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Soil management in organic rainfed vineyards in the Penedès region (Catalonia, NE Spain) with cover crops and mulches. Effects on weed flora and vine vigor

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In Mediterranean organic vineyards, repeated mechanical tillage is the standard strategy for weed control, but it contributes to soil degradation, fuel consumption, and carbon emissions. This study evaluated alternative soil management practices—cover crops in the alleyways and organic mulches under the vine row—to reduce tillage while maintaining weed suppression and vine vigor. Two field trials were conducted over two growing seasons (2021–2022), characterized by exceptionally dry conditions, in a rainfed *Vitis vinifera* L. cv. Chardonnay organic vineyard in the Penedès region, NE Spain. In the alleyways, two winter grasses (*Hordeum vulgare* and *Lolium multiflorum*) were sown and compared to traditional tillage management. Under the vine row, an organic pine wood chip mulch was compared to a tilled control Weed cover, vine vigor (i.e. yield, pruning weight, exposed leaf area), and canopy geometry and structure (using the principle of light detection and ranging, LiDAR) were recorded and analyzed. Cover crops effectively suppressed weeds (<10% cover), but also reduced vine vigor in both years, particularly under these extreme drought conditions. LiDAR-derived data confirmed significantly smaller canopy dimensions in vine rows bordered by cover crops compared to those between tilled alleyways. The pine mulch maintained low weed pressure and supported vine growth, showing persistence over two seasons. These results highlight the potential of organic mulching as a sustainable alternative to mechanical under-vine in-row tillage in dryland vineyards. However, the competitive impact of alleyway cover crops on vine performance must be carefully considered in water-limited environments.

KEYWORDS
cover crops, LiDAR, organic mulches, soil management, vineyard, weed flora

1 Introduction

In Mediterranean organic vineyards, particularly in Spain, soil tillage is the most common strategy to control weeds (MAPA, 2024). However, some authors point out that fuel consumption in vineyards results in more than twice the carbon footprint of pesticide or fertilizer use (Jradi et al., 2018). Additionally, this approach can be expensive and sometimes complex, especially when weeds proliferate under the vine row, where they compete most intensely with the vines. Furthermore, depending on the architecture, vegetative structure and proliferation of certain weeds, continuous interventions are required for effective control. In contrast, in other wine-growing regions and production systems, weed management is often based on chemical control without soil disturbance, which presents different trade-offs in terms of soil quality, biodiversity, and long-term sustainability (Griesser et al., 2022).

Annual weeds are typically effectively controlled through tillage, although their staggered germination and emergence over several weeks or even months require repeated interventions (Davis et al., 2018). Vineyards host annual weed species with varying germination periods. In the study region, winter species, such as *Stellaria media, Galium aparine, Hordeum murinum, Veronica hederifolia*, and *Polygonum aviculare*, germinate between November and January and complete their cycle by May–June (Grundy et al., 2003). In contrast, summer species like *Chenopodium album, Amaranthus retroflexus, Setaria verticillata*, and *Echinochloa crus-galli* germinate in April and May, completing their cycle by late summer or autumn (Jursík et al., 2010). Additionally, there are perennial weed species that maintain active underground organs (roots, rhizomes, or stolons) during the winter, allowing regeneration, such as *Convolvulus arvensis, Cynodon dactylon*, and *Cirsium arvense*, especially from April onwards (Davis et al., 2018; Valencia-Gredilla et al., 2020). This diversity in weed life forms, seasonality, and high adaptability to vineyard soil management ensures their presence throughout the growing season.

The frequent mechanical interventions mentioned above are the primary weed control strategy in most Mediterranean dryland vineyards, particularly in organic vineyards. In addition to these interventions, plant protection in organic systems relies almost exclusively on preventive phytosanitary treatments (e.g., sulfur and copper) due to the limited availability of curative products. This constraint often requires repeated applications closely linked to weather conditions and disease pressure, increasing the number of machinery passes throughout the season. Collectively, these practices contribute to increase CO_2 emissions and fuel consumption. Furthermore, repeated soil tillage can lead to the loss of soil structure and biodiversity, compromising the sustainability of production (Visconti et al., 2024). Continuous machinery traffic can also cause soil compaction, increasing the risk of root asphyxiation in vineyards, runoff and soil erosion (Batey, 2009; Biddoccu et al., 2016; Keller et al., 2017).

Vineyard weed management distinguishes between two soil management areas: the inter-row space (alleyway) and the area beneath the vine row (or cordon). The implementation of a vegetative cover (cover crop) in the alleyways and an organic mulch under the cordons presents an interesting alternative to reduce the need for mechanical interventions in both areas. A vineyard cover crop is a soil maintenance technique that involves keeping the vineyard soil surface covered with vegetation, either through spontaneous flora or by sowing specific cover crops for this purpose (EVENA, 2012). The implementation of a cover crop offers multiple agronomic and environmental benefits, such as increasing soil organic matter, biomass, and microbial activity, as well as enhancing soil structure, water retention capacity and fertility. Additionally, cover crops reduce runoff and erosion (Gómez et al., 2011; Guzman et al., 2019), facilitate machinery movement even on rainy days (Capello et al., 2019), and exert competitive pressure on weed emergence (Baumgartner et al., 2008). Both, spontaneous and sown cover crops can provide desired soil improvements such as increased fertility, organic carbon, and macroaggregate stability; and in the case of the spontaneous cover, greater biomass can be achieved depending on its composition and establishment (Guzman et al., 2019). Organic mulches, on the other hand, have a weed-suppressing effect due to both their physical properties (light and temperature interception) and potential allelopathic compound release, reducing the emergence of certain weed species by up to 80% (Dhima et al., 2006; Cabrera-Pérez et al., 2022). In vineyards, mulching has also been observed to improve various soil quality indicators, such as moisture and structure (Zribi et al., 2011; DeVetter et al., 2015).

