Reducing Greenhouse Gas Emissions in the Vineyard: Advances in the Search to Develop More Sustainable Practices.

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Summary

Mitigation of greenhouse gas (GHG) emissions in agriculture is one of the most urgent research subjects in the framework of enhancing environmental stewardship. Improving such stewardship is rapidly becoming a key marketing issue in addition to subjecting growers to increasing scrutiny from regulatory agencies. For example, a recent action taken by the United States Environmental Protection Agency was its endangerment finding for GHGs (http://www.epa.gov/climatechange/) such as CO_2 and N_2O. This finding subjects greenhouse gases to scrutiny under the Clean Air Act of the United States. Thus, it is critical we conduct research and development to report baseline levels of GHG emissions and discover new ways of lessening their emission in grape production. We have been successful in this endeavor in a Merlot vineyard in the Napa Valley of California where have been growing it for 7 years under minimum-tillage conditions. During this time period we have been:

1. Acquiring baseline information on CO_2, N_2O and CH_4 emissions and modeling temporal and spatial nature of emissions events.
2. Quantifying both aboveground primary productivity and belowground primary productivity as well as standing stocks of carbon.
3. Assessing changes in soil organic carbon as a consequence of switching to a minimum-tillage management regime.
4. Assessing devigoration of vines subjected to minimum-tillage cover crops and exploring ways to minimize undesirable devigoration.
5. Gathering ancillary data on soil physical properties and environmental conditions (temperature and moisture) for use in modeling exercises needed to make broader estimates of annual CO_2, N_2O and CH_4 emissions in vineyards under diverse proposed management scenarios.

Introduction

The carbon footprint of a vineyard can be defined as a comprehensive measure of the quantity of greenhouse gases (GHGs) produced and consumed. This metric provides an indication of whether or not we are contributing to the increase of GHGs in the atmosphere, and therefore to global climate alteration. For this reason, developing vineyards with neutral carbon (C) footprints can be reasonably defined as a long-term vineyard practice that would contribute to global sustainability. There is currently tremendous uncertainty concerning the quantity of GHGs produced and consumed in vineyards (Carlisle et al. 2010). The GHGs of interest are those defined by the International Panel on Climate Change's 2006 Assessment (IPCC, 2006) as the major agricultural GHGs and consist of carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Nitrous oxide and CH_4 have 310 and 21 times the radiative forcing potential of CO_2 when projected over a 100 year lifetime (IPCC, 2006). For this reason, production of small quantities of these gases can offset the absorption (sequestration) of CO_2 in agricultural settings. In developing carbon footprint metrics for vineyards, it will be important to have comprehensive assessments of production and consumption of CO_2, N_2O and CH_4 for proposed sustainable management practices, and a number of regulatory organizations are adopting this approach in their assessments (CARB, 2009).

Carbon sequestration (C-sequestration), on the other hand, is traditionally defined as the removal of CO_2 from the atmosphere and storage in carbon sinks through physical or biological processes, in this case photosynthetic CO_2 assimilation. The most important

vineyard sink would consist of soils (Figure 1) where long-term cultivation has greatly depleted soil organic carbon compared to the forest ecosystems from which many vineyards were established (Carlisle et al. 2006; Suddick et al. 2010). Improving C-sequestration in vineyards may involve adopting practices that would increase carbon deposition and storage in the soil C pool.

