Agronomy for Sustainable Development (2025) 45:46
https://doi.org/10.1007/s13593-025-01046-x

RESEARCH ARTICLE

Soil management shapes the functional diversity of the inter-row vegetation in Mediterranean vineyards

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Accepted: 25 July 2025 / Published online: 13 August 2025
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Abstract

Weed control in vineyards often relies on intensive tillage, which can negatively affect soil health. While cover crops offer potential benefits (such as weed suppression and soil improvement), they may also compete with grapevines. Few studies have examined inter-row management from a functional perspective. Understanding how soil management shapes inter-row plant communities is essential to support beneficial groundcover–vine interactions and foster plant assemblages that deliver multiple ecosystem services. To fill this gap, we assessed how different inter-row soil management strategies influence plant biomass, diversity, and functional traits (specific leaf area, height, and Grime strategies) in two farms in Chianti Classico (Italy). Treatments included tillage, mulched spontaneous vegetation, green-manured pigeon bean (*Vicia faba* var. minor), and a barley–clover (*Hordeum vulgare–Trifolium squarrosum*) mixture, either mulched or green-manured. This is the first research on the topic based on data of biomass by species. Soil management significantly influenced inter-row biomass, species diversity, and plant traits. Tillage reduced biomass and selected homogenous, high-specific leaf area communities. In spring, cover crops yielded more biomass than tillage; pigeon bean was most productive and led to less diverse plant communities. Mulched cover crops supported less competitive assemblages in autumn, though autumn sowing may increase erosion risks. Mulched spontaneous vegetation maintained permanent soil cover but selected stable, competitive plant assemblages. Overall, mulched groundcovers can enhance biodiversity without compromising grapevine yield. Alternating sown and spontaneous mulched vegetation presents a promising, sustainable alternative to tillage, promoting soil conservation and supporting functionally diverse plant communities in vineyard inter-rows.

Keywords Barley · Clover · Pigeon bean · Cover crop mixture · Functional traits · Tillage

1 Introduction

Weeds are among the highest concerns for grape producers, and extensive efforts are invested in their control. Weeds can strongly compete with vines mainly through the uptake of nutrients and water, thereby potentially causing detrimental effects on grape yield and quality (Barranco-Elena et al. 2024; Gagliardi et al. 2024). This is particularly relevant in Mediterranean vineyards, where water scarcity and summer drought can be severe and may substantially limit grape production (Romero et al. 2022). Furthermore, climate change is expected to cause more erratic and scarce rainfall, which poses an additional threat to water availability (Ramos 2017; Sodini et al. 2023). On the other hand, climate change is also causing more intense precipitation (IPCC 2023), which may trigger severe soil erosion problems (Straffelini et al. 2022).

Modern weed control in vineyards is usually based on herbicide application and intensive tillage practices. These

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practices are often associated with negative environmental effects, mainly related to soil degradation (Rodrigo-Comino et al. 2018; Gristina et al. 2022). Intensive tillage management has been often indicated among the main culprits for the high soil erosion rates that characterize Mediterranean vineyards (e.g., Biddoccu et al. 2020). In this context, soil groundcovers, either sown or spontaneous, can play a role in mitigating the environmental impact of weed management and soil tillage practices (Barranco-Elena et al. 2024; Ramírez-Pérez et al. 2024) (Fig. 1). Cover crops (CC) and spontaneous natural vegetation cover are agro-ecological practices that can substantially reduce soil erosion, one of the most severe threats to the sustainability of Mediterranean viticulture (Marques et al. 2010; Fernando et al. 2024). The combined effect of reduced soil erosion and organic matter input provided by groundcovers has been shown to be instrumental in improving soil organic matter (SOM) as compared to tillage (López-Piñeiro et al. 2013; Liebhard et al. 2024). The roots of inter-row vegetation also improve soil aggregation through rhizodeposition and belowground residues (Belmonte et al. 2016). Likewise, groundcovers can improve habitats and provide substrate and resources to sustain soil life (Hendgen et al. 2018; O'Farrell et al. 2023). Groundcovers also hold potential to provide other non-soil-related ecosystem services (ES), such as pest control, pollination, and plant biodiversity (Winter et al. 2018).

Despite the numerous ES potentially provided by groundcovers, vine growers are generally reluctant to apply agro-ecological inter-row management practices because they are concerned by the potential competition between groundcovers and vines. Several studies have explored the effects of groundcovers on grape quality and vine stress in comparison to tillage (e.g., Guerra et al. 2022; Griesser et al. 2022; Horel and Zsigmond 2023), but yield losses are seldom reported (e.g., Warren Raffa et al. 2022). It is therefore critical to address the trade-off between grape production and environmental benefits to discuss more sustainable management practices with farmers and foster the provision of ES in vineyards (Hall et al. 2020). Win-win strategies may include the selection of low competitive groundcovers able to minimize inter-row vegetation management interventions and at the same time provide several environmental benefits (e.g., support of beneficial microorganisms and arthropods, regulation of surface runoff and erosion) (MacLaren et al. 2019). In this respect, the study of the vineyard plant community response following soil/weed management practices is of paramount importance (Kazakou et al. 2016).



Fig. 1 Barley and squarrose clover cover crop mixture sown in a Chianti Classico vineyard (Tuscany, IT) (Photocredit: Dylan Warren Raffa).

Taxonomic studies and the use of vegetation diversity indexes, although common, do not provide information on the degree of weed competitiveness and hence on their potential negative effects on the crop (Bàrberi et al. 2018). Conversely, the "response-and-effect" functional trait approach offers a suitable perspective to characterize the response of groundcover communities to environmental filters and provides information on the effect that inter-row plant assemblages can potentially have on the main crop (Garnier and Navas 2012). The traits of the most abundant species determine the functional structure of a community and thus its effect on ecosystem functions/services, which is described by a set of community weighted means (CWM) (i.e., the weighted average of the trait values based on the relative biomass of each species) (Garnier et al. 2004).

Overall, agricultural management practices such as tillage represent strong drivers of weed community changes (Armengot et al. 2016; Steenwerth et al. 2016; Guerra et al. 2021). Frequent tillage operations in vineyards have been reported to reduce weed diversity compared to mowing (Gago et al. 2007), which resulted in plant assemblages with high biodiversity values (Guerra et al. 2022). Tillage also affects the functionality of the plant communities, particularly selecting for assemblages that maximize resource exploitation, growth, and reproduction in the short term (i.e., ruderal species) (Grime 1988; Zirbel et al. 2017). Moreover, inter-row tillage and herbicide use in vineyards have been shown to select for homogenous plant communities with low trait variability (trait convergence), while groundcovers stimulate trait divergence, i.e., high species diversity and high trait variability (Kazakou et al. 2016). One of the few studies on functional weed traits in vineyards concluded that soil disturbance plays a key role in structuring weed communities according to Grime's strategy. Specifically, tillage favors nutrient-demanding species with a ruderal strategy, while mowing supports hemicryptophytes with a competitive strategy (Fried et al. 2022). These studies clearly indicate the relevance of investigating the effects of soil management practices on inter-row plant communities. Consequently, this approach allows to identify strategies that promote high value biodiversity assemblages able to strike a

balance between productive and environmental objectives. Although the response-and-effect trait framework has been widely adopted in arable crops, its use on perennial crops and vineyards has been limited. Furthermore, the performance of agro-ecological management practices proposed in the literature can be affected by different pedo-climatic conditions (Warren Raffa et al. 2021; Brooker et al. 2024). In this paper, we studied five soil management practices in two organic farms in Chianti Classico (Tuscany, Italy), which represent the most common soil management schemes in the area. The goal of this research was to assess how local soil management practices affected the competitive potential of plant communities and their biodiversity value in a typical Mediterranean climate. We aim to test the following hypotheses:

– Tillage promotes plant assemblages with lower diversity indexes compared to soil conservation practices, such as mowing.
– Tillage selects for weed assemblages with higher ruderality traits, such as higher specific leaf area (SLA), and a larger abundance of ruderal species (*sensu* Grime), while introducing cover crops promotes assemblages with more competitive traits, such as height.

