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Unravelling the effects of vineyard inter-row vegetation on soil biodiversity in South Africa

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ABSTRACT

For sustainable viticulture it is suggested that farmers maintain vegetation cover in inter-rows to promote ecological balance. However, the extent to which inter-row vegetation influence soil biodiversity and associated ecosystem functions remains an open question. This study explored how different vineyard inter-row vegetation management practices influence soil fauna diversity, composition and functional structure. The research was conducted across 24 sites in the Stellenbosch area, Western Cape, South Africa. Three treatments were compared: bare (no vegetation), covered (vegetation allowed to grow), and natural (natural fynbos vegetation outside of the crop areas). Natural vegetation and covered vineyards had significantly higher species diversity and proportion of detritivores compared to bare vineyards. Vegetation cover had a positive influence on soil fauna diversity, particularly for spiders, and functional groups such as detritivores, omnivores, and predators. However, herbivores were negatively affected by vegetation cover, suggesting that vineyards with higher vegetation cover may have fewer herbivores. Litter cover was the primary variable influencing soil fauna diversity and composition, highlighting the importance of retaining organic matter in vineyards. The study also shows that plant species richness had a negative impact on ant species diversity, possibly due to increased competition for resources. In contrast, spiders were positively affected by litter cover, which may have facilitated prey trapping and reduced soil disturbance. The findings of this study emphasize the significance of vegetation management in maintaining soil fauna diversity and composition in vineyards. The results suggest that covered vineyards can support a more diverse range of soil fauna, which can contribute to ecosystem services. Overall, this study highlights the importance of adopting sustainable vineyard management practices that prioritize soil fauna conservation and biodiversity.

1. Introduction

Globally, vineyards are often managed intensively to maximize wine production, disregarding potential negative impacts on biodiversity and ecosystem services. This approach can lead to environmental degradation, including elevated soil erosion rates (Puig-montserrat et al., 2017), degradation of soil fertility and contamination of groundwater (Bordoni et al., 2019). As a result, the long-term sustainability of vineyard ecosystems is compromised, highlighting the need for more balanced management practices that prioritize both productivity and environmental stewardship (Pretty et al., 2018).

Inter-row vegetation management is a common practice in vineyards (Kesser et al., 2023). It generally refers to the deliberate selection and management of plant species or allowing spontaneous vegetation to grow between vine rows to enhance ecosystem services (Giffard, 2022). This practice has gained popularity in recent years due to its potential benefits, including water conservation, improved soil health, increased biodiversity, and reduced erosion (Costello and Daane, 1998; Möth et al., 2023; Novara et al., 2018). Economically, inter-row vegetation reduces soil preparation costs (Novara et al., 2018), increases vineyard longevity (Gonçalves et al., 2020), and enhances wine quality and reputation (Fiera et al., 2020b), ultimately contributing to a more sustainable and profitable vineyard ecosystem.

Furthermore, vineyard inter-rows serve as vital biodiversity hotspots within agricultural landscapes, particularly when vegetated (Fiera et al., 2020b). These areas support a diverse range of fauna, delivering essential ecosystem services such as primary production, pest control, pollination, erosion prevention, and soil nutrient cycling. However, tillage practices, weed management, and agrochemical applications aimed at controlling competition for water and nutrients between vines

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and weeds, significantly impact the presence and abundance of these beneficial organisms (Sharley et al., 2008; Thomson and Hoffmann, 2007). Furthermore, simplified vineyard landscapes with reduced vegetation diversity and cover can limit the movement and colonization of beneficial macrofauna, exacerbating biodiversity declines (Cataldo et al., 2020). Of particular interest are vineyard soil biodiversity, as it is a key driver of ecosystem services, such as the decomposition of organic matter, fixing nitrogen, and controlling pests and diseases, supporting soil health and fertility (Ouédraogo et al., 2007). These processes can influence grape yield and quality, and ecosystem resilience, thereby underpinning the sustainability of vineyard ecosystems (Bradford et al., 2014; Fiera et al., 2020a; Tsiafouli et al., 2014).

Viticulture is an integral part of South Africa's agricultural sector, with the country being one of the world's leading wine producers (Paiola et al., 2020). However, the intensification of vineyard management practices has raised concerns about the environmental impact of viticulture, particularly on soil biodiversity (Geldenhuys et al., 2021). In South African vineyards, different vegetation management strategies are employed. These include clean cultivation, where all vegetation is removed between vine rows to minimize competition for water with the vines (Kesser et al., 2023), and cover cropping, where specific plants are sowed or spontaneous vegetation is allowed to grow to enhance soil health and biodiversity (Eckert et al., 2020; Liebhard et al., 2024) and reducing soil erosion while promoting ecological balance (Birkhofer et al., 2019; Ochoa-Hueso et al., 2024). Due to the current paradigm shift towards sustainability and the need to implement ecologically sound strategies in vineyard ecosystems (Fiera et al., 2020b; Scherr and Mcneely, 2008), strategies for more sustainable viticulture recommend maintaining vegetation cover in inter-rows.

Numerous studies, both international and local, have demonstrated that implementing best management practices in vineyards has a positive impact on the diversity of ground-dwelling arthropods (Addison et al., 2013; Bruggisser et al., 2010; Eckert et al., 2020; Gaigher and Samways, 2010; Geldenhuys et al., 2021; Thomson and Hoffmann, 2007). However, information on the extent to which different inter-row vegetation management practices impact soil biodiversity and associated ecosystem services remains limited. This knowledge gap is particularly significant in South Africa, where viticulture is a significant contributor to the economy and environmental sustainability is a growing concern.

