Can Carbon Sequestration in Vineyard Soils Provide an Internationally Valid Offset for Greenhouse Gas Emissions?

Robert White, Nick Madden and Alfred Cass

Robert White is a consultant in soil sciences in Victoria, Australia, and emeritus professor in the School of Agriculture and Food at the University of Melbourne.

Nick Madden is a soil scientist with Napa, Calif.-based Vineyard Soil Technologies.

Alfred Cass is the owner of Alfred Cass & Associates, a Santa Rosa, Calif.-based soil sciences firm.

CLAIMS HAVE BEEN MADE in the media and recent scientific publications for winegrowers to be able to earn monetary credits by sequestering carbon in their soils to offset greenhouse gas emissions. This article distinguishes between carbon sequestration, storage and soil carbon content. It examines these claims by reviewing published literature on soil carbon content and storage as influenced by various management practices. It also examines data on long-term soil C measurements in commercial vineyards. The potential for earning carbon credits is evaluated in the context of two government-sponsored programs–the Australian Emissions Reduction Fund and the California Healthy Soils Program, which are promoted to landholders on the grounds of not only offsetting greenhouse gas emissions but also improving soil health.

Introduction

Carbon (C) sequestration in soil has been widely promoted as a means of offsetting a substantial fraction of the world's anthropogenic greenhouse gas (GHG) emissions (*www.4p1000.org*), sometimes referred to as a negative emissions strategy (Paustian et al. 2019). In the promotion of this aspirational concept, scientists and policymakers have focused on broad acre-agriculture (Lal and Bruce 1999), for which the soil management practices necessary to achieve significant and consistent increases in soil C have been well researched. However, more recently, enthusiasm has been expressed in the scientific literature (Madgett 2019, 2020) and the media (Bonterra Vineyards 2018, Brinkley 2019) for sequestration of C in vineyard soils, where comparatively little research has been carried out.

This article discusses the potential or otherwise for C sequestration in vineyard soils in the context of two government programs: the Emissions Reduction Fund (ERF) in Australia (*www.cleanenergyregulator.gov.au/ERF*) and the Healthy Soils Program (HSP) in California (2020 Healthy Soils Program Incentives Program). These programs exemplify the practical implementation of this concept, whereby landholders can earn a monetary reward (C credits) for achieving a verifiable reduction in net GHG emissions through a change in management. The article discusses what the best options for soil management change in vineyards may be and the constraints that exist, with examples from the literature and from commercial vineyard data.

Some Definitions

True sequestration involves the capture of atmospheric carbon dioxide (CO_2) by photosynthesizing plants, its deposition in organic materials in the soil via plant litter, fallen branches, root secretions, root decay and animal manures where it is permanently retained. In practice, the definition of permanence is highly flexible. In the Australian ERF, the period of "permanence" can be chosen by the landholder as either 25 or 100 years (nearly all recent projects in the Australian Clean Energy Regulator's (CER) register are for 25 years (*www.cleanenergyregulator.gov.au*). In California's HSP, grants are awarded for three years with the proviso that the approved management practice is continued for a further three years. Because the meaning of permanence is so flexible, we prefer the term soil C storage (e.g., C stored per ha to 0.3 m depth) rather than C sequestered. Carbon storage is calculated from soil C content (weight of C/weight of soil) by multiplying by the soil bulk density and correcting for rock fragments greater than 2 mm diameter to the chosen depth.

Emissions of other major GHG from viticultural activities comprise methane (CH_4) and nitrous oxide. The global warming potentials of these gases, relative to carbon dioxide on a mole for mole basis, are calculated for a 100-year life span as 28 and 265, respectively (*www.ipcc.ch/assessment-report/ar5*). Thus, emissions of GHG that include all three gases are expressed as carbon dioxide equivalents (CO_2-e).

Net GHG emissions from a viticultural management practice on a defined area of land are calculated as the difference between GHG emissions (in CO_2-e) immediately after and before a specified period. Emissions to be accounted for are those produced by any mechanical operations (seed sowing, cultivation, spraying, harvesting and so on) and those associated with any inputs and their production (fertilizer, organic amendments and pumping of irrigation water), before and after the specified period. The GHG emissions, before implementation, comprise the baseline data. If, as a result of practice change, GHG emissions are increased, the increase must be less than the increase in soil C, expressed in CO_2-e/ha, for valid C credits to be awarded. On the other hand, if soil C has not changed or even decreases during the specified period, net emissions must decrease substantially for any offset of GHG emissions to be credited.

