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ORIGINAL RESEARCH ARTICLE

Vineyard floor management intensity impacts soil health indicators and plant diversity across South Australian viticultural landscapes

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ABSTRACT

Throughout the last thirty years, major shifts in vineyard floor management have been observed. Challenges initially posed by intensive tillage included high rates of soil erosion and the degeneration of soil structure and soil organic matter, which lead viticulturists to depend more heavily on herbicide use as an effective weed control strategy. However, an increase in herbicide persistence and toxicity in water, soils, and grapevines, increasing resistance of common weeds; and pressure from consumers and regulators to reduce their use is directing a shift towards an overall reduction in herbicide usage. This has led to more frequent tillage to manage vegetation in vineyards, while in some instances, cultural practices including slashing and animal grazing are used solely or in conjunction. However, little is known about the holistic effects of these varying practices on vineyard soils and biodiversity across landscapes in Australia. Thus, to comparatively assess the environmental impacts of different floor management practices, soil health indicators and plant dynamics were seasonally measured in the mid- and under-vine rows at twenty-four vineyard sites and four native sites in the Barossa Valley, Eden Valley, and McLaren Vale, all located in South Australia, where different intensities of floor management were implemented. Vineyard sites were categorised based on the frequency of herbicide and/or tillage passes particularly in the under-vine area into Low (no annual management passes), Medium (one annual management pass), and High (two to four annual management passes) intensity groups. Findings revealed similarities in the vineyard mid-rows across the management intensities, yet the under-vine rows displayed many differences; in particular, there were more plant species, higher plant coverage, and greater plant biomass in the Low management intensity group. Furthermore, as management intensity decreased, the relative richness of ruderal plant species also decreased, giving way to a plant community mainly comprised of slow-growing, perennial Poaceae and Fabaceae species in the Low-intensity management group. These differences in plant dynamics drove a suite of soil responses including faster water infiltration, higher soil ammonium-N and total nitrogen, and a tendency of higher soil gravimetric water content at the time of sampling. These results suggest that after an initial period of establishing these more extensive vineyard floor management practices, low levels of soil disturbance in the under-vine rows may contribute positively to improving natural ecosystem synergy and functionality between soil and plants. Therefore, our findings lend insights into how the varying intensity of floor management practices, rather than differing management ideologies *per se*, across a viticultural landscape can be intrinsic supporters of agroecosystem resilience under South Australian conditions.

KEYWORDS: vineyard floor management, soil health, biodiversity, management intensity, management ideology, viticultural landscape

INTRODUCTION

Vineyard floors in warm, dry landscapes including those in South Australia, have traditionally been managed using intensive practices such as tillage and herbicides to control weeds and vegetation, thereby limiting competition with grapevines for water and nutrients to not compromise yields (Celette *et al.,* 2009). However, there is increased awareness about the environmental impacts associated with chemical herbicides and high-intensity tillage, both of which can result in increased coverage by bare earth and, thus, detrimentally affect soil health and biodiversity (Winter *et al.,* 2018; Guzmán *et al.,* 2019). As such, many recent investigations have been made to explore the potential of increasing vineyard floor ground cover using sown or spontaneous vegetation in addition to reducing the frequency and intensity of tillage and herbicides, and their associated relationships to ecosystem service provisioning (Garcia *et al.,* 2018; Abad *et al.,* 2021).

Although there has been a noticeable shift in vineyard floor management towards more extensive and ecological practices in the last two decades, there are differences in the rates of adoption between winegrowing regions and between the mid-row and under-vine row areas in vineyards (Payen *et al.,* 2022). While it has been demonstrated that in some vineyard sites, competition with grapevines for water and nutrients limiting grapevine yield is one of the main factors restraining the use of complete vineyard floor vegetation cover (Karl *et al.,* 2016a; Guerra *et al.,* 2022), this yield discrepancy is not always significant (Giese *et al.,* 2014). Recent investigations of complete vineyard floor coverage systems have been predominantly focused in cool, wet winegrowing regions such as those in the Eastern United States, where many studies have indicated improved provisioning of ecosystem services in addition to more ideal vine balance as a result of these strategies (Vanden Heuvel and Centinari, 2021).

Further to the exploration of how management practices impact environmental health indicators is the discussion of how third-party certifications, such as organic, may compare to a gradient of management intensity categories as an alternative method to categorising vineyard practices. Findings from a South African life cycle assessment (LCA) suggested that diesel and energy requirements were the main contributors to the overall end-point footprint effects on the ecosystem and human health and that the reduction of herbicides and insecticides did not, in fact, impact their model outcome (Russo *et al*., 2021). This leads to the school of thought that unless farming practices replacing agrochemical usage (such as tillage) were compensated by reducing fertilisers or irrigation, these non-chemical alternatives may instead contribute more significantly to global warming potential (Russo *et al.,* 2021). In addition to these insights on energy consumption, improving carbon sequestration in vineyard soils has been identified as a premier goal for agroecological vineyard management around the world given its cascade of associated ecosystem benefits and services (Brunori *et al.,* 2016). A meta-analysis on the impacts of soil carbon sequestration in vineyards under different management schemes similarly concluded that no-tillage vineyard systems and those that add organic amendments achieved the highest rates of soil organic carbon sequestration (Payen *et al.,* 2021).

Increasing plant coverage, as opposed to coverage by bare soil, in vineyards across Mediterranean climates has been previously shown in a plethora of studies to enhance biodiversity at different trophic levels (Danne *et al.,* 2010; Winter *et al.,* 2018), whilst improving soil water infiltration rates (García-Díaz *et al.*, 2018), improving carbon sequestration (Guzmán *et al.,* 2019; Marks *et al.,* 2022), reducing run-off and erosion (Ruiz-Colmenero *et al.,* 2013), and improve overall functionality across different soil types (Salomé *et al.*, 2016). Management practices that promote higher levels of plant coverage such as reduced tillage, mowing, and grazing are, therefore, suggested as means to improve the longevity of vineyard agroecosystems. As management ideologies including certification-based approaches such as organic are not given on a plant-coverage basis per se, it is not always the case that organic management fosters better soil health and biodiversity (Bruggisser *et al.,* 2010), and it is suggested that instead, specific floor management practices to determine plant coverage may be the underlying significant contributors in these outcomes (Coll *et al.,* 2011; MacLaren *et al.,* 2019).

Vineyard floor plant diversity and community dynamics in Mediterranean vineyards are strongly linked to floor management practices and intensities (Nascimbene *et al.,* 2013; Kazakou *et al.,* 2016; Fried *et al.*, 2019; MacLaren *et al.,* 2019; Guerra *et al.*, 2021; Guerra *et al.*, 2022), with the main trade-off that growers have to consider being the competitive nature of plant species with vineyard yield and the ecosystem services lent by these plant species to support biodiversity and soil functionality (Garcia *et al.*, 2018). There is evidence to suggest that minimal vegetation management in vineyards may support less competitive plant species, and, thus, the need for management action decreases whilst biodiversity improves (MacLaren *et al.,* 2019). In addition to the specific site conditions, agronomic management practices are strong predictors of the surviving plant species and community dynamics, as herbicides, tillage, and mowing have different modes of action that select for or against particular species (Navas, 2012). Tillage practices in vineyards can promote plants that are fast-growing and with high specific leaf areas (Kazakou *et al.,* 2016; MacLaren *et al.,* 2016), while herbicides may select for species with smaller seed masses that germinate rapidly (Guerra *et al.,* 2021). In addition to specific floor management practices, management ideology also tends to be associated with determining plant species richness, as was the case in a South African vineyard landscape (MacLaren *et al.,* 2019), yet was not an important contributor to plant diversity in Swiss vineyards (Bruggisser *et al.,* 2010) or across European arable farming landscapes (Garland *et al.*, 2021).

In addition to there being positive evidence to suggest that enhancing vineyard floor plant coverage is favourable from

an environmental perspective, there is also growing interest in reducing herbicide use and intensive tillage from the perspective of French vignerons (Moneyron *et al.,* 2017), supported by wine industry professionals worldwide who ranked soil health, water use efficiency, and biodiversity as the top three most important environmental indicators for their businesses (Santiago-Brown *et al.,* 2015). Even from the perspective of wine consumers, integrating cover crops into vineyard systems would eventuate in a higher willingness to pay for wines produced using these practices (Kelley *et al.,* 2022).

Given these trends in increasing vineyard floor plant coverage and different approaches to the categorisation of vineyard management intensity and ideology, we propose to investigate how different practice intensities and ideologies, from disturbed to complete vineyard floor coverage, and conventional to organic management, are used by commercial vineyards in drier, yet irrigated viticultural regions. Specifically, we aim to assess how these systems comparatively affect plant diversity and soil health indicators across dense viticultural landscapes. Findings from another viticultural landscape study in a drier climate in Spain indicated that vineyards with cover crops compared to bare soil had higher soil organic carbon and greater plant biomass; however, this study focused solely on vineyard mid-row areas (Guzmán *et al.,* 2019). Furthermore, another landscape study demonstrated that high mid-row management intensity at vineyards across Austria, France, Spain and Romania reduced plant species richness (Hall *et al.,* 2020). In French winegrowing regions, environmental conditions were the primary drivers of vineyard floor species composition, yet richness and abundance were directly correlated to management practices (Fried *et al.,* 2019). Therefore, it is yet to be determined how plant diversity and soil health indicators compare in drier yet irrigated vineyard sites across a landscape with different floor management intensities and ideologies, and in both the mid-row and under-vine row areas. To address these questions, a comprehensive investigation at the landscape level of varying intensity levels of vineyard floor management practices used in the Barossa Valley, Eden Valley, and McLaren Vale regions was conducted to explore the effects on various environmental indicators of biodiversity and soil health.

MATERIALS AND METHODS

1. Description of vineyard and unmanaged native sites

This study was conducted during the 2020–2021 growing season at twenty-four commercial vineyard sites and four unmanaged native sites in the Barossa Valley, Eden Valley, and McLaren Vale Geographical Indications (GIs) of South Australia. As shown in Table 1, five vineyard sites and one native site were included from both the Barossa Valley and Eden Valley; and in McLaren Vale, there were fourteen vineyard sites and two native sites included in the study. All vineyard sites are planted with red winegrape varieties and have a range of different mid-row and under-vine floor management practices (Table 1), in addition to management ideologies (Table 2). At each vineyard site, three equidistant replicates of three panels, containing three or four vines each, were established along the longest diagonal transect of the site. Samples were collected from the mid-row and under-vine areas at each replicate separately. The four native unmanaged sites were all located adjacent to vineyard blocks included in the study, and at each of these, three equidistant replicates were also established along the longest diagonal transect of the site, each totalling approximately fourteen metres in length to coincide with the average length of the replicates in the vineyard sites.