2 Materials and methods

2.1 Sites and experimental design

The experiment was conducted from 2017 to 2020 in two organic farms in the Chianti Classico wine district (Tuscany, Italy):

- San Giusto a Rentennano (SG) (43°22′14.1″N 11°25′19.4″E): situated in Gaiole in Chianti (Siena province) at an elevation of 233 m above sea level. The area experiences an average annual rainfall of 801 mm and an average temperature of 14.4 °C. The soils are loamy with moderate gravel content (5–15%), developed from marine sands and Pliocene conglomerates;
- Montevertine (MT) (43°30′06.2″N 11°23′29.0″E): situated in Radda in Chianti (Siena province) at 425 m above sea level. Here, the average annual rainfall is 824 mm, and the temperature averages 12.6 °C. The soils are stony, ranging from silty clay loam to clay loam, and are derived from marls and limestone of the Sillano formation.

Both experimental vineyards have an average slope of about 10%. The vines (*Vitis vinifera*, L. cv. Sangiovese R10, rootstock 420 A) were planted in rows (2.50 × 0.8 m, equivalent to 5000 plants ha^{-1}) with a southwest orientation at SG and a southeast orientation at MT. The vineyards were established around the same time (1995 at SG and 1991 at MT). The training system used is Guyot at SG and spurred cordon at MT.

Five inter-row soil management practices were studied:

- Tillage, performed three times per year, in autumn, spring, and summer (CT);
- Cover crop (CC) of pigeon bean (*Vicia faba* L. var. *minor* (Peterm.em. Harz) Beck.), sown in autumn and incorporated as green manure in late spring (PBI);
- CC mixture of barley (*Hordeum vulgare* L.) and squarrosum clover (*Trifolium squarrosum* L.), sown in autumn and mown in late spring and left on soil surface as dead mulch (BCM);
- CC of barley and squarrosum clover, sown in autumn and incorporated as green manure in late spring (BCI);
- Spontaneous vegetation, mown in late spring and left on soil surface as dead mulch (S).

In all the treatments, the under-row space was kept weed-free by mechanical weeding. Detailed information concerning the experimental design can be found in Warren Raffa et al. (2021 and 2022).

2.2 Soil analysis and soil variability surveys

Soils were sampled in 2017 prior to the establishment of the treatments. Soil was analyzed for texture, SOM, total N, exchangeable K, exchangeable Mg, total limestone, and gravel. The two experimental sites were also surveyed with an electromagnetic induction sensor and a gamma-ray spectroradiometer to study the soil variability of the sites. Details on the analytical methods, elaboration of soil maps, and related analyses can be found in Warren Raffa et al. (2021).

2.3 Vegetation biomass, diversity indexes, and functional traits

Aboveground plant (CC and spontaneous vegetation) biomass was collected in late spring (May–June), before CC termination, and in autumn (October–November) across 3 and 2 years, respectively. Sixty samples per farm were taken in a 0.25 m^2 quadrate at each sampling time. Plant biomass was collected, separated by species, and oven-dried at 70 °C for 48 h.

We selected functional traits that could serve as a proxy for resource competition between groundcovers and vines, namely, specific leaf areas (SLA), plant height, and Grime strategy.

Specific leaf area (SLA), defined as the ratio of leaf area to leaf dry mass, is widely considered a key indicator of relative growth rate and photosynthetic capacity and thus serves

as a proxy for competitive potential (Garcia et al. 2019). Plant height is commonly associated with biomass production and correlates with rooting traits, making it relevant for competition studies (e.g., Little et al. 2021) and soil conservation research, where deeper root systems help mitigate soil sediment loss (e.g., Lees et al. 2021). Grime and Pierce (2012) identified three ecological factors—competition, stress, and disturbance—that shape vegetation dynamics, classifying plant species accordingly. This framework has been tested in French vineyards and has proven effective in assessing resource availability and disturbance gradients across more than 100 vineyards (Fried et al. 2022)

Data on Grime strategy, SLA, and plant height were retrieved from the database developed by Bàrberi et al. (2018), the LEDA database (Kleyer et al. 2008), and the BIOLFLOR database (Klotz et al. 2002). Species Grime strategy was expressed as a percentage of competitiveness (C) and ruderalism (R), as proposed by Pierce et al. (2017). Total biomass was calculated as the sum of CC and spontaneous species. We also investigated the effect of soil management on diversity indexes. Species richness (SR), plant community diversity (Shannon's diversity, *H'*), dominance (Simpson's dominance, D), and evenness (Pielou's evenness, *J*) were calculated based on plant biomass. In the context of this paper, the analyses have been carried out on the inter-row vegetation as a whole, thus including also the three species sown as CC (barley, squarrosum clover, and pigeon bean).

2.4 Statistical analysis

Differences in species biomass were first tested using permutational multivariate analysis of variance (PERMANOVA). Based on the results of this analysis, the dataset was analyzed separately per season and site. The Bray-Curtis dissimilarity measure was tested using PERMANOVA; no transformation on data was applied since homogeneity of dispersion across the combined groups was tested through a permutation test, randomly shuffling group labels and recalculating the test statistic to generate a null distribution. This approach provides a non-parametric means of testing the null hypothesis that the group dispersions are equal (*betadisper* and *permutest* function from *vegan* package). Non-metric multidimensional scaling (NMDS) was performed on each dataset with the Bray-Curtis dissimilarity index, using two dimensions (k=2). We then selected the species that explained a significant ($p<0.01$) proportion of total variance to study their association with treatment and year. These analyses were carried out using the *vegan* package of the R program. Finally, the indicator species analysis was carried out per season at each experimental site through the *multipatt* function (*indicspecies* package). The IndVal index (Φ) is the product of (i) the probability of a site being a member of the site-group due to the presence of the species and (ii) the frequency of occurrence of that species in the site (De Cáceres et al. 2010). Φ is a measure of association between a species and a group of samples and can be used to identify which species are associated with a particular treatment. Consequently, it may serve as a practical tool for land managers to evaluate the effects of their practices.

We used linear and generalized linear models (GLMs) to study the effects of treatments on diversity indexes and functional traits. The soil maps were used to obtain soil parameters in each sampling point to take into account the soil variability within the experimental plots: SOM, clay, silt, sand, K, Mg, gravel, and total limestone. Including soil variables in the regression model was reported to be an effective strategy to control the experimental error, especially in on-farm trials where soil can be heterogeneous. Previous publications demonstrated that including spatial soil covariates reduced Type I error regardless of the design and randomization (Alesso et al. 2019; Warren Raffa et al. 2022). Variables to be included in the statistical model to assess the effects of soil management practices on biomass, diversity indexes, and functional traits were selected using the feasible solution algorithm (*rFSA* package). In the case of linear models, residuals were assessed visually, and a Shapiro-Wilk test was performed. In all the other cases, the goodness of fit of GLMs was assessed through the Kolmogorov-Smirnov, dispersion, and outlier tests (*DHARMa* package). Differences between treatment means were compared using a post-hoc Tukey test (α=0.05) (*emmeans* package). All statistical analyses were performed in R (version 4.0.3, 2020).

