the rotary star hoe, and the motorized discs (1711.21 kPa). No difference emerged between the motorized discs and the blade weeder.

In 2023, in the plot managed by the chain mower, the lowest soil penetration resistance (2262.83 kPa) was recorded compared to plots managed with the other tools ($p < 0.05$). In plots managed with motorized discs (2927.95 kPa), a higher penetration resistance was recorded compared to plots managed with the blade weeder (2556.77 kPa) ($p < 0.05$), while in those managed with the rotary star hoe, similar results were observed (2733.56 kPa) compared to both the motorized discs and the blade weeder. Soil penetration resistance values relatives of each depth in 2022 and 2023 are shown in Table 7.

Table 7. Soil penetration values at each depth in 2022 and 2023 (standard errors).

	2022		2023	
Depth (cm)	**Soil Penetration Resistance (kPa)**		**Soil Penetration Resistance (kPa)**	
	Values (SE)		**Values (SE)**	
25.0	2949.44 (148.64)	a	3520.9 (100.94)	b
22.5	3112.71 (148.64)	a	4304.38 (100.94)	a
20.0	2772.33 (148.64)	ab	4049.52 (100.94)	a
17.5	2770.08 (148.64)	ab	3549.29 (100.94)	b
15.0	2195.00 (148.64)	bc	3297.60 (100.94)	bc
12.5	1766.65 (148.64)	cd	3065.04 (100.94)	c
10.0	1440.35 (148.64)	de	2476.06 (100.94)	d
7.5	955.85 (148.64)	ef	1983.08 (100.94)	e
5.0	433.23 (148.64)	fg	1347.63 (100.94)	f
2.5	210.85 (148.64)	g	745.67 (100.94)	g
0	113.33 (148.64)	g	483.88 (100.94)	g

Means distinguished by different letters indicate statistically significant differences at $p < 0.05$ (HSD test).

Over the two years of the trial, 2022 and 2023, a similar trend was observed regarding the soil penetration resistance recorded for each depth. In 2022, greater resistance to penetration was found at depths of 22.5 and 25 cm, while in 2023, higher values were found at depths of 20 and 22.5 cm.

In 2022, a higher soil penetration resistance was recorded before the under-row weed control interventions (1921.53 kPa) compared to after the interventions (1482.08 kPa) ($p < 0.05$), while in 2023, the opposite trend was observed with values of 2874.11 kPa after the interventions, and 2366.44 kPa before the interventions ($p < 0.05$).

3.4. Tools' Operative Performances

The average operative parameters of each tool per treatment, such as average working speed, total turning time, total field time, and fuel consumption per unit area, are shown in Table 8.

Table 8. Operative performances, including average working speed, total turning time, total field time, and fuel consumption per unit area of each tool employed per treatment.

Tools	Working Speed (km h^{-1})	Total Turning Time (h ha^{-1})	Total Field Time (h ha^{-1})	Fuel Consumption (kg ha^{-1})
Chain Mower	2.85	0.26	3.78	24.24
Motorized Discs	2.18	0.19	4.79	36.72
Blade Weeder	3.57	0.24	3.04	16.59
Rotary Star Hoe	7.69	0.15	1.45	5.00

The rotary star hoe presented a higher working speed compared to the blade weeder, the chain mower, and the motorized discs, with an average increase of 179.3%. The chain mower presented a lower working speed compared to the blade weeder and the rotary star hoe, with decreases of 20.2% and 62.9%, respectively, while it showed a slightly higher working speed compared to the motorized discs with an increase of 30.7%. The chain mower showed a slightly higher total turning time compared to the motorized discs and the rotary star hoe, with increases of 36.8% and 73.3%, respectively, and similar values to the blade weeder. The motorized discs showed the highest total field time compared to the other machines tested, with an average increase of 104.9%, while the rotary star hoe presented the lowest total field time, with an average decrease of 61.2%. The chain mower and the blade weeder showed similar values of total field time. The motorized discs showed the highest fuel consumption value, with an average increase of 269.07%, followed by the chain mower, the blade weeder, and the rotary star hoe. The rotary star hoe obtained the lowest fuel consumption, with an average decrease of 78.54%.

