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SHORT COMMUNICATION

Removal of pruned vine biomass (PVB) from vineyards – Examining the impact of not incorporating PVB into vineyard soils

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ABSTRACT

The wine industry worldwide faces increasing challenges to achieve sustainable levels of carbon emission mitigation. This study seeks to establish the feasibility of harvesting winter pruned vineyard biomass (PVB) for potential use in carbon footprint reduction as a renewable biofuel for energy production. Of particular interest is the role PVB plays as a carbon source in vineyard soils and what effect annual removal might have on soil carbon. An investigation was carried out in the Coombe vineyard, Waite Campus (University of Adelaide), Australia. Vines are grown in a Vertic clay loam soil with well-managed mid-row swards in a temperate zone. A comparison was undertaken of two mid-row treatments after 13 years of consistent management: 1) the deliberate exclusion of PVB from every third row, and 2) in the remaining rows PVB was incorporated at an average of 3.4 and 5.5 t/ha in two 0.25 ha blocks containing Shiraz and Semillon respectively. In both 0-10 cm and 10-30 cm soil core sample depths, combined soil carbon % values in the desired range of 1.80 to 3.50 were not significantly different between treatments or cultivars and yielded an estimated 42 t/ha of soil carbon. Other key physical and chemical values were likewise not significantly different between treatments. Results suggest that in a temperate zone vineyard, managed such as the one used in this study, there is no long-term negative impact on soil carbon sequestration through removing PVB. This implies that growers could confidently harvest PVB for use in biofuel production.

KEYWORDS: Pruning, biomass, soil-carbon, vineyards, biofuel

INTRODUCTION

1. Utilisation of PVB as a source of biofuel

As the complex science around climate change matures the agriculture sector is uniquely placed to develop strategies to mitigate the impact current practices contribute to that change (Locatelli *et al*., 2015). In terms of greenhouse gases (GHG), the agriculture sector is reported to contribute a per capita average of approximately 4.47 Mg CO_2-e per year to the atmosphere, and as a result, the agriculture sector has identified the reduction of its carbon footprint as an important part of climate change mitigation (Lal, 2022).

Plant waste biomass streams from agriculture have been identified and frequently reviewed as an important potential feedstock for bioenergy (i.e., electricity generation or liquid fuels for combustion) and continue to be developed in many countries (Carpenter *et al*., 2014; Dale *et al*., 2011). In Australia, Farine *et al*. (2012) reviewed the potential contribution of biomass to the production of bioelectricity and biofuel from agricultural residues, and they suggest that responsibly harvested biomass has the potential to mitigate 26 Mt CO_2-e, which is equivalent to 38 % of road transport emissions and 5 % of the national Australian emissions. Brosowski *et al*. (2016) also reported in their review of 93 biomass waste streams that between 7 % and 13 % of German primary energy consumption and target consumption respectively could be met using biomass waste. Pruned vineyard biomass (PVB) can be considered one such waste stream and importantly satisfies a key sustainability parameter: it is a by-product of a high-quality crop which does not require the dedication of extra land for production (Popp *et al*., 2014).

For PVB to be used as a source of bioenergy, the chemical and physical properties need to be described favourably for its efficient use as a feedstock in combustion, pyrolysis, and gasification technologies (Stucley *et al*., 2008). Chemical qualities which affect emissions, ash contamination, and biofuel quality need to be optimal, while physical characteristics including particle size, bulk density, moisture content and gross calorific value determine consumption efficiency and minimise emission contamination (Van Loo and Koppejan, 2002). The dry basis concentration of Carbon (C), hydrogen (H), and oxygen (O) are the main constituents of the gross calorific value of the fuel source, these parameters (as well as other chemical constituents) in PVB being suitable for efficient combustion (Cavalaglio and Cotana, 2007; Sun *et al*., 2020). Preliminary research demonstrates that PVB has a High Heating Value of between 13.08 and 22 Mj/Kg (Manzone *et al*., 2016; Picchi *et al*., 2013; Spinelli *et al*., 2012; Tenu *et al*., 2019). These values are comparable to those of forestry hardwood tree species, but lower than those of softwood tree species traditionally used for combustion (Manzone *et al*., 2016).

In some vineyards, PVB removal is performed routinely. The end fates of PVB vary from controlled open-air burning, composting, pyrolysis for bio-char production, and various forms of bioenergy. Several researchers report the logistics, processes and costs involved in this practice which may be barriers to adoption by growers in some regions (Magagnotti *et al*., 2013; Spinelli *et al*., 2010). In other vineyards, PVB is left in situ and either incorporated into the soil through cultivation or left on the soil surface. Notwithstanding the reluctance of some growers to changing local/cultural mid-row management practices (Cerdà and Rodrigo-Comino, 2021), what is not clear in the literature is the impact the removal of PVB might have on the soil C cycle, if it is a valuable source, and on the nutrients being returned to the soil.

2. Impact of PVB on vineyard soil chemical properties

Establishing the role PVB plays in the dynamics of soil C and nutrient cycling in viticultural soils requires experimental trials over several years, if not decades, as changes occur slowly, even in the topsoil layer (Garcia *et al.,* 2018). Long-term studies including PVB are rare and those that do exist focus on the role that cover crops, composts, mulches, and fertilisers play in the mid-row, rather than the impact of PVB *per se* (Besnard *et al*., 2001; García-Orenes *et al*., 2016; Morlat and Jacquet, 1993). In a rare 27-year trial in the Loire Valley, France, Morlat and Chaussod (2008) reported differences in sequestered soil C where mid-row cover crops were not used. Dried PVB was incorporated into the soil at 2 t/ha compared with a control of no PVB. Upon completion of the study in 2008, a 19 % decline in sequestered C in the control was recorded. Where PVB was incorporated a significantly higher amount of sequestered C at 8 t/ha was recorded. N also declined in both treatments, but concentration was significantly lower in the control compared with the PVB treatment: 0.60 and 0.72 g/k respectively. While P and K were seen to increase in both control and treatment, their concentrations were not significantly different. The vineyard in question was planted in a calcareous sandy soil with a limited water holding capacity and low cation exchange capacity, which indicates that PVB in this scenario can be an important source of sequestered C and nutrient. While PVB production can vary between years, regions, cultivars and management regimes, annual inputs of 3 t/ha of fresh weight and a C concentration of 43 to 50 % once dried are expected (Cavalaglio and Cotana, 2007; Mendívil *et al*., 2013; Tenu *et al*., 2019), suggesting a hypothetical upper limit of 1.5 t/ha contribution of C to the soil per annum if incorporated into the soil.

