Proceedings of the 19th Association of Public Authority Surveyors Conference (APAS2014)
Pokolbin, New South Wales, Australia, 31 March – 2 April 2014

Estimating and Predicting Carbon Sequestration in a Vineyard using Precision Viticulture Techniques

John Goward
University of New South Wales
j.goward@hotmail.com

Mark Whitty
University of New South Wales
m.whitty@unsw.edu.au

ABSTRACT

The aim of this paper is to estimate and predict the carbon footprint of a vineyard, on a yearly basis, by employing precision viticulture techniques to investigate the carbon sequestered in the vineyard and by analysing carbon emissions from the vineyard. Soil surveys, vine measurements and a Geographic Information System (GIS) were used to estimate the carbon in the vineyard. The project vineyard, located near Orange, is approximately 300 hectares in size and constitutes 18 blocks. It has 8 different grape varieties grown on it. It was determined that the vineyard has a positive carbon footprint of approximately 69 tonnes per year, and soil carbon accounts for about 70% of the total carbon sequestered. The vineyard manager would have a possibility to save $1,100 per year if the Carbon Farming Initiative was implemented for viticulture, however this would likely be outweighed by the management costs required to evaluate the carbon performance on an ongoing basis. Precision viticulture technologies such as GIS, soil surveys and spatial measurements have facilitated an understanding of the vineyard, and have aided in establishing that the vineyard has a positive carbon footprint. This paper demonstrates that vineyards have the capability to promote a carbon neutral environment by the inclination of perennial vines to sequester carbon and to stimulate long-term storage of carbon in the soil, hence proving the ability of grape vines to have a positive impact on climate change.

KEYWORDS: *GIS, precision viticulture, carbon sequestration, carbon cycle*.

1 INTRODUCTION

1.1 Background

With the introduction of spatial technologies, Precision Viticulture (PV) has evolved in the pursuit of higher quality wine and consistent yields. PV has been available since 1999, when the first commercially available grape yield monitor came onto the market (Bramley and Hamilton, 2004). Spatial data is being used by viticulturists who are currently using Geographic Information Systems (GIS) to help them accurately understand the parameters that affect their yields and quality of grapes from different vineyards (King et al., 2005).

The idea of PV has been utilised in this study with an emphasis on measuring the ability of vineyards to either successfully sequester carbon (hereafter referred to as C) from the atmosphere, or release C into the atmosphere, hence measuring the C footprint of vineyards. A C footprint can be defined as a comprehensive measure of the amount of greenhouse gases produced and consumed, and is used to determine whether or not individual operations are contributing to the increase of greenhouse gases in the atmosphere and therefore global climatic change (Carlisle et al., 2009). For this reason, developing vineyards with neutral C footprints can be reasonably defined as a long-term vineyard practice that would contribute to global sustainability. Furthermore, in 2011 the Australian Government introduced the Carbon Farming Initiative scheme, which allowed land managers to earn carbon credits by storing carbon or reducing greenhouse gas emissions on their land. Whereas the implementation of a carbon tax is highly dependent on political will, a methodology needs to be devised to prove the C footprint, the foundations of which are laid in this paper.

1.2 Literature Review

Precision viticulture technologies were introduced to the Australian wine industry in the late 1990s, hence they are relatively new for viticulturists. In 2005, the Cooperative Research Centre for Viticulture conducted a study to identify the factors influencing the adoption of three Precision Viticulture Technologies (PVTs). The technologies studied were soil mapping, vigour mapping and yield mapping.

From the study it became clear that few growers used PVT in planning and management of grape yield variability and grape quality variability. This is mostly because the growers were satisfied with the way they were managing the variability using well established techniques, and saw little advantage in managing their vineyards at a more detailed level. It is also understood that the growers that had used PVTs were using them to inform decision making such as confirming problems or mapping the areas of variability in fruit yield and quality within the vineyard (Hill et al., 2005). PVTs address variations through the use of Global Navigation Satellite System (GNSS) technology and GIS, coupled with tools for measuring and monitoring vineyards at high spatial resolution, such as remote sensing, yield monitors and high-resolution soil surveys (CSIRO, 2006).

There is currently tremendous uncertainty concerning the quantity of greenhouse gases produced and consumed in vineyards (Carlisle et al., 2010). Maintaining a vineyard emits greenhouse gases through operations such as tractor driving and other sources of fossil fuel combustion. In contrast, the growing of perennial vines has the propensity to sequester C, through photosynthesis, into its woody matter and also into the soil for perpetual storage. However, long-term cultivation has greatly depleted soil organic carbon compared to the forest ecosystems from which many vineyards were established (Suddick et al., 2010).

Williams et al. (2011) evaluated carbon stocks and woody plant diversity across vineyard blocks and adjoining woodland ecosystems for an organic vineyard in northern California. C was measured in soil from 44 one-metre deep pits and in above-ground woody biomass from 93 vegetation plots. GIS was used to analyse how a suite of variables affects C stocks, including tree and shrub species, topographic variables (slope, elevation and aspect), maps of soil and vegetation type, and remotely-sensed spectral data. Overall, Soil Organic Carbon (SOC) varied 1.7-fold among vineyards. Within vineyard tracts, there were no correlations found between SOC and vine age, slope, aspect or elevation.

