agronomy

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Assessment of a Chain Mower Performance for Weed Control under Tree Rows in an Alley Cropping Farming System

Lorenzo Gagliardi, Marco Fontanelli *, Christian Frasconi, Mino Sportelli, Daniele Antichi, Lorenzo Gabriele Tramacere, Giovanni Rallo, Andrea Peruzzi and Michele Raffaelli

Department of Agriculture, Food and Environment, University of Pisa, Via del Borghetto 80, 56124 Pisa, Italy
* Correspondence: marco.fontanelli@unipi.it

Abstract: In the area under tree rows of alley cropping systems, coarse plant material as well as pruning material or stones may be present, so the use of a mower equipped with chains as cutting a tool could be advantageous. A mower designed for under-row weed control in orchards, equipped with an automatic tree-skipping mechanism, was modified by replacing blades with chains with the aim of evaluating its performance in an alley cropping system. A first trial was carried out in an open field to preliminarily compare the chain mower with the version equipped with blades in relation to different settings of working speed (1.6 and 2.4 km·h^{-1}) and rotation speed of the cutting tool (1830 and 2500 rpm). Weed biomass reduction, weed cover reduction, weed height reduction, weed biomass regrowth, and clipping size were assessed. In a second trial, the performance of the mowers with different setting configurations was assessed in an alley cropping system under a more critical environmental condition for mowing, i.e., the presence of dew. Weed biomass reduction, weed cover reduction, weed height reduction, and the mowers' field capacity with different working speed settings were assessed. No major differences emerged between the mowers and the chain mower performance was comparable to that of the standard blade mower. The setting with the high working speed and high rotation speed of the cutting tool turns out to be the best compromise, obtaining a weed biomass reduction of 59.6%, a weed cover reduction of 40.9%, and a higher field capacity compared to the setting with the low working speed, with an increase of 47.9%.

Keywords: agroforestry; under-row weed control; automatic tree-skipping; mechanical weed control; no-till strategies

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Citation: 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. https://doi.org/10.3390/agronomy12112785

Academic Editor: Anestis Karkanis

Received: 15 September 2022
Accepted: 6 November 2022
Published: 9 November 2022

1. Introduction

The ability of agriculture to fulfill the food demand of a growing world population is currently threatened by multiple factors, such as climate change, soil degradation, depletion, and pollution of water resources [1]. As environmental issues and ecological sustainability gain more relevance and the research for environmentally friendly practices becomes increasingly important [2,3], agroforestry strategies are being explored with growing interest as sustainable approaches to land use. Agroforestry essentially refers to land use systems that, through the intercropping of trees and/or shrubs along with crops and/or animals, diversify and support production for greater socioeconomic and environmental benefits for land users [4,5]. Alley cropping represents a common agroforestry practice that consists of growing arable crops in alleys between widely spaced rows of trees or shrubs. This practice proved to benefit the agricultural systems by increasing overall productivity and resilience and promoting the rehabilitation of degraded soils [6,7]. However, some constraints may be related to a potential decrease in arable crop yield due to competition with trees, higher management needs, and greater labor demand [8]. In particular, under-row weed control can represent a major issue. Weeds can compromise the success of new agroforestry planting establishment [9]. Indeed, the optimal growth and survival of many tree species grown in temperate agroforestry systems can be hindered by weed competition [9–11].

Schroeder and Naeem [12] observed that weed control positively influenced the annual height increment, total basal diameter, and height of the tested agroforestry tree species. Furthermore, the risk that some weeds spread from the under-row area towards the crop in the alley, leading to yield losses, should be considered [13–15]. To date, the most common methods used to manage under-row weeds in alley cropping systems are mulching, chemical applications, and mowing. Mulching can be achieved by applying straw or other recalcitrant and cheap plant material under the row or by applying plastic mulch [16,17]. However, generally, large-scale mulching is cost-intensive [18]. The use of living mulch, i.e., cover crops planted in main crop stands and maintained as a living ground cover for part of or the whole growing season, provides many useful ecosystem services. Nevertheless, the proliferation of vegetation can create a too-competitive environment for the establishment and growth of trees [19]. On the other hand, the application of chemicals (i.e., herbicides), despite their effectiveness, not only causes environmental pollution but can also damage trees, making it necessary to shield them before treatments [12,16]. Mowing represents another weed control method commonly adopted in alley cropping systems. This practice can effectively reduce the competitiveness and longevity of perennial weeds and prevent the production of seeds for many types of weeds avoiding their spread [20,21]. Chen et al. [22] found that mowing effectively regulates the root amount and depth of mowed plants with consequent improvement of soil moisture. Furthermore, this practice can promote soil conservation by maintaining a permanent sod that helps to protect the soil from erosion [23]. In the under-row area of alley cropping systems, mowing can be performed by operators with motorized mowers [24], string trimmers, or with tractor-mounted mowers [25]. The tractor-mounted flail mowers employed in these contexts perform a side shift movement through a hydraulic lateral transverse function or hydraulic arms, cutting weeds along the tree row and skipping trees [26,27]. However, the use of these machines for this purpose can be laborious, as the lateral movement occurs following the command of the operator. On the other hand, the use of machines with an automatic tree-skipping mechanism (by means of a feeler, for example, such as those for under-row weed control in orchards), would make the practice easier for the operator [23]. Indeed, according to this tree-skipping mechanism, the mowing implement, due to the presence of a feeler rod, can enter the row in the working position and automatically exit whenever the feeler perceives the pressure of tree trunks. Among mowers, the rotary impact types are increasingly used due to their simplicity in construction and low maintenance cost [28]. These mowers can be equipped with various types of cutting tools, and their performance is strictly related to cutting edge sharpness and cutting speed. Generally, as the rotation speed of the cutting tool increases and the working speed decreases, the effectiveness of the cutting tool increases [29–31]. Furthermore, for tools that perform impact cutting, the cutting action is also linked to the plant inertia that, by conferring the opposing force, allows tools to penetrate the plant material. Thick stalks have higher inertia than thinner stalks, thus requiring lower cutting speed to be penetrated by the cutting tool [29]. The environmental conditions in which mowing is performed can also influence its effectiveness. In the presence of moisture on the leaves' surface, wet clippings, tending to easily bunch up, can cause the clogging of the mowers, thus jeopardizing the mowing operation [32]. In forest scenarios, chain mowers are often employed for clearing operations [33–35]. Chain mowers can effectively clear coarse plant material and are suitable for use in areas with high stoniness since chains simply bend over these obstacles whereas blades become frequently damaged [34–36]. It is well-known that the longer a cutting tool lasts before wearing out and needing to be changed, the better it is for the user. The use of chain mowers could be advantageous for under-row management in alley cropping contexts since coarse plant material, tree residues (such as pruning materials), or stones may be present in this area. To the best of our knowledge, there has been no research testing a chain mower with an automatic tree-skipping mechanism for under-row weed control in alley cropping farming systems. In this research, a mower designed for under-row weed control in orchards was modified by replacing blades with chains with the aim of evaluating its performance in an alley cropping context. The weed control effect of the chain mower was evaluated in comparison with the commercial version equipped with blades. The performances of the two mower versions were assessed in relation to different settings of the working speed and rotation speed of the cutting tool, preliminarily in an open field and then in an alley cropping farming system.

2. Materials and Methods

Two trials were performed in 2022 at the Centre for Agri-environmental Research “Enrico Avanzi”, San Piero a Grado (Pisa), Italy (43°40′48′′ N, 10°20′49′′ E, 1 m.a.s.l.) to assess the chain mower performance as a means of under-row weed control in alley cropping systems. The first trial was carried out in an open field managed as weedy fallow, with the aim of comparing the weed control effect of the two mower versions with different setting configurations to preliminarily identify any ineffective ones. The second trial was conducted in a real alley cropping farming system to compare the two mower versions’ weed management performance in the under-row area. In this second trial, the mowers’ performance with different setting configurations was also assessed in a more critical environmental condition for mowing, such as with the presence of dew, to identify the most suitable setting configuration.

2.1. The Mowing Machine

Mowing was carried out with a tractor-mounted under-row mower (Dondi, Bastia Umbra, Italy) designed for weed control in orchards (Figure 1). The machine is driven by the power take-off and is equipped with an independent hydraulic system. The mowing implement is represented by a horizontal disc case (Ø 0.40 m) and 4 axial cutting blades (Figure 2a,b) driven by a hydraulic motor. The chain mower was obtained by replacing each blade with grade 8 chains in tempered steel (EN 818-2) (Figure 2c). The technical characteristics of the two cutting tools are shown in Table 1.

(a) (b)

Figure 1. Rear (**a**) and lateral (**b**) view of the under-row mower.

(a) (b) (c)

Figure 2. Different kinds of cutting tool: (**a**) blade; (**b**) cross section of the blade; (**c**) chain.

Table 1. Cutting tools' technical characteristics.