3 Results

3.1 Biomass and species richness

Total plant biomass was significantly affected by all the factors included in the model and their interactions (Table S1). Treatment effect on biomass varied across seasons (Fig. 2A). S had the highest biomass (dry matter—DM) in autumn (811 kg DM ha^{-1} ± 105. 6), which was significantly higher than CT (370 kg DM ha^{-1} ± 68.7) and BCI (468 kg DM ha^{-1} ± 69.3). In spring, PBI had the highest total biomass production (4437 kg DM ha^{-1} ± 511.4), which was almost twice that observed in CT (2288 kg DM ha^{-1} ± 316.7). Total vegetation biomass in BCM (3633 kg DM ha^{-1} ± 394.3) and BCI (3687 kg DM ha^{-1} ± 383.1) did not differ significantly from that of PBI, whereas S (3308 kg DM ha^{-1} ± 270.3) had a significantly higher vegetation biomass than CT. The biomass of the spontaneous vegetation was comparable under BCM (1001 kg DM ha^{-1} ± 172.2) and BCI (981 kg DM ha^{-1} ± 209.8), where it accounted for about 26% and 27% of the total biomass, respectively. PBI showed the highest

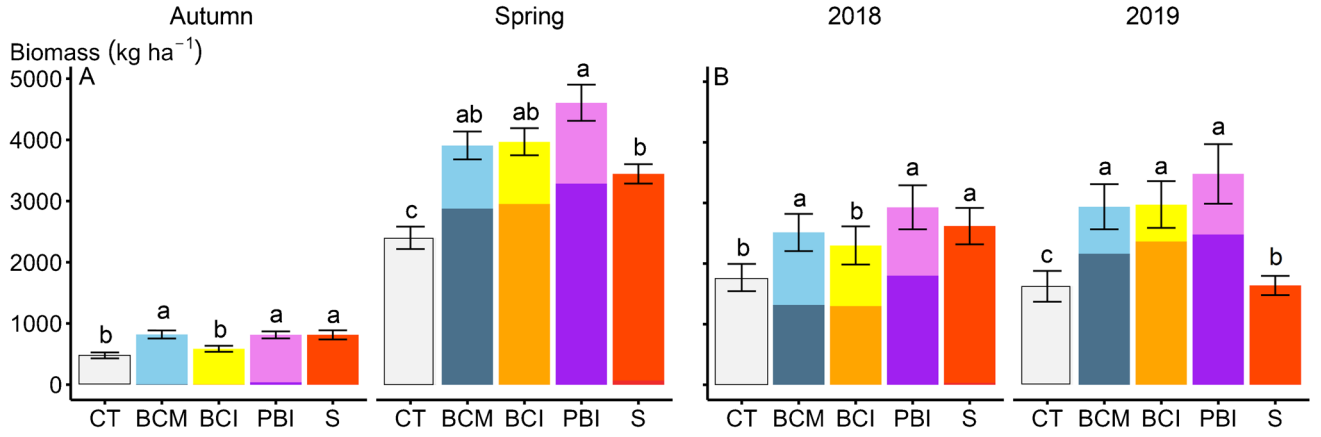


Fig. 2 Total groundcover aboveground dry biomass (kg DM ha^{-1}) averaged over farms and partitioned between cover crops (darker shades) and spontaneous vegetation (lighter shade), analyzed across **A** season and treatment and **B** year and treatment. Only years when sampling was carried out both in spring and autumn were included in (b). CT, conventional tillage; BCM, mulched cover crop of barley + squarrosum clover; BCI, cover crop of barley + squarrosum clover incorporated in the soil; PBI, pigeon bean cover crop incorporated in the soil; S, mulched spontaneous vegetation. Treatments (a) and year (b) indicated by different letters are significantly different at $p<0.05$ (Tukey test). Bars denote standard errors of the mean ($n=600$).

spontaneous vegetation production among CC treatments, both in absolute terms (1604 kg DM ha^{-1} ± 161.9) and proportionally (36%). Treatment effect on biomass varied significantly across years, but CT was consistently the treatment with the lowest spontaneous vegetation biomass, in 2018 at par with BCI (Fig. 2B).

Mean species richness (excluded CC species) was significantly affected by treatments (Table S1), with the mulched barley-clover mixture showing the highest value in autumn, at par with the spontaneous vegetation (7.1 species ± 0.4) which, however, was not significantly different from PBI (5.6 species ± 0.3) (Fig. 3A). In spring, species richness was generally higher than in autumn, with S showing higher values (12.1 species ± 0.4) than BCM (10.7 species ± 0.4) and CT (10.5 species ± 0.5). Species richness was higher in 2018 (9.3 species ± 0.3) than in 2019 (8.5 species ± 0.2) (Fig. 3B).

3.2 Spontaneous plant community composition

A total of 132 species were identified across the two experimental sites. The PERMANOVA revealed a

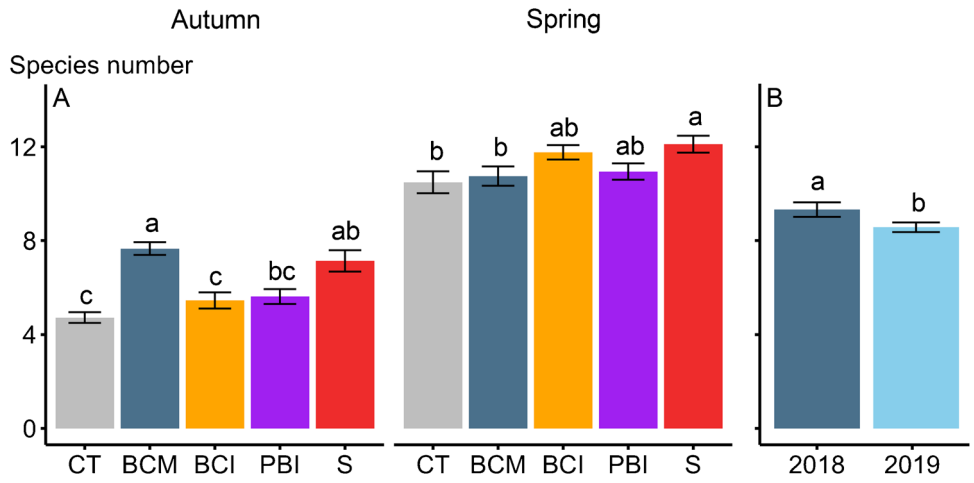


Fig. 3 Species richness (excluded CC species) in each **A** treatment and season and **B** year. Only years when sampling was carried out both in spring and autumn were included in **B**. CT, conventional tillage; BCM, mulched cover crop of barley + squarrosum clover; BCI, cover crop of barley + squarrosum clover incorporated in the soil; PBI, pigeon bean cover crop incorporated in the soil; S, mulched spontaneous vegetation. Treatments (a) and year (b) indicated by different letters are significantly different at $p<0.05$ (Tukey test). Bars denote standard errors of the mean ($n=600$).

significant effect (R^2=0.46) of all the three factors and their interactions (Table S2). Specifically, treatment, season, farm, and the treatment x season interaction accounted for more than 80% of the total variance explained. Based on these results, we broke down the dataset by season and farm to improve the representation of the ordination analyses.

3.2.1 Montevertine (MT) site

A total of 79 spontaneous species were found at MT in spring. The PERMANOVA indicated that the model explained 72% of the variability, with treatments accounting for more than 63% of the model's R^2 (Table 1). According to the PERMANOVA, treatment, year, the "treatment x year," and "treatment x replicate" interactions were significant.

The ordination analysis showed marked differences across treatments at MT in spring (Fig. 4A). Data points referring

Table 1 Results from the permutational multivariate analysis of variance (PERMANOVA) of plant species biomass collected in spring and autumn at Montevertine (MT) and San Giusto a Rentennano (SG) in 2018, 2019, and 2020 (autumn data were not recorded in 2020). Significance: **; ***significant at $p \leq 0.01$ and $p \leq 0.001$, respectively; *ns*, non-significant.