Practices that conserve soil organic matter and reduce soil disturbance will protect the largest single reservoir of C in the farm system. Reducing soil disturbance has been shown elsewhere to decrease C loss (Paustlan, 2000). The small differences in soil C between paired woodland and vineyard sites, compared to another study that compared woodlands to conventional vineyards (Carlisle et al., 2006), suggest that the no-till, cover cropping practices and organic matter management used in this study system are conducive to soil C retention.

The above-ground C in the wood of grape vines was estimated for all tracts (management units) on the five ranches using the age and number of vines per tract. Vine wood volume was estimated based on vine age, which was calculated from a regression analysis based on samples of different ages. For each sample, measurements were taken for main trunk height, main trunk diameter at 0.5 m above the ground surface, cordon lengths from the main trunk, and a standard estimate of cordon diameter using age (2.5 cm of growth in the first five years, then 0.25 cm each additional year). Vine trunks and cordons were assumed to be straight cylinders of constant diameter. From these measurements, Carlisle et al. (2006) formulated a regression equation:

$$volume = 179.19 \text{ x } age^{1.3303} \quad (1)$$

This equation was derived by fitting a power function to the relationship between vine age and above-ground wood volume for 29 vineyard tracts, for vines under the age of 23. Vine biomass was then calculated by multiplying volume by wood density. Vine wood density was based on an analysis of Chardonnay vines on one of the ranches and given as 0.95 g dry weight/cm^3 fresh volume. Carbon content for vine wood was estimated as 50% of dry weight (Birdsey, 1992; Smith et al., 2003).

Keightley (2011) illustrates the contribution of viticultural carbon to that of agriculture at large, which can be used for gauging offsets to fossil fuel carbon emissions. A vineyard was sampled with a terrestrial laser scanning technique, paired with soil sampling and fruit yield. This study found that vines averaged 1.93 kg of dry biomass and when combined with root biomass, constituted only 2% of the total perennial vineyard carbon. The approach taken in this study was based on research by Williams and Biscay (1991), Clingeleffer and Krake (1992) and Mullins et al. (1992), which took into account the roots as a proportion of vine biomass. Roots, trunk and cordon biomass values are measured separately in these studies and provide biomass partitioning ratios. Among the three studies it was found that root, trunk and cordon biomass were approximately equal, providing a basis for estimation of root biomass from measures of above-ground biomass. The method set vine organic carbon mass at 45% of the oven-dry biomass and assumed that the roots were to be approximately 30% of vine biomass.

Increasing SOC can improve soil health and can help to mitigate climate change, and although there is a limit on the amount of organic carbon that can be stored in soils, large losses in the past mean that many Australian agricultural soils have the potential for large increases (Chan, 2008). A carbon footprint can be defined as a comprehensive measure of the amount of greenhouse gases produced and consumed, and it is used to determine whether or not individual operations are contributing to the increase of greenhouse gases in the atmosphere (CSWA, 2009).

It has been recognised that vineyards both produce carbon emissions and consume carbon emissions, which gives the opportunity for vineyard operators to actually consume more carbons than they emit, in turn decreasing the effects of global warming. Vineyards produce carbon emissions from agricultural activities such as tractor driving and electricity usage. However, carbon emissions are consumed by the growing of grapes through photosynthesis by the long-term storage in vegetative structures and soils. Therefore it is important to look at viticultural management procedures that can increase the total carbon consumed.

Thus the objective of this work is to estimate and predict the C footprint of a vineyard, on a yearly basis, by employing PV technologies to investigate the C sequestered in the vineyard and by analysing C emissions from the vineyard. Section 2 firstly presents the methodology used for estimating the soil and vine carbon levels and the corresponding volume of carbon sequestered each year. It then details the methodology for estimating the volume of carbon emitted from the vineyard each year. Section 3 presents the experimental results and infers the overall carbon footprint. The conclusion follows in Section 4, along with recommendations for improving the carbon footprint of similar vineyards.

2 CARBON FOOTPRINT ESTIMATION

The vineyard investigated in this study is managed by Jarrett's Wines and is a small to medium (300 hectare) vineyard located 30 km south-west of Orange, NSW – approximately 300 km west of Sydney, Australia. The vineyard has a total of 18 blocks, and over 178,000 vines. In each of the blocks a different variety of red and white grape vines are cultivated, including Chardonnay, Sauvignon Blanc, Riesling, Pinot Gris, Shiraz, Cabernet Sauvignon Merlot and Pinot Noir (Figure 1). The tools used to assess the vineyard's C footprint were a combination of land surveys, soil surveys, soil laboratory analysis, measurements of vines, and GIS management.