This study sought to understand how vineyard inter-row vegetation influence soil fauna diversity, assemblage composition and functional composition in vineyards. Soil fauna species diversity, composition, and functional group composition were compared among three treatments, (1) vineyards with vegetation cover, (2) vineyards without vegetation cover, and (3) neighbouring natural fynbos (as reference). Vegetation variables which could be possibly responsible for shaping soil fauna responses were also measured. Understanding the impacts of vineyard inter-row vegetation management on soil biodiversity can provide important information to support the design of sustainable and biodiversity-friendly viticulture. While the influence of inter-row vegetation management on soil biodiversity in vineyards has been extensively studied globally, there is a notable gap in research within the South African context. Comprehensive investigations into the impacts of inter-row vegetation on soil biodiversity, particularly in the unique ecosystems of South Africa, remain scarce and only a few studies have explored this dynamic. This study provides context-specific insights for South African ecosystems, which may have unique characteristics and species compositions. Ants (Formicidae), beetles (Coleoptera), and spiders (Araneae) were used focal taxa, because of their well-defined ecology and taxonomy, together with their well-known response to managements effects in production landscapes, both in terms of taxonomic and functional diversity. It is hypothesised that vineyards with inter-row vegetation cover will have higher soil fauna diversity, more diverse assemblage composition, and a greater range of functional groups compared to vineyards without vegetation cover and will more closely resemble the biodiversity patterns observed in neighbouring natural fynbos ecosystems.

2. Materials and methods

2.1. Study area and design

The study was conducted at 24 sites spread across eight commercial wine farms within the Cape Floristic Region (CFR) in the Stellenbosch area, Western Cape (Fig. 1). This Mediterranean region has dry and hot summers (temperatures ranging between 24 and 35 °C) and cool, wet winters (temperatures ranging between 10 and 20 °C). The annual winter rainfall is approximately 515 mm. Sampling blocks were selected to represent the following treatments: (1) Bare/no-cover: vineyards where vegetation had been controlled prior to the growing season either by tillage or herbicides, and consisted of bare ground between the vines; (2) Cover: vineyards where vegetation between the vines is allowed to grow over the growing season. The inter row vegetation consisted of both sown seed mixes (Poaceae, Gramineae) and spontaneous cover crop (i.e. grasses and weeds that were not planted); (3) Natural: natural remnant (fynbos) vegetation patches on the farms that served as natural reference sites.

Each treatment was replicated eight times, totalling 24 spatially independent sampling sites. Where multiple sites of the same treatment occurred on a single farm, sites were separated by at least 200 m. Generally, vineyard cover crop type and management in this region varies between farms, often depending on environmental conditions, and cultivar. In most vineyards, annual cover crops are sown in autumn, often consisting of cereals and legumes, or alternatively spontaneous agricultural weeds are allowed to grow within the vineyard inter-rows. In many regions, cover crops are controlled mechanically or chemically at the start of the growing season to prevent competition with the vines for water. However, in certain regions, vineyards are left vegetated or partially vegetated over the growing season if the environmental conditions allow it. Detailed management information (including cultivation history) of each sampling site is presented in Appendix 1.

2.2. Fauna sampling

Sampling was conducted over two seasons, from October to November 2023 (spring), and March to April 2024 (autumn). Soil fauna was sampled using pitfall traps and soil monoliths located in vineyards and neighbouring natural habitats (fynbos). Three soil monoliths (25 ×25 ×30 cm) (Swift and Bignell, 2001) at 5 m apart were dug from each sampling plot after clearing the litter layer. Soil from the monoliths was placed onto a white plastic tray and hand sorted for soil fauna. The cleared leaf litter layer was also inspected for fauna. Three pitfall traps (9.5 cm diameter and 8 cm deep) were placed 5 m adjacent to each soil monolith (Appendix 2) and filled with a mixture of ethylene glycol and three drops of detergent to lessen surface tension. The traps were collected after 7 days, and the sampled individuals were preserved with 70 % ethanol and taken to the laboratory for sorting and identification. Thereafter, individuals were sorted into morphospecies when species level identification was not possible (Beattie and Oliver, 1996). Functional groups (detritivores, herbivores, predators or omnivores) were also assigned to species based on their morphological characteristics and family identity for ants (Slingsby, 2017), beetles (Scholtz and Holm, 1985), and spiders (Dippenaar-Schoeman, 2023).

2.3. Vegetation characteristics

A 1 m quadrat was placed at random three times within a site's boundary (5 m radius surrounding the pitfall traps and where monolith excavation took place) to record various vegetation and soil characteristics associated with the fauna samples. Vegetation characteristics were systematically measured within each quadrat as follows: (1) Number of