Parameters		Chain *	Blade *
Mass	g	94.3	397.6
Length	mm	118	151
Width	mm	21	51
Thickness **	mm	6	8

* Measurements refer to the single cutting tool. ** For the chain, the value corresponds to the wire diameter.

The cutting widths were 0.35 m and 0.32 m, respectively, for the blade and the chain mower versions. The mower is the one-sided type; thus, one pass on either side of the tree row is required for completing the row management. The presence of a horizontal feeler rod and a single-acting hydraulic cylinder allow the mowing disc to enter the row and automatically exit whenever the feeler perceives the pressure of tree trunks. The minimum distance between tree trunks to guarantee the optimum operation of the mower is 0.80 m. The disc case prevents cutting tools from damaging tree trunks. The mass of the machine is equal to 400 kg. During each trial, the mower was coupled with a Fiat DT 70-90 tractor (FiatAgri, Torino, Italy) powered by a 52.2 kW diesel engine.

2.2. Experiment Layout

In the first trial, the performances of the chain mower and the blade mower were compared in an open field with sandy loam soil and managed as weedy fallow, considering two working speeds (1.6 and 2.4 km·h^{-1}) and two rotation speeds of the cutting tool (1830 and 2500 rpm). The configuration settings of the machine with different working speeds and rotation speeds of the cutting tool were adjusted by identifying the appropriate combination of the range and speed gearbox of the employed tractor. The working speed was measured by recording the time taken by the tractor coupled with the mower to travel a known distance. The rotation speed of the cutting tool was detected with Extech 461920 Mini Laser Photo Tachometer Counter (Extech, Nashua, NH, USA). The tachometer employed measures in rpm in the range from 2 to 999,999 rpm, with a resolution of 0.1 rpm. During the first trial, mowing was performed with both mower versions on 5 February 2022. The adopted experimental design was a randomized complete block design with three replications. Each block was 10 m long. Both mower versions were tested with four different types of setting configurations each, according to the working and rotation speeds: (i) low working speed and low rotation speed of the cutting tool (Lws + Lrs); (ii) low working speed and high rotation speed of the cutting tool (Lws + Hrs); (iii) high working speed and low rotation speed of the cutting tool (Hws + Lrs); (iv) high working speed and high rotation speed of the cutting tool (Hws + Hrs). The tested setting configurations and the diagram describing the tested factors and relative levels in the first trial are shown in Table 2 and Figure 3, respectively.

Table 2. Main properties of the research concerning the tested setting configurations.

Settings	Working Speed (ws)		Rotation Speed (rs)	
Lws + Lrs	km·h^{-1}	1.6	rpm	1830
Lws + Hrs	km·h^{-1}	1.6	rpm	2500
Hws + Lrs	km·h^{-1}	2.4	rpm	1830
Hws + Hrs	km·h^{-1}	2.4	rpm	2500

L—Low; H—high; ws—working speed; rs—rotation speed.

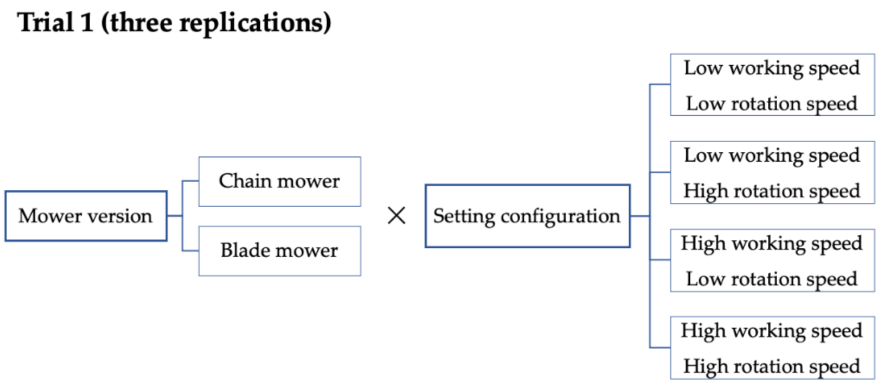

Figure 3. Diagram describing tested factors and relative levels in the first trial.

During the first trial, the most abundant weeds presents in the field when mowing was performed belonged to the genus *Lolium*. For this trial, weed biomass reduction, weed cover reduction, weed height reduction, weed biomass regrowth, and size of clippings produced were assessed.

The second trial was performed in an alley cropping system that consisted of a three-year rotation of annual grain crops planted between rows of poplar trees. The crop rotation included durum wheat (*Triticum turgidum* subsp. durum (Desf.) Husn.), sorghum (*Sorghum bicolor* L. Moench), and pigeon bean (*Vicia faba* L. var. minor Beck). The poplar trees along the rows were various clones of the hybrid poplar *Populus* × *canadensis* Moench planted in February 2019. Poplar trees provide high-value timber that is sold for plywood production. Three rows consisted of trees placed with 5 m of distance between each other and the distance between rows was 18 m. In this system, the arable crop is sowed between tree rows and a 2 m wide zone without crop was provided between tree rows and the arable crop. During this second trial, mowing was carried out on 11 February 2022 (Figure 4). Performing under-row weed control in this period allows the reduction of weed pressure and therefore competition with poplar trees at the time of their spring vegetative restart. The under-row weed control performance of the two mower versions with the above-mentioned setting configurations was evaluated both in the presence and in the absence of dew (Figure 5). To evaluate the mowers' performance in a critical environmental condition, mowing was tested at 9:30 a.m., according to the higher level of dew. Successively, at 12:00 a.m., a no-dew condition was identified and then tested. The times when mowing interventions were performed were chosen according to a preliminary dew monitoring followed in the two days preceding the trial. At this scope, leaf wetness sensors, described in Section 2.3, were used. Dew and no-dew mowing interventions lasted 50 min each. To ensure that both mower versions and their setting configurations acted under the same dew conditions, each mowing treatment was arranged so that the respective mowing alternately ran. During this second trial, a randomized complete 10 m long block design with three replications was adopted. In particular, each block was identified within the three spatial replicates of the field occupied by durum wheat in 2021/2022. Soil texture was sandy clay loam. Weed cover reduction, weed height reduction, weed biomass reduction, and field capacity of the two mower versions with different setting configurations were assessed. In the second trial, the majority of weeds encountered in the fields belonged to the genera *Lolium* and *Poa*.

Figure 4. Mowing performed on 11 February 2022: (**a**) front view of the working mowing disc; (**b**) rear view of the working mowing disc.

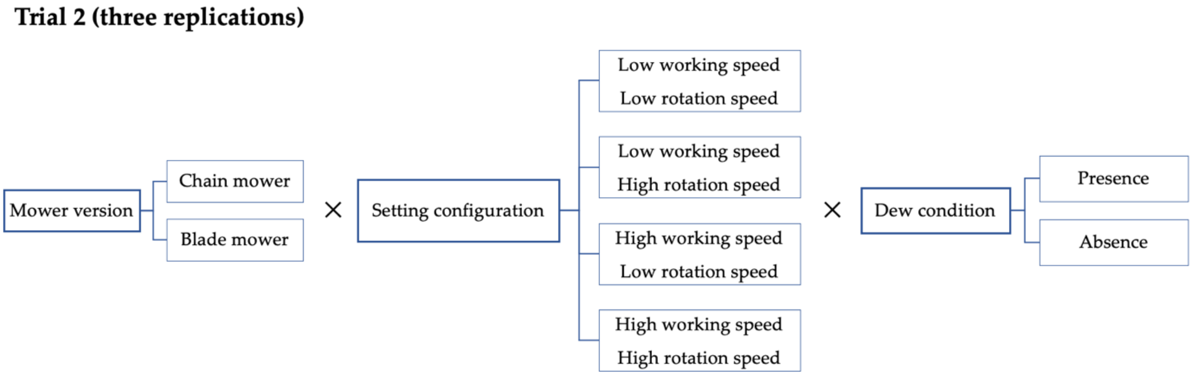

Figure 5. Diagram describing tested factors and relative levels in the second trial.

2.3. Data Collection

In each trial, weed cover, weed height, and weed biomass were determined before and four days after mowing treatments, according to Pergher et al. [23]. For the first trial, the measurements before treatment were carried out on 5 February 2022, just before the treatment was performed, while the measurements after treatment were executed on 9 February 2022. During the second trial, the surveys before treatment were carried out on 10 February 2022, i.e., the day before treatment, while the surveys after treatment were performed on 15 February 2022. Weed cover, which corresponds to the weed soil visual cover, was determined using a Nikon Coolpix 7600 (Nikon corporation, Tokyo, Japan) to shoot picture-task inside a square frame of 30 × 25 cm. Subsequently, pictures were analyzed with the Canopeo app [37], which provides the weed cover percentage by measuring the green pixel percentage of the 30 × 25 cm picture-task. Average weed population height was measured inside the square frame with a folding ruler. Three measurements for each replicate were carried out for weed cover and weed height before and after treatments. Weed biomass measurements were performed by cutting and collecting the live aboveground weed biomass present in the square frame of 30 × 25 cm. Total fresh biomass was then oven-dried at 100 °C for 3–4 days (until mass was constant) and dry biomass was then determined. One measurement per replicate of weed biomass was performed, before and after treatments. During the second trial, weed biomass, weed cover and weed height values were collected in the area between tree trunks.

