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Evaluating the Impact of Mowing, Wire Mulching, and Shallow Tillage on Under-Row Weed Management and Operational Performance in an Italian Vineyard

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Abstract

Soil degradation in vineyards represents an increasing concern. Among vineyard management practices, under-row weed control is often performed through mechanical methods relying on equipment that may negatively affect soil health, highlighting the need to evaluate more sustainable solutions for soil preservation. This study, conducted during the 2024 growing season in Palaia (Pisa, Italy), aimed to evaluate and compare three under-row weed management strategies, each characterized by the implementation of two weed control interventions. One strategy was based on low-impact soil tillage, consisting of two operations: a first intervention performed with a rollhacke and a second one with a blade weeder. The other two strategies relied on weed cutting without soil disturbance from the implements: one involved two interventions with an under-vine mower, while the other included two interventions with a wire mulcher. No significant differences were observed in terms of weed biomass among the tested strategies, although the tillage-based solution generally resulted in greater weed height (41.31 cm), yet always below the cluster zone. In terms of total weed cover, the mowing-based strategy achieved the highest value (28.33%). The mowing-based strategy also showed higher species richness (2.17) compared with the mulching-based strategy, and a higher Shannon index (0.25) than both other strategies, highlighting the potential ecological value of this approach. However, from an operational perspective, the tillage- and mulching-based strategies proved to be the most efficient, both in terms of operating time (2.54 and 2.02 h ha^{-1}, respectively) and fuel consumption (10.63 and 11.47 kg ha^{-1}, respectively). On average, these two strategies reduced operating time and fuel consumption by 73.79% and 74.39%, respectively, compared with the mowing-based strategy.

Keywords: conservation agriculture; no-till; organic vineyard; mechanical weed control

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1. Introduction

Weed control is a key management operation and often represents one of the major cost items in agricultural production [1,2]. Weeds compete with grapevines for resources such as water, light, and nutrients, thereby potentially reducing plant vigour and yield. It has been shown that weed competition can reduce yield by up to 37%, the number of clusters per vine by 28%, and berry weight by 3% [3]. Weeds can also produce allelopathic substances, resulting in negative effects on grapevine growth [4]. In addition, they can interfere with essential cultural operations such as pruning and harvesting, act as hosts for organisms harmful to the vine, increase relative humidity and promote the development of diseases, as well as lower vineyard temperatures, thereby increasing the risk of damage from spring frosts [3,5,6].

The weed flora of each vineyard is the combined result of pedoclimatic conditions, surrounding environments, agronomic practices, and previous weed management strategies, thus becoming a distinctive characteristic of different viticultural contexts [7].

Under-vine weed control is particularly critical, as it requires interventions in the area between vine trunks, with the risk of causing damage to the crop. In organic farming systems, mechanical control based on tillage intervention remains one of the few effective methods available [8,9]. However, these methods can also have negative environmental impacts, particularly on soil health. Soil degradation is one of the major challenges in viticulture. In this context, intensive tillage practices may exacerbate this problem by promoting organic matter loss and, under certain conditions, soil compaction. The latter may result from repeated machinery traffic associated with tillage operations and the use of implements that can contribute to the formation of compacted subsurface layers, thereby increasing soil susceptibility to erosion processes [10,11]. Soil compaction is detrimental, as it promotes several negative effects. By deforming soil structure, reducing porosity, and altering pore morphology, compaction triggers a cascade of negative effects on water retention and movement, root development, and nutrient availability [12,13].

Several types of equipment are available for weed control through soil tillage, with different modes of action and impacts on soil. Among the implements used for this purpose are, for example, rotary harrows and small ploughs. The rotary harrow consists of a working unit that rotates around a vertical axis on which tines are mounted, operating at a depth of approximately 10 cm. Small ploughs are composed of a frame equipped with a working head fitted with a mouldboard that turns the soil from the under-vine row toward the inter-row, operating at depths ranging from 15 to 20 cm [14]. Both these implements can provide effective weed control; however, they may negatively affect soil structure, the former by excessively pulverizing the worked soil layer, and the latter by potentially contributing to the formation of a compacted subsurface layer. As an alternative, equipment such as blade weeders and rollhacke can be used. A blade weeder consists of a blade that slightly penetrates the soil surface, while a rollhacke consists of star-shaped vertical discs that rotate as the tractor advances close to the vine row [15]. Mechanical weed control methods also include mowing and shredding. These operations can be carried out using under-vine mowers equipped with horizontal discs with blades. Such machines allow biomass to be cut at a set height, leaving a residual sward that can provide a protective effect against erosion processes [16]. However, to date, many winegrowers still rely on the use of mechanical mulchers with wires. In this case, the implement's working unit is a horizontal rotor fitted with flexible wires of varying lengths and diameters [17]. Weed control through mowing or mulching results in less damage to soil structure caused by the working tool, thereby better promoting soil conservation [9]. However, the effects on weed populations may also differ. Tillage, for example, can lead to a higher presence of annual plant species, which reproduce exclusively by seed, because the strong soil disturbance stimulates the germination of weed seeds [18]. In contrast, mowing mainly selects perennial forms, due to the incomplete destruction of plants and their regrowth from vegetative organs such as rhizomes or stolons [19]. Tillage can also be associated with a greater abundance of ruderal species, fast-growing plants with high seed production and early emergence, making them highly competitive and well-adapted over time to survive high levels of disturbance [20–22].

Furthermore, unlike tillage, weed control through mowing can promote higher species richness [23–25]. The control methods based on tillage or mowing/mulching, can also lead to differences in terms of the durability of their effects. A study compared three under-row weed management strategies: flaming, soil tillage, and mechanical mowing, including their effects on weed regrowth. Eighteen days after the last intervention, soil tillage reduced under-row weed biomass by about 41% compared to mowing, likely because tillage causes greater vegetation disturbance, making regrowth more difficult [9]. A faster weed regrowth may require the next operation to be carried out earlier, and this aspect should be taken into consideration by the grape grower.

During the growing season, grape growers perform several under-row weed control operations, which differ according to the sequence in which implements are used to optimize weed control effectiveness. The aim of the present study is to evaluate the effects of three different under-row weed management strategies based on equipment with lower soil disturbance compared with the implements still widely used for mechanical weed control. One strategy involved reduced-disturbance soil tillage, whereas the other two relied on weed cutting, either through mowing or mulching. For this purpose, the three strategies were compared in terms of weed control performance, considering their effectiveness, the impact on floristic composition, the effect on soil moisture, and their operational performance.