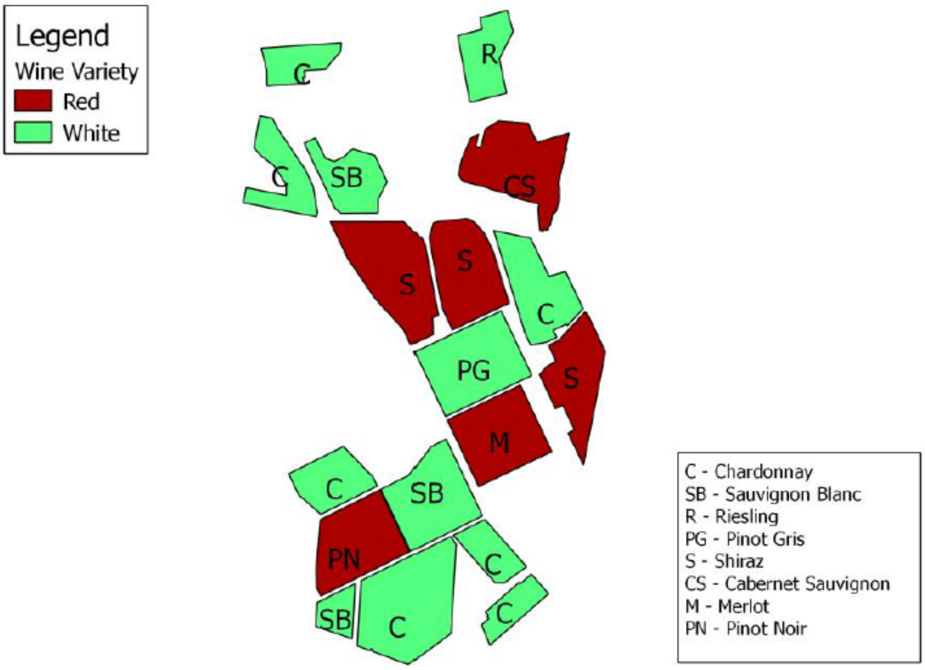

Figure 1: Wine varieties grown at Jarrett's of Orange.

Mapping the geographic boundaries of the study area was the first step to correctly identify where the C estimation was situated. The investigation into C sequestered was comprised of analysing the amount of soil and vine C. The inquiry into C emitted from the vineyard was done by an analysis of vineyard practices, including electricity usage, fuel usage and fertiliser applications. The emergence of all of these aspects resulted in a carbon footprint. The footprint was estimated on a yearly basis with prediction models from all of the obtained data.

2.1 Soil Carbon Sequestration

2.1.1 Field Survey and Baseline

The boundaries of each block were surveyed in December 2011 using differential GPS to a horizontal accuracy of 10 centimetres – the accuracy stated in the Carbon Farming Initiative (CFI) spatial mapping guidelines (Australian Government, 2012).

Numerous soil surveys had previously been undertaken on the vineyard to assess soil limitations of root growth and to provide management recommendations that optimise soil conditions for wine grapes within each management unit (Figure 2). More so, soil samples from the surveys were sent to a laboratory to specify the SOC content of the soil. The original field surveys were conducted in 1998 and 2010, which allowed the baseline C to be assessed. SOC contents derived from these surveys was used to calculate the amount of C per block, and hence the amount of soil C without the introduction of viticultural activities. In 2009 and 2012, carbon testing was conducted on soil samples from each block and analysed to give SOC values after the introduction of viticulture. The baseline SOC and the SOC values from the later years were used to compare and calculate how much C was sequestered or emitted from farming activities.

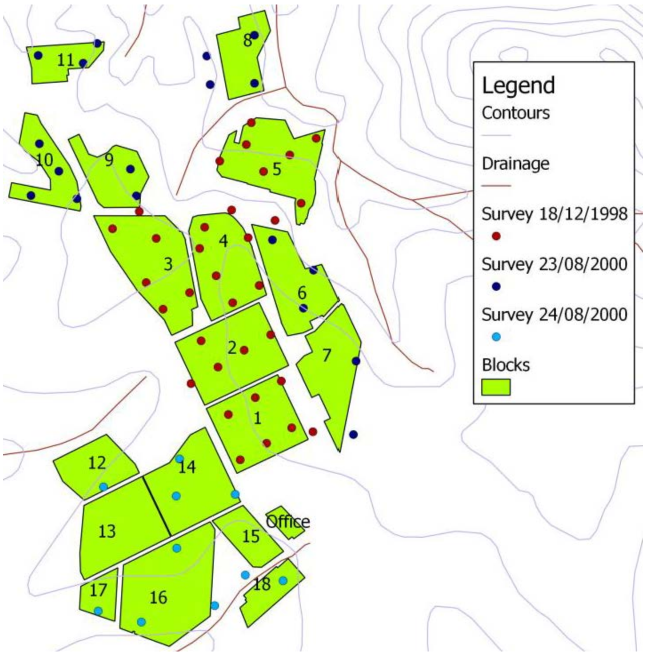

Figure 2: Locations of soil samples from baseline surveys.

Laboratory analysis of the soil samples at depths of up to 30 cm provided the organic carbon content, or SOC, using the Walkley-Black method as well as an estimate of the bulk density of the soil (McKenzie and McBratney, 2001). Chan's formula (Chan, 2008) was then used to calculate the baseline of C per hectare and per block.

2.1.2 Volume of Carbon Stored in the Soil

To evaluate how much C has been sequestered into the soil, soil samples from subsequent years were analysed. In 2009, soil samples from each block were taken and sent to the laboratory. Vineyard manager, Justin Jarrett, took samples from 20-30 locations on each block, at depths of 30 cm. Each sample within the designated block was combined, giving a good average soil sample to be analysed at the lab, for each individual block. In 2012, soil samples using the same method were taken from blocks 4, 9 and 16. A sample was also taken from unused land at the front of the vineyard lot to detect an SOC value for unused land in the area. The soil samples were sent to SESL Australia and the SOC was determined by the Walkley-Black method. The total C per block was then calculated and the difference between this and the baseline was found, showing the net carbon stored in the soil by the vineyard.