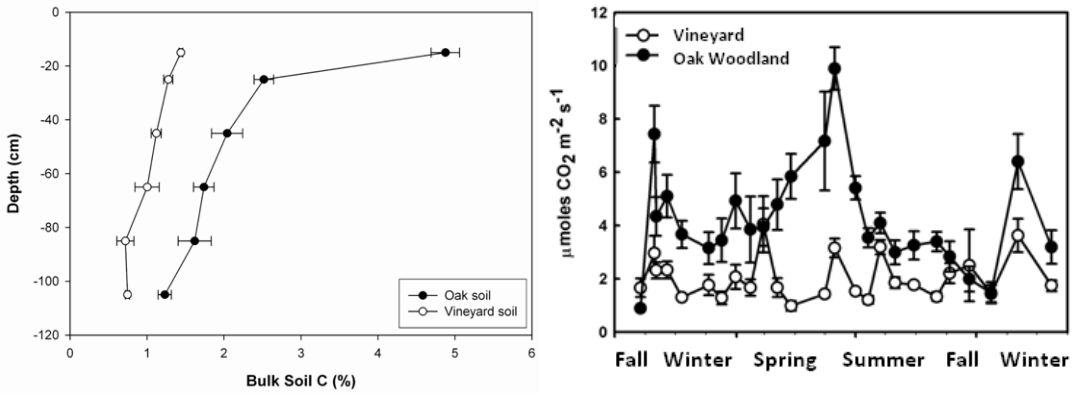

Figure 1: In the left panel are organic C contents (%) in a Merlot vineyard (open circles) and adjacent oak-woodland (closed symbols) and in the right panel are seasonal rates of CO_2 production for the same vineyard and woodland during 2002-2003 (Carlisle, 2009).

Unfortunately, there are a number of knowledge gaps concerning vineyard practices and the influences of such practices on C-sequestration. In example, measures of root response to management practice are lacking, in particular where practices that might increase total below ground carbon allocation and therefore soil C-sequestration are utilized (Smart et al. 2006; Carlisle et al. 2010). Furthermore, as soil C increases soil respiration should also increase (Figure 1) until a new equilibrium between soil C deposition and soil C mineralization is established. Our research aims to construct working budgets of GHGs and C-sequestration in a Napa Valley vineyard being managed with a cover crop under 'conservation' (minimum-) and conventional-tillage and has been ongoing since 2003. The project allows us to address a number of knowledge gaps for minimum-tillage in a cool climate region. In this report we focus mainly on how conservation tillage has affected N_2O emissions, root proliferation and root biomass accumulation for Cabernet Sauvignon growing on *Vitis riparia* x *V. rupestris* cv 101-14 rootstock.

Material and Methods

We are currently in the seventh year of managing the vineyard under minimum-tillage to promote C-sequestration, and completing the second year of comprehensive greenhouse gas emissions monitoring. Starting in October of 2003, we planted a dwarf barley (*Hordeum vulgare* cv UC602) at an approximate rate of 180 kgs seed per hectare. The three tillage treatments we examined consisted of: (1) minimum-tillage with a dwarf barley cover crop (*Hordeum vulgare* cv UC602); (2) conventional-tillage with the same barley cover crop; and (3) conventional-tillage with resident (weedy) vegetation. Our definition of conservation tillage (minimum-tillage) consists of surface discing (2.5 cm) in autumn, when needed to prepare a seed bed for planting the current seasons cover crop. The conventional-tillage treatments in contrast are deep cultivated (20-30 cm) twice

annully using a disc harrow, once in spring (mid-April) and once in summer (mid-June). Each 5th year the minimum-tillage treatment is also deep cultivated once to alleviate soil compaction problems that result in vine de-vigoration. The minimum-tillage treatment was cultivated heavily for the first time during October of 2008 (year 5), adhering to decisions that many viticulturalists might make with a long-term, minimum-tilled cover crop.

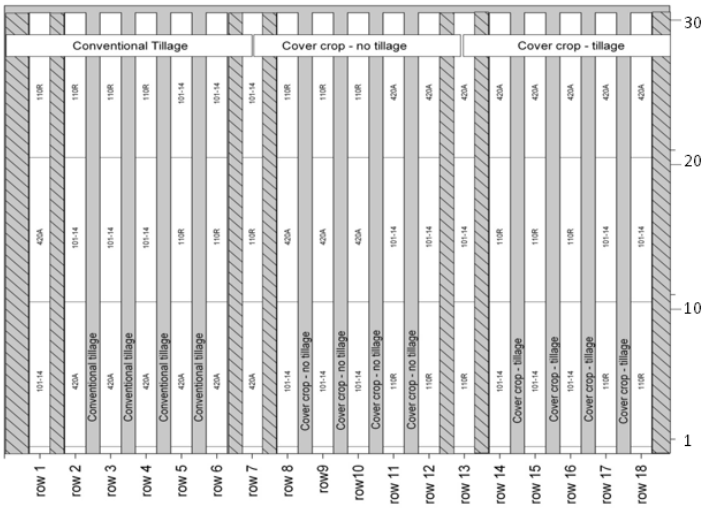

Figure 2: Experimental design for a Cabernet Sauvignon vineyard managed under conventional- and minimum-tillage (no-tillage) practices with 3 rootstocks. Shown is one repetition (block) with 6 rows of vines and 30 vines per treatment. The ongoing study only examines the *V. riparia* x *V. rupestris* 101-14 rootstock.