The Concept of Additionality

Certain requirements must be met if soil C sequestration is to be validated as a genuine offset, *additional* to what is currently being achieved in a vineyard. For example, it is not acceptable for organic materials, such as compost or manure applied to vineyard soil, to be derived off-site. Generally, this is a zero-sum action because these organic materials should be returned to the soil at their site of origin. The only case where this action might be acceptable is if the organic materials were waste materials that would otherwise have been combusted—this might apply to biosolids. Another possibility is that the waste materials would have been placed in a landfill where decomposition under anaerobic conditions could release C as CH_4, which is a much more potent GHG than CO_2.

Converting organic materials to biochar, before being applied to vineyard soil, might also be acceptable because biochar is more resistant to decomposition and hence longer lived in the soil than the original material. However, for the effect on emissions to be net positive, the production of CO_2 and other GHG during the process of biochar production, transport and application, must be less than the CO_2-e attributable to the extra C stored in the soil. Furthermore, because biochar can directly increase the soil C content, in the Australian ERF biochar C is quantified and discounted in the calculations for crediting.

The concept of additionality is important in determining C sequestration that can offset GHG emissions over and above what are currently being achieved. For example, soil C storage in an established vineyard is on-going and therefore is counted as offsetting existing emissions. Only if soil C storage can be increased by implementation of a new management practice can extra sequestration be counted as an offset for GHG emissions. This principle underlies both the Australian ERF and the California HSP programs.

The following section gives examples of the possibility of additional C storage from practice change. However, none of these examples compares changes in soil C (expressed as CO_2-e) with net GHG emissions, following practice change. Some of the difficulties in measuring changes in soil C on a per hectare basis are also discussed.

Examples of Changes in Soil Carbon in Vineyard Soils

MULCH, COMPOST AND MANURES

Longbottom and Petrie (2015) gave a summary from the literature of measured changes in soil C in vineyards, following mulch, compost or manure applications. Although these results generally showed positive increases, they do not satisfy the above criterion that organic amendments must be derived on-site nor in some cases was the sampling depth for soil C down to an adequate depth (0.3 m). One exception was the 28-year trial of Morlat and Chaussod (2008, also reported by Lejon et al. 2007), wherein crushed prunings were applied annually at 2 Mg/ha to the inter-rows of a Cabernet Franc vineyard on a sandy soil in the Loire Valley, France. Between 1976 and 2004 the soil organic carbon (SOC) stored under this treatment *decreased* by 2.7 Mg/ha to 0.3 m depth. However, when compared with the control treatment, the stored soil C *increased* by 5.6 Mg/ha to the same depth. Considering the uncertainty in these measurements of soil C storage due to spatial variability, these figures indicate a small but variable increase in C storage through the return of prunings to this sandy soil in a low rainfall environment (annual rainfall 525 mm).

The compost and manure treatments, applied annually over 28 years, produced substantial increases in soil C storage. For example, the application of 16 Mg/ha of spent mushroom compost each year produced an increase of 22 or 29 Mg C/ha to 0.3 m, depending on whether the SOC in the treated soil was compared to the original SOC of this soil or with the control soil, respectively. However, as a practical method of increasing soil C, this practice does not comply with the requirements for sequestration. In addition, large applications of compost and manure over time would elevate the nutrient load in the soil to a level where salinity and nutrient leaching problems could be expected. Higher concentrations of potassium in the root zone could lead to elevated must pH values and associated fermentation problems in the winery (Mpelasoka et al. 2003). Morlat and Chaussod (ibid.) did not comment on this.

COVER CROPS

Establishing a cover crop in a vineyard previously tilled or clean-cultivated is a practice change that could produce an increase in SOC and a potential GHG offset. Of the results reported by Longbottom and Petrie (ibid.), changes in SOC ranged from negative to small or medium-positive, depending on the soil type, depth of sampling, climatic environment and duration of the experiment. Unfortunately, unlike the work of Morlat and Chaussod (ibid.), changes in soil C stored per hectare could not always be calculated because soil bulk densities were not quoted. Some examples of the variable nature of the latter results are given in **TABLE 1**.