2.1.3 Predicting Soil Carbon Sequestration

The soil C was predicted by using the SOC values measured at the baseline, and setting a linear regression to the SOC values taken in 2009. Using this regression allowed for rough predictions into future and past years. Blocks 4, 9 and 16 had SOC samples taken in 2012; the predictions were compared to these sampled values, which is discussed in section 3.1.2.

All of the data was imported to QGIS to spatially analyse the results for soil and vine C. TIN interpolations enabled the spread of the soil C to be spatially visualised for the baseline and surveys undertaken in 2009. The difference in the spread endorsed an understanding in the change of soil carbon over the years after the vineyard was assembled. The spatial variation in vine carbon was also visualised and managed with the GIS.

2.2 Vine Carbon Sequestration

2.2.1 Measuring of Vines

The ideology of the process of measuring the vines was to find an average volume of each vine, to the best of our ability, to estimate the total carbon on the vineyard. An independent measurement of each vine was next to impossible as there are a total of 178,000 vines on the vineyard. Over the 300 ha vineyard, one vine from each corner of each block were measured, to give a total of 4 vines per block where possible. The following parts of the vines were measured: trunk diameter, trunk height, cordon diameter and cordon length (Figure 3).

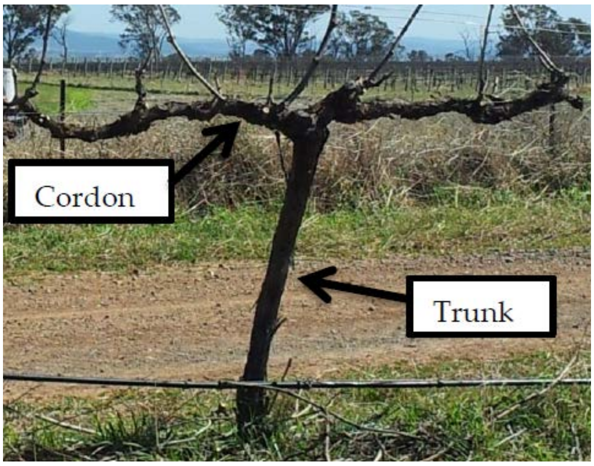

Figure 3: Vine with perennial trunk and cordon.

2.2.2 Volume of Carbon Stored in Vines

The volume of the vine wood, and the biomass of the vine wood, needs to be considered before calculating the C content of the vine. The total volume of each of the vines was determined by assuming that the cordon and the trunk are both perfect cylinders.

The dry biomass needs to be determined after the total volume is calculated; to do this vine wood density for the vines has to be resolved. The vine wood density was determined to be 0.95g dry weight/cm^3 fresh volume based on an analysis of Chardonnay vines in a study by (Williams et al., 2011). The value determined by them for the vine wood density was used for this study. Vine biomass is then calculated by multiplying vine volume by wood density.

Whole vine perennial biomass was expressed as 1.42 times the above-ground biomass, as described by Mullins et al. (1992), Clingeleffer and Krake (1992) and Williams and Biscay (1991). Roots were assumed to be approximately 30% of vine biomass based on the reported biomass values for roots, trunk and cordons (roots averaging 30% of the sum of all three categories) (Keightley, 2011).

The C content used for the vine wood was 45% of dry weight (Schlesinger, 1997). The C content per vine was determined by multiplying the biomass of the vine by 45%. The amount of C per block was estimated by multiplying the C content per vine by the number of vines in the block.

2.2.3 Predicting Vine Carbon Sequestration

To predict the vine C sequestration, the average vine volume per block was fitted to a power function, the form of which is given in equation 1. The equation had not been validated for vines older than 23 years, so this was the maximum prediction during the project. Individual parameters of the fit were recorded for each block based on the current vine measurements.

2.3 Farm Carbon Emission

The carbon footprint of the vineyard is assessed on a yearly basis according to:

$$\begin{aligned} \text{total } C_n &= [\text{Carbon Sequestered}] - [\text{Carbon Emitted}] \\ &= [(VC_n + SC_n) - (VC_{n-1} + SC_{n-1}) - (SC_{BL})] - [Elec_n + Fuel_n + Fert_n] \qquad (2) \end{aligned}$$

where n is the year of interest, BL is the baseline, VC is the vine carbon, SC is the soil carbon, $Elec$ is C emissions from electricity usage for the year, $Fuel$ is C emissions from fossil fuel combustion for the year and $Fert$ is C emissions from fertiliser applications for the year. Total C_n is the C stored for the year, where a negative value is C emission and positive value is C sequestration.

The positive contributors (sequestration) were all calculated in the methods explained in previous sections, and by summing the amount of C stored in the vines with that stored in the soil. The negative contributors (emissions) of C into the atmosphere were calculated using the Australian Wine Carbon Calculator (WFA, 2014). The region for the spreadsheet was set to NSW, and values used were from the management records of the vineyard. All of the values obtained were from 2011/12 and used as an average for other years.

The fuel and electricity usage was obtained by probing into the vineyards administration database to get values for the average amounts of fuel and electricity used per year. The vineyard also has solar panels in place, so the offset of electricity generated was utilised as well, significantly decreasing the total amount of electricity used. It must be noted that if electricity generation outweighs the total amount of electricity used, then it can be used as a positive contributor to the C equation.