For the parameters relating to weed biomass, weed cover, and weed height, the efficacy of both mower versions with each setting configuration was measured as the percentage of reduction (*R*) of initial values of the aforementioned parameters assessed on each plot according to the following Equation (1):

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

where x_b and x_a are the entity of the parameter (in this case weed biomass, weed cover, or weed height) assessed before and after treatments, respectively.

During the first trial, clipping size, and weed biomass regrowth were also assessed. Clippings were collected immediately after the treatment and manually measured in length, whereas weed biomass regrowth was collected fifteen days after treatment in the properly marked same areas and the percentage increase in biomass was estimated.

The field capacity of both mower versions with different setting configurations of working speed was estimated in the alley cropping system considering the theoretical field time (i.e., the time the machine effectively operates at an optimum working speed and works over its full width of action) and the turning time.

In the second trial, weed leaf wetness was measured with the A-series leaf Wetness Sensor (Spectrum Technologies Inc., Aurora, IL, USA), a grid-like resistance-based sensor coupled to a datalogger LogBox-AA (Novus, Canoas, Brazil). LogChart-II software (Novus, Canoas, Brazil) was used to configure the datalogger and download and display data. The sensor estimates the wetness by measuring the resistance on the grid. Indeed, the sensor presents a circuit board with interlacing gold-plated fingers. Condensation on the device decreases the resistance between the fingers, which is measured as an analog signal in 16 voltage levels. Subsequently, the measurement was converted into a leaf wetness value through the application of the following Equation (2), such that if $\frac{V}{5} < 0.83$:

$$Leaf\ Wetness = -18.3 \times \left(\frac{V}{5}\right) + 15 \quad (2)$$

Instead, if $\frac{V}{5} > 0.83$, leaf wetness equals 0. The parameter V is the sensor voltage output ranking from 0 to 5 volts and 5 is the voltage supplied at the sensor. Leaf wetness value ranges from 0 to 15 and leaves are considered wet with values above 6. Dataloggers were set up to record measurements every 15 min. Two sensors were arranged in the field for two days before treatment and were removed after the last mowing treatment. Sensors were placed above the ground in order to mimic the condition of weed leaves as much as possible. In order to perform accurate measurements, at the time of installation, it was ensured that the sensors' surface were cleaned of conductive material, such as leaves, grass, dirt, and salts.

2.4. Statistical Analysis

Data were analyzed using the statistical software R (version 4.1.2.; R Foundation for Statistical Computing: Vienna, Austria) [38]. Normality distribution was evaluated using the Shapiro–Wilk test, while the Bartlett test was employed for the homoscedasticity. Arcsine or square root transformations of data were applied when needed to meet the normality assumption. For the first trial, two-way ANOVA was performed to assess the effect of mower version, setting configuration, and interactions between factors on weed biomass reduction, weed cover reduction, weed height reduction, weed biomass regrowth, and size of clippings.

For the second trial, three-way ANOVA was performed to assess the significance of different mower versions, setting configurations, dew conditions, and interactions between factors on weed biomass reduction, weed cover reduction, and weed height reduction. An LSD post hoc test at the 0.05 probability level was executed for both trials with the package "agricolae" [39]. The extension package "ggplot2" (Elegant Graphics for Data Analysis) was used to plot graphs.

3. Results

3.1. First Trial: Performances of the Two Mower Versions in the Open Field

3.1.1. ANOVA Analysis Results

Two-way ANOVA revealed a significant effect of setting configuration on weed biomass reduction ($p < 0.01$), whereas mower version and the interaction between mower version and setting configuration did not affect the parameter. Mower version had a significant effect on weed cover reduction ($p < 0.001$), while setting configuration and their interaction did not affect the parameter. Weed height reduction was not affected by the considered fixed factors. ANOVA highlighted a significant effect of both mower version and setting configuration on clipping size ($p < 0.001$ and $p < 0.05$, respectively), while their interaction did not affect the parameter. Weed biomass regrowth was not affected by the considered fixed factors. Results of two-way ANOVA are reported in Table 3.

Table 3. F-values and *p*-values estimations from two-way ANOVA.

Factors	WBR (%)		WCR (%)		WHR (%)		CS (cm)		WBRg (%)	
	F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value
Mower Version	0.043	0.839	20.280	***	0.068	0.795	12.555	***	0.605	0.450
Setting Configuration	6.585	**	0.888	0.453	2.446	0.073	2.763	*	0.355	0.787
Mower Version ´ Setting Configuration	0.454	0.718	0.293	0.830	2.140	0.105	1.681	0.174	0.468	0.709

*** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$. WBR—Weed biomass reduction; WCR—weed cover reduction; WHR—weed height reduction; CS—clipping size; WBRg—weed biomass regrowth.

Since data are disputed as a % of the reduction of the parameters' initial values and not as absolute values, mean values of weed biomass, weed cover, and weed height measured before the mowing treatment on the experimental field are shown in Table 4.

Table 4. Parameter mean values recorded before the mowing treatments of the first trial (standard error).

	Nr. Observations		Values (SE)
Weed Biomass	24	g d.m.·m^{-2}	133.88 (7.78)
Weed Cover	72	%	45.7 (1.3)
Weed Height	72	cm	13.86 (0.28)

3.1.2. Differences between the Two Mower Versions' Performance

During the first trial, differences between chain and blade mower were only observed in terms of weed cover reduction and clipping size. The mower equipped with chains achieved the best results of weed cover reduction compared to the blade mower ($p < 0.05$), with back-transformed mean values of 92.6% and 84.3%, respectively. Concerning the clipping size, the chain mower produced larger clippings (back-transformed mean value of 8.66 cm) compared to the blade mower (back-transformed mean value of 6.95 cm) ($p < 0.05$).

3.1.3. Setting Configuration Effect on Mowing Performance

Both weed biomass reduction and clipping size were affected by each machine's setting configuration. In the first trial, averaged across mowing versions, the weed biomass reduction achieved by mowers with the Lws + Hrs setting was higher compared to mowers with Hws + Lrs and Lws + Lrs setting configurations (68.6% vs. 28.7% and 24.9%, respectively) ($p < 0.05$). No difference emerged between weed biomass reduction obtained by mowers with the Hws + Hrs setting and mowers with the other tested settings (Figure 6).

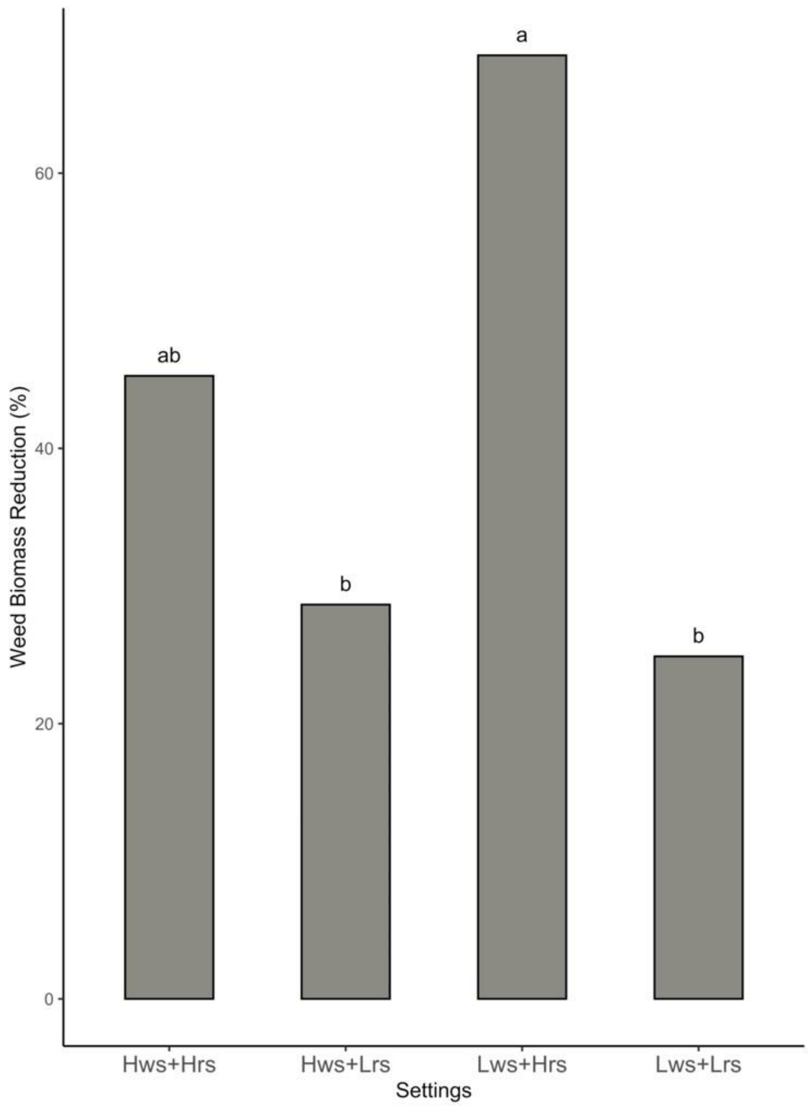

Figure 6. Effect of setting configurations on weed biomass reduction. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test). Hws—High working speed; Lws—low working speed; Hrs—high rotation speed; Lrs—low rotation speed.

