Benefiting the environment, the community and high quality grapes and wine

California Vineyard Greenhouse Gas Emissions:

Assessment of the Available Literature and Determination of Research Needs

California Sustainable Winegrowing Alliance

Authors:
Eli Carlisle, David Smart, Larry E. Williams and Matt Summers

Project Partners:
Allied Grape Growers
American Vineyard Foundation
California Association of Winegrape Growers
California Farm Bureau Federation
California Grape and Tree Fruit League
Sun-Maid Growers of California
University of California, Davis
Wine Institute

CALIFORNIA
SUSTAINABLE WINEGROWING
ALLIANCE

September 2010 www.sustainablewinegrowing.org

TABLE OF CONTENTS

List of Figures and Tables

Figures

Tables

Benefiting the environment, the community and high quality grapes and wine

California Vineyard Greenhouse Gas Emissions: *Assessment of the Available Literature and Determination of Research Needs*

CALIFORNIA
SUSTAINABLE WINEGROWING
ALLIANCE

Authors:
Eli Carlisle, David Smart, Larry E. Williams and Matt Summers

CSWA would like to thank the California Department of Food and Agriculture, the U.S. Department of Agriculture Specialty Crop Innovation Grant Program, and the University of California, Davis for making this publication possible.

Project Partners:
Allied Grape Growers
American Vineyard Foundation
California Association of Winegrape Growers
California Farm Bureau Federation
California Grape and Tree Fruit League
Sun-Maid Growers of California
University of California, Davis
Wine Institute

1.0 Summary of Findings

Agriculture is both a source of and sink for greenhouse gases (GHGs). The three major GHGs produced by agricultural activities consist of carbon dioxide (CO_2, Section 3), nitrous oxide (N_2O, Section 4), and methane (CH_4, also Section 4), which are absorbed and emitted from plants and soils as a result of plant and microbial metabolic activities and management practices.

Vineyards may have lower carbon (C) footprints than a number of other crops because of vineyard-specific management practices that are conservative with respect to nitrogen (N) fertilization, along with the storage of C in permanent vine structures such as roots, trunks, and cordons. With the passage of the 2006 California Global Warming Solutions Act (AB32), grape growers in the State of California (State) may be expected to increasingly monitor and seek mitigation strategies for GHG emissions. To do this, reliable methods for quantifying and modeling vineyard emissions and C sequestration are required. For this assessment, the authors present: 1) a literature review to capture what is known about California vineyard GHG production and sequestration potential, and 2) a strategic plan that prioritizes research to advance understanding of the influence of vineyard management practices on GHG emissions.

1.1 Report Structure

The introduction of this report consists of a broad overview of California's GHG production by sector and gas type. Focus is placed on agriculture and in particular the state-wide contributions of perennial crops. Additional background information on California's agricultural GHG production and mitigation potential is presented along with a general overview of the biogeochemistry of the C and N cycles and their interactions. The main body of the report is comprised of a more detailed literature review of how agricultural management impacts GHG production and sequestration, particularly in vineyards. Additional agricultural systems were included in the report to illustrate the current knowledge of the biogeochemical processes. The main body has been divided into sections dealing with the three major biogenic GHGs including a section concerning carbon dioxide (CO_2) emissions and photosynthetic absorption and a section that deals with nitrous oxide (N_20), and methane (CH_4) emissions (and assimilation in some limited cases). Within these sections, the review is further organized into sub-sections dealing with irrigation practices and farm equipment, fertilizer use, above- and below-ground net primary productivity, and C sequestration to illustrate how these activities influence GHG emissions in vineyards. The conclusion of the report emphasizes what research is needed to produce a reasonable estimate of California's vineyard GHG footprint.

The report is organized overall into the following sections:

- **Section 1: Summary of Findings**
- **Section 2: Introduction and Background for Biogeochemical Cycles**
- **Section 3: Vineyard Carbon Dioxide Emissions and Potential C Sequestration**
- **Section 4: Vineyard Nitrous Oxide and Methane Emissions**
- **Section 5: Conclusions**

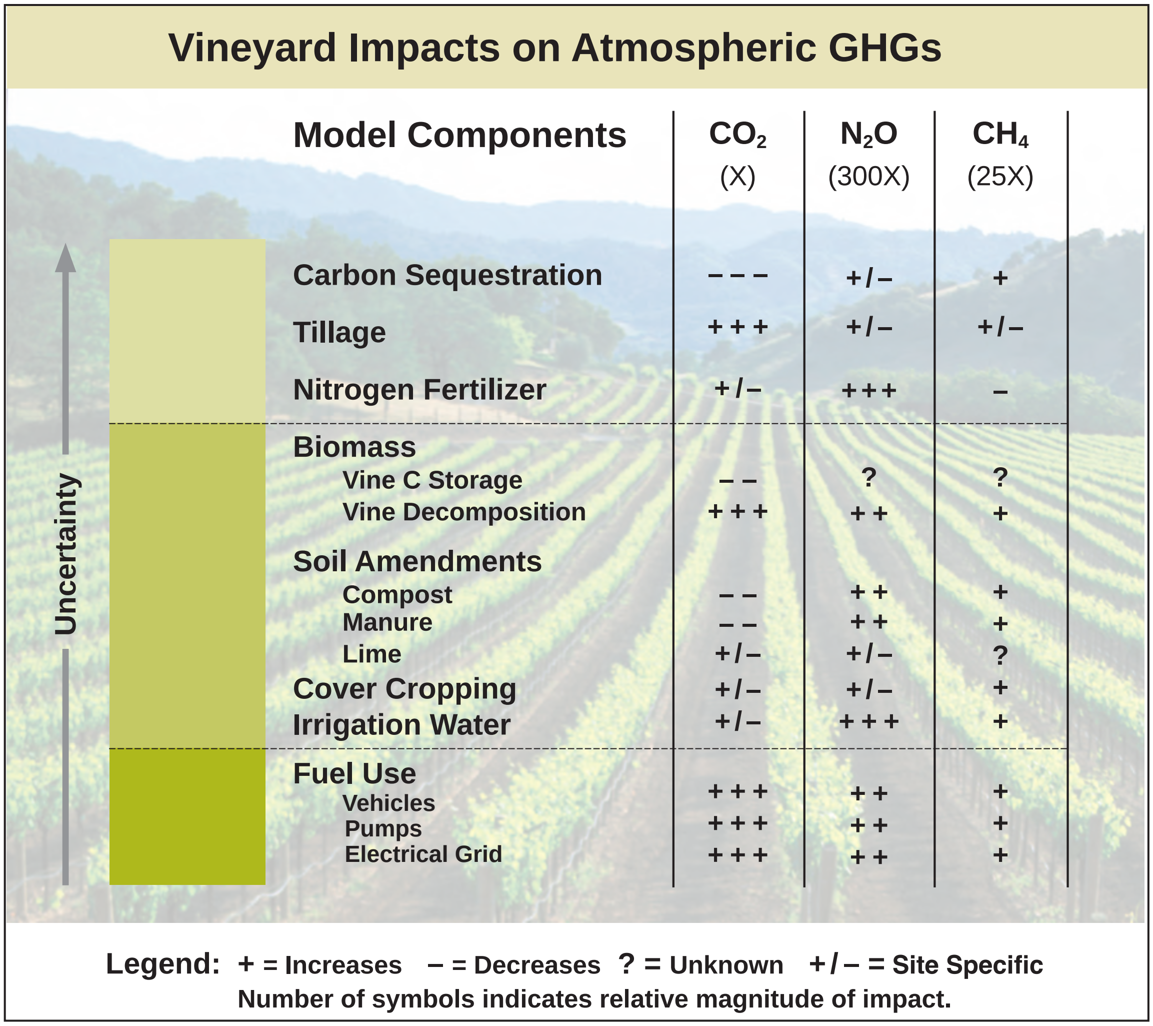
1.2 General Conclusions

There is limited published research pertaining to vineyard GHG production or sequestration in California. A synopsis of the available literature is described here. Because of a scarcity of vineyard-specific information, relevant research from other cropping systems is used to characterize the expected mechanisms involved in GHG emissions and C sequestration in vineyards.

Agriculture and forestry are estimated to account for only about 8.3% or 40.8 million metric tons of CO_2 equivalents of California's total annual GHG production (CEC 2005). The role that agriculture can play in reducing annual GHG emissions through C sequestration or improved management practices is therefore correspondingly small. However, of the different agricultural cropping systems, perennial systems such as vineyards, orchards, perennial pasturelands, and forests clearly represent the greatest potential to store C.

Depending on application of nitrogen (N) fertilizer and vineyard floor management, fossil fuel combustion (eg., tractor operations, irrigation, frost control power consumption) likely represents the single largest source of GHGs generated by the growing of vineyards. Soil physical states (e.g. temperature, C content, moisture level, oxygen concentration) and management practices such as tillage and cover cropping can also strongly influence vineyard GHG emissions (Figure 1).

The extent to which management practices affect C sequestration in vineyards is not fully understood. Permanent vine structures (i.e., roots, trunk, and cordons) and cover crops probably represent the greatest opportunities for C sequestration within vineyards. Management practices can enhance the amount of C temporarily stored in permanent vine structures and cover crops. However, the longer-term fate of sequestered C depends on what is done with the vines and land at the end of the vineyard lifecycle. Organic amendments have been shown to increase soil C storage in vineyards, and, depending on amendment type and management, can increase soil C storage by roughly 100%. However, organic amendments may also increase N_20 emissions (see below). Such feed forward kinds of interactions highlight uncertainties pointed out in this document and require further investigation. Additional plantings associated with conservation reserve programs and/or the retention or restoration of native, non-vineyard habitat on grower-owned properties may represent further opportunities for improving C sequestration.



Vineyard Impacts on Atmospheric GHGs

Model Components	CO_2 (X)	N_2O (300X)	CH_4 (25X)
Carbon Sequestration	– – –	+ / –	+
Tillage	+ + +	+ / –	+ / –
Nitrogen Fertilizer	+ / –	+ + +	–
Biomass			
Vine C Storage	– –	?	?
Vine Decomposition	+ + +	+ +	+
Soil Amendments			
Compost	– –	+ +	+
Manure	– –	+ +	+
Lime	+ / –	+ / –	?
Cover Cropping	+ / –	+ / –	+
Irrigation Water	+ / –	+ + +	+
Fuel Use			
Vehicles	+ + +	+ +	+
Pumps	+ + +	+ +	+
Electrical Grid	+ + +	+ +	+

Legend: + = Increases – = Decreases ? = Unknown + / – = Site Specific
Number of symbols indicates relative magnitude of impact.

Figure 1: Graphic summarizing the expected impacts of vineyard management practices and physiological processes on CO_2, N_20, and CH_4 production. Methane is not expected to contribute greatly to the vineyard GHG footprint. The number of plusses and minuses is indicative of the relative importance to total GHG emissions.

Carbon is stored in various pools within the vineyard landscape including permanent vine structures, short-lived vine structures, and soil organic matter, which itself is composed of different pools (Figure 2). These pools store C for different lengths of time for which specific time constants (half-lives) are mostly unknown. Short-lived vine C pools (e.g., leaves, green shoots, and fruit pulp) and non-perennial cover crops are generally discounted in most C budgets as they largely undergo mineralization in soils, converting the seasonal C produced back to CO_2 within about one year under typical vineyard floor management practices. However, this is an assumption based on data from other cropping systems.

Currently, no data exists on decomposition dynamics of various vineyard C pools and what portion (cellulose and lignin) of the current season's 'short-lived' C pools enter more recalcitrant pools. Permanent vine structures (e.g., trunk, permanent roots, and cordons) store C longer since they are composed predominantly of cellulose and lignin, but the longevity of sequestration depends on the ultimate fate of these structures, as aforementioned. Soils have short-lived (labile) and long-lived (recalcitrant) C pools with storage times ranging from months to centuries. Vineyard management practices, particularly tillage, strongly impact C exchange among these pools, and thus the potential of the vineyard to sequester and store C over long time periods.

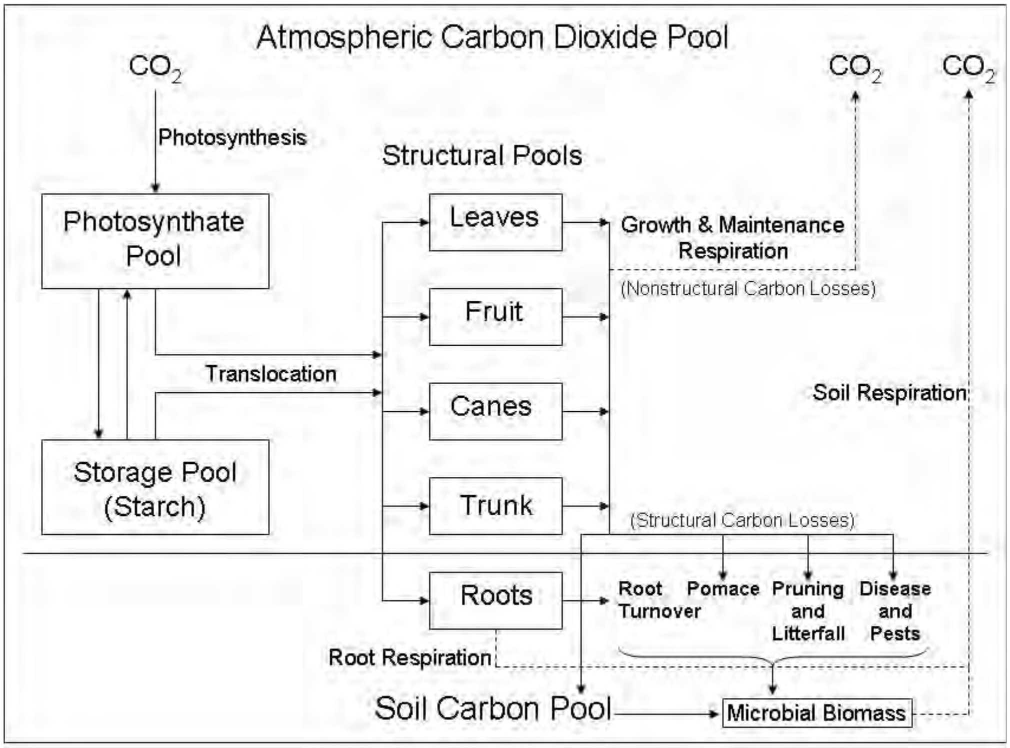


Figure 2: Conceptual model of the vineyard C cycle including the components that contribute to emission of CO_2 by soil respiration. Vine structures potentially contributing to C sequestration include the trunk, roots, and cordons (included here as part of the trunk).

Nitrogen (N) limits growth more than any other nutrient. As N is the primary constituent of the amide bond in proteins, a strong linear relationship exists between N content in leaves and photosynthesis. For this reason, application of N fertilizers influences the assimilation of C and therefore size of C pools by increasing vine and cover crop growth rates and total biomass. Higher rates of N fertilization can consequently increase C stored in biomass. Nonetheless, the increased use of N fertilizers also can increase nitrous oxide (N_20) production. Nitrous oxide has roughly 300 times the global warming potential of CO_2 (IPCC, 2007), so small increases in N_20 emissions can offset relatively large increases in biomass C storage. The interactions among fertilizer applications, C allocation to permanent and short-lived vine structures, and soil factors influencing N_20 emissions are complex and have not been fully studied in vineyards.

1.3 Research Needs

There is a dearth of published research in California viticulture as it pertains to GHG production or sequestration. Therefore, research from other cropping systems was used to illustrate the mechanisms involved in vineyard GHG emissions and C sequestration. More information from appropriately designed field studies is required to support reasonable estimates of vineyard GHG emissions and C sequestration. The following list categorizes the research needed for improved understandings and quantification of vineyard GHG inventories, which is ranked and given timeframes in Figure 3.