	MT				SG			
	R^2		Pr (>F)		R^2		Pr (>F)	
	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn
Treatment	0.46	0.16	***	***	0.40	0.13	***	***
Year	0.06	0.08	***	***	0.08	0.04	***	**
Replicate	0.01	0.04	***	***	0.01	0.02	**	ns
Treatment x year	0.11	0.07	**	***	0.10	0.04	***	ns
Treatment x replicate	0.03	0.11	**	***	0.03	0.07	***	ns
Year x replicate	0.01	0.02	ns	***	0.01	0.01	ns	ns
Treatment x year x replicate	0.04	0.06	ns	***	0.04	0.05	ns	ns

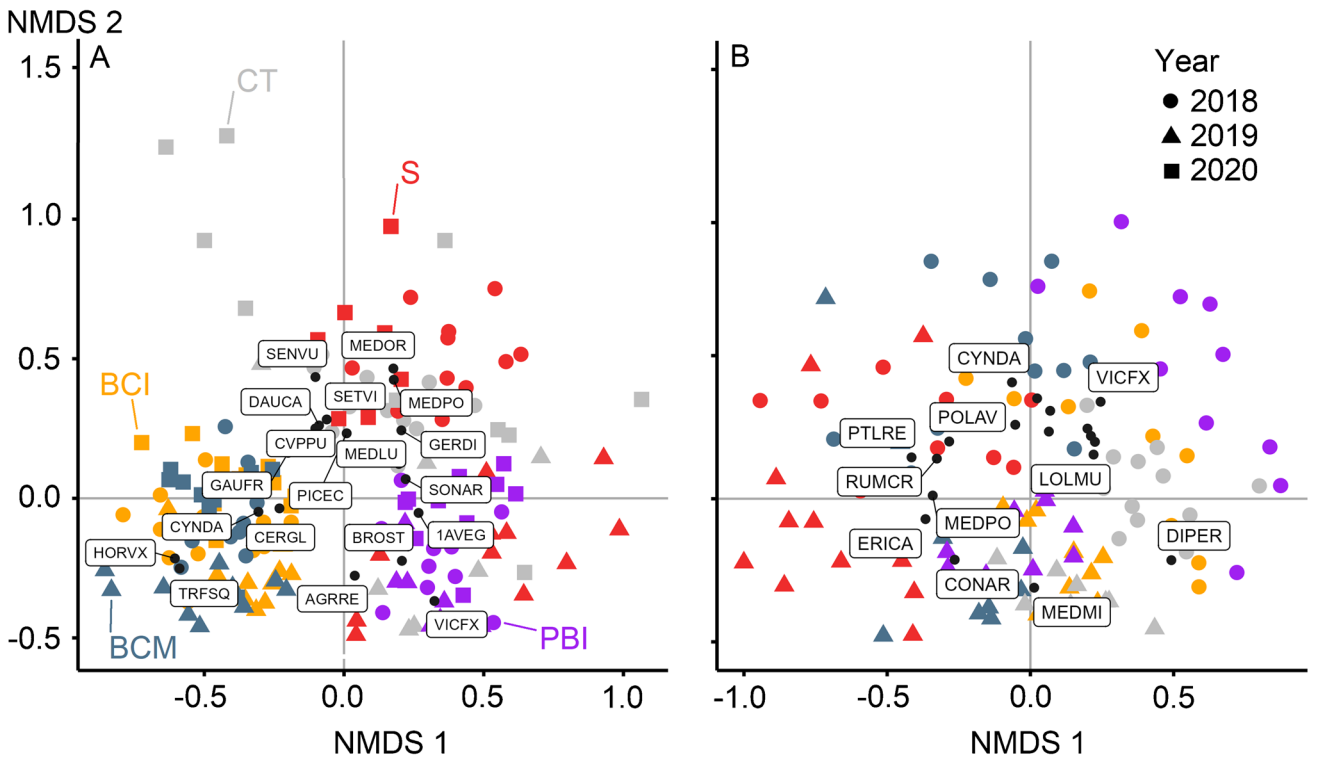


Fig. 4 Non-metric multidimensional scaling (k=2) of plant communities found at Montevertine (MT) in **A** spring (3-year average, NMDS stress value: 0.28) and **B** autumn (2-year average, NMDS stress value: 0.28) across five groundcover treatments. Colored points represent plant communities in individual sampling areas (quadrates) based on species biomass data. Black points and text boxes indicate the species that resulted significant (p<0.01) upon the environmental fitting. Plant species are reported in EPPO codes (Table S3). CT, conventional tillage; BCM, mulched cover crop of barley + squarrosum clover; BCI, cover crop of barley + squarrosum clover incorporated in the soil; PBI, pigeon bean cover crop incorporated in the soil; S, mulched spontaneous vegetation.

to the treatments including CC (BCI, BCM, and PBI) were less scattered across the graph than those referring to S and CT, suggesting that spontaneous vegetation community composition was more stable across the years under sown CC. In terms of indicator species, CT was mainly characterized by *Veronica persica* L. (Φ =0.71) and *Polygonum aviculare* L. (Φ =0.65). Concerning the other treatments, S was mainly associated with *Medicago polymorpha* L. (Φ =0.79) and *Medicago orbicularis* L. (Φ =0.75); BCI was characterized only by squarrosum clover (Φ =0.71), while BCM was characterized by barley (Φ =0.73) and *Cynodon dactylon* L. (Φ =0.54). PBI was strongly associated with pigeon bean (Φ =1.00) and *Lolium perenne* L. (Φ =0.39).

A total of 49 spontaneous species were found at MT in autumn. PERMANOVA explained about 55% of the variability, with all the factors and the interactions tested being significant at $p<0.001$ (Table 1). Nevertheless, treatments did not segregate clearly in the ordination plot, although data points tended to spread across the first ordination axis (NMDS1) according to tillage intensity (Fig. 4B). Data also segregated quite markedly by year, since values of the second ordination axis (NMDS2) ≤0 were mostly associated with 2019 data. Our analysis did not yield any indicator species for CT, whereas PBI was mainly associated with pigeon bean (Φ=0.87) and *Geranium dissectum* L. (Φ=0.87), BCI with *Diplotaxis erucoides* L. (Φ=0.53) and *Euphorbia helioscopia* L. (Φ=0.52), BCM with *Cynodon dactylon* L. (Φ=0.61) and *Setaria viridis* L. (Φ=0.52), and S with *Rumex crispus* L. (Φ=0.73) and *Medicago polymorpha* L. (Φ=0.68).

3.2.2 San Giusto a Rentennano (SG) site

A total of 96 spontaneous species were found at SG in spring. PERMANOVA showed a high level of variability explained by the model (R^2= 0.68) with treatment showing a high explanatory power (R^2=0.40) (Table 1). The ordination showed visible differences across treatments (Fig. 5A), with BCM and BCI being strongly isolated from the other treatments. While S and PBI strongly overlapped, CT segregated more clearly, although with marked differences across years. In terms of indicator species, BCI was associated with squarrosum clover (Φ=0.74), while BCM was also associated with barley (Φ=0.74) and *Mentha longifolia* L. (Φ=0.45). PBI was mainly associated with pigeon bean (Φ=1.00) and *Potentilla reptans* L. (Φ=0.58), and S overlapped with PBI and partly with CT, especially in 2018. Conversely, in 2019 and 2020, spontaneous communities of S appeared more similar to PBI than CT. S was mainly associated with *Gaudinia fragilis* L. (Φ=0.80) and *M. polymorpha* (Φ=0.76), while CT was associated with *P. aviculare*, (Φ=0.70) and *C. dactylon* (Φ=0.57).