2. Materials and Methods

The experiment was conducted in 2024 at Tenuta Montefoscoli, an estate owned by Castellani, located in Palaia (Pisa, Italy) (43°33′54″ N, 10°44′23″ E). The vineyard (*Vitis vinifera* L., cv. Vermentino) was established in 2019, with vines spaced 2.30 m between rows and 0.8 m within rows. Vines were trained to a unilateral Guyot system. The soil is characterized by a sandy loam texture according to the USDA classification, with a predominance of sand (61.81%), followed by silt (21.89%) and clay (16.30%) [26]. The site is characterized by a Mediterranean climate, with rainfall peaks typically occurring in spring and autumn (Figure 1).

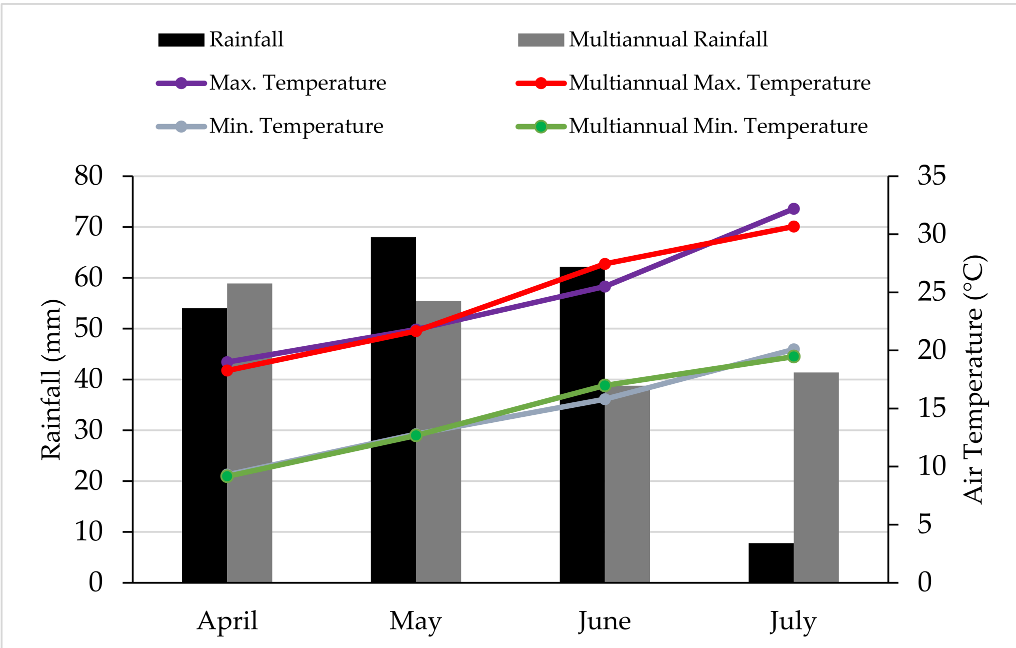


Figure 1. Monthly total rainfall (mm) and mean minimum and maximum air temperatures (°C), together with the corresponding long-term (multiannual) data, at the experimental site during the trial period.

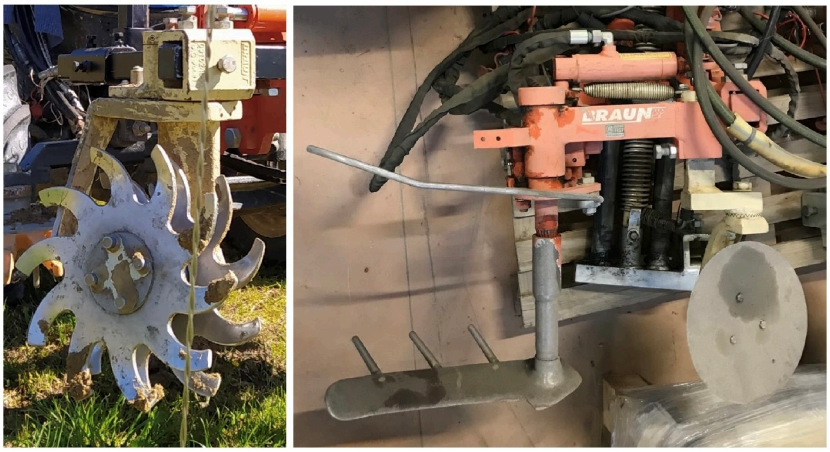
2.1. Under-Row Weed Control Strategies and Experimental Layout

The trial was conducted from May to July 2024. During this period, three under-row weed management strategies were compared: one based on soil tillage and two based on weed cutting, through mowing or mulching. Each strategy included two under-row weed control interventions. The first intervention was carried out on 14 May 2024, while the second took place on 21 June 2024. For the mowing-based strategy, both interventions were performed using an under-vine mower (Dondi, Bastia Umbra, Italy). The operating unit consisted of a single horizontal disc housing (Ø 0.40 m) equipped with four axial cutting blades, providing a cutting width of 0.35 m (Figure 2a). A horizontal feeler allowed the disc to enter the row and automatically retract upon contact with vine trunks. The machine was powered by the tractor power take-off (PTO) and featured an independent hydraulic system. During the trial, the mower was rear-mounted on the tractor. In the mulching-based strategy, a wire-equipped mulcher was used for both interventions. The Bioagri mulcher (SALF, Piacenza d'Adige, Italy) consisted of a supporting frame carrying two horizontal rotors partially enclosed by protective guards. Each rotor is equipped with nylon wires (4 mm diameter, circular cross-section), approximately 85 cm in length (Figure 2b). Each rotor carries a total of 14 flexible cutting filaments, symmetrically arranged into two opposing sets, with seven filaments positioned above and seven below the rotor axis. During rotor rotation, the flexible wires strike the vegetation with a downward motion, fragmenting the weeds into smaller pieces. The machine is powered by the tractor PTO and is equipped with an independent hydraulic system. It does not feature a feeler; when the working head encounters a vine trunk, it is pushed toward the inter-row by the tractor forward motion and subsequently returns under the row by spring action. In the present trial, the working heads were adjusted to avoid direct entry under the row, while remaining sufficiently close to allow effective wire action in the under-row area. The mulcher with wires was front-mounted on the tractor.