Vineyard research priorities: Carbon dioxide production and C sequestration

- Develop C budgets for vineyards in a range of regions, management scenarios, and for different grape crops (wine grapes, raisins, and table grapes)
- Quantify the decomposition rates of different grapevine tissues such as leaves, canes, fruit, and roots
- Quantify the proportion of vine biomass C (leaves, roots, canes, and other pruned material) that becomes incorporated into soil organic matter
- Measure the annual incremental increase and C density in vine wood for a range of varieties, rootstocks, age of vines, and typical vineyard trellis systems and management practices
- Measure the capacity (here defined as total soil C increment over time) of various cover crops and organic amendments to add C to soil organic matter
- Determine how soil C storage is influenced by tillage in different soils and climates
- Measure the interactions between the vineyard C and N cycles and how they influence GHG emissions
- Determine the ability of peripheral plantings (e.g. hedgerows) and habitat restoration and conservation to sequester C

Vineyard research priorities: Nitrous oxide production

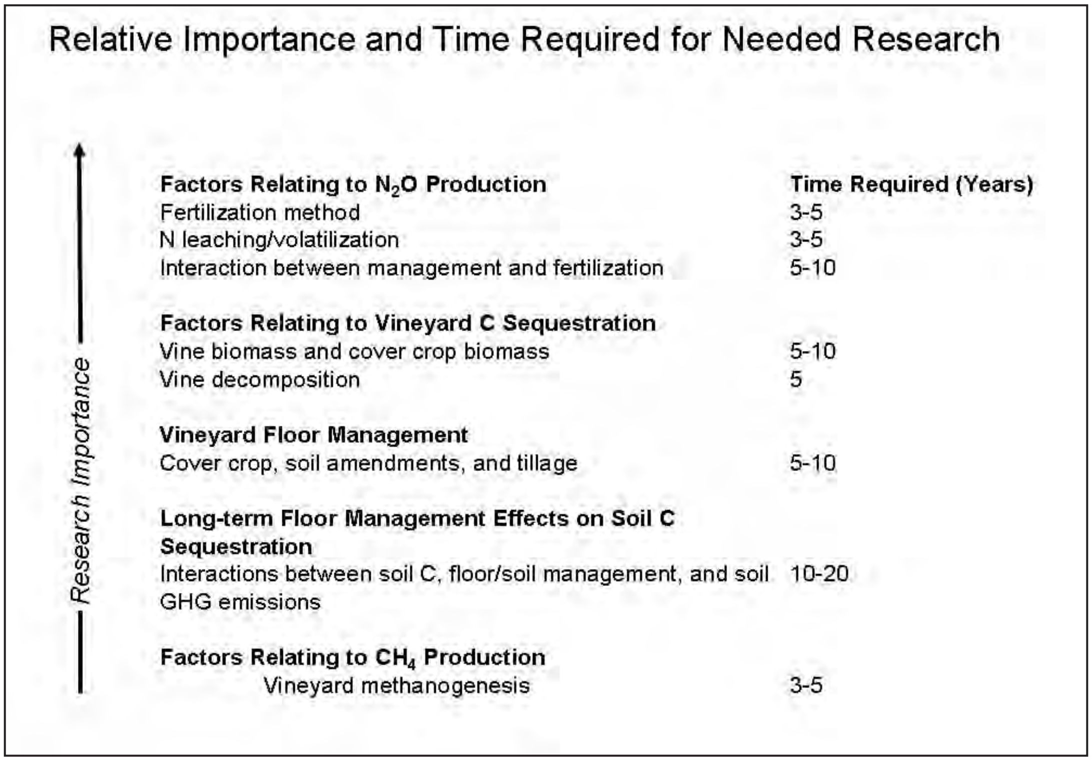
- Determine vineyard N budgets for different grape growing regions and crops (wine grapes, raisins, and table grapes)
- Determine impact of using different irrigation, fertilizer, vine, and vineyard floor management practices on the vineyard N budget
- Develop California-specific emission factors (e.g. IPCC 2006) for direct N_20 losses from applied synthetic and organic fertilizers, incorporated crop residues, and soil management
- Develop California-specific emissions factors for indirect N_20 losses from N leaching, volatilization,

and other routes of N mobilization and offsite movement

- Measure the effects of cover crop presence or absence on N_20 emissions across a range of cover crops and soil management activities
- Determine how the interaction between cover crop presence or absence and application of different levels of tillage and organic soil amendments impacts N_20 losses
- Quantify N_20 production by organic and other alternative vineyard management approaches across a range of soils and regions
- Measure temporal variation in vineyard N_20 losses in different regions and under different management approaches
- Determine typical vineyard N fertilizer application practices including timing, amount, and type of fertilizer used for wine grapes, raisin, and table grapes

Vineyard research priorities: Methane production

- Quantify vineyard CH_4 emissions in different growing regions, soils, and under different management practices
- Quantify vineyard CH_4 consumption in different growing regions, soils, and under different management practices
- Develop annual budgets of CH_4 emissions from vineyards under different irrigation management across a range of soil types and production practices



Relative Importance and Time Required for Needed Research

Factors Relating to N_2O Production	**Time Required (Years)**
Fertilization method	3-5
N leaching/volatilization	3-5
Interaction between management and fertilization	5-10
Factors Relating to Vineyard C Sequestration	
Vine biomass and cover crop biomass	5-10
Vine decomposition	5
Vineyard Floor Management	
Cover crop, soil amendments, and tillage	5-10
Long-term Floor Management Effects on Soil C Sequestration	
Interactions between soil C, floor/soil management, and soil GHG emissions	10-20
Factors Relating to CH_4 Production	
Vineyard methanogenesis	3-5

Figure 3: Relative importance and an optimistic estimate of the time required to achieve results for quantifying vineyard GHG emissions.

Much of the specified research requires multiple years of field experimentation to collect data for improving California-specific vineyard GHG models (Figure 3). For example, determining the extent of the role that N_20 plays in vineyard GHG emissions requires experiments in several soil types and regions that examine how different N management strategies impact N_20 emissions as well as how those N management practices affect the ability of the vines and soil to sequester C. Moreover, longer-term research is important for reducing uncertainty and accounting for seasonal and environmental variability. Data acquired in these investigations, even under short-term (3-5 year) scenarios can be incorporated into modeling exercises and accelerate the production of information useful to growers, and to improve understanding by regulators and policy makers.

2.0 Introduction and Background for Biogeochemical Cycles

Greenhouse gases (GHGs) are transparent and do not interact with incoming short-wavelength solar radiation. But they absorb strongly longer wavelength infrared terrestrial radiation leaving the earth's surface, and thus contribute to warming of the Earth's atmosphere. The increasing atmospheric concentration of these gases effectively alters the balance of energy transfer between the atmosphere, land, and ocean, resulting in a slow and unequivocal warming of the planet. The most important GHGs in agriculture include CO_2, CH_4, N_20, and water vapor. Tropospheric ozone is also a very important GHG, but its short atmospheric lifetime and local distribution make accurate modeling of its effects difficult. Several other man-made gases have much higher capacities to absorb infrared radiation (radiant heat), including sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and chlorofluorocarbons (CFCs).

Each of these gases has a different physical ability to absorb and re-radiate infrared radiation. Global warming potential (GWP) is a measure by which the warming properties and atmospheric lifetimes of different gases can be compared to the GWP of CO_2, which is set to a value of 1. The GWP of gases is partially determined by how long they remain in the atmosphere (lifetimes). As a result, the GWP of a given gas is usually associated with a time frame by which to compare it with other gases that may remain in the atmosphere for shorter or longer periods, such as 20, 100, or even 500 years. For example, even though SF_6, HFCs, and CFCs have 100 year GWPs ranging from 1,400-22,800, they are released in extremely small amounts, and do not make a major contribution to California's overall GHG emissions, representing less than 3% of the GWP weighted GHG inventory in 2004 (CEC 2005).

This report focuses only on the biogenic gases CO_2, CH_4, and N_20, which are the primary gases produced (and consumed) by agricultural and viticultural production. Properties owned by grape growers commonly include other land-use types including wetlands, grasslands, and forested areas. Some of these land-use types have been used to illustrate the production and possible mitigation of GHGs. An attempt has been made to constrain much of this discussion to Californian vineyards, but the dearth of vineyard specific data from any region has required us to draw upon examples from other agricultural and regional systems where there is overlap of general management scenarios (e.g. orchards). Moreover, the intent was to limit discussion to areas of Mediterranean climates, although this was not always feasible, in as much as the vast majority of grapes are grown in such climates.

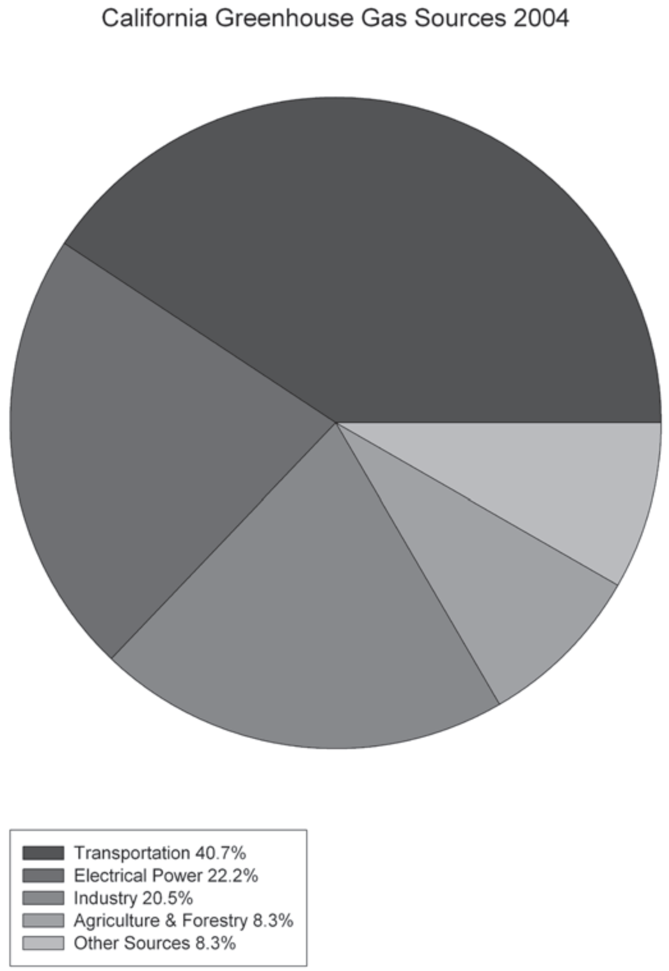


Figure 4: California greenhouse gas sources in 2004 by sector (CEC 2005). Agriculture & Forestry includes the C storage of the forestry industry which makes the agricultural contribution smaller than it might otherwise be.

2.1 IMPACTS OF AGRICULTURE

2.1.1 GHG Production

While transportation, power generation, and the manufacturing industry represented most of California's GHG production according to the California Energy Commission (CEC, 2005), agriculture, including forestry, accounted for roughly 8.3% of California's total production of 493 million metric tons of CO_2-equivalent GHG emissions in 2004 (CEC 2005; Figure 4). Agricultural lands are the primary source of N_20 both in California and globally (CEC 2005, IPCC 2007). According to the most recent California GHG inventory in 2004, CO_2 produced from fossil fuel combustion in all sectors (Figure 5) represented 81% of California's GHG emissions. Non-fossil fuel sources of CO_2 such as soil tillage and the combustion of biomass produced 2.8% of emissions. Nitrous oxide (6.8%), methane (5.7%), and other GHGs with high GWP such as HFCs and CFCs (2.9%) represented the balance of GHG emissions (Figure 5). Agriculture was the single largest producer of CH_4 and N_20, comprising 38% and 59% (CEC 2006a), respectively, of the total state-wide emissions of these gases in 2002.

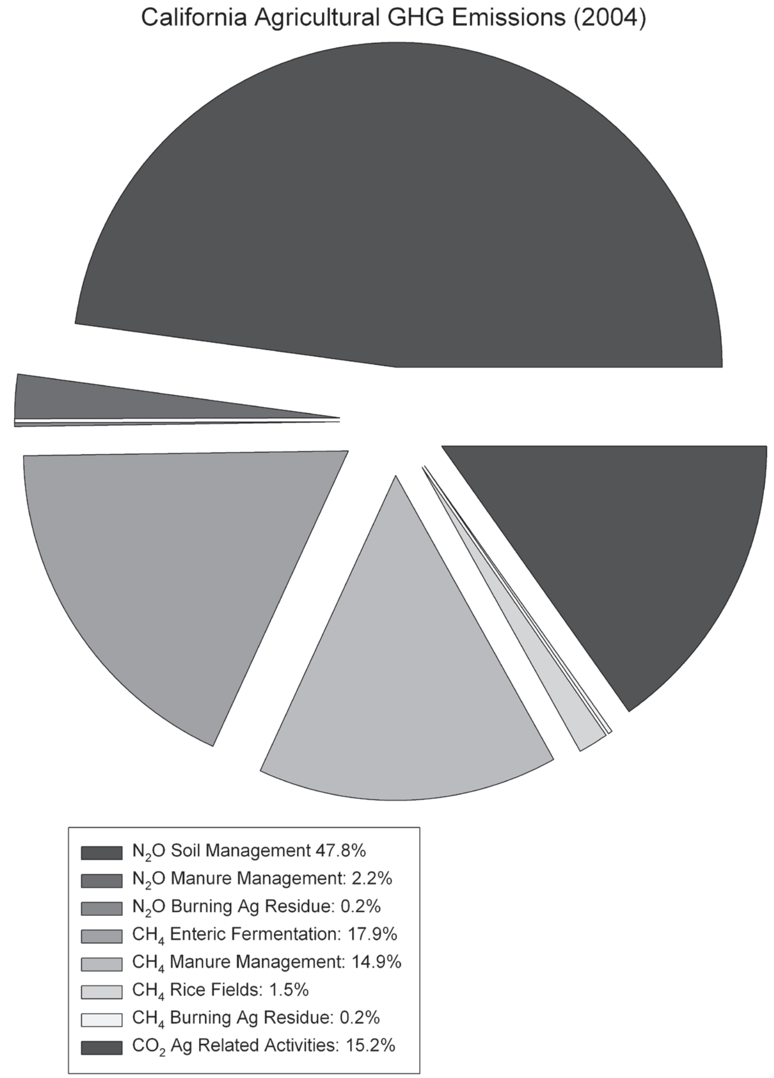


Figure 5: California agricultural GHG emissions broken down by gas and activity. Data modified from CEC (2006b)

Agricultural GHG emissions are primarily composed of $N_2$0 (50.2%) and CH_4 (34.5%) with CO_2 comprising only about 15.2% (CEC 2006b; Figure 5). Most agricultural CO_2 emissions are produced through the combustion of fossil fuels during field operations such as tractor passes for soil cultivation and pest control, harvest-related activities, irrigation and water pumping, and, to a lesser extent, frost control measures. Agricultural soil tillage operations and burning are additional sources of non-fossil fuel derived CO_2. The synthesis of inorganic N fertilizers also produces CO_2 during the Haber-Bosch process, which generates ammonium from hydrogen and dinitrogen gas (N_2) at high temperatures and pressures. Nitrogen fertilizers applied to soils and soil management (e.g., tillage) are the major sources of agricultural $N_2$0 production. Animal husbandry is responsible for most of the agricultural production of methane (CEC 2005), although soils that contain little or no oxygen may produce methane as a result of methanogenic bacterial activity (Paul and Clark 1996).

Historically, the North American conversion of prairies, grasslands, and forests to agriculture has resulted in the release of up to five petagrams (5 Pg) of C (Lal 1998; Figure 6). Through the 1960s, agricultural land use was responsible for more CO_2 production than fossil fuel combustion (Houghton et al. 1983, Desjardins et al. 2005). The Midwestern prairies and grasslands typically chosen for conversion to agriculture were highly fertile, contained very large amounts of organic matter, and were susceptible to C loss through soil disturbance activities such as tillage, which accelerates C loss through microbial oxidation and erosion. Most agricultural soils have lost between 25-75% of the pre-conversion C concentration (Lal 2007). In some cases, soils have lost 20-30% of their C within 20 years of conversion to agriculture (West and Post 2002).