4. Discussion

4.1. Weed Control

Concerning weed biomass reduction between vine trunks, the chain mower (55.4%) achieved similar results to the motorized discs (61.2%) and the blade weeder (70.2%), while the rotary star hoe achieved lower results (23.4%). This is in agreement with Berk et al. [33], according to which higher yield losses were recorded when the vineyard under-row area was managed with a rotary star hoe rather than a blade weeder. Results obtained by the chain mower between vine trunks align with the observations made by Pergher et al. [9] for an under-vine mower, which achieved reductions in weed biomass ranging from 40.3% to 68.0%. Instead, chain mower results around vine trunks (25.4%) are lower than those obtained by the same authors for the under-vine mower, with values in the range of 37.0 to 47.6%. This may be due to the distance between the cutting elements and the horizontal disc case necessary to avoid damage to trunks [8]. In this case, the chain mower horizontal disc case was 0.40 m wide, and the cutting width was 0.32 m [29]. The blade weeder achieved a higher weed height reduction (50.6%) compared to the chain mower (35.9%), the motorized discs (33.6%), and the rotary star hoe (24.1%), which yielded similar results to each other. Nonetheless, the results of weed height reduction for the latter tools are considered satisfactory. Indeed, their weed height reduction allows the reduction in weed competitiveness [24,34] and the maintenance of weeds below the bunch height, thus preventing the creation of humid conditions that could favor the onset of diseases [35]. Furthermore, these reductions allow for the prevention of weed interference with vineyard operations [36]. Overall, better weed biomass and height reduction results were observed between vine trunks (with values of 52.6% and 46.7%, respectively) compared to around vine trunks (with values of 24.8% and 25.5%, respectively). This confirmed what was observed by Lanini et al. [37], according to which most of the tools used to control weeds under-row have limited effectiveness around vine trunks. The chain mower, the blade weeder, and the motorized discs obtained weed cover reduction results similar (with values of 79.2, 79.2, and 75.6%, respectively) and higher compared to the rotary star hoe (53.0%). Results obtained by chain mower are slightly lower compared to those observed by Manzone et al. [38] for a brush weeder with a resulting weed cover reduction of approximately 95%. However, brush weeder wires in soil with high stone content tend to be damaged frequently, and their replacement can lead to a reduction in the working capacity of the weed control intervention. In contrast to what other authors observed [24], according to which mowing is associated with greater plant coverage compared to tillage, in this case, the chain mower obtained weed cover reduction results similar to those achieved by tools that perform weed control with tillage. This is probably due to the chain mower's mechanism of action, whose chains operate by abrasion, therefore with light contact on the soil surface.

4.2. Effect on Weed Flora Composition

A slightly higher weed species richness was recorded in 2023 (2.35) rather than in 2022 (1.87). This could be due to the higher precipitations in the months of March, April, May, and June in 2023 compared to 2022. This is in agreement with what was observed by Hu et al. [39], according to which, as rainfall increases, plant species richness can increase. In fact, the increase in precipitation improves the availability of water and nutrients, allowing more species to better tolerate environmental conditions. Moreover, higher values of species richness were observed in the first treatment of the year (2.95), performed during spring, compared to the second treatment (1.28) carried out during summer. This could be related to the higher temperatures and reduced water availability in the summer period [40]. No significant differences emerged between the tools used in terms of species richness, Shannon diversity index, evenness, and annual and perennial plant species coverage. Concerning the position, no differences emerged either for species richness or evenness, while the Shannon diversity index was slightly higher between vine trunks (0.32) rather than around them (0.25). Therefore, between vine trunks, there may have been a slightly greater number of weed species, or a more uniform distribution of these, or both. This could be associated with the tools' higher work effectiveness between trunks rather than around them. The greater intensity and frequency of disturbance between trunks may have allowed more weed species to develop by promoting access to limited resources (water, light, and nutrients), thus limiting their interspecific competition [41]. The Shannon diversity index was greater in the first treatment of the year (0.35) compared to the second one (0.22). This could be associated with spring temperatures and water availability more favorable to the development of different plant species [40]. Both annual and perennial species coverage was greater around vine trunks (with values of 18.8 and 19.8%, respectively) rather than between them (with values of 9.8 and 13.8%, respectively). This may also be explained by the lower disturbance of weeds around trunks, which would have allowed greater growth and, therefore, greater coverage of weed species present in this position. Therefore, these results seem to confirm the limits of the effectiveness of these tools in controlling weeds in the position around trunks [37].