(a) (b)

Figure 2. Tools employed in the two cutting-based strategies: the horizontal disc with axial cutting blades (**a**) and the wire-equipped mulcher (**b**).

For the tillage-based strategy, the first intervention was performed using a rollhacke (Braun, Landau in der Pfalz, Germany), while in the second intervention a blade weeder (Braun, Landau in der Pfalz, Germany) was employed. The rollhacke is a star-shaped tool that rotates with tractor forward motion, breaking the soil and throwing it toward the vine row, thereby burying and suppressing the weeds (Figure 3a). The blade weeder consists of a horizontal blade that enters the soil superficially and cuts the weeds at shallow depth (Figure 3b). The rollhacke does not include a feeler, whereas the blade weeder is equipped with one. Both implements were mounted on a ventrally positioned frame. During all trials, the implements were mounted on a New Holland T4.90 F tractor powered by a 63 kW diesel engine. The different strategies were assessed using a randomized complete block design with three replications. Each block consisted of seven vine rows, each approximately 150 m long. For the machine equipped with a single working unit, the treatment was performed on one vine row only, which was treated on both sides. For the machine equipped with two working units, three vine rows were involved during the operation; however, only the central row was treated on both sides and considered for measurements. To perform the assessments, the first and last 50 m of each row were excluded, and only the central 50 m were considered, as this section represented the area where the treatment was effectively carried out at the selected working speed. The use of blocks allowed field heterogeneity to be accounted for in the experimental design. Before the beginning of the trial, a weed control intervention was carried out across the entire vineyard area involved in the experiment using a blade weeder on 5 March 2024.



(a) **(b)**

Figure 3. Tools employed in the tillage-based strategy: the rollhacke (**a**) and the blade weeder (**b**).

Table 1 shows the dates on which the under-row weed control operations were carried out during the trial for the different management strategies, together with the specific implement used for each intervention.

Table 1. Dates of under-row weed control operations performed during the trial under the different management strategies and implements used for each intervention.

	Date	Tillage-Based Strategy	Mowing-Based Strategy	Mulching-Based Strategy
1st Intervention	14 May 2024	Rollhacke	Under-vine mower	Mulcher with wires
2nd Intervention	21 June 2024	Blade Weeder	Under-vine mower	Mulcher with wires

2.2. Data Collection

Parameters related to the weed control performance of the different strategies were evaluated, including weed biomass, weed height, and weed cover. Measurements were taken 4 days after the first intervention on 18 May 2024 (R1), 30 days after the first intervention on 13 June (R2), and 10 days after the second weed control intervention on 1 July (R3). Prior to the start of the trial, measurements were also carried out to characterize the vineyard involved in the study.

Weed biomass was assessed by cutting and collecting the live aboveground biomass within a 30 × 25 cm frame. The collected fresh biomass was then oven-dried at 100 °C for

3–4 days until a constant weight was reached, after which the dry biomass was recorded. Two weed biomass measurement were taken for each replicate.

Weed height was measured using a folding ruler within the same frame used for biomass assessment. Two measurements per replicate were performed for this parameter.

Total weed cover, defined as the visual proportion of soil covered by weeds, was evaluated by capturing images within a square frame using a Nikon Coolpix 7600 camera (Nikon Corporation, Tokyo, Japan). The photographs were then processed with the Canopeo app, which determines weed cover percentage based on the proportion of green pixels detected within the 30 × 25 cm sampled area. Two measurements per replicate were performed for the total weed cover parameter.

The cover of each weed species present within the frame was visually estimated. The weed species present within the frame were identified directly in the field. Also, for this parameter, two measurements per replicate were carried out.

For all parameters, measurements were performed at the same location over time along the involved vine rows, except for weed biomass, as this assessment was destructive. For weed biomass, different sampling points were used, although they were located close to the previous assessment sites.

The measurement of individual weed species cover allowed the calculation of weed cover according to life cycle (i.e., the total cover of annual and perennial species), species richness, the Shannon diversity index, and evenness, thus enabling the assessment of the immediate effects of the management strategies on these parameters.

The Shannon diversity index was calculated according to the following Formula (1):

$$H = -\sum_{i\,=\,l}^{S} p_i \times ln(p_i) \tag{1}$$

where H is the Shannon diversity index, p_i is the relative proportion of the ith species based on its cover, and S is the total number of species (species richness). Evenness was estimated using the following Formula (2):

$$E = \frac{H}{ln(S)} \tag{2}$$

where H represents the Shannon diversity index and S represents species richness.

During the trial, soil moisture content was measured to evaluate the effect of the weed control strategies. Soil samples were collected at two depths: 0–15 cm and 15–30 cm. The collected samples were oven-dried at 105 °C until a constant weight was reached to determine moisture content. The survey was conducted on 24 May (10 days after the first treatment), 3 June (20 days after the first treatment), 18 June (35 days after the first treatment), and 5 July (14 days after the second treatment). For this parameter, one measurement per replicate was performed.

During the trial, operating speeds were recorded for the tools used for under-row weed control. This allowed the theoretical field time to be estimated, i.e., the period during which the implements operate at optimal working speed while covering their full working width. In addition, hourly fuel consumption per unit area was estimated for each operation performed with the different tools, using the following Formula (3):

$$Ch = W \times d \times Cs \tag{3}$$

where Ch denotes the tractor's hourly fuel consumption (kg fuel h^{-1}), W is the tractor power output (kW), d represents the engine load factor, which varies depending on the implement used (with values of 0.21, 0.33, 0.35, and 0.40 for the rollhacke, blade weeder, under-vine mower, and wire mulcher, respectively [27–29]), and Cs indicates the tractor's energy efficiency (kg fuel kWh^{-1}). In this study, the tractor's energy efficiency (*Cs*) was assumed to be 0.25 kg fuel kWh^{-1}.

These data were used to estimate the field operation time and the total fuel consumption per unit area for the overall strategy.

2.3. Statistical Analysis

Data were analyzed using R software (version 4.5.2; R Foundation for Statistical Computing, Vienna, Austria). Normality was assessed using the Shapiro–Wilk test, while homoscedasticity was evaluated using Bartlett's test. To assess the effects of the weed control strategy, sampling date (or survey), and their interaction, a two-way ANOVA was performed. The effects of the strategy, sampling date, and weed life cycle type (perennial vs. annual), as well as their interactions on weed cover by life cycle, were evaluated conducting a three-way ANOVA. Finally, to assess the effects of the management strategy, sampling depth, and sampling date on soil moisture content, a three-way ANOVA was also applied. Mean comparisons were performed using Tukey's HSD (honestly significant difference) post hoc test ($p < 0.05$). Graphs were generated using the "ggplot2" R package.