Fertiliser use was obtained from the job sheets over the year. Each time the fertiliser was used, the amount used was recorded on the time sheet. The nitrogen content and the quantity used for each different brand of fertiliser enabled an estimate of how much C was emitted from the fertiliser usage (WFA, 2014).

3 RESULTS

3.1 Soil Carbon Sequestration

3.1.1 Survey Results

Figure 4 shows the SOC baseline measurements, all of which fall in the range between 0.5 and 3.5. The majority of the SOC content is between 0.5 and 1.5, with a medium amount between 1.5 and 2.5, and a slight amount between 2.5 and 3.5. A small amount in the red range is expected because an SOC between 2.5 and 3.5 is considered to be relatively high (DEPI, 2011). However, the blue range of SOC is considered to be low by the same reference, even though this is the majority of the SOC over the vineyard. The values between 2.5 and 3.5 could be considered outliers. The interquartile range was calculated for the samples and it was determined that values above 2.25 could be considered outliers, however the values were kept as it cannot be proven that the sample was taken incorrectly.

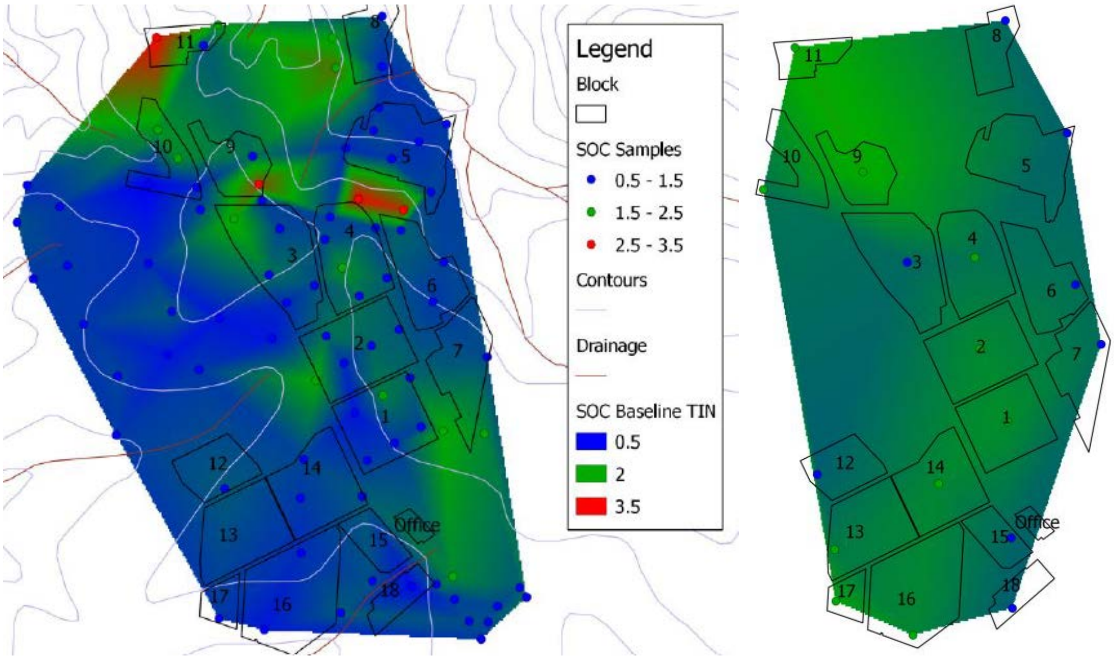

Figure 4: SOC levels extrapolated over the study area with the baseline values at left and 2009 survey results at right. Evidence of an overall increase in the SOC is shown by the general shift from blue to green.

The contours and drainage lines on this map paint an interesting picture. At the end of the drainage lines there is an inclination towards a higher SOC content (generally in the 1.5 – 2.5 range) compared to the majority of the soil. The higher SOC contents at the end of the drainage line conjectures SOC may be transported in heavy rains to the bottom of catchment areas. Also, the extrapolated map indicates that the bulk of the higher SOC contents is at the northern end of the vineyard, during the baseline samples. It appears that the top end of the vineyard has a more condensed catchment for water draining off the higher slopes, again suggesting that the higher SOC is from drainage.

The map generated for the 2009 samples suggests that overall the soil C has increased. However, the higher SOC values around 3.5 which were measured in the baseline were not determined. The results of the 2009 survey shows that again the northern part of the vineyard has the highest soil C. However, the southern part of the vineyard has now increased its C storage (in comparison to the baseline). When the baseline was surveyed, the SOC was generally in the range of 0.5 – 1.5, and in 2009 the values mostly ranged from 1.57 – 2.07. This clearly shows a significant increase in C sequestered in the soil due to the introduction of viticulture in the area. The average SOC increase per year for each block is shown in Figure 5.

In the entire vineyard there are no SOC values less than 1.32, where before this was the majority of the SOC. Conversely, there has also been a drop of SOC in some areas. There are no values in the 2.5 – 2.5 range, while there were four of these values in the baseline data. This could be due to farming activities, or solely because those higher values in the baseline were outliers. The 2009 survey consisted of taking 20 – 30 samples from each block to determine an average SOC, so it is quite likely that there were higher SOC samples, but the average used is better to determine a complete SOC value for the block.