4.3. Soil Penetration Resistance

Regardless of the tool employed, in both 2022 and 2023, values of resistance to soil penetration increased as the depth increased, with values from 113.33 to 3112.71 kPa in 2022 and from 483.88 to 4304.38 kPa in 2023. In 2022, higher soil penetration resistance values were found before the under-row weed control interventions were carried out (1921.53 kPa) rather than after them (1482.08 kPa). This could be explained by the lower soil moisture content when the survey was carried out before the treatments compared to the survey carried out after the treatments. Instead, in 2023, a greater value of soil penetration resistance was observed after the two interventions were carried out (2874.11 kPa) rather than before the two interventions (2366.44 kPa). This result can also be explained by the different soil moisture content at the times in which the surveys were carried out. Impediments of grapevine root penetration can be observed above penetrometer readings of 2000 kPa [42,43]. Overall, lower soil penetration resistances were observed in plots managed with chain mower (1602.42 and 2262.83 kPa in 2022 and 2023, respectively) compared to plots managed with tillage, particularly compared to blade weeder in 2022 (1920.21 kPa) and compared to all other tools tested in 2023 (with values equal to 2556.77, 2733.56, and 2927.95 kPa, for the blade weeder, the rotary star hoe, and the motorized discs, respectively). This would confirm that tillage can promote soil compaction [13]. Soil compaction negatively influences the crop-producing role of soil, water and nutrient availability, vulnerability to soil erosion, and natural biological activity of soil [44]. Therefore, the mechanism of action of the chain mower, i.e., operating by abrasion with light contact on the soil surface, seemed to have a lower impact on soil health compared to tillage interventions. Furthermore, compared to tools that control under-row weeds with tillage, the chain mower's mechanism of action does not involve the risk of damaging vine roots [7].

4.4. Operative Performances

Regarding the tools' operative performances, the average working speed of the rotary star hoe is higher compared to the other tested tools, with an average increase of 179.3%, also recording the shorter average field time (1.45 h ha^{-1}). Indeed, the rotary star hoe is one of the tools employed for under-row weed control in vineyards with the highest working speed [8] and, therefore, very advantageous in terms of timeliness of intervention. The motorized discs, on the other hand, presented a lower average working speed (2.18 km h^{-1}) compared to the other tools tested and, therefore, the highest field time (4.79 h ha^{-1}). The chain mower and the blade weeder recorded intermediate values of working speed and field time (with values equal to 2.85 and 3.57 km h^{-1} and 3.78 and 3.04 h ha^{-1} for the chain mower and the blade weeder, respectively). The same trend was observed for average fuel consumption, with the motorized discs obtaining the highest values 36.72 kg ha^{-1}, followed by the chain mower (24.24 kg ha^{-1}), the blade weeder (16.59 kg ha^{-1}), and the rotary star hoe (5.00 kg ha^{-1}).

Therefore, overall, the chain mower achieved satisfactory results, proving to be a reliable tool for the management of weeds under the rows in vineyards. Indeed, its weed control performance is comparable to the other tool tested, commonly used for this purpose in the vineyard. Despite the higher fuel consumption than rotary star hoe and blade weeder, the availability of a chain mower could bring significant management advantages for viticulturists who work in vineyards with a high stone content where commonly used tools can encounter issues such as damage [45,46]. Moreover, as evidenced by the obtained results, the chain mower, resulting in a less impactful action on the soil compared to other tested tools that perform tillage, tends to a greater preservation of soil health. In this regard, using mowing for under-row management or other alternative strategies to tillage, such as mowing cover crops in the inter-rows and conveying biomass under the vines as mulch, can increase soil conservation. This is a critical aspect, especially considering the severe soil degradation conditions experienced by vineyards in the Mediterranean region [14].

5. Conclusions

In this study, the chain mower obtained encouraging results in terms of weed control, particularly in terms of weed biomass reduction (55.4 and 25.4%, between and around vine trunks, respectively), weed height reduction (35.9%), and weed cover reduction (79.2%). The results are, in fact, comparable or higher with respect to those obtained by the other tools tested commonly used for under-row weed management in the vineyard. All the tools evaluated showed limits of effectiveness in the control of weeds around vine trunks rather than between them, with values of weed biomass and height reductions of 24.8% and 25.5% and 52.6% and 46.7%, respectively. Results regarding the evaluation of the effect of the tools on weed flora composition seem to confirm this trend. The chain mower obtained higher field time and fuel consumption results compared to the blade weeder and the rotary star hoe. Nevertheless, its versatility of use even in soils with a high stone content where commonly used tools can be damaged, and the lower impact on the soil compared to tools that operate tillage make it a potentially very advantageous means for under-row weed management in the vineyard. Further mechanical and agronomic studies could be useful to improve the performance of the chain mower both between vine trunks, in particular, around them, evaluating in different planting layouts, different dimensions of both the cutting element and the feeler, which allows the vine-skipping mechanism.