Based on the results in **TABLE 1**, the effect of establishing a cover crop on soil C storage is seen to be variable. In NE Sardinia (Seddaiu et al. 2013), soil C stored was 7.1 Mg/ha to 0.2 m depth less under a cover crop compared with tilled soil. However, taking the best positive result for a cover crop—that of treatment A in the 10-year data of Fourie et al. (2007) and assuming a median bulk density of 1.33 Mg/m^3, the estimated increase in soil C stored is 2.6 Mg C/ha to 0.3 m depth. The discrepancy in these estimates of the effect of a cover crop derives from the relatively short period of study, the spatial variability of SOC and the fact that small changes are being measured against a large background of soil C.

Moreover, in none of these trials was the net change in GHG emissions associated with the practice change calculated. Thus, whether there was a creditable offset of GHG emissions associated with the practice change (and any increase in SOC) could not be determined.

TABLE 1 Examples of changes in soil carbon (%) and soil carbon storage (Mg C/ha.soil depth) in vineyard soils

Source	Location	Duration (years)	Soil and its management	Depth of sampling (m)	Bulk density (Mg/m³)	Change in soil C (%)	Change in soil storage (Mg C/ha.depth)
Goulet et al. (2004)	Champagne region, France	5	Calcareous sandy loam, blue grass cover crop	0-0.05	n.d.	+1.04	
Goulet et al. (2004)	Champagne region, France	9	As above	0-0.2	n.d.	-0.12	
Seddaiu et al. (2013)	NE Sardinia	13	Coarse sandy soil, volunteer cover crop, prunings retained, irrigated	0-0.2	1.22	-0.14[1]	30.7[2]
Seddaiu et al. (2013)	NE Sardinia	13	Tilled, no prunings returned, no irrigation	0-0.2	1.35		37.8[2]
Fourie et al. (2007)	Oliphants River, South Africa	5	A. Sandy soil, rye or oats cover crop, sown annually, irrigated	0-0.3	n.d.	+0.04	
Fourie et al. (2007)	Oliphants River, South Africa	5	B. As above but cover crop sown biennially	0-0.3	n.d.	+0.04	
Fourie et al. (2007)	Oliphants River, South Africa	10	As for A above	0-0.3	n.d.	+0.065	
Fourie et al. (2007)	Oliphants River, South Africa	10	As for B above	0-0.3	n.d.	+0.04	

[1] No initial measurements and no control plots; this figure is the change in C% between the two treatments

[2] This is the actual soil C storage at the time of measurement; the difference between the two treatments is 7.1 Mg/ha.0.2 m

Other Vineyard Measurements

Other authors (e.g., Williams et al. 2011, 2020) have measured the total C stored in vines plus soil on a single occasion or over an interval as short as one year (Brunori et al. 2016). For relatively young vineyards, total C storage increased as expected with time, but no partitioning of the C increase between vines and soil was revealed, possibly because of the large uncertainty associated with the SOC values measured at very low sampling densities. However, soil C storage in established vineyards does not qualify as a potential GHG offset: a landholder must establish a new vineyard or change the management of an existing vineyard to participate in a GHG offset program, such as the ERF or HSP.