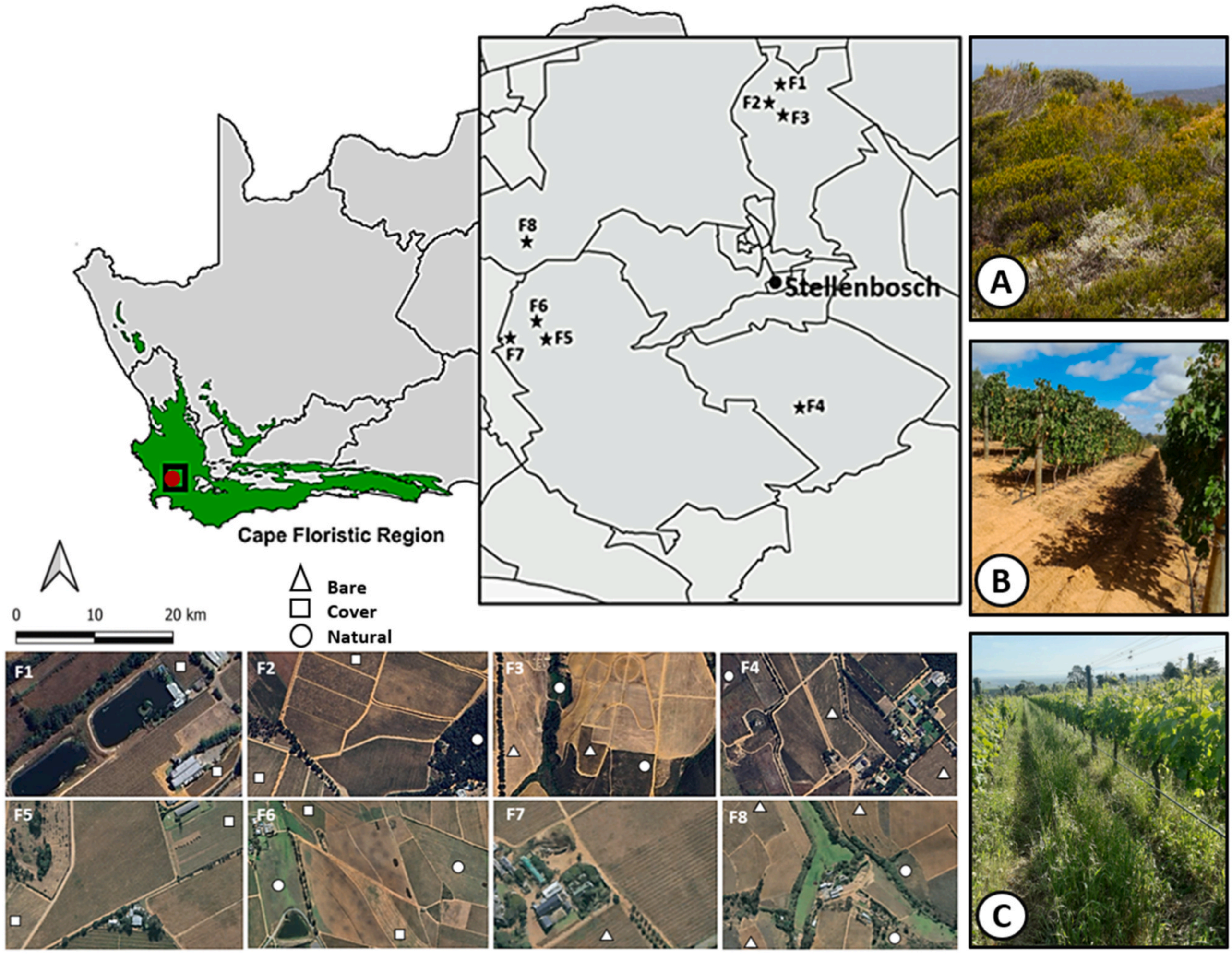

Fig. 1. Area map and design for the 24 study sampling sites (A =Natural, B = Bare, C = Cover) distributed across eight farms (F1, F2, F3, F4, F5, F6, F7, F8) in Stellenbosch, South Africa.

flowering plants: estimated by counting the number of plant species exhibiting reproductive structures (2) Plant richness: estimated by counting the total number of distinct plant species present within each quadrat (including non-crop/spontaneous species), (3) Litter cover: by estimating the percentage of the quadrat area covered by decomposing organic matter, such as leaves and twigs, (4) Vegetation cover: The total percentage of the quadrat area occupied by above-ground plant material, including stems, leaves, and flowers, was measured, (5) Bare ground: estimated by measuring the percentage of the quadrat area devoid of vegetation or litter. Data from the three replicate quadrats per site were averaged for the analyses (Appendix 4, 5).

2.4. Data analyses

2.4.1. Soil fauna diversity and functional structure

All data analyses were performed with R statistical software version 4.4.0 (R Core Team, 2024). Species diversity (Shannon's entropy) was calculated using the *hillR* package of diversity (Li, 2021). To calculate the functional structure, species were categorised into four functional groups (predators, herbivores, detritivores, and omnivores) according to their known feeding habits and morphological characteristics. Species were given a binary score of 1 or 0 for whether they were predators, herbivores, omnivores, or detritivores. The scores were then used along with the matrix of species abundance at the different sites to measure the com- munity weighted mean (CWM). The CWM values were calculated for each of the four feeding groups as a measure of species functional composition, using the "*functcomp*" function of the *FD* package in R (Laliberté et al., 2015; Laliberté and Legendre, 2010) which computes the composition of functional communities as measured by the trait values of the community-level weighted means (Lavorel et al., 2008; Piano et al., 2020). The CWM values range from 0 to 1, with higher values indicating a greater relative abundance of species belonging to a given feeding group (e.g., predators, herbivores). For example, a CWM of 0.75 for predators means that 75 % of the individuals recorded at that site were predatory species. This index provides a measure of the functional composition of communities, weighted by species abundances. The CWM index does not have a fixed minimum or maximum in general; however, because binary (0/1) trait scores are used, the resulting values range between 0 and 1. The *lme4* package (Bates et al., 2015) was used to generate generalised linear mixed-effects models (GLMMs) for Poisson distributed (species diversity) and Gamma distributed responses (functional CWM). Moran's *I* test detected spatial autocorrelation when tested for with the *ape* package (Paradis et al., 2022). All models included the random factor of "elevation" to account for the observed spatial autocorrelation (see, Appendix 3). Differences in species diversity measures and functional structure between the land-uses were tested using the using the "*Anova*" function, and significant probability (p) values were subjected to pairwise comparison using Tukey post-hoc tests with the *multcomp* package (Hothorn et al., 2008).