In terms of C sequestration, the complex cyclical interactions between soil type and climate, additional inputs of composts and mulches (Cass and Roberts, 2005; Chan *et al*., 2010; Webster and Buckerfield, 2003), cover crops, cultivation and GHG mitigation and emissions have been widely reported (Tezza *et al*., 2019; Vendrame *et al*., 2019; White, 2015). The specific contribution that PVB may play in that cycle is less clear. In fact, in the general literature, vine leaves, PVB and other canopy debris are regarded simply as contributors to soil organic matter (McCarthy *et al*., 1992; White, 2015).

Given that information regarding the contribution PVB makes to C sequestration in vineyard soil management is

limited, the impact of its removal is unknown. Results from Morlat and Chaussod (2008) demonstrated PVB to be an important source of C which contributes to soil structure and C sequestration in the absence of other inputs. In vineyards where mid-row cover crops are grown, the importance of PVB to the C cycle may be insignificant, and it therefore may be possible to remove it for further processing with little or no impact on soil C.

For this study, a vineyard which has been managed consistently with introduced mid-row crops for 13 years was identified. Mid-row soils from which PVB was deliberately removed were compared with soils in the same vineyard to which PVB had been incorporated over the same period. Soils at stratified depth fractions were analysed to test the hypothesis that PVB may not be an important contributor of C to vineyard soils.

MATERIALS AND METHODS

1. Experimental site details and management

Planted in 1992, the Coombe vineyard is located in Adelaide city at the Waite Campus of the University of Adelaide, in South Australia (34°58'02S; 138°38'58E; elevation 119m). The climate is defined as Mediterranean dominated by hot dry summers (Mean January temperature 23.4 °C) and mild wet winters (Mean June temperature 12.1 °C) (Tapper and Tapper, 1996). Winter dominant average annual rainfall is 547.1 mm (BOM, 2021). In the 2.25 ha vine area, the soil type was described after two soil pits were dug in 2016 as Vertic, Red Dermosol; a thick, non-gravelly, clay loam which tends to be high in organic matter, nutrient availability and moisture-holding capacity, according to the Australian Soil Classification system (Hall, 2016; Isbell, 2016). For comparison, the classification of these soils according to the World Reference Base for soil resources is presented in Table 1 (WRB, 2015).

Within the main vineyard area, two 0.25ha blocks were identified for the study site containing Shiraz (clone BVRC12) and Semillon (clone SA32) planted on their own roots. Rows are 85 m long and orientated north south. Row spacing in both blocks is set at 3 m, and vine spacing for Shiraz is 2.7 m (1234 vines ha) and for Semillon 1.8m (1852 vines ha). Vines are trained to a bilateral permanent cordon at a height of 0.75 m and pruned annually by hand to two node spurs at between 15 to 26 spurs/vine. Irrigation is typically applied at the equivalent of 1-1.2 ML/ha for Shiraz and 1.5–2 ML/ha for Semillon, depending on the season.

In 2019, permanent swards were introduced to the whole vineyard area and grown across all mid-rows. In the autumns of 2019 and 2020, all mid-rows in both blocks were cultivated once with no herbicide for seed bed preparation. A combination of Pasture Genetics® seed blends were sown in both years. Species included, annual rye grass (*Lolium perenne*), Convoy Continental cocksfoot (*Dactylis glomerata*), summer active tall fescue (*Festuca arundinacea*), SARDI Rose Clover (*Trifolium hirtum*) and Silver Snail Medic (*Medicago scutellata*). Crops were slashed once during the growing season, allowed to set seed in late spring, slashed in early summer and left in situ. Problematic weeds are either physically removed or subjected to targeted herbicide treatment.

2. Vineyard experimental design and treatments

2.1. Treatments

The allocation of the treatments was dictated by the pruning management procedures of the block, which had been designed to accommodate the whole of the vineyard's bird netting system (Figure 1a). Applied at veraison, these nets cover three rows each (Figure 1b). During pruning in winter, PVB was deliberately excluded from every third row. This prevented the PVB from becoming entangled with the side of the bird nets and damaging them when removed post-harvest. This practice has been carried out for 13 years since 2008, and it impacted directly this project's design and restricted the establishment of a randomised plot design. To this end, a split plot design was used (Figure 2). As a result, two treatments were key to this experimental design: Treatment 1 Without PVB and Treatment 2 With PVB, in two cultivar blocks (Shiraz, clone BVRC17, and Semillon, clone SA32). Each cultivar block comprised three subblocks of three rows each; PVB was excluded from one mid-row (Treatment 1) and randomly distributed across the remaining two mid rows (Treatment 2) in which PVB was retained including the randomly distributed PVB from Treatment 1 (Figure 2). PVB weights over three seasons ranged from 92.4 kg/mid-row to 184.9kg/mid-row for Shiraz

TABLE 1. Classification of two soil profiles in accordance with the Australian Soil Classification and World Reference Base for Soil Resources from field sites.