2. Categorization of sites into floor management intensity groups

Floor management practices, namely those used to control weeds, conserve soil health, and conserve water (Guerra and Steenwerth, 2012), were used to categorise the sites into three distinct floor management intensity groups of Low, Medium, and High (Table 1). Sites in the Low-intensity group did not use any 1-3 passes of tillage nor herbicides in the under-vine row and managed the mid-rows only by slashing and animal grazing. Sites in the Medium-intensity group included one pass of herbicides or tillage in the under-vine row, while the mid-row was managed only by slashing and animal grazing. The High-intensity group was characterized by sites that used between two and four passes of herbicides in the under-vine row and a mid-row managed with cover crops or permanent vegetation with tillage and slashing. The native unmanaged sites were located adjacent to vineyard blocks and did not undergo any reported floor management interventions. All sites included in this study had been managed consistently for at least the previous three growing seasons prior to collecting measurements (Table 1). Management ideologies of the growers from each site are shown in Table 2 along with a simplification of these ideologies into the four groups: Regenerative, Conventional, Low-input, and Organic for comparison purposes.

3. Plant diversity surveys

Plant surveys to assess plant species diversity and coverage were carried out at all sites during four seasonal sampling times spanning the 2020-2021 growing season in winter (June-July) 2020, spring (September-October) 2020, summer (December) 2020, and autumn (February-March) 2021. Specific attention was made to avoid rainfall events occurring between sampling different sites within each seasonal sampling campaign. At each of the sites, a total of nine mid-row and nine under-vine row assessments were made. The surveys were undertaken by placing a $1m^2$ frame with a 10 × 10 cm grid in the centre of the panel in each mid-row and under-vine area, after which the plant species and per cent ground coverage within the frame were identified (Guzmán *et al.,* 2019). After the species surveys were carried out, a 0.25 m^2 frame was placed in the middle of each mid- and under-vine row replicate and all above-ground plant biomass was harvested and dried for seven days at 65 °C, after which it was weighed. Sørensen and Shannon diversity

TABLE 1. Characteristics of the vineyard sites and their floor management practices.

Site ID	GI[a]	Year of vine planting	Elevation (m)	Soil texture[b]	Time (yrs.)[c]	Type of mid-row[d]	Mid-row veg. mgt. practices[e]	Mid-row passes[f]	Type of under-vine row[g]	Under-vine veg. mgt. practices[h]	Under-vine passes[f]	Months of grazing animals	Management intensity group[i]
1	EV	1998	395	Loamy sand	5	SS	S	2	BE	H	4	1	High
2	BV	1992	290	Loam	30	CC	S + T	2 + 1	BE	H	2	1	High
3	MV	1999	55	Silty clay loam	15	SS	S	3	BE	H	4	-	High
4	BV	1995	280	Loam	15	CC	S + T	3 + 1	BE	H	2	-	High
5	EV	1997	390	Loamy sand	23	SS	S	3	BE	H	2	-	High
6	EV	1990	350	Loamy sand	30	CC alt. SS	S + T	1 + 0.5	BE	H	2	-	High
7	MV	1999	60	Loam	22	CC alt. SS	S + T	1 + 0.5	BE	H	3	-	High
8	MV	1973	190	Loamy sand	15	CC	S + T	3 + 1	BE	H	3	-	High
9	MV	1998	110	Silty loam	15	CC	S + T	3 + 1	BE	H	2	-	High
10	EV	1998	430	Loamy sand	24	SS	S	2	BE	H	1	3.5	Medium
11	BV	2010	310	Loamy sand	15-20	CC	S + T	1 + 2	BE	T	3	-	Medium
12	BV	late 1960's	285	Sand	6	SS	S + T	2 + 1	SS	S + T	1 + 3	-	Medium
13	MV	2001	75	Loamy sand	12	CC alt. SS	S + T	3 + 0.5	SS	T	3	4	Medium
14	MV	1996	80	Loamy sand	10	SS	S	2	SS	H	1	3.5	Medium
15	MV	1971	70	Loamy sand	14	SS	S	2	BE	H	1	-	Medium
16	MV	1997	140	Loamy sand	6	CC	S + T	1 + 1	SS	T	1	3	Medium
17	MV	2016	82	Silty loam	4	Mix SS + CC	S	2	SS	T	1	0.5	Medium
18	BV	2009	285	Loam	3	SS	S	3	SS	-	-	-	Low
19	EV	1998	395	Loamy sand	5	SS	S	2	SS	-	-	1	Low
20	MV	1999	90	Silty loam	14	SS	S	5	SS	S	2	-	Low
21	MV	1989	175	Silty loam	10	SS	S	2	SS	S	1	1.5	Low
22	MV	1990	110	Loam	20	SS	S	2-3	SS	-	-	-	Low
23	MV	1993	110	Loamy sand	8	SS	S	2	SS	-	-	-	Low
24	MV	early 2000's	100	Silty loam	6	CC alt. SS	S + T	2 + 0.5	SS	-	-	-	Low
25	EV	-	385	Loamy sand	80	NV	-	-	-	-	-	-	Native
26	BV	-	280	Loam	50	NV	-	-	-	-	-	-	Native
27	MV	-	180	Silty loam	> 20	NV	-	-	-	-	-	-	Native
28	MV	-	70	Loamy sand	20	NV	-	-	-	-	-	-	Native

[a] Australian Geographical Indication (GI): BV: Barossa Valley, EV: Eden Valley, and MV: McLaren Vale.

[b] Australian Soil Classification as determined by MIR spectroscopy (Isbell and National Committee on Soil Terrain, 2021).

[c] Time that specified vineyard management has been implemented in years (yrs).

[d] Predominant type of mid-row vegetation: CC: annually sown cover crop, CC alt. SS: rows with annual alternating sown cover crop and spontaneous sward, Mix SS + CC: spontaneous sward with a mix of cover crop species direct drilled, and SS: spontaneous sward.

[e] Mid-row vegetation (veg.) management (mgt.): S: slash and T: tillage.

[f] Passes of vegetation management indicated for the mid-row or under-vine row vegetation management in order of listed practice.

[g] Predominant type of under-vine row: BE: bare earth and SS: spontaneous sward.

[h] Under-vine row vegetation (veg.) management (mgt.): Herbicide: H, S: slash, and T: tillage.

[i] Floor management intensity group: High: mid-row cover crops or spontaneous sward with a bare earth under-vine row managed with 2 or more passes of herbicides, Medium: mid-row cover crops or spontaneous sward with bare earth or spontaneous sward under-vine row managed with either 1 pass of herbicides or 1–3 passes of tillage, Low: mid-row spontaneous sward or cover crops alternating with spontaneous sward with a spontaneous under-vine row without management or managed by slashing, and Native: native area adjacent to a vineyard that has not received management intervention for at least the last 20 years.

TABLE 2. Summary of vineyard management ideology in the grower's own words and simplified for categorisation purposes.

Site ID	Management ideology (grower's own words)	Management ideology (simplified)
1	Holistic regenerative	Regenerative
2	Minimum intervention, traditional	Conventional
3	Grow balanced vines in relation to terroir	Conventional
4	Improve soil	Conventional
5	Typical management	Conventional
6	Mix of old and new school	Conventional
7	Conventional	Conventional
8	Low-impact, traditional	Conventional
9	Low-input	Low-input
10	Leave the soil alone	Low-input
11	Biodynamic	Organic
12	Regenerative farming	Regenerative
13	Biodynamic	Organic
14	Low-input, integrated pest management	Low-input
15	Little inputs	Low-input
16	Biodynamic	Organic
17	Regenerative agriculture	Regenerative
18	Biodynamic	Organic
19	Holistic regenerative	Regenerative
20	Low-input, tracking towards organic	Low-input
21	Biodynamic	Organic
22	Organic	Organic
23	Hands-free, no weed control, biodynamic preparations	Low-input
24	Organic	Organic

index calculations were made to investigate how the plant communities compared between the three management intensity groups and the native sites during the four sampling seasons using the following formulas:

$$Sørensen\ index = \left(2 \times \frac{c}{a+b}\right) \times 100$$

Equation 1. Sørensen index, where *a* refers to the total number of species in one plant community, *b* refers to the total number of species in a different plant community, and *c* refers to the number of species common in both plant communities. Sørensen index values compare species in different communities and range from 0 to 100, with 0 indicating no common species and 100 indicating that all species are common. Values above the threshold of 70 indicate that the species in the two communities are similar (Magurran, 2004).

$$Shannon\ diversity\ index = -\sum[(\rho_i)\ \times \log(\rho_i)]$$

Equation 2. Shannon diversity index, where $\rho_i = \frac{n}{N}$, where *n* refers to the individual number of given plant species and *N* refers to the total number of individuals in the plant community. The Shannon diversity index is an indicator of species richness within a community, with the range starting at 0, indicating a community with one specie, and having no upper limit. Typical ranges for this index are between 1-3.5 (Magurran, 2004).

4. Measurement of soil health indicators

At the same time as plants were surveyed, 500 g composite soil samples were collected from the top 2-12 cm in the mid- and under-vine rows at each replicate to assess plant-available nitrogen as nitrate ($N\text{-}NO_3^-$) and ammonium ($N\text{-}NH_4^+$), and soil gravimetric water content. Soil dry bulk density and *in situ* water infiltration measurements were measured in mid- and under-vine rows in triplicate at every replicate during spring 2020. Water infiltration was measured following the two-trial, single-ring method where rings of volume size 300 cm^3 were hammered gently 2 cm into the soil surface and the time for 100 mL of water to completely pass into the soil was measured (USDA NRCS, 1999). A second measurement was repeated in the same ring, which was the value used for this study to reduce the effect of unevenly saturated soils, which can have an effect on water infiltration rates into

the soil profile (Porzig *et al.*, 2018). During the autumn of 2021, soil samples were collected and comprehensive soil physiochemical analyses were measured by the Eurofins Australian Precision Agriculture Laboratory (Eurofins APAL, Adelaide, Australia, https://www.apal.com.au/Home.aspx) including soil texture, pH (1:5 soil:water), electrical conductivity, cation exchange capacity, total nitrogen and carbon, total organic carbon, and plant-available phosphorus (Colwell) according to the protocols in Rayment and Lyons (2011).