3. Results

3.1. Weed Infestation Level Before the Start of the Trial

The initial conditions in terms of infestation level and floristic composition were uniform across the vineyard where the trial was conducted, and Table 2 reports the corresponding mean values.

Table 2. Mean values of weed biomass, height, ground cover, and floristic composition parameters in the vineyard prior to the start of the trial.

	Unit	Value (SE)
Weed biomass	g d.m. m^{-2}	300.21 (52.99)
Weed height	cm	55.69 (1.70)
Total weed cover	%	58.12 (3.01)
Annual species coverage	%	35.94 (4.02)
Perennial species coverage	%	18.83 (3.02)
Species richness		4 (0.22)
Shannon diversity index		0.42 (0.03)
Evenness		0.84 (0.02)

The mean soil moisture in the vineyard where the trial was conducted was also uniform, with average values of 17.42% in the upper 15 cm and 18.42% at depths between 15 and 30 cm.

3.2. Effect of the Weed Control Strategies

Two-way ANOVA revealed that the strategy had no significant effect on weed biomass, whereas the survey ($p < 0.05$) and the interaction between strategy and survey ($p < 0.001$) significantly affected this parameter. Regarding weed height, the strategy ($p < 0.001$), the survey ($p < 0.001$), and the interaction between the two factors ($p < 0.001$) had a significant effect on this parameter. In terms of weed cover, machine ($p < 0.05$), survey ($p < 0.001$) and their interaction ($p < 0.01$) had an effect on the parameter (Table 3).

Regarding weed biomass, higher values were recorded at the survey carried out after the first weed control intervention R1 (129.40 g d.m. m^{-2}) compared with the final assessment R3 (54.15 g d.m. m^{-2}). The weed biomass values observed at the second assessment R2 (97.37 g d.m. m^{-2}) were intermediate and did not differ substantially from those recorded at the first and third assessments. At the first survey, the biomass

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values obtained with tillage (434.57 g d.m. m^{-2}) were higher than those observed for the mowing-based strategy (52.84 g d.m. m^{-2}) and the mulcher-based strategy (36.12 g d.m. m^{-2}), corresponding to percentage increases of 722.44% and 1103.03%, respectively. These differences were not observed in the second and third surveys. Moreover, during these surveys, the tillage-based strategy resulted in the lowest absolute biomass values, with 57.14 and 30.45 g d.m. m^{-2} recorded at R2 and R3, respectively (Figure 4).

Table 3. Results of the two-way ANOVA evaluating the effects of strategy, survey, and their interaction on weed biomass and weed height, and results of the three-way ANOVA assessing the effect of strategy, survey and species and their interaction on weed cover.

	Weed Biomass		Weed Height		Total Weed Cover	
	F Value	*p*	F Value	*p*	F Value	*p*
Strategy	2.71	0.078	41.09	***	4.47	*
Survey	4.22	*	46.76	***	29.39	***
Strategy × Survey	11.45	***	32.61	***	6.32	**

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

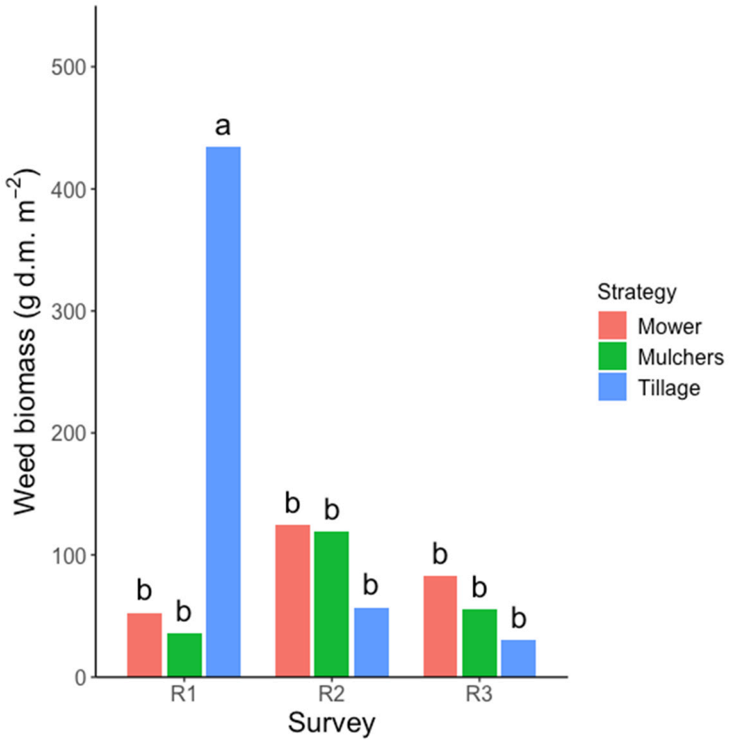

Figure 4. Effect of the interaction between weed control strategy and survey on weed biomass. Means labelled with different letters are significantly different at $p < 0.05$ (HSD test).

In terms of weed height, greater values were observed in plots managed with tillage (41.31 cm) compared to those managed with mowing (25.06 cm) or mulching (21.50 cm). No differences were found between the mowing- and mulcher-based strategies. In R2, greater weed height values were recorded compared to R1 and R3, with measurements of 38.89, 32.08, and 16.89 cm, respectively. At the first survey, the tillage-based strategy showed greater weed height compared to the mowing and mulching strategies. No differences were observed among the three strategies at the second survey (R2), with values ranging from 36.92 to 40.42 cm, nor at the third survey (R3), with values between 9.25 and 21.92 cm (Figure 5).