A total of 48 spontaneous species were found at SG in autumn of 2018 and 2019. In this case, the PERMANOVA showed a lower R^2 as compared with the other models (R^2=0.36), and less clear differences among treatments (Fig. 5B). Still, treatment and year came out as significant factors (Table 1). CT was characterized by *Calendula arvensis* (Vaill.) L. (Φ=0.41), PBI by *Agrostis stolonifera* L. (Φ=0.35) and *Heliotropium europaeum* L. (Φ=0.31), BCI by barley (Φ=0.44) and *Mercurialis annua* L. (Φ=0.40), BCM by *Medicago lupulina* L. (Φ=0.67) and *M. longifolia* (Φ=0.57), and S by *P. reptans* (Φ=0.57) and *Hypericum perforatum* L. (Φ=0.48).

3.3 Diversity indexes

The Shannon diversity index (*H'*) was positively correlated ($\rho>0.85$; $p<0.001$) with all the diversity indexes considered, except with Pielou evenness (*J*). H' and J were then analyzed through regression models. Treatment significantly affected *H'* (Table 1) with BCM (1.31 ± 0.05, averaged over sites and years) increasing the *H'* in autumn as compared with all the other treatments (Fig. 6A). Conversely, in spring, S recorded the highest *H'* (1.62 ± 0.03), while CT (1.51 ± 0.05) did not differ significantly from S, BCI, or BCM. PBI had the lowest *H'* (1.06 ± 0.06) in spring, highlighting the dominance of pigeon bean in this treatment. On average, *H'* also varied differently between seasons within the two sites (higher values in spring at SG vs no difference at MT; Fig. 6B) and also between years (higher values in 2018 than 2019; Fig. 6C)

Treatment effects on evenness (*J*) differed across seasons (Table 1). In autumn, BCI showed the highest *J* (1.56 ± 0.06) and was significantly different from S (1.30 ± 0.07), while the rest of the treatments showed intermediate values. In spring, CT (1.52 ± 0.04) and S (1.51 ± 0.03) showed very similar *J* and were significantly different from the other treatments, with PBI showing the most uneven spontaneous community

3.4 Weed functional traits

Specific leaf area of the spontaneous vegetation (community weighted mean) was significantly affected by treatment, farm, and by the "farm x season" interaction (Table S1). SLA was highest in CT, BCM, and BCI (ranging from 27.0 to 27.4 $cm^2\ g^{-1}$) than in PBI (25.8 $cm^2\ g^{-1}$), while S (24.8 $cm^2\ g^{-1}$) showed the lowest value. On average, SLA was slightly higher in spring (27.0 $cm^2\ g^{-1}$ ± 0.18) than in autumn (26.6 $cm^2\ g^{-1}$ ± 0.17) at MT (S4). Conversely, SLA was 12% higher in autumn compared to spring at SG (S4).

Treatment effect on plant height varied strongly between seasons (Table S1). CT showed the lowest value of plant height (50.9 cm ± 3.1) in autumn, ca. 50% lower than S, while CC treatments showed intermediate values (Fig. 7A).

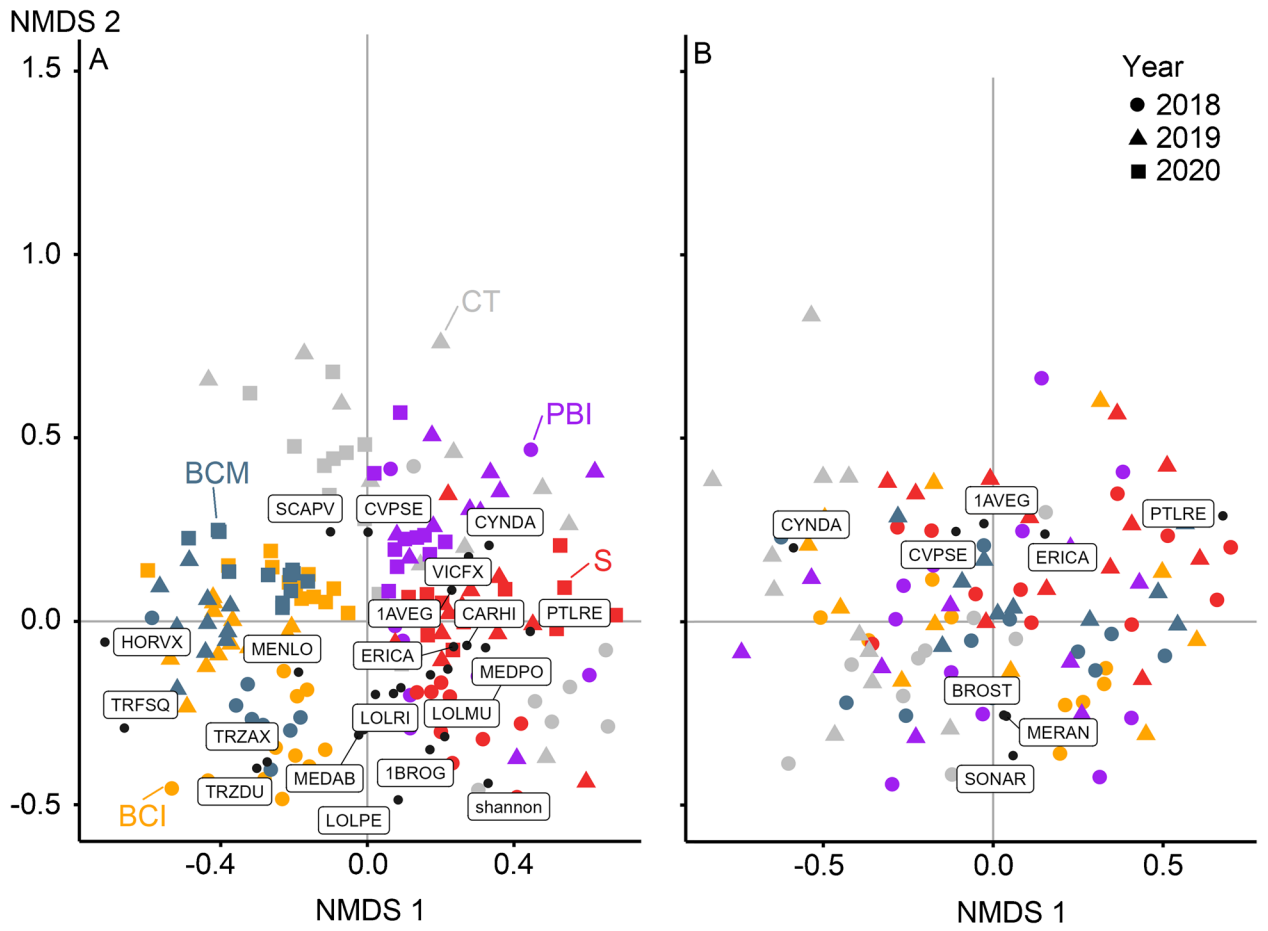


Fig. 5 Non-metric multidimensional scaling (k=2) of plant communities found at San Giusto a Rentennano (SG) in **A** spring (3-year average, NMDS stress value = 0.27) and **B** autumn (2-year average, NMDS stress value = 0.26) across the five groundcover treatments. Points represent spontaneous communities species in individual sampling areas (quadrates) based on species biomass data. Black points and text boxes indicate the species that came out as significant (p<0.01) upon the environmental fitting. Plant species are reported in EPPO codes (Table S3). CT, conventional tillage; BCM, mulched cover crop of barley + squarrosum clover; BCI, cover crop of barley + squarrosum clover incorporated in the soil; PBI, pigeon bean cover crop incorporated in the soil; S, mulched spontaneous vegetation.

These latter treatments showed the highest plant height in spring (from 93.6 to 98.8 cm), which was on average 35 and 26% higher than in CT and S, respectively (Fig. 7A). The magnitude of plant height across treatments differed between sites, with larger differences between CT and the other treatments at SG than MT (Fig. 7B). Finally, plant height was also significantly different between seasons, with higher values observed in spring at both sites (Fig. 7C).