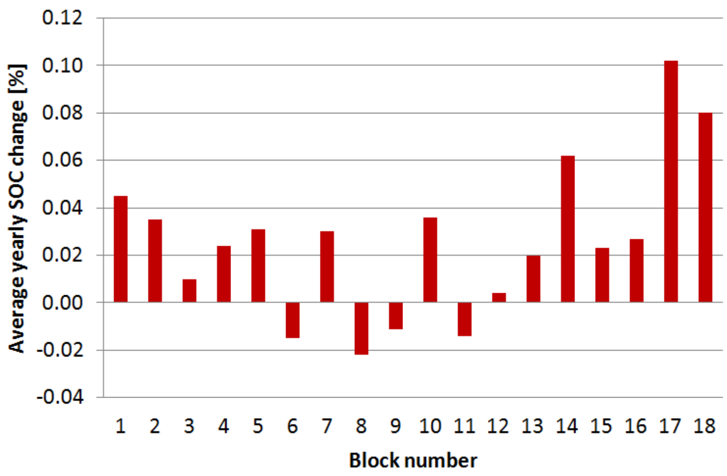

Figure 5: Average SOC increase per year in each block.

3.1.2 Prediction Results

In 2012, soil surveys were performed at blocks 4, 9 and 16 to calculate an average SOC value for each block. The recorded values were compared to the predicted values as shown in Table 1, allowing for the accuracy of the linear prediction to be realised and to also enforce whether the C for the subjective block actually increased or decreased as predicted with the linear regression. The evidence would have been more substantial and implicating if surveys were carried out on every block again, but this data was not available.

Table 1: Error in SOC prediction when compared with 2012 soil sample.

Block	2012 Prediction [% SOC]	2012 Measurement [% SOC]	Error [% SOC]
4	1.57	1.70	0.13
9	2.02	1.70	0.32
16	1.93	1.10	0.83

The 2012 sample showed that the prediction was 0.83 off and it agreed that the SOC in Block 4 is increasing compared to the baseline. However, the rate at which it is increasing is significantly slower than the prediction, and from 2009 to 2012 the results suggest that there has been a substantial decrease in the SOC value. It could be that the C is actually tending to decrease as of 2009 in this block. However, the decision to use a linear fit was simply because there is not enough data to support evidence of another regression fit; any of these results could be an outlier.

The total soil sequestered per year is estimated to be 81.54 tonnes, and makes up the majority of the C sequestered in the vineyard. The estimation per year is at a constant because of the linear fit to all of the SOC values interpreted; this would more than likely not be the case if samples were taken in each year because SOC stowage is unpredictable. The percentage of soil C, in comparison to vine C, decreases each year because the prediction of vine C storage slightly increases per year, while soil remains constant.

3.2 Vine Carbon Sequestration

3.2.1 Survey Results

The analysis on C in the vines is based solely on the single measurements completed in 2012 (Table 2). There were no measurements taken in other years, so each block has been fitted to the same growth formula at different scales. In order to keep the analysis at a constant, the vines have been investigated at 13 years of growth, since this was the age of the majority of the vines when they were measured. Blocks 6 – 18 were all measured at 13 years old. However, blocks 1, 3, 4 and 5 were measured at 14 years old, and block 2 was measured at 2 years old. The volumes of these vines at age 13 have been predicted by the growth formula. It must be noted that the prediction of block 2 at age 13 is very uncertain because that is 11 years in the future.

Investigating the spatial variation of the volume of vines per block shown in Figure 6, there does not appear to be any pattern for the growth in the vines. Nevertheless, the two highest volumes of vines per block are right next to each other (blocks 14 and 15). This could be a coincidence, or it could be due to reasons such as more sunlight and readily available water.

Table 2: Measured vine carbon.

Block	Variety	Type	# Vines	C per vine [kg]	Total C [t]
6	Chardonnay	White	10,750	1.89	20.31
10	Chardonnay	White	7,096	1.55	11.03
11	Chardonnay	White	6,832	1.62	11.04
12	Chardonnay	White	6,116	1.84	11.23
15	Chardonnay	White	4,139	3.33	13.77
16	Chardonnay	White	16,092	1.86	29.90
18	Chardonnay	White	3,683	2.18	8.02
9	Sauvignon Blanc	White	7,470	1.11	8.31
14	Sauvignon Blanc	White	11,054	3.34	36.88
17	Sauvignon Blanc	White	2,760	1.30	3.59
8	Riesling	White	6,849	1.44	9.86
2	Pinot Gris	White	15,900	0.78	12.34
3	Shiraz	Red	15,078	2.53	38.14
4	Shiraz	Red	12,482	2.21	27.53
7	Shiraz	Red	10,524	2.82	29.64
5	Cabernet Sauvignon	Red	13,742	3.11	42.75
1	Merlot	Red	12,960	1.90	24.62
13	Pinot Noir	Red	14,478	1.27	18.35