The same trends in soil C loss hold true for California. A Napa Valley vineyard located where an oak woodland formerly grew was estimated to have lost greater than 30 Mg C ha-1 in the plow layer (0-30 cm), or roughly half of the total soil C in the 60+ years since conversion (Carlisle et al. 2006). This value fits in the range of C lost in annual cropping systems. Drainage of wetlands such as those found in the Delta for agriculture at the beginning of the 20th century has also resulted in huge losses of C. Historically, over thousands of years, anoxic (without oxygen) conditions in wetland soils allowed accumulations of very large amounts of C, ranging up to >85% by mass (Morris et al. 2004). The introduction of oxygen to these C-rich soils in response to drainage and tillage resulted in very high CO_2 production through microbial consumption of organic matter (Tate 1980). The restriction of water sources through the California Central Valley Project further accelerated exposure and C loss as CO_2 (Frayer et al. 1989).

The conversion of wildlands to agriculture included such activities as deforestation, tillage, and soil drainage, and resulted in the direct loss of organic matter through burning, disruption of soil aggregates, and changes in the plant communities formerly present on these soils (Lal 2004). Soil aggregates protect organic matter (soil C) from decomposition by either preventing microbial access and/or limiting oxygen diffusion (Reicosky et al. 1997). Once aggregates are fractured, microbes have access to much of the formerly protected organic matter which is then consumed, mineralized, and lost as CO_2 through soil respiration (CO_2 produced by soil microbes and root respiration) (Reicosky et al. 1997). Tillage and other activities that disturb the soil can also result in physical loss of organic matter through erosion (Jacinthe et al. 2004), especially when fields are located on slopes.

Managing agricultural systems to maximize crop production prevents a substantial portion of the annual net primary production (ANPP, annual increase in plant biomass) from entering the soil to replace C lost through activities such as harvest and tillage. This is clearly one consequence of a highly successful food production system, but is thought to be less of a problem in woody perennial crops such as vineyards (Kroodsma and Field 2006), as a result of decreased tillage and increased C deposition into soil and permanent structures common to perennial cropping systems. In addition, the possibility exists that cultivated species have been bred under conditions where nutrients and water are not limited, and thus, root system development and below ground net primary production may be diminished relative to the wild types.

2.1.2 GHG Mitigation

Agriculture clearly has demonstrated potential to sequester or store C in soils. Agricultural soils are thought to have roughly the capacity to store up to 60-70% of the amount of soil C lost during conversion from natural systems to agriculture and subsequent crop management (Lal 2002). A number of agricultural management systems or practices have been shown to enhance rates of C input into soils. It is estimated that if all agricultural lands in the U.S. were managed to enhance soil C storage these soils could sequester 75-208 Tg of C yr-1 (reviewed in Hutchinson 2007). In annual crops, conservation and no-till systems in the Midwestern U.S. and Canada have shown C sequestration rates of 0.1-0.8 Mg C ha-1 yr-1 (Lal 2002) and 0.2 Mg C ha-1 yr-1 (Hutchinson 2007), respectively.

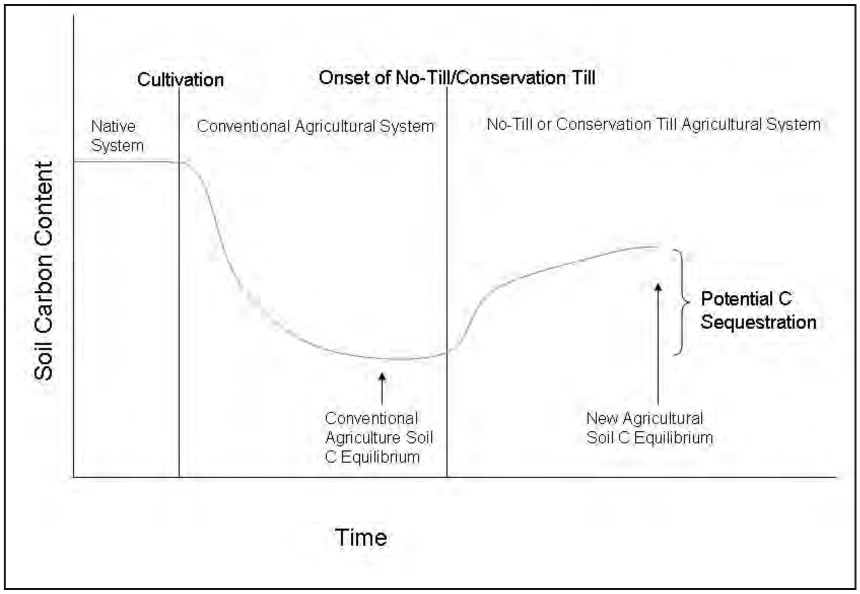


Figure 6: The effects of cultivation on soil C content. Cultivation results in a sharp drop in soil C, as aggregates are broken and exposed to microbial consumption. After 5-20 years, stored soil C reaches a new, lower equilibrium. Conversion to a no-till or conservation till soil management may result in increased C storage (possibly up to 60-70% of pre-disturbance soil C) (Lal, 2002).

The use of cover crops in place of bare fallow during rotations in annual (Lal 2002) and perennial cropping systems (e.g. Smith et al. 2008, Steenwerth and Belina 2008a) has been shown to increase soil C storage. After five years under a permanent cover crop planted in the vineyard alleys, soil C was roughly 1.4 times greater than a bare fallow treatment (1.1% vs 0.72% total soil C, respectively; Smith et al. 2008, Steenwerth et al. 2008a). Increasing fertilizer application rates can increase plant/crop production and may represent another opportunity to enhance C sequestration. However, the cost of increased CO_2 emissions from the production and application of the fertilizer and potential higher rates of N_20 emissions derived from the applied fertilizer (Johnson et al. 2007) needs to be evaluated. The extent to which alternative production practices in California perennial crops systems will affect total GHG consumption and production and the levels at which saturation of the soil C pool occurs is not known.

Conservation programs (such as the Conservation Reserve Program of the U.S. Department of Agriculture's Natural Resources Conservation Service) that encourage removing marginal lands from production and restoring degraded wetlands also represent very good C storage opportunities. Grape growers may have other lands that are not in production that can be utilized in a manner similar to the Conservation Reserve Program to help mitigate or offset GHG emissions from viticultural management. Conservation tillage and no-till systems may offer further mitigation potential through decreasing tractor passes and fuel usage, one of the largest sources of CO_2 emissions, although these practices can also decrease yields in annual cropping systems (Jackson et al. 2004). Conservation tillage and no-till systems also help sequester soil C by decreasing the amount of soil disturbance, allowing for the formation of soil aggregates protected from microbial activity (Six 2004). Presently, conservation and no-till approaches are utilized in many California vineyards (CSWA 2004).

Perennial crops may offer a greater potential to sequester C than annual crops (Kroodsma and Field 2006). Perennial crops generally require less tillage and soil disturbance, use more targeted irrigation/fertilization management systems, and store large amounts of C in the living above- and belowground biomass (trunks, limbs, cordons, etc.). Perennial crops often have much deeper root depth distributions (Smart et al. 2006), which also increase the potential to store C (Dalal et al. 2003). Unlike annual row crops in California (Jackson et al. 2005, Minoshima et al., 2007), perennial crops may suffer lower yield loss under reduced or no tillage, due to their architecture, management, and deeper root systems.

A modeling study of the ability of California agriculture to sequester C found that perennial crops had very high sequestration potentials relative to annual crops (Kroodsma and Field 2006). Their model found that agricultural fields converted from annual crops to vineyards and orchards might sequester an average of 68 and 85 g C m-2 yr-1. Kroodsma and Field (2006) determined that California agriculture sequestered 14.5 Tg of C (or roughly 0.7% of total GHG emissions during that period) in the soil and perennial crop biomass over 21 years. If waste biomass from orchards and vineyards was used as an energy source instead of fossil fuels, they estimated that up to 1.6% of emissions over those 21 years could have been offset (Kroodsma and Field 2006). The results of this study highlight the fact that although California agriculture may have a relatively limited potential to mitigate GHG emissions, actual field verification data are needed to test the assumptions of this model. In addition, although agricultural C sequestration might have limited influence on overall California GHG budgets, conservation practices that sequester C would have a large influence on agriculture-specific GHG budgets (see Pacala, 2004 and Socolow for a discussion of stabilization wedges).

2.2 Terrestrial Biogeochemical Cycles

2.2.1 Carbon Cycle

The biogeochemical cycling of C is a complex process involving the movement of C among the major global C pools of the atmosphere, soil, biota, and oceans. The oceans represent the largest single C pool, containing roughly 38000 Gigatons (Gt, 109 tons) of C. Soils are estimated to contain approximately 1550 Gt C, slightly greater than what is thought to be contained in global terrestrial biota (560 Gt C) and the atmosphere (750 Gt C) combined (Schlesinger 1997).

Soil organic matter is initially composed of the decaying and decomposed remains of plants, which are then processed by microbial and physical processes to gradually produce more stable compounds (resistant to decomposition). Carbon in the form of CO_2 is absorbed from the atmosphere during the process of photosynthesis. Roughly half of the total C captured is converted to carbohydrates used as structural plant material or energy reserves (eg., stored starch). The other half is respired back into the atmosphere as a result of plant metabolism. The carbohydrates, proteins, and other C sources produced by photosynthetic activity of plants and other autotrophic organisms (e.g. cyanobacteria) represent the C (energy) available for the vast majority of heterotrophic organisms to utilize and ultimately respire back into the atmosphere as CO_2.

Labile soil C pools are composed of such organic matter that is easily consumed and respired by soil microbes. The soil C pool is dynamic, with the total amount of C present in the soil determined by the input of fresh organic material (e.g. leaves, roots, canes, and thinned clusters) and the release of CO_2 mainly produced from C mineralization (conversion of organic matter to CO_2) by microbial organisms (Amundson 1998). Carbon that is not easily consumed by heterotrophs (e.g. cellulose and lignin) and is a major constituent of structural plant organs eventually enters the more recalcitrant soil C pools. The labile and recalcitrant soil organic matter pools represent the majority of the standing C in soils (Schlesinger 1997).

Inorganic C in the form of Cates also represents a sizeable C pool, especially in more arid environments. But the soil C pool is primarily composed of soil organic matter, at least in soils with relatively acidic pH levels. Inorganic C can contribute to total soil C content in more alkaline soils. The use of Cates such as lime or dolomites to control soil acidity during agricultural operations can represent a major source of CO_2 (Mosier et al. 2005) for viticulture in regions where soil acidity is a problem.

Human activities such as the extraction and combustion of fossil fuels used in transport, energy generation, industrial activities, and the production of agricultural fertilizers have had an impact on the balance of the global C cycle. These activities added large quantities of CO_2 to the atmosphere apart from the natural C cycle and have resulted in a net increase in the size of the atmospheric C pool consisting of CO_2. The increase in atmospheric CO_2 has not been balanced by increased plant production and associated photosynthetic activity, nor by absorption of CO_2 into the oceans (Schlesinger 1997).

2.2.1.1 Methane and the Carbon Cycle

Methane is another important C-based greenhouse gas that is part of the global C cycle. Methane is produced during microbial decomposition of organic matter under anaerobic (without oxygen) conditions by methanogenic bacteria. Wetlands and agricultural fields (e.g. rice paddies) with saturated soils or standing water can produce relatively large amounts of CH_4. Methane production derived from animal husbandry (enteric fermentation) accounted for over 50% of agricultural CH_4 production, and together with manure management contributed to approximately 95% of total agricultural CH_4 emissions (CEC 2006) in California. Most other agricultural CH_4 emissions are related to agricultural burning and rice production (CEC 2006). Vineyards are considered to be upland crops and therefore not expected to be a major producer of CH_4.

Methanotrophic bacteria in the soil consume CH_4, and release CO_2 into the atmosphere (Paul and Clark 1999). Methanotrophs are especially common where large amounts of methane can be found (i.e. wetlands), but they can be found in all soils and particularly forest soils of high C content. Globally, it has been estimated that soils consume on average 0.3 kg CH_4 ha-1 yr-1 (Gregorich et al. 2005). However, in most cases (i.e. non-wetland soils), methane consumption is limited by diffusion rates of methane from the atmosphere into the soil. Agricultural fields that are fertilized with inorganic N fertilizers generally have little to no methanotrophic activity (Venterea et al. 2005, Gregorich et al. 2005). Thus, in the case of California's vineyards, it might be expected that the inter-row or alley soils have the potential to serve as a CH_4 sink, and in the unlikely event that CH_4 is actually produced in vineyards; the most probable source would be under the drip emitters after irrigation. However, no studies were found that have examined CH_4 production or consumption by vineyards.

2.2.2 Nitrogen Cycle

The biogeochemical N cycle (N cycle; see Figure 7) represents one of the most important and complex nutrient cycles with respect to climate change. Nitrogen forms are extremely diverse as a consequence that stable and reactive forms can exist in a range of 8 (-3 to +5) oxidation-reduction states. A distinction is made between reactive forms of N (NH_4+, NO_2- and NO_3-, plus the gaseous forms of NH_3, N_20, and NOx) and the more stable N forms of dinitrogen (N_2) and assimilated N (phenolics and the amide bond of amino acids). Dinitrogen gas is extremely stable and environmentally benign and assimilated N can be retained in biomass and thus not generally transported off site. One goal of management would be to diminish offsite transport of reactive forms of N while still providing sufficient quantities for economically successful production. Of importance to vineyard C footprints are the N transformations carried out by nitrifiers (nitrification) and denitrifiers (denitrification) that occur during mineralization of organic matter and N fertilizers and generate nearly all of the reactive forms of N.

The vast majority of N found in terrestrial ecosystems is in living and dead organic matter. Cycling of N is controlled by soil microbial activity. Microbes are responsible for converting organic N (e.g. proteins found in organic matter) into inorganic N forms such as nitrate (NO_3-) and ammonium (NH_4+) that higher plants and microbial organisms can absorb and utilize (Paul and Clark 1999). These conversions are often referred to as N-transformations and involve a series of oxidation and reduction reactions that transform N between its most reduced (NH_4+) and oxidized (NO_3-) forms. Microbial organisms are also responsible for the presence of the majority of naturally occurring N found in the soil, as certain groups of microbes (N-fixers) are the means by which N enters the plant and soil biota. Most N-fixers form symbiotic relationships with plants such as legumes, although free-living N-fixers are also common. N-fixers are capable of converting N_2 (comprising roughly 78%

of the elemental composition of the atmosphere) into organic forms of N (such as proteins), thus making N available for other organisms to use when N-fixers die and decompose. During the decomposition process, the vast amount of the N contained within organisms is first converted to NH_4+ via ammonification.

Ammonium, in turn, can be transformed by a ubiquitous assemblage of microbial organisms, known as nitrifiers, that oxidize NH_4+ into nitrite (NO_2-) and then nitrate (NO_3-) by using the reducing equivalents (electrons) from NH_4+ to assimilate CO_2 in a process referred to as nitrification (Clark and Paul 1999). Nitrification requires oxygen (aerobic conditions) in order to proceed. During this conversion, some N may be lost as nitrous oxide (N_20), a very potent GHG. The NO_3- ultimately produced by nitrification can be leached from the soil into the saturated zones where it is no longer accessible for plant use. This mobilized NO3-, as well as any other soil NO_3- found in saturated soils, is then made available to microbes (denitrifiers) that participate in a process called denitrification, in which NO_3- is used as an electron acceptor under anaerobic (without oxygen) conditions during electron transport phosphorylation, and ultimately convert such N into N_2 and N_20 which then enter the atmosphere. Most of the N transformed by denitrification is returned to the atmosphere as N_2. Denitrification can also take place in aerobic soils in low oxygen microsites or aggregates, and this process represents one of the major sources of agricultural N_20 production. Soil microbes may also be responsible for N_20 consumption in the soil via reduction to N_2 gas, although this is not thought to be significant (Clark and Paul 1999). All forms of applied N (e.g. conventional synthetic fertilizers, manures, and other organic sources) can produce N_20 through nitrification and denitrification.

