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VITICULTURE ORIGINAL RESEARCH ARTICLES

# Under-vine cover crops in viticulture: impact of different weed management practices on weed suppression, yield and quality of grapevine cultivar Riesling (*Vitis vinifera* L.)

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**KEYWORDS:** viticulture, soil management, under-vine vegetation, intra-row vegetation, weed control, herbicide, mechanical tillage

## ABSTRACT

Sustainable viticulture increasingly depends on alternative floor management strategies to improve vineyard resilience to weather extremes, while supporting grapevine health and economic viability. One such strategy is the use of perennial and short-lived biennial cover crops as an alternative to mechanical tillage and herbicide applications for under-vine weed control. This study aimed to evaluate the effects of the under-vine cover crops red fescue (*Festuca rubra*), wild thyme (*Thymus serpyllum*), black medic (*Medicago lupulina*), and a commercial herb mixture in comparison to spontaneous vegetation, mechanical tillage and herbicide treatments on weed suppression, soil conditions, and grapevine performance in a non-irrigated vineyard with a cool to moderate climate. To assess the impact of the different treatments, soil vegetation coverage, soil moisture, and soil temperature were measured. Grapevine performance was evaluated in terms of yield, berry weight, must composition, cluster looseness, and bunch rot infection levels caused by *Botrytis cinerea*.

Under-vine cover crops effectively suppressed weed growth over time, reducing overall weed cover to levels comparable to mechanical tillage and herbicide treatments. Further, they influenced soil conditions by increasing soil moisture and reducing soil temperature extremes at a depth of 6 cm. During the vegetation period in 2023, soil moisture levels were lowest with mechanical tillage. In contrast, the use of cover crops, such as red fescue, helped to maintain higher soil moisture levels over time and significantly lowered soil temperatures compared to herbicide treatments. Cover crop treatments resulted in looser cluster architecture, which was associated with a lower incidence and severity of *Botrytis* bunch rot. The highest disease levels occurred in herbicide-treated plots in 2024. Yield, must composition and berry weight were unaffected by the treatments, except that herbicide application resulted in significantly higher yield compared to under-vine cover cropping with wild thyme, which may indicate competition between wild thyme and grapevines for resources.

The results suggest that under-vine cover crops offer several agronomic benefits, including improved moisture retention, regulation of soil temperature and reduced disease pressure, making them a viable alternative for sustainable vineyard management. However, potential trade-offs between yield and long-term soil conservation should be considered when implementing this practice.

## INTRODUCTION

Weed management in vineyards is essential to maintain grape yield and quality. This is particularly important in the under-vine zone, where weeds compete directly with the vines for water and nutrients or grow excessively, potentially interfering with vineyard management and vine development (Abad *et al.*, 2021; Celette & Gary, 2013; Giese *et al.*, 2014; Guerra *et al.*, 2022; Kesser *et al.*, 2023; Lines *et al.*, 2024).

Traditionally, weed control is achieved primarily through herbicide application or mechanical weeding. However, the use of herbicides is controversial due to potential impacts on the environment and human health (van Bruggen *et al.*, 2021). Mechanical weeding, such as tillage, is an alternative to herbicide treatment and is especially used in organic viticulture (Renaud-Gentié *et al.*, 2019). Depending on the machines used, soil conditions and operator skills, this method also presents certain disadvantages, including carbon and organic nutrient release through decomposition of soil organic matter and its mineralisation (Ferreira *et al.*, 2020), higher soil erosion potential and variable weed control efficiency (Manzone *et al.*, 2020). Economically, tillage has the risk of vine damage and is associated with additional costs for energy, machinery and labour (Jacquet *et al.*, 2021). Given these challenges, there is a growing need for alternative, sustainable weed management strategies in modern viticulture. Another reason for the adoption of alternative weed control strategies is the promotion of the European Green Deal's goals, which address both herbicide use and mechanical tillage. The European Commission has developed an action plan aiming to reduce the use and risk of chemical and hazardous pesticides as well as nutrient losses by 50 % by 2030 (Bremmer *et al.*, 2021).

The implementation of cover crops in the under-vine zone has already been shown to be an effective method of weed control that also improves soil health (Abad *et al.*, 2022; Guerra *et al.*, 2022). Cover crops suppress weeds through displacement, competing for resources and releasing allelopathic compounds (Sturm *et al.*, 2018). The high sensitivity of weeds to shading may be the main reason behind the suppressive effect of cover crops; however, no studies have yet clarified this relationship (Cabrera-Perez *et al.*, 2024).

While some studies have explored the use of spontaneous vegetation as a permanent under-vine cover, which may contribute to soil health improvements such as enhanced microbial activity (Chou *et al.*, 2018; Griesser *et al.*, 2022), other research indicates further long-term benefits. For instance, García-Díaz *et al.* (2018) showed that in Spanish vineyards, spontaneous vegetation compared to mechanical weeding improved water infiltration and soil organic carbon, which led to higher soil moisture levels. Similarly, Kesser *et al.* (2023) demonstrated that long-term under-vine coverage by spontaneous vegetation altered plant community composition and soil dynamics without negatively affecting yield in two South Australian vineyards. Importantly, they also showed that less intensive vineyard floor management, such as allowing spontaneous vegetation to persist, can enhance overall plant biodiversity and support beneficial ecological functions, potentially reducing input costs over time. Nevertheless, there are also notable drawbacks. Spontaneous vegetation under vines has shown negative impacts on soil moisture, potentially leading to reduced berry weights (Griesser *et al.*, 2022). A key limitation of using spontaneous vegetation is the lack of control over plant composition, which may result in the proliferation of undesirable or highly competitive species (Monteiro *et al.*, 2012; Steenwerth *et al.*, 2016). Additionally, certain weed species serve as hosts for disease vectors, potentially increasing the risk of grapevine infections. For instance, *Bois noir*, a widespread grapevine yellows disease, is transmitted by *Hyalesthes obsoletus*, whose population density depends on the presence of its host plants, such as stinging nettle (*Urtica dioica*) and field bindweed (*Convolvulus arvensis*) (Schweigkofler *et al.*, 2018). This highlights the importance of targeted weed management strategies to minimise disease risks. Regular mowing may be required to prevent excessive plant height, especially in rainy conditions (Mainardis *et al.*, 2020). Mowing vegetation can serve as a short-term water management strategy by temporarily reducing vegetation competition for water. However, plant mowing favours species with deep roots and storage organs, primarily perennial plants adapted for rapid regrowth (Mainardis *et al.*, 2020).

In contrast, selected cover crops offer a more controllable approach, allowing vineyard managers to balance weed suppression, soil health and vine performance. Selecting the appropriate cover crop is essential for adapting to local climate conditions and ensuring compatibility with the vineyard management strategy (Marks *et al.*, 2022).

To be effective, cover crops must outcompete weeds, thereby reducing the need for mechanical or chemical interventions while avoiding negative effects on yield and fruit quality. However, cover crop species with strong growth could reach the canopy or grape bunch zone increasing humidity and the risk of fungal infections (Jordan *et al.*, 2016). Additionally, cover crop species with shallow root systems can decrease the risk of competition with the deeper-rooted vines for water and nutrients, provided that species exhibit limited biomass production and a low water demand during periods when water is required by the grapevine. Furthermore, cover crops are ideally perennial or self-regenerating, ensuring long-term soil cover while being resilient to frost, drought and warm conditions (Abad *et al.*, 2023).

Another critical factor in the use of under-vine cover crops is water competition, which strongly influences vine growth and grape quality, particularly in drought-prone regions (Fleishman *et al.*, 2023) or vineyards without irrigation options. Cover crops can affect soil water dynamics in opposite ways. They may enhance soil water retention and infiltration by improving soil structure, increasing soil organic matter and promoting aggregate stability, thereby reducing evaporation losses and surface runoff (Abad *et al.*, 2023; Fleishman *et al.*, 2023). In contrast, several studies have shown that cover crops can compete with vines for available

water, especially when root systems overlap within the same soil layer (Monteiro *et al.*, 2012) or under conditions of limited rainfall in springtime (Celette & Gary, 2013; Celette *et al.*, 2008). Therefore, identifying cover crop species that balance soil water conservation with minimal competition for vine resources remains a key challenge for sustainable vineyard floor management.

