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Greenhouse Gas Mitigation Opportunities in California Agriculture

Review of California Cropland Emissions and Mitigation Potential

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ABSTRACT

Agriculture contributes approximately 7% of California's total greenhouse gas (GHG) emissions; less than 3% of the state total comes from croplands. Efforts to reduce California's agricultural GHG emissions from croplands will require sound information regarding how specific agricultural management practices impact those emissions over the landscape. A review of agricultural literature was conducted on studies that quantified GHG emissions in California annual and perennial croplands. This report reviews the available scientific literature relevant to GHG emissions from California croplands and quantitatively assesses the biophysical potential of various agricultural mitigation strategies relevant to California cropping systems. A total of 20 studies were identified, relating to 10 specific management practices in California croplands. Where possible, data from these studies were used to estimate the biophysical mitigation potential of various agricultural management practices. This work revealed that 3 of the 10 management practices—farmland preservation, expansion of perennial crops, and manipulation of nitrogen fertilizer rates—have high to medium relative mitigation potential. However, reliably estimating the biophysical mitigation potential of these practices is not possible at this time due to many uncertainties and lack of information. Relatively few field studies conducted in California rigorously examine GHG emissions from changes in agricultural management activities and practices. Thus, more research is needed to inform future management and policy alternatives.

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PREFACE

In January 2012, Duke University's Nicholas Institute for Environmental Policy Solutions published *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature, third edition*, which presents a side-by-side comparison of the biophysical greenhouse gas (GHG) mitigation potential of 42 agricultural land management activities based on the most recent data from field experiments, modeling, and expert review. This report is intended as an addendum. It documents the biophysical GHG mitigation potential of California's cropping systems for the purpose of examining land management practices and activities relevant to California.

INTRODUCTION

In 2009, the state of California emitted a total of 457 Tg CO_2e across all economic sectors (CARB 2011). Of this total, California's agriculture sector emitted 32.1 Tg CO_2e, or 7.0% of the state's total. The relative contribution of greenhouse gases from California agriculture differs substantially from that of the total emissions from the state. Most notably, nitrous oxide emissions only make up 3% of total emissions across all sectors but up 33% of emissions from the agricultural sector (Table 1). Similarly, carbon dioxide accounts for a smaller proportion of emissions in agriculture (9%) than it does across all sectors of California (86%).

Table 1. California Agricultural Emissions by Gas in 2009 and the Ten-Year Average

	2009	2000-2009 Average
Greenhouse Gas	**Tg CO_2e (% of Total)**	**Tg CO_2e**
CH_4	18.7 (58%)	17.1
CO_2	2.8 (9%)	4.3
N_2O	10.6 (33%)	10.4
Total	**32.1**	**31.8**

Source: CARB (2011).

Emissions from California agriculture come from a variety of sources, but three sources account for nearly 90% of total emissions (Table 2): manure management (32.2%), enteric fermentation (fermentation that takes place in the digestive system of animals; 28.9%), and agricultural soil management (the practice of utilizing fertilizers, soil amendments, and irrigation to optimize crop production; 28.1%). These three sources and energy use from agricultural activities (8.2%) make up over 97% of emissions from agriculture (CARB 2011).

Table 2. California Agricultural Emissions by Source in 2009

Agricultural Source	2009 Emissions (Tg CO_2e)	Percentage of Total
Manure management	10.34	32.2
Enteric fermentation	9.28	28.9
Soil management	9.02	28.1
Energy use	2.63	8.2
Rice cultivation[a]	0.58	1.8
Histosol cultivation[b]	0.16	0.5
Residue burning	0.06	0.2

Source: CARB 2011.
[a] Primarily methane emissions
[b] Primarily N_2O emissions combined with loss of soil C as CO_2

Objectives

This report presents a review of scientific literature examining greenhouse gas (GHG) emissions from California's annual and perennial cropping systems. These emissions sources represent less than 3% of the state's total GHG emissions and approximately 39% of California's agricultural emissions. This California-based literature review provides most of the data used in this report to estimate the biophysical mitigation potential of various agricultural management practices.

Default Emissions Factors Used by CARB and IPCC

Statewide estimates of N_2O emissions from agricultural soils are based on emissions inventory guidelines developed by the International Panel on Climate Change (IPCC 2006). At present, California uses default emission factors (EFs) that are derived from a global dataset of field experiments covering a wide range of crops, environments, water management regimes, and N management practices (Bouwman, Boumans, and Batjes 2002a; Bouwman, Boumans, and Batjes 2002b; Stehfest and Bouwman 2006). The IPCC's default EFs for N_2O are defined as the proportion of applied N (from synthetic fertilizer, organic fertilizer, manure, and N-fixing crops) that is directly and indirectly emitted as N_2O. Direct emissions are those that occur directly from the field where the N is applied. Indirect emissions are those that occur elsewhere in the environment following runoff into surface water, leaching of nitrate-N or volatilization, or emissions of other gaseous N forms (e.g., NOx or NH_3). The EF for direct N_2O emissions from typical agricultural soils is 1% of applied N; an additional 0.35–0.45% emitted indirectly following runoff, leaching, and volatilization (IPCC 2006).

A high degree of uncertainty is associated with the IPCC's default EFs due to natural variation in rates of N_2O flux measured across a wide range of environmental conditions and cropping practices (Table 3; IPCC 2006). For example, the uncertainty range for the EF for N fertilizers applied to agricultural soils is 0.003–0.03 kg N_2O–N per kg N applied (Table 3). The uncertainty range for direct and indirect N_2O emissions thus exceeds 100%. This uncertainty restricts the precision of California's statewide GHG inventory. Soil types and regional climates further influence emissions. Consequently, data from local to regional agricultural experiments is needed to develop California-specific EFs and to calibrate process-based biogeochemical models (e.g., DAYECENT, DNDC, COMET-VR) that can help to reduce the uncertainty and improve the precision of N_2O emissions estimates for various California cropping systems (Olander et al. 2011).

Table 3. Default Values and Uncertainty Range for IPCC Emissions Factors Used to Calculate Direct and Indirect N_2O Emissions from Agricultural Soils in the California Greenhouse Gas Emissions Inventory

Emission Factor Description	EF Default Value	Uncertainty Range
Direct N_2O emissions		
Proportion of N applied to soils via synthetic fertilizer, organic fertilizer, manure, N-fixing crops that is emitted as N_2O	0.01	0.003–0.03
Proportion of N deposited by livestock on pastures, rangeland, and paddocks that is emitted as N_2O	0.02	0.007–0.06
N emitted as N_2O per unit area of cultivated organic soils (kg N per ha)	8	2–24
Indirect N_2O emissions		
Fraction of synthetic fertilizer N that volatilizes	0.1	0.03–0.3
Fraction of organic fertilizer and manure N that volatilizes	0.2	0.05–0.5
Leaching rate: Fraction of applied N lost to leaching and runoff	0.3	0.1–0.8
Proportion of N volatilized and re-deposited on soils that is emitted as N_2O	0.01	0.002–0.05
Proportion of N lost to leaching and runoff that is emitted as N_2O	0.0075	0.0005–0.025

Source: IPCC (2006).

BACKGROUND AND APPROACH

Methods

This report examines the available scientific literature with the goal of evaluating the biophysical mitigation potential of various crop management practices relevant to California agriculture. Its geographic focus is field and modeled studies conducted within California. Published studies in peer-reviewed literature were the primary basis for the review; other sources of information were theses, dissertations, and government reports.

In *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States: A Synthesis of the Literature*, Eagle et al. (2012) examined biophysical mitigation potential of 42 agricultural land management activities. This report focuses on a subset of those crop management activities that are the most relevant to California agriculture. For any given management activity, the approach was to determine the management treatment considered the most widely practiced by growers. Within each reviewed activity, the “standard” or “conventional” management practice was treated as the baseline emissions value. The effects of alternative management practices on emissions were then assessed relative to this baseline conventional treatment—for example, conventional tillage, which is widely practiced in California’s annual systems. These comparisons produced a biophysical mitigation potential, defined as the difference between the control treatment and the alternative management activity. In other words, positive values reflect a net increase in mitigation potential, as GHG emissions are reduced relative to the control. Likewise, negative values reflect a net decrease in mitigation potential, where emissions are increased relative to the control.