5. Statistical analyses

Data analysis were performed using R (version 4.1.2, R Core Team, 2021). Non-parametric Kruskal-Wallis tests were used to measure differences in the measured plant diversity including species richness and biomass, in addition to various soil health indicators between the management intensity groups, as the data were not normally distributed within the groups. All figures were made in ggplot2 in R. Principal component analyses (PCA) were conducted to assess for relationships between the measured soil and plant variables, for which the "factoextra" package in R was used. Finally, a linear mixed model was developed where environmental and management practices were included to assess their effects on measured soil and plant variables. The vineyard sites included random effects in these linear mixed models, for which the "BiometryTraining" package was used in R (Nielsen *et al.,* 2021).

RESULTS

1. Floor management intensity impacted under-vine seasonal plant and soil measurements

Plant cover, plant biomass, and plant species richness were measured consistently at every vineyard and native site across the winter, spring, summer, and autumn seasons to account for both environmental and anthropogenic fluctuations over time. The mid-rows of the vineyard sites in different management intensity groups—High, Medium, and Low—were not different from one another at any point during the 2020-2021 growing season for all three of the aforementioned plant variables and showed similar trends to the plant dynamics in the native sites (Figure 1). Alternatively, plant dynamics in the under-vine areas of the vineyards were very different between the management intensity groups, where the group managing with Low intensity had consistently much greater plant cover than the Medium and High groups across all four seasons, with the latter being the lowest of the three groups at all four seasonal sampling points. Plant biomass was always highest in the Low group; however, the Medium group was not different in the winter and summer sampling times. The High management intensity group consistently had the lowest plant biomass. Species richness was more similar among the three management groups, which was only different at the Autumn sampling time where the Medium group had an average of 10.5 species, compared to 7.5 in the Low group and 6.2 in the High group (Figure 1).

Seasonal soil dynamics of gravimetric water content, total nitrogen, nitrate-N, ammonium-N, pH, and electrical conductivity were also assessed at the mid- and under-vine rows of all sites and the native sites, however, the management intensity groups did not reveal as many differences as were observed with the plant measurements. Consistent with the plant dynamics in Figure 1, the seasonal soil dynamics were similar across all management intensity groups at all seasonal time points (Figure 2). The only differences between groups occurred during spring when soil ammonium and soil electrical conductivity were significantly higher in the Low group, 1.89 g kg^{-1} and 0.36 dS m^{-1}, respectively, compared to the Medium and High groups, which were statistically the same (Figure 2).

2. Management intensity was a driver of seasonal plant species abundance

Vineyard floor coverage by plants in different taxonomic families was more similar between the management intensity groups for the mid-row areas (Figure 3A) compared to the under-vine areas (Figure 3B) across all four sampling seasons. The mid-row area consisted predominantly of grass species in the Poaceae family regardless of management intensity or season, with the Low and Native groups consistently having the most coverage by Poaceae species throughout the year, ranging from 41.9 % in autumn to 52.6 % in spring for the Low group and from 50.1 % in winter to 78.0 % in summer for the Native group (Figure 3A). Another seasonal trend consistent with all management groups was the high presence of soursob (*Oxalis pes-caprae* L.) in the Oxalidaceae family during the winter sampling campaign, which ranged from 17.1 % in the Low group to 30.4 % in the Medium group and was then reduced to range from 1.1 % in the Low group to 5.7 % in the High group as temperatures warmed in spring. Plant species in the Fabaceae family represented a high degree of coverage in the winter in the Low group with 14.4 % coverage, whilst in spring, they were most prevalent in the Medium and Low groups, with 16.2 % and 19.9 % coverage, respectively. During each seasonal sampling campaign, plants species in the Asteraceae family were consistently highest in coverage in the Medium group where they ranged from 6.4 % in autumn to 17.1 % in spring, while they constituted the least coverage in the Low and Native intensity groups across all four seasons, when their peak was in spring for both groups at 3.3 % and 4.6 %, respectively. Bare earth was always highest in the High group and was 31.7 % at its highest point during the autumn, compared to 30.7 % for the Medium group, 8.7 % for the Low group, and 4.9 % for the Native sites (Figure 3A).

In the under-vine area of the vineyards, a similar narrative to the mid-row presented itself with the barest earth occurring in the High management group during all four seasons, ranging from its lowest in winter at 44.1 % to its highest in autumn at 65.2 % (Figure 3B). The Low group, on the other hand, had the lowest range of bare earth for the vineyard groups across all four seasons with 0.1 % in winter to 7.4 % in autumn, which was more comparable to the Native sites, ranging from 0 % in winter to 4.9 % in autumn. The highest prevalence of

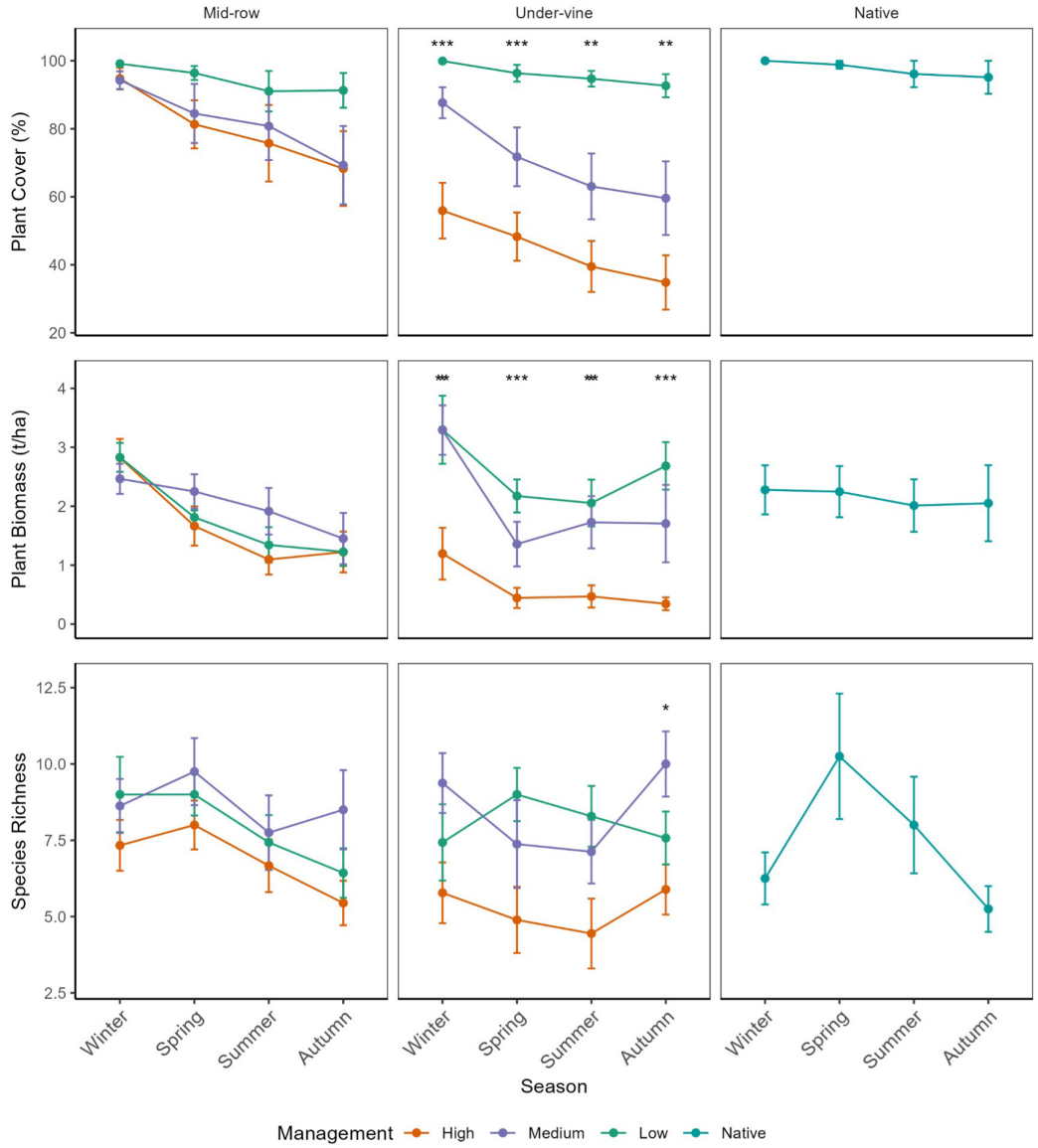


FIGURE 1. Line graphs depicting mean and standard errors of seasonal plant measurements: plant ground cover, plant biomass, and plant species richness measured at all sites in the mid- and under-vine rows, and native sites during the 2020-2021 growing season (winter-spring 2020 and autumn 2021).

Sites are grouped according to management intensity High, Medium, or Low, shown with Native. Kruskal-Wallis non-parametric tests were carried out to assess for differences between groups and are indicated by *** ($p < 0.001$), ** ($p < 0.01$), and * ($p < 0.05$).

plants in the Asteraceae family occurred during winter in the High group with 5.6 % and Medium group with 10.5 %, while the Low and Native groups had 3.8 % and 2.8 % coverage by Asteraceae plants during this time. During the more active growing season in spring, Fabaceae plants became more prominent in the Medium, Low, and Native groups, with 7.1 %, 10.2 %, and 6.7 % coverage, respectively, compared to 1.1 % in the High group. Similar to the mid-row, Poaceae species consistently contributed to the most coverage in the Low and Native groups across all seasons in the under-vine row, ranging from 56.4 % in winter to 57.4 % in autumn for the Low group and 52.4 % in winter to 69.6 % in autumn for the Native group (Figure 3B).