Mowers with the Lws + Hrs setting also produced smaller clippings (back-transformed mean value of 6.77 cm) compared to the other setting configurations (back-transformed mean values ranging from 7.93 to 8.31 cm) ($p < 0.05$). Results achieved with the other setting configurations were similar (Figure 7).

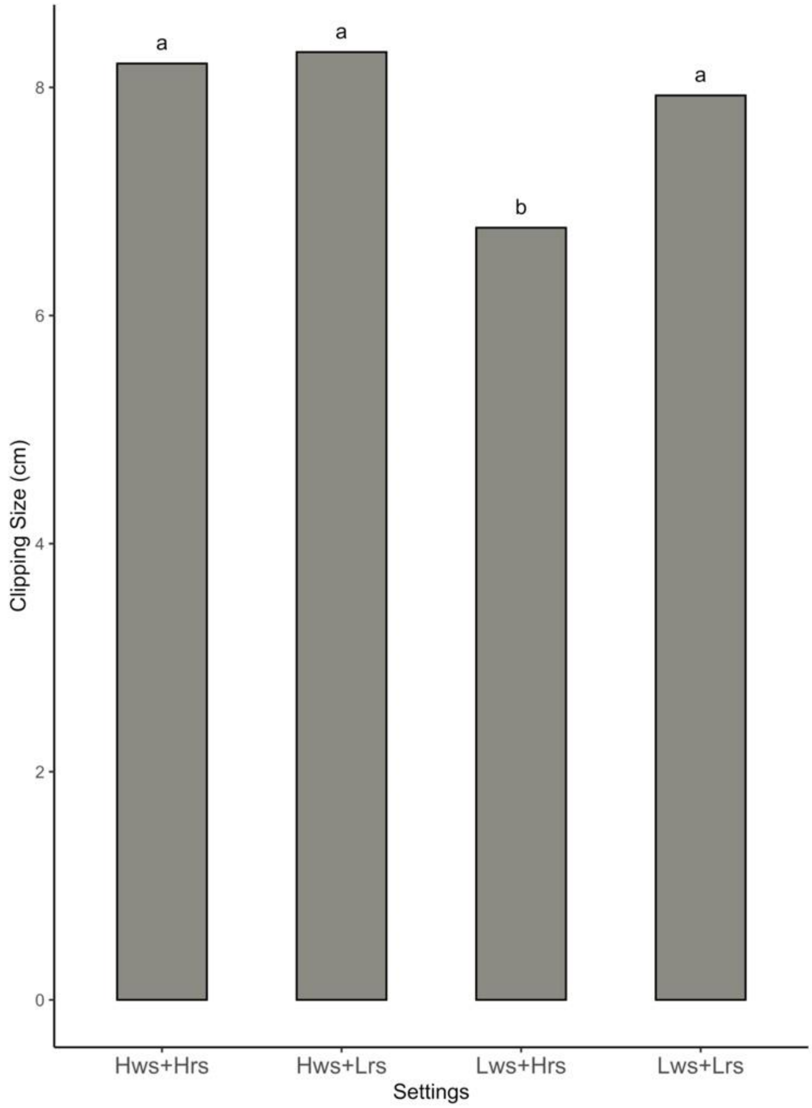

Figure 7. Effect of setting configuration on clippings size. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test). Hws—High working speed; Lws—low working speed; Hrs—high rotation speed; Lrs—low rotation speed.

3.2. Second Trial: Performance of the Two Mower Versions in the Alley Cropping Farming System

Leaf wetness sensors measured an average leaf wetness of 6.35 during the mowing treatment carried out from 9:30 a.m. to 10:20 a.m. on 11 February 2022, thus evidencing the presence of dew on the leaves' surface. Sensors detected an average leaf wetness of 0 during the mowing treatment performed from 12:00 p.m. to 12:50 p.m. on the same day, pointing to the absence of dew. Figure 8 reports the trend of the average leaf wetness on the day of the mowing treatments measured by sensors.

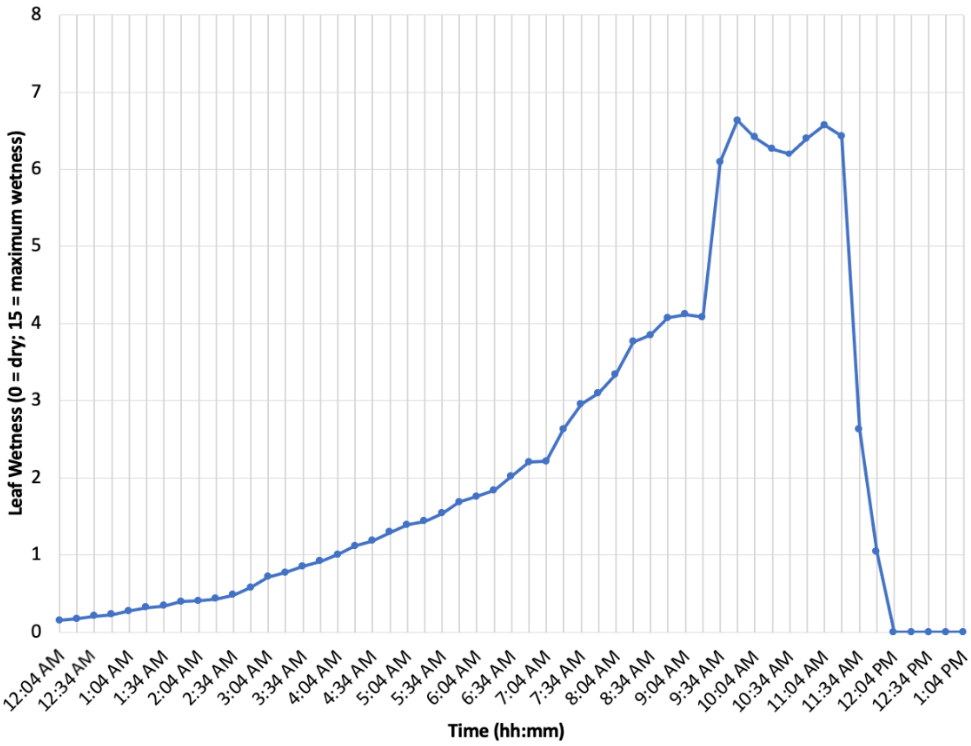

Figure 8. Trend of average leaf wetness values recorded on 11 February, i.e., the day the mowing treatments were performed.

3.2.1. ANOVA Analysis Results

Three-way ANOVA showed that both the setting configuration and the interaction between mower version and dew condition affected weed biomass reduction ($p < 0.05$ for both the fixed factors). Mower version, dew, and the other interactions did not affect the parameter. Weed cover reduction was affected by setting configuration ($p < 0.01$), dew condition ($p < 0.01$), and the interaction between mower version and dew condition ($p < 0.05$), while the mower version and the other interactions were not significant for this dependent variable. Weed height reduction was affected by the mower version ($p < 0.001$), the interaction between mower version and setting configuration ($p < 0.01$), and the interaction between mower version, setting configuration, and dew ($p < 0.05$). Results of three-way ANOVA are shown in Table 5.

Table 5. F-value and *p*-value estimations from three-way ANOVA.

Factors	WBR (%)		WCR (%)		WHR (%)	
	F-Value	*p*-Value	F-Value	*p*-Value	F-Value	*p*-Value
Mower Version	1.461	0.236	2.159	0.144	16.832	***
Setting Configuration	4.077	*	4.566	**	1.169	0.324
Dew	2.760	0.107	7.042	**	0.580	0.448
Mower Version ´ Setting Configuration	0.523	0.670	0.514	0.673	5.297	**
Mower Version ´ Dew	4.564	*	5.258	*	1.337	0.250
Setting Configuration ´ Dew	2.027	0.131	1.543	0.207	1.264	0.290
Mower Version ´ Setting Configuration ´ Dew	0.305	0.822	2.054	0.110	2.897	*

*** $p < 0.001$; ** $p < 0.01$, * $p < 0.05$. WBR—Weed biomass reduction; WCR—weed cover reduction; WHR—weed height reduction.

Since data are disputed as a % of the reduction of the parameters' initial values also for the second trial, mean values of weed biomass, weed cover, and weed height measured in the alley cropping field (along the tree row) before the mowing treatments are shown in Table 6.