In this context, the implementation of strategies aimed at reducing mechanical interventions in vineyards should be aligned with improved sustainability, thereby supporting decision-making consistent with Spanish CAP subsidies that promote the establishment of cover crops. However, in rainfed Mediterranean vineyards, this decision remains particularly challenging, as trade-off between productivity and sustainability still needs to be carefully weighed and can only be clarified through experimental evidence. To reduce mechanical interventions for weed control in the vineyards of Familia Torres, the implementation of cover crops in the alleyway, as well as organic mulches beneath the vine row, is being considered. Previous studies have shown promising results. Cover crops based on grasses (*Bromus diandrus, Hordeum vulgare, Lolium multiflorum*) have been effective in vineyards in Rioja, Navarra, and Lleida (Ibáñez, 2015; EVENA, 2012; Valencia-Gredilla et al., 2020; Recasens et al., 2023). Similarly, chopped vine pruning mulches applied beneath the under-vine area have proven effective in vineyards in València (Buesa et al., 2021). The success of cover crop establishment and persistence depends as much on regional rainfall patterns as on irrigation availability. Regarding organic mulching, material consistency and durability are key factors. Previous studies (Cabrera-Pérez et al., 2022) have shown that a 10 cm thick and 40 cm wide pine chip mulch under the vine row is highly effective in suppressing weed emergence while maintaining a high soil cover (>90%) and a persistence of at least three years. The use of organic mulches in the under-vine area could facilitate weed suppression by providing a competitive yet low-impact cover that stabilizes the soil surface and reduces weed emergence. Additionally, the persistence of organic mulches could reduce the need for mechanical interventions. Meanwhile, the

establishment of cover crops in the alleyways could compete with existing weeds, particularly winter-spring species, and after mowing or rolling, create a soil cover that could help limit the runoff and erosion and prevent the growth of some summer annual weeds (Cabrera-Pérez et al., 2023).

In addition, Cabrera-Pérez et al. (2022) used the principle of light detection and ranging (LiDAR) to assess the effect of weeds, cover crops and organic mulches on vine development. The authors compared and validated the results of manual traditional canopy development measurements with those obtained with a mobile terrestrial laser scanner (MTLS) based on LiDAR. The measurements based on LiDAR proved consistent and reliable. LiDAR-based technology was used in agriculture for the first time by Walklate (1989) and Wangler et al. (1993). Other articles focus on the methodology to produce and improve the accuracy of point clouds (Rosell Polo et al., 2009; Moreno et al., 2020; Lavaquiol-Colell et al., 2025) and extract parameters from vine canopies (Siebers et al., 2018; Del-Moral-Martínez et al., 2020; Chedid et al., 2023 and Vélez et al., 2023). LiDAR-derived data have been used alone to detect weeds in annual crops (Andújar et al., 2013; Shahbazi et al., 2021) and fused with RGB imagery to quantify weed infestation (Ban et al., 2024; Romero and Heenkenda, 2024);. However, to our knowledge, no studies, beside Cabrera-Pérez et al. (2023), have used LiDAR to assess the effect of weeds, cover crops and organic mulches on vine development.

The objective of the study was to assess the effects of two different soil management strategies, namely cover crops in the alleyways and organic mulch in the under-vine area, with the aim of reducing tillage. In the alleyway, the cover crop installation capacity of *H. vulgare* and *L. multiflorum* and their competition against weeds was assessed, as well as their effects on vine vigor compared to traditional alleyway tillage. In the under-vine area, the effect of an organic mulch (chopped pine wood) on vine vegetative growth (through direct and indirect measures), yield, and weed control, was compared to that of tilled control.

2 Materials and methods

2.1 Site description

The evaluation of the effect of cover crops (cover crop trial) and mulching (mulching trial) on weed flora and on vineyard vigor was performed using data obtained from a vineyard located in Catalonia, Northeastern Spain, namely in Torrelavit at 200 m.a.s.l. (P.D.O. Penedès, Barcelona) owned by the cellar Jean Leon (Grupo Familia Torres S.A.) (Figure 1). The vineyard was planted in 2003 with *Vitis vinifera* (L.) cv. Chardonnay grafted onto 140Ru rootstock at a spacing of 2.2 m by 1.1 m and is organically managed. Vines were trained as bilateral cordon and shoots were vertically trellised with a pair of steel catch wires. Traditional weed management consisted of four to five tillage operations per season in both the under-vine zone (in-row) and the alleyways (inter-row). The experiment was carried out during 2021 and 2022. The climatic classification of the area is warm temperate with dry hot summers (Csa) (Kottek et al., 2006), with an average annual precipitation of 505 mm and a mean annual temperature of 15.1 °C (average minimum of 4.2 °C and average maximum of 27.6 °C) for the 2006–2022 period. Weather conditions during the experiment period are summarized in Figure 2. The soil corresponds to typical Calcixerept, with a loam to silty loam texture.

2.2 Experimental design

For the cover crop experiment, in November 2020 and in October 2021, two different cover crops were sown. *Hordeum vulgare* L. at a sowing rate of 120 kg/ha, and *Lolium multiflorum* Lam. at a sowing rate of 40 kg/ha, both in strips of 1.5 m with a mechanical seeder GIL SX Multisem (Julio Gil Águeda e Hijos, S.L., Madrid, Spain). These cover crops were compared with the traditional soil management in the region which consists of mechanical in-row and inter-row tillage. The experimental design was a randomized complete block design with three replicates, considering the soil management as the main factor with three levels: 1) Cover crop of *H. vulgare*, 2) Cover crop of *L. multiflorum*, 3) Traditional tillage (Figure 3) The cover crops were sown in the same inter-row areas in both experimental years in order to maintain consistency in soil management practices across seasons. Cover crops were left to grow until the end of their cycle in June, when they were mowed, and their residues were left on the soil surface. In the traditional tillage treatment, five mechanical inter-row soil tillage operations were carried out in 2021 on January 26th, March 3rd, May 10th, May 27th, and August 30th, and four in 2022 on April 6th, June 15th, August 30th, and November 25th.