Beyond their role in weed suppression, under-vine cover crops contribute to biodiversity enhancement by promoting root development, soil fauna and insect diversity, fostering biological soil activity, supporting nutrient cycling and enhancing long-term soil fertility (Abad *et al.*, 2023; Garcia *et al.*, 2018; Giffard *et al.*, 2022; Winter *et al.*, 2018). Additionally, cover crops increase soil organic matter content and improve soil structure (Marks *et al.*, 2022). From a hydrological perspective, under-vine cover crops may increase soil infiltration rates and reduce surface runoff, helping to prevent soil erosion and nutrient leaching, particularly nitrate loss (Vanden Heuvel & Centinari, 2021). Furthermore, soil coverage from cover crops influences microclimate conditions by reducing soil temperature fluctuations and modifying soil moisture dynamics (Bavougian & Read, 2018). These effects enhance vineyard sustainability, particularly in regions experiencing climate variability, extreme rainfall events, or prolonged droughts. However, the impact of under-vine cover crops on soil moisture availability remains uncertain. While some studies suggest that cover crops increase water infiltration and retention, others indicate that they may compete with grapevines for water, particularly in dry climates (Bavougian & Read, 2018).

The effects of under-vine cover crops on vine growth and yield remain highly debated. Some studies suggest that cover crops reduce vine vigour and berry size (Chou & Vanden Heuvel, 2019; Coniberti *et al.*, 2018b), while others indicate that they increase root length density at deeper soil layers, leading to improved drought resilience (Fleishman *et al.*, 2023). A reduction in vine vigour can be beneficial in high-vigour vineyards, as it results in looser grape clusters, reducing the risk of *Botrytis* bunch rot caused by the fungus *Botrytis cinerea* (grey mould) (Coniberti *et al.*, 2018a; Fleishman *et al.*, 2023). Compact grape bunches have been shown to be associated with high nitrogen and water availability and are more susceptible to diverse diseases, such as *Botrytis* bunch rot, causing important economic losses for viticulture through a reduction in crop yield and grape quality (Tello & Ibáñez, 2018). Additionally, deeper root growth enhances vine water uptake efficiency, potentially improving grape quality and adaptation to drought conditions (Fleishman *et al.*, 2023).

There are few studies focusing on annual under-vine cover crops, especially in regions such as the northeastern U.S., where cover crops need to be re-established each year to accommodate hilling-up practices (Centinari *et al.*, 2016; Chou & Vanden Heuvel, 2019; Jordan *et al.*, 2016). In contrast to annual cover crops, perennial cover crops generally require only one soil preparation and seeding event to establish long-term vegetative cover, assuming successful establishment (Centinari *et al.*, 2016). This significantly reduces management effort by eliminating the need for repeated tillage or herbicide applications, leading to cost savings in labour, fuel and material expenses over time (Vanden Heuvel & Centinari, 2021). However, perennial cover crops may increase the risk of competition with grapevine for water and nutrients compared to annual cover crops (Celette *et al*., 2008).

The objective of this study was to determine whether under-vine cover crops can serve as a viable and sustainable alternative to chemical and mechanical weed management in viticulture. Therefore, this study investigated the effects of the under-vine cover crops red fescue (*Festuca rubra*), wild thyme (*Thymus serpyllum*), black medic (*Medicago lupulina*), and a commercial herb mixture compared to spontaneous vegetation, mechanical tillage and herbicide treatments on weed suppression, soil conditions, and grapevine performance. To assess the impact of the different treatments, soil vegetation coverage, soil moisture, and soil temperature, as well as grapevine yield, berry weight, must composition, cluster looseness and *Botrytis* bunch rot infection levels were measured.

## MATERIALS AND METHODS

### 1. Description of experimental sites and variants

The study was conducted from 2022 to 2024 in a non-irrigated vineyard. Riesling clone N90 on the rootstock SO4 was planted in 2014 with an inter-row spacing of 2.0 m and an intra-row spacing of 1.0 m. The trellis system is a vertical shoot position. The vineyard is located in Neustadt/Weinstraße (49.3734° N 8.1821° E) in the Pfalz region of Germany, which is characterised by a cool to moderate climate with moderate humidity (Figure 1). According to the USDA soil texture classification (9 fractions), the soil at the study site is classified as loam, with a pH of 7.1 and a soil organic matter content of 2.0 %, estimated from soil organic carbon (Corg × 1.72). Standard cultural practices included plant protection using conventional fungicides. A permanent inter-row vegetation cover composed of grasses, legumes and herbs, including both sown and spontaneously established species, was maintained between the vine rows (2 m width) and mown two to three times annually. For the purposes of this study, four under-vine cover crop treatments were established, representing contrasting functional traits relevant to vineyard management: a perennial grass, red fescue (*Festuca rubra*); a drought-tolerant forb, wild thyme (*Thymus serpyllum*); a nitrogen-fixing legume, black medic (*Medicago lupulina*), and a herb mixture as an example of a multi-component cover crop (composition can be found in Table S1). Spontaneous vegetation (control) and two standard practices, mechanical tillage and chemical treatment (herbicide application), were used as control treatments.

The experiment was established in a randomised complete block design (RCBD) with four replications. Each treatment

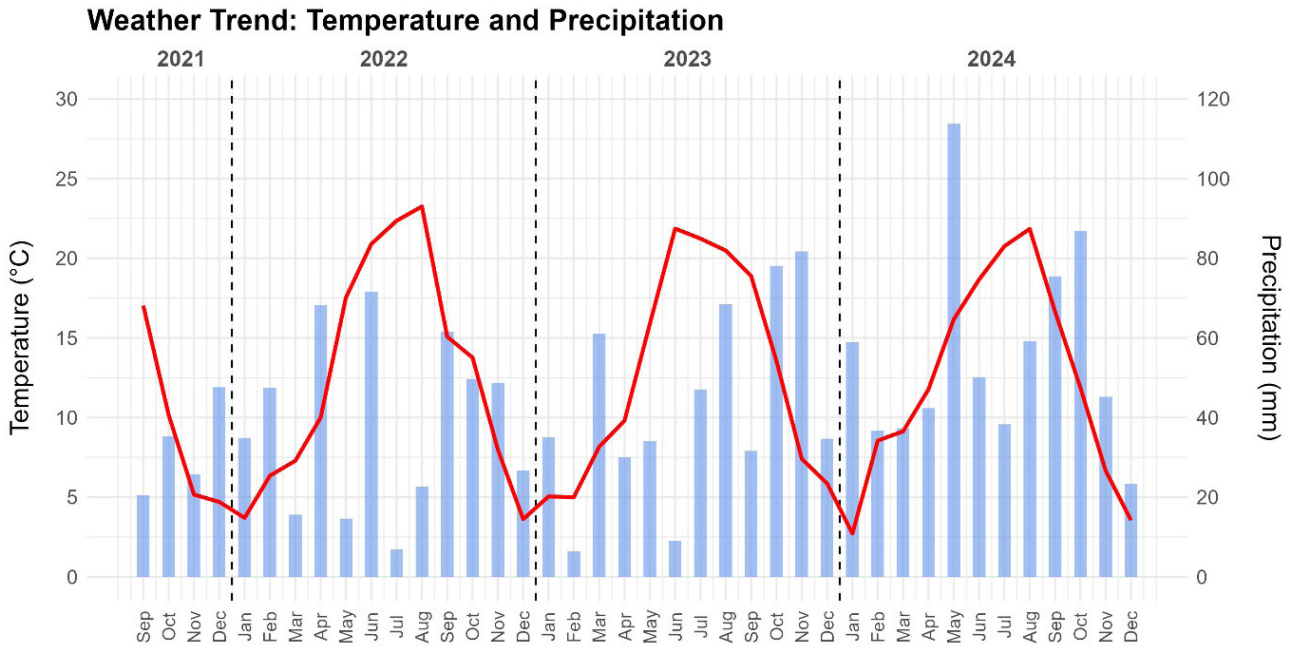



**FIGURE 1.** Weather conditions during the experimental period were obtained from a weather station located at 49.3683° N 8.1855° E, 140 m a.s.l., approximately 630 m from the experimental site: Average monthly air temperature (°C) at a height of 2 m (red line) and sums of monthly precipitation (mm) (blue bars). Data was provided by "Agrarmeteorologie Rheinland-Pfalz" (www.wetter.rlp.de/Agrarmeteorologie).

replicate (plot) measured 15 m in length and 0.5 m in width and comprised 15 consecutive vines within a single row. Thus, a total of 60 vines were assigned per treatment (15 vines × 4 replicates). In September 2021, the under-vine soil of all plots was uniformly prepared using a disc plough, followed by hand hoeing and raking.