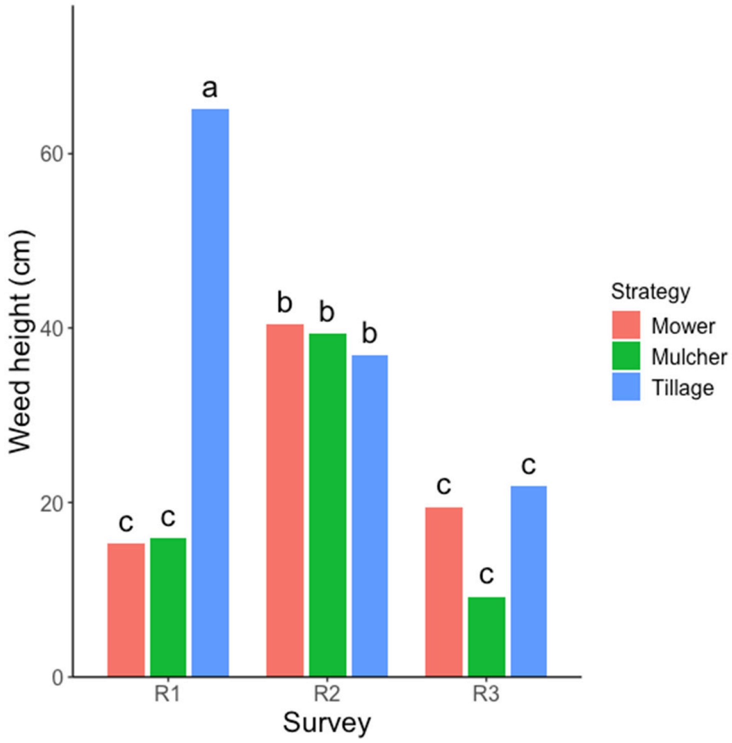

Figure 5. Effect of the interaction between weed control strategy and survey on weed height. Means labelled with different letters are significantly different at $p < 0.05$ (HSD test).

The strategies based on mowing achieved a higher value of total weed cover compared to the one based on mulching and the one based on tillage, with values of 28.33, 16.82, and 18.83%, respectively. In R1 and R2, higher total weed cover values were recorded compared to R3 (32.91, 27.70 and 3.37%, respectively). In R1, the tillage-based and mowing-based strategies showed similar total weed cover values (43.80% and 38.36%, respectively), which were higher than those observed for the mulching-based strategy (16.58%). In R2, the tillage-based strategy resulted in a lower total weed cover compared with both the mulching-based and mowing-based strategies (11.35%, 31.46%, and 40.30%, respectively). In R3, the three strategies produced comparable results, with an average total weed cover of 3.37% (Figure 6).

The three-way ANOVA highlighted that, in terms of weed cover by life cycle, strategy ($p < 0.05$), survey ($p < 0.001$), life cycle ($p < 0.001$), the interaction between strategy and survey ($p < 0.001$), the interaction between strategy and life cycle ($p < 0.001$), and the interaction between survey and life cycle ($p < 0.001$) all had a significant effect on the parameter, whereas the three-way interaction was not significant. The two-Anova revealed that the strategy affected both species richness ($p < 0.05$) and Shannon diversity index ($p < 0.01$), while it did not affect evenness. The survey and the interaction did not affect the three parameters (Table 4).

The mowing-based strategy (20.42%) achieved higher weed cover by life cycle values compared to the mulcher-based strategy (12.64%), whereas no significant differences were observed between the tillage-based strategy (15.17%) and the other two strategies. In R2 (22.69%), higher weed cover by life cycle values were observed compared to R3 (9.50%), while in R1 (16.03%) intermediate values were obtained. Higher values were recorded for perennial species (22.67%) compared to annual species (9.48%). In R1, the tillage-based strategy (26.50%) achieved higher weed cover by life cycle values than the mulcher-based strategy (9.33%), while no differences emerged compared with the mower-based strategy (12.25%). In R2, the tillage-based strategy (12.50%) showed lower weed cover by life cycle than the mower-based strategy (29.67%) and similar values—although lower in absolute terms—compared with the mulcher-based strategy (25.92%). In R3, there were no differences between tillage (6.50%) and the strategies based on the mower (19.33%) and the mulcher (2.67%), while the latter showed a lower value than the mower-based strategy (Figure 7).

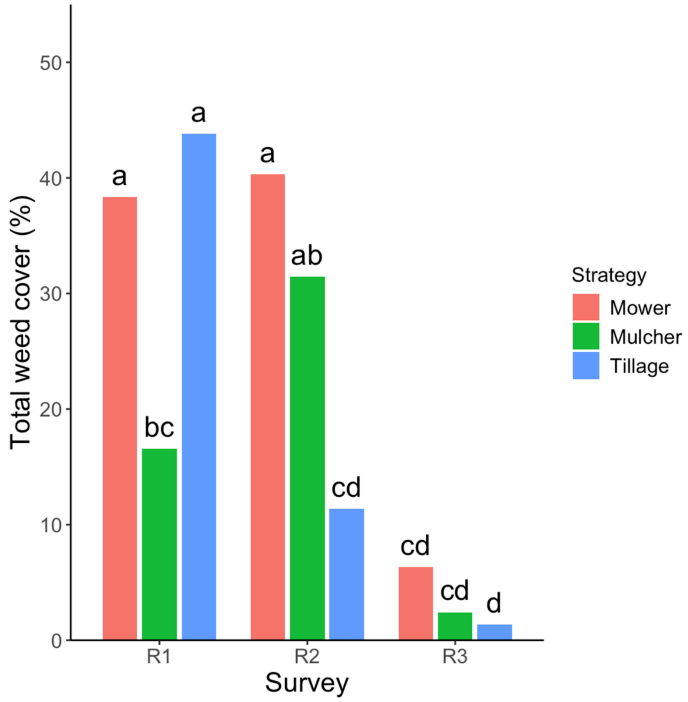

Figure 6. Effect of the interaction between weed control strategy and survey on total weed cover. Means labelled with different letters are significantly different at $p < 0.05$ (HSD test).