For the mulching experiment, a chopped pine wood mulch (mainly *Pinus sylvestris* L.) was applied manually only once, at the beginning of the experiment in November 2020, with a width of 30 cm and a thickness of 20 cm. This treatment was compared to the traditional under-vine tillage. The experimental design was a

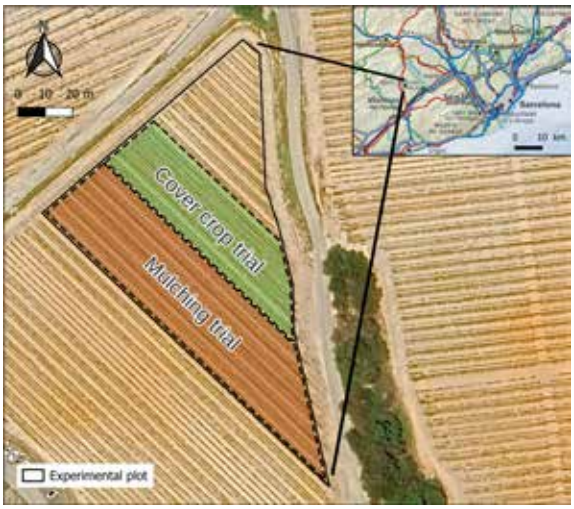

FIGURE 1
Location of the experimental site and delimitation of the Cover Crop and Mulching trials. Background map: Google Satellite orthophotography. Inset map: Topographic map from ICGC (Institut Cartogràfic i Geològic de Catalunya).

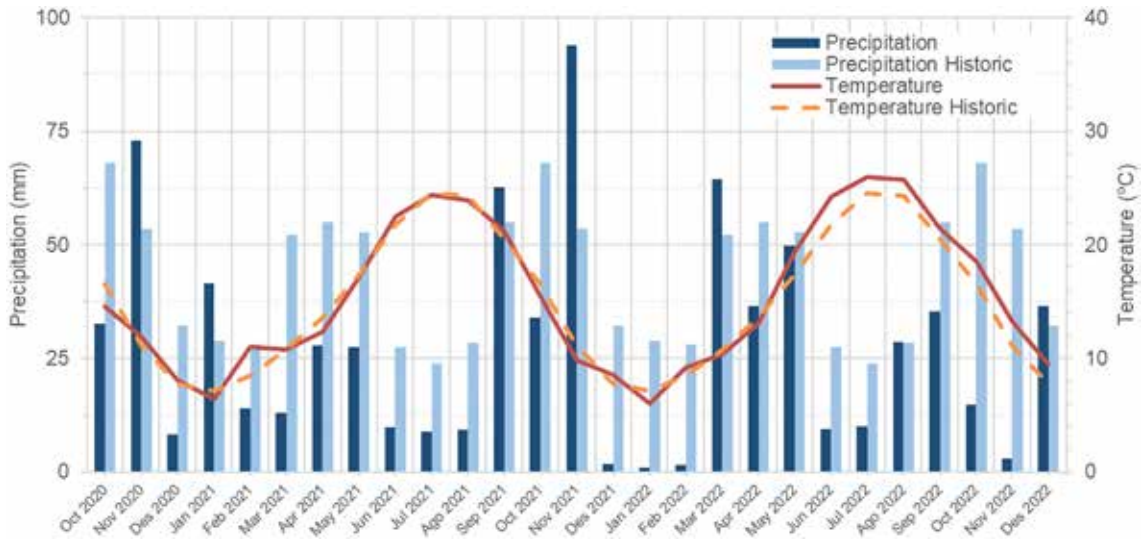

FIGURE 2
Weather conditions for the experiment period taken from the weather station of Sant Sadurní d'Anoia (Meteo.cat), located 7 km away. Blue bars and grey bars represent total monthly precipitation during both seasons and average monthly precipitation of 20 years, respectively. Red lines represent mean monthly temperature during both seasons and average monthly temperature of 20 years, respectively.

randomized complete block design with three replicates, considering the under-vine soil management as the main factor with two levels: pine mulch and tillage (Figure 4). In the tillage treatment, under-vine mechanical tillage operations were carried out in 2021 on January 26th, March 3rd, March 31st, April 20th, May 27th, July 2nd, and October 19th, while in 2022 they were carried out on January 27th, March 14th, April 6th, May 10th, June 15th, and August 30th.

The whole vineyard was rainfed and organically fertilized uniformly according to the standard practice of the farm. In 2021, Negrot Eco (INFERIN, Balaguer, Spain) was applied in powder form at a rate of 502 kg ha^{+1}, and the organic nitrogen fertilizer Labinor N10 (Productos LABIN, Igualada, Spain) was applied at 40 kg ha^{+1}. In 2022, the organic amendment Fervohumus (FERVOSA, Manlleu, Spain) was applied at a rate of 5,000 kg ha^{+1}.

2.3 Cover crop, mulching and weed sampling

Weed surveys in the cover crop and mulching trials were conducted monthly between January and June in 2021 and 2022. In the cover crop assay, vegetation assessments were carried out along the alleyways using four fixed sampling zones per alleyway (1.5 m wide × 6 m long), evenly distributed along the inter-row to account for within-alley spatial variability. Tractor wheel tracks fell outside the cover cropped area. Within each sampling zone, the percentage cover of the sown cover crop species and spontaneous weed flora (including other grasses not sown) was visually estimated separately, following standard ground cover assessment procedures commonly used in vineyard studies and in our previous works (Valencia-Gredilla et al., 2020; Recasens et al., 2023). Cover crop species were distinguished from weeds based on their known botanical identity and sowing pattern, while all non-sown species were classified as weeds.

In the mulching experiment, assessments were performed in four fixed sections per replicate (60 cm wide × 6 m long) located directly under the vine row. In each section, the percentage of soil surface covered by the mulch material and the percentage of weed cover emerging through or adjacent to the mulch were visually estimated. All assessments were conducted by the same trained observer throughout the study to minimize subjectivity.