Global Warming Potential

In this assessment of biophysical mitigation potential, annual emissions reductions for CO_2, CH_4, and N_2O are expressed in tons of CO_2 equivalents per hectare (i.e., t CO_2e ha^{-1} yr^{-1}), which is equivalent to Mg CO_2e ha^{-1} yr^{-1}. The statewide GHG inventory conducted by the California Air Resources Board uses the 100-year global warming potential (GWP) values from the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report to standardize CH_4 and N_2O emissions in CO_2 equivalents (IPCC 1995; Table 4). This report follows this convention so that its mitigation potential estimates are consistent with California inventory methods. However, it should be noted that the IPCC has revised its GWP values for CH_4 and N_2O in its fourth and fifth assessment reports (IPCC 2007, 2013). If California eventually adopts the IPCC’s revised GWP values, this report’s mitigation potential estimates would need to be revised accordingly.

Table 4. IPCC 100-year Global Warming Potential Values

	100-Year Global Warming Potential		
Gas	**Second Assessment Report**	**Fourth Assessment Report**	**Fifth Assessment Report**
CO_2	1	1	1
CH_4	21	25	34
N_2O	310	298	298

Sources: IPCC (2006, 2013).

LITERATURE REVIEW

Emissions Benefits of Farmland Preservation

Changing land use patterns are known to have important effects on GHG emissions both globally and locally. In regions where large-scale conversion of native grasslands, wetlands, and forests to agricultural land uses is occurring, the loss of C stored in vegetation and soil can be a significant source of GHG emissions (Fearnside 2000; IPCC 2007). However, in California, conversion of native habitat to agriculture has not been the predominant land use trend in recent decades. Between 1984 and 2008, more than 1.3 million acres of farm and grazing lands in California are estimated to have been taken out of agricultural production (FMMP 2008). Approximately 859,000 acres of irrigated farmland and 458,000 acres of grazing and non-irrigated farmland were lost over this period; more than 1 million acres statewide were converted to urban land uses (FMMP 2008). Low-density rural housing, habitat restoration, and mining account for the remaining farmland losses statewide.

How do these shifts in land area from agricultural to urban land uses affect California's overall GHG emissions at the landscape level? A recent study in California has highlighted the importance of farmland preservation as a key strategy for stabilizing and reducing California's future GHG emissions across multiple economic sectors. Haden et al. (2013) conducted an inventory of agricultural emissions from Yolo County for 1990 and 2008 and found that emissions had declined by approximately 10%. This reduction in agricultural emissions was due largely to an 8% loss of irrigated cropland acreage (Table 5). They also estimated that average emissions per unit area in Yolo County were about 70 times higher for urban land uses (152.0 t CO_2e ha^{-1} yr^{-1}) relative to irrigated cropland (1.99-2.19 t CO_2e ha^{-1} yr^{-1}) (Haden et al. 2013). Included in the estimate of urban emissions in Yolo County are those associated with residential and industrial energy use and transportation. Between 1992 and 2008, roughly 3,000 ha of cropland in Yolo County were converted to urban land uses with notably higher emissions per unit area (FMMP 2013). The 150 t CO_2e ha^{-1} yr^{-1} difference between urban and cropland emissions does not reflect mitigation potential as defined in this report unless urban land were converted back to farmland, which is unlikely. Rather, it emphasizes the important role of farmland preservation in curbing future emissions from urban sprawl. As such, Haden et al. (2013) argue that aligning farmland preservation efforts with new statewide and regional development policies (SB 375) may be among the most important steps that state agencies can take to achieve the mitigation targets set by AB 32.

Table 5. Land Area and Average Emissions Rates for Urban Land Uses and Irrigated Cropland in Yolo County

	Land Area (ha)		Average Emissions Rate (t CO2e ha^{-1} yr^{-1})	
Land-use Category	**1990**	**2008**	**1990**	**2008**
Urban land uses	9,078	12,072	152.0	Data not available
Irrigated cropland	139,407	131,439	2.19	1.99

Source: Adapted from Haden et al. (2013).

Despite the potential for GHG mitigation through farmland preservation, more research is needed to develop better regional estimates of average rates of emissions per unit area across a wide cross-section of urban, industrial, agricultural, and natural land use categories in California. Likewise, additional work examining the possibility of emissions leakage, in this case where preserving farmland from urban development in one location might prompt additional urbanization and emissions in another location, will also be needed to give a full accounting of the emissions benefits of this approach. But regardless of these uncertainties, keeping farmland intact will maintain opportunities to reduce emissions and sequester C in agricultural soils and vegetation through future adoption of innovative agricultural practices.

Expansion of Perennial Crops

In their review of biophysical mitigation potentials of 42 agricultural land management activities, Eagle et al. (2012) found that some of the activities with the largest mitigation potential involved increasing the area of perennial croplands. For example, changing from an annual to a perennial crop yielded a projected average net impact of 2.92 t CO_2e ha^{-1} yr^{-1}, and changing from cropland to pastureland yielded a projected average net impact of 4.33 t CO_2e ha^{-1} yr^{-1}. In particular, incorporating woody perennials offered large GHG emission reductions: changing to *short-rotation woody crops* yielded a projected average net impact of 5.24 t CO_2e ha^{-1} yr^{-1}, and changing to *agroforestry* yielded a projected average net impact of 4.97 t CO_2e ha^{-1} yr^{-1}. (These values include both direct land impacts and upstream processes.) It could be a fruitful exercise to examine the mitigation potential of incorporating additional perennial crops into the California landscape. However, a significant portion of the GHG emissions reductions in woody perennial projects are the result of storing C in biomass, which is not a long-term sink, because processes and events such as decomposition and wildfire will release more than 90% of the sequestered C back to the atmosphere.

Agriculture occupies 27% of the 101.5 million acres of total land in California (UCAIC 2009). The 27.6 million acres of farmland includes 14 million acres of pasture and rangeland, 8.5 million of harvested cropland, and the remainder in woodland, non-harvested cropland, or other uses (UCAIC 2009). Table 6 shows the harvested areas of California's main crops types, separated into perennial and annual crops. The majority of California cropland (57% or 4.8 million acres) is occupied by some form of perennial crop, either woody (orchards and vineyards) or herbaceous (alfalfa and hay).

The percentage of total California farmland in orchard and vineyards (34%) is much greater than the national average of 1.2% (UCAIC 2009), reflecting the state's the large fruit, nut, and grape export industry. California leads the nation in the production of the following woody perennials: almonds, apricots, dates, figs, grapes, kiwifruit, kumquats, lemons, limes, olives, peaches, pears, persimmons, pistachios, plums, pluots, pomegranates, and walnuts (NASS 2011). Agricultural statistics indicate that over the past few decades, woody perennials increasingly occupy a larger proportion of the California landscape. This trend suggests the apparent role that woody perennials are already playing in mitigating GHG emissions in California. However, detailed inventories on standing stocks of soil and vegetative carbon in orchard and vineyard systems are rare and can be difficult to accurately quantify (Williams et al. 2011). In addition, only a few published studies (discussed below) examine GHG emissions in California orchards and vineyards or the effects of management on these systems: grapes (Garland et al. 2011) and almonds (Smart, Suddick, and Pritchard 2006; Schellenberg et al. 2012; Alsina, Fanton-Borges, and Smart 2013).