Waite Pit Site	Australian Soil Classification (ASC)[a]	World Reference Base for soil resources (WRB)[b]
JJ_W01	Vertic, Pedaric, Red Dermosol; thick, non-gravelly, clay loam, clayey, deep	Vertic, Endostagnic, Rhodic Luvisol (Endoclayic, Cutanic, Differentic)
JJ_W02	Vertic Eutrophic, Red Dermosol; thick, non-gravelly, clay loam, clayey, deep	Vertic, Chromic Luvisol (Endoclayic, Cutanic, Differentic)

[a] (Isbell, 2016).
[b] (WRB, 2015).

1a: Coombe vineyard trial site



1b: Net configuration over three rows



FIGURE 1. 1a) Arial image of the Coombe vineyard with bird netting system in place over the whole vineyard including the trial site (Coombe B Shiraz and C Semillon). Each net prevents bird ingress (Google, 2019). 1b) Nets are placed over every three rows (Source: Pike 2017). Waite Campus vineyards, University of Adelaide.

[a]Coordinates (34°58′02S; 138°38′58E; elevation 119m).

Shiraz (BVRC 17)	ROW#																
No PVB Mid Row	BLK 1	x	x	x	x	x	x			x	x	x	x	x	x		
	10																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	11																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	12																
No PVB Mid Row	BLK 2	x	x	x	x	x	x			x	x	x	x	x	x		
	13																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	14																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	15																
No PVB Mid Row	BLK 3	x	x	x	x	x	x			x	x	x	x	x	x		
	16																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	17																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	18																
	19																
	BUFFER ZONE																
	20																
Semillon SA32																	
No PVB Mid Row	BLK 4	x	x	x	x	x	x			x	x	x	x	x	x		
	22																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	23																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	24																
No PVB Mid Row	BLK 5	x	x	x	x	x	x			x	x	x	x	x	x		
	25																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	26																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	27																
No PVB Mid Row	BLK 6	x	x	x	x	x	x			x	x	x	x	x	x		
	28																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	29																
With PVB Mid Row		x	x	x	x	x	x			x	x	x	x	x	x		
	30																

FIGURE 2. Map of vineyard block replicates used for this trial. Distribution of treatments by strip plot design due to vineyard management. Treatments per cultivar block: green = without PVB, 3 replicates; no colour = with PVB, 6 replicates. Soil sample sites (x) are illustrated: n = 6 and n = 12 per subblock respectively. Stratified soil sample depths per site: 0-10cm and 10-30cm. Waite Campus vineyards, University of Adelaide, autumn 2021.

and 142.0 kg/mid-row to 284.1 kg/mid-row for Semillon. The PVB, air dried in situ, was incorporated into the top 30 cm of the soil by a rotary hoe used for cultivation the following season in autumn. Each subblock was divided into north and south and, to eliminate border effects, no-sample areas were established: a 5.4 m no-sample zone at the end of each mid-row and a 10.8 m no-sample zone in the centre of each mid-row to delineate the north and south ends of each subblock.

2.2 Soil sampling and analysis

In each mid-row, soil samples were collected from the centre of the row in August of 2021 when the soil was at field capacity after winter rains. Six evenly distributed sample sites in each of the northern and southern zones in the centre of each row were identified and aligned with the middle of each corresponding panel. Changes to C concentration occur in the topsoil, generally to a depth of 30 cm. For each sample site, stratified topsoil sample fractions, 0-10 cm and 10-30 cm, were collected by hand auger with a head diameter of 10 mm. By combining all six samples from each depth fraction, a homogenous composite sample was obtained resulting in a total of 6 samples from the 'with PVB' treatment and 12 'without PVB' in each of the cultivar blocks. Chemical Analysis was conducted by Australian Precision Ag Laboratories, Hindmarsh, South Australia (APAL).

C stocks (Mass C, t/ha) were calculated from a weighted average C concentration of stratified soil concentration % values, using the following equations (Cavagnaro and Lines pers comm 2022).

1) Weighted average C % (WC %) = Soil C % ($depth_{0\text{-}10cm}$/3) + 2 * ($depth_{10\text{-}30cm}$/3)

2) Mass of Soil t/ha (M) = (Bulk Density = 1.3 t/m *V =Volume of soil/ha – 3000 tonnes at 0 – 30 cm)

and

3) Σ = (WC %/100) *M

Where: WC % = Weighted average C %.

M = Mass of soil t/ha

2.3. Vine PVB sampling

Average pruning weights were calculated to establish baseline data for the potential weight of PVB that contributed to the trial site of each cultivar. During dormancy, all shoots on representative vines were pruned to two node spurs and their collective weight was measured using a spring-loaded handheld balance. In July, average pruning weights for Shiraz (2012, 2017, 2018 and 2020) and Semillon (2015 to 2020) were combined and averaged at 2.71 kg/vine and 2.96 kg/vine respectively (Table 2). Samples of cane fragments between 5cm to 7cm long from 100 canes per cultivar were also collected and homogenised. Subsamples were sent for analysis to Australian Precision Ag Laboratories, Hindmarsh, South Australia (APAL) to determine C and nutrient concentration.

2.4. Plant tissue analysis

Five leaf petioles from the leaf opposite the basal bunch were destructively sampled at 80 % flowering (Cooke, 1967) from three randomly selected vines per vine row in each subblock of both cultivars. This process has been executed annually for 8 years as part of standard management operations. To determine chemical concentration and compare with results in PVB, Chemical Analysis was conducted by APAL.