Author Contributions: Conceptualization, M.R., M.F. and C.F.; methodology, L.G. and M.R.; software, S.M.L.; validation, S.M.L. and A.P.; formal analysis, L.G. and S.M.L.; investigation, L.G., M.F., C.F. and A.P.; resources, M.R.; data curation, L.G. and S.M.L.; writing—original draft preparation, L.G. and M.R.; writing—review and editing, S.M.L., M.F., C.F. and A.P.; visualization, A.P.; supervision, M.R., C.F. and M.F.; project administration, M.R.; funding acquisition, M.R. and A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to acknowledge Alessio Neri of Ornellaia Winery for hosting the trial and offering technical support, the Dondi group for providing the under-vine mower, and the research group of Professor Antonio DiTommaso, in particular, Sophie Westbrook, for their precious support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. OIV (Organizzazione Internazionale Della Vigna e del Vino). Nota Di Congiuntura Del Settore Vitivinicolo Mondiale Nel. 2022. Available online: https://www.oiv.int/sites/default/files/documents/OIV_Nota_di_congiuntura_del_settore_vitivinicolo_mondiale_nel_2022_0.pdf (accessed on 15 September 2023).
2. Casson, A.; Ortuani, B.; Giovenzana, V.; Brancadoro, L.; Corsi, S.; Gharsallah, O.; Guidetti, R.; Facchi, A. A Multidisciplinary Approach to Assess Environmental and Economic Impact of Conventional and Innovative Vineyards Management Systems in Northern Italy. *Sci. Total Environ.* **2022**, *838*, 156181. [CrossRef]