Another important component of California perennial croplands is alfalfa and hay. These irrigated systems occupy nearly 23% of California cropland (Table 6) and therefore warrant special consideration here. To date, only one study conducted in California has quantified GHG emissions from forage systems. Burger and Horwath (2012) measured annual N_2O emissions in first- through fifth-year alfalfa stands. Stand age had a large effect on emissions: fifth-year stands emitted 5.2 kg N_2O-N ha^{-1} yr^{-1}, and first-year stands emitted 2.3 kg N_2O-N ha^{-1} yr^{-1}. These rates were higher than in other crops examined in the study (tomatoes, lettuce, wheat, and rice) and were also higher than rates from other studies examining alfalfa emissions outside of California (2.3–4.2 kg N ha^{-1}) (Duxbury, Bouldin, Terry, and Tate 1982); 1.9 kg N ha^{-1} (Robertson, Paul, and Harwood 2000); 1.0 kg N ha^{-1} (Wagner-Riddle et al. 1996); 0.67–1.45 kg N ha^{-1} (Rochette et al. 2004)). Studies outside California have demonstrated lower annual N_2O emissions in alfalfa than in row crops (Wagner-Riddle and Thurtell 1998; Rochette et al. 2004; Dusenbury et al. 2008).

Table 6. California Harvested Cropland and Percent of Total Area

Crop	Harvested Area (1,000 acres)	Percent of Total Area
Perennials		
Orchards and vineyards	2,872	34
Alfalfa and hay	1,953	23
Annuals		
Vegetables and melons	1,197	14
Cotton	695	8
Rice	531	6
Wheat and barley (grain)	485	6
Other	733	9

Source: UCAIC (2009).

Nitrogen Management

Nitrogen is an essential input to maintaining high crop yields in California's agricultural systems. However, the addition of N in both synthetic and organic forms leads to emissions of N_2O that occur during nitrification and denitrification. Fluxes of N_2O are highly variable in time and space due to numerous factors such N management, soil type, temperature, water content, oxygen levels, and the availability of C and N (in both NH_4 and NO_3 forms). Denitrification is the main mechanism of N_2O loss when the NO_3 level and soil water content are high. Losses of N_2O can also occur during nitrification under aerobic soil conditions. Nutrient management strategies that seek to increase a crop's N use efficiency by optimizing the rate, source, placement, and timing of N application can help minimize N_2O emissions to the atmosphere and maintain the high yields essential for economic interests and global food security.

Nitrogen Fertilizer Rate

Evidence from numerous field studies conducted globally and in California indicates that there is a strong effect of N rate on N_2O emissions (Bouwman, Boumans, and Batjes 2002a; Burger and Horwath 2012). The default emissions factors used by the IPCC assume a linear relationship between N rate and N_2O emissions (IPCC 2006). This simple linear relationship is largely a function of the high variability of N_2O flux measurements reported across a global dataset of field experiments. For the most part, the assumption of linearity is useful and appropriate when N rates are closely aligned with crop N requirements (Bouwman, Boumans, and Batjes 2002a). However, when available N exceeds crop N requirements, the rate of N_2O efflux often increases significantly (McSwiney and Robertson 2005; Grant et al. 2006; van Groenigen et al. 2010).

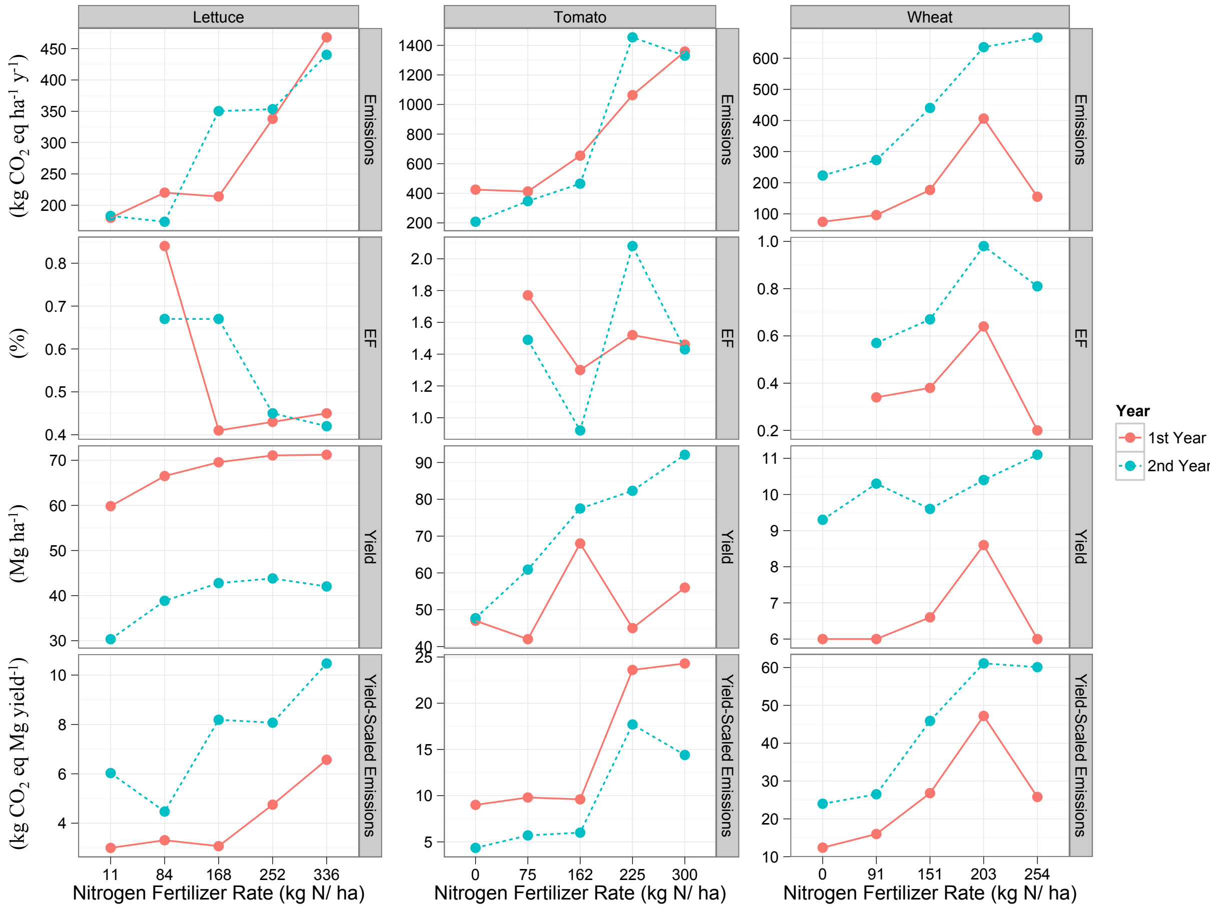
Reducing N rates below what is required to support optimal crop growth can also "mine" the soil of nutrients and mineralize organic matter, leading to loss of soil C and increased CO_2 emissions. Reducing N rates could therefore compromise both the short- and long-term productivity of agroecosystems. One of the adverse effects of lower crop yields is that additional conversion of natural forests, grasslands, and wetlands to meet global food demands would likely increase GHG emissions at larger spatial scales. Recent efforts to consider the importance of crop yields when examining agricultural emissions have led to the creation of *yield-scaled emissions* (Mosier, Halvorson, Reule, and Liu 2006; van Groenigen et al. 2010; Murray and Baker 2011). Scaling or relativizing N_2O emissions by crop yield helps balance the inherent tradeoff between productivity and N_2O emissions by providing a metric that reflects the efficiency of N fertilizer use in the system.

In California, several field experiments and one modeling study have tested the effects of fertilizer rate on N_2O emissions. Burger and Horwath (2012) quantified the effects of N fertilizer rate on N_2O emissions through a two-year study of lettuce, tomato, and wheat cropping systems in the California Central Valley. N inputs ranged from zero to above recommended input quantities. The data are summarized in Figure 1.

Lettuce was grown in a field in Salinas, California, and urea ammonium nitrate was applied 10 days after planting, followed by fertigation through subsurface drip tape for remaining applications. Increasing fertilizer rate generally increased N_2O emissions; the highest rates yielded more than twice the emissions relative to the lowest rates (Figure 1). Over both years, emissions factors were lowest at the highest three N rates and highest at the lowest N rate. Lettuce yields increased with increasing fertilizer rates until the 252 kg N ha^{-1} rate and then plateaued. Yield-scaled emissions were lowest at 84 kg N ha^{-1} (2nd year) and 168 kg N ha^{-1} (1st year), but increased sharply with higher N rates.