The amount of reactive forms of N produced by nitrification and denitrification is the subject of some uncertainty in as much as it would strongly depend on environmental conditions and the physiological condition of the microbial organisms (Firestone and Davidson 1989). More N_20 is produced by dentrification while greater quantities of nitric oxide (NO) are generally produced by nitrification (Conrad 2002). Temperature is a primary driver of both processes (Fireston and Davidson 1989, Butterbach-Bahl et al. 2004) with increasing rates observed up to a temperature of approximately 35•C (Kesik et al. 2004). Another major constraint on nitrification and denitrification is soil moisture, or, more accurately, water filled pore space (WFPS). Denitrification is generally faster when WFPS exceeds 60-65% and anaerobic conditions prevail, while nitrification is favored by aerobic conditions (Davidson 2000). However, the transition from more anaerobic driven emissions to aerobic emissions is not well defined (Davidson 1991). Particle size distribution and bulk density determines WFPS for a given quantity of water delivered in a precipitation or irrigation event, and this is also thought to present a diffusion limitation to N trace gas emissions from soils (Carlisle 2009).

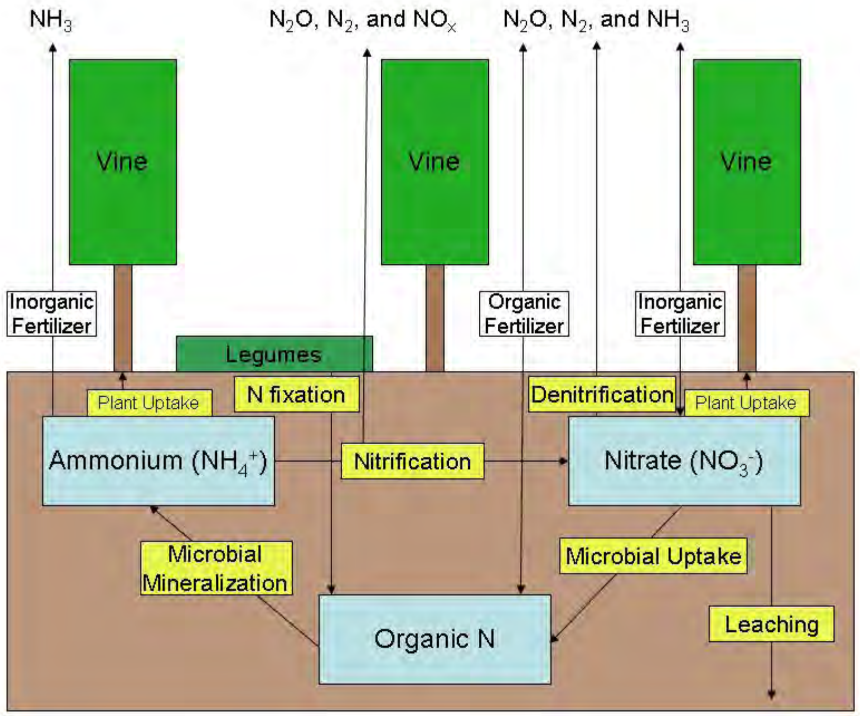


Figure 7: Conceptualized and simplified model of the vineyard N cycle with a focus on those microbial processes that generate reactive N trace gases, including greenhouse gases. Those processes are mainly nitrification, a two step oxidation process of NH4+ + O2→NO_2-, and, NO_2- + H_2O → NO_3- and denitrification, which consists of the generalized reduction of NO3−→NO2−→ NO + N_20 → N2.

The use of N fertilizers and amendments, especially inorganic N fertilizers produced by human activities, and the use of legume-rich cover crops represent a clear disruption of the natural N cycle. Application of synthetic fertilizers to agricultural and agroforestry systems is estimated to be responsible for up to one-half of global biologically available N (Vitousek et al. 1997). As a result, human activities have substantially increased the transport of N between the atmospheric and terrestrial pools. There are no current comprehensive measures of annual N fertilizer use or N_20 emissions from vineyards. Estimates based on regional modeling efforts and N use patterns that were taken from the U.C. Davis Department of Agricultural and Resource Economics Cost and Return analyses (http://coststudies.ucdavis.edu/current.php) indicated that between 8-12 kg hectare-1 (7-11 lbs acre-1) N_20-N are emitted from vineyards (CEC 2004). But the 67.5 kg hectare-1 (60 lbs acre-1) of N fertilizer taken from the Cost and Return studies is likely an overestimate of typical vineyard N applications.

2.2.3 Linkage of Carbon and Nitrogen Cycles

The N and C cycles are strongly linked and form one of the many coupled biogeochemical cycles. Photosynthetic rates (CO_2 fixation) are partially controlled by the amount of ribulose bisphosphate carbon dioxide oxygen fixing protein enzyme (RuBisCO, the primary enzyme for the production of carbohydrates during photosynthesis). The concentrations of RuBisCO and chlorophyll found in plants are strongly sensitive to N availability.

Higher amounts of plant available N result in increased CO_2 fixation, and ultimately more growth in plants. The decomposition of organic matter is often controlled by available N, as soil microbes need a certain amount of N to meet their living requirements in order to fully process organic matter during mineralization. At the same time, without an adequate supply of organic matter, the N cycle is hampered. Denitrifiers require energy rich C sources to apparently fuel the reduction of NO_3- to N_20 and ultimately N_2. Nitrifiers, on the other hand, use the electrons produced during the conversion of NH4+ to NO3- . Accordingly, practices like tillage that mobilize and result in oxidation and loss of soil C foster nitrification. This leads to the mobilization of NO3- and therefore potential for contamination of ground waters and increased NO_3- availability for denitrification. Thus management of C in soils can influence the N cycle while management of N can influence the C cycle. Teasing apart the relationships that contribute in either a positive or negative manner to vineyard C footprints when management practices are altered in vineyards and other perennial crops would involve a major research undertaking.

The production of methane (CH_4), another C-based GHG, is also linked to the N cycle. The presence of NO_3- inhibits methanogenesis (production of CH_4) which will not proceed until all available NO_3- is depleted and assimilated or converted to N_20 or N2 gas (Kahlil and Baggs 2005, Chan and Parkin 2001). Soils that are water saturated or in estuaries and other wetlands produce high CH_4 and N_20. But in agricultural soils, particularly in the arid West, production of N_20 would be intermittent and dependent on water filled pore space and NO3- concentration following irrigation or rainfall (see section 4.1.1). As can be seen, water is a very important driver that regulates the interactions of C and N.

3.0 Vineyard Carbon Dioxide Emissions and Carbon Sequestration

Carbon dioxide uptake through photosynthesis and release through plant and soil respiration have been studied more thoroughly than the consumption and emission of vineyard N_20 and CH_4. However, even these data are relatively scant, and more information is needed on vineyard management practices and how they impact vineyard C sequestration and GHG emissions in order to generate an accurate vineyard GHG footprint.

3.1 Irrigation and Farm Equipment

Irrigation and farming equipment that consume fossil fuels, such as tractors, ATVs, harvesters, some frost control devices, etc., are responsible for an undefined, but very important amount of vineyard CO_2 emissions depending on management practices. The energy costs of irrigation may represent a relatively large source of GHG production, especially in areas with extremely high evapotranspiration demand such as the San Joaquin Valley. For this report, estimates for fuel consumption during typical vineyard management practices were obtained from the Vineyard Cost and Return analyses (http://coststudies.ucdavis.edu/current.php). Reported values of fuel (gasoline and diesel) use in California vineyards ranged from 20 to 50 gallons acre-1 (about 185 to 470 liters hectare-1) (Cost and Return Studies, Hal Huffsmith, Trinchero Family Estates). There are no vineyard specific studies of CO_2 production from fossil fuel combustion, but a number of relevant comprehensive studies on annual cropping systems exist. Koga et al. (2006) and Desjardins (2005) examined the GHG costs of annual crops throughout their life cycle including production, transportation, and final use (life cycle analyses). In both studies, fossil fuel combustion represented a large percentage of total GHG emissions. For every gallon of gasoline and diesel combusted, approximately 9.02 and 10.4 kg of CO_2 are released, respectively (Koga et al. 2006, IPCC 2006). Any differences in data between vineyard and annual crops in terms of GHG emissions per gallon of fuel used appear to be small, and would be based on relations incorporating maximum power take-off (PTO) horse power, type of fuel used and vehicle maintenance requirements (e.g., lubrication) (American Society of Agricultural Engineers 2002) rather than crop type. Relative to annual cropping systems, fossil fuel use in viticulture may represent a larger proportion of total GHG emissions as a result of typically more conservative soil, fertilizer, and irrigation management.

Irrigation often leads to increased vine biomass (Williams 1996), and, as a result, irrigated vineyards may potentially store more C in permanent vine structures (see section 3.3) as well as non-permanent structures. This greater production of biomass and associated C may contribute to greater C storage in the soil. Nonetheless, increased irrigation and soil water content may also lead to higher N_20 production (see section 4.1.1) while more conservative water use might diminish such emissions. Soil moisture is often a limiting factor for soil microbes as well, and irrigation will enhance soil CO_2 produced via microbial activity where water is applied. Finally, electricity or energy otherwise supplied through fossil fuel combustion is required to pump water resulting in greater total GHG emissions. Crops with lower irrigation demands like grapes would generate less GHGs from energy consumption for irrigation.

3.2 Nitrogen Fertilizer Use

Production of synthetic N fertilizers results in the emission of CO_2 as well as N_20. The Haber-Bosch process combines N_2 and H_2 gases to form NH_3 which can then be converted into other inorganic forms of N including NH_4+, NO_3-, and urea fertilizers. For example, production of urea and UAN (Urea, Ammonium-Nitrate) fertilizers resulted in the emission of 1848 and 1844 g CO_2 equivalents per kg fertilizer N (reviewed in Wood and Cowie 2004). Currently, much uncertainty exists in the quantity of fertilizer used in California vineyards. For reasons related to fruit quality, N use is often restricted in winegrape vineyards to a greater extent than table grape and raisin vineyards. In addition rates of application vary over the lifetime of the vineyard. As much as 60 lbs acre-1 (about 67.5 kg hectare-1) might be applied during establishment of wine grape vineyards (Cost and Return Studies) while rates can be lower thereafter. For table grapes, 60 lbs N per acre per year may be more of the norm (Jennifer Hashim personal communication). Higher application rates of N fertilizer will increase the amount of biomass (C sequestration) that vines can add each year. However, this may come at the cost of increased denitrification and N_20 production (See section 4.2). Grape crop type and vineyard maturity will affect the use of synthetic fertilizers and, therefore, the emission components associated with their production.

Research Need: Information is needed concerning the trade offs between N application and N_20 production versus C sequestration.

3.3 Photosynthesis and Carbon Sequestration

Photosynthesis is the process by which plants use light to reduce CO_2 and produce carbohydrates. Plants distribute the produced carbohydrates, or photosynthate, to areas in the plant that require energy or use C skeletons (structural materials) for growth. It is important to gain an understanding of how the vine distributes these carbohydrates, as where these carbohydrates reside can significantly impact the ability of a vineyard to sequester C (Figure 8). Much of a vine's annual production of photosynthate is used for respiration and fruit production, as cells utilize the sugars to produce energy to grow and stay alive. In fact, fruit probably represents the largest sink for C during the growing season.

The allocation of C among the many vine structures and storage pools is an important consideration of vineyard C sequestration (Figure 8) but there is limited information concerning how management influences C allocation patterns. In general, grapes and other perennial crops have been estimated to use 25-75% of their annual primary production in cellular respiration (Amthor 1989). For grapevines, Williams (Williams, 2000) estimated 40-50% of their photosynthate was consumed in respiration, with a large proportion of the 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. Older and larger vines require larger amounts of energy to stay alive than smaller vines. Whole plant photosynthetic rates are strongly affected by management and vineyard establishment because net C gain, or ANPP (annual net primary productivity), is dependent on light interception versus the total shaded leaf area. Shaded leaf area has very low photosynthetic rates but still respire C, so a net C loss occurs (Mullins et al. 1992). Thus, trellis systems, training scheme, irrigation, and row orientation as well as pruning and thinning practices can substantially influence light interception and, consequently, total vine photosynthesis and ANPP (Williams 2000). Plant respiratory costs are not generally included in calculations of GHG emissions. Net C assimilation, which can be estimated with well constrained ground-based measures of ANPP and BNPP (belowground net primary productivity), along with soil respiration measurements to relate this to the quantities of C 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 (Snyder et al. 2000; http://www.nacarbon.org/nacp/about.html) as well as modeling exercises.

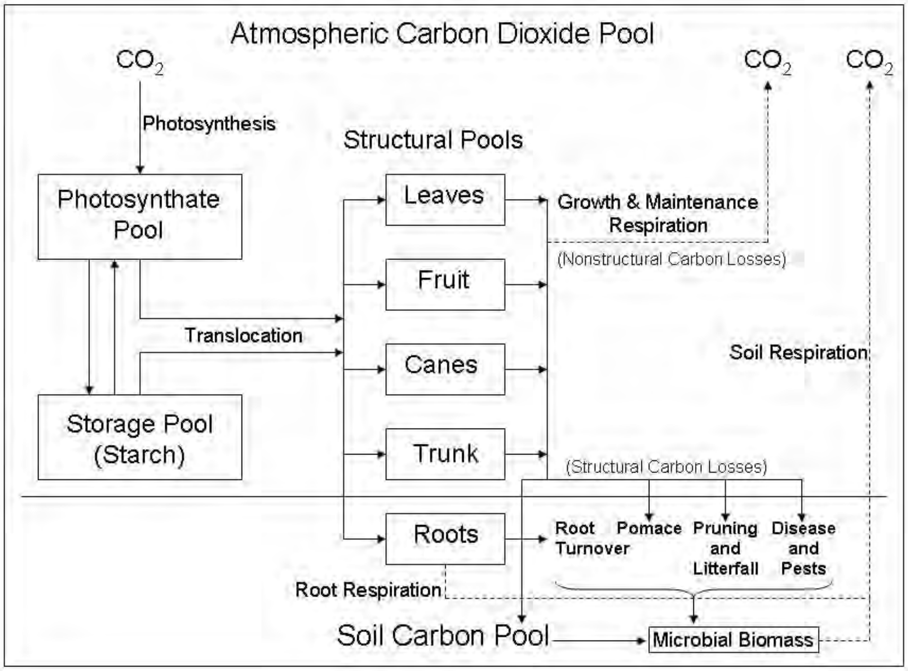


Figure 8: Conceptual model of the vineyard C cycle including the components that contribute to emission of CO_2 by soil respiration. Vine components that may potentially contribute to soil C storage (sequestration) are also included.

If photosynthate production exceeds the demands of maintenance respiration, then C skeletons and ATP are utilized for growth processes (e.g. proteins, lipids, cellulose). These C skeletons are allocated to vine organs including the fruit, trunk, stems, leaves, and roots depending on demand. Fruit production serves as the primary sink for photosynthate following fruit set, with fruit production representing 20-70% of total dry weight gain of grape vines (Williams and Biscay 1991, Mullins et al. 1992, Williams 1996; Table 1). Variety and management probably have the strongest influence on this percentage. Chenin blanc grown in the San Joaquin Valley (SJV) allocated 37% of non-respired photosynthate to fruit production (Williams 1996, Mullins et al. 1992). Irrigated Thompson Seedless table grapes grown in a similar location, on the other hand, allocated 44 to 69% of biomass into fruit (Williams 1996). Williams (1996) found that non-irrigated Cabernet Sauvignon in Napa Valley allocated only 20% of their aboveground biomass to fruit.

Research Need: Information is needed concerning the trade offs between N application and N_20 production versus C sequestration.

Trunks, cordons, and roots represent the more permanent structures of grapevines. These woody structures represent the best opportunity for sequestering C within the vine. While there have been no published wood density values from California, trunks of Vitis vinifera in South Africa were found to have an average dry density of 0.597 g cm-3, and a C content of 43.7% (Munaluna and Miencken 2008). Any management practice affecting C allocation to these structures can affect the capacity of vineyards to sequester C. The amount of photosynthate allocated to these structures depends heavily upon other factors such as edaphic conditions, seasonal environmental variation, variety, rootstock, and management practices. Vineyard management practices that impact photosynthate distribution include training and trellis systems, hedging, irrigation, fertilization, cover cropping, vineyard establishment, vine density, and row orientation (Archer and Strauss 1991, Mullins et al. 1992, Williams 1996). Annual climatic variation can affect grapevine distribution of photosynthate. For example Williams (1996) observed variation in annual trunk increment of greater than 40% during a three-year study of Thompson Seedless grapes in the San Joaquin Valley.