2.4.2. Soil fauna assemblage composition

Differences in soil fauna assemblage composition between the different treatments were tested with multivariate generalised linear modelling using the *mvabund* package with the function "*manyglm*" (Wang et al., 2012). Multivariate models were fitted with a negative binomial distribution, assuming quadratic mean-variance and estimated through the "PIT- trap" resampling approach at 999 permutations. The results were visualised with model based latent variable biplots using the *Boral* package (Hui, 2016).

2.4.3. Effects of vegetation on fauna diversity, functional structure, and composition

To determine the effect of vegetation characteristics on soil fauna diversity and functional CWM, mixed-effects models, were performed with elevation as a random variable. To begin with, multicollinearity between vegetation variables was measured using the *car* package (Fox et al., 2019) by calculating the variance inflations factors (VIF) on rescaled variables, factors with VIF scores of > 4 (bare ground and number of flowering plants) were excluded from modelling (Zuur et al., 2010). Best models were identified and selected using forward selection based on Akaike's information criterion (AIC) values within the package *AICcmodavg* (Mazerolle, 2020). Models containing AICc values of ≤ 3 from the upper model were included in model averaging. Generalised linear models (GLMs) for multivariate abundance data, implemented by the *"manyglm"* function within *mvabund* package (Wang et al., 2012) were used to determine the most important vegetation variables influencing soil fauna assemblage composition.

3. Results

A total of 3858 individuals representing 121 arthropod species or morphospecies were sampled. These included 1830 Coleoptera (71 species), 850 Formicidae (19 species), and 1178 Araneae (31 species).

3.1. Effects of treatment on soil fauna diversity

The total soil fauna species diversity differed significantly across the different treatments ($\chi^2 = 18.15$; $p < 0.001$) (Fig. 2a), with the lowest recorded within the bare treatment. The pairwise test showed that the total species diversity between the natural treatment and cover treatments did not differ significantly ($Z = -2.23$; $p = 0.97$).

The diversity of ants also differed significantly between the three treatments ($\chi^2 = 21.16$; $p < 0.001$) (Fig. 2b) and was highest within the treatment with vegetation cover. The pairwise test revealed similarities in ant diversity between covered and natural treatments ($Z = -2.12$; $p = 0.089$).

The highest beetle diversity was observed within the natural treatment with significant differences between the three treatments ($\chi^2 = 6.40$; $p = 0.04$) (Fig. 2c). The pairwise test showed no significant differences in beetle diversity between bare and covered treatments ($Z = 1.78$; $p = 0.18$) as well as between covered and natural treatments ($Z = 0.61$; $p = 0.81$). The spiders within the bare treatments were significantly lower in species diversity compared to those found in natural and bare treatments ($\chi^2 = 35.30$; $p < 0.001$) (Fig. 2d), with the pairwise test showing no significant differences in spider diversity between natural treatment and covered treatments ($Z = -1.875$; $p = 0.14$).