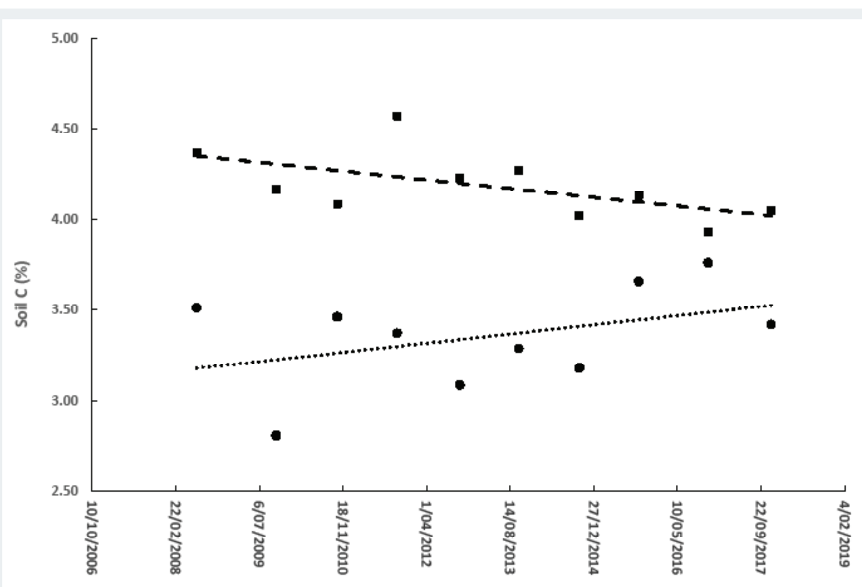

FIGURE 1 Trends in SOC (0-0.12 m) for a Pinot Noir block (●) and Chardonnay block (■) in the Yarra Valley, Australia. Pinot Noir trend line y = 0.0001x - 0.8362; Chardonnay trend line y = -0.0001x + 8.1485

Results from a commercial vineyard in the Yarra Valley, Australia, provide an example of practical changes in soil C in a Chromosol (Alfisol) over a lengthy period. **FIGURE 1** shows the trends in soil C (0-0.12 m) for blocks of Pinot Noir and Chardonnay vines under constant management for 10 years. A permanent cover crop of mixed grass and broad leaf species was grown and intermittently mown, with the mowings thrown under the vines. In the middle period (2010-12) grape marc (pomace) compost (5 Mg/ha) and reactive phosphate rock (RPR, 200 kg/ha) were broadcast on the Pinot Noir block; 500 kg/ha of Organic Plus, RPR (200 kg/ha) and agricultural lime (5 Mg/ha) were broadcast on the Chardonnay block. The first point to note is the year-on-year variation in soil C values made on bulked samples analyzed by the same commercial soil testing laboratory. This variability did not seem to be related to the inputs of organic materials. Secondly, the trend line for soil C change was positive for Pinot Noir but negative for Chardonnay. Given a surface soil bulk density of 1.15 Mg/m³, the change in soil C storage to 0.12 m depth was +0.51 and -0.51 Mg C/ha for the Pinot Noir and Chardonnay blocks, respectively. These results indicate that even over 10 years in vineyards on the same soil type under constant management, consistent changes in C storage were difficult to measure.

Similarly, there is little evidence to support the belief that soil C can be increased by vineyard floor management practices used in California. Data in **FIGURE 2** reflect the entirety of these practices on topsoil SOC of 456 paired samples extracted from under-vine and mid-rows of a selection of commercial vineyards in Napa and Sonoma counties between 2005 and 2018. Mean values for under-vine and mid-row were not statistically different. The combined data show, on a regional basis, a negligible increase in SOC over 13 years and reflect the established concept that for a given soil type under relatively uniform climatic and soil management regimes, soil C content reaches an equilibrium value that remains static until a new set of drivers force change (Kane 2015).

The mean value of SOC (± standard deviation) in Napa and Sonoma topsoils over this period remained nearly constant at 1.52 ± 0.78 percent. These ranges are close to the lower end of the SOC spectrum characteristic of Alfisol (Chromosol) soils, the dominant soil order in these counties. The