Table 6. Parameter mean values recorded before the mowing treatments of the second trial (standard error).

	Nr. Observations		Values (SE)
Weed Biomass	48	g d.m.·m^{-2}	205.49 (12.79)
Weed Cover	144	%	50.8 (1.4)
Weed Height	144	cm	15.54 (0.31)

3.2.2. Differences between the Two Mower Versions' Performance

During the second trial, the blade mower achieved a significantly higher reduction in weed height compared to the chain mower (46.9% vs. 36.3%, respectively) ($p < 0.05$). Regarding the effect of the mower version and setting configuration interaction on weed height reduction, the blade mower with the Hws + Hrs setting obtained the best result (57.2%) ($p < 0.05$). No difference emerged in the blade mower performance with Hws + Lrs, Lws + Hrs, and Lws + Lrs settings. The chain mower with the Lws + Hrs setting obtained a higher reduction in weed height compared to the machine with Hws + Hrs and Lws + Lrs settings (44.1% vs. 30.0% and 32.9%, respectively) ($p < 0.05$), and similar results were observed compared to both the same mower with the Hws + Lrs setting and the blade mower with Lws + Hrs, Lws + Lrs, Hws + Lrs settings. The chain mower with the Hws + Hrs setting resulted in a lower weed height reduction compared to the machine with the Lws + Hrs setting and the blade mower with different setting configurations ($p < 0.05$) (Figure 9).

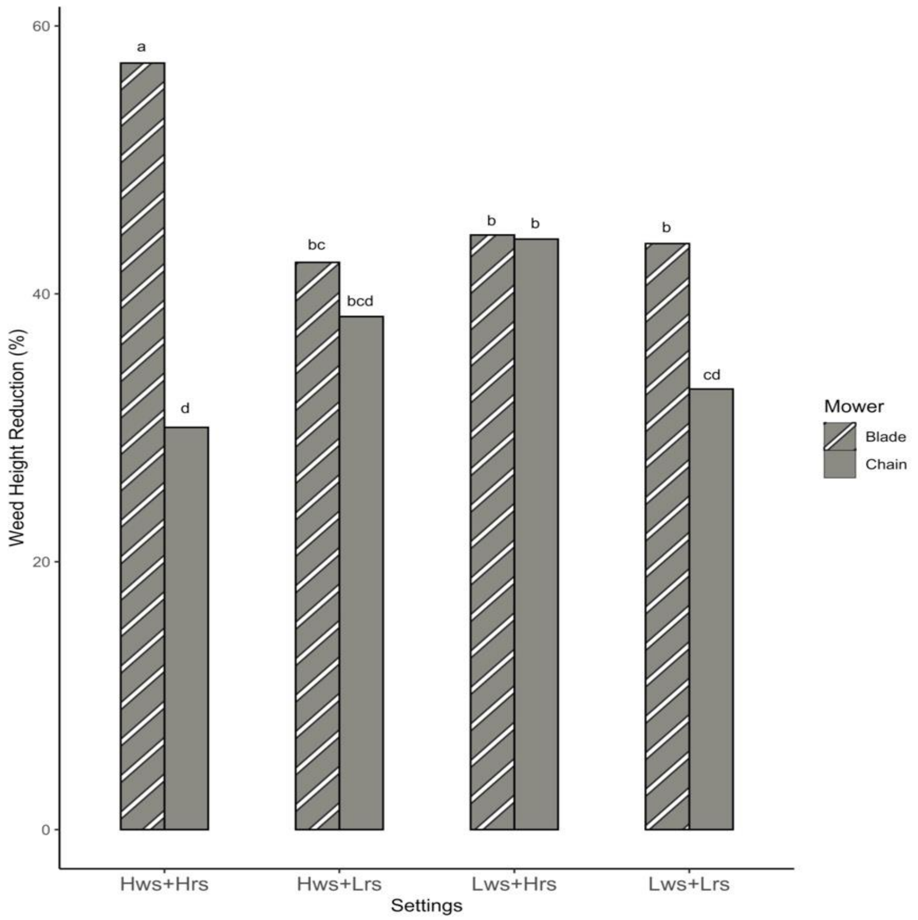

Figure 9. Effect of the interaction between mower version and setting configuration on weed height reduction. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test). Hws—High working speed; Lws—low working speed; Hrs—high rotation speed; Lrs—low rotation speed.

3.2.3. Setting Configuration Effect on Mowing Performance

Mowers with the Lws + Lrs setting achieved a lower reduction in weed biomass compared to Lws + Hrs and Hws + Hrs settings (44.9% vs. 67.9% and 59.6%, respectively) ($p < 0.05$) while no differences emerged between these two settings. Mowers with the Hws + Lrs setting achieved results for weed biomass reduction that were found to be similar to mowers with the other tested settings (Figure 10).

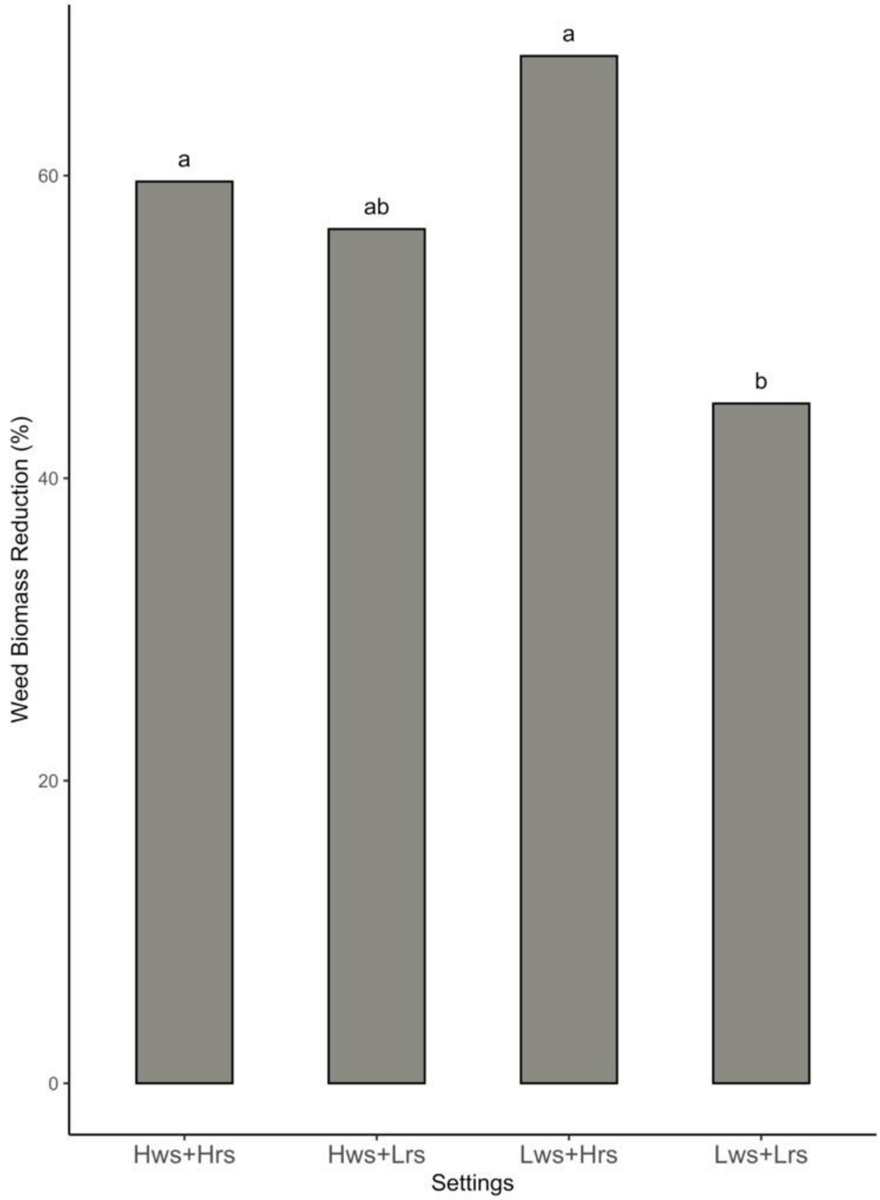

Figure 10. Effect of setting configuration on weed biomass reduction. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test). Hws—High working speed; Lws—low working speed; Hrs—high rotation speed; Lrs—low rotation speed.

Concerning the weed cover reduction, mowers with the Lws + Lrs setting achieved a lower reduction in weed cover compared to mowers with Hws + Hrs and Lws + Hrs settings ($p < 0.05$), with back-transformed mean values of 26.8%, 40.9%, and 36.2%, respectively. No differences emerged in the comparison of mowers with Hws + Hrs and Lws + Hrs settings and between mowers with Lws + Lrs and Hws + Lrs settings (Figure 11).