3. Annual average plant and soil measurements were impacted by management intensity

The average plant species richness sampled at all four seasons during the 2020-2021 growing season was higher in the Medium-intensity mid-rows compared to High-intensity mid-rows in particular, at the $p < 0.1$ level (Table 3). On the other hand, the above-ground plant biomass was similar for all mid-row areas, while plant cover was greatest in the Low and Native sites compared to the High and Medium sites by between 12.3–14.4 % (Table 3).

The Shannon diversity index, which considers the entire population of plant communities in each group compared

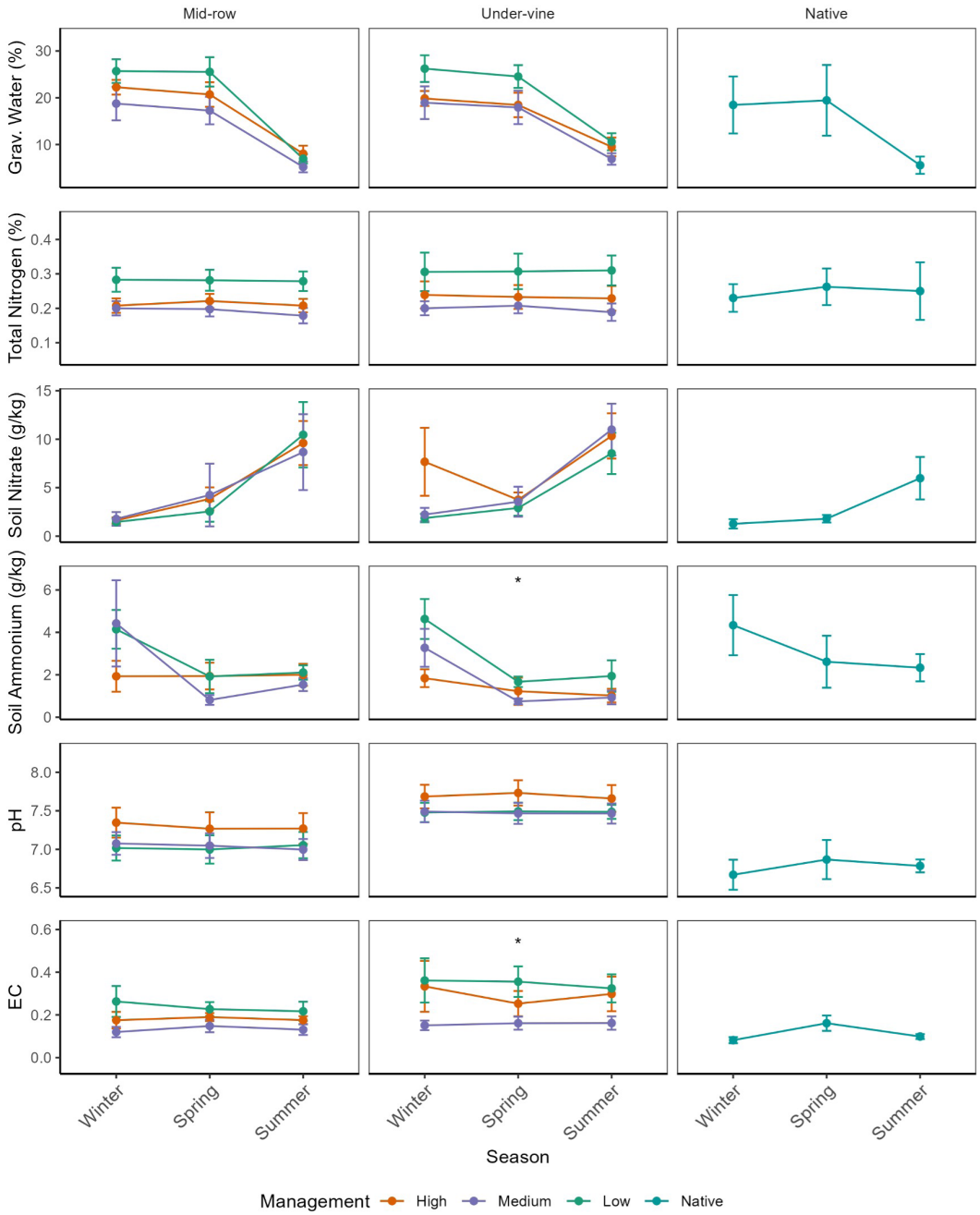


FIGURE 2. Line graphs depicting mean and standard errors of seasonal soil measurements: gravimetric water content (Grav. Water), total nitrogen, nitrate ($N\text{-}NO_3$-), ammonium ($N\text{-}NH_4$+), $pH_{(1:5\ water)}$, and electrical conductivity (EC) measured at all sites in the mid- and under-vine rows, and native sites during the 2020-2021 growing season (winter-spring 2020 and autumn 2021).

Sites are grouped according to management intensity High, Medium, or Low, shown with Native. Kruskal-Wallis non-parametric tests were carried out to assess for differences between groups and are indicated by * ($p < 0.05$).

to individual populations (Magurran, 2004), revealed some insights compared to the raw plant richness counts. These seasonal Shannon diversity indices indicated that the Low group had the highest mid-row species richness for the winter sampling campaign, whilst, in spring, summer, and autumn, the High and Medium groups had the highest species richness. Overall, the High group had a similar plant community to the Medium group and the Low group, as indicated by Sørensen index values of 73.8 % and 72.5 %, respectively (Table 3).

Annual averages of the measured soil properties displayed differences amongst management intensity groups in the mid-rows for the variables of total nitrogen, pH, and electrical conductivity, of which total nitrogen was greatest for the Low-intensity sites and pH was lowest for the Native sites compared to the High sites (Table 3). Electrical conductivity

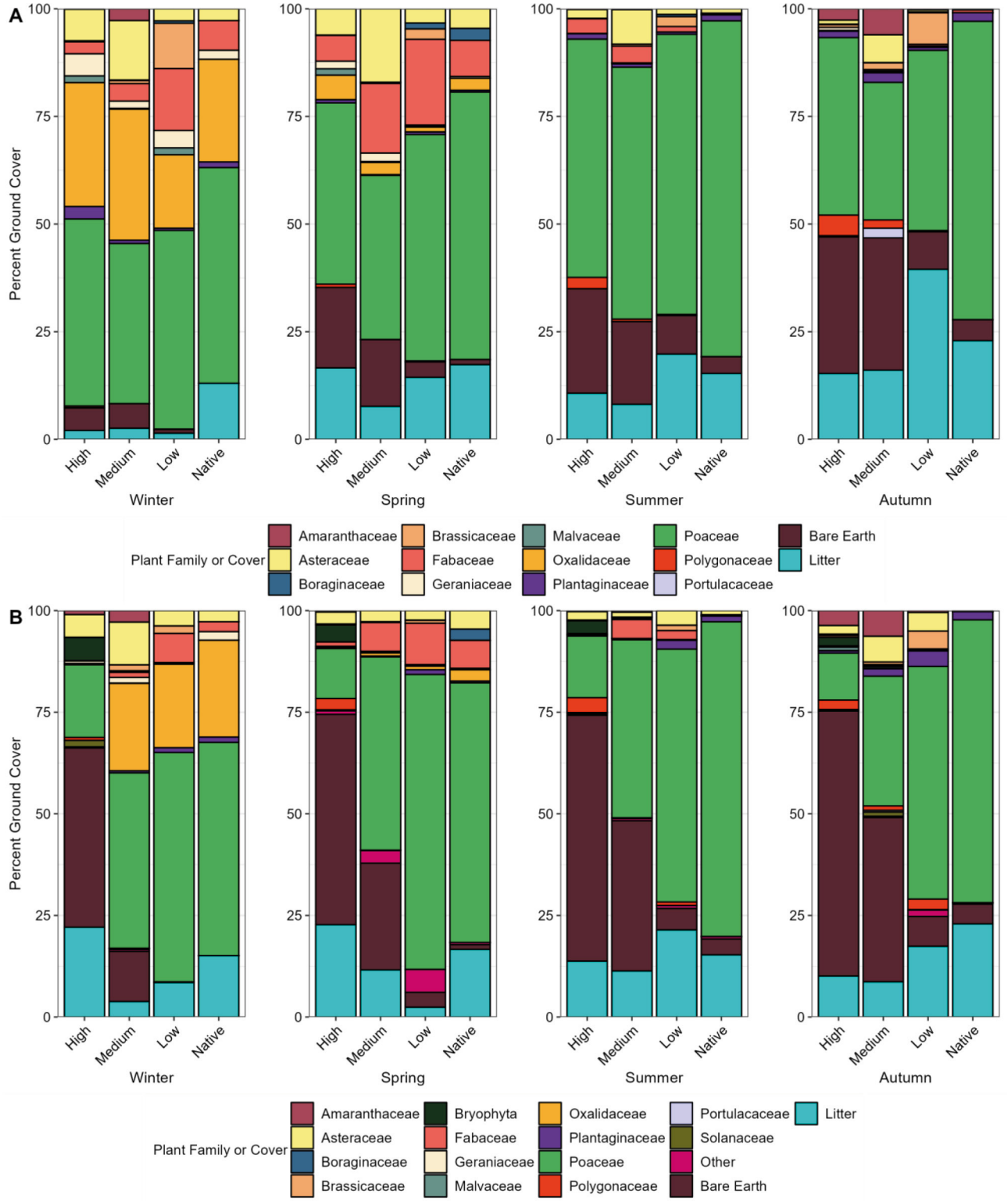


FIGURE 3. Plant family per cent coverage measured seasonally (winter 2020, spring 2020, summer 2020, and autumn 2021) in the (A) mid-rows; and the (B) under-vine rows of the High, Medium, Low, and Native intensity groups.

Plant family per cent ground cover was collated by assessing the per cent ground cover by individual plant species and grouping plants in their designated taxonomic families. The coverage lent by each taxonomic family is expressed as a percentage of the total surveyed floor coverage in all sites within the management intensity group, thus, ground cover of bare soil and litter are also depicted here. For each seasonal sampling time (winter, spring, summer, and autumn), n = 9 at every site.

TABLE 3. Summary of annual average ± standard error of mid-row and under-vine plant and soil measurements measured in the three management intensity groups of High, Medium, and Low, shown alongside the Native sites.