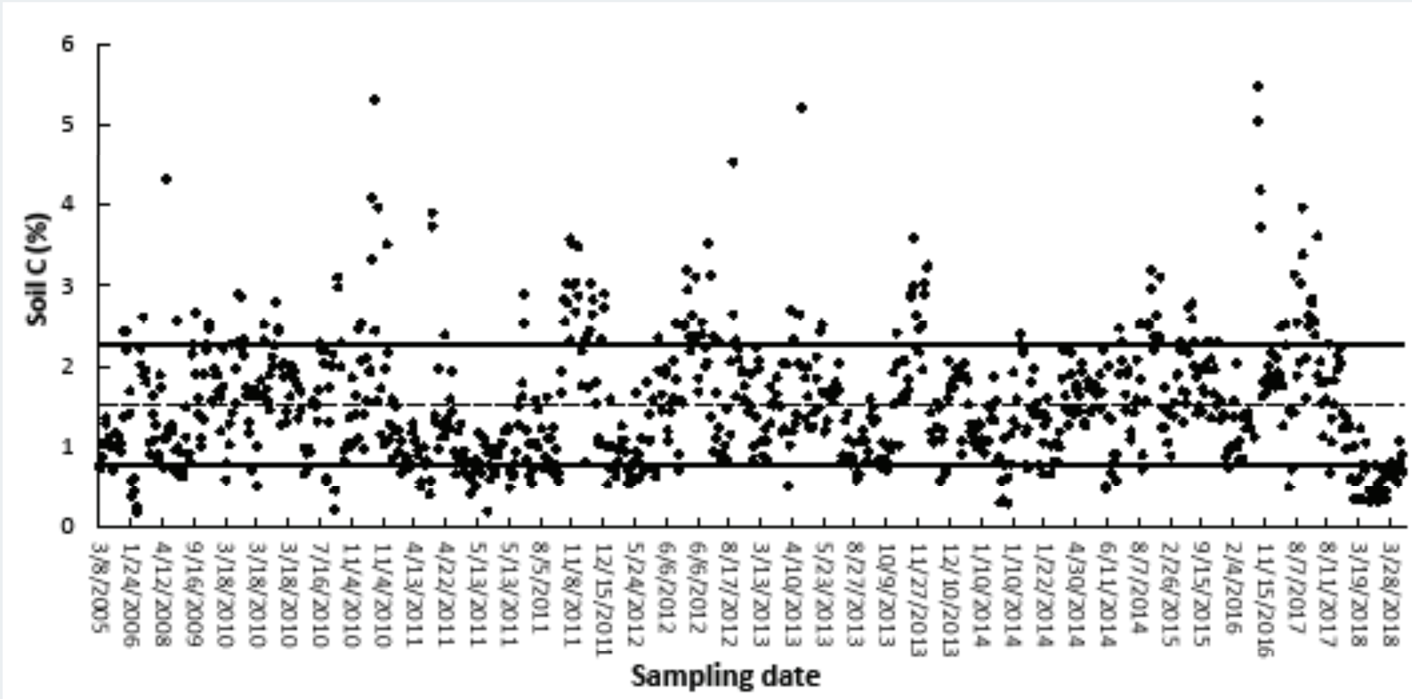

FIGURE 2 Organic carbon (C) contents of topsoil vine-row and mid-row soil samples extracted from commercial vineyards in Napa and Sonoma counties between 2005 to 2018. The mean value (----) and mean ± standard deviation of the mean (·······) are shown.

expected C content for Alfisols ranges from 0.46 to 3.8 percent (Brady 1990, cited by Mitchell and Everest 1995), depending on climate and land management. Spatial analysis of the data (not shown here) shows that values above the mean plus standard deviation (>2.30% C) were largely extracted from higher elevations with cooler meso-climates and possibly younger vineyards. The large majority of samples with C contents within the range of 1.52 ± 0.78 percent C were extracted at lower elevations with warmer meso-climates and predominantly longer-established vineyards.

The predominance of topsoils with relatively low values of SOC in Napa and Sonoma counties suggests that there is capacity for C sequestration, but given the negligible change reflected over 13 years of monitoring, this will require substantial changes in land management to achieve.

Measurement versus Estimation of Soil Carbon Change

The objective of the Australian ERF is primarily to offset GHG emissions although the productivity benefits of increasing soil organic matter are also recognized. Under this program, a limited number of changes in soil management are acceptable; and because any C credits earned need to be valid under international protocols, the requirements for measuring changes in soil C storage are stringent. Soil is sampled intensively to 0.3 m depth and soil C measured by an approved laboratory method to establish a baseline against which any subsequent changes in SOC are assessed. At least two samplings must be undertaken, before credits are awarded, to establish a trend line for soil C change. As part of the project mechanism, participants bid to supply C credits (1 Australian Carbon Credit Unit [ACCU] for 1 Mg CO_2-e avoided or offset) at a price determined by a reverse auction (*www.cleanenergyregulator.gov.au/ERF*).