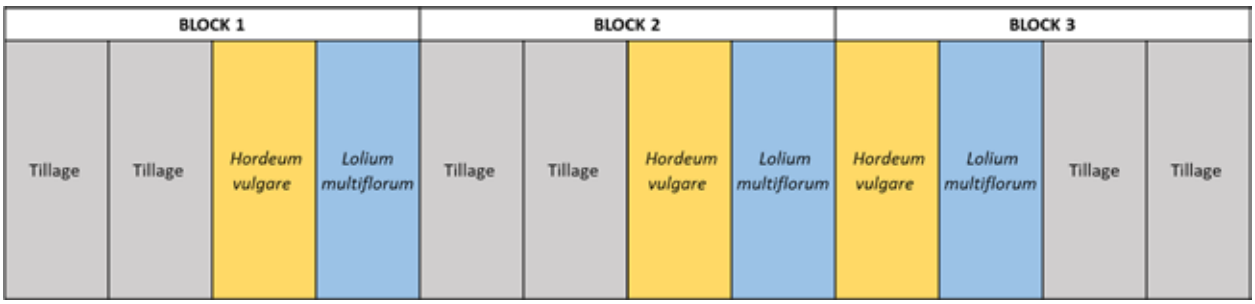

FIGURE 3
Experimental design of the cover crop trial.

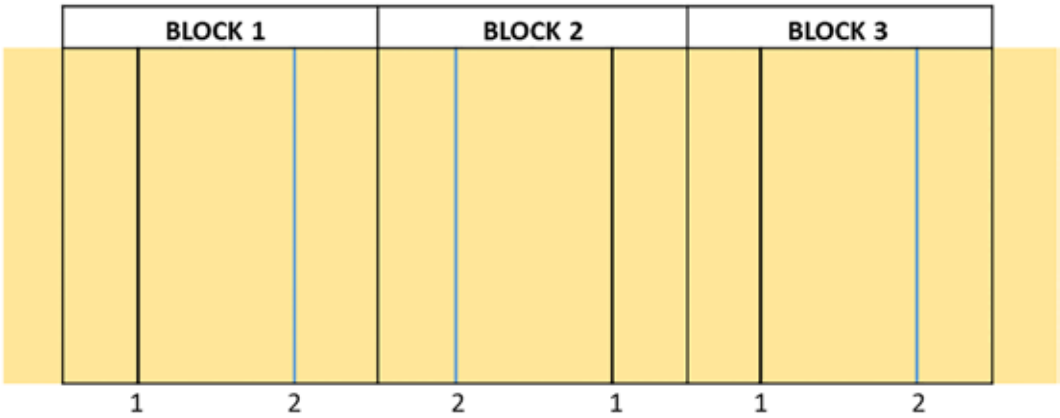

FIGURE 4
Experimental design of the mulching trial. 1: tillage under vine line; 2: mulch of chopped pine wood.

2.4 Direct measurements of vigor parameters

To quantify the agronomical response of the vines to soil management practices, several indicators of vine vigor and productivity were measured along the season, following standard viticultural assessment protocols (Smart and Robinson, 1991). These included exposed leaf area (ELA, m² per vine), number of clusters per vine, total yield (kg per vine) (August 18th in 2021; August 19th in 2022), pruning weight (kg per vine) (November 3rd in 2021; November 8th in 2022), average shoot weight (g), number of shoots per vine, cluster-to-shoot ratio (fertility), and the Ravaz index (yield to pruning weight ratio).

2.5 Canopy characterization based on LiDAR

A mobile terrestrial laser scanning bMS3D system (Viametris, Lourverné, France) based on the light detection and ranging (LiDAR) principle was used to analyze vine canopy development on June 30th of both years. The LiDAR-based unit, transported by a person on an electric all-terrain vehicle, included two VLP-16 sensors (Velodyne, San José, USA), a GNSS receiver, and four RGB cameras (Figure 5, left). The device was driven along each row, to subsequently produce a high-resolution 3D point cloud from which canopy cross-sectional area (CSA) was extracted every 10 cm along the rows (Figure 5, right).

These CSA values (m²) were used as a proxy for vine vegetative growth as described in Cabrera-Pérez et al. (2023) and in Escolà et al. (2023). In the cover crop trial, rows were categorized based on adjacent soil management treatments: "tillage on both sides," "cover crop on both sides," and "mixed" (cover crop on one side and tillage on the other). Mixed rows were further sub-classified into "Tillage–*Hordeum*" and "Tillage–*Lolium*" combinations. In the mulching trial, the canopy structure was evaluated according to each of the four treatments.

2.6 Statistical analysis

All data were analyzed separately for each growing season. Analysis of variance (ANOVA) was performed to detect significant treatment effects. When only two treatments were compared (mulching trial), means were separated using Student's *t*-test, whereas for comparisons involving more than two treatments

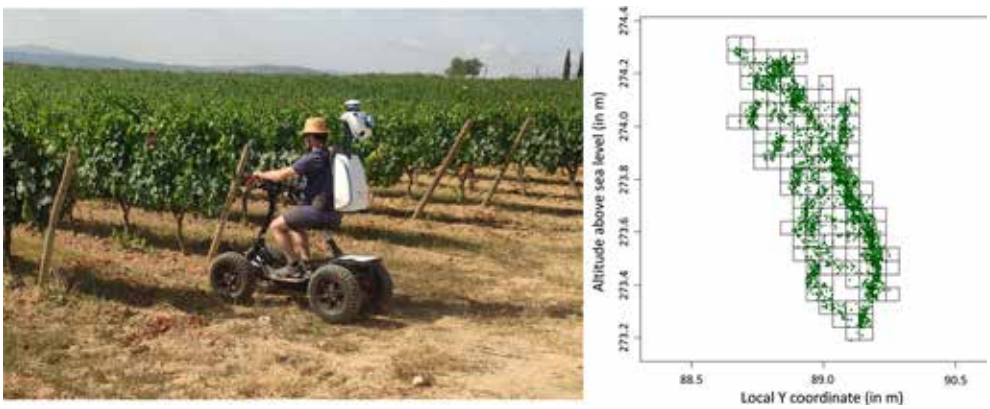

FIGURE 5
Mobile terrestrial laser scanner performing the scan of the experimental plot (left), and example of a cross-sectional view of the vegetation and the determination of its canopy area based on an occupancy grid, in which only the occupied 5 cm × 5 cm cells are computed (right).