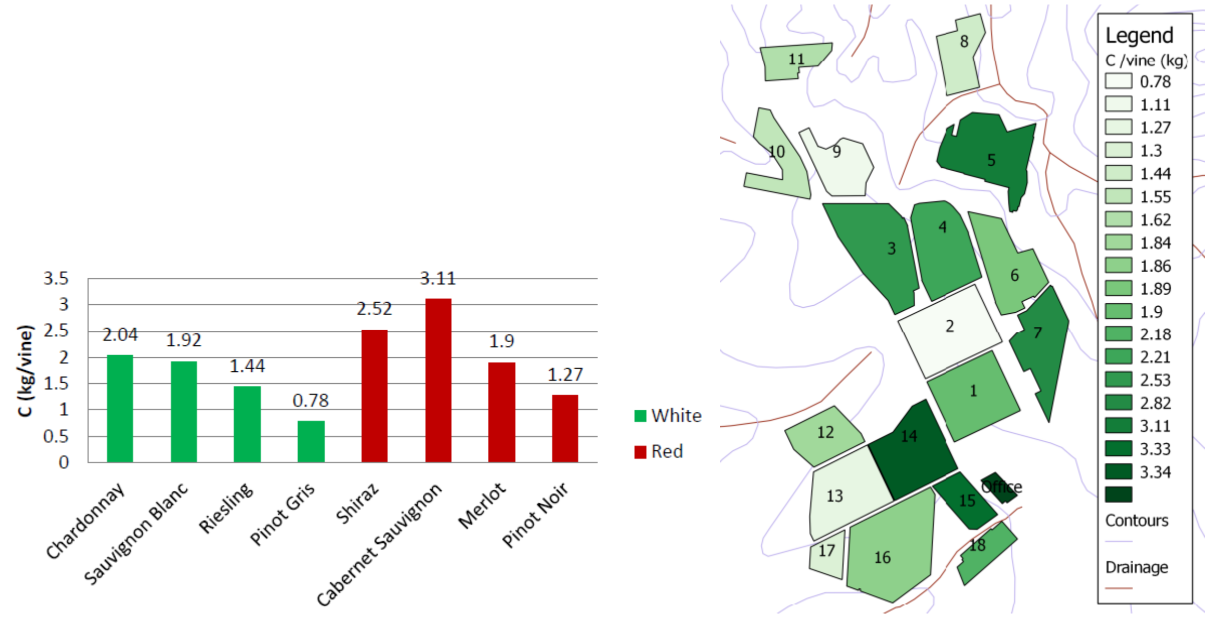

Figure 6: Vine carbon by variety (left) and location (right).

3.2.2 Prediction Results

From the vine measurements in 2012, the calculation estimates that the vines will store 36.14 tonnes of C, i.e. 30.7% of the expected total C sequestered. The predictions for the following years have an increase of 1 tonne, 0.93 tonne, 0.88 tonne and 0.84 tonne consecutively with a decreasing rate of change. This is due to the nature of the power regressions used to fit the growth of the vines. However, the sequestration of vine C for the whole vineyard is a lot more linear than a per block basis, and a linear fit is more suitable than a power regression for the prediction. It must be noted that all of the predictions are only derived from one measurement which is set to a power regression (Williams et al., 2011). To determine the C sequestered per year more veraciously, it is ideal to measure the vines each year and with more true estimation methods (see section 4.3).

3.3 Farm Carbon Emission

3.3.1 Data Sources

The emissions of carbon dioxide into the atmosphere were calculated using the Australian Wine Carbon Calculator (WFA, 2014). The region for the spreadsheet was set to NSW, and values used were from the management records of the vineyard. All of the values obtained were from 2011/12 and used as an average for other years. If the emissions per year need to be known more accurately, it is strongly advised to use the true values per year to delineate the total emission offset for the year.

3.3.2 Fuel

An average of 12,800 litres of diesel fuel per year was combusted in agricultural activities. This amounted to a calculated value of 35 tonnes of C emitted per year. In a more accurate analysis, the exact fuel usage per year would be used.

3.3.3 Electricity

The electricity usage for year 2011/12 was determined from the electricity consumption records of the vineyard. A total of 28,466 kWh of electricity was used. However, there are solar panels located on the vineyard to help offset electricity usage on the farm, for both cost and C reduction, by generating their own electricity from the sun. It was concluded that the solar panels generated 13,580 kWh of electricity. So, there was a total of 14,886 kWh of electricity used from the power grid, resulting in 13.25 tonnes of C emitted.

3.3.4 Fertiliser

The fertiliser was computed by investigating how much of each fertiliser was used per block by the job sheets. All of the fertiliser used per block was added together to give a total amount of each fertiliser used in the year as given in Table 3. The emissions were calculated in the Australian Wine Carbon Calculator, which took into account the N content and an emissions factor. A total of 0.16 t of C was emitted from fertiliser use.

Table 3: Fertilisers used on the vineyard and total carbon emitted from them.

Fertiliser	Fertiliser Applied [kg]	N content [%]	Total emissions [t]
SprayGro (K)	40	5 (SprayGro, 2012)	0.02
Budmate	501	5 (SeaMagic, 2012)	0.04
Sea Magic	1304	5 (Agrichem, 2007)	0.10

The pie chart in Figure 7 shows that fuel usage is the major contributor to C emissions, and emissions from fertiliser use on the vineyard are insignificant. It should be noted that the electricity usage includes the offset from the solar panels. Overall, 48.41 tonnes of C were emitted in 2012.