3. Stoate, C.; Báldi, A.; Beja, P.; Boatman, N.D.; Herzon, I.; Van Doorn, A.; De Snoo, G.R.; Rakosy, L.; Ramwell, C. Ecological Impacts of Early 21st Century Agricultural Change in Europe—A Review. *J. Environ. Manag.* **2009**, *91*, 22–46. [CrossRef]
4. Peigné, J.; Ball, B.C.; Roger-Estrade, J.; David, C. Is Conservation Tillage Suitable for Organic Farming? A Review. *Soil Use Manag.* **2007**, *23*, 129–144. [CrossRef]
5. Hembree, K.J.; Lanini, W.T. *Weeds. UC IPM Pest Management Guidelines: Grape*; University of California Agriculture and Natural Resources: Davis, CA, USA, 2006; Volume 3448.
6. Garcia, L.; Celette, F.; Gary, C.; Ripoche, A.; Valdés-Gómez, H.; Metay, A. Management of Service Crops for the Provision of Ecosystem Services in Vineyards: A Review. *Agric. Ecosyst. Environ.* **2018**, *251*, 158–170. [CrossRef]
7. Guerra, B.; Steenwerth, K. Influence of Floor Management Technique on Grapevine Growth, Disease Pressure, and Juice and Wine Composition: A Review. *Am. J. Enol. Vitic.* **2012**, *63*, 149–164. [CrossRef]
8. Castaldi, R. Lavorazione Del Terreno Nel Sottofila. In *Vite. Meccanizzazione del Vigneto. Guida Alla Scelta e All'utilizzo di Macchine e Attrezzature*; Edizioni L'Informatore Agrario: Verona, Italy, 2018; pp. 67–78.
9. Pergher, G.; Gubiani, R.; Mainardis, M. Field Testing of a Biomass-Fueled Flamer for In-Row Weed Control in the Vineyard. *Agriculture* **2019**, *9*, 210. [CrossRef]
10. Gagliardi, L.; Fontanelli, M.; Luglio, S.M.; Frasconi, C.; Peruzzi, A.; Raffaelli, M. Evaluation of Sustainable Strategies for Mechanical Under-Row Weed Control in the Vineyard. *Agronomy* **2023**, *13*, 3005. [CrossRef]
11. Sozzi, M.; Pasquetti, E.; De Ros, A.; Ferro, F. Performance Evaluation of Automated Implement for Vineyard Mechanical Weed Control. In Proceedings of the 20th International Scientific Conference Engineering for Rural Development, Jelgava, Latvia, 27 May 2021.
12. Bàrberi, P. Weed Management in Organic Agriculture: Are We Addressing the Right Issues? *Weed Res.* **2002**, *42*, 177–193. [CrossRef]
13. Steenwerth, K.; Belina, K.M. Cover Crops Enhance Soil Organic Matter, Carbon Dynamics and Microbiological Function in a Vineyard Agroecosystem. *Appl. Soil Ecol.* **2008**, *40*, 359–369. [CrossRef]
14. Giagnoni, L.; Maienza, A.; Baronti, S.; Vaccari, F.P.; Genesio, L.; Taiti, C.; Martellini, T.; Scodellini, R.; Cincinelli, A.; Costa, C.; et al. Long-Term Soil Biological Fertility, Volatile Organic Compounds and Chemical Properties in a Vineyard Soil after Biochar Amendment. *Geoderma* **2019**, *344*, 127–136. [CrossRef]
15. Belmonte, S.A.; Celi, L.; Stanchi, S.; Said-Pullicino, D.; Zanini, E.; Bonifacio, E. Effects of Permanent Grass versus Tillage on Aggregation and Organic Matter Dynamics in a Poorly Developed Vineyard Soil. *Soil Res.* **2016**, *54*, 797. [CrossRef]
16. AWRI (Australian Wine Research Institute). Undervine Mowing and Whipper Snipping. Available online: https://www.awri.com.au/industry_support/viticulture/weed-management/non-chemical-weed-management/undervine-mowing-and-whipper-snipping/ (accessed on 5 October 2023).
17. Curran, W.S.; Lingenfelter, D.D.; Garling, L. An Introduction to Weed Management for Conservation Tillage Systems. *Pennstate Coop. Ext. Coll. Agric. Sci.* **2009**, *2*, 1–8.
18. Sheley, R. *Mowing to Manage Noxious Weeds*; Montana State University Extension: Bozeman, MT, USA, 2017; Volume 0517SA, pp. 1–2.
19. Mia, M.J.; Massetani, F.; Murri, G.; Neri, D. Sustainable Alternatives to Chemicals for Weed Control in the Orchard—A Review. *Hortic. Sci.* **2020**, *47*, 1–12. [CrossRef]
20. Moretti, M. Mechanical Weed Control Under the Vine. Available online: https://smallgrains.wsu.edu/weeders-of-the-west/2021/07/14/mechanical-weed-control-under-the-vine/ (accessed on 10 October 2023).
21. Nascimbene, J.; Marini, L.; Ivan, D.; Zottini, M. Management Intensity and Topography Determined Plant Diversity in Vineyards. *PLoS ONE* **2013**, *8*, e76167. [CrossRef] [PubMed]
22. Bruggisser, O.T.; Schmidt-Entling, M.H.; Bacher, S. Effects of Vineyard Management on Biodiversity at Three Trophic Levels. *Biol. Conserv.* **2010**, *143*, 1521–1528. [CrossRef]
23. Mainardis, M.; Boscutti, F.; Rubio Cebolla, M.D.M.; Pergher, G. Comparison between Flaming, Mowing and Tillage Weed Control in the Vineyard: Effects on Plant Community, Diversity and Abundance. *PLoS ONE* **2020**, *15*, e0238396. [CrossRef] [PubMed]
24. MacLaren, C.; Bennett, J.; Dehnen-Schmutz, K. Management Practices Influence the Competitive Potential of Weed Communities and Their Value to Biodiversity in South African Vineyards. *Weed Res.* **2019**, *59*, 93–106. [CrossRef]
25. Boscutti, F.; Sigura, M.; Gambon, N.; Lagazio, C.; Krüsi, B.O.; Bonfanti, P. Conservation Tillage Affects Species Composition but Not Species Diversity: A Comparative Study in Northern Italy. *Environ. Manag.* **2015**, *55*, 443–452. [CrossRef]
26. Kellfri Chain Mulcher. Three-Point Linkage. Available online: https://www.kellfri.com/agriculture/grassland-machinery (accessed on 11 October 2023).
27. Ventura Forestry Machines. DLB 410—DADU—Side Belt Mower. Available online: https://www.venturamaquinasforestales.com/en/products/mowers-of-blades-and-chains/dlb-410-dadu-side-belt-mower/ (accessed on 11 October 2023).
28. Wessex International Forestry Rotary Cutter SM-66. Available online: https://www.wessexintl.com/machines/compact-tractor-attachments/rotary-slasher/sm-66/ (accessed on 11 October 2023).
29. Gagliardi, L.; Fontanelli, M.; Frasconi, C.; Sportelli, M.; Antichi, D.; Tramacere, L.G.; Rallo, G.; Peruzzi, A.; Raffaelli, M. Assessment of a Chain Mower Performance for Weed Control under Tree Rows in an Alley Cropping Farming System. *Agronomy* **2022**, *12*, 2785. [CrossRef]

30. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2023.
31. Bates, D.; Maechler, M.; Bolker, B.; Walker, S.; Christensen, R.H.B.; Singmann, H.; Dai, B.; Scheipl, F.; Grothendieck, G.; Green, P.; et al. Package 'lme4'. Linear Mixed-Effects Models Using 'Eigen' and S4. R Package Version 1.1-35.1. Available online: https://cran.r-project.org/web/packages/lme4/lme4.pdf. (accessed on 26 November 2023).
32. Wickham, H.; Chang, W.; Henry, L.; Pedersen, T.L.; Takahashi, K.; Wilke, C.; Woo, K.; Yutani, H.; Dunnington, D. Package 'ggplot2'. Create Elegant Data Visualisations Using the Grammar of Graphics. R Package Version 1.1-35.1. Available online: https://cran.r-project.org/web/packages/ggplot2/ggplot2.pdf. (accessed on 27 November 2023).
33. Berk, P.; Kelc, D.; Vindiš, P. Different Mechanical Control of Weeds under Vines to Reduce Ecological Footprint. *Poljopr. Teh.* **2023**, *48*, 46–55. [CrossRef]
34. Garnier, E.; Navas, M.-L. A Trait-Based Approach to Comparative Functional Plant Ecology: Concepts, Methods and Applications for Agroecology. A Review. *Agron. Sustain. Dev.* **2012**, *32*, 365–399. [CrossRef]
35. 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*; Academic Press: New York, NY, USA, 2016; pp. 479–484.
36. Madge, D. *Organic Farming: Vineyard Weed Management*; Department of Primary Industries: Mildura, Australia, 2007; pp. 1–10.
37. Lanini, W.T.; McGourty, G.T.; Thrupp, L.A. Weed Management for Organic Vineyards. In *Organic Winegrowing Manual*; University of California, Agriculture and Natural Resources: Davis, CA, USA, 2011; pp. 69–82.
38. Manzone, M.; Demeneghi, M.; Marucco, P.; Grella, M.; Balsari, P. Technical Solutions for Under-Row Weed Control in Vineyards: Efficacy, Costs and Environmental Aspects Analysis. *J. Agric. Eng.* **2020**, *51*, 36–42. [CrossRef]
39. Hu, Y.; Li, X.; Guo, A.; Yue, P.; Guo, X.; Lv, P.; Zhao, S.; Zuo, X. Species Diversity Is a Strong Predictor of Ecosystem Multifunctionality under Altered Precipitation in Desert Steppes. *Ecol. Indic.* **2022**, *137*, 108762. [CrossRef]
40. Yao, Z.; Xin, Y.; Yang, L.; Zhao, L.; Ali, A. Precipitation and Temperature Regulate Species Diversity, Plant Coverage and Aboveground Biomass through Opposing Mechanisms in Large-Scale Grasslands. *Front. Plant Sci.* **2022**, *13*, 999636. [CrossRef]
41. Duan, T.; Zhang, J.; Wang, Z. Responses and Indicators of Composition, Diversity, and Productivity of Plant Communities at Different Levels of Disturbance in a Wetland Ecosystem. *Diversity* **2021**, *13*, 252. [CrossRef]
42. Van Huyssteen, L. Interpretation and Use of Penetrometer Data to Describe Soil Compaction in Vineyards. *S. Afr. J. Enol. Vitic.* **1983**, *4*, 59–65. [CrossRef]
43. Zyl, J.V.; Hoffman, E. Root development and the performance of grapevines in response to natural as well as man-made soil impediments. In Proceedings of the 21st GiESCO International Meeting, Thessaloniki, Greece, 23–28 June 2019.
44. Badalíková, B. Influence of Soil Tillage on Soil Compaction. In *Soil Engineering*; Dedousis, A., Bartzanas, T., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; Volume 20, pp. 19–30.
45. Trejon Optimal. The New Generation of Chain Mulcher. Available online: https://s3-eu-west-1.amazonaws.com/static.wm3.se/sites/259/media/251446_File-1481192591.pdf?1544011159 (accessed on 10 January 2024).
46. Limberger, F.W. Grass Trimmer. U.S. Patent 2,676,448, 27 April 1954. Available online: https://www.freepatentsonline.com/2676448.pdf (accessed on 10 January 2024).