3. Statistical Analysis

Carbon and nutrient concentration data collected from soil samples for each treatment were subjected to statistical analysis. Due to the strip plot design in this trial, the potential effects of strip and subblock variability of the treatments on PVB nutrient concentration could not be directly accounted for. Despite these limitations the samples collected allowed for a preliminary assessment of the soil sample treatment means at 0-10cm and 10-30cm. Means of each soil subsample at both depths were subjected to a T-Test assuming equal variance (Microsoft Excel Data Analysis 2016; Version 16.0.5266.1000).

RESULTS

1. Impact of PVB contributions to vineyard mid-row soil properties

Based on average pruning weight and C concentration of dried PVB, data from both cultivars illustrate that, on average, Shiraz and Semillon contribute the equivalent of 3.35 and 5.48 tonnes of PVB per ha per annum respectively (Table 2). As a result, when incorporated into the soil, PVB has the potential to contribute 1.68 and 2.74 tonnes of C annually.

TABLE 2. Estimated average annual PVB weight per cultivar (Shiraz and Semillon) and carbon fractions extrapolated to equivalent tonnes per hectare when spread in field.

Cultivar	Row width (m)	Vine spacing (m)	Planting density (vines/ha)	Average Pruning weight (kg/vine)	Equivalent PVB (t/ha)	C concentration of PVB %	Estimated incorporated (C t/ha)
Shiraz	3	2.7	1235	2.71	3.35	49.97	1.68
Semillon	3	1.8	1852	2.96	5.48	50.15	2.74

[a] Average pruning weights calculated from pruning weights by year: Shiraz BVRC 12 (2012, 2017, 2018 and 2020); Semillon SA32 (2015 - 2020).

TABLE 3. Nutrient concentrations of PVB by cultivar (Shiraz and Semillon) compared with reported optimal levels for combustion.

Cultivar [a]	Carbon %	Std Dev	Nitrogen %	Std Dev	Potassium %	Std Dev	C:N Ratio
Shiraz	49.97	0.21	0.74	0.02	0.69	0.04	67.58
Semillon	50.15	0.30	0.86	0.07	0.73	0.02	58.19
Optimal levels [b]	43.10 – 93.30		0.52 – 1.60		0.67 – 1.06		

[a] Average pruning weights of Shiraz BVRC 12 (2012, 2017, 2018 and 2020); Semillon SA32 (2015 – 2020).

[b] Nutrient concentration range values determined as optimal for combustion in various Vitis vinifera cultivars (Cavalaglio and Cotana, 2007; Mendívil *et al.*, 2013; Sun *et al.*, 2020; Tenu *et al.*, 2019).

TABLE 4. Chemical analysis of soil fractions (0-10 and 10-30 cm) including key values of cation exchange capacity, organic carbon pH, nitrogen, phosphorous and salinity compared with optimal levels.

Key Characteristic	Unit	PVB Treatment [a]	Depth 0-10 (cm)	Depth 10-30 (cm)	Significance Level P-Value [b]	Optimal Level [c]
Organic Carbon	%	N	1.55	0.83	ns	1.80-3.50
		Y	1.58	0.82	ns	
Cation Exchange Capacity	cmol/kg	N	7.64	6.48	ns	5.00-25.0
		Y	8.12	6.50	ns	
pH 1:5 water	pH	N	6.19	6.02	ns	6.50-7.50
		Y	6.31	6.13	0.04	
Nitrate - NO_3^-	mg/kg	N	6.71	6.55	ns	20-50
		Y	7.69	1.58	ns	
Ammonium - NH_4^+	mg/kg	N	1.43	1.93	ns	1.0-10
		Y	1.48	2.27	ns	
Colwell Phosphorus	mg/kg	N	49.50	49.50	ns	40-60
		Y	45.38	45.38	ns	
Salinity EC 1:5	dS/m	N	0.045	0.045	0.03	0.040-0.25
		Y	0.048	0.048	0.03	

[a] PVB from two cultivars Shiraz (BVRC12) and Semillon (SA32) incorporated into soil; N = Without PVB, Y = With PVB where n = 6 and n = 12 per subblock respectively.

[b] T-test assuming equal variance. Significant differences level ($p < 0.05$).

[c] Provided by APAL from (Cockroft, 2012; Lanyon *et al.*, 2004; Proffitt, 2014).

No significant differences were found between treatments or cultivars in any nutrient concentrations in the PVB. The chemical analysis of PVB revealed that by vine dormancy the final concentrations of measured key macronutrients were well within the optimal level for both cultivars in terms of efficient use for combustion as a biofuel (Table 3). In terms of use in the vineyard, however, the concentrations of these nutrients may have an impact on vineyard nutrition if left in situ. Moreover, the high C:N ratio may impact N availability once in the soil nutrient cycle.

2. Impact of removal of PVB from the vineyard on mid-row soil properties

The concentrations of most key characteristics (i.e., cation exchange capacity (CEC), ammonium and phosphorous) were generally within or close to the desired range (Table 4). The values for soil nitrate indicate a concentration below the desired level. Despite significant differences, soil salinity values are well below the toxicity thresholds. Whilst the measured pH suggests slightly acidic soils, the pH range at which nutrients are accessible to plants are satisfied (Table 4).

TABLE 5. Estimated sequestered carbon by treatment in the top 30 cm of soil.

Treatment[a]	Depth (cm)	Soil Carbon (%)	Weighted average carbon (%)	Bulk Density (t/cm 3) [b]	Total Soil Carbon (t/ha)
Without PVB	0 -10	1.55	1.07	1.3	42
	10 - 30	0.83			
With PVB	0 - 10	1.58	1.07	1.3	42
	10 - 30	0.82			

[a] Collective values averaged for both Shiraz and Semillon blocks per treatment where n = 6 and n =12 per sub block respectively.
[b] Bulk density values based on historical data for Urrbrae Red Brown Earths (Greacen, 1981).