Immediately after soil preparation, cover crops were sown by hand at rates based on the supplier's recommendations, with an additional 20 %. Seeding rates were 48 kg ha$^{-1}$ for red fescue, 6 kg ha$^{-1}$ for wild thyme, 24 kg ha$^{-1}$ for black medic, and 12 kg ha$^{-1}$ for herb mixture. After sowing the cover crops and in the spontaneous vegetation treatment, no additional measures were taken in the under-vine zone during the experimental period. Mechanical tillage was carried out 4 to 5 times per year with a disc plough. In the first year of the study (2022), no herbicides were applied, so data collection for this treatment was limited to 2023 and 2024. In 2023, two applications were carried out: one with glyphosate (720 g ha$^{-1}$) and flazasulfuron (10 g ha$^{-1}$) and one with glyphosate only (720 g ha$^{-1}$). In 2024, two applications were again carried out with the same scheme. All herbicide applications were performed in the under-vine area (0.6 m width) with a water volume of 100 L ha$^{-1}$.

## 2. Site-specific weather conditions

The average temperature over the past five years was 12.2 °C, with an annual mean precipitation of 521 mm. During the vegetation period (May – September) in 2022–2024, mean temperature was 19.4 °C and total precipitation averaged 235 mm, with considerable differences between the three experimental years in terms of heat periods and rainfall distribution (Figure 1).

The average temperature over the three years was similar, ranging from 12.7 °C to 12.8 °C, with the highest values recorded between June and August. Total precipitation in 2022 was the lowest of the three years at 469 mm, with a particularly dry period in July and August (7 mm and 23 mm). In 2023, total precipitation was 517 mm. While June remained exceptionally dry (9 mm), a notable increase in precipitation occurred just before harvest in August. In 2024, precipitation was significantly higher at 667 mm, with wet conditions particularly in May (114 mm) and during harvest time in August and September (59 mm and 76 mm).

## 3. Vegetation coverage (VC)

To estimate the cover ratios, four measurement points (0.4 m wide and 1 m long) between two vines were used for each plot (each treatment and replicate). Using the Londo scale (Londo, 1976), the proportions of bare ground, dead plant material (litter), sown plant species (cover crops), and non-sown but spontaneously grown plant species (weeds) were classified into one of 13 rating classes (< 1 %, 1–3 %, 3–5 %, 5–15 %, 15–25 %, 25–35 %, 35–45 %, 45–55 %, 55–65 %, 65–75 %, 75–85 %, 85–95 %, 95–100 %). The mean values of the classes were used to calculate the vegetation coverage of cover crops and weeds (only living plants). Soil coverage was calculated as the sum of coverage of litter, cover crops and weeds. Vegetation cover (VC) was assessed in May, July, and September each year, approximately one to eleven weeks (no tillage close to September) after mechanical tillage and two to nine weeks after herbicide application. In 2024, the first VC assessment was conducted shortly before the spring herbicide treatment. The assessments corresponded roughly to key phenological stages: May, shortly before flowering, July at the pre-veraison stage, and September around harvest.

### 4. Soil moisture and temperature

Multi-sensor TOMST® TMS dataloggers (TOMST, Czech Republic) were installed vertically in the soil at 6 cm and 40 cm depth to record volumetric soil moisture ($cm^3/cm^3$) and soil temperature (°C). The selected depths were chosen to capture soil conditions in both the upper soil layer directly affected by under-vine management (6 cm) and a deeper layer within the grapevine rooting zone (40 cm). In each plot, one datalogger was placed centrally between two vines in the under-vine area to capture representative conditions. Data were logged at 15-minute intervals throughout the vegetation period from May to September in 2023 and 2024, capturing both short-term variations and long-term trends. With the time-domain transmission method, raw soil moisture values are recorded and converted to volumetric soil moisture using the calibration function in the supplied Lolly software. For statistical analysis, mean soil moisture and temperature per replicate and year were calculated as the average of all probe readings over the measurement period.

### 5. Grape quality and quantity

For the bending degree of rachis (°), an indirect estimation of cluster looseness, 100 bunches per plot were classified into five classes (90°, 45–90°, 10–45°, 0–10° and 0°; corresponding to very loose, loose, dense, compact and very compact clusters) according to Ipach *et al.* (2005).

The bunch rot incidence and severity of *Botrytis cinerea* infection on grapes were determined on 100 grapes (50 east- and 50 west-orientated) based on the EPPO guideline PP 1/17(3) "*Botrytis cinerea* on grapevine". Incidence was calculated as the proportion of infected clusters, and severity was estimated for each cluster using a seven-class scheme (0 %, 1–5 %, 6–10 %, 11–25 %, 26–50 %, 51–75 %, 76–100 %), describing the proportion of the cluster surface affected. A sample of 100 berries per plot was randomly collected from different parts of multiple grape clusters across the canopy to ensure a representative selection for berry weight determination and must analysis. Berries were homogenised (BagMixer® 400 CC, Interscience, Saint-Nom-la-Bretèche, France), pressed, and the must clarified by centrifugation (4500 $min^{-1}$, 5 min; Hettich Rotanta 460 R, Andreas Hettich GmbH & Co. KG, Tuttlingen, Germany). Clarified must was analysed by FTIR spectroscopy (WineScan™ FT120, FOSS Analytical A/S, Hillerød, Denmark) to determine must density (must sugar content, expressed as °Oechsle) and total acidity (g $L^{-1}$). To assess yield per vine, grapes from six vines per plot were harvested and weighed individually for each treatment replicate.

### 6. Statistical analysis

All statistical analyses were performed using R (version 4.x, R Core Team, 2024). One-way ANOVA was conducted for each month and year for vegetation cover (VC) and for each year for all other measured parameters, with treatment as a fixed effect and plot (replicate) as a random effect. As analyses were performed separately for each time point, observations were treated as independent, and a repeated-measures analysis was not applied. Post-hoc comparisons were performed using Tukey's HSD test (agricolae package) to assess pairwise differences between treatment means. The level of statistical significance was set at $\alpha = 0.05$. Normality was tested using the Shapiro-Wilk test (included by default in base R). For homogeneity of variances, Levene's test was applied using the car package. If either assumption was violated, appropriate data transformations (*e.g.*, logarithmic or square root transformations) were considered.

For multivariate analysis, principal component analysis (PCA) was performed using scaled numeric variables to explore overall treatment effects and to identify key variables contributing to variation. PCA loadings were plotted to illustrate the contribution of different parameters to the principal components. In addition, permutational multivariate analysis of variance (PERMANOVA) was performed using the vegan package with Euclidean distance metrics to statistically assess differences between treatments. Data visualisations were performed using ggplot2 and the associated R packages.

## RESULTS

### 1. Vegetation coverage (VC)

The average vegetation coverage (VC) of the weeds and cover crops varied considerably across treatments, months and years (Figure 2).

In 2022, weed coverage in the control was higher compared to mechanical tillage and all cover crops, except for wild thyme (no chemical treatment in 2022). Mechanical tillage reduced weed coverage not only in all months of 2022 but also in May 2023 and July 2024 compared to the control. The chemical treatment, introduced in 2023, consistently resulted in lower weed coverage than the control and, except for July in both 2023 and 2024, lower coverage than mechanical tillage. In July 2023, the chemical treatment showed higher weed coverage than all other treatments except for wild thyme. Compared to the control, the cover crops showed different weed suppression effects: red fescue and the herb mixture reduced weed coverage in all three years. Wild thyme first showed a reduction of weed coverage in May 2024, which continued in the following months. Black medic exclusively reduced weed coverage from May 2022 to May 2023.