(cover crop trial), means were compared using Tukey's honest significant difference (HSD) test at a significance level of $\alpha = 0.05$. Statistical analyses were conducted using JMP® version 15 (SAS Institute, Cary, NC, USA).

3 Results

3.1 Cover crop trial (alleyways)

The establishment of both barley (*H. vulgare)* and ryegrass (*L. multiflorum*) cover crops was negatively affected by below-average rainfall in both years. According to data from the Sant Sadurní d'Anoia meteorological station, located 7 km away, total precipitation between winter and spring was 53% below the historical average in 2021 and 51% below in 2022. Consequently, cover crop ground cover was modest during the vegetative cycle. In 2021, maximum ground cover reached 38% for both species in June, while in 2022, maximum cover reached 50% for barley and 82% for ryegrass (Table 1). No statistical differences were observed across the treatments for the cover crop coverage.

In both years, weed cover in the alleyways where cover crops were sown remained very low (Table 2). Weed infestation in ryegrass plots never exceeded 3.8%, and in barley plots reached a maximum of 19.6% in June 2022. In the tillage treatment, weed cover values were very low during 2021. However, in late spring 2022, weeds covered nearly 30% of the alleyways in May and June, significantly higher than those observed in the alleyways with cover crop, until the tillage operation carried out on June 15th reduced weed cover to nearly 0% by the end of June.

The different vine vigor parameters at the end of each growing season are presented in Tables 3a and 3b. In each case, two scenarios are considered: vines flanked on both sides either by tilled alleyways or by cover crops. Due to the limitations of the experimental design, where only the most homogeneous area was used for the essay and the number of rows where limited, no distinction was made between the cover crop species (barley or ryegrass) in the case of vines with adjacent cover crops, and a similar competitive effect was assumed, as both are annual winter grasses with comparable growth cycles.

Despite their weed suppression potential, cover crops showed a measurable competitive effect on vine vigor. Vines flanked by tilled alleyways consistently displayed greater exposed leaf area (ELA) and biomass production than those bordered by cover crops. In 2022, differences in yield (0.84 kg vine^{+1} under tillage vs. 0.56 kg vine^{+1} under cover crops) were statistically significant, as were also pruning weight and shoot weight in both years. On the other hand, the number of clusters per vine and the Ravaz index were not significantly affected by alleyway management. Shoot number/vine showed no difference in 2021 but was significantly higher in cover-cropped vines in 2022.

LiDAR-based canopy analysis confirmed these trends (Table 4). Vines bordered by tilled alleyways had a significantly greater canopy cross-sectional area than those with cover crops on both sides. In "mixed" rows, intermediate canopy development was observed, with differences depending on the cover crop species. In 2021, combinations with *H. vulgare* (Tillage–*Hordeum*) resulted in significantly greater canopy area than combinations with *L. multiflorum* (Tillage-*Lolium*). However, in 2022, no significant differences were found between the two mixed treatments. When data from both seasons were pooled, a consistent gradient in canopy area was evident: tilled > mixed > cover crop.

3.2 Mulch trial

The pine mulch maintained low weed cover throughout both seasons, with maximum values of 10.1% in June 2022 (Table 5). The few weeds that emerged under the mulch were mostly perennial species with vegetative propagation structures (*Convolvulus arvensis*, *Oxalis debilis* subsp. *corymbosa*). Weed suppression was comparable to that achieved with traditional tillage, except for a brief period in 2022 when tillage plots showed lower weed cover immediately after intervention.

In both seasons, ELA and number of clusters per vine were slightly higher in mulched vines than in those managed with under-vine tillage, although differences were only statistically significant for ELA in 2022 and cluster number in 2021 (Table 6a). Yield was also higher in mulched vines (0.99 kg vine^{+1} and 1.16 kg vine^{+1} in 2021 and 2022, respectively) than in tilled ones (0.77 kg vine^{+1} and 0.95 kg vine^{+1}), though differences were not statistically significant (Table 6a). Other vigor-related parameters showed no clear differences between the two strategies (Table 6b).

LiDAR-derived data analysis supported these observations (Table 7). In both years, mulched vines showed significantly larger canopy cross-sectional areas than those under mechanical tillage.

4 Discussion

Despite the initial reluctance of some winegrowers to introduce vegetation into vineyards, cover crops have increasingly been

TABLE 1 Cover crop soil coverage (%) in each sampling date during 2021 and 2021–2022 (mean values ± standard errors of the mean).

Treatment	18/01/2021	05/02/2021	05/03/2021	09/04/2021	28/04/2021	27/05/2021	18/06/2021
Ryegrass coverage (%)	6.3 ± 0.3	7.6 ± 0.6	16.8 ± 0.7	20.4 ± 0.7	24.6 ± 1.3	29.2 ± 1.2	37.1 ± 1
Barley coverage (%)	13.5 ± 1.1	16 ± 0.7	23.3 ± 0.7	27.3 ± 0.9	32.1 ± 1.6	33.8 ± 1.3	37.9 ± 0.7
2022	14/12/2021	24/01/2022	28/03/2022	09/05/2022	03/06/2022	30/06/2022	
Ryegrass coverage (%)	14.9 ± 1.6	14.3 ± 1.5	36.4 ± 2.6	55.9 ± 2.7	82.5 ± 2.1	62.1 ± 3.6	
Barley coverage (%)	15.8 ± 2.3	16.4 ± 2	28.6 ± 2.4	41.7 ± 2	49.2 ± 2.7	50 ± 2.6	

TABLE 2 Weed coverage (%) in the three treatments (mean values ± standard errors of the mean).