TABLE 6. Key nutrient concentration of grapevine cultivar petioles [a].

	Nitrate – N mg/kg	Nitrogen %	Phosphorus %	Potassium %
Shiraz	34	0.76	0.54	2.19
Semillon	< 30	0.72	0.47	2.24
Optimal level [b]	500-1200	0.80-1.10	0.25-0.50	1.8-3.0

[a] Collective values averaged for both Shiraz and Semillon blocks collected at flowering.
[b] (Krstic and Collings, 2003; Reuter and Robinson, 1997).

Except for salinity at both depths and pH at 10-30 cm, no significant differences were found between treatments in any key soil characteristics at either depth fraction. For each individual depth fraction of soil, C concentration was lower than the desired level. Factors used to convert soil C % to total sequestered C are provided in Table 4. Therefore, given that there were no significant differences in soil C concentration, it is not unexpected that soil C at 42 t/ha is equal in both treatments, regardless of cultivar (Tables 4 and 5).

3. Impact of removal of PVB from the vineyard on vine nutrition

Annual petiole samples taken in the Shiraz and Semillon blocks at flowering (E-L 23) indicate that nitrate concentration (34mg/kg and <30mg/kg respectively) and nitrogen (0.76 and 0.72 % respectively) found in plant tissue analysis is consistent with suboptimal levels. This is consistent with the suboptimal levels of N found in the soil as reported above. However, concentrations of P and K were above optimal levels: in Shiraz 0.5 and 2.19 % and in Semillon 0.47 and 2.24 % respectively (McCarthy *et al*., 1992) (Table 6). Each year, the petiole samples from both cultivars consistently gave similar results.

4. Pruned vine biomass (PVB) as a source of biofuel

The data from the chemical analysis of the PVB (Table 2) show that the C concentration in Shiraz is 49.9 % and in Semillon 50.1 %. These values are consistent with the findings of Cavalaglio and Cotana, (2007); Mendívil *et al.* (2013); Tenu *et al.* (2019). While the concentrations of nitrogen, potassium and C are closer to the inferior level of optimal, this should be no impediment to the use of PVB. Successful combustion is reported to occur when the ideal parameters are met (Cavalaglio and Cotana, 2007; Mendívil *et al*., 2013; Sun *et al*., 2020; Tenu *et al*., 2019).

DISCUSSION

1. Impact of PVB contributions to vineyard mid-row soil properties

The results in Table 2 suggest a high level of PVB production in this site. Aside from the role that the carbon and nutrient concentrations of PVB play in the efficient burning of biofuel, if left in situ the nutrients captured within the lignified framework of PVB may make an important contribution to the carbon and nutrient cycle of the vineyard soil (White, 2015). However, it is important to note that the concentrations of nitrate and ammonium in this study were at the lower end of optimal, suggesting that PVB may not be a significant contributor of these elements after 13 years. Furthermore Morlat and Chaussod (2008) reported a decrease in soil N concentration over 27 years in the control (0.72 – 0.60 g/kg) and the PVB treatment (0.83 – 0.72 g/kg), noting that the final N concentration in the treatment was significantly higher than in the control. By contrast, P and K concentrations (g/kg) increased over the same period, but the differences between the control and treatment were not significant. These results may be important to a grower who, for example, grows in a soil of low fertility and cation exchange capacity, and/or where the use of cover crops is eschewed (Álvaro-Fuentes *et al*., 2008; Steenwerth and Belina, 2008; Veenstra *et al*., 2007).

However, in our study, we did not find any significant differences in the concentration of any of the key elements between treatments in either cultivar block. This suggests that after 13 years PVB may not be an important contributor of these elements in our specific context. It is important to consider the differences in soil conditions, management practices and duration of the study that may have influenced the outcomes. Further research, including long-term investigations in different vineyard systems, would provide a more comprehensive understanding of the contributions of PVB to soil properties.

2. Impact of removal of PVB from the vineyard on mid-row soil properties

After 13 years of deliberate exclusion of plant vineyard biomass (PVB) from mid-row management, the results (Table 4) indicate no significant difference between the organic C (OC) concentration within the top 30cm of soil (2.38 %) and that of the treatment in which PVB was incorporated into the top 30cm of soil for the same duration (2.40 %), resulting in an estimated 42 t/ha of sequestered C (Table 5 - over five times the amount reported in France (Morlat and Chaussod, 2008). These findings challenge the notion that long-term inclusion of PVB in vineyard soil significantly contributes to soil organic C in this particular context.

It is noteworthy to consider these results when the average annual values were 3.35 t/ha and 5.48 t/ha of PVB incorporated into the soil of the Shiraz and Semillon blocks respectively (Table 2). By contrast, Morlat and Chaussod (2008) incorporated dried PVB into the soil at a lower rate of 2 t/ha and observed a significantly higher level of sequestered OC (8 t/ha) compared with the control of no biomass, which showed a 19 % decline in sequestered OC; this difference in the rate of PVB incorporation and the resulting effect on sequestered OC made it an important contributor in their study.