Greenhouse gas emissions, CO_2

To quantify the influence of tillage on annual soil CO_2 respiration, we have been directly monitoring emissions from permanent 10 cm-diameter soil collars within treatments of rootstock 101-14, a stock of medium vigor widely used in Napa Valley. The permanent collars are compatible with attachment to a dynamic flow system (Luo and Zhou, 2007) for quantifying soil surface CO_2 fluxes (Licor Inc. LI-6400 model 6400-09 Flux Chamber, Lincoln, Nebraska). The permanent collars in the alleyways are measured at least every two weeks.

Greenhouse gas emissions, N_2O

Seasonal emissions are acquired from static chambers placed over permanent collars at the soil surface. Two chamber sizes will be employed as developed in our previous Kearney project: a large 25 cm diameter chamber that better constrains emissions where the rates are extremely high, and a smaller 12.5 cm diameter chamber that substantially reduces the time constant for emissions capture.Gas samples of 13 cc will be removed from the chamber at 0, 30 and 90 minutes (or 0, 15 and 45 minutes depending on rates and objective) and injected into evacuated 12 cc exetainers. N_2O will be analyzed on the gas chromatograph (GC) using a Poropak Q Column (1.8 m, 80/100, 90ºC) with a ^{63}Ni electron capture detector. CH_4 will be analyzed on the GC with a Poropak Q Column and a flame ionization detector (300ºC). Rates of N_2O emission will be calculated using modifications to the approach described by Smart and coworkers [64] [65]. Each exetainer measured will be sampled in duplicate. N_2O (or CH_4) emissions will be calculated according to:

$$J_{N2O} = d[N_2O]/dt * Vn/RA * P_a/P_s * T_a/T_s$$

where J is the apparent net flux of N_2O (or CH_4) from the soil surface (umol m^{-2} s^{-1}), $d[N_2O]/dt$ is the change in N_2O (or CH_4) concentration in the chamber over time, V is the chamber volume (L), P_a, P_s, T_a and T_s are ambient (a) and standard (s) atmospheric pressures (Pascals) and temperatures (Kelvin), R is the universal gas constant and A is the chamber area (m^2).

Greenhouse gas emissions, CH_4

Seasonal CH_4 emissions were acquired from the same static chambers placed over permanent collars at the soil surface as used for N_2O emissions. The gas samples were analyzed using a thermal conductivity detector on the same gas chromatograph system used for the N_2O samples. Data for CH_4 emissions are not being presented in this report.

Root carbon deposition

In order to quantify standing root crop and derive estimates of total belowground carbon allocation using root turnover rates and standing root crop (Giardina and Ryan, 2002), we harvested roots at peak fine root production (Eissenstat et al. 2007; Bauerle et al. 2008). To do this we used a combination of trenching and large cylindrical cores to quantify roots. Roots were collected in a known volume of soil from the same depths for which we have comprehensive root population data (Bauerle et al. 2008). After collection, soils were sieved (4 mm) and roots washed and separated from any soil particles remaining in the sieve by floating them in water. This approach decreased loss of fine roots (McKenry 1984). Root samples were dried at 60ºC for biomass and C content determination.