Treatment	05/02/2021	05/03/2021	09/04/2021	28/04/2021	27/05/2021	18/06/2021	23/07/2021
Tillage weed coverage (%)	0.2 ± 0.1 a	0.0 ± 0.0 a	1.3 ± 0.7 a	1.1 ± 0.7 a	0.0 ± 0.0 a	0.8 ± 0.2 a	0.1 ± 0 a
Ryegrass weed coverage (%)	0.3 ± 0.1 a	0.4 ± 0.3 ab	0.7 ± 0.3 a	1.1 ± 0.5 a	1.2 ± 0.5ab	0.5 ± 0.2 a	0.0 ± 0.0 a
Barley weed coverage (%)	0.1 ± 0 b	0.7± 0.2 b	1.4 ± 0.2 a	2.4 ± 0.5 a	4.9 ± 0.8 b	1.3 ± 0.3 b	0.1 ± 0 a
2022	14/12/2021	24/01/2022	28/03/2022	09/05/2022	03/06/2022	30/06/2022	
Tillage weed coverage (%)	0.4 ± 0.1 a	0.0 ± 0.0 a	0.9 ± 0.7 a	27.4 ± 2.8 c	26.8 ± 6.9 c	0.4 ± 0.3 a	
Ryegrass weed coverage (%)	0.6 ± 0.2 b	1.2 ± 0.5 b	2.7 ± 1.1 ab	0.5 ± 0.2 a	3.8 ± 1.2 a	2.2 ± 0.6 a	
Barley weed coverage (%)	1.6 ± 0.4 c	4.8 ± 1.2 c	7.9 ± 1.3 b	9.4 ± 1.1 b	19.6 ± 3.5 b	2.1 ± 0.5 a	

Values followed by different letters within columns indicate significant differences ($p < 0.05$) according to the Tukey test.

adopted due to their agronomic and environmental benefits and the economic incentives growers can receive (Garcia et al., 2018). In this study, the use of winter annual grasses (*H. vulgare* and *L. multiflorum*) in the alleyways resulted in effective suppression of spontaneous weed flora. Weed coverage remained below 10% in all cases and was particularly low in *L. multiflorum* plots, where values did not exceed 2.7% during the critical spring period. These results are consistent with previous studies conducted in Mediterranean vineyards reporting a strong weed-suppressive capacity of grass cover crops (Ibáñez, 2015; Baumgartner et al., 2008; Valencia-Gredilla et al., 2020).

However, a clear competitive effect on vine vigor was observed, particularly under the extremely dry conditions prevailing during the experimental period. Vines flanked by tilled alleyways showed consistently higher cross-sectional area, pruning weight, and yield than those flanked by a cover crop. These differences were statistically significant for several parameters, especially in 2022, a year characterized by a severe drought.

Although two different grass species were used as alleyway cover crops (*H. vulgare* and *L. multiflorum*), their effects were considered equivalent for the purpose of the statistical analysis due to their morphological and functional similarity. Both species belong to the same functional group of annual winter grasses and exhibit comparable growth cycles. Previous reviews and comparative studies indicate that the agronomic effects of cover crops on vine performance are primarily driven by their functional type (grass vs. legume vs. mixture) rather than by species identity within the same group. Experiments comparing several grass species have reported consistent trends in soil coverage and erosion reduction, weed suppression, water competition, and soil mineral composition changes with differences among species being minor compared with those among functional groups (e.g., *Hordeum vulgare*, *Lolium multiflorum*, and *Avena sativa* showing similar outcomes under Mediterranean conditions) (Abad et al., 2021; Varga et al., 2012; Gontier et al., 2014; Messiga et al., 2015). Therefore, grouping both covers as a single "grass cover crop" category is justified from a functional perspective. Nonetheless, the small differences observed in the LiDAR readings between tillage–*Hordeum* and tillage–*Lolium* combinations in 2021 suggest that species × year interactions, driven by rainfall variability, may modulate the intensity of competitive effects. This observation is consistent with previous research showing that the agronomic response to annual cover

TABLE 3A Vigor values (I) of vines flanked by tilled alleyways or by cover crops on both sides (mean values ± standard errors of the mean).

Treatment	ELA (m^2/vine)		Clusters number / vine		Yield (kg / vine)	
	2021	2022	2021	2022	2021	2022
Tillage	8673 ± 402.70 a	9084 ± 359.80 a	12.2 ± 1.20 a	13.3 ± 0.80 a	0.69 ± 0.10 a	0.84 ± 0.12 a
Cover crop	7692 ± 373.60 b	7152 ± 320.00 b	11.3 ± 1.60 a	14.3 ± 1.30 a	0.53 ± 0.11 a	0.56 ± 0.10 b

Values followed by different letters within columns indicate significant differences ($p < 0.05$) according to the t-test.

TABLE 3B Vigor values (II) of vines flanked by tilled alleyways or by cover crops on both sides (mean values ± standard errors of the mean).

Treatment	Bunches / vine shoot		Pruning weight (g)		Shoot number / vine		Shoot weight (g)		Ravaz index	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Tillage	0.83 ± 0.1 a	0.97 ± 0.06 a	194 ± 20 a	222 ± 26 a	14.7 ± 0.7 a	13.66 ± 0.5 a	13.2 ± 1.7 a	16.31 ± 1.9 a	3.84 ± 0.5 a	3.87 ± 0.5 a
Cover crop	0.83 ± 0.1 a	0.94 ± 0.08 a	114 ± 20 b	126 ± 16 b	13.6 ± 0.9 a	15.44 ± 0.9 b	8.4 ± 1.4 b	7.98 ± 0.9 b	5.66 ± 0.8 a	4.97 ± 0.9 a

Values followed by different letters within columns indicate significant differences ($p < 0.05$) according to the t-test.

TABLE 4 LiDAR-derived mean cross-sectional area of the vine canopy for rows treated with different alleyway managements in adjacent alleyways.