Regarding the VC of cover crops, both red fescue and the herb mixture showed the highest values across all three years. However, red fescue maintained higher coverage at the beginning (May and July 2022) and at the end of the trial period (September 2024) compared to the herb mixture. Wild thyme grew more slowly and took 3 years to establish well (> 50 % coverage). Black medic showed rapid growth in the first 1.5 years, similar to red fescue, but was unable to establish for 2 years or more (< 9 % coverage). In 2024, 3 years after sowing, the VC of sown plants was 91.4 % for red fescue, 68.6 % for wild thyme, 0.3 % for black medic and 72.5 % for the herb mixture, indicating the strong capability of red fescue to suppress under-vine weeds.

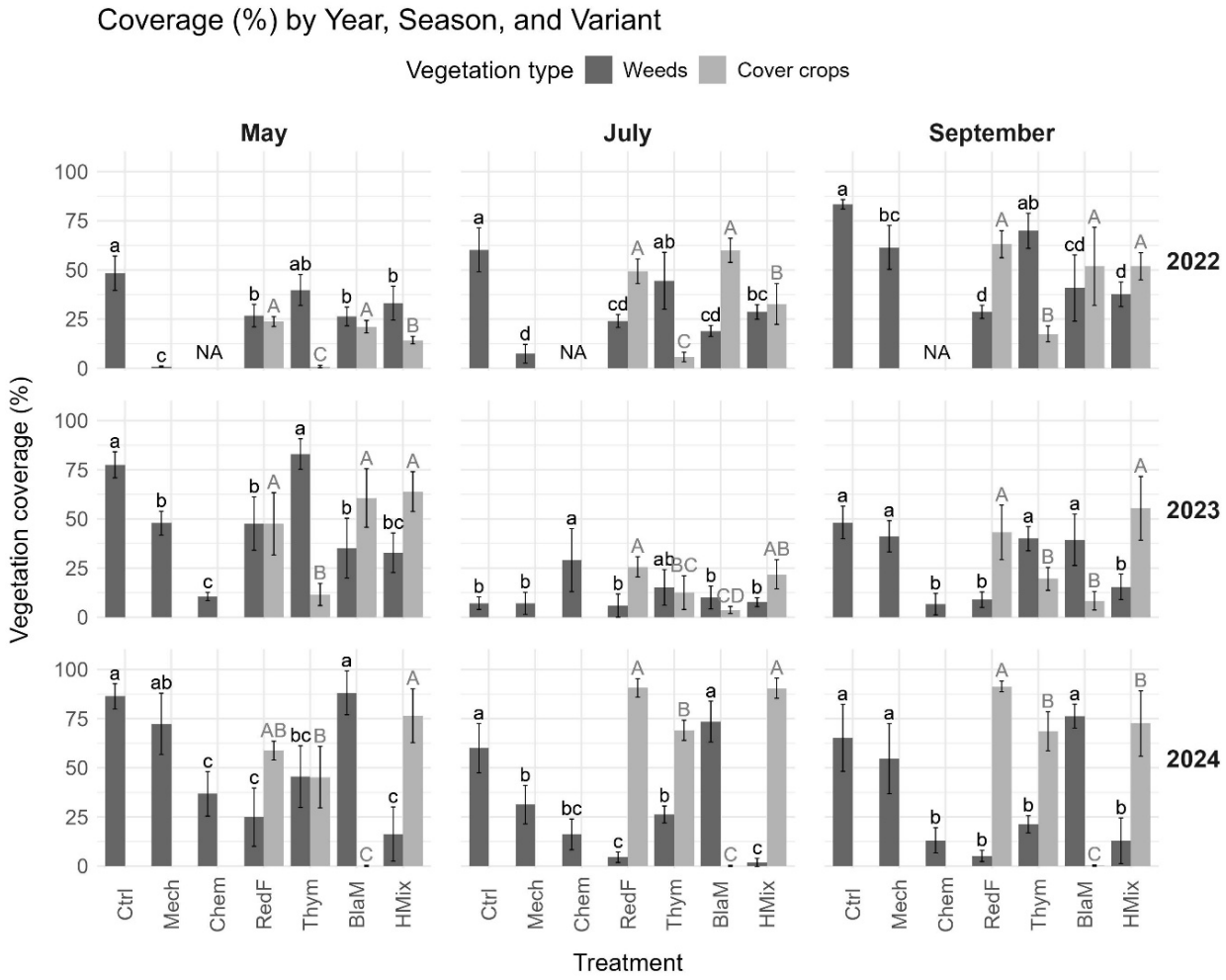



**FIGURE 2.** Average vegetation coverage (%) separated in weeds (dark grey bars) and cover crops (light grey bars) of different ground management treatments: control (Ctrl), mechanical tillage (Mech), chemical treatment (Chem), red fescue (RedF), wild thyme (Thym), black medic (BlaM), and herb mixture (HMix) across three years (2022–2024) and three months in the seasons (May, July (Jul), September (Sep)). Cover crops were sown in September 2021. Different letters above the bars indicate significant differences between treatments within each season and year, on Tukey's HSD test ($p < 0.05$, n = 4). Error bars indicate standard deviation (SD). No data was available for the chemical treatment in 2022.

## 2. Soil moisture and soil temperature

The following analysis focuses on red fescue as a representative under-vine cover crop, since it demonstrated the best cover crop establishment and persistence throughout the experimental period. The effects of ground management treatments on soil moisture at a depth of 6 cm are shown in Figure 3.

In 2023, the mechanical tillage had the lowest soil moisture content (0.17 $cm^3/cm^3$) of all treatments. The chemical treatment exhibited the highest soil moisture (0.36 $cm^3/cm^3$), while red fescue and control maintained intermediate moisture levels (0.29 $cm^3/cm^3$). In 2024, a general increase in soil moisture across treatments was observed compared to 2023. Mechanical tillage again had the lowest soil moisture (0.29 $cm^3/cm^3$) and remained significantly lower than chemical treatment, which retained the highest soil moisture (0.47 $cm^3/cm^3$), followed by red fescue (0.40 $cm^3/cm^3$) and control (0.39 $cm^3/cm^3$). Compared to soil moisture, the soil temperature at a depth of 6 cm (Figure 4) showed different effects of the treatments.

In 2023, the chemical treatment had a higher average soil temperature (20.9 °C) than red fescue (20.1 °C). In 2024, a general decrease in soil temperature across all treatments was observed compared to 2023. Chemical treatment (19.7 °C) remained the warmest treatment in 2024, with significant differences compared to the other tested treatments. The highest recorded soil temperature values (outliers above the upper whisker) were lowest in red fescue in both years, with maximum differences of approximately 5 °C compared to the chemical treatment in 2023 and 12 °C compared to mechanical tillage in 2024. These represent absolute temperature peaks recorded during the same measurement periods. The highest temperature peaks (upper whisker, including outliers) were lowest in red fescue in both years, with differences at 5 °C (compared to chemical treatment in 2023) and 12 °C (compared to mechanical tillage in 2024).