		High	Medium	Low	Native	*p*-value	Sig.
Mid-row plant measurements	Plant species richness	6.86 ± 0.42	8.66 ± 0.55	7.96 ± 0.49	7.67 ± 0.82	0.083	°
	Plant biomass (t·ha^{-1})	1.70 ± 0.19	2.02 ± 0.18	1.80 ± 0.16	2.19 ± 0.22	0.384	
	Plant cover (%)	80.03 ± 4.50 b	82.21 ± 4.51 b	94.47 ±2.02 a	97.36 ± 1.60 a	0.001	**
	Living plants (% of total plants)	60.81 ± 6.21	55.41 ± 6.97	60.43 ±7.19	59.26 ± 9.21	0.936	
	Shannon diversity index—Winter	2.56	2.44	2.71	2.21		
	Shannon diversity index—Spring	2.85	2.78	2.39	2.43		
	Shannon diversity index—Summer	2.64	2.62	2.14	2.14		
	Shannon diversity index—Autumn	2.40	2.87	1.95	1.76		
	Sørensen index—High (%)	-	73.8	72.5	52.5*		
	Sørensen index—Medium (%)		-	66.7*	49.4*		
	Sørensen index—Low (%)			-	57.5*		
Mid-row soil measurements	Soil gravimetric water (%)	17.00 ± 1.68	13.74 ± 1.98	19.40 ± 2.37	14.5 ± 3.54	0.182	
	Soil total nitrogen (%)	0.21 ± 0.01 bc	0.19 ± 0.01 c	0.28 ± 0.02 a	0.25 ± 0.03 abc	0.003	**
	Soil nitrate-N (mg·kg^{-1})	5.02 ± 1.06	4.90 ± 1.74	4.82 ±1.44	3.01 ± 0.94	0.506	
	Soil ammonium-N (mg·kg^{-1})	1.96 ± 0.35	2.26 ± 0.73	2.72 ± 0.46	3.09 ± 0.65	0.141	
	Soil pH $_{(water)}$	7.29 ± 0.11 a	7.04 ± 0.08 ab	7.02 ± 0.09 ab	6.77 ± 0.10 b	0.050	*
	Electrical conductivity (dS·m^{-1})	0.18 ± 0.02 a	0.13 ± 0.01 b	0.24 ± 0.03 a	0.11 ± 0.02 b	0.002	**
Under-vine plant measurements	Plant species richness	5.25 ± 0.50 b	8.47 ± 0.59 a	8.07 ± 0.49 a	7.67 ± 0.82 a	0.0003	**
	Plant biomass (t·ha^{-1})	0.61 ± 0.14 b	2.02 ± 0.27 a	2.55 ± 0.22 a	2.19 ± 0.22 a	< 0.001	***
	Plant cover (%)	44.62 ± 3.93 c	70.51 ± 4.59 b	95.90 ± 1.24 a	97.36 ± 1.60 a	< 0.001	***
	Living plants (% of total plants)	36.11 ± 5.94 b	49.88 ± 7.23 ab	62.34 ± 5.13 a	59.26 ± 9.21 ab	0.0377	*
	Shannon diversity index—Winter	2.38	2.65	2.24	2.21		
	Shannon diversity index—Spring	1.85	2.57	2.23	2.43		
	Shannon diversity index—Summer	1.50	2.30	2.19	2.14		
	Shannon diversity index—Autumn	2.05	2.76	2.10	1.76		
	Sørensen index—High (%)	-	70.2	57.8*	42.3*		
	Sørensen index—Medium (%)		-	66.0*	47.1*		
	Sørensen index—Low (%)			-	60.3*		
Under-vine soil measurements	Soil gravimetric water (%)	15.94 ± 1.48	14.60 ± 1.99	20.45 ± 2.05	14.5 ± 3.54	0.0981	°
	Soil total nitrogen (%)	0.23 ± 0.02 b	0.20 ± 0.01 b	0.31 ± 0.03 a	0.25 ± 0.03 ab	0.0213	*
	Soil nitrate-N (mg·kg^{-1})	7.25 ± 1.47	5.59 ± 1.29	4.43 ± 0.98	3.01 ± 0.94	0.1303	
	Soil ammonium-N (mg·kg^{-1})	1.36 ± 0.27 b	1.65 ± 0.39 b	2.75 ± 0.49 a	3.09 ± 0.65 a	0.0099	**
	Soil pH $_{(water)}$	7.69 ± 0.09 a	7.47 ± 0.08 a	7.49 ± 0.06 a	6.77 ± 0.10 b	< 0.001	***
	Electrical conductivity (dS·m^{-1})	0.29 ± 0.05 a	0.16 ± 0.02 b	0.35 ± 0.05 a	0.11 ± 0.02 b	< 0.001	***

Measurements in the Native sites are shown alongside the management intensity groups and are compared with a Kruskal–Wallis non-parametric test. Differences between groups are indicated by lower-case letters and significance is indicated by *** ($p < 0.001$), ** ($p < 0.01$), * ($p < 0.05$), and ° ($p < 0.1$). Shannon diversity indices were calculated seasonally for each group, while Sørensen indices were calculated based on the total species identified over the entire year of sampling. A value greater than 70 % for the Sørensen index indicates that the plant communities between the two groups are similar. Dissimilar groups (< 70 % similar species) are noted with a *.

was similar for the Low and High sites, which were both significantly greater than the overall annual electrical conductivity in the Medium and Native sites (Table 3).

Alternatively, there were greater differences measured between management intensity groups in the under-vine areas, where plant species richness was higher in the Medium, Low, and Native groups compared to the High-intensity group. The widest range of plant species richness was observed in the Native sites, which was between seven and twenty-one species and had the highest standard error of

all groups. However, the plant species richness as indicated by the Shannon diversity index was always highest in the Medium group for the under-vine area across all seasons, and was on average, lowest in the High group. The High and Medium groups were the only groups that had similar plant communities as determined by the Sørensen index being greater than 70 %, at 70.2 %, while the Low group was most similar to the Native group, at 60.3 % (Table 3). Similarly, the highest management intensity decreased plant biomass by 76.1 % compared to the lowest intensity, which was the same as both Medium intensity and Native sites. For the under-vine areas, the average plant biomass ranged from 0.05–1.91 t ha^{-1} for the High-intensity group, 1.61–3.69 t ha^{-1} for the Low-intensity group, and 0.79–3.83 t ha^{-1} for the Medium-intensity group. These findings indicate that the more frequent usage of tillage and/or herbicides, in particular by the High-intensity group where between two and four herbicide passes were used per year to control under-vine vegetation, are effective at reducing plant biomass and species richness. In addition, the average plant biomass was the least variable across the sites managing with Low intensity where no passes of tillage and/or herbicides were used to manage vegetation, resulting in the highest average biomass (Table 3). In addition, different management intensities resulted in lower plant coverage in the High and Medium under-vine areas, which were 53.5 % and 26.5 % lower, respectively, than the Low group, which was similar to the Native group. Living plant cover was only different between the Low and High management intensity groups and was 42.1 % decreased as a result of the higher management intensity (Table 3).

Soil gravimetric water content in the under-vine rows averaged across the year was the highest in the sites managed with Low intensity, but only at a level of $p < 0.1$ due to high seasonal and site variability displayed by large standard errors; however, it is notable that the Low-intensity sites had 28.3 %, 40.1 %, and 41.0 % higher gravimetric water content than the High, Medium, and Native sites, respectively, which were statistically similar to one another (Table 3). Under-vine soil total nitrogen was also highest in the Low-intensity sites, which was different from the High sites by 34.8 % and Medium sites by 55.0 %, while it was similar to the Native sites. Soil nitrate-N in the under-vine areas was the same across all intensities and the native sites, where it showed high annual and site variability with standard errors ranging from 0.94 to 1.47 mg kg^{-1}. The other form of inorganic nitrogen, namely soil ammonium-N, was however, higher in the Low and Native sites compared to the High and Medium sites by significant margins of 102.2–127.2 % and 66.7–87.3 %, respectively. Furthermore, it was found that pH was significantly lower in the Native sites, while the under-vine management intensity did not impact the pH of the vineyard sites, however, electrical conductivity was lowest in the Medium intensity and Native sites (Table 3).

4. Soil organic carbon was not impacted, while soil water infiltration rate was increased by lower management intensity in the under-vine area

Measurements of soil organic carbon were not different between the management intensity groups for both mid-row and under-vine areas, where they ranged from 0.94–4.08 % in the mid-rows and 0.98–6.21 % in the under-vine rows across all sites. Soil organic carbon was variable at the Native sites as well, where it ranged from 1.82–6.19 % (Figure 4). Similar to plant biomass, the average soil water infiltration rates measured in the mid-rows of the vineyards was not different depending on the different management intensity

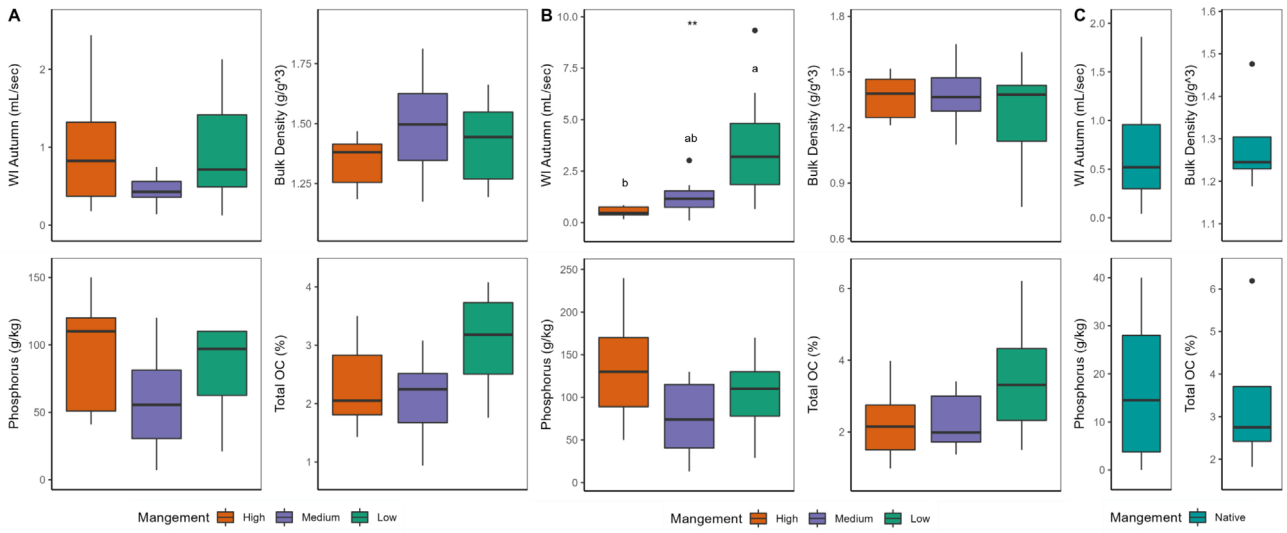


FIGURE 4. Boxplots depicting the median and ranges of soil measurements: water infiltration measured in autumn (WI Autumn), dry bulk density, Colwell phosphorus, and total organic carbon (OC), measured at all sites in the (A) mid- and (B) under-vine rows, and (C) native sites during the spring of 2020.