The California HSP appears to be more focused on improvement in soil health through soil C increase, and the requirements for assessing GHG offsets are more relaxed. Financial grants up to US$100,000 are awarded in advance to applicants who agree to implement an eligible management practice, which for vineyards must be maintained for three years, with a further three years of monitoring. Soil samples are to be taken annually for soil C measurements, but there is no apparent criterion for soil C change that needs to be met. Rather, the GHG reduction benefit is obtained from a "qualitative ranking" of the management practice as approved by the Natural Resource Conservation Service.

The HSP scheme cannot rigorously quantify how much GHG reduction, as Mg CO2-e/ha/year, can be achieved in a given project: it is based on the imputed GHG reduction achieved by a specified management practice during a limited period of three years. However, this makes the program much easier to implement and more attractive to winegrowers than the Australian ERF, with its heavy and costly emphasis on repeated sampling and soil C measurements. Having gone through several iterations since its inception in 2014, the methodology of the ERF is currently being revised to simplify its implementation. Under consideration is a "hybrid" approach whereby the output of a deterministic model of C turnover, calibrated against soil core measurements, will be used to estimate changes in soil C storage (Clean Energy Regulator 2020).

Conclusions

Soil carbon storage can be increased in vineyards by applying organic mulch, compost or manures as Morlat and Chaussod (ibid.) demonstrated in a long-term trial. However, unless these materials are generated on-site, the gains in soil C storage are not true GHG offsets: this is merely transferring organic matter from one site to another. This constraint is recognized in the Australian ERF where such treatments are not accepted as approved practices for earning ACCUs. Contrary to this, compost obtained from an off-site certified facility is acceptable under the California HSP. However, any C credits generated could not be claimed as internationally verifiable offsets.

The return of vineyard prunings is a possible way of increasing soil C storage. However, again as the Morlat and Chaussod (ibid.) results showed, any significant increase in soil C storage was difficult to demonstrate, possibly because of the uncertainty associated with soil C measurements. On the other hand, the pruning weight in this trial of 2 Mg/ha represents a low average weight of prunings from VSP-trellised vines in a vineyard of 5,000 vines/ha (Skinkis 2013). Hence it is possible that the return of larger amounts of prunings in a moderately vigorous vineyard could achieve greater soil C storage.

Based on experience in broad-acre agriculture (Alskaf et al. 2021), the most promising method for increasing soil C storage in vineyards is likely to be by abolishing tillage and growing a permanent cover crop in the mid-rows. However, in trial results to date (see **TABLE 1**) consistent increases in storage have been difficult to demonstrate because of uncertainty in soil C measurements and the short duration of observations. A further point is that in many regions where irrigation is necessary, a permanent cover crop is likely to increase the demand for water, which may be in short supply and adds to the energy cost if pumped.

As indicated, the major constraints in using soil C storage in vineyards to offset GHG emissions are the limited management options that satisfy international protocols and the difficulty of reliably measuring small changes in soil C. In Australia, the uncertainty in outcome, coupled with the cost of soil sampling and analysis required under the ERF, has been a deterrent to landholders when the value of an ACCU is only about AUD16/Mg CO_2-e. Indeed, none of the 900+ projects on the current CER register involves sequestering C in vineyard soil. Although the California HSP avoids the financial difficulties by paying grant money up-front and estimating soil C benefits from approved soil management practices, this does not produce internationally acceptable C credits. The main benefit in this scheme is in improving soil health. **WBM**

Acknowledgements

We are indebted to Rob Sutherland of De Bortoli Wines for the data presented in **FIGURE 1** and to Dr Paul Anamosa of Vineyard Soil Technologies for data presented in **FIGURE 2** and for valuable comments on an early draft of this article.

References

Alskaf, K., Mooney, S.J., Sparkes, D.L., Wilson, P. and Sjogersten, S. (2021). Short-term impacts of different tillage practices and plant residue retention on soil physical properties and greenhouse gas emissions. *Soil and Tillage Research* 206, 1-12.

Bonterra Vineyards (2018). In pursuit of a vital carbon system. Retrieved 23 November 2020, from *www.bonterra.com/soil-study*

Brinkley, J. (2019). Farming and carbon. The Press Democrat. Santa Rosa, California, USA, Sonoma Media Investments. *www.pressdemocrat.com*. 2 June 2019: Letter to the Editor.