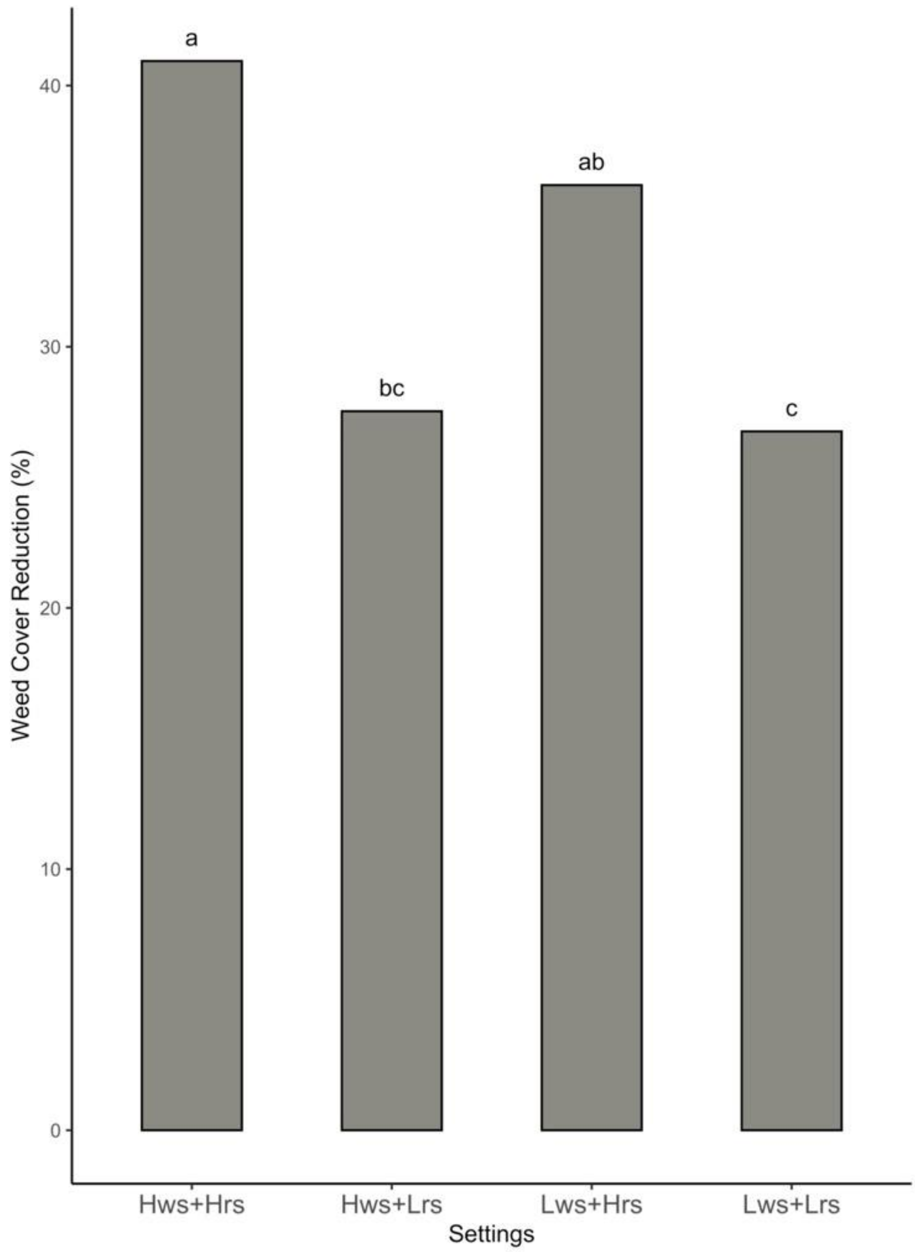

Figure 11. Effect of setting configuration on weed cover reduction. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test). Hws—High working speed; Lws—low working speed; Hrs—high rotation speed; Lrs—low rotation speed.

3.2.4. Effect of Dew Conditions on Mowing Performances

The blade mower achieved a greater weed biomass reduction in the absence of dew compared to the presence of dew (69.0% vs. 51.1%), while no differences emerged in the comparison of the chain mower performance in different dew conditions. In the absence of dew, the blade mower achieved a higher weed biomass reduction compared to the chain mower (53.3%) ($p < 0.05$), while in presence of dew, no significant differences between the two mower versions emerged (Figure 12).

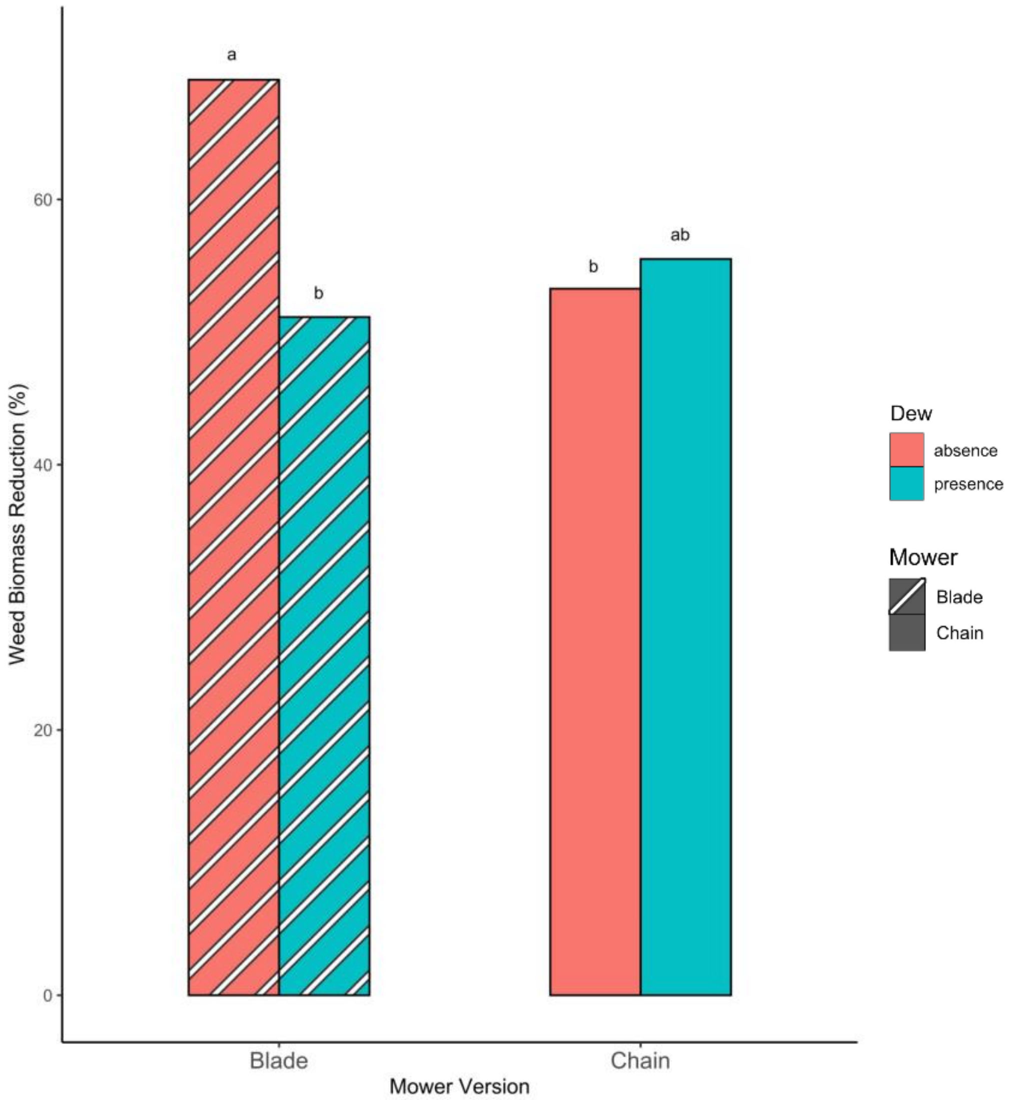

Figure 12. Effect of the interaction between mower version and dew condition on weed biomass reduction. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test).

In general, mowers in the presence of dew obtained a lower reduction in weed cover compared to the performed treatment in the absence of dew ($p < 0.05$), with back-transformed mean values of 28.9% and 37.0%, respectively. The blade mower operating in the absence of dew resulted in a greater reduction in weed cover (back-transformed mean value of 43.0%) compared to the presence of dew (back-transformed mean value of 27.9%) and compared to the chain mower in both the absence and presence of dew (back-transformed mean values of 30.9% and 30.0%, respectively) ($p < 0.05$). The chain mower achieved similar results for this parameter in both dew conditions (Figure 13).