Sites are grouped according to management intensity High, Medium, or Low, shown with Native. Kruskal–Wallis non-parametric tests were carried out to assess for differences between groups and are indicated by * ($p < 0.05$) and ** ($p < 0.01$) where different lowercase letters indicate differences between groups.

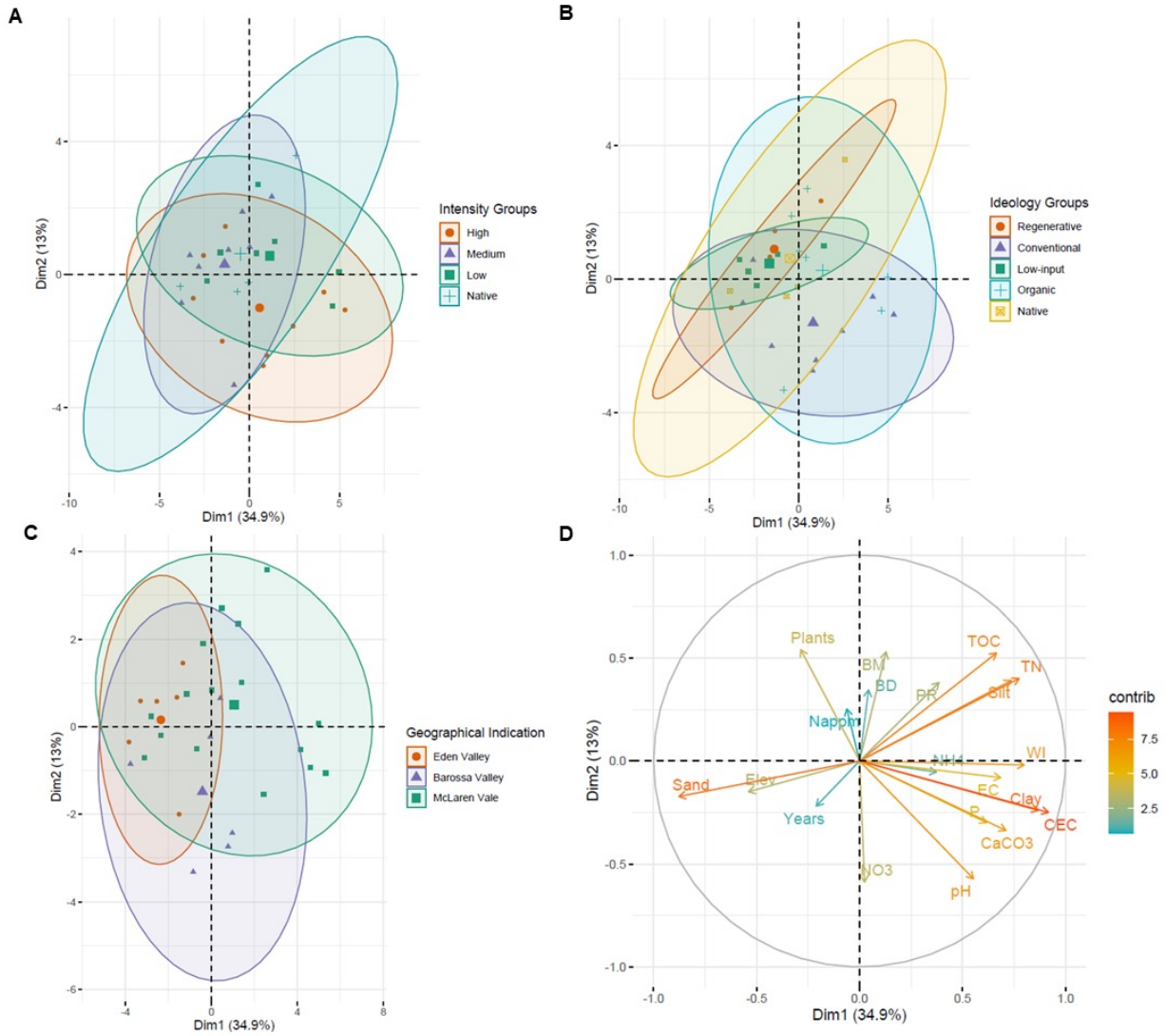


FIGURE 5. Principal component analyses (PCA) of soil and plant measurements from the different vineyard sites collected from the mid-rows and native sites. Sites were grouped according to different categorisations: (A) management intensity of High, Medium, Low, and Native; (B) management ideologies of regenerative, conventional, low-input, organic, and native; (C) Geographical Indications of Eden Valley, Barossa Valley, and McLaren Vale; and (D) a PCA bi-plot of the contribution (contrib.) of each of the measurements.

Confidence ellipses at the 90 % level are shown for each of the grouping variables. Measurements included are soil % sand (Sand), soil % clay (Clay), soil % silt (Silt), soil dry bulk density (BD), soil pH water (pH), soil penetration resistance (PR), soil nitrate-N (NO3), soil ammonium-N (NH4), soil cation exchange capacity (CEC), soil Colwell phosphorus (P), soil calcium carbonate (CaCO3), soil total organic carbon (TOC), soil total nitrogen (TN), soil water infiltration rate (WI), site elevation (Elev.), irrigation water sodium in ppm (Nappm), total number of plant species (Plants), average plant biomass (BM), and total number of years of management implementation (Years).

groups, yet there were differences between groups for the under-vine areas with the Low-intensity sites displaying faster infiltration rates compared to the High-intensity sites (Figure 4A,B). In both the mid- and under-vine rows, there was no apparent effect of management intensity on the other two soil measurements of bulk density and plant-available Colwell phosphorus (Figure 4A,B).

5. Multivariate analyses indicate that management intensity in the under-vine row area is a significant driver of soil and plant measurements across viticultural landscapes

PCA analyses of all measured soil, plant, and site characteristics were conglomerated to compare differences between management intensity groups, management ideology groups, and GIs for for the mid-row and under-vine vineyard

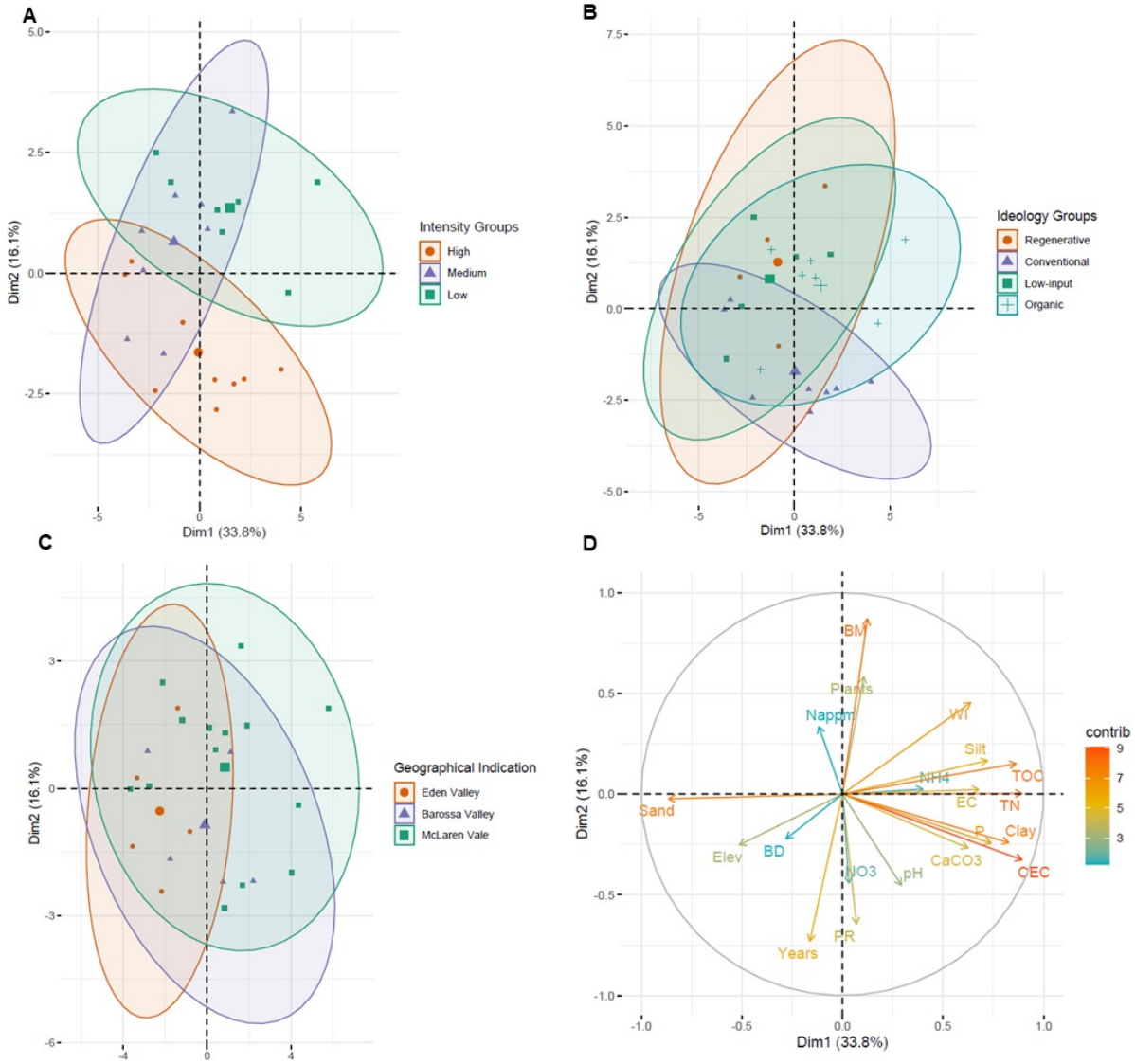


FIGURE 6. Principal component analyses (PCA) of soil and plant measurements from the different vineyard sites collected from the under-vine rows. Sites were grouped according to different categorisations: (A) management intensity of High, Medium, and Low; (B) management ideologies of regenerative, conventional, low-input, and organic; (C) Geographical Indications of Eden Valley, Barossa Valley, and McLaren Vale; and (D) a PCA bi-plot of the contribution (contrib.) of each of the measurements.