Tomatoes were grown in a furrow-irrigated tomato-wheat rotation, though the fields were left fallow over the rainy season. Starter fertilizer (N-P-K 15-15-15) was used (except in zero-N plots), followed by side-dressed urea ammonium nitrate at six weeks. With one exception (highest N rate in second year), N_2O emissions increased with N input (Figure 1). Emissions factors varied greatly across treatments, but the 162 kg N ha^{-1} treatment returned the lowest emissions factor in both years. In the first year, tomato yields showed no relationship with N rate, but in the second year, yields increased linearly with N rate. Yield-scaled emissions in tomatoes showed a strong and consistent trend across both years: yield-scaled emissions were comparable with N treatments 162 kg N ha^{-1} and lower. Above 162 kg N ha^{-1}, yield-scaled emissions increased dramatically (i.e., N_2O emissions increased at a greater rate than tomato fruit yields).

Figure 1. N_2O emissions, Emission Factors (EF), Yields, and Yield-Scaled Emissions under Lettuce, Tomato, and Wheat over Two Growing Seasons in California



Source: Burger and Horwath (2012).

Winter wheat was grown on two grower fields in Dixon, California. In the first year, wheat followed a tomato crop, while in the second year, wheat followed a four-year-old alfalfa field. Fertilizer was applied as ammonium sulfate, anhydrous ammonia, and urea. N_2O emissions increased with N input in both years, except for the highest N rate in the first year (Figure 1). Emissions factors exhibited similar patterns across N rates in both years: they increased with N rate and then declined sharply at the highest N rate (254 kg N ha^{-1}). Burger and Horwath (2012) note that among the different combinations of fertilizer treatments, the plots with anhydrous ammonia had consistently higher emissions. In the second year of the experiment, fertilizer rate had a lesser effect on yield compared with the first year, likely due to a large mineralizable soil N pool following alfalfa termination. Yield-scaled emissions were the lowest when no N was applied (0 N rate), with modest increases at 91 kg N ha^{-1} and larger increases thereafter. This result likely reflects the lower N requirements winter wheat has relative to the horticultural crops of lettuce and tomatoes.

A second study by Smart, Suddick, and Pritchard (2006) examined the effects of fertilizer rate on N_2O emissions in a vineyard in Napa County, California. It revealed a similar trend of increased N_2O emissions with N rate (Table 7). The authors suggested that their finds justified the need for developing a combination of strategies, including ideal N rate and application strategies, in wine grapes.

Table 7. N Input, N_2O Emissions and Emissions Factor Measured in a Napa Valley Vineyard

N Input (kg N ha^{-1})	N_2O Emissions (kg CO_2eq ha^{-1} y^{-1})	Emissions Factor (% of applied N emitted as N_2O)
0	14.88	
5.61	23.56	1.51
44.9	40.3	0.32

Source: Smart et al. (2006).

These studies clearly show a relationship between increased fertilizer application and increased N_2O emissions. These tradeoffs need to be carefully examined to find an optimal balance between productivity and emissions. Growers rely on several sources to determine fertilizer N application rates: previous records and experience and recommendations from soil test labs, certified specialists in nutrient management, and representatives of fertilizer distributors.

Recommendations from soil test labs rely on proprietary algorithms and information developed by the individual labs with little or no validation required for the prescription given to growers. Often fertilizer distributors employ nutrient management specialists—a potential conflict of interest. The prescriptions made by fertilizer distributors have little or no oversight. Growers already have an inherent economic incentive to only apply as much fertilizer as is required for optimal productivity. However, this incentive is often confused with management for maximum productivity rather than for maximum profit. In addition, N fertilizer recommendations can be site, crop, and management specific and can change with integration of new practices, such as changes in irrigation techniques. Growers require more independent tools such as computer programs or applications (apps) for their smart phones and tablets to assist them in site-specific fertilizer N recommendations. Moreover, the usability (plug and play without changing code) of biogeochemical models for academic and industry research efforts is required to better estimate site-specific and regional impacts of fertilizer N use. In conclusion, more research and tools are needed to determine optimal N rates in a suite of California cropping systems—that is, rates that balance productivity and efforts to mitigate GHG emissions.

Nitrogen Fertilizer Source

The source of N fertilizer that is being applied can have important and complex effects on GHG emissions. Key factors to consider for various N fertilizer sources are (1) the fossil fuel emissions (CO_2, CH_4, N_2O) associated with fertilizer manufacture through the Haber Bosch process and (2) the direct N_2O emissions from soils following fertilizer application. In California, urea ammonium nitrate, anhydrous ammonia, and urea are the three most common fertilizers used in agriculture; an annual average of approximately 182,000, 146,000, and 72,000 metric tons, respectively, were sold between 2002 and 2007 (CDFA 2007). Differences associated with these N fertilizer sources could offer opportunities to mitigate emissions. That said, in some cases substituting one N fertilizer for another is not appropriate for specific cropping systems and their associated management practices (i.e., fertigation, equipment, timing limitations, and so on).

This report focuses on the direct N_2O emissions from soils following fertilizer application rather than fossil fuel emissions related to producing and transporting N fertilizers. However, reasonable emissions estimates for the manufacture of various N sources are available (Snyder, Bruulsema, Jensen, and Fixen 2009; Burger and Venterea 2011). These estimates, which account for the manufacturing processes used to produce various fertilizer sources, suggest the range of fuel-related emissions are as follows: ammonia (0.53-0.77 kg CO_2-C kg^{-1} N) < urea (0.69-0.93 kg CO_2-C kg^{-1} N) < urea ammonium nitrate (1.24-1.36 kg CO_2-C kg^{-1} N) < ammonium nitrate (1.94 kg CO_2-C kg^{-1} N) (Burger and Venterea 2011).

There are also important differences among fertilizer types with respect to the direct N_2O emissions that occur following fertilizer application. These differences are often related to short- and long-term changes in soil pH caused by chemical reactions between the fertilizer and the soil. For example, anhydrous ammonia and urea can cause an increase in soil pH that can last one to two weeks and an increase in NO_2^- that can last for longer periods (Venterea and Rolston 2000; Mulvaney, Khan, and Mulvaney 1997; Burger and Venterea 2011). However, like other ammonium fertilizers, anhydrous ammonia and urea also generate high NH_4 concentrations that are subject to N_2O losses through nitrification and long-term pH decline under aerobic conditions as well as denitrification under anaerobic conditions. Research also suggests that acidifying fertilizers (e.g., ammonium sulfate, ammonium phosphate, ammonium nitrate) tend to promote higher N_2O emissions during denitrification than alkaline forming fertilizers, particularly on soils that have a low initial pH (Mulvaney, Khan, and Mulvaney 1997). The effects of N source on N_2O emissions are highly variable across different climates, crops, soil types, irrigation regimes, and fertilizer management practices, and several global reviews have concluded that the differences in emissions among fertilizer types are often marginal (Stehfest and Bouwman 2006).

A number of field experiments in U.S. corn cropping systems have found that N_2O emissions from anhydrous ammonia tend to be higher than from urea, urea ammonium nitrate, and other N fertilizers (Table 8). A field study examining wheat found higher N_2O emissions with anhydrous ammonia relative to urea under conventional tillage but recorded higher emissions with urea under no-till management (Burton, Li, and Grant 2008a). Fujinuma, Venterea, and Rosen (2011) found approximately 40% and 200% higher N_2O emissions from corn plots where anhydrous ammonia was injected at depths of 0.2 and 0.1 meters, respectively, than from plots where urea was broadcast and then incorporated.