3.2. Effects of treatment on soil fauna functional groups

The soil fauna functional composition measured through the CWM,

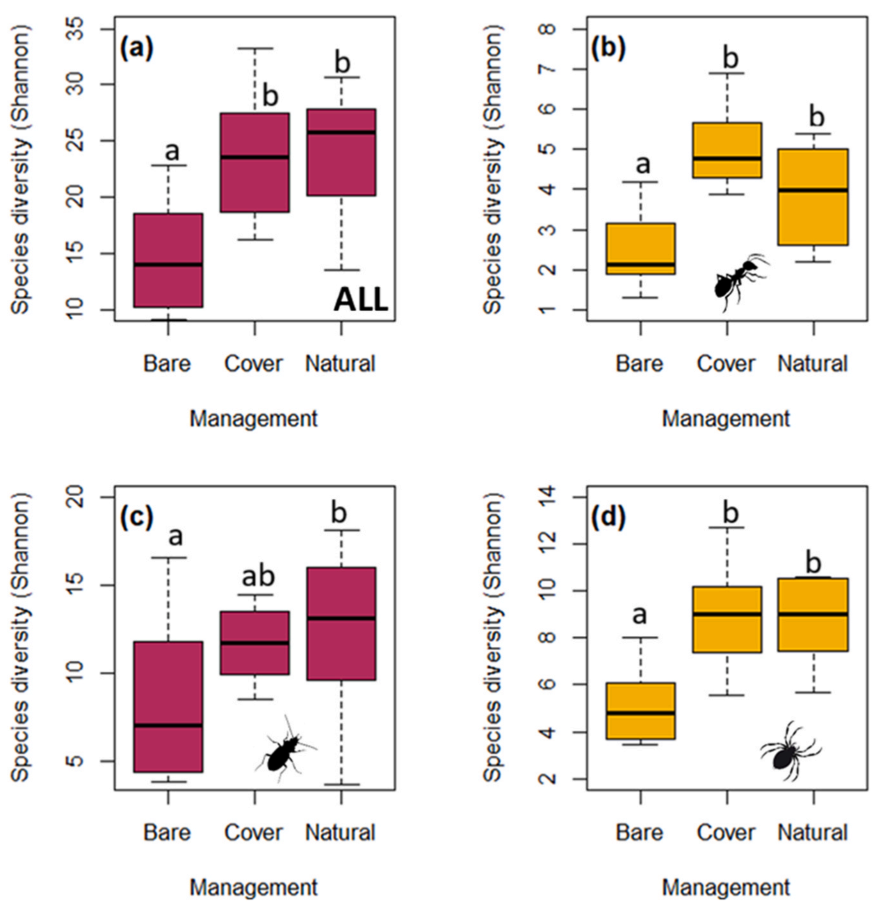

Fig. 2. Differences in soil fauna diversity between different treatments. Total fauna (a), Formicidae (b), Coleoptera (c), and Araneae (d). Mean values with dissimilar letters are significantly different (Tukey's post-hoc tests at $p < 0.05$). The central horizontal line indicates the median, the boxes represent the interquartile range, and the whiskers show the standard deviation for each treatment.

showed different responses to treatment (Fig. 3). When looking at the detritivores, the highest proportion was recorded within the covered treatments, and all the treatments differed significantly from each other ($\chi^2 = 23.05$; $p < 0.001$) (Fig. 3a). The herbivores did not differ significantly across the different treatments ($\chi^2 = 4.78$; $p = 0.09$) (Fig. 3b). The predators differed significantly between the bare and covered treatments ($Z = 2.91$; $p = 0.01$) and between the bare and natural treatments ($Z = 2.52$; $p = 0.03$) (Fig. 3c). The omnivores did not differ significantly between the three treatments ($\chi^2 = 5.26$; $p = 0.07$) (Fig. 3d).

3.3. *Effects of management of soil fauna assemblage composition*

The multivariate analyses revealed significant soil fauna composition responses to management (Fig. 4). The assemblage composition of both the total soil fauna (Obs.stat = 303.9; $p = 0.02$) (Fig. 4a,b) and ants (Obs.stat = 52.81; $p = 0.03$) (Fig. 4c,d) only differed between the bare and covered treatments. Beetles did not significantly differ in composition between any of the treatments (Fig. 4e,f). Spiders' composition strongly differed between bare and natural treatments (Obs.stat = 93.37; $p = 0.02$), as well as between natural and covered treatments (Obs.stat = 73.78; $p = 0.05$) (Fig. 4g,h).

3.4. *Effects of vegetation characteristics on soil fauna diversity, functional CWM, and composition*

Taxonomic groups were mainly influenced by litter cover which had significant and positive effects on total species diversity ($t = 5.17$; $p < 0.001$), as well as spiders ($t = 5.67$; $p < 0.001$) (Table 1) and ants' diversity. Plant species richness had significantly negative effects on ants ($t = -3.46$; $p < 0.001$). Beetles were the only group not significantly influenced by any of the vegetation characteristics (Table 1).

With regards to the functional groups, vegetation cover had a significantly positive influence on predators ($t = 6.07$; $p < 0.001$), omnivores ($t = 2.43$; $p < 0.05$), and detritivores ($t = 3.33$; $p < 0.001$) (Table 1). On the other hand, vegetation cover had a significantly negative influence on herbivores ($t = -3.02$; $p < 0.01$).

When considering assemblage composition, vegetation characteristics had significant effects only on the total fauna and beetle assemblages, while other groups (ants and spiders) were not influenced by these variables (Table 2). Essentially, the total soil fauna composition was only influenced by litter cover ($\chi^2 = 16.57$; $p < 0.05$), while beetles were influenced by litter cover ($\chi^2 = 12.74$; $p < 0.05$) and plant species richness ($\chi^2 = 12.09$; $p < 0.05$) (Table 2).

4. Discussion

Effective vineyard inter-row vegetation management is crucial for maintaining vineyard health, productivity, and sustainability. Properly managed inter-row vegetation can reduce soil erosion, improve soil health, and increase water infiltration (Rocher et al., 2024). Moreover, inter-row vegetation can provide habitat for beneficial insects and microorganisms, promoting biodiversity and ecosystem services (Kassel et al., 2018). Here, there were significant impacts of vineyard inter-row vegetation on soil fauna diversity, functional structure, and assemblage composition. These findings underscore the importance of vegetation characteristics, such as vegetation cover, litter cover, and plant species richness, in shaping soil fauna communities.