Confidence ellipses at the 90 % level are shown for each of the grouping variables. Measurements included are soil % sand (Sand), soil % clay (Clay), soil % silt (Silt), soil dry bulk density (BD), soil pH water (pH), soil penetration resistance (PR), soil nitrate-N (NO3), soil ammonium-N (NH4), soil cation exchange capacity (CEC), soil Colwell phosphorus (P), soil calcium carbonate (CaCO3), soil total organic carbon (TOC), soil total nitrogen (TN), soil water infiltration rate (WI), site elevation (Elev.), irrigation water sodium in ppm (Nappm), total number of plant species (Plants), average plant biomass (BM), and total number of years of management implementation (Years).

areas and native sites (Figures 5 and 6). Management intensity groups of High, Medium, Low, and Native did not result in significant differences at a confidence level of 90 %, as indicated by the overlapping ellipses in Figure 5A. A similar trajectory was followed for the impact of management ideology, which did not appear to be a significant definer for the mid-row areas, although it is interesting to note that the Regenerative and Low-input ideologies were least variable amongst their own groups compared to the Conventional, Organic, and Native groups (Figure 5B). Furthermore, the Eden Valley GI was the most different from the Barossa Valley and McLaren Vale GIs, contributed primarily by the higher soil sand content and elevation found at these sites, whilst the McLaren Vale sites were characterised by faster soil water infiltration, higher total organic carbon, higher total nitrogen, and higher silt content for the mid-rows (Figure 5C).

The clearest significant separation by grouping variables for the under-vine row measurements can be attributed to the management intensity groups, with the Low and High

TABLE 4. Sum of squares, Wald statistic, and *p*-values showing the fixed effects of site characteristics compared to management in linear mixed models of different plant and soil measurements where sites are included as a random effect.

Part 1/2

		Df	Sum of squares	Wald statistic	*p*-value	Sig.
Total organic carbon	Vineyard area	3	344.0	475.0	< 0.001	***
	Sand % content	1	25.78	35.60	< 0.001	***
	Geographical indication	2	4.57	6.31	0.043	*
	Elevation	1	1.27	1.76	0.185	
	Management intensity	2	3.26	4.51	0.105	
	Management ideology	3	2.39	3.30	0.348	
	Management practices	3	0.79	1.09	0.779	
Total nitrogen	Vineyard area	3	2.93	605.5	< 0.001	***
	Sand % content	1	0.19	39.71	< 0.001	***
	Geographical indication	2	0.01	1.63	0.443	
	Elevation	1	0.00	0.45	0.501	
	Management intensity	2	0.02	3.29	0.193	
	Management ideology	3	0.02	4.25	0.236	
	Management practices	3	0.01	1.34	0.720	
Water infiltration rate	Vineyard area	3	41.42	33.90	< 0.001	***
	Sand % content	1	36.33	29.72	< 0.001	***
	Geographical indication	2	3.53	2.88	0.236	
	Elevation	1	0.32	0.26	0.607	
	Management intensity	2	10.64	8.70	0.013	*
	Management ideology	3	5.20	4.26	0.235	
	Management practices	3	16.99	13.90	0.003	**
Winter plant % cover	Vineyard area	3	401,254	2024	< 0.001	***
	Sand % content	1	96.00	0.48	0.487	
	Geographical indication	2	315	1.59	0.452	
	Elevation	1	167	0.84	0.359	
	Management intensity	2	4703	23.72	< 0.001	***
	Management ideology	3	164	0.83	0.843	
	Management practices	3	3082	15.55	0.001	**
Winter plant biomass	Vineyard area	3	330	259	< 0.001	***
	Sand % content	1	0.01	0.01	0.936	
	Geographical indication	2	0.21	0.17	0.919	
	Elevation	1	0.22	0.18	0.676	
	Management intensity	2	15.67	12.29	0.002	**
	Management ideology	3	6.94	5.44	0.142	
	Management practices	3	6.59	5.17	0.160	
Summer plant % cover	Vineyard area	3	86,648	185	< 0.001	***
	Sand % content	1	14.00	0.03	0.865	
	Geographical indication	2	9332	19.89	< 0.001	***
	Elevation	1	349	0.75	0.388	
	Management intensity	2	5456	11.63	0.003	**
	Management ideology	3	1324	2.82	0.420	
	Management practices	3	4013	8.55	0.036	*

Part 2/2

		Df	Sum of squares	Wald statistic	*p*-value	Sig.
Summer plant biomass	Vineyard area	3	19.09	28.13	< 0.001	***
	Sand % content	1	0.10	0.15	0.696	
	Geographical indication	2	6.90	10.17	0.006	**
	Elevation	1	3.10	4.57	0.032	*
	Management intensity	2	11.55	17.02	< 0.001	***
	Management ideology	3	5.86	8.63	0.035	*
	Management practices	3	1.46	2.15	0.542	
Species richness	Vineyard area	3	2398	168	< 0.001	***
	Sand % content	1	12.69	0.89	0.345	
	Geographical indication	2	41.38	2.91	0.234	
	Elevation	1	0.78	0.06	0.815	
	Management intensity	2	275	19.28	< 0.001	***
	Management ideology	3	24.79	1.74	0.628	
	Management practices	3	24.62	1.73	0.631	

Vineyard area includes mid-row, under-vine, and native; management intensity includes high, medium, low, and native; management ideology includes regenerative, conventional, low-input and organic; management practices include slashing, tillage, herbicide, and grazing. A multiple comparisons test was carried out between the variables and significance is indicated where *** ($p < 0.001$), ** ($p < 0.01$), and * ($p < 0.05$).

groups displaying different characteristics (Figure 6A). The Low-intensity group were driven by higher plant biomass and species richness, as well as faster soil water infiltration, total organic carbon, total nitrogen, electrical conductivity, silt content, and ammonium-N than the High-intensity group, which was defined by soils with higher soil sand content, site elevation, soil bulk density, years of management implementation, and soil penetration resistance (Figure 6A). Management ideologies and GIs did not lend to significant observable differentiations as grouping variables for the vineyard under-vine areas (Figure 6B,C).

From the linear mixed model created to investigate significant predictors of soil and plant variables shown in Table 4, it was apparent that the vineyard area (mid-row, under-vine, or native) was always a highly determinant factor ($p < 0.001$) for all tested variables of soil total organic carbon, soil total nitrogen, soil water infiltration rate, winter and summer plant % cover, winter and summer plant biomass, and plant species richness. This clearly establishes how different the mid- and under-vine rows of vineyards, and native sites, are from one another regarding these variables. For all the soil variables, the soil type (sand % content) was a highly important driver, while GI was only relevant for soil total organic carbon (Table 4). Soil water infiltration rate, on the other hand, was largely driven by floor management practices and management intensity. The plant variables of winter and summer plant cover and biomass, and species richness all similarly showed the significance of management intensity as a predominant predictor in determining all of these outcomes, while specific management practices were also relevant in determining winter and summer plant % cover. Both summer plant % cover and plant biomass were also driven by GI, indicating regional trends that developed later in the growing season, while management ideology was also important to predict summer plant biomass (Table 4).

DISCUSSION

In this study, we explored how floor management practices in twenty-four commercial South Australian vineyards contributed to shaping the environmental characteristics of these viticultural landscapes, primarily by their impact on plant dynamics and species diversity in addition to various soil health indicators. The holistic nature of our investigation included vineyard sites managed with varying degrees of floor management practices and intensity where measurements were undertaken in both the mid- and under-vine row areas, in addition to four adjacent native unmanaged sites. This approach thereby broadened the results of this study to capture vineyard landscapes in their entirety. Soil and plant measurements were conducted seasonally during the 2020–2021 growing season so that fluctuations with both climate and management practices could be captured simultaneously. Our findings suggested that grouping the vineyard sites into a progression of management intensity groups (High, Medium, and Low) resulted in vast differences in the vineyard under-vine rows predominantly for the measured plant variables, while the measured soil health indicators were less sensitive to the different degrees of management intensity.

Seasonal plant and soil measurements were less sensitive to the impacts of the three progressive groups of management intensities, however, the annual summary of the measurements distinguished the management intensity groups more significantly. The vineyard mid-rows did not show any differences in annual plant or soil measurements,

however, there did tend to be more plant species identified overall in the Low and Medium groups than in the High group (p-value = 0.083), which was similar to other vineyard landscape studies where mid-row plant diversity was assessed in Spain (Guzman *et al.*, 2019) and across Europe (Hall *et al.,* 2020), in these cases where spontaneous, mown mid-rows supported higher levels of plant diversity than those that underwent more intense management practices such as herbicides and tillage.

Interestingly, the seasonal fluctuations in plant Shannon diversity indicated that the Low and Native groups tended to decrease in plant diversity as the growing season progressed from winter to the following autumn and that plant communities were generally different in the winter compared to the summer sampling times, which is consistent with what Fried *et al.* (2019) reported across 46 vineyards in France. In the present study, it was apparent that intermediate management intensity was carried out by growers in the Medium group was associated with the highest Shannon diversity in the under-vine rows, while the lowest Shannon diversity in spring and summer was realised when more than two passes of herbicides were applied to the under-vine rows. Herbicide use in French vineyard under-vine rows had similar effects, reducing both the richness and abundance of species, whilst a combination of tillage and mowing promoted both species richness and abundance (Fried *et al.,* 2019).