Various grape varieties produce and distribute photosynthate differently, although this may also be a function of different management practices and vineyard location. Well-irrigated vines had greater leaf area and potential photosynthetic rates than dry farmed or deficit irrigated vines (Williams and Matthews 1990). A number of studies have measured whole vine photosynthate allocation in the Napa and San Joaquin Valleys and resulted in substantial variation in ANPP even for vineyards grown in the same area and planted with the same variety (Williams and Biscay 1991, Williams and Smith 1991, Mullins et al. 1992, and Williams 1996; See Table 1). Interactions between rootstock and scion affect annual biomass increases. Williams and Smith (1991) found that while Cabernet Sauvignon grafted to 5C and AXR1 rootstocks produced the same amount of trunk biomass, if it was grafted to the St. George rootstock, annual biomass production was only about 65% of that of the other rootstocks, and St. George is considered to be a more vigorous rootstock. Consequently, there is much uncertainty concerning how many of the variables that have an influence on C sequestration, including management practice, variety, rootstock and environmental factors, interact. Much more information acquired under controlled experimental needs to be collected to get a better idea of how much C is stored in the trunk, cordon, and roots of grapevines in California.

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). Root biomass values represent an instantaneous measure of root mass due to uncertainties about root age. Mass produced per annum was determined by dividing a harvested vine by its age. Fruit, stem, and leaf mass were determined from a single year's production. Only studies that provided more comprehensive data for both aboveground and belowground biomass 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	N/A	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
Standing Biomass (Mg/ha)*	14.31	6.27	N/A	N/A	19.48	N/A
Total Carbon (Mg/ha)*	6.44	2.82	N/A	N/A	8.77	N/A
Root:Trunk Ratio	0.56	0.5	0.33	N/A	0.46	1.2

* Assuming 1282 vines ha^{-1} for the Thompson Seedless table grape vineyards and, and 1920 vines ha^{-1} for the wine grape vineyards. Information on density is not provided consistently in all reports cited below.

[1] Williams (1996)

[2] Williams and Smith (1991)

[3] Clingeleffer and Krake (1992)

[4] Smart and Stockert (unpublished data)

[5] Mullins *et al.* (1992)

[6] Saayman and Huyssteen (1980)

Root biomass may represent an important contributor to soil C sequestration in vineyards, as grapevines tend to produce a relatively deep root system (Smart et al. 2006). There is a large variation in reports of grapevine root production. The few published reports of root biomass increment range from 140 to 360 g vine-1 year-1 (Table 1). Another study (Araujo and Williams 1988) found 350 g year-1 allocated to the root system in Thompson Seedless, which is similar in magnitude to Williams' other studies in the San Joaquin Valley. However, some data indicate that these numbers might be underestimates. For instance, annual standing root biomass increases of 1000 g year-1 are not unusual for Thompson Seedless and Barbera varieties (Williams and Biscay 1991) grown in the San Joaquin Valley. This highlights that rootstock usage imparts an additional layer of complexity on root biomass production, as some rootstocks produce a greater number of roots than others (Bauerle et al. 2008) and root depth distributions can differ between rootstocks (Figure 9, McKenry 1984, Williams and Smith 1991, Morano 1995, Smart et al. 2006). 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 San Joaquin Valley 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). However, Williams and Smith (1991) found no difference in annual root biomass among three root-stocks (AXR1, 5C, and St. George) grafted to the same scion in Napa Valley.

Extrapolation of data from what is currently available in the literature is extremely challenging due to many other variables that have not been measured, such as effects and interactions among age, soil type, rootstock, irrigation, and the process of vineyard establishment. Drip irrigated vines tend to have different root distributions than furrow or flood irrigated vines (Williams and Smith 1991) and these differences may strongly impact the total root production of a vineyard. In addition, strong spatial variation across vineyard rows and alleyways makes the process of scaling root biomass estimates from individual vines or trenches challenging. McKenry (1984) found significant variation in both vertical and horizontal distribution of roots (Figure 9). Saayman and Van Huysteen (1980) and Morlat and Jacque (2003) found lateral spread of roots was somewhat restricted outside the vine row but nevertheless found root densities were still relatively high at 1.5 m from the trunk. For soil type, Nagarajah (1987) found root length densities to depend on soil texture, with coarse textured soils having the lowest root densities and fine textured soils having the highest.

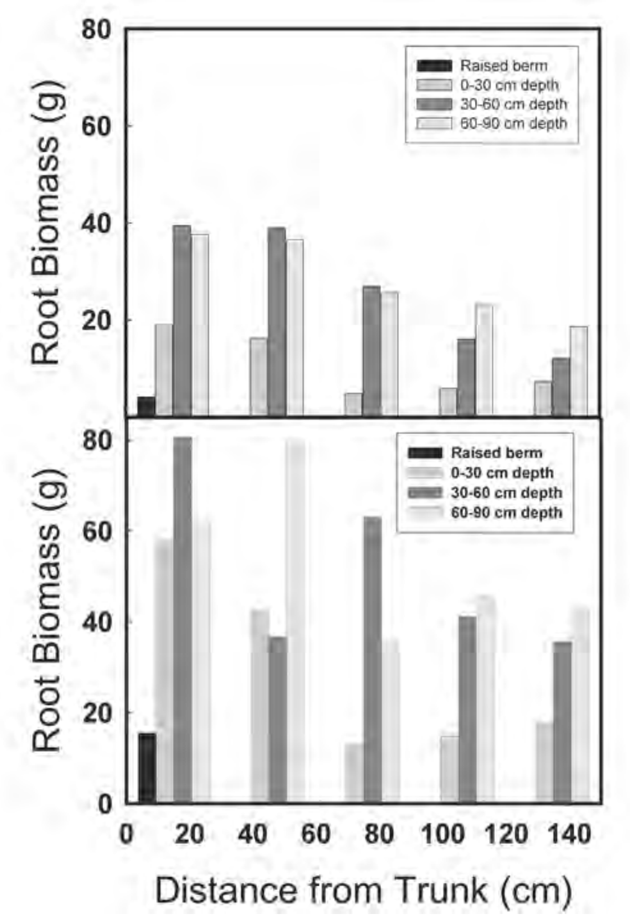


Figure 9: Root fresh biomass (g m2) for top window Vitis vinifera cv Thompson Seedless and for the lower window V. solonis X V rupestris cv Ramsey (modified from McKenry, 1987 reproduced with permission of the American Journal of Enology & Viticulture).

Because roots are difficult to study in the field, efforts have been made to establish ratios between root and trunk biomass (root:trunk ratios). Published ratios vary from roughly 0.33 to 1.2 (Table 1). Similarly, root:shoot ratios varied depending on row spacing, trellis type, and trellis height (Mullins et al. 1992). Increasing vine density can result in decreased vegetative growth per vine (Archer and Strauss 1991, Mullins et al. 1992). Mullins and others (1992) found that increasing vine density from 1120 to 1680 vines ha-1 resulted in 30% less vine shoot biomass but had no effect on root production per vine. Thus, biomass per ground area increased by 20% in as much as vine density was 1.5 times greater. However, Archer and Strauss (1985) found that after the density increased beyond 2000 vine ha-1, root growth per vine also started to decrease. Vines managed under deficit irrigation (52% of the total evapotranspiration demand) produced 31% less root biomass, 17% less trunk biomass, and 26% less cordon biomass (Mullins et al. 1992). At the same time, water stress and the time of year in which it occurs, have been found to interact in complex ways that result in different carbohydrate storage strategies in roots, fruit, and shoots (Comas et al. 2005).

Non-permanent vine structures include fine roots, canes, and leaves. With the exception of fine roots, the portions of biomass entering soil organic matter pools is unknown and may depend on management. For all non-permanent structures, it is unknown how large a fraction enters the recalcitrant pools and thus how large a source of C sequestration they represent. Biomass production of vine structures is strongly controlled by many of the same environmental factors and propagation conditions (rootstock) pointed out above (Table 1). Even within the same region and the same variety, substantial variation has been noted (Williams 1996). Thompson Seedless produced from 1308 to 1554 g leaves vine-1 and 1891 to 2227 g canes vine-1 dry weight (Williams 1996, Williams 2000). In another study, Williams et al. (1985) found that Thompson Seedless produced between 1100 and 1800 g leaf per vine and between 700 and 2200 g cane dry weight per vine. Christensen (2000) found that the typical Thompson Seedless vineyard produced 2240 kg prunings per hectare. Pinot Noir grown in Oregon produced 678-1209 g pruning material per vine (Vasconcelos and Castagnoli 2000). Plant material has generally been assumed to be composed of roughly 45% C (Schlesinger 1997). Unpublished data from D. Smart, R. Spencer, and E. Carlisle found percent C values in grape root tissue to range 38-45% in samples taken from several vineyards in the Oakville region. Taken over an entire vineyard, the leaf, stem, and cane biomass can represent a sizeable amount of C. For example, at the Oakville site (Smart et al., unpublished data) this biomass amounts to 1911 kg C ha-1 (Table 1).

Research Needs:

- More research is needed to understand the effects of vineyard management practices, variety, rootstock, edaphic conditions, seasonal environmental variation, and their interactions on photosynthate distribution in grape vines.
- Additional data on grapevine organ C storage and wood density is needed for calculating non-soil vineyard C sequestration.

The biomass from pruning and, to a smaller extent, thinning excess leaves and fruit of vines (summer pruning) may be a potential C sequestration source. After pruning, canes are often shredded and incorporated into the soil. Much of the C in this biomass will be lost as CO_2 as it decomposes. However, some will be retained as soil organic matter, where it might persist for an undetermined amount of time. Lal (2004b) estimated the percentage of plant biomass C entering the soil as long-term soil organic matter ranging from 2 to 20%. No published information on decomposition of grapevine aboveground biomass or roots was found.

Research Need: Research on grapevine tissue decomposition rates is needed in order to more accurately assess C storage in soils.

Another potential source of C sequestration is vineyard row cropping, or growing cover crops. Permanent cover cropping has been shown to increase soil organic matter significantly over bare fallow rotations in annual systems (Johnson et al. 2007). Growing cover crops in the vineyard rows is likely to allow some C sequestration to occur, although any potential soil C increases can be negatively affected by as little as one light tillage pass annually (Grandy et al. 2007). The presence of cover crops can impact soil N cycling as well. Cover crops have been found to decrease NO3- leaching in fertilized annual cropping systems in California (Jackson 2000, Jackson et al. 2004; see section 4.2). Currently, very little data exists that examines the effects of cover crops on soil C and N cycling in vineyards or any other woody perennial crop, despite the fact that many of California's vineyards are managed with some form of cover crop (CSWA 2004). Few published studies were found that examined the ability of vineyard cover crops to affect soil C in California. Steenwerth and Belina (2008a; see also Smith et al. 2008) found that vineyard alley soil C increased after five years in the two permanent cover crops Trios (Triticale x trioscale) and Merced Rye (Secale cereale) relative to a bare cultivation treatment (9.45 ± 0.034 and 10.98 ± 0.030 versus 7.18 ± 0.18 mg C kg-1 soil from 0-20 cm depth, or roughly 15.9, 18.6 and 12.1 metric tons hectare-1, or 7.1, 8.3, and 5.4 tons C acre-1) in a Greenfield Chardonnay vineyard.

Research Need: Research is needed to understand the ability of different cover crops (annual and perennial) to increase soil C in vineyards.

Vineyard floor management should influence the capacity for vineyards to sequester C in the soil in as much as alleys represent a large fraction of vineyard area and undergo cultivation. Tillage, even light tillage such as surface disking, disturbs the soil, breaking up aggregates and exposing previously protected soil organic matter to microbial decomposition (Calderon and Jackson 2002, Reicosky and Lindstrom 1993, Reicosky and Archer 2007, Six et al. 2004, Grandy et al. 2007), resulting in oxidation and loss of soil C. Tillage also results in loss of soil organic N through the same processes, although this will be discussed later (see section 4.3). Accelerated rates of CO_2 emission occur following any disturbance of the soil. Koga et al. (2006) found in Japanese annual cropping systems that 64-76% of total CO_2 emissions (including that associated with fossil fuel consumption) came from the decomposition of soil organic matter. While these soils contained large amounts of C, this study highlights the importance of this source of CO_2. No-till agricultural operations in annual crops enhance C sequestration (West and Post 2002) as well as decrease fossil fuel usage. This same effect may be observed in vineyards, although similar studies have not directly addressed this topic in Mediterranean and other xeric environments (but see D. Pierce, MSc. Thesis U.C. Davis). Kroodsma and Field (2006) modeled the ability of California's agriculture to sequester C. Their models suggested that lands converted from annual cropping systems to perennial systems like vineyards and orchards had the greatest rates of C sequestration, storing 68 and 85 g m-2 yr-1, respectively. Land already in vineyards and orchards, on the other hand, sequestered 24 and 26 g m-2 yr-1, respectively. They also concluded that no-till systems would increase C sequestration. At the current time, insufficient field data exists to fully assess the effects of vineyard disking and cover cropping on vineyard soil C sequestration.

Research Need: An assessment of the impacts of different tillage strategies on soil C in different regions of California is needed to help evaluate the effectiveness of these strategies in sequestering C.

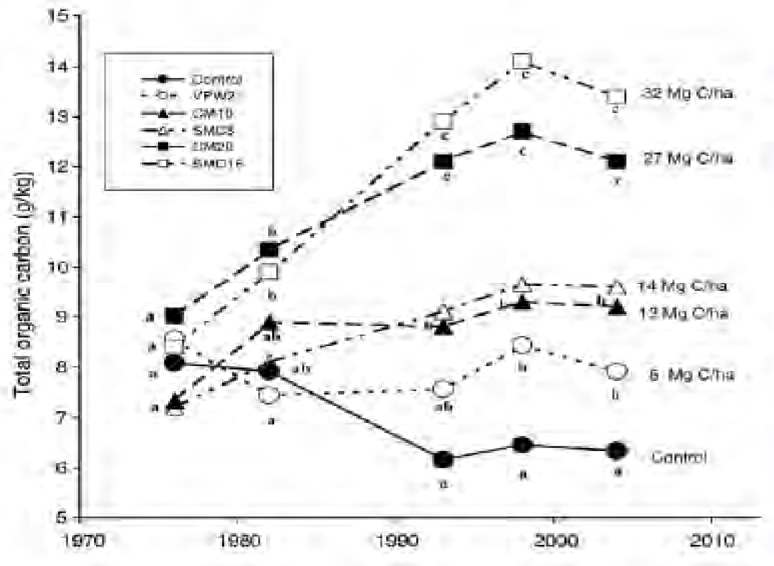


Figure 10: Long-term changes in measured total organic C concentrations in topsoil (0-0.3 m depth) and amounts of sequestered C in different organic treatments of the Chinon experiment (Loire Valley, France). Control: no amendments; VPW2: 2 tons crushed pruned vine-wood (dry wt ha-1 yr-1); CM10: 10 tons cattle manure (fr wt ha-1 yr-1); SMC8: 8 tons spent mushroom compost (fr wt ha-1 yr-1); CM20: 20 tons cattle maure (fr wt ha-1 yr-1); SMC16: 16 tons spent mushroom compost (fr wt ha-1 yr-1). No cover was planted in any of the trials, and all organic matter was tilled into the soil immediately after application. Morlat and Chaussod (2008); Am. J. Enol. Vitic. 59:353-363. Reprinted with permission of the American Journal of Enology and Viticulture.