The proportion of competitive and ruderal species (*sensu* Grime) was significantly affected by treatments (Table S1). In autumn, the lowest values of C were found under BCM and CT (26.0%). In spring, competitive species were highest in PBI (53.7% ± 1.03), a proportion more than double that of all other treatments (S5). Competitive species were least abundant in S than in the barley-clover mixtures but were at par with CT.

Spontaneous vegetation management had the lowest proportion of ruderals in autumn (43.2% ± 5.9), which was significantly different from CT (48.8% ± 7.8), BCM (46.9% ± 8.0), and BCI (50.1% ± 9.0), and the highest in spring, at par with CT (S5). In spring, the lowest proportion of ruderal species was observed in PBI (38.2% ± 3.6), while BCM (45.6% ± 2.6) and BCI (46.2% ± 3.0) showed intermediate values.

4 Discussion

4.1 Spontaneous vegetation biomass

Our data showed a strong effect of soil management practices on inter-row vegetation biomass. Spring tillage significantly reduced the biomass of the spontaneous vegetation in the autumn in all the tillage-based treatments except in PBI, in which the recycling of N from the pigeon bean may have stimulated weed emergence/sprouting and growth after the

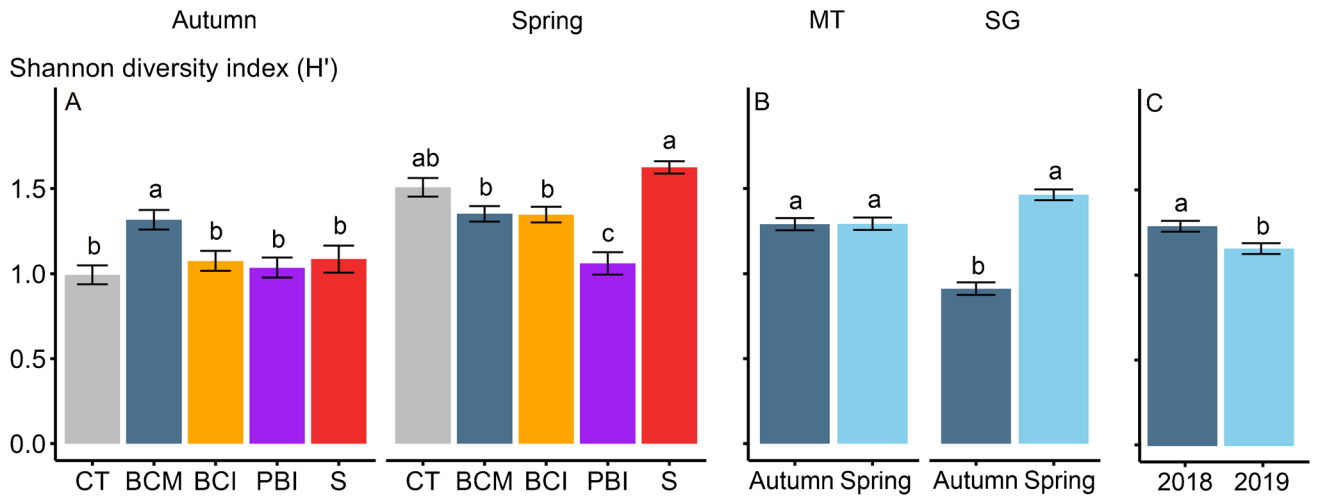


Fig. 6 Shannon diversity index (H') in each **A** treatment and season; **B** season and farm; and **C** year. Only years when sampling was carried out both in spring and autumn were included in (c). CT, conventional tillage; BCM, mulched cover crop of barley + squarrosum clover; BCI, cover crop of barley + squarrosum clover incorporated in the soil; PBI, pigeon bean cover crop incorporated in the soil; S, mulched spontaneous vegetation; MT, Montevertine; SG, San Giusto a Rentennano. Treatments (a) season (b) and year (c) indicated by different letters are significantly different at $p<0.05$ (Tukey test). Bars denote standard errors of the mean ($n=600$).

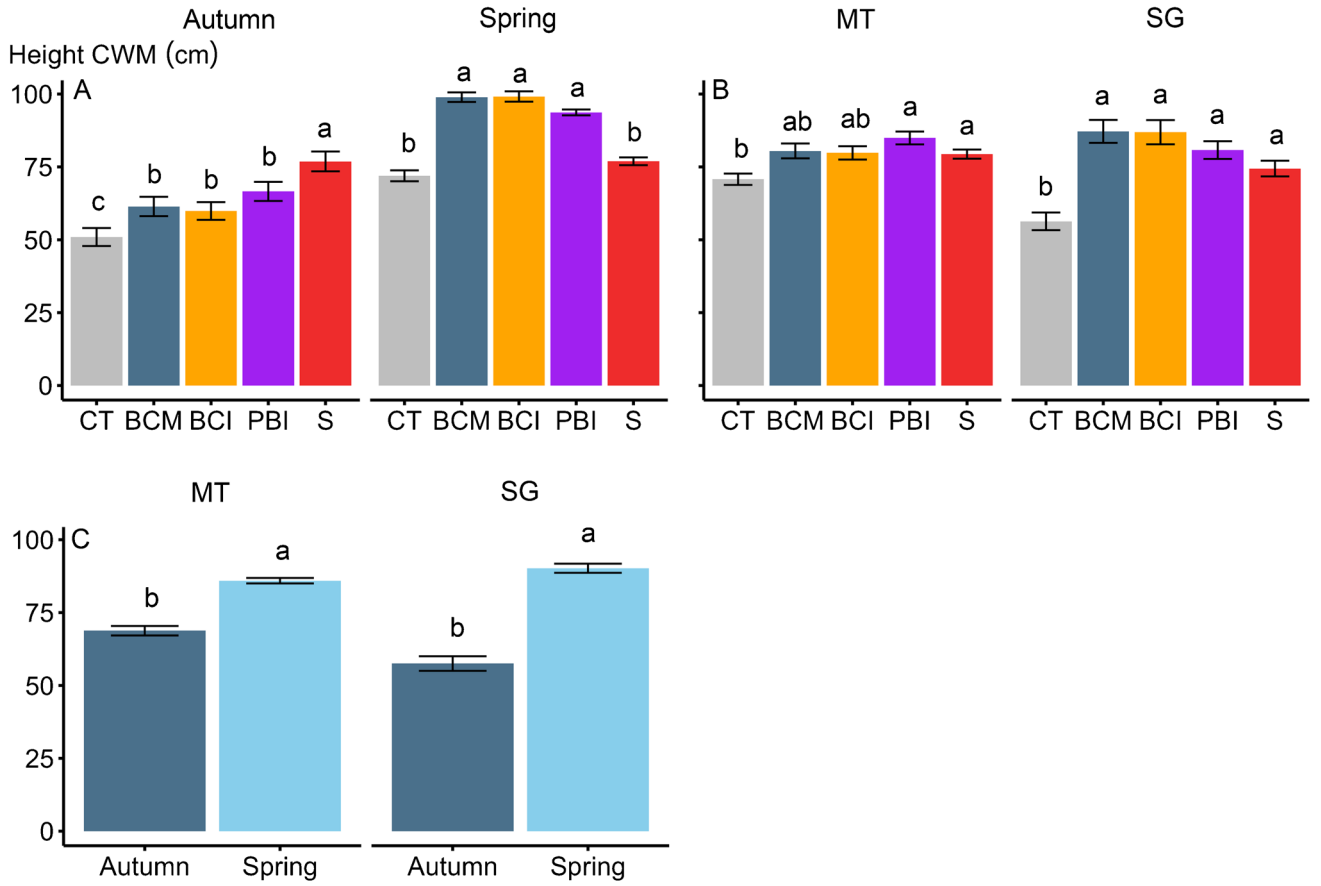


Fig. 7 Community weighted means of plant height (cm), in each **A** treatment and season; **B** treatment and farm; and **C** season and farm. CT, conventional tillage; BCM, mulched cover crop of barley + squarrosum clover; BCI, cover crop of barley + squarrosum clover incorporated in the soil; PBI, pigeon bean cover crop incorporated in the soil; S, mulched spontaneous vegetation; MT, Montevertine; SG, San Giusto a Rentennano. Treatments (a, c) and seasons (b) indicated by different letters are significantly different at $p<0.05$ (Tukey test). Bars denote standard errors of the mean ($n=600$).