Plant species dynamics changed significantly depending on season and management intensity in the studied South Australian viticultural landscape. Ruderal plants such as species identified in the Asteraceae and Polygonaceae families were primarily the common sowthistle (*Sonchus oleraceaus,* L.), hairy cat's ears (*Hypochaeris radicata*, L.), bristly ox-tongue (*Helminthotheca echioides*, L.), and wireweed (*Polygon erectum*, L.) (Table S1), all of which have similar functional traits of being rapidly growing, producing large amounts of seed, having high specific leaf area, and early emergers; thus, making them very competitive and difficult to manage (Navas, 2012). These Asteraceae and Polygonaceae species were more relatively prevalent in vineyards with Medium and High levels of management intensity in the mid- and under-vine rows where tillage and herbicides were used as management practices. Tillage was shown to increase the prevalence of species with high specific leaf area by both Kazakou *et al.* (2016) and Guerra *et al.* (2021), while MacLaren *et al.* (2019) also found that higher levels of management intensity and soil disturbance increased ruderal weed abundance in vineyards. These ruderal species have adapted over time to survive high levels of disturbance (Grime, 1977), which is why they are more prolific as management intensity increases. Alternatively, when only mowing or grazing was used to manage vegetation in the Low-intensity sites, the relative abundance of ruderal plant species was much lower and instead, the plant community was dominated by slower-growing, perennial, and less competitive species primarily in the Poaceae and Fabaceae families, which was also very similar to previous evidence by Guerra *et al.* (2021), MacLaren *et al.* (2019), and Nascimbene *et al.* (2013) who all suggested that the best way to reduce competitive species in Mediterranean vineyards is to manage vegetation by mowing.

Native sites showed a similar number of plant species as the Medium and Low management groups but had significantly more species than the High group for both the mid-row and under-vine areas. A vineyard landscape study across the Okanagan Valley found that low-intensity management of vineyard mid-rows in the region led to similar plant communities and diversity as adjacent native areas which was similar to the dynamics found by our study (Holland *et al.,* 2016). Plant cover was annually greater in the Low and Native groups for both vineyard areas, while seasonal dynamics only displayed differences in the under-vine areas of the vineyards, signifying that this is the area of major management and ensuing environmental differences in South Australian viticultural landscapes. These substantially differing findings from the mid-row and under-vine areas open the discussion as to what practices are used, and how they holistically impact soil health and biodiversity on a landscape scale.

Soil measurements at different seasonal time points had relatively large ranges within the management intensity groups, thus, there were no differences between the groups for the mid-row area, and the under-vine area displayed differences only in the spring measurements of soil ammonium-N and soil electrical conductivity, which were both greatest for the Low-intensity group. These higher values for ammonium-N in the Low-intensity group could indicate that the complete floor plant coverage offered by this management style could be stimulating the nitrifying activity of soil microorganisms or could be a combined effect of the higher coverage lent by leguminous plant species in the Fabaceae family, which can biologically fix nitrogen (El Sabagh *et al.,* 2020), with during the winter and spring months. The annual soil measurements revealed a similar trend, as soil nitrogen was highest for both the mid- and under-vine row areas of the vineyards with Low management intensity and more long-term plant coverage, in which there was a higher proportion of coverage from Fabaceae species. This supports findings by Karl *et al.* (2016b), whose study determined that under-vine plant cover reduced the leaching of nitrogen from the soil compared to under-vine areas that used herbicides or cultivation to reduce vegetation coverage in a cool, wet East Coast vineyard after three years of annual under-vine cover crops. In general, it has been discovered that the presence of living plant coverage in vineyards can lead to improved soil carbon levels and, thus, reduced rates of soil nitrogen leaching (Steenwerth and Belina, 2008); and more recently, even across diverse European cropping systems, longer-term living plant coverage was the greatest contributor to improved soil multi-functionality and soil bacterial activity (Garland *et al,* 2021).

Furthermore, the under-vine areas of the Low-intensity group tended to have the highest annual soil gravimetric water content of all groups including the Native sites

(p-value = 0.0981), which again could be resultant of the continuous year-round living plant coverage that was the highest for this group. Although maintaining living plants in the under-vine area has commonly been considered a source of potential competition for water in the under-vine area, the long-term continuous plant coverage that was practised by the seven vineyard sites in the Low-intensity group indicated an improvement in soil structural characteristics including water infiltration. This was similar to findings from a Spanish vineyard study that showed long-term spontaneous vegetation compared to tillage improved water infiltration rates and soil organic carbon, which led to higher levels of soil moisture (García-Díaz *et al.,* 2018). On the other hand, these results somewhat counter the more common findings from other Mediterranean vineyards worldwide, such as by Celette *et al.* (2009) and Celette and Gary (2013) who showed that grass-cover in vineyard mid-rows decreased both soil moisture and soil nitrogen by directly taking up available water faster than evaporation from bare soil, leading to a reduction in natural rates of nitrogen mineralisation because of the drier soil conditions that limit the activity of bacteria to complete the nitrification process. However, in this study, unlike at these French vineyards, all sites (aside from one which was rain-fed) used drip irrigation to irrigate their vines, particularly in the warm, dry months of summer and early autumn. Perhaps this finding then provides information for growers who use irrigation, that even in warm, dry climates, living under-vine plant coverage can then improve the soil–grapevine dynamic by facilitating water infiltration, carbon sequestration, and nitrogen mineralisation occurring in this area of the vineyard. Marks *et al.* (2022) explored the potential of various species of under-vine cover crops to facilitate the improvement of soil carbon stocks under South Australian conditions, and, in fact, found that after four years of a trial period, carbon stocks were improved by an average of 23 % by maintaining under-vine plant cover. It is very possible that the higher plant biomass and living plant coverage found in the under-vine areas of the Low-intensity sites contributed positively to faster water infiltration by the provision of bio-pores created by permanent plant roots (García-Díaz *et al.,* 2018), in combination with less frequent passes by machinery to apply tillage or herbicide treatments, of which there were none applied to the Low-intensity group of sites.

Grouping the vineyard sites into categories based on management intensity versus management ideology appeared to have little impact on the soil and plant measurements in the mid-rows, again supporting our finding that Australian mid-rows are similarly managed across the landscape to include floor plant coverage for most of the year. Under-vine areas were best categorised by management intensity compared to ideology, as it appears that the number of passes with either herbicides and/or tillage rather than ideology, was the primary driver of both plant species diversity and soil measurements such as water infiltration rate. Findings from a vineyard landscape study in the Western Cape of South Africa found similar outcomes that plant diversity and coverage by native vegetation were only driven by the choice and intensity of floor management practices and did not depend on ideology (MacLaren *et al.,* 2019). Instead, similar to our findings in this South Australian context, specific plant species in South Africa were, specific plant species were different in terms of their functional traits of height, seed mass, and specific leaf area depending on management practice intensity instead of ideology (MacLaren *et al.,* 2019), indicating an overall faster turnover of resources and life span of the weed species that are managed with higher rates of disturbance (Kazakou *et al.,* 2016). Garland *et al.* (2021) similarly chose to use management intensity as a comparative metric for farm management rather than ideology, as they also found little differences in soil outcomes across a wide landscape of organic and conventional sites.

Despite the high adoption rate to manage vineyard mid-rows with year-round plant coverage of more than 85 % as our study showed, the organic certification rates for vineyards in Australia have been steadily declining since 2014, as by 2019, less than 1 % of all vineyard area (2500 ha) was certified organic, compared to, for example, Spain, with 121,000 ha of certified organic vineyards, or France, with at least 8 % of vineyards being certified organic (OIV, 2021). Interestingly, these countries are much more likely to manage vineyard mid-rows with tillage to control vegetation, which is permitted by organic certification bodies, with only 5.4 % of Spanish vineyards using mid-row vegetative cover in 2012 (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2012 as cited in Marques *et al.,* 2015) and 45 % of French vineyards using this practice (Agreste, 2017 as cited in Payen *et al*., 2022). We, therefore, present an alternative situation to the organic certification option, that plant coverage duration should be included as a primary factor in determining the long-term resilience, sustainability, and health of a viticultural ecosystem. Vineyards are a prime opportunity to practice complete floor coverage for most of the growing season, as grapevines are a permanent crop whose roots have the potential to seek water and nutrients from deep soil depths and can even produce fruit of higher quality and more balanced yields when complete floor coverage is intact (Giese *et al.,* 2014; Karl *et al.,* 2016a; Coniberti *et al.,* 2018).

The main takeaway from this viticultural landscape study in South Australia is that higher under-vine management intensity by tillage and herbicides across vineyard sites with different characteristics consistently resulted in lower plant species richness, biomass, and slower water infiltration. Although it was not investigated in the present study, many other vineyard investigations have demonstrated that increased floor plant coverage by spontaneous or native species not only benefits the soil ecosystem (Karl *et al.,* 2016b; Marks *et al.,* 2022) but also improves the habitat for natural enemies in other Australian vineyard sites (Danne *et al.,* 2010) and likewise in Italian vineyards (Muscas *et al.,* 2017) to further improve the holistic functionality of vineyard agroecosystems.

CONCLUSION

This study assessed the impact of vineyard floor management intensity on plant biodiversity and soil health across South Australian viticultural landscapes. Findings demonstrated that plant species richness and biomass, in addition to soil water infiltration in the under-vine areas were negatively associated with increasing management intensity. The plant coverage contributed by ruderal, noxious plant species, particularly those in the Asteraceae (Compositae) and Polygonaceae (Buckwheat) families increased as management intensity increased, suggesting that reducing the use of herbicides and tillage will foster a plant community primarily composed of less competitive, perennial species in the Poaceae (Grass) and Fabaceae (Leguminosae) families. Soil organic carbon was not significantly different between management intensity groups due to its high variability between sites. The findings from this study also investigated the significance of floor management intensity compared to management ideology as comparative drivers of the measured environmental properties using PCA and a linear mixed model, both of which demonstrated that the intensity of management practices was more significant in defining soil and plant dynamics than was management ideology. Furthermore, there was a high correlation between lower management intensity and increased plant coverage, plant biomass, plant species richness, soil total nitrogen, and soil water infiltration. We, therefore, propose that maintaining complete vineyard floor coverage in irrigated vineyards, such as those in South Australia, could contribute positively to the viticultural landscape and prolong the productivity and resilience of vineyards in these regions. Floor management strategies should be selected with the utmost consideration to balance production goals with environmental health, as the long-term resilience of vineyards may be compromised by higher-intensity practices.

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