Brady, N. (1990). *The Nature and Properties of Soils*. 10th Edition. Cranbury, USA, Macmillan Publishing Company.

Brunori. E., Farina, R. and Biasi, R. (2016). Sustainable viticulture: the carbon-sink function of the vineyard agro-ecosystem. *Agriculture Ecosystems and Environment* 223, 10-21.

Clean Energy Regulator (2020) DRAFT: Understanding your soil carbon project. STAKEHOLDER CONSULTATION VERSION 1.0, Australian Government, Canberra.

Fourie, J.C., Agenbag, G.A. and Louw, P.J.E. (2007). Cover crop management in a Sauvignon Blanc/Ramsey vineyard in the semi-arid Olifants River Valley, South Africa. 3. Effect of different cover crops and cover crop management practices on the organic matter and macro-nutrient contents of a sandy soil. *South African Journal of Enology and Viticulture* 28, 92-100.

Goulet, E., Dousset, S., Chaussod, R., Bartoli, F., Doledec, A.F. and Andreux, F. (2004). Water-stable aggregates and organic matter pools in a calcareous vineyard soil under four soil-surface management systems. *Soil Use and Management* 20, 318–324.

Kane, D. (2015). Carbon sequestration potential on agricultural lands: A review of current science and available practices. Retrieved 30 November 2020, from *sustainableagriculture.net/wp-content/uploads/2015/12/Soil_C_review_Kane_Dec_4-final-v4.pdf*.

Lal, R. and Bruce, J.P. (1999). The potential of world cropland soils to sequester C and mitigate the greenhouse effect. *Environmental Science and Policy* 2, 177–185.

Lejon, D.P. H., Sebastia, J., Lamy, I., Chaussod, R. and Ranjard, L. (2007) Relationships between soil organic status and microbial community density and genetic structure in two agricultural soils submitted to various types of organic management. *Microbial Ecology* 53, 650-663.

Longbottom, M.L. and P.R. Petrie (2015). Role of vineyard practices in generating and mitigating greenhouse gas emissions. *Australian Journal of Grape and Wine Research* 21: 522-536.

Madgett, O. (2019) Can grapegrowers become heroes of climate change? *Australian and New Zealand Grapegrower and Winemaker* 664, 31-32.

Madgett, O. (2020) Drawing a line in the soil. *Australian and New Zealand Grapegrower and Winemaker* 677, 22-25.

Mitchell, C.C. and Everest, J.W. (1995). Soil testing and plant analysis. Southern Regional Fact Sheet SERA-IEG-6*1. Retrieved 7 November 2019, from *aesl.ces.uga.edu/sera6/FACT/SERA-6-FS-1.pdf*.

Morlat R. and 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, 353-363.

Mpelasoka, B.S., Schachtman, D.P., Treeby, M.T., Thomas, M.R. (2003). A review of potassium nutrition in grapevines with special emphasis on berry accumulation. *Australian Journal of Grape and Wine Research* 9, 154-168.

Paustian, K., Larson, E., Kent, J., Marx E. and Swan, A. (2019) Soil C sequestration as a biological negative emissions strategy. *Frontiers in Climate* 1, 1-11.

Seddaiua, G., Porcua, G., Leddaa, L., Roggeroa, P., Agnellib, A., Cortic, G. (2013). Soil organic matter content and composition as influenced by soil management in a semi-arid Mediterranean agro-silvo-pastoral system. *Agriculture, Ecosystems and Environment* 167, 1-11.

Skinkis, P. A. (2013). How to measure dormant pruning weight of grapevines. EM 9069. Retrieved 16 January 2021, from *catalog.extension.oregonstate.edu/em9069*.

Williams, J.N., Hollander, A.D., O'Geen, A.T., Thrupp, L.A., Hanifin, R., Steenwerth, K., et al. (2011). Assessment of carbon in woody plants and soil across a vineyard woodland landscape. *Carbon Balance and Management* 6, 1-14.

Williams J.N., Morandé, J.A., Vaghti, M.G., Medellin-Azuara, J. and Viers, J.H. (2020). Ecosystem services in vineyard landscapes: a focus on aboveground carbon storage and accumulation. *Carbon Balance and Management* 15, 23-33.