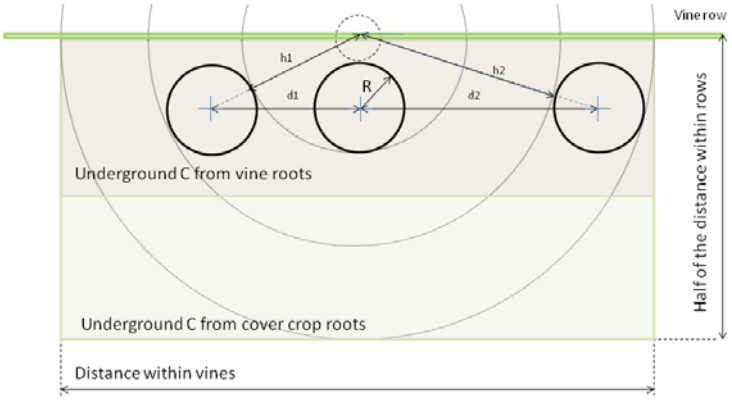

Figure 3: Orientation of large diameter (25 cm) cylinders used to extract root and soil samples from around Cabernet Sauvignon vines growing for seven years under conventional and conservation tilled cover crops.

Results and Discussion

Soil CO_2 emissions

Soil respiration (CO_2 emissions, Luo and Zhou 2007) from the respective vineyard floor management scenarios were very similar in magnitude to those reported in a neighboring vineyard (Carlisle et al. 2006). Following 7 years of fairly comprehensive investigation of these vineyards we have found that the major deviations in CO_2 emissions occur during events such as precipitation and cultivation.

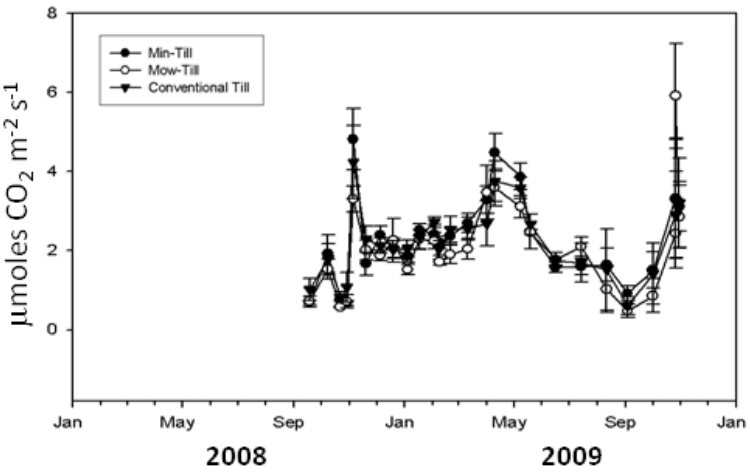

Figure 4: Soil respiration (umoles CO_2 m^{-2} s^{-1}) in the minimum-tillage barley cover crop (Min-Till), the conventional-tillage barley cover crop (Mow-Till) and the conventional-tillage resident (weedy) vegetation (Conventional Till) during 2008 and 2009. Sharp increases during both 2008 and 2009 are related to first precipitation events.

Soil respiration in the minimum-tillage cover crop was substantially lower during the early spring tillage event in 2005 when soils were still moist and temperatures warming (Figure 4). Immediately following tillage soil respiration increased nearly four-fold in the conventional-tillage cover crop treatment ($P < 0.001$) in comparison to minimum-tillage and independent of diurnal variation (Figure 5). The rate of CO_2 emission did not return to the baseline levels observed in the minimum tillage treatment until nearly 1-3 weeks in 2005 (Steenwerth et al. 2008). When spring or fall rainfall occurs after mowing or tillage we observe increases in all treatements and in tillage treatments soil respiration can increase as much as 5-6 times the baseline rates (Figure 5). All three treatments responded to precipitation in fall, but with varying magnitudes.

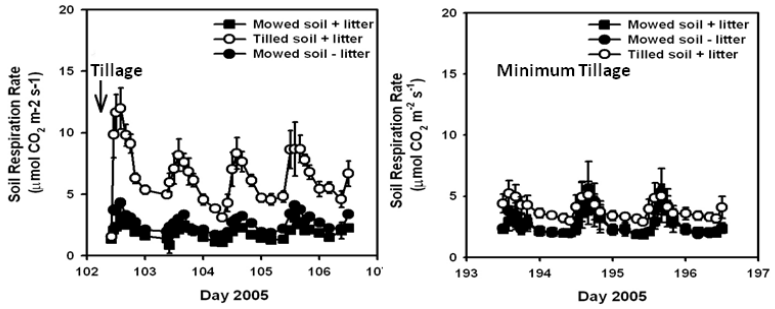

Figure 5: Soil respiration (CO_2 emissions, umoles CO_2 m^{-2} s^{-1}) during a tillage event (left panel) in 2005 monitored for 3 to 4 days and baseline rates observed near the end of the summer dry season. Shown are CO_2 emissions rates for the minimum-tillage barley cover crop with and without mowed surface litter (Mowed soil + litter and Mowed soil – litter, respectively) and the conventional-tilled cover crop treatment (Tilled soil + litter).