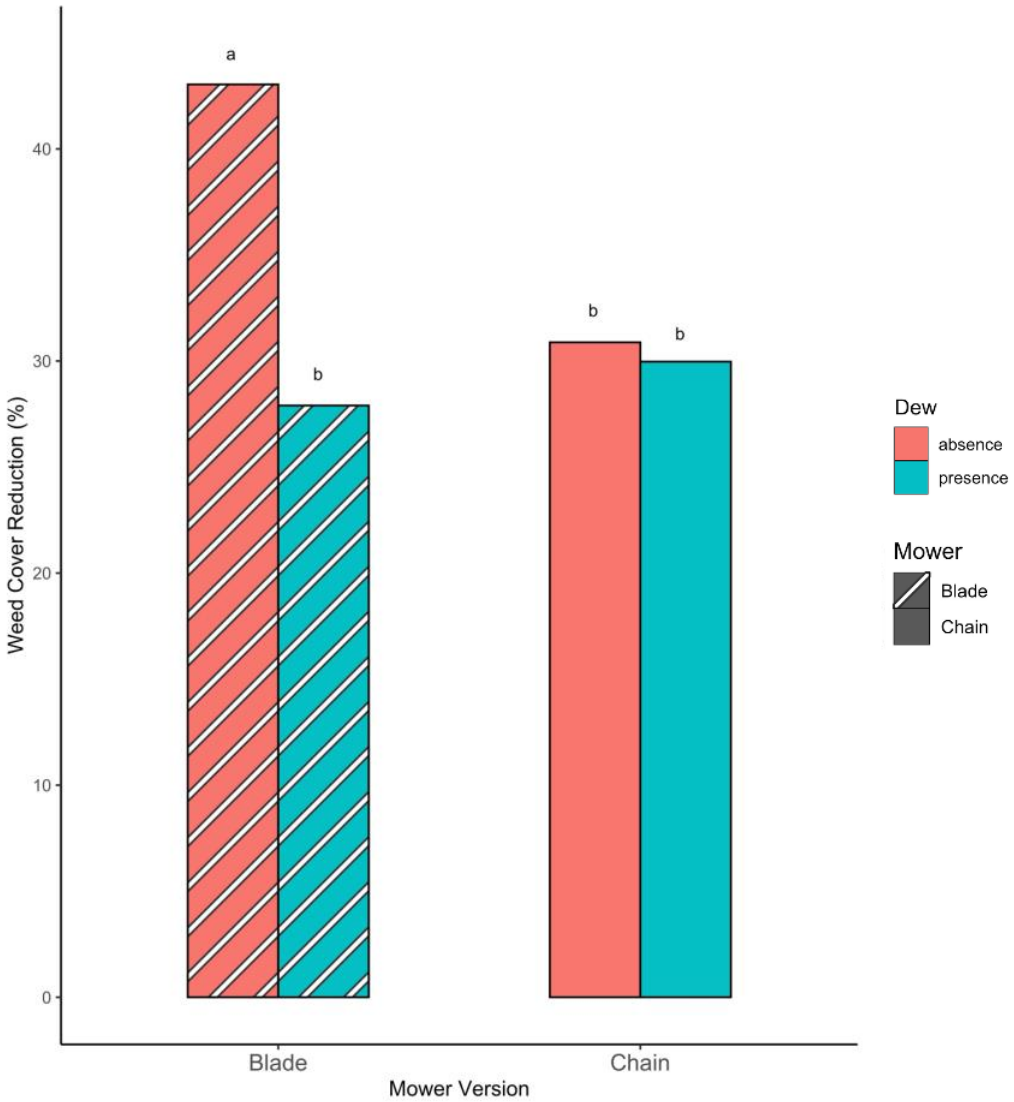

Figure 13. Effect of the interaction between mower version and dew conditions on weed cover reduction. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test).

Dew did not affect weed height reduction within the individual combinations of mower version and setting, with the exception of the chain mower with the Lws + Hrs setting (Figure 14). The chain mower with the Lws + Hrs setting in the presence of dew obtained a higher weed height reduction (53.6%) compared to the absence of dew (34.6%) and compared to the same mower with Hws + Hrs and Lws + Lrs settings in both dew conditions (with weed height reduction of 27.0% and 33.1% for Hws + Hrs setting, and of 31.9% and 33.8% for Lws + Lrs setting in the absence and the presence of dew, respectively). No differences emerged between the chain mower with the Lws + Hrs setting in the presence of dew and the same mower with the Hws + Lrs setting in absence of dew, while the Hws + Lrs setting in the presence of dew achieved a lower weed height reduction (34.8%) ($p < 0.05$). The blade mower with the Hws + Hrs setting in the absence of dew achieved a higher weed height reduction (64.3%) compared to the same mower with the other settings in both dew conditions (ranging from 36.9% to 44.6% in the absence of dew and from 42.9% to 47.8% in the presence of dew) ($p < 0.05$). The blade mower with the Hws + Hrs setting in the absence of dew obtained a higher weed height reduction compared to the chain mower with different settings ($p < 0.05$), with the exception of the chain mower with the Lws + Hrs setting in presence of dew.

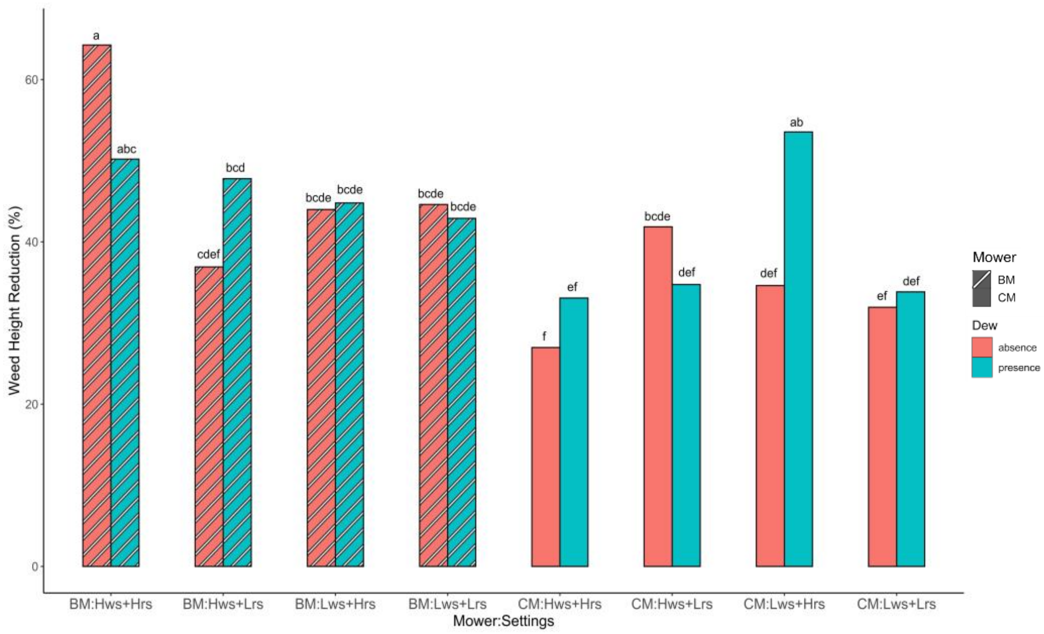

Figure 14. Effect of the interaction between mower version, setting configuration, and dew conditions on weed height reduction. Means denoted by different letters are significantly different at $p < 0.05$ (LSD test). BM—Blade mower; CM—chain mower; Hws—high working speed; Lws—low working speed; Hrs—high rotation speed; Lrs—low rotation speed.

3.3. Field Capacity with Different Working Speed Settings

Both mower versions' operative parameter values with the two different working speed settings are reported in Table 7.

Table 7. Estimated field capacity of the mowers with the two different working speeds.

Performance		Low Working Speed (Lws)	High Working Speed (Hws)
Working speed	$km \cdot h^{-1}$	1.60	2.40
Working width	m	9.00	9.00
Theoretical field capacity	$ha \cdot h^{-1}$	1.44	2.16
Theoretical field time *	$h \cdot ha^{-1}$	0.69	0.46
Total turning time *	$h \cdot ha^{-1}$	0.02	0.02
Field time **	$h \cdot ha^{-1}$	0.71	0.48
Field capacity **	$ha \cdot h^{-1}$	1.40	2.07

* Time required to carry out the under-row mowing treatment in a hypothetical area of 10,000 m^2 (30.00 m wide and 333.33 m long). ** Considering the theoretical field capacity and time and the turning time.

Comparing the mowers' field capacity with different working speed settings, it is possible to observe the higher field capacity of the mower with the high working speed setting with an increase of 47.9% compared to the low working speed setting.