Agricultural soil amendments such as green and animal manures, compost, or other biomass additions may increase soil C storage. Morlat and Chaussod (2008) performed a long term (28 year) field trial adding different organic amendments to a Cabernet Franc vineyard in the Loire Valley. They observed that the addition of cattle manure (20 tons ha-1 yr-1 fresh weight) and spent mushroom compost (16 tons ha-1 yr-1 fresh weight) roughly doubled the initial total organic C present in the soil at the end of the trial (Figure 10). This corresponded to an increase in soil C of roughly 27-32 Mg C ha-1(roughly 30-35 tons C acre-1). They also observed that the control plot (planted with no interrow cover) lost roughly 20% of its initial C over the same period. The incorporation of crushed and dried pruned vine-wood kept the total organic C constant over the trial. This research was conducted on sandy calcareous soils, and under different climate and soil types, these increases are likely to change. The effectiveness at increasing soil C using commonly available organic amendments under different floor management practices in California should be determined.

Research Need: Research is needed to understand the ability of different organic amendments to increase soil C in vineyards.

The use of Cates from agricultural lime (CaCO3 and/or dolomite (CaMg(CO3)2), an amendment to neutralize soil acidity, can produce large amounts of CO_2, and under certain conditions, lime additions may increase the C content of soils, at least temporarily (Robertson and Grace 2004). Mosier et al. (2006) found that in Colorado, most lime is lost as CO_2, producing 474 kg CO_2 per metric ton of lime (or roughly 130 kg C per metric ton). West and McBride (2005) surveyed U.S. agricultural soils and found that roughly 59 kg C per metric ton limestone was released. In soils where acidity is mostly brought about by organic acid production rather than stronger mineral acids such as nitric acid production from fertilization, loss of lime as CO_2 is much lower, and in some cases liming these soils can increase C storage in the soil as the lime is converted to biCate rather than CO_2 (Robertson et al. 2000, Robertson and Grace 2004, West and McBride 2005). Regardless, this emission source needs to be quantified in California vineyards where lime applications are practiced.

Research Need: Research is needed to examine the effects of agricultural liming in Californian vineyards on soil CO_2 production and C storage.

4.0 Vineyard Nitrous Oxide and Methane Emissions

The literature on non-CO_2 greenhouse gas production in vineyards is very sparse. Few published studies that measured N_20 emissions in Californian vineyards were found. No published studies examined vineyard CH_4 production. Due to the lack of valid vineyard information, non-vineyard data has been included in this report to give some idea of numbers in other agricultural systems, as well as the processes and mechanisms involved. While the mechanisms involved will be the same, data reported here is mostly gathered from annual cropping systems, and their direct utility to perennial crops like grapes is uncertain.

4.1 Irrigation and Farm Equipment

4.1.1 Soil irrigation

The N and water cycles are strongly linked. Denitrification is generally considered to be an anaerobic process where NO_3- is utilized as an electron acceptor in lieu of oxygen (O_2) during electron transport phosphorylation. The concentration of O_2 in water is roughly 0.12% that in air and for this reason O_2 quickly becomes limiting in saturated soils. As mentioned previously (section 2.2.1), methanogenesis, or production of methane, is also strongly controlled by soil O_2 concentration. Thus, wet soil conditions, especially saturated anaerobic soils, are strongly correlated with N_20 and CH_4 production. Nitrification, in contrast, takes place under aerobic soil conditions and is generally considered to be a minor source of N_20. Denitrification is generally thought to represent the largest agricultural source of N_20 (Venterea et al. 2005), and anaerobic conditions are necessary for this process to proceed. Vineyard methanogenesis is not considered to be of major importance. The use of drip irrigation may produce fewer opportunities for large scale anaerobic conditions in vineyards (Hajrasuliha et al. 1998). However, in other systems in different soils, denitrification and N_20 emissions have been observed using this type of irrigation system (e.g. Scheer et al. 2008). Rolston and others (1982) found that soil denitrification rates decreased if irrigation events occurred more infrequently (once every two weeks), relative to more frequent irrigation events (one to three times per week) for the same amounts of applied water and fertilizer. Rolston and colleagues also found that most N lost through denitrification was lost as N_2 rather than N_20. However, this experiment was performed on a fairly sandy soil, and these results may not be indicative of typical vineyard soils. Regardless, their results may indicate that some vineyards which are irrigated rarely may have very low denitrification rates, and therefore very low rates of N_20 emissions.

> **Research Need:** Research is needed on how irrigation strategies and amounts affect vineyard N_20 and CH_4 production in different soils.

4.1.2 Fossil Fuel Combustion

The combustion of fossil fuels used to power some irrigation pumps as well as other farm equipment produces small amounts of CH_4 and N_20. For example, diesel produces 4 g N_20 (1.20 kg CO_2e) gallon-1 (IPCC 2006).

While the overall quantities of these gases produced are small, with respective GWPs of 25 and 298 times that of CO_2, even small amounts can contribute substantial CO_2 equivalent emissions. Quantifying N_20 and CH_4 emissions during combustion is difficult due to variations in equipment maintenance and operating temperatures which are the main factors responsible for their production. For this reason, calculations of fossil fuel derived N_20 and CH_4 are more susceptible to error than CO_2 emissions (IPCC 2006).

4.2 FERTILIZER USE

The use of inorganic fertilizers in agriculture is one of the largest sources of anthropogenic N_20 production (IPCC 2007). Inorganic N can be lost through volatilization of NH_3, N_2, and N_20 following their production via nitrification and denitrification (Mosier et al. 2005).

Table 2: Effects of different environmental factors on N_20 production via denitrification and nitrification. Modified from CEC (2005)

Factor	Effect on N_2O		Notes
	From denitrication	From nitrification	
Low soil oxygen	↑	↑,↓	Complex relationship
High soil moisture	↑	↑,↓	Decreases soil oxygen
Fine soil texture	↑	↑,↓	Decreases soil oxygen
High soil carbon	↑	--	More energy for process to proceed
High quality soil organic matter	↑	--	More nitrogen and available energy
Low soil pH	↑,↓	--	Mixed effects observed
Warm soil Temperature	↑	↑	Higher microbial activity rates
High NH_4^+ availability	--	↑	NH_4^+ substrate for nitrification
High NO_3^- availability	↑	--	NO_3^- substrate for denitrification
Crop type	↑,↓	↑,↓	Proxy for other variables
Soil Tillage	↑,↓	↑	Increases available organic nitrogen

Studies on annual cropping systems have found that N_20 production is closely correlated with anaerobic soil conditions (Bouwman et al. 2002, Lemke et al. 2007), high levels of soil organic matter (Six et al. 2004), high quality soil organic matter as defined by a low C:N ratio (C:N) (Huang et al. 2004), tillage (Jackson et al. 2003, Six et al. 2004, Venterea et al. 2005), fertilizer type (Akiyama et al. 2000, Venterea et al. 2005) as well as method of delivery (Scheer et al. 2008), fertilizer amount (Chadwick et al. 2000), and soil type and pH (Sanchez-Martinez et al. 2008) (See Table 2).

Few studies pertaining to N_20 production in woody perennial agricultural systems were found. Gregory et al. (2005) found that perennial timothy grass crops in eastern Canada lost 1.2-2.2% of applied N as N_20, roughly comparable to many annual cropping systems. However, they also observed from a large data set that perennial crops, including timothy, tended to produce lower levels of N_20 than annual cropping systems. Hajrasuliha and others (1998) observed no evidence that denitrification occurred during the growing season under modified drip emitters (trickle irrigation) in a Thompson Seedless vineyard in the San Joaquin Valley, although there was evidence of NO_3- leaching which may result in indirect production of N_20. Steenwerth and Belina (2008b) researched the effects of vineyard alley floor management on soil N dynamics in a Chardonnay vineyard in Greenfield, California. They found that N_20 production differed between cover cropped areas using Trios (Triticale x Trioscale) and Merced Rye (Secale cereale) and a bare cultivated treatment. The soils under the cover crops had greater annual rates of N_20 production than the bare cultivated soils (Table 3). These N_20 emissions ranged from 1.6 to 3 times less N_20 production than has been observed in annual crops and unfertilized cover crops. However, these values are likely underestimates as they were not measured after precipitation events when large N_20 fluxes are likely to be observed (Christensen et al. 1990). Steenwerth and Belina also observed NO3- leaching rates of roughly 4 to 6% of applied N in the vine row (Steenwerth and Belina in review). The IPCC uses a value of 30% for its calculations of NO_3- leaching, suggesting that indirect California N_20 production should be less than that predicted by the IPCC equation (IPCC 2006; see later this section). Another long-term experiment in a table grape vineyard in Delano found higher rates of N_20 production (Suddick and Smart unpublished data) after fertilization than was observed by Steenwerth and Belina (2008b). Although Steenwerth and Belina (2008b) found that N_20 emissions were correlated with total amounts of inorganic N present in the soil, relationships between soil moisture, temperature, cover crop presence/absence, organic C, and inorganic N pools were not always clear, and substantiate the need for more information on these relationships in Mediterranean climate soils.

Table 3: Annual N_20 emissions from vineyard alley soils under permanent cover and bare cultivation treatments in Greenfield, CA (data from Steenwerth and Belina, 2008b).

	N_2O emissions (g N_2O-N ha^{-1}± S.E.)	Inorganic soil N (mg kg^{-1})_
Bare Cultivation	466.7 ± 39.7	0.88 ± 0.03
Merced Rye	693.9 ± 73.8	0.98 ± 0.05
Trios	565.3 ± 35.8	1.20 ± 0.04

Grapevines do not appear to be a particularly good competitor for N. Vos et al. 2004 found that grapes (Vitis labrusca cv Niagara and Concord) absorbed less than 20% of applied N (68 kg N ha-1), while Williams (1996) also observed that San Joaquin Thompson Seedless had low N uptake efficiency from both furrow (14%) and drip (42%) N applications of 28 kg ha-1. Vos and others (2004) also found that uptake was much lower if N was applied during budbreak. Peacock and others (1989) made similar observations in California and noted that N uptake was highest during July and September in Thompson Seedless grown in the San Joaquin Valley. The general inability to account for N in crop N budgets in part reflects an inability to account for the numerous environmental loss pathways. Agronomists often refer to this as the N loss enigma (Robertson 1997). Low N uptake after fertilizer is applied may lead to relatively rapid movement of NO_3- through the soil profile due to leaching (Hajrasuliha et al. 1998), especially if the fertilizer is applied in the spring when the possibility of precipitation remains high (Peacock et al. 1989). Use of drip irrigation systems may have some impact on the movement of NO_3- through the soil profile. Leaching of NO_3- may result in small amounts of indirect N_20 emissions (IPCC 2006), although this source of N_20 is very uncertain and poorly described. Nonetheless, it must also be kept in mind that N retained by microbial organisms in soils may be absorbed by perennial crops like grape in subsequent years, thus increasing competitiveness and N use efficiency (NUE).

The type of fertilizer applied may affect vineyard N_20 production. Venterea et al. (2005) found that the use of UAN fertilizers produced less N_20 in Michigan maize and soybean fields than broadcast urea or anhydrous ammonia. Furthermore, the behavior of the different fertilizers depended on the tillage system. Hajrasuliha and others (1998) observed that some synthetic N fertilizers (urea in this case) stayed in the rooting zone of San Joaquin Valley Thompson Seedless grape vines for longer periods than NO_3- based fertilizers. Nitrate fertilizers or fertilizers that are quickly nitrified to nitrate can quickly leach out of the soil profile and not be captured by plants (Hajrasuliha et al. 1998). In addition to polluting groundwater, leaching can result in indirect denitrification as NO_3- in the water can be transported offsite, deposited and denitrified into N_2 and N_20 (IPCC 2006). N_20 production is higher in soils with pH > 6 (Feng et al. 2003; Table 2). Soils with more acidic pH levels tended to produce less N_20 through denitrification, and nitrification production of N_20 apparently reaches its highest rates in soils with pH levels between 5 and 8 (Sanchez-Martin et al. 2008). All of these factors should be considered when trying to produce vineyard GHG inventories, and point to the likelihood that such inventories may be site specific.

Research Need: Information is needed about the effects of synthetic and organic fertilizer management on vineyard N_20 production in different regions and soils of California.

Fertilizer applications also impact CH_4 production. Most natural soils are capable of some CH_4 consumption, while agricultural soils can be sinks and sources of CH_4 over the course of the year depending on management (Chan and Parkins 2001). Lee et al. (2006) found that a maize field in Yolo County, California served as a small CH_4 sink. However, application of inorganic N fertilizers has been observed to stop CH_4 consumption in many soils (Chan and Parkin 2001, Johnson et al. 2007, Kahlil and Baggs 2005). Tillage has not been found to significantly impact CH_4 consumption in some agricultural or forested systems (Suwanrawee and Robertson 2005), whereas in another study (Ball et al. 1999) tillage did negatively impact soil CH_4 production and consumption. This is another area in which no information exists for vineyards.

Research Need: Information is needed to address the effects of vineyard management practices on CH_4 production and consumption in vineyard soils

4.3 INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC) ESTIMATES OF AGRICULTURAL N_2O EMISSIONS

In regions where no specific N_20 emissions data have been gathered, as is the case in California agricultural systems, a standard practice when constructing GHG budgets is to follow the 2006 IPCC Guidelines for National GHG Inventories. The standard N_20 inventory practice is to multiply total N load (fertilizer inputs plus soil mineralization pool) by an emissions factor of 1% to estimate N_20 loss for inorganic N fertilizers (IPCC 2006). This estimate represents a mean measure of N_20 emissions using data from many different fertilizer types and application methods across many environments (Stehfest and Boumann 2006). Many agricultural studies have examined soil N_20 production, but most have taken place in annual cropping systems using flood irrigation, furrow irrigation, or dryland systems. A few studies have examined N_20 production using drip irrigation which is more common in California perennial crops. One such study found that cotton grown under drip irrigation in Uzbekistan resulted in the loss of 0.4% to 2.6% of applied N as N_20, which is on average slightly higher than the 1% IPCC emission factor (Scheer et al. 2008) and emphasizes that IPCC emissions factors may not account for the range of conditions and management scenarios influencing N loss. In contrast, Hajrasuliha and others (1998) observed no N_20 production in a San Joaquin Valley vineyard, although this may have been influenced by the length of the measurement interval.

The IPCC uses two different sets of emission factors to estimate total agricultural production of N_20. One set calculates direct emissions, or those produced directly as a result of fertilizer application or soil management. This measurement has an uncertainty of up to ± 120% depending on the crop. The other estimates indirect emissions, or those resulting from leached or volatilized N that will be deposited to produce N_20 somewhere other than the agricultural field from which it originated. The estimate for indirect emissions in particular is uncertain (up to ± 500%), as little data exists in the literature. Furthermore, confidence in the importance of these sources of N_20 is not high, in part due to the difficulty of determining these values in the field. Both equations take into account all N management activities commonly found in agriculture. Activities include additions of synthetic N fertilizers, organic N fertilizers such as animal manures, annual N input from N-fixing plants such as legumes used in cover crops, N content of incorporated crop residues (such as vineyard pruning material), incorporated cover crop biomass returned to the soil during cultivation, and N lost through enhanced soil N mineralization following soil tillage. Nonetheless, each estimate is bounded by error, and thus, a large degree of uncertainty exists. A need that has emerged from work in this area is that region-specific indirect and direct emission factors are needed to produce more valid estimates. Verification of the IPCC emission factors has not been done in California's vineyards. Until such verification exists, using this method to account for N_20 production will result in potentially large errors.

Research Need: Emission factors for specific to regional climatic variation in different California grape growing regions need to be established to increase IPCC assessment accuracy.