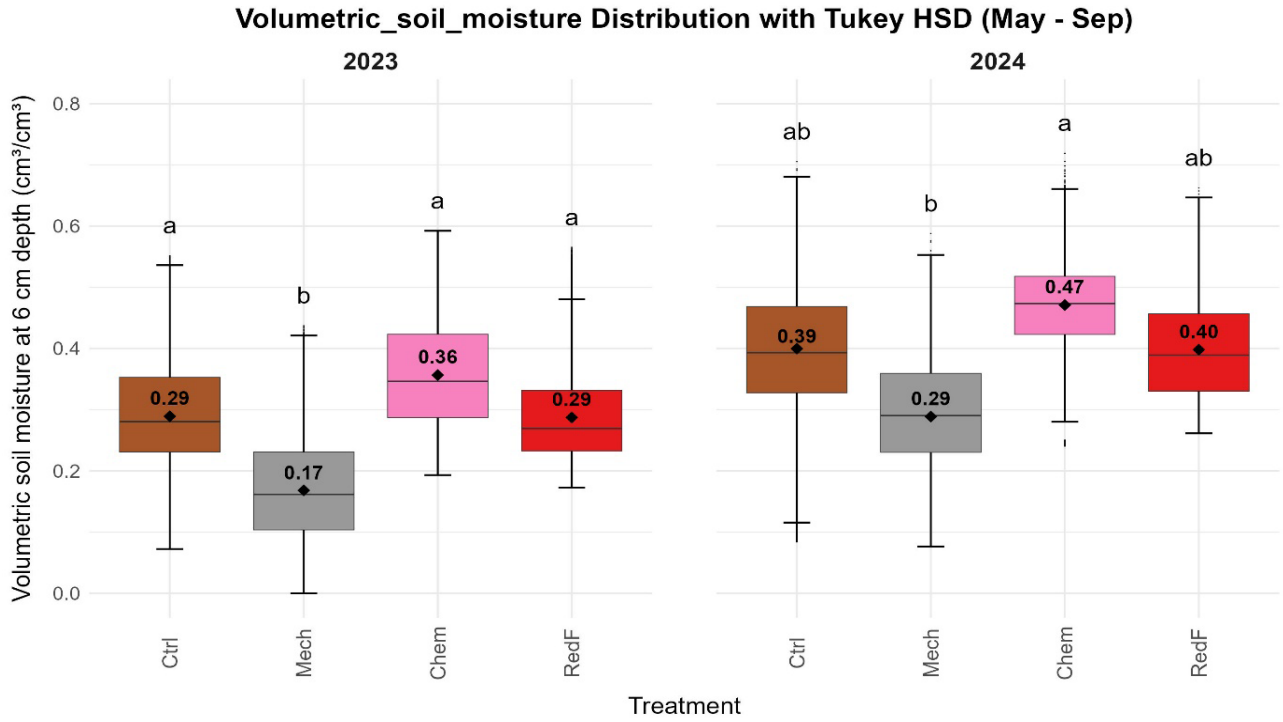



**FIGURE 3.** Average volumetric soil moisture ($cm^3/cm^3$) at a depth of 6 cm of different ground management treatments: control (Ctrl), mechanical tillage (Mech), chemical treatment (Chem), and red fescue (RedF) in the years 2023 and 2024 during the vegetation period (May till September). Different letters above the bars indicate significant differences between treatments within each year, based on Tukey's HSD test ($p < 0.05$, n = 4, approximately 58,800 observations per treatment and year). Error bars indicate standard deviation (SD). Mean values are displayed inside the boxes. Outliers are displayed as dots.

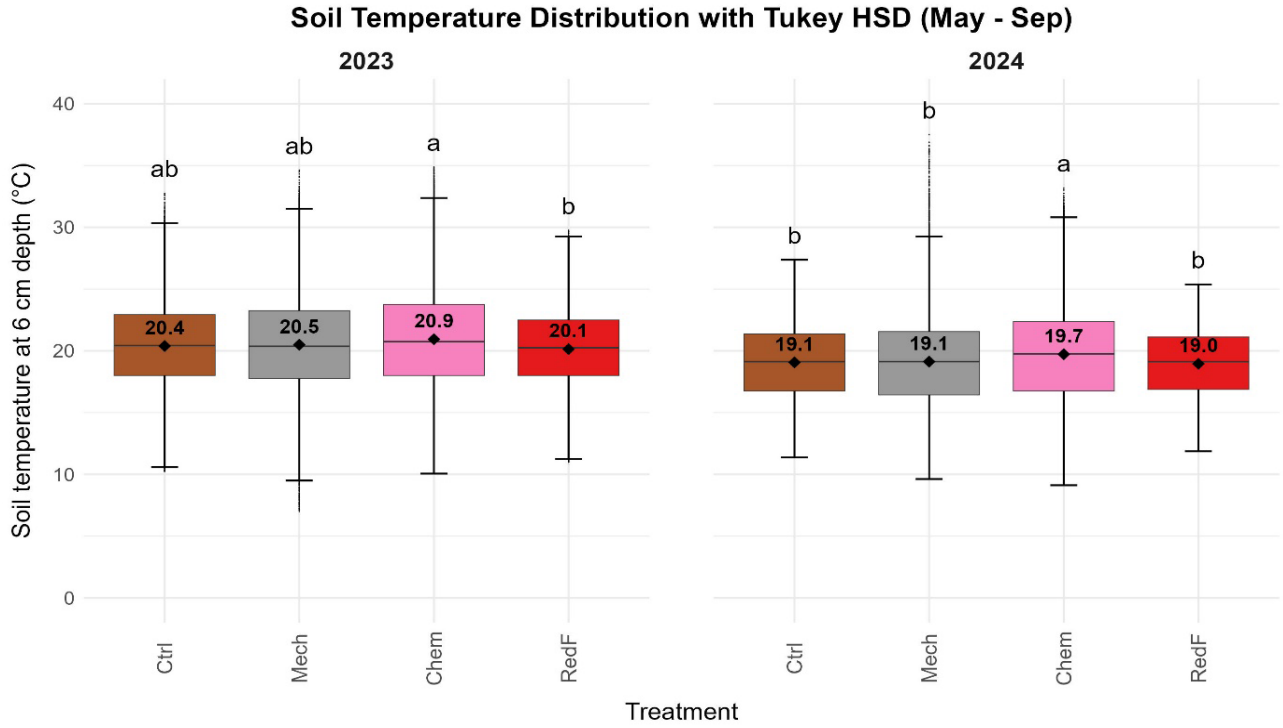



**FIGURE 4.** Average soil temperature (°C) at a depth of 6 cm of different ground management treatments: control (Ctrl), mechanical tillage (Mech), chemical treatment (Chem), and red fescue (RedF) in the years 2023 and 2024 during the vegetation period (May till September). Different letters above the bars indicate significant differences between treatments within each year, based on Tukey's HSD test ($p < 0.05$, n = 4, approximately 58,800 observations per treatment and year). Error bars indicate standard deviation (SD). Mean values are displayed inside the boxes. Outliers are displayed as dots.

While soil moisture and soil temperature were significantly influenced by treatments at a depth of 6 cm, measurements at 40 cm depth (Figure S1) followed similar trends but did not show statistically significant differences between treatments in both 2023 and 2024.

## 3. Grape quality and quantity

In terms of the incidence and severity of *Botrytis cinerea* bunch rot, no significant differences were found in 2023, but differences were observed in 2024 (Figure 5).

In 2023, bunch rot incidence ranged from 48.2 % (control) to 63.0 % (chemical treatment) and severity ranged from 2.0 % (red fescue) to 3.4 % (mechanical tillage). In 2024, chemical treatment had a higher bunch rot incidence (81.0 %) than all other treatments. The lowest values were detected in red fescue with 55.0 %. Regarding bunch rot severity, the chemical treatment showed the highest values (14.4 %), significantly higher than the control (6.1 %) and red fescue (7.6 %). All values recorded for the quality and quantity in all treatments of the grapes are shown in Table S2.

The principal component analysis (PCA) for 2023 and 2024 shows a clear differentiation between the ground management treatments (Figure 6).

In 2023, the first dimension (43.3 % variance explained) primarily separates treatments based on soil coverage, yield and must density, while the second dimension (18.0 % variance explained) accounts for *Botrytis* severity, berry weight, and cluster looseness. Red fescue is strongly associated with higher soil coverage and increased cluster looseness. Chemical treatment correlates with higher berry weight but also increased *Botrytis* severity and frequency. Control plots are positioned closely to must density and soil coverage, indicating a moderate effect. Mechanical tillage forms a separate cluster but does not strongly correlate with any specific trait.