To better understand the reasons behind the observed differences between our results and this other study, it is important to consider the various production practices in the Coombe vineyard. In this site, the system of production involves the distribution of fresh PVB over two out of every three rows. Additionally, the management activities of the site differ. In particular, the incorporation of permanent mid-row swards, including several N-fixing species, and their maintenance may contribute to a shift in the overall functioning of the vineyard soil ecosystem (Celette *et al*., 2009; Coll *et al*., 2009; Salomé *et al*., 2016). These practices may enhance carbon cycling and nutrient availability in the soil, potentially offsetting the contribution of PVB. Moreover, the high fertility characteristics of the soil at the Waite campus (Table 1), including its composition and water holding capacity, may interact with the presence or absence of PVB and mid-row species, resulting in different outcomes compared with other studies in similar climates. Many studies report that cover crops of various species contribute positively to C sequestration in soils (Garcia *et al*., 2018), although the rates of change to soil C vary. For example, after four years of permanent cover crop use, Celette *et al*. (2009) found no significant differences in Soil Organic Matter (SOM) content as a measure of C. Morlat and Jacquet (2003) reported a significant increase after 27 years in vineyard soils under permanent sward cover compared with no crops in the control. Belmonte *et al*., (2016) reported that, after three years, significant increases in SOM content were observed. These variances could be accounted for by differences in crop PVB production through differences in soil type and quality and changing climate conditions (Celette *et al*., 2009; Coll *et al*., 2009; Salomé *et al*., 2016). In addition, various studies report a positive enhancement of C cycles in semi-arid/ Mediterranean environments when cultivation is minimised and cover crops are properly managed (Álvaro-Fuentes *et al*., 2008; Steenwerth and Belina, 2008; Veenstra *et al*., 2007).

Therefore, the presence of these factors may have influenced the outcomes observed in our study. However, to provide a more comprehensive understanding of these dynamics, further investigation in other production systems, including management practices such as cultivation, would be valuable. This additional research may strengthen the support for our results and provide more insight.

3. Impact of removal of PVB from the vineyard on vine nutrition

From the evidence presented here, it could be inferred that the removal of PVB has a minimal effect on vine nutrition, particularly when comparing the results of nutrient measurements between soil, PVB and petioles. The concentrations of P and K fall within the desired range. However, it is important to note that the concentrations of N in the soil (Table 4) and petioles (Table 6) are at the lower end of optimal, while there is an overall positive value of key nutrients in the PVB (Table 2). Despite the lower levels of N, P and K in petioles, there is no evidence of and nutrient deficiencies impacting vine health, yield, or grape quality. It should be acknowledged that accurately identifying the factors contributing to these lower levels of N is challenging, but the C:N ratio of the PVB and the soil may play a role.

Table 3 shows that the C:N ratio for PVB was 62.60 for Shiraz and 63.17 for Semillon, may have resulted in the immobilisation of N in the soil. Ratios of this level are not unexpected in vine prunings and other high C crops such as cereal straws (White, 2015). Soil C:N ratio values of 80 and up to 100 are possible and can have an important impact on slowing N mineralisation (García-Orenes *et al*., 2016; Pereg *et al*., 2018). This might explain the lower than ideal N concentrations recorded in petiole samples at flowering. However, since soil sampling only occurred at one time point in one season, it is difficult to draw a definitive correlation between the reported N concentration in the petioles and soil. In future research, the inclusion of multiple sampling points across the season and over several years may provide more insight.

One of the limitations of this study is that we are not able to test these concepts in terms of PVB nutrient concentration based on treatments. The strip plot design constraints in relation to vineyard management did not allow for the separation of vines between the "With PVB" and "Without PVB" treatments with a true buffer zone between them (Figure 2). This means that vines adjacent to a mid-row in which PVB was withheld were equally exposed to a mid-row where it was not. A randomised trial where treatments are separated by buffer zones could help eliminate these limitations.

4. Pruned Vine biomass (PVB) as a biofuel

In terms of the use of PVB as a biofuel feedstock, the results presented in Table 2 demonstrate that physiochemical concentrations of PVB measured in both Shiraz and Semillon are consistent with results in previous studies. The nutrient and C concentrations in the PVB of both Shiraz and Semillon (%N = 0.74 and 0.86, %K = 0.69 and 0.73 and %C = 49.97 and 50.15 respectively) meet the parameters of an efficient burning fuel as determined by previous research (Cavalaglio and Cotana, 2007; Mendívil *et al.*, 2013; Tenu *et al.*, 2019). Therefore, based on our findings, PVB holds promise as a viable and efficient biofuel feedstock.

CONCLUSION

The findings of this study suggest that PVB plays a limited role in terms of its contribution to soil carbon and nutrients in this site. However, it is important to note that the lack of information on the starting soil carbon concentration limits our ability to fully interpret the rate at which changes occurred. Additionally, the changes to soil and cover crops management over time may have influenced the dynamics observed in this study, and further investigation is needed to better understand their specific impacts.

From a bioenergy perspective, the findings suggest that PVB could be harvested for use as a reliable biofuel with minimal impact on long term soil properties. However, while the contribution of PVB to the soil nutrient and carbon cycles appears minimal, it is worth considering that growers in soils of lower fertility classifications may rely on PVB as an important source of C and nutrients and potentially improving soil structure. Furthermore, cover crops may fulfil this role more effectively.

To address the limitations of this study and gain a more comprehensive understanding further investigations should be conducted in which PVB is removed from vineyards in varying climatic regions; mid-row crop use and other soil types may provide additional insight. Such studies should aim to include information on the starting soil concentration as well as include multiple sampling points across seasons and years to better understand the correlation between PVB and soil. Additionally, it is essential to explore and define the logistical challenges, costs, and processing end fates of PVB in other countries, especially those where the costs of production and logistics are higher or processing infrastructure is still developing, as these factors may be barriers to adoption.

To summarise, while the findings of this study indicate that the contribution of PVB to soil carbon in this specific site was minimal, further research is needed to validate these findings in different contexts. It will be crucial to consider the limitations of this study and the region-specific factors and cultural management practices. This will provide a more comprehensive understating of the potential contribution of PVB in enhancing soil carbon sequestration.