Table 8. Annual N_2O Mitigation Potential Associated with Changing N Fertilizer

Source	Crop	Placement[a]	Tillage	Region	N_2O Mitigation Potential (t CO2e ha^{-1} yr^{-1})
Anhydrous Ammonia→ Urea					
Bremner et al. (1981)	Fallow	I → SS	Roto-till	MN, USA	0.68
Thornton et al. (1996)	Corn	I → I	No-till	TN, USA	1.85
Venterea et al. (2005)	Corn	I → B	Conv. till	MN, USA	0.90
	Corn	I → B	Red. till	MN, USA	1.05
	Corn	I → B	No-till	MN, USA	0.37
Venterea et al. (2010)	Corn	I → B	Conv. till	MN, USA	0.35
Burton et al. (2008a)	Wheat	I → B	Conv. till	MB, Canada	0.02
	Wheat	I → B	Conv. till		0.03
	Wheat	I → B	No-till		-0.11
	Wheat	I → B	No-till		-0.16
Breitenbeck & Bremner (1986)	Corn	I → B	Conv. till	MN, USA	0.06
Fujinuma et al. (2011)	Corn	I → B	Conv. till	MN, USA	0.06
	Corn	I → B	Conv. till		0.31
Anhydrous Ammonia → Urea Ammonium Nitrate					
Venterea et al. (2005)	Corn	I → SS	Conv. till	MN, USA	0.75
	Corn	I → SS	Red. till	MN, USA	0.90
	Corn	I → SS	No-till	MN, USA	0.34
Anhydrous Ammonia → Aqua Ammonia					
Bremner et al. (1981)	Fallow	I → SS	Roto-till	IA, USA	0.68
Urea → Urea Ammonium Nitrate					
Halvorson et al. (2010)	Corn	I → SS	No-till	CO, USA	0.04
Venterea et al. (2005)	Corn	I → SS	Conv. till	MN, USA	-0.15
	Corn	I → SS	Red. till	MN, USA	-0.15
	Corn	I → SS	No-till	MN, USA	-0.03
Urea Ammonium Nitrate → Calcium Ammonium Nitrate					
Schellenberg et al. (2012)	Almonds	I → SS	Not reported	CA, USA	0.08
Urea → Calcium Nitrate					
Breitenbeck et al. (1980)	Fallow	I → SS	Roto-till	IA, USA	0.04
Bremner et al. (1981)	Fallow	I → SS	Roto-till	IA, USA	0.03

Source: Adapted from Burger and Venterea (2011).
[a] Placement of anhydrous ammonia (AA) is always through injection, whereas other N fertilizers (UAN, Urea, CAN, CN, Aqua Ammonia) can be applied by surface spraying, injection (Urea), and broadcast (Urea) methods.
I = injected; SS = surface sprayed; SB = surface banded; B = broadcast.

Measurable differences in the N_2O emissions of urea, urea ammonium nitrate, ammonium sulfate, ammonium nitrate, calcium nitrate, and calcium ammonium nitrate have been small and inconsistent in the published literature. In a series of field and laboratory studies, Tenuta and Beauchamp (2003) found urea to have higher N_2O emissions than ammonium sulfate, ammonium nitrate, and calcium nitrate. Halvorson, Del Grosso, and Alluvione (2010) also measured higher N_2O emissions from urea relative to urea ammonium nitrate when both fertilizers were applied to corn in surface bands (Table 8). Conversely, Venterea, Burger, and Spokas (2005) found lower N_2O emissions from broadcast urea than from surface-sprayed urea ammonium nitrate.

In a California almond orchard, Smart (2011) and Schellenberg et al. (2012) found that annual N_2O emissions from plots receiving calcium ammonium nitrate (0.53 kg N_2O-N ha^{-1} yr^{-1}) were 34% lower than those that received urea ammonium nitrate (0.80 kg N_2O-N ha^{-1} yr^{-1}), but these differences were not statistically significant (Table 8). With the exception of these studies on almonds, all of the aforementioned experiments were conducted in corn and wheat cropping systems outside of California. Therefore, further field research is needed to determine whether consistent effects of N fertilizers on N_2O emissions occur in California's annual and perennial cropping systems.

Placement of Nitrogen Fertilizer

Fertilizer placement can have significant implications for yields and N_2O emissions. Fertilizers can be surface applied (through broadcasting, spraying, or banding) or injected by subsurface banding, depending on the crop and the form of the fertilizer. Another way in which fertilizers are delivered to crops is through fertigation through surface or subsurface drip irrigation or microsprinklers. Improper placement of fertilizers can lead to diminished yield potentials, increased N loss to the environment, and decreased nutrient use efficiencies, ultimately resulting in economic losses to the farmer.

To date, no studies examining N_2O emissions from different depths of fertilizer placement have been conducted in California. However, research conducted outside of California suggests that placement method and depth can influence rates of N_2O emissions (Snyder, Bruulsema, Jensen, and Fixen 2009; Fujinuma, Venterea, and Rosen 2011; van Kessel et al. 2013).

Although their results vary, several studies indicate that placing N fertilizer in shallow bands can increase N_2O emissions relative to broadcasting. Engel, Liang, Wallander, and Bembenek (2010) conducted a study in Montana that found that subsurface banding of urea at a depth of 5 cm increases cumulative N_2O emissions due to higher NO_2^- accumulation when compared to broadcast application. Although banding resulted in higher emissions than broadcast application at the 200 kg N/ha rate, no difference was observed between broadcast application and banding at the recommended rate of 100 kg N/ha. Similarly, Halvorson and Del Gross (2013) found that N_2O emissions were higher from surface-banded fertilizer than from surface broadcast application of urea applied at 202 kg N/ha. Maharjan and Venterea (2013) also observed significantly higher N_2O emissions from mid-row banding of both urea and polymer urea relative to surface banding followed by incorporation of these N sources. Conversely, Hultgreen and Leduc (2003) measured higher N_2O emissions from surface broadcasting than from subsurface banding in two years of three years in a study conducted in Saskatchewan, Canada.

In Iowa, Breitenbeck and Bremner (1986) found that anhydrous ammonia injected at 30 cm depth produced N_2O emissions that were 107% and 21% greater than when injected at 10 cm and 20 cm, respectively. One possible reason for these findings is that N is lost in the form of NH_3 when placed at relatively shallow depths and not incorporated into the soil due to volatilization and thus N_2O is not directly measured. However, this NH_3 is ultimately deposited back to the landscape elsewhere and can be converted to plant-available forms or to N_2O (Snyder, Bruulsema, Jensen, and Fixen 2009).

In a meta-analysis examining effects of tillage, climate, and fertilizer placement on N_2O emissions, van Kessel et al. (2013) found in nine studies (53 total comparisons) that fertilizer placement below 5 cm in no-till/reduced-till systems lowered N_2O emissions relative to conventional till systems. When these studies were subset by humid and dry environments, only the humid systems showed statistical differences with fertilizer placement. Further research is needed to examine fertilizer placement interactions with local soil types, climate, crops, and management regimes specific to California, but the effects of placement depth on N_2O emissions may be lower in California's Mediterranean climate, which has a relatively dry summer growing season.

Timing of Nitrogen Applications

Although no California-based studies have investigated the impact of N fertilizer timing on N_2O emissions in detail, the theoretical mechanism is reasonably well understood. Crop N requirements are relatively low at seeding, but demand increases rapidly as plant growth proceeds (Eagle et al. 2012). Thus if N is applied to meet plant requirements at a particular growth stage, excess N is likely to be less exposed to N_2O losses through nitrification and denitrification. Given excess N in the form of NH_4^+ at any stage, nitrification will occur, increasing the pool of soil nitrate. The nitrification process is likely to be a source of N_2O and can occur at relatively low soil moistures (Zhu, Burger, Doane, and Horwath 2013). Excess soil nitrate can be quickly lost through denitrification, resulting in the production of N_2O. Denitrification occurs most rapidly when water-filled pore space is greater than 60%, as O_2 is depleted, but it can take place in microsites within soil pores as well. The loss of excess N is also likely to be exacerbated by irrigation, though it will occur regardless of conditions (Burger et al. 2005).