Treatment	Mean canopy cross-sectional area (m^2)	
	2021	2022
Tillage, both sides	0.199 ± 0.0016 Aa [2485]	0.168 ± 0.0011 Aa [2406]
Mixed (tillage and cover crop)	0.187 ± 0.0015 A [3107]	0.157 ± 0.0008 B [3033]
Tillage-*Hordeum*	0.195 ± 0.0021 a [1458]	0.156 ± 0.0013 b [1426]
Tillage-*Lolium*	0.181 ± 0.0022 b [1649]	0.158 ± 0.0011 b [1607]
Cover crop, both sides	0.152 ± 0.0011 Bc [3213]	0.133 ± 0.0008 Cc [3117]

Values followed by different uppercase or lowercase letters within columns indicate significant differences ($p < 0.05$) according to the Tukey test for three and four levels, respectively. The mixed treatment is shown both grouped and ungrouped (mean values ± standard errors of the mean [observations]).

crops in vineyard alleyways can range from positive to negative depending on climate, soil properties, management intensity, and production system (Dzvene et al., 2023), highlighting the delicate balance between weed control, soil improvement, and competition with the crop in water-limited environments (Ehrenfeld et al., 2005; Abad et al., 2021).

Several authors have reported that while grass cover crops improve water infiltration in winter, grass transpiration in spring leads to water stress values similar to those of the grapevines managed under bare soil (Celette et al., 2005; Celette and Gary, 2013; Cunial et al., 2025). The results presented in this paper confirm that winter cover crops can effectively contribute to weed suppression, but they may also compete with vines for soil water during spring—an effect that is exacerbated under rainfed conditions and particularly relevant in Mediterranean vineyards without supplemental irrigation, as previously demonstrated by Muscas et al. (2017). In addition, based on evidence from the literature, winter cover crops have been reported to potentially improve soil structure, enhance biodiversity, and reduce the carbon footprint of vineyard management systems (Dong et al., 2025), although these aspects were not directly assessed in the present study.

Under average rainfall conditions, however, winter annual cover crops such as those evaluated here would be expected to show faster establishment, higher soil cover and greater biomass production, thereby enhancing their potential benefits in terms of soil protection and weed suppression (Celette et al., 2008; Abad et al., 2021). Previous studies conducted under less restrictive water availability conditions have reported more stable cover crop performance, while the impact on vine water status seemed to depend on cover crop species, percentage of soil covered, and the timing and duration of their development throughout the season, among others (Celette and Gary, 2013; Muscas et al., 2017).

In the context of climate change, characterized by increased rainfall variability and more frequent drought events in Mediterranean regions (IPCC, 2021), the performance of cover crops will likely depend on species selection and adaptive management strategies. Winter annual species with short growing cycles and early senescence may remain suitable options, as they allow soil protection during the rainy period while minimizing water competition during the critical summer months (Abad et al., 2021). Therefore, although cover crop establishment may be increasingly challenged under future climatic scenarios, their strategic use during wetter years or seasons could still contribute positively to the resilience and sustainability of Mediterranean rainfed viticulture.

Regarding organic mulching, pine wood chips proved to be a promising alternative to mechanical under-vine in-row tillage. Weed coverage in mulched plots remained low across both years, with the few escapes mainly consisting of perennial species capable of vegetative propagation. This is consistent with previous studies showing the effectiveness of mulches in creating a physical barrier to light and limiting weed emergence (Teasdale and Mohler, 2000; Cabrera-Pérez et al., 2022). The low weed cover values observed under the tillage treatment were largely attributable to the repeated use of mechanical cultivation (both in the cover crop and mulch trials). While these operations were effective in suppressing weed emergence, they required a high number of interventions throughout the growing season, highlighting the greater management intensity associated with this practice.

Moreover, vine vigor under the pine chip mulch treatment was generally comparable to or slightly greater than that observed under traditional tillage, particularly in terms of exposed leaf area and cluster number. Although not always statistically significant, these consistent trends indicate that organic mulching does not constrain vine growth and may even enhance it under Mediterranean conditions. Similar responses have been reported in vineyards managed with woody mulches, where improved vegetative development and yield were associated with enhanced soil water availability and reduced competition from weeds (DeVetter et al., 2015; Zribi et al., 2011; Fraga and Santos, 2018).

The positive response observed under the pine chip mulch can be explained by several complementary mechanisms. First, organic

TABLE 5 Weed coverage (%) in the two under-vine treatments (mean values ± standard errors of the mean).

Treatment	05/02/2021	05/03/2021	09/04/2021	28/04/2021	27/05/2021	18/06/2021	23/07/2021
Tillage	0.5 ± 0.2 a	0.2 ± 0.1 a	0.8 ± 0.2 a	1.1 ± 0.2 a	0.5 ± 0.1 a	0.7 ± 0.2 a	0.3 ± 0.1 a
Mulch	0.0 ± 0.0 b	0.0 ± 0.0 a	0.2 ± 0.1 a	0.8 ± 0.3 a	2.4 ± 1.1 a	2.4 ± 1.3 a	0.4 ± 0.4 a
Date	14/12/2021	24/01/2022	28/03/2022	09/05/2022	03/06/2022	30/06/2022	
Tillage	0.3 ± 0.04 a	0.0 ± 0.0 a	0.7 ± 0.2 a	12.0 ± 2.3 a	3.4 ± 1.9 b	4.5 ± 0.4 a	
Mulch	0.0 ± 0.0 b	0.1 ± 0.05 a	1.3 ± 0.9 a	4.2 ± 1.9 b	10.1 ± 0.6 a	3.9 ± 1 a	

Values followed by different letters within columns indicate significant differences ($p < 0.05$) according to the t-test.

TABLE 6A Vigor values (I) of vines for each under-vine treatment (mean values ± standard errors of the mean).

Treatment	ELA		Clusters number / vine		Yield (kg / vine)	
	2021	2022	2021	2022	2021	2022
Tillage	9769 ± 226 a	9049 ± 201 b	10.3 ± 0.6 b	13.6 ± 0.7 a	0.77 ± 0.08 a	0.95 ± 0.08 a
Mulch	10265 ± 222 a	9755 ± 264 a	12.7 ± 0.8 a	14.5 ± 0.7 a	0.99 ± 0.08 a	1.16 ± 0.08 a

Values followed by different letters within columns indicate significant differences ($p < 0.05$) according to the t-test.