The PERMANOVA result ($F = 21.18$, $p = 0.001$) confirms significant differences among treatments, indicating that ground management practices strongly influence grapevine performance and fruit characteristics. In 2023, significant differences among treatments were observed in soil coverage

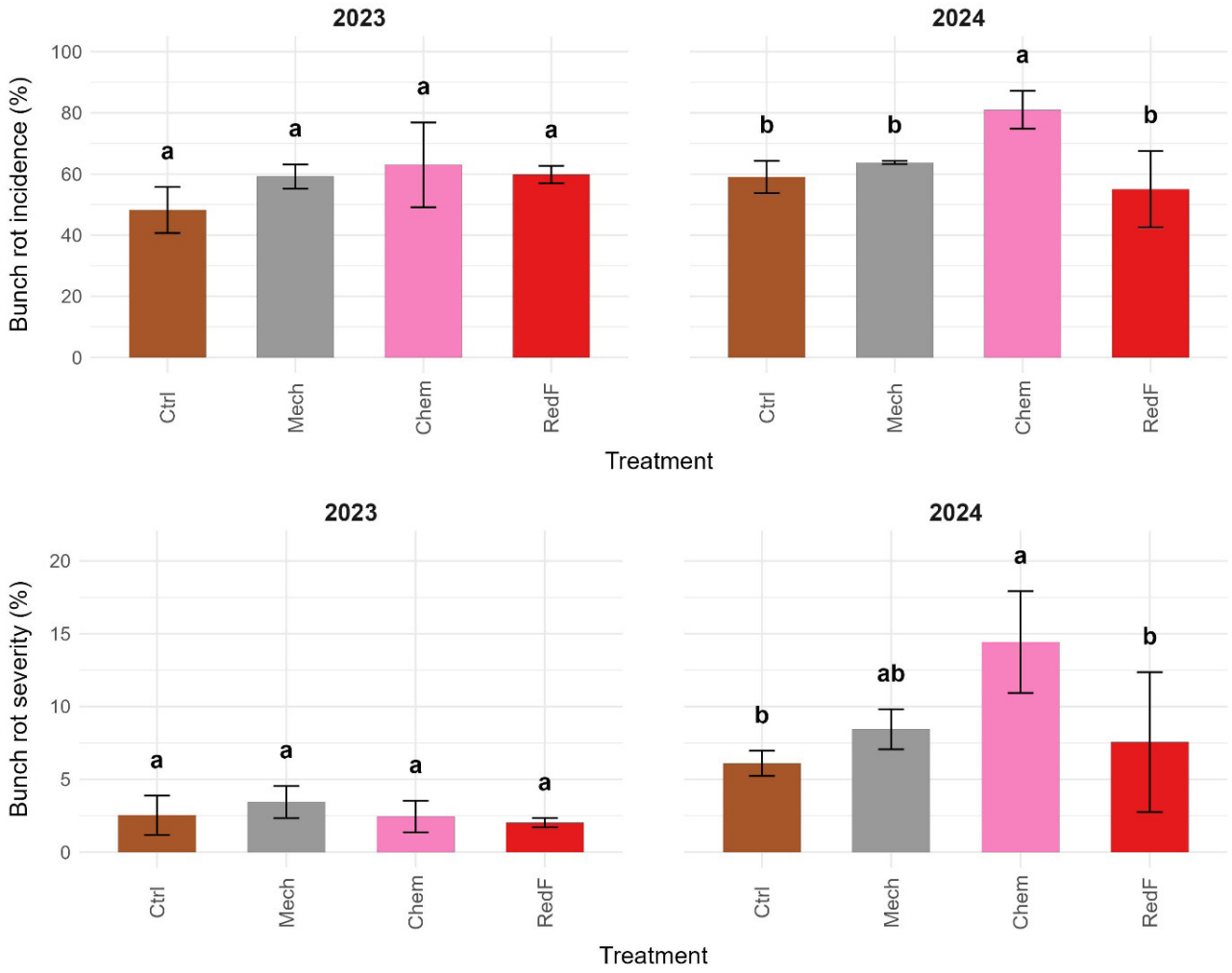



**FIGURE 5.** Average *Botrytis cinerea* bunch rot incidence (top) and severity (bottom) of different ground management treatments: control (Ctrl), mechanical tillage (Mech), chemical treatment (Chem), and red fescue (RedF) in the years 2023 and 2024. Different letters above the bars indicate significant differences between treatments within each year, based on Tukey's HSD test ($p < 0.05$, n = 4). Error bars indicate standard deviation (SD).

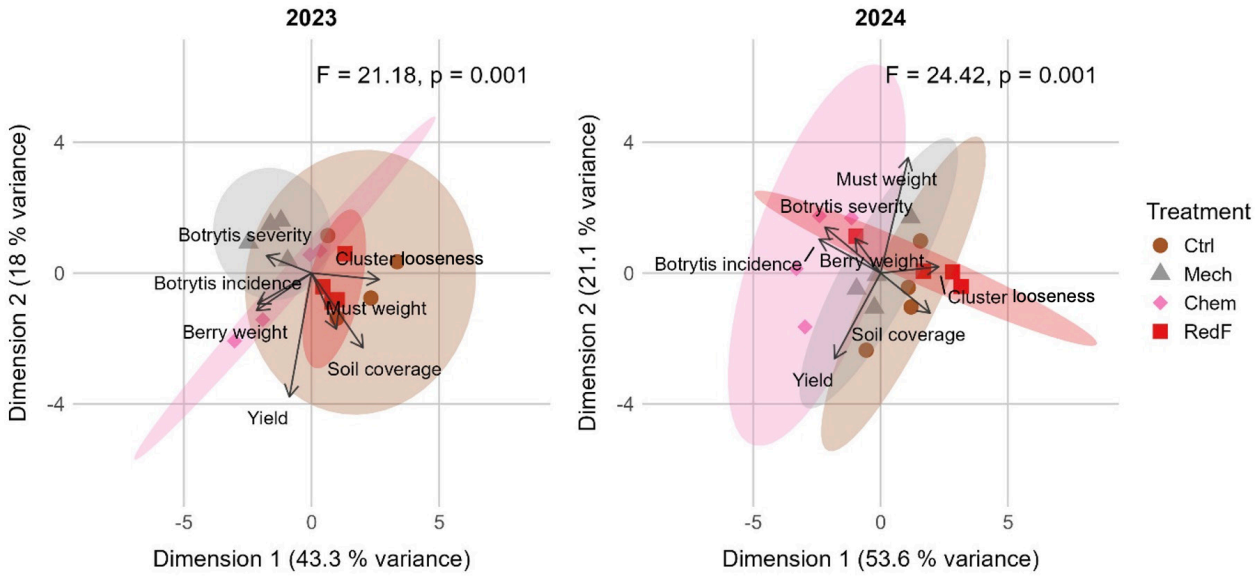



**FIGURE 6.** Principal component analysis (PCA) biplots with PERMANOVA results for the years 2023 (left) and 2024 (right), showing the effects of different ground management treatments (control (Ctrl), mechanical (Mech), chemical (Chem), and red fescue (RedF)) on various grapevine parameters. The ellipses represent the 95 % confidence intervals for the different treatments with n = 4. The arrows indicate the variables contributing to the separation among treatments, including yield, must density, cluster looseness, berry weight, *Botrytis* incidence, *Botrytis* severity and soil coverage (including coverage of weeds, cover crops and dead plants). The percentage values on the axes represent the explained variance for each principal component. The PERMANOVA test results (F and *p*-values) indicate significant differences among the ground management treatments in each year.

and cluster looseness (bending degree of rachis), according to pairwise comparisons in Table S2. The soil coverage was highest with red fescue and the control compared to the chemical treatment, which in turn was higher than the mechanical treatment. The loosest clusters were found in the control and red fescue, which differed from the mechanical and chemical treatments.

The PCA biplot for 2024 highlights differences between ground management treatments, with the first dimension (53.6 % variance explained) primarily differentiating treatments by soil coverage, yield and must density, while the second dimension (21.1 % variance explained) reflects *Botrytis* severity, berry weight, and cluster looseness. Red fescue is associated with higher cluster looseness. Chemical treatment is closely related to higher berry weight and increased *Botrytis* incidence and severity. Control plots are linked to moderate soil coverage and must density. Mechanical tillage shows no strong association with any particular trait but remains closer to yield.

The PERMANOVA result (F = 24.42, $p$ = 0.001) confirms that ground management treatments significantly influence grapevine performance, with clear separation between treatments. Compared to 2023, the variance explained by the first dimension increased, indicating a stronger differentiation in 2024. In 2024, treatments differed significantly in soil coverage, cluster looseness and *Botrytis* incidence and severity (Table S2). Red fescue and the control showed a higher soil coverage than the mechanical treatment, which in turn was higher than the chemical treatment. The loosest clusters were found in red fescue, which differed from the chemical treatment, and the chemical treatment showed higher *Botrytis* incidence and severity than the control and red fescue.