Soil N_2O emissions

Very few studies exist to our knowledge on N_2O production in woody perennial agricultural systems (Carlisle et al. 2010; Suddick et al. 2010). Gregory et al (2005)

found that timothy, a perennial crop in eastern Canada, lost from 1.2-2.2% of applied N as N_2O and was roughly comparable to some annual cropping systems. Nonetheless, Hajrasuliha and others (1998) observed no evidence that denitrification occurred under drip irrigation emitters grape, but my group has found substantial N_2O emissions regularly during drip and microjet-sprinkler irrigation events. We are constraining these emissions events using temporal and spatial models from measures after precipitation or fertigation events, when the largest N_2O fluxes are clearly observed (Figure 6 and 7).

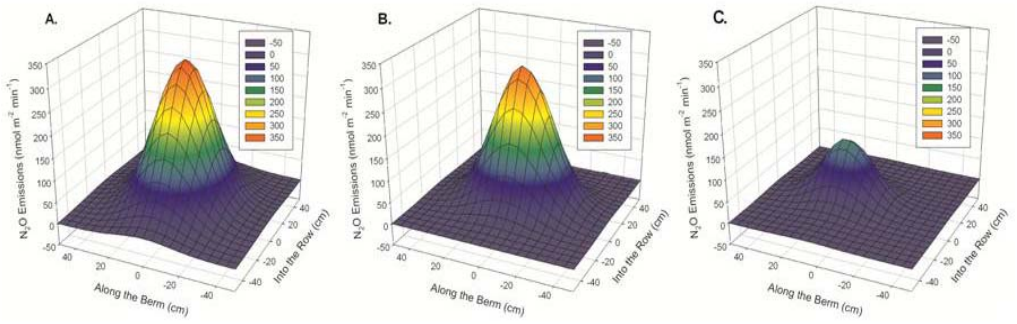

Figure 6: Shown are N_2O emissions (nmol N_2O m^{-2} min^{-1}) surrounding the drip irrigation zone following a vineyard fertigation with approximately 35 kg N ha^{-1} applied as KNO_3. Shown in panel A. are rates measured at 9 h following the application of fertilizer, in panel B. at 12 h and in panel C. at 15 h following application.

We have also been conducting event-related emissions measurements in order to constrain peak periods of nitrous oxide emissions (e.g. N-fertilization and precipitation events). Spatial constraint of N_2O emissions during fertilization has involved gas sampling in transects that run across and along the vine row, with more intensive sampling in the drip zone itself. We have modeled these event related emissions using Gaussian fits to develop three-dimensional models of the drip zone, which will then be scaled up to the entire vineyard so that the elevated rates we have observed in the drip zone do not artificially elevate the total N_2O flux from the vineyard. Differences between vine row and drip-zone are the subject of year-round study. In combining spatial (Figure 6) with temporal observations (Figure 7) we have been able to more tightly constrain emissions of N_2O from these three treatments. To date we conclude that 1) over 90% of N_2O emitted occurs during and immediately after N=fertigation events (Figure 7), 2) overall N_2O emissions from these vineyards are small but it is too preliminary to determine whether or not emissions post fertigation exceed or are below 1% emission factor employed in the IPCC 2006 assessment, and 3) no differences are discernable among treatments.