incorporation of the CC (Pardini et al. 2002). Compared to tillage, mulched treatments (BCM, S) showed significantly higher spontaneous vegetation biomass in autumn, which is not detrimental to the vines and could play a key role in mitigating soil erosion in the rainiest season. In spring, total plant biomass ranged between 2.3 and 4.4 Mg DM ha^{-1} under CT and PBI, respectively. Spontaneous vegetation management showed a similar plant biomass than sown CCs. Kazakou et al. (2016) measured about 3.8 and 5.2 Mg DM ha^{-1} in spring in France under spontaneous and *Medicago* spp. groundcovers, respectively. Similarly, Steinmaus et al. (2008) reported a total biomass of mown-CC in Californian vineyards to account on average for 6.0 Mg DM ha^{-1}, while biomass production from resident vegetation was 4.2 Mg DM ha^{-1}. We also found a lower spontaneous species biomass under the barley + clover mixture as compared with pigeon bean in spring, likely due, among other factors, to the capacity of squarrosum clover to cover the soil and develop a deep-branched taproot (Ranaldo et al. 2020). The findings are in line with Cunial et al. (2025) who report that a CC with barley, oats, and clover in the mixture produced a dry biomass of 1.5 Mg ha^{-1}, which effectively suppressed weed biomass and also benefitted soil moisture conservation.

4.2 Spontaneous vegetation community composition

Our analysis clearly identified inter-row soil management as a strong filter for plant communities. Treatment effect was always significant and explained a large portion of the variability, more so in spring. Steenwerth et al. (2016) also highlighted the role of tillage as a strong driver of changes in plant community composition as compared to mown treatments, irrespective of CC type. Conversely, Fried et al. (2019) found that season, rather than management, was the main factor affecting plant assemblages. Nevertheless, the same author reported a strong effect of soil disturbance on the weed flora in a large-scale viticultural study in France (Fried et al. 2022). Our results suggest that both factors strongly affect spontaneous community composition, but soil management practices appeared to have a stronger effect.

Concerning individual species, we found *Polygonum aviculare* to be a significant indicator species of CT in both farms in spring, confirming findings by Mainardis et al. (2020). This is also consistent with the literature on arable weeds, which highlights the role of autumn tillage in increasing the emergence of this species (Royo-Esnal et al. 2015). *Calendula arvensis* was significantly related to tillage in autumn at SG. This species was already reported to be favored by mechanical disturbance in vineyards (Wilmanns 1993). *Medicago* spp. and *Conyza canadensis* were among the indicator species in both farms in spring under S and have already been found in low-disturbed systems, such as in no-till plots (Gago et al. 2007). In autumn, *Potentilla reptans* was a good indicator species under S at both sites. *Potentilla reptans* is a pioneer perennial species with above-ground buds (hemicryptophytes), often associated with mulch (Wilmanns 1993). The CC treatments were mainly associated with the presence of the sown species in spring, while in autumn, *P. aviculare* and *Convolvulus arvensis* were common at both farms under mulched-CC. Being a creeping, rhizomatous, perennial summer weed, *C. arvensis* can thrive in no-tilled soils in spring and summer (Davis et al. 2018).

4.3 Spontaneous vegetation diversity indexes

Soil management had a highly significant effect on species richness, Shannon diversity, and Pielou evenness. We found species-richer communities in autumn under mulched treatments and in spontaneous vegetation compared to tillage. Conversely, in spring, there was a reduction in the number of species in treatments based on mulched-CC and tillage compared to S. Contrasting results on the effect of soil management practices on weed species diversity are reported in the literature. Some authors reported a significant reduction under CCs and tillage compared to spontaneous groundcovers (Kazakou et al. 2016; Hall et al. 2020). Particularly, Guerra et al. (2022)—which, to the best of our knowledge, is the longest experiment carried out on this topic—found that tillage led to lower species diversity, while mulched spontaneous groundcover resulted in increased diversity with high biodiversity value. Contrarily, Steenwerth et al. (2016) found a lower number of species and *H'* under CCs compared to tillage. Finally, MacLaren et al. (2019) did not find any significant effect of soil management on species richness.

As suggested by Kazakou et al. (2016), we expected that soil disturbance would have decreased *H'* and *J* and thus favored an uneven plant community characterized by a low number of dominant species. In contrast, CCs and resident vegetation would have increased *H'* and *J* and thus favored assemblages with a higher number of species with similar abundance. Nevertheless, our results did not confirm these hypotheses. Although in autumn BCM and BCI showed higher *H'* and *J*, respectively, CCs in spring had a significant negative effect on both *H'* and *J* as compared with the resident vegetation. Our results thus suggest that CCs could be identified as a strong selection filter towards less diverse communities dominated by a low number of species, but effects depend on the assessment period and on CC species. In the present study, the CC-based treatments (PBI, BCM, BCI) were managed by sowing the CC in the autumn on tilled soil and then letting the CCs grow until their termination in spring. Therefore, the final results of the CC-based treatments on spontaneous species diversity might have been due to the simultaneous and, likely, interacting effects of autumn tillage and CC specific growth intensity

and dynamics. This calls for further studies in similar and different conditions to unravel the relative contribution of autumn tillage and CC type on floral diversity. Concerning CC mixture composition, the literature confirms that when CC stands are made up of one or few species, they can severely affect weed establishment, thus resulting in a net decrease of plant diversity (Hall et al. 2020). Moreover, CC stands characterized by high biomass have been shown to increase the filtering effect, thereby strongly affecting structure and composition of spontaneous communities (Steenwerth et al. 2016). These findings support our results and especially the strong selective effect of high biomass-producing pigeon bean on *J* and *H'*. Other authors found tillage to be more selective than CC (Sanguankeo and León 2011; Kazakou et al. 2016) or showed no effect of soil management practices on *H'* or *J* (MacLaren et al. 2019). Given the varying effects observed across different conditions and assessment periods, these findings highlight the need for further studies to disentangle the relative contributions of cover crop type, biomass production, and soil management practices on plant diversity.

4.4 Inter-row vegetation functional traits

We studied the effect of management practices on a set of functional traits related to competition between groundcovers and grapevines. We found a strong tillage effect in selecting communities with higher SLA as compared to spontaneous groundcover. SLA is related to faster plant growth rate, which is an important trait in frequently disturbed environments. Variable results are reported in the literature, with some studies confirming the effect of tillage on selecting communities with higher SLA (Kazakou et al. 2016; Hall et al. 2020) and others that reported no differences (MacLaren et al. 2019; Mainardis et al. 2020). We also found a strong effect of the cereal + legume CC on SLA, irrespective of management, but not of the pigeon bean CC. The results obtained by Kazakou et al. (2016) with *Medicago* spp. are in line with ours regarding pigeon bean. Furthermore, our results concerning the lowest SLA of spontaneous communities under mown spontaneous vegetation are in agreement with the literature (Hall et al. 2020; Kazakou et al. 2016).