## DISCUSSION

### 1. Effectiveness of different weed management strategies on weed suppression

The findings of this study indicate that some cover crops can provide effective weed suppression, approaching the effectiveness of mechanical and chemical treatments over time. However, this effect was strongly species dependent. Weed suppression was closely related to the level of soil cover achieved, highlighting the importance of rapid canopy development and sustained shading as key mechanisms (Brust *et al.*, 2014). Red fescue and the herb mixture developed dense and persistent canopies over time, resulting in the most consistent weed suppression. In contrast, wild thyme demonstrated slower establishment, which likely reduced its early competitive effect, although its performance improved as plant cover increased over time. These observations are consistent with mechanisms described by Nosratti *et al.* (2023), emphasising that effective weed suppression depends on rapid establishment and the ability to outcompete weeds for light and resources, as well as the formation of a physical barrier. Establishment of red fescue and the herb mixture continued after periods of frost and drought, indicating a high tolerance to environmental stress, which likely contributed to their persistence and long-term weed suppression. In contrast,

black medic showed only short-term effects due to its short-lived biennial life cycle, limiting its persistence. Although weed suppression in cover crop treatments was initially lower than under mechanical tillage, comparable levels were achieved after the establishment phase, and by the final year, effectiveness approached that of chemical control.

The effect of mechanical tillage on weed suppression varied considerably between months and years, as it was strongly influenced by the timing of tillage. Weed regrowth was particularly pronounced in autumn when tillage was stopped early to avoid negative effects on grape health. It is important to note that tillage brings new weed seeds to the surface and enhances soil nitrogen mineralisation, both of which promote weed emergence flushes (Guerra & Steenwerth, 2011), but also provide nitrogen to the grapevine (Ferreira *et al.*, 2020), potentially influencing vegetative growth, grape yield and quality. The chemical treatment provided consistent weed suppression, except in July 2023, when most plants wilted due to drought, while glyphosate-resistant bindweed (*Convolvulus arvensis*) continued to grow. In general, individual plant species favoured by mechanical or chemical treatments may pose a risk due to increased water use or potential pathogen transmission (Monteiro *et al.*, 2012; Schweigkofler *et al.*, 2018).

The spontaneous vegetation in the control treatment showed reduced growth over time after a strong occurrence in the first year, consistent with the findings of Kesser *et al.* (2023). Due to the relatively low rainfall during the vegetation periods of 2022 and 2023 (Figure 1), overall vegetation growth, including weed development in the control treatment, was limited (Figure 2). High water availability and optimal conditions for spontaneous vegetation of the control could strongly increase its growth, requiring additional interventions such as mowing or hand-weeding to prevent excessive weed growth (Vukicevich *et al.*, 2019). The first year is particularly critical, as cover crops still need time to establish sufficient vegetation coverage.

Like previous research (Abad *et al.*, 2020; Torun, 2024), this study confirms that cover crops can be an effective strategy for weed management and can serve as a viable alternative to chemical weed control. The effectiveness of cover crops depends on species-specific traits, with perennial species providing longer-term suppression, whereas annual or short-lived species may require reseeding.

## 2. Impact on vineyard soil parameters

In this study, soil moisture and temperature were measured at a depth of 6 cm, representing the upper soil layer rather than the main grapevine rooting zone, which is typically located below 20 to 30 cm (Celette *et al.*, 2008; Celette & Gary, 2013). At the 6 cm depth, red fescue maintained higher soil moisture than mechanical tillage, yet the expected evaporation-reducing effect of soil shading was not evident, as the chemical treatment, with minimal vegetation cover, showed similar moisture levels to the cover crop. This outcome aligns with previous work indicating that cover crops can influence soil water in contrasting ways depending on species traits and seasonal water demand (Monteiro *et al.*, 2012; Abad *et al.*, 2023; Fleishman *et al.*, 2023). Although vegetation type did not differ statistically between the control (spontaneous vegetation) and red fescue, species-specific evapotranspiration rates may still influence surface soil moisture (Bavougian & Read, 2018).

The presence of cover crops contributed to reduced soil temperatures, aligning with findings from Abad *et al.* (2023). Red fescue exhibited lower average soil temperatures as well as lower maximum temperatures compared to the chemical treatment, highlighting the shading effect of the ground cover. This demonstrates how vegetation cover provides protection from solar radiation, helping to prevent excessive soil heating (Bavougian & Read, 2018). Soil microbial activity is highly temperature-dependent, and fungal and bacterial growth rates have been reported to reach their optimum between 25 and 30 °C. At higher temperatures, microbial activity declines, particularly for fungi, resulting in a shift toward a higher bacterial-to-fungal ratio under warmer conditions (Pietikäinen *et al.*, 2005). Regarding our results, both the control (spontaneous vegetation) and cover crops such as red fescue and the herb mixture showed higher and more stable soil coverage than the mechanical and chemical treatments. This stability is particularly beneficial as vegetation cover not only helps to mitigate extreme soil temperatures, but also reduces soil erosion and enhances water infiltration (Abad *et al.*, 2023).

Beyond these short-term effects, the interaction between cover crops and vines extends belowground through root competition and distribution. While we did not measure vine root depth in this study, the literature suggests that competition for water and nutrients largely depends on the spatial overlap and depth of root systems, generally inducing vine roots to penetrate deeper soil layers (Celette *et al.*, 2008). This effect is particularly evident in the inter-row areas, where both vine and cover crop roots coexist, whereas in the under-row and deeper horizons, vine roots typically dominate, exploiting distinct pedological zones (Abad *et al.*, 2023; Celette *et al.*, 2008). Different soil management strategies influence this dynamic by modifying the availability of water and nutrients and the physical structure of the soil. Studies have shown that permanent cover crops can stimulate deeper vine rooting and reduce root density in the upper soil layers (Bavougian & Read, 2018; Vanden Heuvel & Centinari, 2021), suggesting an adaptive response that may improve drought resilience over time. In our study, changes in soil moisture were only observed in the upper soil layer, while no differences were detected at 40 cm depth (Figure S1), which corresponds to the main root zone of the vines. This indicates that under-vine vegetation primarily affected the surface soil without substantially influencing water availability in deeper layers.

Nevertheless, this belowground competition can limit vine access to water and nutrients in dry years, potentially affecting vine vigour and yield, particularly in shallow soils or regions with low rainfall (Abad *et al.*, 2023). Thus, the balance between soil protection, water conservation, and competitive interactions needs to be carefully managed through species selection and spatial design of the under-vine vegetation.

## 3. Impact on grapevine yield and quality

Cover crops, such as red fescue, had positive effects on grape bunch structure and health, particularly by reducing the incidence and severity of *Botrytis cinerea* bunch rot. Cover crops contribute to reduced vegetative growth, more aerated canopies and less compacted bunches, all of which are associated with lower fungal disease pressure (Göblyös *et al.*, 2011). Previous research has also shown that permanent under-vine cover crops can reduce disease incidence compared to herbicide weeding, even when other grapevine growth parameters remain similar (Coniberti *et al.*, 2018a). Other studies, such as Valdés-Gómez *et al.* (2011), demonstrated that under-vine cover cropping can reduce vine vigour and thereby decrease disease pressure.

In the PCA of 2023 and 2024, the incidence of bunch rot was negatively correlated with cluster looseness (positively correlated with cluster compactness), suggesting that under-vine vegetation leads to reduced nutrient and water supply to grapes compared to bare soil, thereby decreasing the potential for *Botrytis cinerea* development (Mundy *et al.*, 2022; Tello & Ibáñez, 2018). Although no significant differences in berry weight or yield were observed between treatments (except for wild thyme in 2024), variations in bunch rot incidence and cluster morphology indicate that under-vine vegetation may have influenced vine growth or microclimatic conditions to a limited extent. These effects appear to have occurred independently of overall yield parameters. It should be noted that yield was determined without performing a pre-harvest sorting of infected bunches, which may have slightly increased the apparent impact of *Botrytis* infection on total yield. As Tello and Ibáñez (2018) showed, compact grape bunches are associated with high nitrogen and water availability and are more susceptible to various diseases such as *Botrytis* bunch rot, causing significant economic losses in viticulture through reduced yield and grape quality. Since not only red fescue, but also mechanical tillage and the control showed higher vegetation coverage and lower *Botrytis cinerea* levels in September 2024 compared to the chemical treatment, it is possible that the specific plant species is not decisive. Instead, a reduction in vine vigour, potentially influenced by the vegetation and associated resource demand, may contribute to lower cluster compactness and reduced bunch rot, as suggested by Vanden Heuvel and Centinari (2021).