4.4 EFFECTS OF VINEYARD BIOMASS AND VINEYARD FLOOR MANAGEMENT ON NITROUS OXIDE EMISSIONS

Nitrous oxide emissions from agricultural soils are affected by many different interacting factors, but water and N fertilizer seem to have the strongest effect. High levels of soil organic matter can enhance N_20 production by providing microbes with a non-limiting energy source (Chadwick et al. 2000; Table 2). Similarly, soils with organic matter having low C:N ratios (labile, easily metabolized organic matter) provide readily utilized substrates for soil microbes. This can increase denitrification rates both by providing more N as well as enhancing microbial growth and oxygen consumption rates, which further enhances denitrification rates by increasing the anaerobic soil volume (Goek and Ottow 1988, Huang et al. 2004). Building soil C through organic fertilizer additions, cover cropping, or no-till practices may have the added consequence of increasing N_20 emissions (Six et al. 2004), at least initially. However, tomatoes produced under both organic and conventional agricultural practices were found to have similar amounts of annual N_20 production, although fluxes of N_20 occurred at different times (Burger et al. 2005). Non-leguminous cover crops have been found to decrease nitrate leaching in annual cropping systems (e.g. Jackson et al. 2004) as well as vineyards. The presence of a vineyard alley cover crop has been found to decrease NO3- leaching (King and Berry 2005) and associated potential indirect N_20 emissions and water quality issues (Bugg and Van Horn 1998), improve vine N status (King and Berry 2005), and potentially decrease the need for synthetic fertilizer applications (Bugg and Van Horn 1998, Patrick et al. 2004, King and Berry 2005). King and Berry (2005) found that the a leguminous Strawberry clover (Trifolium fragiferum L. 'Palestine') cover crop improved grape vine N status in a Sacramento vineyard. They also demonstrated that vines were capable of accessing alley floor soil N. However, the effects of the interactions among vineyard floor, soil, and vine management on vineyard N_20 production is not understood.

> **Research Need:** Research is needed to better understand the interactions among soil physical parameters, soil C, N_20 production, and vineyard floor management in Californian vineyards.

Tillage has been observed to have both strong and variable effects on N_20 production. Tillage disturbs soil aggregates and exposes previously protected organic N to microbial utilization and mineralization (the conversion of organic forms to mineral forms, mainly NH_4+ and NO_3-). Inorganic mineral N then supports additional N_20 production through nitrification and denitrification (Venterea et al. 2005). However, after reviewing available data, Six et al. (2004) concluded that converting to a no-till for annual cropping systems initially increased production of N_20 in both humid and drier environments. In fact, decreases in N_20 production were not realized until no-till management had been practiced for 10 years in humid areas, and 20 years in dry regions. However, at that time, substantial decreases in total GHG production were often observed. Long-term studies of at least 5 to10 years will be required to determine the effects of vineyard floor management practices on GHG production.

Vineyard organic waste (prunings, thinning material, leaves, etc.) deposited on the ground and, in many cases, incorporated into the soil is a source of organic N that might be lost as N_20 as a result of microbial decomposition. Vine biomass has different levels of N. Leaves have the highest N concentration primarily as a result of the large amounts of the RuBisCO enzyme in photosynthetically active tissues. Williams and Smith (1991) analyzed the biomass of a Cabernet Sauvignon vineyard in Napa Valley and found that leaves, stems, and canes contain roughly 2%, 0.35%, and 0.24% N, respectively. It is unlikely there will be substantial differences in N content of these structures based on variety (L.E. Williams personal communication), so it may be possible to use these values in calculating N additions to vineyard soil.

Much of the material described in this section originates from annual cropping systems and, therefore, has an uncertain relationship to woody perennial crops like grapes. However, the processes involved in the production of N_20 and CH_4 will be the same for annual and perennial cropping systems, and this information is valuable in highlighting what needs to be further researched in California's vineyards. Production of N_20 in particular will probably represent a sizeable percentage of total vineyard GHG production when GWP is taken into consideration, and represents one of the most critical research areas.

Research Need: Research on all aspects of N_20 production in vineyards is needed as it represents the area of least understanding in order to generate accurate estimations of vineyard GHG footprints.

5.0 CONCLUSIONS

5.1 Research Needs

Little published data for California viticulture exists that explicitly addresses greenhouse gas production or the potential for C sequestration. More research in all areas outlined in this assessment is needed for an accurate inventory of the greenhouse gas production and consumption of California vineyards. Achieving this goal will require long-term (3-5 years minimum) monitoring of vineyards in order to better constrain inter-annual variation. Long-term research will also be required in order to make accurate estimates of soil C sequestration in these systems. It has been estimated, based on data acquired in C sequestration programs initiated in the Midwest, that more than 10 years of monitoring would be required to constrain emissions, ANPP, and BNPP under diverse management strategies (e.g., Robertson et al. 2000).

There are a number of different approaches that can be taken to address the question of vineyard greenhouse gas footprints. Using the approach that the IPCC uses for global calculations can be a useful first step. Emission factor approaches such as those used by the IPCC do not currently deal with complex interactions caused by changes in management practice and local soil and climate variations, and are therefore driven almost exclusively by N inputs and fossil fuel consumption. These two factors are likely to account for a large part of total vineyard GHG emissions.

Due to the complex and nonlinear interactions between various soil and crop management factors (fertilizer type, irrigation, soil C, rootstock and variety, row management, soil type and pH, etc.), using a process-based model such as DNDC (Li et al. 1997) or DAYCENT (Del Grosso et al. 2001) models will likely produce more reasonable and better constrained estimates in a shorter time frame, as these models already incorporate physical, chemical, and biological C and N cycling mechanisms that would need to be experimentally determined for the development of accurate emissions factors. However, the quality of the products of such models is highly dependent on the quality of the model inputs (e.g., N fertilizer additions). Since most of the important viticultural GHG-related information is not known, even these more complex process-based models will produce lower quality estimates of total GHG emissions. Determining many of the necessary model inputs will require a shorter period of research than for the production of similar quality products using the IPCC model. Until research produces appropriate input information, and/or growers provide researchers with pertinent information (e.g., fossil fuel consumption, type and quantity of N fertilizer additions), the model input values will depend on non-substantiated estimates of N utilization such as that used in recent CEC reports (e.g., CEC 2004). In that report (CEC 2004), vineyards were estimated as being the second largest producer of N_20 among all California Specialty Crops, which based on the relatively small of amounts of N fertilizer typically applied in viticulture compared with other specialty crops, is highly unlikely to be accurate. Regardless of what model is used to calculate emissions, more ground verification data is needed in order to reduce uncertainty caused by nonlinear processes such as emissions behavior following precipitation events, as well as to generate needed model inputs. The research needs listed throughout this report largely will be useful for either modeling approach.

The use of peripheral plantings, habitat restoration, and conservation of C-rich landscapes such as oak woodlands and riparian zones may very well represent the best opportunity for vineyard C sequestration. Research on C storage in these systems, including potential C-storage gains produced via restoration and peripheral plantings, represents an important research area. Additionally, growers and policy-makers may wish to investigate the benefits of adopting policies that reward growers for managing their land in such a way.

5.1.1 Carbon Dioxide

Of the three major biogenic GHGs, CO_2 has been most frequently measured in Californian viticulture. It is also likely to have a very large effect on vineyard GHG footprints, due primarily to fossil fuel combustion. There is some baseline data on soil respiration, overall vine respiration, annual net primary productivity, partitioning of photosynthate within the vine, annual increases in permanent vine structures, and production of CO_2 through fossil fuel combustion. However, much of this data is from Thompson Seedless grapes grown in the San Joaquin Valley or from the Oakville region of Napa Valley.

Various research needs to be done including the determination of varietal differences in production and distribution of photosynthate, even if only to demonstrate few impacts. Effects of different management systems including irrigation and fertilizer types and amounts, row cropping, and the addition of pruning materials to the vineyard floor on soil and vine C sequestration should be investigated. The effects of trellis system and vine management on vine biomass production in different vine organs should be measured. Finally, decomposition studies specific to grapevine biomass should be made to observe how much C is mineralized, and how much might be stored in the soil as affected by floor management.

As mentioned earlier, the practicality of using peripheral plantings and habitat restoration and conservation to contribute to C sequestration should be determined. Research into the C storage of these systems could potentially provide very important information for policy makers as well as modelers and growers.

5.1.2 Nitrous Oxide

Nitrous oxide production likely has a disproportionately significant impact on total vineyard greenhouse gas emissions relative to its size. However, there is little supporting research. Vineyards may not produce as much N_20 as annual crops (Smart et al. 2008, Steenwerth and Belina 2008b). However, nitrous oxide emissions were highly variable in these vineyard studies with coefficients of variation of 100%, similar to those reported by Stehfest and Bouwman (2006) and Bouwman et al. (2002) for annual cropping systems. The IPCC reported an expected uncertainty of -30 to +300 % for N_20 calculations based on use of their emissions factors (IPCC, 2006). The interactions between different vine and soil management systems, soil type, soil pH, cover crop presence/absence, tillage frequency, fertilizer type and application, etc. are complex and difficult to model. More field information is needed to fully characterize vineyard management effects on N_20 production.

Research needs associated with N_20 and vineyards will depend to some degree to what model is used predict N_20 fluxes from soils. For inventories that use the approach from the Guidance for National Greenhouse Gas Inventories (IPCC 2006), basic vineyard N_20 production as a function of fertilizer N input, N mineralization rates, and total biomass N inputs including additions such as pruning and suckering products, must be determined for a reasonable estimate of total N_20 production. While it is very uncertain how important indirect N_20 emissions are in total GHG production, measurements of indirect N_20 production through leaching and volatilization processes should be made in order to create California, and preferably region-specific emission factors. For process-based models, other important factors such as basic measures of nitrification and denitrification rates in California vineyard soils from different regions should be made in addition to the research needs suggested for verifying IPCC emission factors. Determining these values will require both long- and short-term observations and experiments, as N_20 fluxes are ephemeral and extremely spatially heterogeneous, with most N_20 production occurring just after fertilization and irrigation and/or precipitation. Further, there is a high degree of uncertainty with respect to N_20 emissions for different N fertilization strategies such as the use of organic management and cover cropping with leguminous crops to decrease synthetic N application. Finally, quantifying interactions associated with increasing soil C content (C sequestration) and N_20 and CH_4 emissions is very important and must be obtained to fully constrain vineyard GHG footprints.

5.1.3 Methane

Although vineyard methanogenesis is not expected be a significant source of methane, no supporting data exists. Basic research on CH_4 production and consumption in vineyard soils should be done. In particular, the effects of different types of vineyard management on CH_4 production and consumption should be investigated. Different irrigation, tillage, and fertilizer systems may have important impacts. Location (e.g., Sacramento Delta) and vineyard landscape position (e.g., slope, toe-slope, valley floor, sites with high water tables that represent potential sites of methanogenesis) should be examined. Additionally, vineyards may represent a net sink for methane. However, due to the expected small impact of CH_4 on vineyard GHG footprints, research in this area is lower priority.

5.2 SUMMARY

The objectives of this report were: 1) generate a literature review to illustrate what is known about Californian vineyard GHG production and sequestration potential, and 2) create a roadmap to assist in prioritizing further research. This paper has summarized the available scientific literature related to emissions of GHGs in vineyards and potential vineyard C sequestration in vines and soil. Published relevant research was very limited, especially in Californian systems. To increase the utility of this paper, scientific literature from annual cropping systems was brought to bear upon several key issues and to illustrate processes involved in the production of biogenic GHGs, particularly the gases N_20 and CH_4 for which little to no published data was found. This information was also used to highlight areas in which more research is needed to adequately characterize the impacts of California's vineyards on the production of GHGs and on C sequestration.

6. ACKNOWLEDGEMENTS

The authors and the California Sustainable Winegrowing Alliance and other project partners gratefully acknowledge the comprehensive comments of Dr. Hans Shultz, Institut für Weinbau und Rebenzüchtung, Fachgebiet Weinbau, Forschungsanstalt, D-65366 Geisenheim, Germany, Mr. Hal Huffsmith of Trinchero Family Estates, Dr. Joe Browde and Andrew Arnold of SureHarvest, and Allison Jordan and Lisa Francioni of the California Sustainable Winegrowing Alliance who greatly improved the content and clarity of this report.

7.0 REFERENCES:

Akiyama, H., Tsuruta, H., Watanabe, T. (2000) N_20 and NO emissions from soils alter application of different chemical fertilizers. Chemosphere- Global Change Science 2: 313-320.

Amthor, J.S. (1989) Respiration and Crop Productivity. Springer-Verlag, New York.
Amundson, R., Stern, L., Baisden, T., and Wang, Y. (1998) The isotopic composition of soil and soil-respired CO_2. Geoderma 82: 83-114.

Araujo, F., and Williams, L.E. (1988) Dry matter and nitrogen partitioning and root growth of young field-grown Thompson Seedless grapevines. Vitis 27: 21-32.

Archer, E., and Strauss, H.C. (1985) Effect of plant density on root distribution of three-year-old grafted 99 Richter grapevines. South African Journal of Enology and Viticulture 6: 25-30.

Archer, E., and Strauss, H.C. (1991) The effect of vine spacing on the vegetative and reproductive performance of Vitis vinifera L. (cv. Pinot noir). South African Journal of Ecology and Viticulture 12: 70-76.

Ball, B.C., Scott, A., Parker, J.P. (1999) Field N_20, CO_2, and CH_4 fluxes in relation to tillage, compaction, and soil quality in Scotland. Soil Tillage Research 53: 29-39.

Bauerle, T.L., Eissenstat, D.M., Granett, J., Gardner, D.M., Smart, D.R. (2007) Consequences of insect herbivory on grape fine root systems with different growth rates. Plant, Cell and Environment 30: 786-795.

Bauerle, T., Smart, D.R., Bauerle, W., Stockert, C.M. and Eissenstat, D.M. (2008) Root foraging in response to heterogeneous soil moisture in two grapevines that differ in potential growth rate. New Phytologist 179:857-866.

Bouwman, A.F., Boumans, L.J.M., Batjes, N.H. (2002) Emissions of N_20 and NO from fertilized fields: summary of available measurement data. Global Biogeochemical Cycles 16: 1058, doi:10.1029/2001GB001811.

Bugg, R.L., and M. Van Horn. 1998. Ecological soil management and soil fauna: best practices in California vineyards. Pp. 23-34 in: R. Hamilton, L. Tassie, and P. Hayes (eds). Proceedings of the Viticulture Seminar: Viticultural Best Practice, Mildura Arts Centre, 1 August, 1997, Mildura, Victoria, Australia. Australian Society For Viticulture And Oenology, Inc., Adelaide, South Australia, Australia.

Burger, M., L.E. Jackson, E.J. Lundquist, D.T. Louie, R.L. Miller, D.R. Rolston, and K.M. Scow (2005) Microbial responses and nitrous oxide emissions during wetting and drying of organically and conventionally managed soil under tomatoes. Biology and Fertility of Soils 42:109-118.

Butterbach-Bahl, K. et al.. (2004) Quantifying the regional source strength of N-trace gases across agricultural and forest ecosystems with process based models. Plant and Soil 260:311-329.

Calderon, F.J., and Jackson, L.E (2002) Rototilling, disking, and subsequent irrigation: effects on soil nitrogen dynamics, microbial biomass, and carbon dioxide efflux. Journal of Environmental Quality 31: 752-758.

CEC (2004) California Energy Commission. Quantifying carbon dynamics and greenhouse gas emissions in agricultural soils of California: a scoping study. CEC-500-04-038.

CEC(2005) California Energy Commission. Research roadmaps for greenhouse gas inventory methods. CEC-500-2005-097.

CEC (2006a) California Energy Commission. Climate change: challenges and solutions for California agricultural landscapes. CEC-500-2005-189-SF.

CEC (2006b) California Energy Commission. Inventory of California greenhouse gas emissions and sinks: 1990 – 2004. CEC-600-2006-013-S.

California Sustainable Winegrowing Alliance. (2009) California Wine Community Sustainability Report Executive Summary.

Carlisle, E.A., Steenwerth, K.L, and Smart, D.R. (2006) Effects of land use on soil respiration: conversion of oak woodlands to vineyards. Journal of Environmental Quality 35: 1396-1404.

Chadwick, D., Pain, B.F., and Brookeman, S.K.E. (2000) Nitrous oxide and methane emissions following application of animal manure to grassland. Journal of Environmental Quality 16: 786-797.

Chan, A.S.K., and Parkin, T.B. (2001) Methane oxidation and production activity in soils from natural and agricultural ecosystems. Journal of Environmental Quality 30: 1896-1903.

Christensen, S., Simkins, S., Tiedje, J.M. (1990) Temporal patterns of soil denitrification; their stability and causes. Soil Science Society of America Journal 54: 1614–1618.

Christensen, L.P. (2000) Vine Pruning In Raisin Production Manual ed. L.P. Christensen. University of California Agriculture & Natural Resources Communications Services.