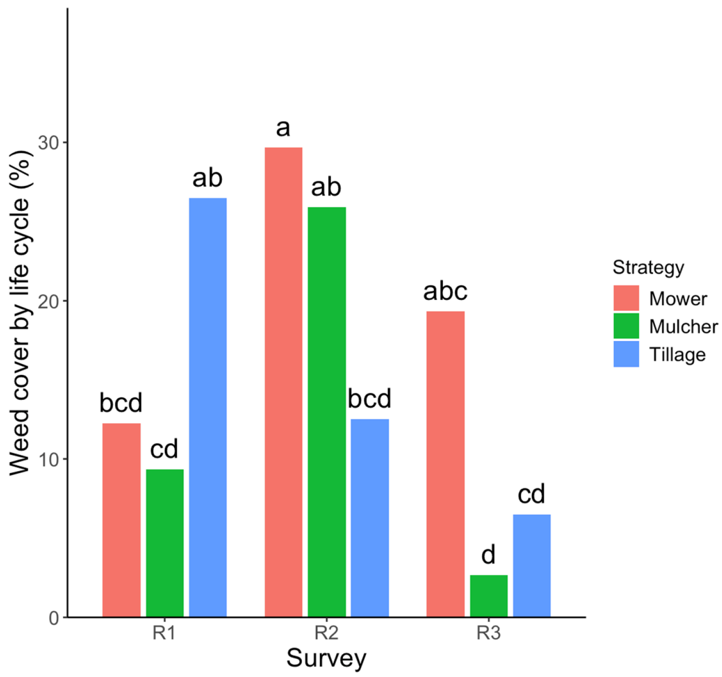

Figure 7. Effect of the interaction among survey and the strategy adopted on weed cover by life cycle. Means labelled with different letters are significantly different at $p < 0.05$ (HSD test).

Table 4. Results of the three-way ANOVA investigating the effects of strategy, survey, life cycle, and their interactions on weed cover by life cycle, and of the two-way ANOVA evaluating the effects of strategy, survey, and their interaction on species richness, Shannon diversity index, and evenness.

	Weed Cover by Life Cycle		Species Richness		Shannon Diversity Index		Evenness	
	F-Value	***p***	**F-Value**	***p***	**F-Value**	***p***	**F-Value**	***p***
Strategy	3.77	*	3.44	*	5.41	**	2.88	0.072
Survey	10.41	***	3.10	0.055	3.10	0.055	0.17	0.841
Strategy × Survey	7.77	***	2.22	0.083	0.39	0.813	0.80	0.538
Life cycle	31.20	***	-	-	-	-	-	-
Strategy × Life cycle	12.43	***	-	-	-	-	-	-
Survey × Life cycle	64.97	***	-	-	-	-	-	-
Strategy × Survey × Life cycle	2.01	0.100	-	-	-	-	-	-

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

In both the mower-based and mulcher-based strategies, greater weed cover of perennial species (34.17 and 19.33%, respectively) was observed compared to annual species (6.67 and 5.94%, respectively), whereas in the tillage-based strategy no differences in cover were detected between annual (15.83%) and perennial species (14.50%) (Figure 8).

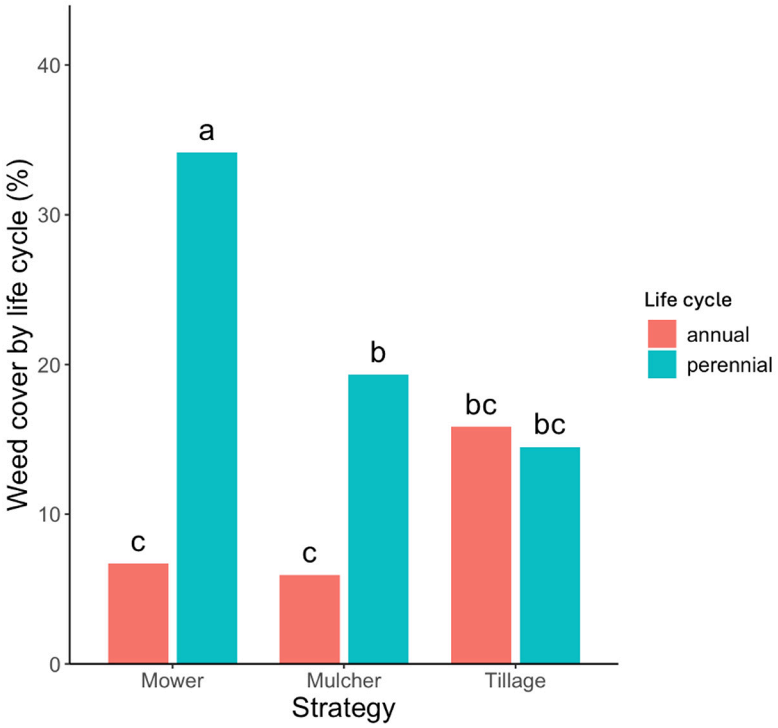

Figure 8. Effect of the interaction between the strategy and the species on weed cover. Means labelled with different letters are significantly different at $p < 0.05$ (HSD test).

In R1, the cover of annual species (26.50%) was higher than that of perennial species (5.56%), whereas in R2 and R3 the cover of perennial species (45.11% and 17.33%, respectively) was higher than that of annual species (0.28% and 1.67%, respectively) (Figure 9).

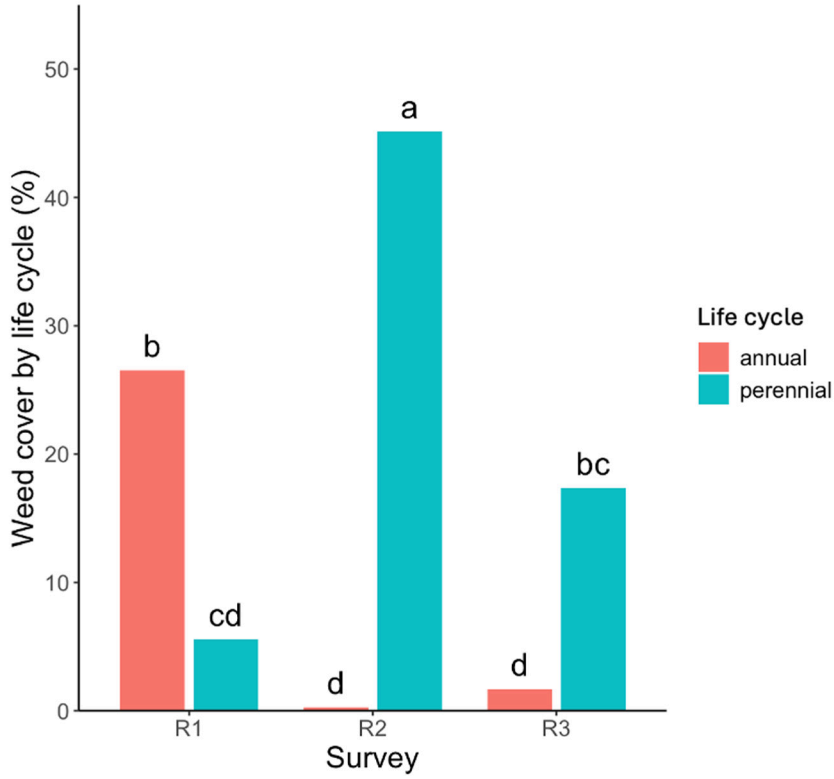

Figure 9. Effect of the interaction among survey and species on weed cover. Means labelled with different letters are significantly different at $p < 0.05$ (HSD test).