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REFERENCES

Álvaro-Fuentes, J., López Sánchez, M. V., Arrúe, J. L., & Cantero-Martínez, C. (2008). Management effects on soil carbon dioxide fluxes under semiarid Mediterranean conditions. *Soil Science Society of America Journal, 72(1), 194-200*. https://doi.org/10.2136/sssaj2006.0310

Besnard, E., Chenu, C., & Robert, M. (2001). Influence of organic amendments on copper distribution among particle-size and density fractions in Champagne vineyard soils. *Environmental pollution, 112*(3), 329-337. https://doi.org/10.1016/S0269-7491(00)00151-2

Brosowski, A., Thrän, D., Mantau, U., Mahro, B., Erdmann, G., Adler, P., Stinner, W., Reinhold, G., Hering, T., & Blanke, C. (2016). A review of biomass potential and current utilisation–Status quo for 93 biogenic wastes and residues in Germany. *Biomass and Bioenergy, 95*, 257-272. https://doi.org/10.1016/j.biombioe.2016.10.017

Carpenter, D., Westover, T. L., Czernik, S., & Jablonski, W. (2014). Biomass feedstocks for renewable fuel production: a review of the impacts of feedstock and pretreatment on the yield and product distribution of fast pyrolysis bio-oils and vapors. *Green Chemistry, 16*(2), 384-406. https://doi.org/10.1039/C3GC41631C

Cass, A., & Roberts, D. (2005). Compost use in premium vineyard development. *The Australian & New Zealand Grapegrower and Winemaker*(497a), 36-40. https://doi.org/10.2558/1446-8212..497a.3518

Cavalaglio, G., & Cotana, S. (2007). Recovery of vineyards pruning residues in an agro-energetic chain. *Peach, 2*(6).

Celette, F., Findeling, A., & Gary, C. (2009). Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate. *European Journal of Agronomy, 30*(1), 41-51. https://doi.org/10.1016/j.eja.2008.07.003

Cerdà, A., & Rodrigo-Comino, J. (2021). Regional farmers' perception and societal issues in vineyards affected by high erosion rates. Land, 10(2), 205.

Chan, K., Fahey, D., Newell, M., & Barchia, I. (2010). Using composted mulch in vineyards—effects on grape yield and quality. *International Journal of Fruit Science, 10*(4), 441-453. https://doi.org/10.1080/15538362.2010.530135

Cockroft, B. (2012). *Soil management for Australian irrigated horticulture*. Land & Water Australia.

Coll, P., Arnal, D., Blanchart, E., Hinsinger, P., Cadre, E. l., Souche, G., & Villenave, C. (2009). Viticultural soils quality: benefits of permanent grass cover on soil chemical characteristics and soil biological indicators. *Progrès Agricole et Viticole, 126*(22), 527-531.

Cooke, G. W. (1967). *The Control of Soil Fertility*. Crosby Lockwood and Son Ltd.

Dale, V. H., Kline, K. L., Wright, L. L., Perlack, R. D., Downing, M., & Graham, R. L. (2011). Interactions among bioenergy feedstock choices, landscape dynamics, and land use. *Ecological Applications, 21*(4), 1039-1054. https://doi.org/10.1890/09-0501.1

Farine, D. R., O' Connell, D. A., John Raison, R., May, B. M., O' Connor, M. H., Crawford, D. F., Herr, A., Taylor, J. A., Jovanovic, T., Campbell, P. K., Dunlop, M. I. A., Rodriguez, L. C., Poole, M. L., Braid, A. L., & Kriticos, D. (2012). An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia. *GCB Bioenergy, 4*(2), 148-175. https://doi.org/10.1111/j.1757-1707.2011.01115.x

García-Orenes, F., Roldán, A., Morugán-Coronado, A., Linares, C., Cerdà, A., & Caravaca, F. (2016). Organic fertilization in traditional mediterranean grapevine orchards mediates changes in soil microbial community structure and enhances soil fertility. *Land Degradation & Development, 27*(6), 1622-1628. https://doi.org/10.1002/ldr.2496

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., & Metay, A. (2018). Management of service crops for the provision of ecosystem services in vineyards: A review. *Agriculture, Ecosystems and Environment, 251*(C), 158-170. https://doi.org/10.1016/j.agee.2017.09.030

Google (2019). *Vineyard area image [Goolge Earth image]* Retrieved 25 March from https://www.google.com.au/earth/

Greacen, E. (1981). Physical properties and water relations. In J. Oades, D. Lewis, & K. Norrish (Eds.), *Red Brown Earth's of Australia* (pp. 83-96). Waite Agricultural Research Institute, University of Adelaide and the CSIRO Division of Soils.

Hall, J. (2016). *Soil Characterisation Sites - Waite Campus Sites JCC_WO1 and JCC_WO2*. J. C. Consulting.

Isbell, R. (2016). *The Australian soil classification*. CSIRO publishing.

Krstic, M., & Collings, S. (2003). *Growing quality grapes to winery specification : quality measurement and management options for grapegrowers*. Winetitles.

Lal, R. (2022). Reducing carbon footprints of agriculture and food systems. *Carbon Footprints, 1*(1), 3.

Lanyon, D. M., Hansen, D., & Cass, A. (2004). *The effect of soil properties on vine performance*. CSIRO Land and Water Black Mountain.

Locatelli, B., Pavageau, C., Pramova, E., & Di Gregorio, M. (2015). Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs. *Wiley Interdisciplinary Reviews: Climate Change, 6*(6), 585-598. https://doi.org/10.1002/wcc.357

Magagnotti, N., Pari, L., Picchi, G., & Spinelli, R. (2013). Technology alternatives for tapping the pruning residue resource. *Bioresource Technology, 128*, 697-702. https://doi.org/10.1016/j.biortech.2012.10.149

Manzone, M., Paravidino, E., Bonifacino, G., & Balsari, P. (2016). Biomass availability and quality produced by vineyard management during a period of 15 years. *Renewable Energy, 99*, 465-471. https://doi.org/10.1016/j.renene.2016.07.031

McCarthy, M., Dry, P., Hayes, P., & Davidson, D. (1992). Soil Management and Frost Control. In B. Coombe & P. Dry (Eds.), *Viticulture 2* (pp. 148-208). Winetitles.