Clingeleffer, P.R., Krake, L.R. (1992) Response of Cabernet fran grapevines to minimal pruning and virus infection. American Journal of Enology and Viticulture 43: 31-37.

Comas, L.H., Anderson, L.J., Dunst, R.M., Lakso, A.N., and Eissenstat, D.M. (2005) Canopy and environmental control of root dynamics in a long-term study of Concord grape. New Phytologist 167: 829-840.

Conrad, R., Microbiological and biochemical background of production and consumption NO and N_20 in soil, In Trace Gas Exchange In Forest Ecosystems, H. R. Gasche, Editor. 2002, Spinger: New York. p. 3-33.

Dalal, R.C., Wang, W., Robertson, G.P., Parton, W.J. (2003) Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Australian Journal of Soil Research 41: 165-195.

Davidson, E.A. (1991) Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes, J.E. Rogers and W.B. Whitman, Editors, American Society for Microbiology, Washington, D. C. p. 219-235.

Davidson, E.A. et al.. (2000) Testing a conceptual model of soil emissions of nitrous and nitric oxides. Bioscience 50: 667-680.

Del Grosso, S. J., W. J. Parton et al.. (2001) Simulated effects of land use, soil texture and precipitation on N gas emissions using DAYCENT. In Nitrogen in the Environment:
Sources, Problems and Management. R. F. Follett and J. L. Hatfield. Amsterdam,
Netherlands: Elsevier. 413–432.

Desjardins, R.L., Smith, W., Grant, B., Campbell, C., and Riznek, R (2005) Management strategies to sequester carbon in agricultural soils and to mitigate greenhouse gas emissions. Climatic Change 70: 283-297.

Feng, K., Feng, Y., and Hutsch, B.W. (2003) Nitrous oxide emission as affected by liming and acidic mineral soil used for arable agriculture. Nutrient Cycling in Agroecosystems 67: 283-292.

Firestone, M. and Davidson, E. (1989) Microbiological basis of NO and N_20 production and consumption in soil. In Exchange of Trace Gases Between the Terrestial Ecosystem and the Atmosphere., M.O. Andreae and D.S. Shimel, Editors. 1989, John Wiley & Sons: New York. p. 7-21.

Frayer, W.E., Peters, D.D., and Pywell, H.R. (1989) Wetlands of the California Central Valley--Status and Trends--1939 to mid 1980's: Portland, Oreg., U.S. Fish and Wildlife Service, 28 p.

Goek, M., and Ottow, J.C.G. (1988) Effect of cellulose and straw incorporation in soil on total denitrification and nitrogen immobilization at initially aerobic and permanent anaerobic conditions. Biology and.Fertility of Soils 5:317–322.

Grandy, A.S., Loecke, T.D., Parr, S., Robertson, G.P. (2006) long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. Journal of Environmental Quality 35: 1487-1495.

Gregorich, E.G., Rochette, P., Vanden Bygaart, A.J., Angers, D.A. (2005). Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil and Tillage Research 83: 53-72.

Hajrasuliha, S., Rolston, D.E., Louie, D.T. (1998) Fate of 15N fertilizer applied to trickle-irrigated grapevines. American Journal of Enology and Viticulture 49: 191-198.

Huang, Y., Zou, J., Zheng, X., Wang, Y., Xu, X. (2004) Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios. Soil Biology & Biochemistry 36: 973-981.

Hutchinson, J.J., Campbell, C.A., Desjardins, R.L. (2007) Some perspectives on carbon sequestration in agriculture. Agricultural and Forest Meteorology 142: 288-302.

IPCC (2006) Intergovernmental Panel on Climate Change. Guidelines for National Greenhouse Gas Inventories. Prepared by the Greenhouse Gas Inventories Programme, S.Eggelston, L. Buendia, K. Miwa, T. Ngara, K. Tanabe. Eds. Institute for Global Environmental Strategies (IGES), Japan.

IPCC (2007) Intergovernmental Panel on Climate Change WGI, Fourth Assessment Report, Climate Change 2007: The Physical Science Basis. Summary for Policymakers. IPCC Secretariat, c/o WMO, 7bis, Avenue de la Paix, C.P.N. 2300, 1211 Geneva 2, Switzerland.

Jacinthe, P.A., R. Lal, L.B. Owens, and D.L. Hothem. (2004) Transport of labile carbon in runoff as affected by land use and rainfall characteristics. Soil and Tillage Research 77: 111-123

Jackson, L.E., Calderon, F.J., Steenwerth, K.L., Show, K.M., Rolston, D.E. (2003) Responses of soil microbial processes and community structure to tillage events and implications for soil quality. Geoderma 114: 305-307.

Jackson, L.E. (2000) Fates and losses of nitrogen from a nitrogen-15 labeled cover crop in an intensively managed vegetable system. Soil Science Society of America Journal 64: 1404-1412.

Jackson, L.E., I. Ramirez, R. Yokota, S.A. Fennimore, S.T. Koike, D. Henderson, W.E. Chaney, F.J. Calderón, and K. Klonsky (2004) On-farm assessment of organic matter and tillage management on vegetable yield, soil, weeds, pests, and economics in California. Agriculture, Ecosystems, and Environment 103:443-463.

Johnson, J.M.F., Franzluebbers, A.J., Weyer, S.L, and Reicosky, D.C.(2007) Agricultural opportunities to mitigate greenhouse gas emissions. Environmental Pollution 150: 107-124.

Kesik, M., et al. (2006) Future scenarios of N_20 and NO emissions from European forest soils. Journal of Geophysical Research 111:222-238.

Khalil, M.I., Baggs, E.M. (2005) CH_4 oxidation and N_20 emissions at varied soil water-filled pore spaces and headspace CH_4 concentrations. Soil Biology & Biochemistry 37: 1785-1794.

King, A.P., and Berry, A.M. (2005) Vineyard δ15N, nitrogen, and water status in perennial clover and bunch grass cover crop systems of California's central valley. Agriculture, Ecosystems, & Environment 109: 262-272.

Koga, N., Sawamoto, T., Tsuruta, H. (2006) Life cycle inventory-based análisis of greenhouse gas emissions from arable land farming systems in Hokkaido, northern Japan. Soil Science and Plant Nutrition. 52: 564-574.

Kroodsma, D.A., Field, C.B. (2006) Carbon sequestration in California agriculture, 1980-2000.

Lal, R. (2002) Soil carbon dynamics in cropland and rangeland. Environmental Pollution 116: 353-362.

Lal, R. (2004a) Carbon sequestration in soils of central Asia. Land Degradation and Development 15: 563-572.

Lal, R. (2004b) Soil carbon sequestration impacts on global climate change and food security. Science 304: 1623-1627.

Lal, R. (2007) Carbon management in agricultural soils. Mitigation and Adaptation
Strategies for Global Change 12: 303-322.

Lal, R., Kimble, J.M., Follett, R.F., Cole, C.V. (1998) Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Ann Arbor Press, An Imprint of Sleeping Bear Press, Chelsea, Michigan.

Lee, J., Six, J., King, A.P., van Kessel, C., Rolston, D.E. (2006) Tillage and field scale controls on greenhouse gas emissions. Journal of Environmental Quality 35: 714-725.

Lemke, R.L., Zhong, Z., Campbell, C.A., Zentner, R. (2007) Can pulse crops play a role in mitigating greenhouse gases from North American agriculture? Agronomy Journal 99: 1719-1725.

Li, C., Frolking, S., Crocker, G.J., Grace, P.R., Klir, J., Korchens, M., Poulton, P.R., (1997) Simulating trends in soil organic carbon in long-term experiments using the DNDC model. Geoderma 81: 45–60.

McKenry, M.V. (1984). Grape root phenology relative to control of parasitic nematodes. American Journal of Enology and Viticulture 35:206-221.

Minoshima, H., Jackson, L.E., Cavagnaro, T.R., Sánchez-Moreno, S., Ferris, H., Temple,S.R., and Mitchell, J.P.(2007) Soil food webs and carbon dynamics in response to conservation tillage in legume rotations in California. Soil Science Society of America Journal 71:952-963.

Morano, L. (1995). An analysis of Vitis species and rootstock crosses: Vineyard root distribution patterns, root growth and metabolic response to flooding in the greenhouse and associated soil and plant communities of wild vines. Department of Viticulture & Enology, U.C. Davis: 157 pp.

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

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

Morlat, R., and Chaussod, R. (2008) Long-term additions of organic amdendment in a loire valley vineyard. I. Effects on properties of a calcareous sandy soil. American Journal of Enology and Viticulture 59: 353-363.

Morris, D.R, Gilbert, R.A., Reicosky, D.C., and Gesch, R.W. (2004) Oxidation potentials of soil organic matter in histosols under different tillage methods. Soil Science Society of America Journal 68: 817-826.

Munaluna, F., and Meincken, M. (2008) An evaluation of South African fuelwood with regards to calorific value and environmental impact. Biomass and Bioenergy 33: 415-420.

Mosier, A.R., Halvorson, A.D., Peterson, G.A., Robertson, G.P., Sherrod, L. (2005) Measurement of net global warming potential in three agroecosystems. Nutrient Cycling in Agroecosystems 72: 67-76.

Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu, X.J. (2006) Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. Journal of Environmental Quality 35: 1584-1598.

Mullins, M.G., Bouquet, A., Williams, L.E. (1992) Biology of the grapevine. Cambridge University Press, Cambridge.
Pacala, S. and R. Socolow (2004) Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. Science 305: 968 – 972.

Patrick, A.E., Smith, R., Keck, K., and Berry, A. (2004) Grapevine uptake of 15N-labeled nitrogen derived from a winter-annual leguminous cover-crop mix. American Journal of Enology and Viticulture 55: 187-190.

Paul, E.A., and Clark, F.E. (1996) Soil Microbiology and Biochemistry, Second Edition. Academic Press, San Diego.

Peacock, W.L., Christensen, L.P., and Broadbent, F.E. (1989) Uptake, storage, and utilization of soil-applied nitrogen by Thompson Seedless as affected by time of application. American Journal of Enology and Viticulture 40: 16-20.

Peacock, W.L., Christensen, L.P., Hirshfelt, D.J. (1991) Influence of timing of nitrogen fertilizer application on grapevines in the San Joaquin Valley. American Journal of Enology and Viticulture. 42: 322-326.

Reicosky, D.C., and Archer, D.W. (2007) Moldboard plow tillage depth and short-term carbon dioxide release. Soil and Tillage Research 94: 109-121.

Reicosky, D.C., Dugas, W.A., Torbert, H.A. (1997) Tillage-induced soil carbon loss from different cropping systems. Soil & Tillage Research 41: 105-118.

Reicosky, D.C., and Lindstrom, M.J. (1993) Fall tillage method: effect on short-term carbon dioxide flux from soil. Agronomy Journal 85: 1237-1243.

Robertson, G.P. and Grace, P.R. (2004) Greenhouse gas fluxes in tropical and temperate agriculture: the need for a full-cost accounting of global warming potentials. Environment, Development and Sustainability 6: 51-63.

Robertson, G.P., Paul, E.A., Harwood, R.R. (2000). Greenhouse gases in intensive agriculture: contributions of individual gases to radiative forcing of the atmosphere. Science 289: 1922-1925.

Rolston, D.E., Sharpley, A.N., Toy, D.N., and Broadbent, F.E. (1982) Field measurement of denitrification 3: rates during irrigation cycles. Soil Science Society of America Journal 46: 289-296.

Saayman, D.D. Huyssteen, L.V. (1980) Soil preparation studiets. I. The effect of depth and method of soil preparation and of organic material on the performance of Vitis vinifera (var Chenin blanc) on Hutton/Sterkspruit soil. South African Journal of Viticulture 1: 107-121.

Sanchez-Martin, L., Vallejo, A., Dick, J., Skiba, U.M. (2008) The influence of soluble carbon and fertilizer nitrogen on nitric oxide and nitrous oxide emissions from two contrasting agricultural soils. Soil Biology & Biochemistry. 40: 141-151.

Scheer, C., Wassmann, R., Kienzler, K., Ibragimov, N., Eschanov, R. (2008) Nitrous oxide emissions from fertilized, irrigated cotton (Gossypium hirsutum L.) in the Aral Sea Basin, Uzbekistan: influence of nitrogen applications and irrigation practices. Soil Biology & Biochemistry 40: 290-301.

Schlesinger, W.H. (1997) Biogeochemistry. An Analysis of Global Change. Academic Press, San Diego

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K. (2004). The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biology 10: 155-160.

Smart, D.R., Schwass, E., Lakso, A., and Morano, L. (2006) Grapevine rooting patterns: a comprehensive analysis and a review. American Journal of Enology and Viticulture 57: 89-104.

Smith, R., L. Bettiga, M. Cahn, K. Baumgartner, L E. Jackson, and T. Bensen (2008) Vineyard floor management effects on soil properties, soil moisture, sediment loss, plant nutrition and grape yield and quality. California Agriculture 62:184-190.

Steenwerth, K., Belina, K.M.(2008a) Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem, Applied Soil Ecology 40: 359-369.

Steenwerth, K., Belina, K.M. (2008b) Cover crops and cultivation: Impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem, Applied Soil Ecology 40: 370-380.

Stehfest, E., and Bouwman, L. (2006) N_20 and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutrient Cycling in Agroecosystems 74: 207-228.

Suwanwaree, P., Robertson, G.P. (2005) Methane oxidation in forest, successional, and no-till agricultural ecosystems: effects of nitrogen and disturbance. Soil Science Society of America Journal 69: 1722-1729.

Tate, R.L. III (1980) Microbial oxidation of organic matter of Histosols. Advances in Microbial Ecology 4: 169-201.

Vasconcelos, M.C., and Castagnoli, S. (2000) Leaf Canopo structure and vine performance. American Journal of Enology and Viticulture 51: 390-396.

Venterea, R.T., Burger, M., Spokas, K.A. (2005) Nitrogen oxide and methane emissions under varying tillage and fertilizer management. Journal of Environmental Quality 34: 1467-1477.

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H., Tilman, D.G. (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecological Applications 7:737-750.

Vos, R.J., Zabada., T.J., Hanson, E.J. (2004) Effect of nitrogen application timing on N uptake by Vitis labrusca in a short-season region. American Journal of Enology and Viticulture 55: 246-252.

Wermelinger, B ., Baumgartner, J., Gutierrez, A.P. (1991) A demographic model of assimilation and allocation of carbon and nitrogen in grapevines. Ecological Modeling 53: 1-26.

West, T.O., and McBride, A.C. (2005) The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions. Agriculture, Ecosystems and Environment 108: 145-154.

West, T.O., and Post, W.M. (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal 66: 1930-1946.

Williams, L.E. (1996) Grape. in Photoassimilate distribution in plants and crops: source-sink relationships ed Zamski, E., and Schaffer, A.A. Marcel-Dekker, Inc. New York.

Williams, L.E. (2000) Growth and Development of Grapevines in Raisin Production Manual ed. L.P. Christensen. University of California Agriculture & Natural Resources Communications Services.

Williams, L.E., and P.J. Biscay (1991) Partitioning of dry weight, nitrogen, and potassium in Cabernet Sauvignon grapevines from anthesis until harvest. American Journal of Enology and Viticulture. 42: 113-117.

Williams, L.E., and M.A. Matthews (1990) Grapevine. In Irrigation of agricultural crops (ed. B.J. Stewart and D.R. Nielsen), pp.1019-1055. Agronomy Monographs, ASA-CSSA-SSSA, Madison, WI.

Williams, L.E., and R.J. Smith (1991) Effect of rootstock on the partitioning of dry weight, nitrogen and potassium, and root distribution of Cabernet Sauvignon grapevines. American Journal of Enology and Viticulture. 42:118-122.

Williams, D.W., Williams, L.E., Barnett, W.W., Kelley, K.M., McKenry, M.V. (1985) Validation of a model for the growth and development of the Thompson Seedless grapevine I. Vegetative growth and fruit yield. American Journal of Enology and Viticulture 36: 275-282.

Wood, S., and Cowie, A. (2004) A review of greenhouse gas emission factors for fertilizer production. IAE Bioenergy Task 38.

Woodwell, G.M. (1983) Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecological Monographs 53: 235-262.