Higher species richness values were observed in plots managed with mowing (2.17) compared to those managed with mulching (1.56), whereas no differences were detected between the tillage-based strategy (1.94) and the other two strategies.

In terms of the Shannon diversity index, higher values were recorded under the mowing-based strategy (0.25) compared to the tillage-based (0.14) and mulcher-based (0.12) strategies.

Neither the main factors nor their interactions had a significant effect on soil moisture content (Table 5).

Table 5. Effect of the strategy adopted, date, depth and their interaction on soil moisture content %.

	Soil Moisture	
	F-Value	***p***
Strategy	0.952	0.393
Date	0.988	0.407
Depth	0.445	0.508
Strategy × Date	1323	0.266
Strategy × Depth	0.745	0.481
Date × Depth	1514	0.224
Strategy × Date × Depth	0.854	0.536

3.3. Operative Performance

Table 6 shows the operative performance of the strategies involved in the comparison.

Among the implements tested, the rollhacke and the mulcher operated at the highest forward speeds, resulting in the shortest field times. In contrast, the mower presented a lower working speed and, as the implement carrier was equipped with a single mowing unit, the field time per operation was substantially higher than those recorded for the rollhacke and the mulcher, with percentage increases of 504.17% and 330.69%, respectively. The lowest fuel consumption per hectare was observed for the rollhacke, whereas the highest fuel consumption was recorded for the mower, which showed an increase of approximately 900% compared with the rollhacke. This difference was mainly attributable to the longer operating time required to manage the treated area. Regarding the strategies, the mulching- and the tillage-based ones resulted in better operational performance than the mowing strategy, with an average time saving of 6.42 h ha^{-1}. A similar trend was observed for fuel consumption, with an average saving of 32.09 kg ha^{-1}. By equipping the mower implement carrier with two working heads, the operational time would have been 4.35 h ha^{-1} and fuel consumption 21.57 kg ha^{-1}, i.e., half of the actual values; however, these values would still have been higher than those recorded for the other strategies.

Table 6. Operational performance of weed control interventions across different strategies, and their overall effectiveness.

		Working Speed		Field Time		Fuel Consumption	
	Tillage						
I Intervention		6.00	km h^{-1}	0.72	h ha^{-1}	2.16	kg ha^{-1}
II Intervention		2.40	km h^{-1}	1.81	h ha^{-1}	8.47	kg ha^{-1}
			Total	2.54	h ha^{-1}	10.63	kg ha^{-1}
	Mowing						
I Intervention		2.00	km h^{-1}	4.35	h ha^{-1}	21.57	kg ha^{-1}
II Intervention		2.00	km h^{-1}	4.35	h ha^{-1}	21.57	kg ha^{-1}
			Total	8.70	h ha^{-1}	43.14	kg ha^{-1}
	Mulching						
I Intervention		4.30	km h^{-1}	1.01	h ha^{-1}	5.73	kg ha^{-1}
II Intervention		4.30	km h^{-1}	1.01	h ha^{-1}	5.73	kg ha^{-1}
			Total	2.02	h ha^{-1}	11.47	kg ha^{-1}

4. Discussion

At the first assessment, carried out four days after the initial weed control intervention, strategies based on grass cutting showed positive results. Solutions based on mowing and mulching resulted in lower weed biomass and weed height compared to the tillage-based solution, with values of 52.84, 36.12, and 434.57 g d.m. m^{-2} for weed biomass, and 15.25, 15.92, and 65.08 cm for weed height, respectively. The type of disturbance and the mechanism of action of the implements used may explain the results observed at this assessment. Indeed, unlike mowing- and mulching-based tools, which directly remove the aboveground weed biomass and therefore produce an immediately visible effect, the tillage implement acts through soil disturbance and disruption of the root system. Consequently, its effect may not have been fully detectable only four days after the intervention. At the second assessment, conducted approximately one month after the first intervention and before the second weed control operation, the differences between mowing- and mulching-based strategies and the tillage-based strategy became less pronounced. Indeed, the three strategies achieved similar results in terms of both weed biomass and weed height. The effects of the tillage-based strategy were therefore more evident, resulting in lower absolute values for both parameters compared to the other two strategies. In terms of total weed cover, at R2 tillage achieved better results than both the mulching- and mowing-based strategies. This outcome, observed one month after the intervention, may be associated with the lower level of disturbance caused by mulcher- and mower-based strategies compared to tillage. Tools based on cutting act only on aboveground biomass and do not affect the soil or belowground organs, potentially allowing faster weed regrowth [30]. It is emphasized that, in agreement with [31,32], the effectiveness of weed control should not be evaluated solely on the basis of its immediate efficacy but also by considering weed regrowth. Faster weed regrowth may indeed require a higher number of interventions during the growing season, with consequent impacts on fuel consumption, machinery availability, and soil compaction due to traffic [33].

Overall, no differences among the strategies were observed in terms of weed biomass, which reached an average value of 124.33 g d.m. m^{-2}. However, with respect to weed height, the tillage-based strategy resulted in higher values (41.31 cm) compared to mowing and mulching. Nevertheless, weed height remained below the grape cluster zone. This is a key aspect, as it helps to avoid conditions of increased humidity around the cluster area, which could otherwise promote the development of fungal diseases [34]. With respect to total weed cover, the mowing-based strategy resulted in the highest value (28.33%) compared to the mulching- and tillage-based strategies. This may be attributed to the different modes of action of the tools employed. Tillage-based tools, even when operating at shallow depths, disturb and break the soil. In contrast, the mulcher used is based on medium-length flails (approximately 85 cm) rotating around a horizontal axis, which strike the vegetation from top to bottom and also impact the soil surface. In the case of the mower, a horizontal cut is performed, removing weeds at a given height while leaving the belowground parts unaffected. As a result, these less-damaged organs may continue to cover the soil or have a higher probability of regrowth, further increasing soil coverage [9]. Higher weed cover may be associated with increased competition, but it may also provide greater soil protection against erosive processes [35]. Regarding the parameter weed cover by life form, both grass-cutting-based strategies showed a higher cover of perennial species than annual species, with the mower-based strategy recording the highest value (34.17%). These results may be attributed, as before, to the mechanism of action of the implements. By avoiding soil disturbance, weed cutting does not promote the germination of seeds already present in the soil. Additionally, when applied in a timely manner, it can suppress annual species by preventing seed production [36]. However, as grass cutting does not disturb the soil, it has less impact on perennial species with belowground vegetative organs, which therefore tend to proliferate [30]. In contrast, the tillage-based strategy resulted in a more balanced distribution of annual and perennial species with values of 15.83 and 14.50%, respectively. This may be attributed to the use of low-impact implements within this tillage strategy, which operate at shallow depths and do not induce intensive soil refinement, thereby allowing the presence of both annual species, typically associated with tillage practices, but also perennial species [37–39].