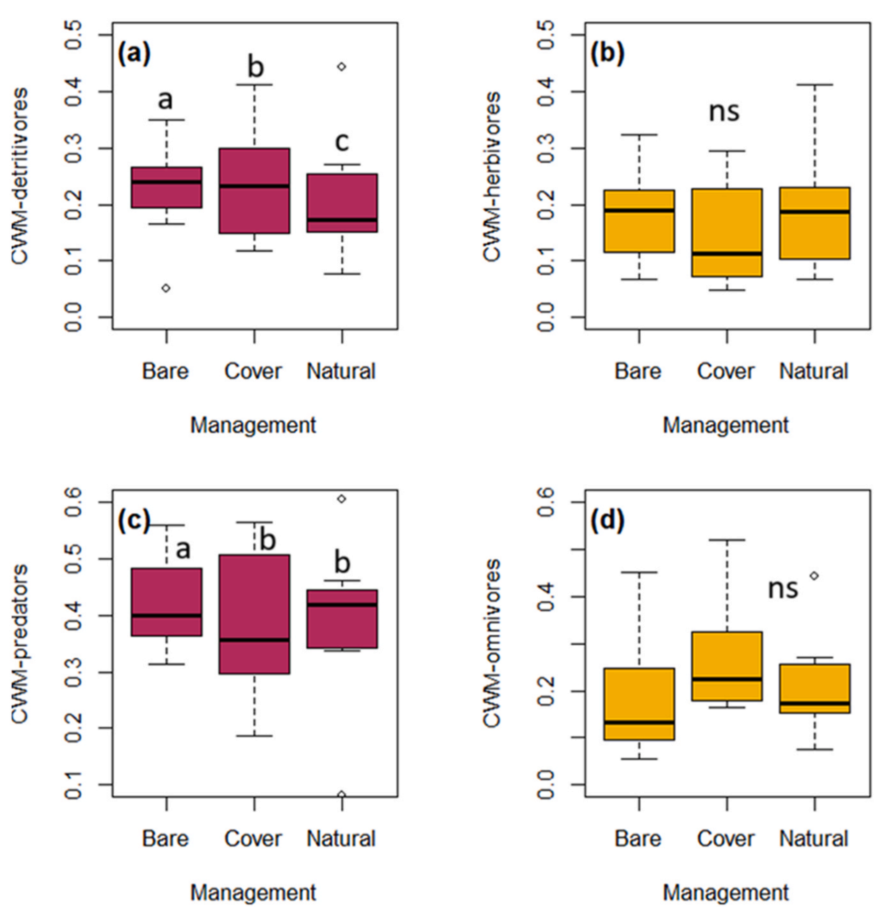

Fig. 3. Differences in proportions of the community-weighted mean (CWM) for (a) detritivores, (b) herbivores, (c) predators, (d) and Omnivores. Means with letters in common are not significantly different (Tukey's post-hoc tests at $p < 0.05$), ns-non significance. The central horizontal line indicates the median, the boxes represent the interquartile range, and the whiskers show the standard deviation for each treatment.

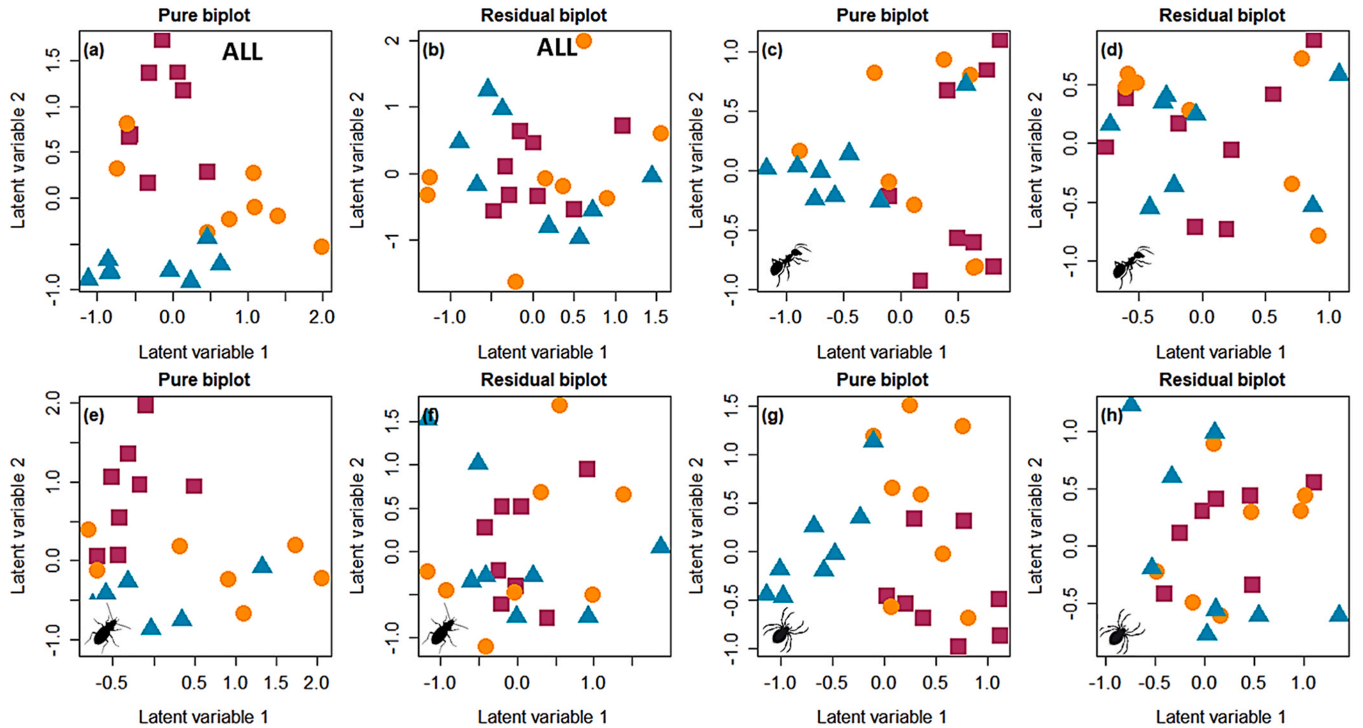

Fig. 4. Model based pure (without predictors) and residual (with predictors) latent ordination plots displaying differences in soil fauna assemblage composition across the different managements. Total fauna (a and b) Formicidae (c and d), Coleoptera (e and f) and Araneae (g and h). Management types are denoted by the coloured points as: Bare = maroon square; Cover = orange circle; Natural = green triangle.