To show the N_2O emissions reduction potential of improved timing of N application, Burton, Zebarth, Gillam, and MacLeod (2008b) tested the effect of a split fertilizer application in a potato cropping system in New Brunswick, Canada. They compared a single application of 200 kg N ha^{-1} at planting versus a split application of 120 kg N ha^{-1} at planting plus 80 kg applied at final hilling. In the first and second years, N_2O emissions were reduced in the split application plots by 0.12 and 0.41 t CO_2e ha^{-1} yr^{-1}. Differences in the magnitude of emissions were mostly explained by rainfall patterns.

More local research is needed to quantify the mitigation potential of improved N fertilizer timing for California's annual and perennial cropping systems. Related strategies for timing and synchronizing N availability with crop nutrient demand through the use of polymer-coated fertilizers, nitrification and urease inhibitors, and various fertigation methods are discussed below.

Nitrogen Fertilizer Efficiency Enhancers

In recent decades, a number of fertilizer products and other chemical additives have been developed with the goal of improving nitrogen use efficiency, stabilizing yields, and reducing N losses through N_2O emissions and NO_3^- leaching. These efficiency-enhancing fertilizer products include polymer-coated fertilizers, nitrification inhibitors, and urease inhibitors.

Polymer-coated fertilizers are encapsulated or chemically modified fertilizers with decreased solubility, causing them to be more slowly released to the soil solution and in closer synchrony with plant uptake over a growing season. Typically, these fertilizers are covered with a semipermeable or sulfur-based coating that reduces their solubility, their microbial activity—specifically nitrification—or both (Trenkel 2010).

Nitrification and urease inhibitors are not fertilizers per se, but rather chemical compounds that are applied with N fertilizers. Certain fertilizer products may include nitrification or urease inhibitors. Nitrification inhibitors interfere with the two-step transformation of ammonium (NH_4^+) to NO_3^- by nitrifying bacteria. NH_4^+ is first oxidized to nitrite (NO_2^-) by *Nitrosomonas* bacteria and finally to NO_3^- by *Nitrobacter* and *Nitrosolobus*. The oxidation of NH_4^+ to NO_3^- can be a source of N_2O. Once in the NO_3^- form, N can be lost through the system by leaching or by denitrification. By temporarily suppressing the activity of the *Nitrosomonas* population, nitrification inhibitors prevent the oxidation of NH_4^+ to NO_2^- and consequently to NO_3^-. By allowing the applied N to stay in the NH_4^+ form longer, the potential for loss as N_2O or NO_3^- is reduced (Trenkel 2010). Urease inhibitors suppress the activity of urease enzymes in the soil and thus reduce the rate of urea hydrolysis (Trenkel 2010). By inhibiting urea hydrolysis, NH_4^+ levels in the soil increase more slowly, which reduces the amount available for nitrification (and loss as N_2O) and also allows for better synchrony between N availability and crop uptake over the season.

To date, no published field studies have been conducted in California that examine these fertilizer products and their possible effects on N_2O emissions. However, several reviews of field studies conducted globally are available (Oenema, Velthof, and Kuikman 2001; Dalal, Wang, Robertson, and Parton 2003; Bolan et al. 2004; Akiyama, Yan, and Yagi 2010). A recent meta-analysis by Akiyama, Yan, and Yagi (2010) is the most comprehensive assessment of polymer-coated fertilizers, nitrification inhibitors, and urease inhibitors, and their effects on N_2O emissions to date. Here, this report uses the review by Akiyama to discuss the potential of enhanced-efficiency fertilizers to reduce N_2O emissions in California cropping systems.

A review of 20 field studies by Akiyama, Yan, and Yagi (2010) suggests that polymer-coated fertilizers reduce N_2O emissions on average reduction by 35% (Table 9). The effectiveness of polymer-coated fertilizers varies widely across land use practices, soil types, and soil moisture regimes. They also tend to be more effective when emissions rates are higher. They tend to be less effective in fertigation systems, such as subsurface drip where N use efficiency is increased (Burger and Horwath, ongoing research). In general, emissions reductions by polymer-coated fertilizers are higher on poorly drained soils (e.g., Gleysols) than on well drained soils such as Andisols in upland field studies. This difference was attributed to the soil water content. Type of coating, its solubility, and application timing can also influence effectiveness.

Akiyama, Yan, and Yagi (2010) also found that nitrification inhibitors in the 85 field studies reduced N_2O emissions by an average of 38% when compared with conventional fertilizer alone (Table 9). Variations in mitigation effectiveness were explained by each inhibitor type's solubility and by environmental factors, such as temperature and moisture. Variations in efficacy also occurred across different land uses. Akiyama, Yan, and Yagi (2010) found that emissions from grasslands were higher on average and that nitrification inhibitors were more effective in reducing emissions from these areas than emissions from other land uses.

Table 9. Average Percent Reduction in N_2O Emissions and 95% Confidence Interval from Polymer-Coated Fertilizers, Nitrification Inhibitors, and Urease Inhibitors

Product	No. of Field Studies	Average % Change in N_2O Emissions	Confidence Interval	
			Max	Min
All Polymer-coated Fertilizers	**20**	**-35**	**-58**	**-14**
All Nitrification Inhibitors	**85**	**-38**	**-44**	**-31**
Dicyanidamide	42	-30	-36	-26
3,4-dimethyl pyrazole phosphate	12	-50	-55	-42
Nitrapyrin	10	-50	-55	-30
Ca-carbide	8	-51	-65	-32
Thiosulfate	4	-19	-33	-15
Neem	8	-14	-25	-7
All Urease Inhibitors	**8**	**-10**	**-35**	**14**

Source: Akiyama et al. (2010).

Compared with nitrification inhibitors and polymer-coated fertilizers, urease inhibitors are less effective in reducing N_2O emissions (Table 9). Akiyama, Yan, and Yagi (2010) attribute this finding to the hydrolysis of urea not being directly related to the production of N_2O, but rather NH_3. However, because urease inhibitors do delay the eventual formation of NH_4^+, they could help reduce eventual emissions from the nitrification of NH_4^+ and subsequent denitrification of NO_3^-, as long as their use is timed with plant uptake of NH_4^+. Data on urease inhibitors' emissions reduction effectiveness come from only eight published studies and therefore are not as robust as similar data for polymer-coated fertilizers and nitrification inhibitors. As noted above, no California-based studies examining polymer-coated fertilizers, nitrification inhibitors, or urease inhibitors are available; thus, more research is needed on these products and their interactions with local soil types, environmental conditions, and crop-specific management practices. Although the market shares of these products have been increasing in recent years, their relatively high cost continues to be a constraint to adoption and use (USDA–ERS 2012)

Irrigation Practices

Irrigation practices can affect GHG emissions through several mechanisms. These mechanisms include (1) emissions from fossil fuel used to pump groundwater and pressurize irrigation systems and (2) GHG emissions from soil that result from differential hydrological interactions among water, soil, and nutrients among various irrigation practices and technologies. This review mainly focuses on the emissions from soil associated with the second mechanism, and because drip and micro-sprinkler irrigation systems are commonly used to deliver both water and fertilizers (i.e., fertigation) throughout the season, this section focuses mostly on N_2O emissions and overlaps to some extent with the N management practices discussed above (e.g., N rate, source, timing, and placement). Irrigation practices may also affect the amount of CH_4 and CO_2 emitted from soil, but these differences are not expected to be large in terms of the overall emissions from most cropping systems and thus are not reported here. Emissions of CH_4 from flooded rice cultivation are a notable exception and are addressed at length in the subsequent section on emissions from California rice systems.