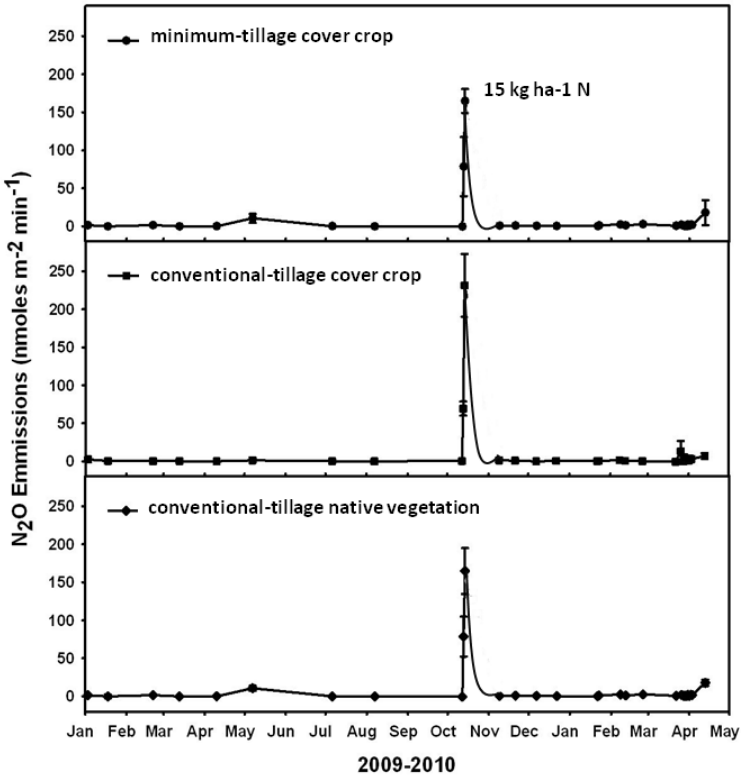

Figure 7: Soil N_2O emissions (nmoles N_2O m^{-2} min^{-1}) during 2009-10. Peak emissions during October were the consequence of a fertigation event of 15 kg N per hectare.

Methane (CH_4) emissions

Methanogenesis is not expected be significant in upland vineyard sites. There is currently no data on this topic to our knowledge. Nonetheless, we have been monitoring CH_4 production and consumption in vineyard soils of the reported experiment. To date we have not observed any methane emissions, or absorption by soils (data not shown).

C-sequestration

Shown in Figure 8 is a conceptual model of the vineyard carbon cycle. Photosynthesis is the process by which plants harvest light energy to assimilate CO_2 and produce carbohydrate. Grapevines distribute photosynthate (carbohydrates) to actively growing tissues in the plant that require energy and carbon skeletons (carbon based structural materials). The distribution of photosynthate is important, as where these carbohydrates are stored and how harvested material is handled can significantly impact the ability of a vineyard to sequester C (Figure 8).

Much of a grapevine's annual production of photosynthate is used by for respiration and fruit production. Woody plants like grapes and other perennial crops have been estimated to use between 25-75% of their annual primary production in the process of cellular respiration (Amthor 1989). Grape vines have been estimated to use 40-50% of their photosynthate for respiration (Williams 2000), with a large proportion of C respired (60-75% of vine respiration) being used for vine growth and fruit production (Wermlinger et al. 1991). The remainder of the respiratory costs is associated with plant maintenance respiration. Older and larger vines generally require a larger amount of

energy to stay alive than smaller vines on account of having larger root systems and wood. Plant respiratory costs are generally not directly included in calculations of GHG emissions since most all plants have a positive net C gain (photosynthesis minus respiration). The respiration of soils, which includes root respiration is included in most budget exercises.

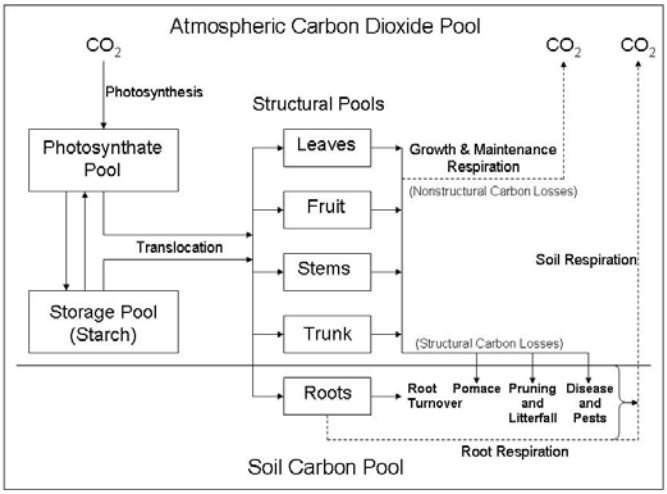

Figure 8: Conceptual model of the vineyard carbon cycle including the components that contribute to emission of CO_2 by soil respiration. Vine components that may potentially contribute to C-sequestration are included at all levels of aboveground productivity and belowground productivity and assume that pomace is returned to the vineyard.