However, in 2022, the control showed a significantly higher incidence of grape bunch rot than the red fescue treatment (Table S2). A possible explanation might be unfavourable microclimatic conditions in the grapevine zone resulting from excessive weed growth, as reflected by the high weed cover in the control treatment. Although this effect was not directly investigated in our study, if under-vine vegetation reaches the fruiting zone and becomes too dense, it can have a negative impact on disease management and fruit exposure (Fleishman *et al.*, 2023; Jordan *et al.*, 2016; Vanden Heuvel & Centinari, 2021).

Moreover, reduced vine vigour has been associated with lower susceptibility to fungal diseases (Silvestroni *et al.*, 2024). While vine vigour parameters were not assessed in this study, Coniberti *et al.* (2018b) demonstrated that red fescue, compared to herbicide treatment, resulted in significantly lower values for pruning weight, cane weight and shaded area. Similar results were shown by Fleishman *et al.* (2023): compared to herbicide treatment, cover crop with red fescue reduced grapevine vegetative growth (pruning weight) significantly across all years by 22 %. Interestingly, the cover crop impacted yield less consistently than vegetative growth (Fleishman *et al.*, 2023).

In our study, yield and berry weight were not affected by the ground management treatments, with one exception: wild thyme showed significantly lower yield compared to the herbicide treatment in 2024. A similar trend was reported by Dittrich *et al.* (2021), who observed reduced grapevine yields when intercropped with *Thymus vulgaris* in a steep-slope vineyard. The authors attributed this to temporary water stress and competition for soil resources during critical growth stages, particularly under dry conditions. In general, under-vine cover crops could decrease berry size and lower the yield due to competition for water and nutrients (Fleishman *et al.*, 2023; Vanden Heuvel & Centinari, 2021). However, several studies have shown that such effects on grapevine growth and yield are little or do not always occur and depend strongly on species selection (Chou & Vanden Heuvel, 2019; Jordan *et al.*, 2016). Must composition (must sugar content and total acidity) did not show any differences among the treatments. In previous studies on under-vine cover crops, no or only minor effects on fruit composition were observed (Giese *et al.*, 2015; Hickey *et al.*, 2016; Karl *et al.*, 2016).

## 4. Challenges and future perspectives

Red fescue was found to be a cover crop that effectively suppressed weeds, had a positive effect on soil moisture and temperature, and had no negative effect on vine performance. However, its establishment can be slow or even fail initially, allowing weeds to dominate, although it may still outcompete them over time. In fact, it reduced the incidence of *Botrytis cinerea*. The study was conducted in a sandy loam vineyard under cool to moderate climatic conditions. Weather conditions (Figure 1) were very variable over the three years of the trial, especially in terms of rainfall events, which led to variations in weed growth, both in terms of species composition and coverage. The results suggest that, depending on the species chosen, under-vine cover crops can help to balance the ecosystem in the vineyard and provide long-term benefits. But their long-term viability depends on site-specific conditions, including soil type, climate, and grapevine water demand.

The control with spontaneous vegetation showed similarly good results regarding grape health and soil microclimate compared to red fescue, except for a higher *Botrytis* incidence in 2022 (Table S2). This suggests that while spontaneous vegetation may provide certain ecological

benefits (Kesser *et al.*, 2023), its species composition and functional effects can vary depending on site conditions and (previous) management. Such variability may influence competition dynamics. As the influence of individual weed species was not investigated, further research is needed to determine whether spontaneous vegetation can achieve similarly positive effects as sown cover crops.

One of the most critical uncertainties is whether cover crops can be established successfully and which effect on water demand predominates: whether excessive water competition occurs or soil water regulation benefits grapevine performance. In humid climates, they may reduce excessive vegetative growth without causing stress, whereas in semi-arid regions, they could intensify drought stress, leading to lower yields (Fleishman *et al.*, 2023). The threshold between beneficial and harmful competition remains unclear and requires further investigation (Vanden Heuvel & Centinari, 2021). Successful establishment can be enhanced through strategies such as selecting fast-germinating or cover-crop mixtures, optimising seeding rates, adjusting sowing timing to local climate, and implementing early-season management like mowing or light irrigation (Sharifi & Zolfaghari, 2025). Nevertheless, practical implementation can be challenging, especially under-vine, where narrow spacing and mechanisation constraints limit sowing and mowing.

Sustainable weed management strategies must be both ecologically and economically viable. Perennial cover crops offer potential cost savings by reducing the need for multiple herbicide applications or repeated tillage operations throughout the growing season, while potentially posing a greater risk of competition with grapevines for water and nutrients. Herbicide and mechanical interventions are typically required several times per year to suppress weed regrowth, increasing labour and fuel costs. In contrast, once well established, perennial cover crops can provide long-term weed suppression with minimal additional input (Steinkellner, 2019). However, the economic feasibility of under-vine cover crops depends on species selection, establishment success and vineyard-specific conditions.

## CONCLUSION

By evaluating the effects of under-vine cover crops compared with spontaneous vegetation, mechanical tillage, and herbicide treatment, this research provides valuable insights into the agronomic benefits and limitations of different under-vine management strategies. In this context, weeds are defined as non-sown plant species that may compete with grapevines or cover crops for light, water, and nutrients in the under-vine zone. While spontaneous vegetation may provide certain ecological benefits, it can also create less predictable conditions for disease management and competition dynamics, highlighting the importance of species selection and weed control intensity in sustainable under-vine management. Nevertheless, spontaneous vegetation represents a practical and low-input option. However, in years with vigorous growth, mechanical mowing may be required to prevent excessive growth, which can increase labour and management effort. Key findings demonstrate that under-vine cover crops, such as red fescue, wild thyme, black medic, and herb mixtures, effectively suppressed weeds, achieving results comparable to mechanical tillage and herbicide applications. However, successful weed control requires adequate soil cover of cover crops. Species differed significantly in establishment and long-term persistence, with red fescue showing the highest persistence over three years. Under-vine vegetation, whether cover crops or spontaneous vegetation, contributed to improved soil moisture retention compared to mechanical tillage and helped reduce soil temperatures relative to herbicide treatment. With the challenges of climate change, such as more frequent droughts and increasing temperature extremes, under-vine cover crops play an important role in buffering climate extremes through their permanent soil cover. In addition, a significant reduction in *Botrytis cinerea* incidence was observed in the cover crop treatments, likely due to improved cluster looseness, highlighting an important disease management benefit. Yield parameters were largely unaffected by under-vine cover crops, with no significant differences in must composition or berry weight between treatments. However, wild thyme resulted in a reduction in yield, highlighting the importance of balancing weed suppression with grapevine performance. Selecting the right species is essential to maximise their agronomic benefits, including improved moisture retention, temperature regulation, and reduced disease pressure, as well as minimising potential trade-offs such as yield reduction.

While this study highlights the potential of under-vine cover crops for sustainable vineyard management, further research is needed to optimise their practical implementation. Future research should focus on understanding species-specific interactions with soil moisture, nutrient availability, and vine growth to optimise their integration into vineyard management. It would also be valuable to evaluate a broader range of species for under-vine cover cropping and to define clear selection criteria, including biomass production, ground coverage, interference with the grape fruiting zone, invasiveness risk, pest sensitivity, drought tolerance and winter hardiness, as suggested by Sharifi *et al.* (2026). Long-term studies are also needed to assess their cumulative effects on soil health, biodiversity and grape productivity.

Overall, the results suggest that under-vine cover crops can be a viable alternative to mechanical tillage and herbicide application in sustainable vineyard management.

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