Cycles of wetting and drying in the soil tend to stimulate emissions of N_2O through denitrification (Appel, 1998; Fierer and Schimel 2002). Therefore, N_2O fluxes are generally elevated just following irrigation, precipitation, and fertilization events, particularly when water-filled pore space is less than 60% (Ruser et al. 2006). Flood and furrow irrigation tend to generate larger extremes in wetting and drying relative to low-volume irrigation systems such as surface and subsurface drip and microsprinkler irrigation systems (Hanson and Bendixon 2000). Several field studies on processing tomatoes and other row crops in California have found that subsurface drip irrigation can leave most of the soil surface dry and maintain soil moisture at between 20% and 30% water-filled pore space near the drip line (Hanson and Bendixon 2000; Hanson and May 2007). Consequently, shifting from flood and furrow irrigation to low-volume irrigation systems is likely to offer opportunities to mitigate N_2O emissions in certain annual and perennial cropping systems.

In a recent meta-analysis of all available data from studies conducted in Mediterranean climates (26 field studies, 1 modeled study), Aguilera et al. (2013) determined mean cumulative N_2O emissions for conventional irrigation (furrow, sprinkler, and micro sprinkler), drip irrigation (surface and subsurface) and rainfed systems to be 4.0, 1.2, and 0.4 kg N_2O-N ha^{-1} yr^{-1}, respectively. Based on their results, which cover a wide range of crop types, average reductions obtained by the shift from conventional to drip irrigation were approximately 0.87 t CO_2e ha^{-1} yr^{-1}.

In California, several studies examining processing tomatoes have measured significant decreases in N_2O emissions under sub-surface drip irrigation relative to conventional furrow irrigation (Table 10). A study by Kennedy (2012) found more than 50% lower seasonal and annual losses of N_2O under an integrated tomato cropping system (subsurface drip irrigation, fertigation, reduced tillage, *Triticale trios* cover crop) relative to a conventional tomato cropping system (furrow irrigation, standard tillage, winter wheat). A study by Kallenbach, Rolston, and Horwath (2010) found similar reductions in N_2O emissions during the growing season under subsurface drip irrigation (relative to furrow irrigation) when tomatoes were preceded by a legume cover crop, but no difference in seasonal emissions in treatments not receiving the cover crop. By including fluxes recorded during the winter season, measurable differences in cumulative annual N_2O emissions were found between subsurface drip and furrow irrigation in both the cover crop and no-cover crop treatments. These studies suggest that subsurface drip irrigation could reduce N_2O emissions, but complex interactions among multiple crop management factors make it difficult to quantify precisely how much of the emission reduction is due to the irrigation treatment alone. Future studies should address this limitation and also examine the possible N_2O reductions from drip irrigation systems (both subsurface and surface) if applied in other vegetable and row crops throughout California.

Very few studies conducted in California have specifically examined the effect of different irrigation practices and technology on N_2O emissions from perennial and orchard cropping systems (Table 10). Smart (2011) and Alsina, Fanton-Borges, and (2013) measured N_2O and CH_4 emissions from a California almond orchard that was fertigated using either a surface drip irrigation system or a stationary micro-sprinkler system (Figure 2). Notably, Alsina, Fanton-Borges, and Smart (2013) reported that cumulative annual N_2O emissions were significantly higher in the drip-irrigated system (1.6 kg N_2O-N ha^{-1} yr^{-1}) than in the micro-sprinkler-irrigated system (0.6 kg N_2O-N ha^{-1} yr^{-1}). Emissions of N_2O in the drip-irrigated system, which applied water and N fertilizer in a concentrated spatial pattern, were positively correlated with water-filled pore space but not with soil mineral-N concentrations (Figure 2). Net emissions of CH_4 were negligible, and no significant differences between the irrigation treatments were found. These recent peer-reviewed papers also draw on preliminary results presented in a series of research reports published by Smart (2009a, b; 2010; 2011; 2012) for the Almond Board of California. Additional studies are needed to assess the extent to which drip and micro-sprinkler irrigation systems might reduce N_2O emissions from other perennial cropping systems, particularly those that commonly use flood irrigation (e.g., walnuts).

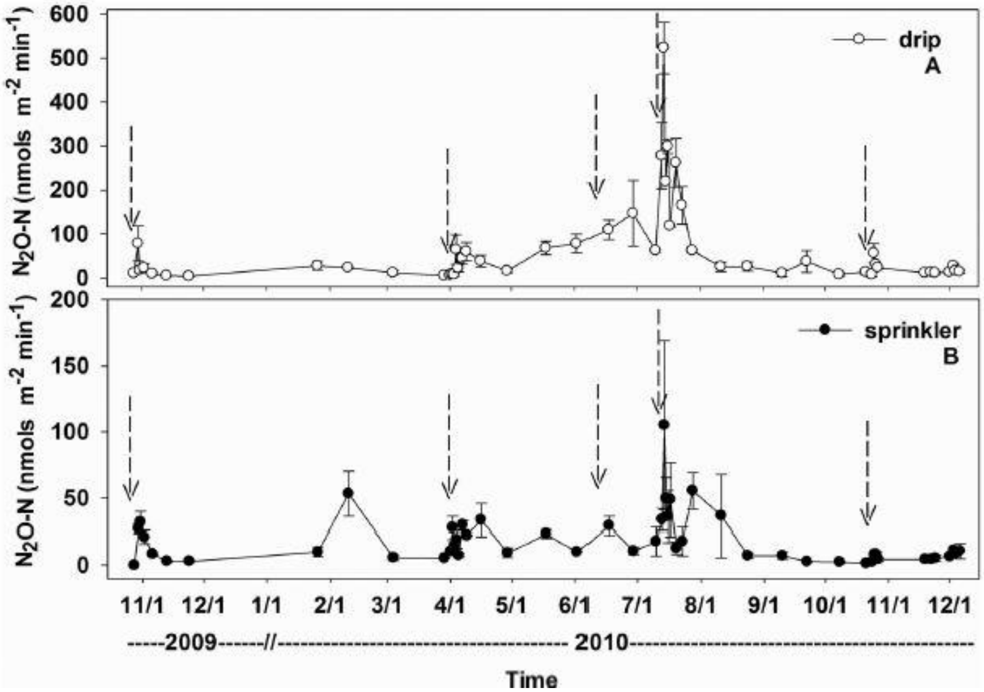
Table 10. Estimates of N_2O Mitigation Potential of Various Irrigation Practices Based on Field Studies Conducted in California and Mediterranean Climates

Study	Data Type	Crop Rotation	N_2O Mitigation Potential (t CO_2e ha^{-1} yr^{-1})
Furrow irrigation → Subsurface drip irrigation			
Kennedy (2012)[a]	Field	Tomato - CC (*Triticale trios*)	0.65
Kallenbach et al. (2010)[a]	Field	CC (legume) - Tomato – Fallow	0.91
Kallenbach et al. (2010)[a]	Field	CC (legume) - Tomato - CC (legume)	1.26
Surface drip irrigation → Microsprinkler irrigation			
Alsina et al. (2013)[a]	Field	Almond	0.31
Conventional Irrigation → Drip Irrigation			
Aguilera et al. (2013)[b]	Field & Model	Multiple crops	0.87

[a] California-specific study.

[b] Results are from a meta-analysis representing the mean from 27 studies in Mediterranean climates across many cropping systems, including 26 field studies and 1 modeled study.

Figure 2. N_2O Emissions (nmol N_2O-N m^2 min^{-1}) Spatially Scaled to the Orchard Level (Fertigation and Driveway Areas) for Micro-Sprinkler Irrigation ("Sprinkler") and Drip Irrigation



Source: Alsina et al. (2013).

Note: Total moles of N_2O emitted were estimated as the integral of the surface defined by the N_2O flux distribution around the fertigation emitters and scaled up using the number of emitters per hectare, plus the N_2O flux observed outside the wet-up area in the orchard driveways. Arrows represent dates when fertigation occurred.

Conservation Tillage and No-Till Management Practices

Conservation tillage and no-tillage management practices seek to reduce the amount of physical disturbance to the soil relative to conventional or standard tillage regimes. Full inversion tillage with a moldboard plow presents the greatest level of disturbance; chisel plow tillage, strip tillage, direct drilling, and full no till are all examples of conservation tillage technologies. Soil disturbance can also be reduced by implementing one or more of these methods within a crop rotation, rather than conventional tillage between every crop (Alvarez 2005; Abdalla et al. 2013).