Whole plant photosynthetic rates are strongly affected by management and vineyard establishment because net C gain (photosynthesis minus respiration), or annual aboveground net primary productivity (ANPP), is dependent on some ratio of the canopy light interception versus the amount of shaded leaf area. Thus, trellis systems, training scheme, irrigation, and row orientation as well as pruning and thinning practices can have substantial influence on total vine photosynthesis and therefore ANPP (Williams 2000). Net C assimilation, which can be estimated with well constrained ground based measures of ANPP and belowground net primary productivity (BNPP), along with soil respiration measurements to relate this to the quantities of carbon sequestered and retained in soils, can provide good information on CO_2 sequestration (Carlisle et al. 2006). There are other approaches to making this estimate that include micrometeorological measures of net ecosystem CO_2 exchange (NEE, http://www.nacarbon.org/nacp/about.html), as well as modeling exercises. In this report, we touch upon ANPP and BNPP measures in cover cropped vineyards under minimum-tillage (explained above) and conventional-tillage, and a vineyard under conventional-tillage where winter annual weeds are allowed to grow into spring (mid-April) prior to tilling.

Table 1: Annual photosynthate partitioning in several different varieties in the San Joaquin Valley (1 and 5), Napa Valley (2 and 4), the Murray River Valley, Australia (3), and South Africa (6). Total biomass was calculated assuming a vine density of 1282 vines ha^{-1}. Studies that provided most of the above data were included in the table.

	Thompson Seedless[1]	Cabernet Sauvignon[2]	Cabernet Franc[3]	Merlot[4]	Chenin Blanc[5]	Chenin Blanc[6]
Roots (g/vine)	365	140	201	263	298	360
Trunk (g/vine)	650	278	612	178	643	300
Stem (g/vine)	2058	1149	1372	853	2274	N/A
Leaves (g/vine)	1440	899	N/A	970	1732	N/A
Clusters (g/vine)	6681	798	N/A	2736	5199	N/A
Total annual Biomass (Mg/ha) 1282 vine/ha	14.31	4.18	N/A	3.91	13.35	N/A
Total annual C (Mg/ha) 1282 vine/ha	6.44	1.88	N/A	1.76	6.00	N/A
Root:Trunk Ratio	0.56	0.5	0.33	1.47	0.46	1.2

[1] Williams (1996)
[2] Williams and Smith (1991)
[3] Clingeleffer and Krake (1992)
[4] Smart and Stockert (unpublished data, root data represent preliminary estimates)
[5] Mullins et al (1992)
[6] Saayman and Huyssteen (1980)

A review of harvest more complete biomass records from the literature and for this investigation shows that yields of carbon (under the assumption that biomass contains 45% carbon) ranges from about 1.75 to 6.5 metric tons per hectare. The range of results reported for root:trunk ratio indicates that this value might be dependent on root harvesting procedure. Nonetheless, Table 1 makes clear that the most substantial C sink in ANPP is fruit, thus, for maximizing C-sequestration potential in a vineyard it is critical to return pomace and rachises to the vineyard floor. For the cover crop experiment reported here, about 1.62 ± 0.20, 1.25 ± 0.15 and 0.55 ± 0.09 metric tons of carbon per hectare would be added to that produced by grape (derived from Table 2). Nonetheless, these values do not include the decomposition rates and soil carbon sequestering potential under these treatments which is a future objective of this project.

Table 2: Table showing the relationship between vineyard floor vegetation treatments during 2009. The lower biomass in the belowground area compacted (alley track) are a consequence of tactor operations.