Table 1
Results for the effects of vegetation characteristics on soil fauna diversity (Shannon) and functional CWM. Test-statistics are displayed as t-values. The variance explained by the explanatory variables is represented by the R^2 value. Variables not included in the best fit models are indicated with a —.

Response variables	R^2	Flowering	Litter (%)	Bare (%)	Vegetation (%)	Plant richness
TAXONOMIC						
Total	0.57	—	**5.17*****	—	−0.64	—
Araneae	0.45	—	**3.27****	—	0.45	—
Coleoptera	0.04	—	—	—	0.76	—
Formicidae	0.63	—	**5.67*****	—	0.01	**−3.46*****
FUNCTIONAL						
Predators	0.38	—	—	—	**6.07*****	1.96
Omnivores	0.78	—	—	—	**2.43***	—
Herbivores	0.48	—	1.07	—	**−3.02****	—
Detritivores	0.51	—	−0.37	—	**3.33*****	—

Significant bold p-values are indicated as: * $p < 0.05$, ** $p < 0.01$.

Table 2
Multivariate generalized linear modelling results, showing the effects of vegetation characteristics on soil fauna composition. Test statistics displayed as Wald $\chi 2$ values.

Variables	Total fauna	Araneae	Coleoptera	Formicidae
Litter (%)	**16.57***	7.94	**12.74***	7.01
Vegetation (%)	12.35	6.70	9.39	4.39
Plant richness	15.21	6.74	**12.09***	6.31

Significant bold p-values are indicated as: *$p < 0.05$, **$p < 0.01$.

4.1. Effects of management of soil fauna diversity, composition, and functional CWM

Diversity assessments showed that both the bare, covered, and natural treatments differed significantly from each other in overall fauna species diversity. The natural vegetation harbored the highest species diversity compared to other treatments, of course this is not surprising since this is a pristine site with limited disturbance. The natural and covered treatments benefited the species diversity of ants similarly with the highest recorded in the covered treatment. Species diversity of beetles only differed between natural and bare vineyards, while displaying similarities to both natural and covered treatments. With regards to spiders, the bare treatments had significantly lower species diversity compared to natural and covered treatments, which did not differ significantly from each other. Soil fauna assemblage composition showed varied responses to management. All the assemblages differed significantly in species composition across the three treatments except for beetles. This pattern may reflect the high functional and taxonomic diversity of beetles, which includes many habitat generalists capable of persisting across a range of environmental conditions (Lövei and Sunderland, 1996; Rainio and Niemelä, 2003). Furthermore, their relatively high dispersal ability and tolerance to habitat modification may buffer beetle assemblages from treatment-specific effects, resulting in more homogeneous community composition across sites (Magura et al., 2004; Niemelä, 1997).

The absence or loss of vegetation cover disturbs the assortment of the natural soil food web structure dominated by various functional guilds

(Geldenhuys et al., 2021; Haddad et al., 2013). Here, soil fauna functional composition showed varying responses to vegetation management. Vineyards with cover had the highest detritivores composition compared to others. The cover could have possibly provided suitable conditions (i.e., shelter, moisture, temperature) for detritivores to thrive (Eckert et al., 2020). The high detritivore within covered vineyards can also be due to adequate food sources for this group (Lichtenberg et al., 2017). Essentially, vegetation provides a constant supply of organic material such as leaves, stems, and roots which are excellent food sources for detritivores (Danne et al., 2010; Landis et al., 2000). Other vineyard management practices, such as irrigation, fertilization, and chemical pest control, can also impact detritivore communities. Irrigation's effects can be context-dependent, with adequate moisture levels enhancing detritivore activity and abundance (Lavelle et al., 2021), while excessive water application may be detrimental. Fertilization type can influence detritivore responses, with organic amendments potentially increasing food quality and quantity (Birkhofer et al., 2008), while synthetic fertilizers may have negative impacts. On the other hand, chemical pest control is likely to negatively impact detritivores through direct toxicity or indirect food web disruptions (Geiger et al., 2010).

Omnivores were more pronounced in covered vineyards; however, they did not exhibit any significant differences between the three treatments. This observation can be explained by the fact that, omnivorous are able to exploit a wide range of food sources and are not depended on specific vegetation structure (Winter et al., 2018; Zhu et al., 2024). This may suggest that omnivores in vineyards are resilient and can thrive in various conditions making their population similar in both covered and bare vineyards. Vineyards with vegetation cover coupled with high plant species diversity are known to have higher herbivorous assemblages (Geldenhuys et al., 2021). Here, herbivores, did not differ significantly across the three treatments, although they were high in the natural vegetation.

Predators in vineyards are reported to benefit from reduced management intensity and increased heterogeneity (Isaia et al., 2006; Sharley et al., 2008). Interestingly, the predatory functional group here was shown to be significantly higher in vineyards with no cover. This result was not anticipated because, vegetation cover has previously been reported to increase the population of predators (Fiera et al., 2020b). Moreover, fields with complex vegetation cover and high plant diversity usually have more parasitic and predatory fauna than vegetation-free fields (Speight and Lawton, 1976). The litter and roots provided by spontaneous and/or cover crops can serve as suitable microhabitats for herbivores, thus benefiting their populations, which in turn can promote the increase of predators (Komatsuzaki, 2008). Therefore, the low record of predators in vineyards with cover can be explained by the low herbivores recorded here. Which means that, conditions within the covered treatment were not optimal enough to support increased herbivores populations which in turn could have supported the proper establishment of predators.