TABLE 6B Vigor values (II) of vines for each under-vine treatment (mean values ± standard errors of the mean).

Treatment	Bunches / vine shoot		Pruning weight (g)		Shoots number / vine		Shoot weight (g)		Ravaz index	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Tillage	0.83 ± 0.05 a	1.00 ± 0.04 a	208 ± 20 a	215 ± 21 a	12.6 ± 0.1 a	14.8 ± 0.6 a	16.5 ± 1.3 a	15.8 ± 1 a	3.76 ± 0.2 a	5.30 ± 0.3 a
Mulch	0.93 ± 0.06 a	0.97 ± 0.06 a	225 ± 19 a	227 ± 11 a	13.5 ± 0.1 a	14.1 ± 0.5 a	16.8 ± 1.4 a	15.1 ± 0.9 a	4.76 ± 0.4 a	4.57 ± 0.4 a

Values followed by different letters within columns indicate significant differences ($p < 0.05$) according to the t-test.

mulches effectively reduce soil evaporation and buffer extreme soil temperatures, leading to improved vine water status during critical phenological stages (Buesa et al., 2021; Cabrera-Pérez et al., 2023). In addition, the high persistence and thickness of pine-based mulches limit weed emergence and growth, thereby minimizing belowground competition for water and nutrients compared with tilled or vegetated soils (Cabrera-Pérez et al., 2022). Furthermore, organic mulches do not actively transpire, which is particularly advantageous under water-limited conditions. As highlighted by Cabrera-Pérez et al. (2023), pine wood mulches can sustain vine vegetative growth and yield without inducing competition, supporting their suitability as a climate-adaptive soil management strategy.

The use of mobile terrestrial laser scanning based on LiDAR provided a high-resolution and objective assessment of canopy architecture, allowing the detection of subtle differences in vegetative growth among soil management treatments. The consistent gradient in canopy development observed in the cover crop experiment (tillage > mixed > cover crop) supports the sensitivity of LiDAR-derived canopy cross-sectional area (CSA) metrics to vineyard vigor and their strong relationship with physiological parameters such as leaf area, pruning weight, and yield. Recent research confirms the value of LiDAR and UAV-based laser scanning for reconstructing vine rows and estimating canopy traits with high spatial detail (Chedid et al., 2023; Escolà et al., 2023; Vélez et al., 2023). In particular, mobile terrestrial laser scanners provide accurate three-dimensional characterization of trellised canopies, enabling detection of lateral asymmetries between alternating rows, as in the mixed treatments of this study. These results are consistent with previous findings in Mediterranean vineyards, such as those reported by Cabrera-Pérez et al. (2023), where LiDAR-derived measurements of canopy structure and vigor correlate with vine water status and yield. In that study, under-vine mulches maintained vine vigor, whereas alleyway cover crops induced measurable water competition detectable through LiDAR-based canopy metrics. Overall, integrating LiDAR measurements into vineyard soil management trials enhances the capacity to link structural canopy responses with physiological and agronomic performance.

TABLE 7 LiDAR-derived mean cross-sectional area of the vine canopy for rows treated with different under-vine soil managements in 2021 and 2022 (mean values ± standard errors of the mean [observations]).

Treatment	Mean canopy cross-sectional area (m^2)	
	2021	2022
Tillage	0.212 ± 0.0015 b [3421]	0.193 ± 0.0011 b [3311]
Mulch	0.227 ± 0.0014 a [3591]	0.211 ± 0.0011 a [3473]

Values followed by different letters within columns indicate significant differences ($p < 0.05$) according to the t-test.

The overall results suggest that partial implementation of a cover crop (e.g. alternating cover and tillage rows) may help mitigate competitive effects while still delivering some of the ecological benefits of cover cropping. Regarding the under-vine management, vines in mulched rows exhibited significantly larger canopy cross-sections than those managed with under-vine tillage. This reinforces the potential of pine chip mulches as both a weed control and vigor-maintaining strategy in dryland, so combining both strategies (cover crops and mulches) may be an interesting management in rainfed vineyards.

5 Conclusions

The use of winter annual cover crops (*Hordeum vulgare* and *Lolium multiflorum*) in vineyard alleyways effectively suppressed weed emergence, maintaining weed cover levels below 10% for most of the season. Under rainfed Mediterranean conditions, these cover crops had a competitive effect on vine vigor, especially in dry years,

reducing yield and pruning weight compared to traditional tillage-based management. LiDAR-based canopy analysis confirmed a vigor gradient: vines flanked by tilled alleyways showed the highest canopy development, followed by those rows with mixed flanks, and those flanked by cover crops on both sides. On the other hand, pine wood chips mulch applied under the vine row effectively reduced weed pressure, with results comparable to tillage, and showed high persistence (over two seasons) and no negative impact on vine vigor. Hence, in rainfed organic vineyards, organic mulching represents a reliable and sustainable alternative to mechanical under-vine tillage.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

CC-P: Investigation, Writing – original draft, Resources, Visualization, Data curation, Formal analysis, Methodology. JL-C: Methodology, Formal analysis, Data curation, Visualization, Writing – review & editing, Investigation. ÀE: Formal analysis, Methodology, Writing – review & editing, Visualization, Data curation, Investigation. BB: Writing – review & editing, Visualization, Conceptualization, Investigation. MT-V: Conceptualization, Funding acquisition, Supervision, Project administration, Writing – review & editing. MT-M: Supervision, Project administration, Writing – review & editing, Conceptualization, Funding acquisition. JR: Supervision, Project administration, Data curation, Visualization, Formal analysis, Methodology, Conceptualization, Investigation, Writing – original draft, Funding acquisition, Writing – review & editing.

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Conflict of interest

Authors MT-V and MT-M were employed by Familia Torres.

The remaining author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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