Cover Crop/Weed Biomass (g m^{-2})	**ANPP Alley**	**ANPP *Track**	**BNPP Alley**	**BNPP Track**
minimum-tillage CC	703.1 ± 113.1	222.8 ± 30.9	69.62 ± 9.69	25.25 ± 7.53
conventional-tillage	550.3 ± 70.3	357.2 ± 67.0	41.98 ± 6.81	50.56 ± 8.45
conventional-tillage	245.3 ± 27.2	275.0 ± 60.3	22.71 ± 4.29	32.85 ± 7.12

*Cover crop production was substantially less in the compacted tractor pass areas.

There is a large variation in annual grapevine root production. Published annual increases in root biomass range from 140 to 360 g vine^{-1} (Table 1). Another study (Araujo and Williams 1988) found 350 g year^{-1} allocated to the roots in Thompson Seedless and there is some evidence indicating annual root biomass increases of 1000 g year^{-1} are not unusual for Thompson Seedless and for the variety Barbera (Williams and Biscay 1991). Rootstock type has been found to effect annual root biomass production. Chenin blanc on 101-14 rootstock grown in South Africa partitioned about 360 g year^{-1} to roots (Saayman and Huyssteen 1980), while own rooted Chenin blanc grown in SJV produced 262 g year^{-1} of root biomass (Mullins et al 1992). Cabernet Sauvignon on rootstock 5C on the other hand produced only 130 g year^{-1} in root tissue (Williams and Biscay 1991) in a non-irrigated vineyard (Table 1). An extremely interesting preliminary result for the investigation reported in here is that imposing a minimum-tillage management scenario increased grape root production (Figure 9).

Figure 9: Shown are the mass of grape root harvested from 25.4 cm diameter x 150 cm deep cores taken in five 30 cm intervals (see Figure 3) for the described minimum-tillage cover crop treatment (MOW), the conventional-tillage cover crop treatment (MOW-TILL) and the conventional-tillage treatment where winter annual weeds grow.

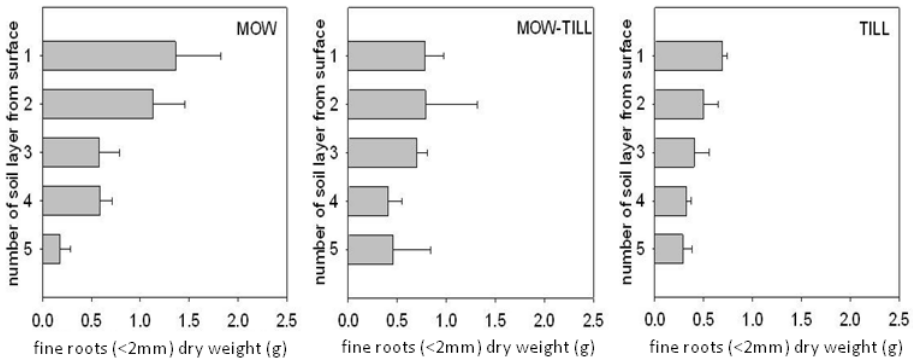

Figure 10: Root biomass distribution by soil depth and fine root age classification. Each interval, 1-5 corresponds to 30 cm of depth.

One of the more interesting aspects of this investigation was the finding that diminishing deep (30 cm) tillage passes in the middle of the vineyard rows over time, significantly increased fine root biomass in the upper 30 cm plow layer (Figure 10). This is contrary to the findings of Van Huysteen (van Huysteen 1988) who found that grape roots diminished under permanent sward and attributed this finding to root competition, where grape roots were considered to be non-competitive with grass roots in the upper soil horizons.

Conclusions

We are finding that there are benefits to employing minimum-tillage practices to cool climate vineyards at least during a time period of 7 years, and when a somewhat non-aggressive species (dwarf barley, *Hordeum vulgare* cv UC602) is used. These benefits include increased BNPP in terms of grape root growth and cover crop root growth. A review of the literature indicated that grape directs vast majority of photosynthate allocated to aboveground production to fruit and associated organs. Thus, to enhance carbon sequestration it is recommended to try to return seeds, skins (pomace) and rachis to the vineyard. There did not appear to be a strong influence on emissions of other greenhouse gases like N_2O, and this may have to do with the fact that we are finding that most N_2O emissions at least in this vineyard are driven by nitrogen fertilization events (fertigation). Our recommendation is to use nitrogen very conservatively in long term nutrient management.

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