4.2. *Effects of vegetation characteristics on soil fauna diversity, functional CWM, and composition*

Litter cover is the main variable which significantly influenced the diversity of the total species diversity as well as the species diversity of ants and spiders. While this result is not entirely consistent with previous studies that emphasize the role of inter-row vegetation cover in enhancing the diversity of beneficial arthropods (Buchholz et al., 2017) it suggests that the structural complexity provided by litter alone may play a similarly important role. Our findings highlight the importance of distinguishing between components of ground cover, such as vegetation and litter, when assessing their influence on arthropod communities. Generally, litter cover supports the population of soil fauna by retaining moisture and creating more stable environments. For spiders, litter cover facilitates the trapping of prey (González and Seastedt, 2001), and reduces soil disturbance, allowing spiders to build more stable burrows and webs (Ciska and Wise, 2011). The ant species were negatively affected by plant species richness. This can be due to the increased plant diversity supporting higher insect abundance, leading to increased competition for ants (Hölldobler and Wilson, 1990). Additionally, diverse plant species can alter soil structure, temperature, and moisture, making it difficult for ants to nest and forage (Cerda et al., 2013). Higher plant species richness often results in more complex and variable root systems, with differences in root depth and density (Wardle et al., 2004), leading to inconsistent soil compaction and porosity. Many ant species rely on stable soil texture to build and maintain their nests, and this variability can make it harder for them to excavate or sustain suitable nest conditions, particularly for species that require specific soil grain sizes or compaction levels (Tschinkel, 2006). Diverse plant canopies also create more heterogeneous shading, which reduces sunlight reaching the soil and lowers surface temperatures (De Boeck et al., 2006). Since ants are ectothermic, cooler soil temperatures can limit their foraging activity or slow brood development, especially for thermophilic species (Cerda et al., 1998). Furthermore, richer plant communities increase evapotranspiration and litter accumulation, altering topsoil moisture levels (Hooper et al., 2000). While some moisture is beneficial, excessive, or inconsistent moisture can flood nests or create unsuitable microhabitats for brood rearing, leading moisture-sensitive ant species to avoid these areas. Combined, these changes in soil structure, temperature, and moisture can make habitats less suitable for certain ant species, particularly those with narrow ecological requirements. Moreover, the increased structural and microclimatic complexity may benefit other invertebrate groups, intensifying interspecific competition as described by Hölldobler and Wilson (1990).

With regards to the functional groups, vegetation cover had a significantly positive influence on detritivores, predators, and omnivores. It is important to note that although, predators were low in covered vineyards compared to bare, here they are found to be significantly affected by vegetation cover. Vegetation cover probably benefitted the composition of predators by providing shelter and ambush sites for them to hide and capture prey (Riechert and Bishop, 1990). Herbivores are the only functional group negatively affected by vegetation cover. The negative effects of vegetation cover on herbivores suggests that vineyards with a higher vegetation cover can be expected to have lower herbivores abundance or diversity (Carlos et al., 2019). Of all the vegetation variables, litter cover is the only variable which influenced the overall soil fauna assemblage composition, while litter cover and plant species richness influenced beetle composition. The increased plants species richness and litter cover is known to create more diverse range of habitats, thereby allowing different beetle species to coexist and thrive (Wang et al., 2022).

This study's findings are subject to several limitations. Firstly, the research was conducted in specific South African ecosystems, which may limit the generalisability of the results to other regions or climates. Additionally, while the study's replicated design provides a robust framework, variations in cover crop types and management practices between farms might have introduced additional variability in the results. Moreover, this study did not investigate the potential trade-offs between biodiversity benefits and vineyard productivity, such as grape yield and quality, which are critical considerations for viticulturists. Future research could benefit from exploring these factors in more detail and replicating the study across multiple sites and years to account for spatial and temporal variability, as well as examining the relationships between inter-row vegetation management, soil fauna communities, and vineyard productivity.

5. Conclusion

This study explored the impact of different vineyard management practices on soil fauna diversity, composition, and functional structure. The results showed that vegetation cover increases soil fauna diversity, with covered and natural treatments having higher species diversity than bare treatments. Different functional groups responded differently to vegetation cover, with detritivores, omnivores, and predators benefiting from it, while herbivores were negatively affected. Litter cover emerged as a key driver of soil fauna diversity and composition, significantly influencing total species diversity, ant and spider diversity, and beetle composition. Overall, the study highlights the importance of vegetation management in shaping soil fauna communities. Vineyards with vegetation cover supported a richer, more functional soil fauna community than bare vineyards, which leads to improved ecosystem services, including nutrient cycling, soil turnover, and pest regulation. Therefore, by promoting ground cover through spontaneous growth or strategic plantings, vineyard managers can adopt sustainable management practices that boost these beneficial services, improving overall vineyard ecological function.

CRediT authorship contribution statement

Emogine Mamabolo: Visualization, Resources, Investigation, Conceptualization, Software, Methodology, Formal analysis, Writing – original draft, Project administration, Funding acquisition, Data curation. **René Gaigher:** Supervision, Formal analysis, Writing – review & editing, Software, Methodology, Conceptualization, Validation, Resources, Funding acquisition. **James S. Pryke:** Software, Funding acquisition, Validation, Resources, Formal analysis, Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2025.109842.

Data availability

Data will be made available on request.

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