Plant height is correlated with different root traits and is thus considered a critical trait related to competitiveness (Gaba et al. 2017) and a proxy to assess groundcover effect on soil aggregation (Garcia et al. 2019). Overall, our data show a strong influence of soil management on plant height. We observed a strong CC effect, irrespective of species and management. Specifically, autumn plant communities under CC were taller than in CT but shorter than in S. Conversely, spring plant communities under CC were the tallest. Our results are apparently in contradiction with the few studies on the topic, which found no differences between mowing and tillage (MacLaren et al. 2019; Mainardis et al. 2020) or taller communities under CT, intermediate under CC (*Medicago* spp.), and shorter plant assemblages under resident vegetation (Kazakou et al. 2016). Although the inclusion of cover crop biomass in the analyses differentiates this work from other papers on the topic, it allows for agronomic considerations about the effect of the inter-row vegetation as a whole on vines and vineyard management. Noteworthy, the higher community mean plant height under S may have relevant management implications for Mediterranean vineyards, which are severely affected by soil erosion (Rodrigo-Comino et al. 2017). The lower plant height found in spring suggests a lower competition of the vegetation in S than in CC-based treatments when the vines are more sensitive to water and nutrient stresses. Conversely, a taller plant assemblage in autumn suggests a likely larger below-ground biomass, which may benefit soil structure and reduce soil erodibility in a period when soils are more vulnerable to sediment losses and competition with vines is not an issue.

Concerning the presence of competitive and ruderal species (C and R, *sensu* Grime), we expected that tillage and CC termination strategy would act as strong filters in differentiating spontaneous species assemblages. Specifically, we expected repetitive tillage to increase R species by favoring the spread of seeds and cuttings as also reported by Kazakou et al. (2016) and Fried et al. (2022). Conversely, sown CC may favor a C strategy due to the stability of the habitat, especially in spring. Despite this, the filtering effect of CC seemed to be independent of CC species and their functional traits, being rather influenced by biomass production and CC management (Smith et al. 2015). It has been suggested that integrated soil or weed management strategies should consist of an array of practices able to foster a species transition from high C and R abundance towards stress tolerant (S *sensu* Grime) weed assemblages (MacLaren et al. 2020). We observed a significant effect of soil management practices on the proportion of C and R species. Pigeon bean was the most productive and the most competitive groundcover in spring, which may potentially affect vineyard performance. The barley-clover mixture showed lower C and higher R proportion in spring compared to pigeon bean, probably due to the fast-growing squarrosum clover, which inhibited the growth of very competitive species (Ranaldo et al. 2020). We did not observe differences between CT and the mulched resident vegetation (S) in C or R proportion in spring, since the mechanical disturbance of mowing and tillage favors cutting and dissemination of spontaneous species biomass and may therefore trigger similar species communities. Inconsistent results on the filtering effects of mowing on CSR species strategies were already found in vineyards (Lososová et al. 2002), while the long-term study published by Fried et al. 2022 reported that mowing led to C-dominated plant

assemblages. It is also likely that a 3-year study like ours might be too short to appreciate substantial changes in the relative proportion of CSR strategies in tillage vs resident vegetation. A different scenario was observed in autumn, where spring and summer tillage significantly affected C and R. Mowing resident vegetation resulted in spontaneous species assemblages characterized by high C and low R scores, thereby reflecting a more stable habitat for the species community compared to tillage. Conversely, spring tillage acted as a filter by selecting more summer growing R-strategists. Concerning CC species, the increased N availability following pigeon bean incorporation (Warren Raffa et al. 2021) may have favored competitive species and, thus, reduced the selective tillage effect under pigeon bean assessed in autumn (Carlesi et al. 2013). Our analysis also revealed that the type of CC termination significantly affected spontaneous species strategies, as mulched-CC showed lower R and C proportions as compared to CC incorporation. These results are congruent with Hall et al. (2020), who found that less intensive vegetation management favors CSR strategists. Considering the framework proposed by MacLaren et al. (2020), this corresponds to a shift towards a *more desirable* "CSR" space implying more functionally diverse communities which compete less with the main crop and are, often, of higher biodiversity value.

5 Conclusion

This study investigated the effects of different soil management practices on the biomass, diversity, and selected functional traits of inter-row groundcovers in the vineyards of the Chianti Classico wine-producing area. To the best of our knowledge, this is the first research on the topic based on data of biomass by species. As hypothesized, autumn tillage decreased inter-row vegetation biomass and selected a less diverse species community with higher SLA compared to the resident vegetation managed as mulch. Spring tillage also acted as a selective filter for more R strategy-based spontaneous species communities as compared with mulched spontaneous vegetation. Therefore, our findings suggest that inter-row tillage can affect the biodiversity value of the inter-row vegetation and potentially select more aggressive species assemblages. Our findings provide relevant additional evidence on the negative effect of tillage in sloping vineyards, which should be considered when designing soil management schemes. We also observed high total biomass production of CC in spring, with pigeon bean being the most productive of the groundcovers tested. As a result, diversity indexes (*H'* and *J*) were the lowest under this CC, which also showed the highest competitive potential in spring. As hypothesized, mulched groundcovers preserved biodiversity (high species richness) in autumn and guaranteed better soil protection (high biomass production) than tillage-based treatments. Among the mulched groundcovers, the sown CC selected for less competitive spontaneous species communities as compared to mulched resident vegetation and CC incorporation. Nevertheless, sowing operations leave the soil uncovered in autumn; therefore, mulched annually sown CC should be used carefully, especially on sloping soils. Conversely, spontaneous vegetation ensured a full soil cover throughout the year but was also associated with more stable and competitive species assemblages (*sensu* Grime), which may become even more abundant in the long term. Alternating these two practices can be an effective strategy to mitigate the potential negative effects related to each groundcover management type. Alternatively, an in-between strategy might be sowing a mixture of perennial species (e.g., a legume like *Medicago sativa* L. and a grass like *Dactylis glomerata* L.) to be renewed when the sward floristic composition becomes functionally degraded (i.e., high abundance of competitive species upon reduction of the sown species cover). Our study is based on biomass sampling at two sites across two seasons over 3 years, but further long-term studies are encouraged to monitor plant community dynamics over extended periods.

Overall, mulched groundcovers may represent a suitable strategy to guarantee soil protection in both spring and autumn. At the same time, mulched groundcovers foster more diverse spontaneous species assemblages, benefitting biodiversity conservation without compromising grapevine yield (Warren Raffa et al. 2022). To this end, the information provided by this study will need to be further integrated with measurements on vine growth and production. This will be critical in order to discuss with farmers soil and weed management strategies able to combine grape production with more environmentally oriented goals and thus ensure the advancement of a more sustainable wine sector.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-025-01046-x.

Acknowledgements The authors wish to acknowledge the Centre for Agri-Environmental Research "Enrico Avanzi" of the University of Pisa for assistance in the field and lab work. Special thanks go to Fattoria San Giusto a Rentennano and Montevertine who hosted and supported this research.

Authors' contributions Conceptualization: D.W.R., D.A., P.B., and S.C.; methodology: D.W.R., P.B., and S.C.; investigation: D.W.R., D.A., A.V.; data analysis: D.W.R., S.C., and A.V.; writing—original draft preparation: D.W.R.; writing—review and editing: D.W.R., P.B., D.A., A.V., and S.C.; supervision: P.B. and D.A.; project administration: D.A. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by Scuola Superiore Sant'Anna within the CRUI-CARE Agreement. This research was partly funded

by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 727321 (IWMPRAISE). D.W.R. has a study grant from the International PhD course in Agrobiodiversity at Sant'Anna School of Advanced Studies, Pisa, Italy.

Data availability The data presented in this study are available on request from the corresponding author. The data are not publicly available as commercial farms were involved in the study.

Code availability The code used in this study is available on request from the corresponding author.

Declarations

Ethics approval Not applicable.

Consent to participate Informed consent was obtained from all subjects involved in the study.

Consent for publication Informed consent for publication was obtained from all subjects involved in the study.

Conflict of interest The authors declare no competing interests.

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