Mendívil, M. A., Muñoz, P., Morales, M. P., Juárez, M. C., & García-Escudero, E. (2013). Chemical characterization of pruned vine shoots from La Rioja (Spain) for obtaining solid bio-fuels. *Journal of Renewable and Sustainable Energy, 5*(3). https://doi.org/10.1063/1.4808043

Morlat, R., & Chaussod, R. (2008). Long-term Additions of Organic Amendments in a Loire Valley Vineyard. I. Effects on Properties of a Calcareous Sandy Soil. *American Journal of Enology and Viticulture, 59*(4), 353-363. https://www.ajevonline.org/content/ajev/59/4/353.full.pdf

Morlat, R., & Jacquet, A. (1993). The soil effects on the grapevine root system in several vineyards of the Loire Valley (France). *Vitis, 32*, 35-42.

Morlat, R., & Jacquet, A. (2003). Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. *American Journal of Enology and Viticulture, 54*(1), 1-7. https://doi.org/10.5344/ajev.2003.54.1.1

Pereg, L., Morugán-Coronado, A., McMillan, M., & García-Orenes, F. (2018). Restoration of nitrogen cycling community in grapevine soil by a decade of organic fertilization. *Soil and Tillage Research, 179*, 11-19. https://doi.org/10.1016/j.still.2018.01.007

Picchi, G., Silvestri, S., & Cristoforetti, A. (2013). Vineyard residues as a fuel for domestic boilers in Trento Province (Italy): Comparison to wood chips and means of polluting emissions control. *Fuel, 113*, 43-49. https://doi.org/10.1016/j.fuel.2013.05.058

Popp, J., Lakner, Z., Harangi-Rákos, M., & Fari, M. (2014). The effect of bioenergy expansion: Food, energy, and environment. *Renewable and sustainable energy reviews, 32*, 559-578. https://doi.org/10.1016/j.rser.2014.01.056

Proffitt, T. (2014). Assessing soil quality and interpreting soil test results. *Recuperado 2014*.

Reuter, D., & Robinson, J. B. (1997). Fruits, Vines and Nuts. In. CSIRO Publishing.

Salomé, C., Coll, P., Lardo, E., Metay, A., Villenave, C., Marsden, C., Blanchart, E., Hinsinger, P., & Le Cadre, E. (2016). The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards. *Ecological Indicators, 61*, 456-465. https://doi.org/10.1016/j.ecolind.2015.09.047

Spinelli, R., Magagnotti, N., & Nati, C. (2010). Harvesting vineyard pruning residues for energy use. *Biosystems Engineering, 105*, 316-322.

Spinelli, R., Nati, C., Pari, L., Mescalchin, E., & Magagnotti, N. (2012). Production and quality of biomass fuels from mechanized collection and processing of vineyard pruning residues. (Report). *Applied Energy, 89*(1), 374. https://doi.org/10.1016/j.apenergy.2011.07.049

Steenwerth, K., & Belina, K. (2008). Cover crops enhance soil organic matter, carbon dynamics and microbiological function in

a vineyard agroecosystem. *Applied soil ecology, 40*(2), 359-369. https://doi.org/10.1016/j.apsoil.2008.06.006

Stucley, C., Schuck, S., Sims, R., Larsen, P., Turvey, N., & Marino, B. (2008). *Biomass Energy Production in Australia: Status, Costs and Opportunities for Major Technologies* (EPL-1A). R. Publication.

Sun, X., Wei, X., Zhang, J., Ge, Q., Liang, Y., Ju, Y., Zhang, A., Ma, T., & Fang, Y. (2020). Biomass estimation and physicochemical characterization of winter vine prunings in the Chinese and global grape and wine industries. *Waste Management, 104*, 119-129. https://doi.org/10.1016/j.wasman.2020.01.018

Tenu, I., Dumitrachi, P.-E., Rosca, R., Cârlescu, P., Naghiu, A., Roman, C., Senilă, L., & Becze, A. (2019). Researches regarding the evaluation of the biomass potential resulted from the dormant pruning of some vine varieties. *Annals of the Faculty of Engineering Hunedoara, 17*(3), 141-144.

Tezza, L., Vendrame, N., & Pitacco, A. (2019). Disentangling the carbon budget of a vineyard: The role of soil management. *Agriculture, Ecosystems and Environment, 272*, 52-62. https://doi.org/10.1016/j.agee.2018.11.002

Van Loo, S., & Koppejan, J. (2002). *Handbook of biomass combustion and co-firing; IEA Bioenergy*. Twente University Press: Enschede, The Netherlands.

Veenstra, J. J., Horwath, W. R., & Mitchell, J. (2007). Tillage and cover cropping effects on aggregate-protected carbon in cotton and tomato. *Soil Science Society of America Journal, 71*(2), 362-371. https://doi.org/10.2136/sssaj2006.0229

Vendrame, N., Tezza, L., & Pitacco, A. (2019). Study of the Carbon Budget of a Temperate-Climate Vineyard: Inter-Annual Variability of CO 2 Flux. *American Journal of Enology and Viticulture, 70*(1), 34-41. https://doi.org/10.5344/ajev.2018.18006

Webster, K. A., & Buckerfield, J. (2003). Spent mushroom compost for viticulture. *Australian & New Zealand Grapegrower and Winemaker*, 39-44.

White, R. E. (2015). *Understanding Vineyard Soils*. Oxford Universtiy Press.

WRB (2015). *World Reference Base for Soil Resources 2015: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps FAO*. IUSS Working Group.