4. Discussion

During the first trial, no major differences emerged between the two mower versions, except for the weed cover reduction, which was greater for the chain mower (92.6% vs. 84.3% for the chain mower and the blade mower, respectively) and the clipping size, which was lower for the blade mower (6.95 cm vs. 8.66 cm for blade mower and chain mower, respectively). The smaller size of clippings produced by the blade mower could be due to the greater sharpness of the cutting tool, which allowed for the cutting of the same plant material several times. In contrast, chains, having a flail action on weed [40], could tend to sweep and then drag the plant material without cutting it several times. Concerning the differences that emerged at the first trial between the tested setting configurations, mowers with the Lws + Hrs setting achieved a higher reduction in weed biomass than machines with Hws + Lrs and Lws + Lrs settings (68.6% vs. 28.7% and 24.9%, respectively). These results confirm those obtained by Yiljep et al. [29], such that as the cutting speed of the tool increases, the cutting efficiency also increases. Lei et al. [30] also stated that the rotation speed of the cutting tool is inversely related to the leakage rate, corresponding to the weight of leakage weeds and the weight of the weeds cut per unit area ratio. On the contrary, the working speed of the under-row mower is positively related to this cutting quality index. However, no significant differences emerged on weed biomass reduction, neither in the comparison between mowers with Hws + Hrs and Lws + Hrs settings, nor between mowers with Hws + Hrs, Hws + Lrs, and Lws + Lrs settings. Moreover, mowers with the Lws + Hrs setting configuration produced smaller clippings (6.77 cm) compared to mowers with other settings (ranging from 7.93 to 8.31 cm). The most likely explanation for this finding is that the low working speed and high rotation speed of the cutting tool allowed for the cutting of the same plant material several times. However, for mulching purposes, it is well-known that a smaller residue is more subject to wind displacement and tends to decompose faster than a coarser material [41].

During the second trial, no differences emerged between the two mower versions in terms of weed cover reduction as in the first trial. The two mowers stood out for the weed height reduction, which was higher for the blade mower compared to the chain mower (46.9% vs. 36.3%, respectively). The blade mower with the Hws + Hrs setting configuration achieved a better result for weed height reduction (57.2%) compared to the other tested settings (ranging from 42.4% to 44.4%). The chain mower with the Lws + Hrs setting obtained a higher weed height reduction (44.1%) compared to the same mower with Hws + Hrs and Lws + Lrs settings (30.0%, and 32.9%, respectively) but no differences emerged between Lws + Hrs and Hws + Lrs settings. The lower weed height reduction obtained by the chain mower may be due to the greater oscillatory movement of the cutting tool associated with the lower stiffness compared to the blade. Furthermore, this could also be due to the different cutting action of a dull cutting tool, such as a chain mower, which tends to mutilate the tip of weeds and therefore present a greater height compared to a sharp one, as other authors observed [42,43].

Mowers with Lws + Hrs and Hws + Hrs settings obtained a greater weed biomass reduction than mowers with the Lws + Lrs setting (67.9% and 59.6%, vs. 44.9%, respectively), while no significant differences emerged neither in the comparison between Lws + Hrs and Hws + Hrs settings, nor between Lws + Hrs, Hws + Hrs, and Hws + Lrs settings. However, results achieved by mowers with different tested settings are in line with results obtained by Pergher et al. [23] for an under-vine mower whose weed biomass reduction values ranged from 40.7% to 59.7%. Furthermore, mowers with Hws + Hrs and Lws + Hrs settings obtained better results than the Lws + Lrs setting for weed cover reduction (40.9% and 36.2% vs. 26.8%, respectively). Regarding the effect of dew on mowers' performances, the blade mower weed cover reduction obtained in the absence of dew (43.0%) was higher than in the presence of dew (27.9%), and compared to the chain mower, both in the absence of dew (30.9%) and in the presence of dew (30.0%). Dew did not affect weed height reduction within the individual combination of mower version and setting, except for the chain mower with the Lws + Hrs setting that achieved a higher weed height reduction in the presence of dew (53.6%) compared to in the absence of dew (34.6%). The blade mower with the Hws + Hrs setting in the absence of dew obtained a higher weed height reduction compared to the chain mower with different settings, with the exception of the chain mower with the Lws + Hrs setting in the presence of dew. Concerning the effect of dew conditions on the mowers' weed biomass reduction, the chain mower seems to be less affected by dew conditions than the blade mower, whose performance was worse in the presence of dew compared to the absence of dew (51.1% vs. 69.0%). No differences emerged between the two mower versions in the presence of dew while in the absence of dew, the blade mower achieved a higher weed biomass reduction than the chain mower (53.3%). However, no clear differences emerged between the two mower versions as the chain mower in the presence of dew achieved similar results of weed biomass reduction compared to the blade mower in the absence of dew.

Overall, no major differences emerged between the two tested mower versions and the chain mower performance was comparable to that of the blade mower, whose reliability is already established [23,30]. This occurred despite the lower sharpness of chains and the context in which the mowing treatments were performed. Indeed, during both trials, the predominant weed species were grasses in the vegetative phase, that is, with a prevalence of leaves over stalks and poorly lignified tissues. These weeds have a lighter inertia compared to weeds in advanced phenological stages with more lignified tissues and thick stalks, making the penetration of the cutting tools into the plant material more difficult [29]. Therefore, the chain mower proved to be a valid tool for under-row weed management in an alley cropping system. The use of a chain mower as a cutting tool works well under challenging conditions, such as clearing operations in forests, allowing the management of grass, shrubs, and coarse plant material. In addition, chains were found to be more versatile than blades as they can be used in the presence of stones where blades tend to become damaged, leading to premature wear and costly repair [33–36,44]. Moreover, blade regrinding can reduce the durability of costly knives [45].

The findings obtained from those trials highlighted that mowers set with the high rotation speed of the cutting tool (2500 rpm) tended to achieve the best results for the analyzed weed control parameters. This is in agreement with Kakahy et al. [46], who found that in passing from a rotation speed of the cutting tool of 1830 to 2553 rpm, despite a slight increase in power consumption of 15%, the effectiveness of mowing performance increased. It is desirable that in the presence of weeds in a more advanced phenological stage, that is, with more lignified tissues and thick stalks, the performance of mowers with both rotation speed settings would have been greater.

In regards to the working speed, the choice of the setting with the high working speed (2.4 $km \cdot h^{-1}$) results in an increase in the mowers' field capacity of 47.9% compared to the setting with the low working speed. Although the chain mower with the Lws + Hrs setting achieved a slightly higher weed height reduction compared to the Hws + Hrs setting, the choice of the Hws setting involves greater efficiency by halving the time required for mowing. Furthermore, it is possible to state that with the higher working speed setting, the feeler has always worked correctly, allowing the mowing disc to enter the row and exit near the trees without damaging trunks, thus ensuring a proper functioning of the machine. Under-row weed management in alley cropping systems can be more efficiently accomplished by using this type of mower with automatic tree-skipping mechanisms than a tractor-mounted flail mower with an operator-controlled side shift or string trimmers that are commonly employed in these contexts. Lei et al. [30] found that the work efficiency of an obstacle avoiding mowers for under-row weed control in orchards is 4.44 times higher than an operator with a string trimmer and 20 times higher than manual weeding. Time-saving is crucial for users, involving lower operational costs and enabling managers to have time for other management operations.

In order to improve the efficiency of the chain mower, the cutting width could be increased. By adopting a mowing implement with a wider diameter instead of requiring a passage on each side to complete the tree row management, a single passage may be sufficient to guarantee satisfactory weed control.

5. Conclusions

In the present study, the use of the chain mower with automatic tree-skipping mechanism for under-row weed control in an alley cropping system obtained encouraging results. Indeed, the performance of the mower with chains was comparable to that of the blade mower, whose effectiveness is well-established. These findings highlight that the chain mower could be employed as a reliable means for under-row weed control in alley cropping systems, proving to be a valid alternative to the methods that are conventionally applied in these contexts. Concerning the tested settings, the setting with the high working speed and high rotation speed turns out to be the best compromise between effectiveness and efficiency, having obtained a satisfactory weed control (weed biomass reduction of 59.6% and weed cover reduction of 40.9%) and a higher field capacity compared to the setting with the low working speed, with an increase of 47.9%.

Nevertheless, further studies are needed to better understand the cutting mechanisms of chains in relation to different weed communities and weed phenological stages. In order to improve the performance of chain mowers as cutting tools, it would also be useful to test square section chains to evaluate any increase in cutting efficiency with a different cutting edge. Furthermore, since chains are suitable for their use in challenging scenarios, such as stony soils, the applicability of the chain mower for under-row management could be evaluated in vineyards, where the frequent soil-high stoniness hinders the equipment that is conventionally employed for this purpose.

Author Contributions: Conceptualization, M.R., M.F., C.F. and D.A.; methodology, M.F., C.F., L.G., G.R. and D.A.; software, M.F. and L.G.; validation, M.F., C.F., M.S., G.R., D.A. and L.G.T.; formal analysis, M.F.; investigation, L.G.; resources, M.R. and D.A.; data curation, L.G. and M.F.; writing—original draft preparation, L.G.; writing—review and editing, M.F., C.F., M.S., G.R., D.A. and L.G.T.; visualization, M.R. and A.P.; supervision, M.R. and M.F.; project administration, M.R. and M.F.; 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: Not applicable.

Acknowledgments: The authors would like to acknowledge the Dondi group for providing the under-row mower and technical support, the Centre for Agri-environmental Research “Enrico Avanzi” for hosting the trials and for the technical support, Andrea Sbrana for the technical support and the use of leaf wetness sensors.

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

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