Mowing also showed a higher species richness value (2.17) compared to the mulching-based solution (1.56), likely because it represents a less intense mechanical disturbance that can be tolerated by a greater number of species. In contrast, in the mulching-based solution, the use of wires that strike the vegetation, cutting and tearing weeds and reaching down to the soil surface, potentially damaging even their collars, may contribute to greater harm to these plants. Consequently, the number of species able to survive and tolerate this disturbance may be reduced, resulting in slower and more gradual regrowth [40]. On the other hand, tillage with shallow implements, compared to conventional ones, can create temporary open niches for species from the soil seed bank, while allowing some less-disturbed perennial species to persist, resulting in intermediate species richness (1.94) [30]. The mowing-based strategy also showed higher Shannon diversity values (0.25) compared to tillage (0.14) and mulching (0.12). Since species evenness did not differ among strategies, the higher Shannon diversity under mowing is mainly due to more species contributing to ground cover rather than changes in their relative abundances. Within this context, it is important to acknowledge that the short-term evaluation of parameters such as species richness, Shannon diversity index, and evenness may represent a limitation, as longer-term assessments are needed to obtain more robust and stable results. However, the present approach still provided valuable insights into the immediate response of weed communities to different management strategies. No differences in soil moisture were observed between the strategies, although tillage initially showed higher weed biomass values. Probably, as the weed control effects of the tillage-based strategy gradually manifested, the competitiveness of the weeds in terms of water uptake decreased.

Based on the estimations, the mulching strategy showed the lowest field time (2.02 h ha^{-1}), the mowing strategy the highest (8.70 h ha^{-1}), and the tillage one an intermediate value (2.54 h ha^{-1}). This is partly because the mower carrier had only one operating unit. Adding a second unit would halve operating time, but values would still exceed those of other management strategies, so the difference mainly reflects the implement's working speed (2.00 km h^{-1}). Mowing is usually not performed at high speeds, as it is based on the use of a disc that repeatedly enters and exits the under-row area avoiding damaging the vines. This finding agrees with Gagliardi et al. [8] who observed longer operating times for a mower-based weed control solution compared to solutions using a blade weeder or a rollhacke. With the mulcher, it was necessary to use a working speed of 4.3 km h^{-1} to avoid causing damage to the vine trunks, given the rotation speed of the rotor of the working head employed, which was considered the most suitable for effective weed control. In the case of tillage, the field time was intermediate; the average value was mainly increased by the second intervention carried out with the blade weeder at a particularly slow working speed (2.40 km h^{-1}), due to the reduced sharpness of the blades. Fuel consumption was higher for the mowing-based strategies (43.14 kg ha^{-1}), whereas the other two strategies showed similar and lower values (10.63 and 11.47 kg ha^{-1}, for the tillage and the mulching-based strategies, respectively), resulting in an average reduction of 74.39% compared to mowing. An aspect that was not considered in the present study, but that deserves further investigation, is the wire consumption of the wire mulcher. In some cases, wire wear and dispersion were observed under field conditions, highlighting the need to quantify the amount of material dispersed in the field to better assess the environmental impact of this equipment, particularly in relation to potential microplastic contamination.

Overall, the three tested strategies achieved similar results in terms of weed control effectiveness. However, each strategy seemed to operate through different mechanisms, resulting in distinct impacts on the vineyard weed community and operational characteristics. In particular, mowing seemed to promote greater soil cover, potentially contributing to improved soil protection against erosion, and increased the number of species present. Conversely, mulching and tillage appeared to be particularly advantageous in terms of operational efficiency, resulting in shorter operating times and lower fuel consumption.

However, it is important to consider that the results are specific to the experimental conditions, including the vineyard characteristics, planting system, grapevine cultivar, pedoclimatic conditions, and the one-year duration of the experiment. Moreover, the results may also depend on the machine configurations adopted, although these were carefully selected to optimize the operational performance of each implement. The choice of the most suitable strategy should be context-specific, opting for a single approach or a combination of them based on specific needs, while always considering soil conservation, biodiversity, and economic sustainability.

5. Conclusions

The three strategies compared all produced positive results. No significant differences were observed in terms of weed biomass among the tested solutions, which reached an average value of 124.33 g d.m. m^{-2}, although the tillage-based solution generally resulted in greater weed height (41.31 cm), yet always below the cluster zone. In terms of total soil weed cover, mowing achieved the highest value (28.33%). Mowing also stood out in terms of species richness (2.17) compared to mulching, and in Shannon index (0.25) relative to both other strategies. This aspect, attributable to the different mechanisms of action of the under-vine mower, may enhance the ecological value of the strategy.

However, from an operational perspective, the tillage- and mulching-based strategies proved to be the most efficient, both in terms of operating time (2.54 and 2.02 h ha^{-1}, respectively) and fuel consumption (10.63 and 11.47 kg ha^{-1}, respectively). On average, these two strategies reduced operating time and fuel consumption by 73.79% and 74.39%, respectively, compared with the mowing-based strategy. Further studies are needed to evaluate the performance of strategies that combine shallow soil tillage implements with vegetation cutting approaches, either through mowing or mulching, and to assess their effectiveness across different vineyard contexts. Moreover, it would be worthwhile to investigate the broader impacts of these strategies by quantifying their effects on soil erosion, soil organic matter content, soil biological activity, grape yield and quality, and profitability. Additional research should also focus on assessing potential vine damage caused by mulchers equipped with wires of different materials and diameters, as well as on quantifying the resulting microplastic contamination in vineyards.

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