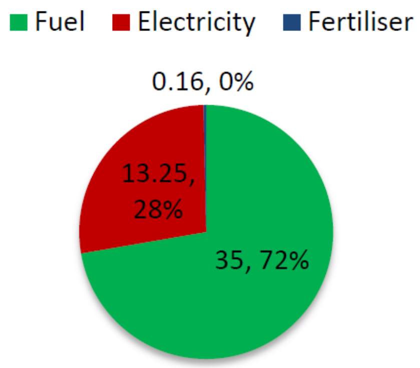

Figure 7: Overall carbon emissions in tonnes.

3.4 Overall Carbon Footprint

From equation 2, the total C footprint of the farm was calculated to be 69.3 tonnes in 2012. After deriving exactly how much C is stored for the year and determining the predictions, a price can be set to the amount of money earned/saved if the Australian Government's CFI is implemented in the vineyard. Despite recent uncertainty regarding such an implementation, we have taken a C price of A$15/t as a nominal value for the purpose of this analysis. Table 4 shows the estimated savings per year, assuming a price of A$15/t using the predictions of the overall C footprint as detailed above.

Table 4: Carbon footprint and savings estimated.

Year	C footprint [t]	Savings [A$]
2012	69.3	$1,040
2013	70.3	$1,055
2014	71.2	$1,068
2015	72.1	$1,082
2016	72.9	$1,094
2017	73.7	$1,106
2018	74.5	$1,118

4 CONCLUDING REMARKS

4.1 Discussion

PV technologies such as GIS, soil surveys and spatial measurements have facilitated an understanding of the vineyard and have aided in establishing that the vineyard has a positive carbon footprint. This study demonstrates that vineyards have the capability to promote a C neutral environment by the propensity of perennial vines to sequester C and to stimulate long-term storage of C in the soil, hence proving the ability of grape vines to have a positive impact on climate change. The effect of fossil fuel combustion, electricity usage and fertiliser applications on greenhouse gas emissions has been analysed, and it has been corroborated that these factors do have a negative effect on the vineyard's C footprint.

Overall, the results show that the vineyard is sequestering more C than it is emitting per year. It has been demonstrated that the vines store about 30% of the total C sequestered over the entire vineyard, and no concrete conclusion could be drawn for the variation of vine volume. The soil C accounts for the remaining 70% of total C sequestration. There are only four blocks in the vineyard that show a decreasing rate of C, while the remaining 14 blocks appear to have an increasing rate of C. It has been estimated that this vineyard has the potential to save A$1,100 per year if a CFI methodology for viticulture was in place. This is significantly less than the time and labour required to obtain the measurements on a regular basis to quantify the actual C footprint.

4.2 Recommendations for Improving the Carbon Footprint

The vineyard investigated in this study incorporates organic and biodynamic farming principles and boasts a record of management procedures to decrease C emissions and increase sequestration. This has been proven by the fact that the total C sequestered in the vineyard has been confirmed to be increasing at a rate of 120 tonnes per year. The vineyard uses a majority of organic fertiliser and in turn uses a minimal amount of nitrogen fertiliser, only emitting around 0.16 tonnes per year which is insignificant compared to electricity and fuel usage. There is a minimum-tillage management scheme in place on the farm, and this has also endorsed a cover crop management with the use of perennial grass. The prolonged subscription to this method has actively sustained C in the soil. Also, pruning and thinning techniques take place on a seasonal basis, absorbing more C into the soil.

Electricity emits on average 13 tonnes of C per year, considering the offset from the solar panels. Even though the vineyard manager has gone to great extents to install solar panels to save money and reduce C emissions, electricity usage could still be restricted by altering irrigation techniques. Drip, flood or furrow irrigation could be implemented in place of the current irrigation system of using electric pumps (CSWA, 2009). This would reduce C emissions by limiting the use of electricity. The highest C emission source on the farm is from the combustion of fossil fuel, resulting in around 35 tonnes of C per year. Reducing fuel usage is one of the most obvious and effective ways to reduce the vineyard greenhouse gas footprint. Additionally, although diesel has a greater energy content per unit volume, it produces more greenhouse gases than gasoline, natural gas or propane. An introduction of hedgerows and more native vegetation such as trees would also have the effect of absorbing more C into the perennial wood and the soil, further offsetting the vineyard's C footprint. All of these management procedures have been shown to implement a positive C footprint within vineyards (Carlisle et al., 2006).

4.3 Future Work

The results for the vine C were based solely on measurements piloted in one year and fitted to a model from a study on another vineyard (Williams et al., 2011), so more measurements would increase the accuracy of the estimations. The soil survey methods from the years 1998 and 2000 were different to the soil surveys completed in 2009 and 2012. The earlier methods were conducted as an official survey and only 61 samples were taken from where the blocks were located. The later methods were comprised of the vineyard manager taking 30 samples from each block, in a spaced manner. The dry combustion method is also a more accurate method to determine the SOC content of soil in a laboratory, compared to the Walkley-Black method (Mikhailova et al., 2003).

ACKNOWLEDGEMENTS

Justin and Pip Jarrett from Jarrett's of Orange deserve special recognition for providing access to all the data necessary for this study as well as access to the farm and background knowledge. Soil surveys and information provided by David McKenzie were extremely useful. Chris Rizos provided support and direction as part of an undergraduate thesis project. Everyone involved in the 'Spatially Smart Wine' project who provided data should be acknowledged – Fadhillah Norzahari, Kate Fairlie, Adrian White and Mitchell Leach.

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