The effects of conservation, reduced, or no tillage (hereafter, *conservation tillage*) relative to conventional tillage have received much national attention. They are also of interest in the context of GHG mitigation potential (Eagle et al. 2012). Reducing or eliminating tillage practices could affect GHG emissions through a variety of mechanisms, both direct and indirect (Alvarez 2005; Abdalla et al. 2013).

Conservation tillage immediately and directly reduces emissions from in-field operations. Accounting for fuel savings is outside of this report's scope, but conservation tillage can reduce emissions 0.03–0.10 t CO_2e ha^{-1} yr^{-1} (Archer, Pikul Jr., and Riedell 2002; West and Marland 2002) and no tillage can reduce emissions 0.07–0.18 t CO_2e ha^{-1} yr^{-1} (Frye 1984; West and Marland 2002).

A large body of literature shows that conservation tillage relative to conventional tillage typically results in a reduction in soil CO_2 emissions, because more organic carbon is stored in soil (Six, Elliott, Paustian, and Doran 1998; Six, Elliott, and Paustian 1999; Grandy and Robertson 2006). However, in some studies, the effects of no tillage and conventional tillage on soil C did not differ (Angers and Eriksen-Hamel 2008).

The reason for these disparate observations is that most studies fail to account for the redistribution of soil C under tillage compared with no tillage.

Most studies show that N_2O emissions increase under conservation tillage, although results vary across studies; some reports show a decrease (see Abdalla et al. 2013 for a recent review). The increase in N_2O emissions under conservation tillage is likely related to soil compaction, which reduces large pores and promotes conditions for denitrification. Conservation tillage typically results in little difference or a decrease in CH_4 emissions from agricultural fields (Abdalla et al. 2013).

Adoption of conservation and no tillage technologies has been very limited in California annual croplands. A 2004 survey of nine Central Valley counties showed that than 2% of total cropland acreage was in conservation tillage (Mitchell et al. 2009). There is potential for greater adoption of conservation tillage practices in California as a mitigation strategy. However, consideration must be given to biophysical and socioeconomic constraints prohibiting conservation tillage in California. These constraints may change as more micro-irrigation systems, such as subsurface drip, are adopted, reducing the need for tillage that is required in furrow irrigation systems. Another important consideration is that the majority of California croplands are already in perennial crops (forages and orchards and vineyards) and are therefore implementing some form of reduced tillage such as conservation or no tillage. Thus, adoption of conservation tillage practices would affect only a minority of California cropland acreage.

Field studies in California have shown inconsistent effects of conservation tillage practices on soil C. Some studies have found increases in soil C with some treatments (Minoshima et al. 2007; Lee et al. 2009); no effects relative to standard tillage practices have also been reported (Minoshima et al. 2007; Veenstra, Horwath, and Mitchell 2007; Kong, Fonte, van Kessel, and Six 2009). Several studies have found that cover crops (discussed below) have overall larger effects on soil C pools than conservation tillage practices (Minoshima et al. 2007; Veenstra, Horwath, and Mitchell 2007; Kong, Fonte, van Kessel, and Six 2009).

Accounting for GHG mitigation by tracking changes in soil C is a complex and difficult process for a number of reasons. First, soil C sequestration and loss is an inherently complex ecosystem process that integrates the chemical and physical properties of soil, mediated through soil biota (Schmidt et al. 2011). Second, soil C sequestration and loss operates at long time scales (years to decades), slowing the detection of any measurable changes between tillage practices. Third, inherent spatial variability in soil C makes it difficult to quantify whole-profile soil C stocks. This variability can diminish statistical power and lead to the conclusion that no differences exist when management may in fact be affecting standing soil C stocks (Kravchenko and Robertson 2011). Fourth, sampling methodology in conservation tillage studies can affect results. Conservation tillage often affects crop root growth throughout the soil profile, concentrating roots at the soil surface, relative to standard tilled soil. These roots differentially increase soil C concentrations on the surface and diminish soil C at lower depths. When only the surface soil is sampled, researchers have often reached erroneous conclusions about soil C gains with conservation tillage relative to standard tillage (West and Post 2002; Baker, Ochsner, Venterea, and Griffis 2007). Finally, the permanence of recently deposited soil C in conservation tillage is a relevant consideration. Permanent no-till systems are rarely practiced, because farmers often till periodically for a variety of reasons (Grandy, Robertson, and Thelen 2006). The soil C that took a decade to accumulate under conservation tillage may be lost in a matter of weeks with a single tillage event (Six, Elliott, Paustian, and Doran 1998; Grandy and Robertson 2006). For all of the reasons outlined above, this report focuses on N_2O emissions, rather than changes in soil C.

Global analyses have shown that N_2O emissions are often higher in the first years after conversion to conservation tillage, and these emissions can contribute to greater global warming potential than the sequestering of soil C (Six et al. 2004). Moreover, mitigation of greenhouse gases by conversion to no-till systems may only be realized with long-term no-till management, because most of the global warming potential is driven by N_2O emissions (Six et al. 2004). In fact, a recent meta-analysis by van Kessel et al. (2013) further demonstrates this point: overall differences in N_2O emissions were not observed in no-till or reduced-till systems relative to conventional till systems. It was only when studies were subset into no-till and reduced-till systems for more than 10 years that a 14% reduction in N_2O emissions was found. Interestingly, this reduction was not apparent in humid climates but was clearly apparent in dry climates, such as California. In dry climates, the meta-analysis showed an average *increase* in N_2O emissions by 38% in no-till and reduced-till systems for less than 10 years and an average *decrease* in N_2O emissions by 34% in no-till and reduced-till systems for more than 10 years (van Kessel et al. 2013). This finding clearly demonstrates the importance of permanence for realized benefits in GHG emissions for California no-till and reduced-till systems.

In California, few studies have examined the effects of conservation tillage on GHG emissions, and most of these have focused on N_2O mitigation potential (Table 11). Because they focus on the first few years following conversion to conservation tillage, they provide little evidence that such tillage practices reduce N_2O emissions relative to conventional tillage practices in California.

Table 11. Mitigation Potential from Conservation Tillage Studies in California

Source	Data Type	Crop	N_2O Mitigation Potential ($t\ CO_2e\ ha^{-1}\ yr^{-1}$)
		Conventional tillage → Conservation tillage	
Lee et al. (2009)	Field	Maize	0.09
		Sunflower	-0.69
		Chickpea	0.49
Garland et al. (2011)	Field	Grapes	-0.02
Kallenbach et al. (2006)	Field	Tomato	0.01
Kennedy (2012)	Field	Tomato	0.65
Kong et al. (2009)	Field	Maize	Insufficient data
Steenwerth and Belina (2010)	Field	Grape	Insufficient data
De Gryze et al. (2009)	Modeled	Alfalfa	-0.02
		Corn	-0.01
		Rice	-0.04
		Tomato	0.04
		Wheat	-0.01
		Safflower	-0.04
		Sunflower	0.07
		Cotton	0.02
		Mellon	-0.01

Lee et al. (2009) measured N_2O emissions four to five years after standard tillage practices were switched to no-till practices. They quantified emissions in three successive crops: (1) corn fertilized at 244 kg N ha^{-1}, (2) sunflower fertilized at 90 kg N ha^{-1}, and (3) chickpea unfertilized. Overall, conservation tillage showed no clear N_2O emissions pattern. It reduced N_2O emissions in corn 0.09 t CO_2e ha^{-1} yr^{-1} compared with standard conventional tillage. In the following crop of sunflowers, it increased N_2O emissions by 0.69 t CO_2e ha^{-1} yr^{-1}, and in the winter crop of chickpea, minimum tillage reduced N_2O emissions an average of 0.49 t CO_2e ha^{-1} yr^{-1} compared with conventional tillage.

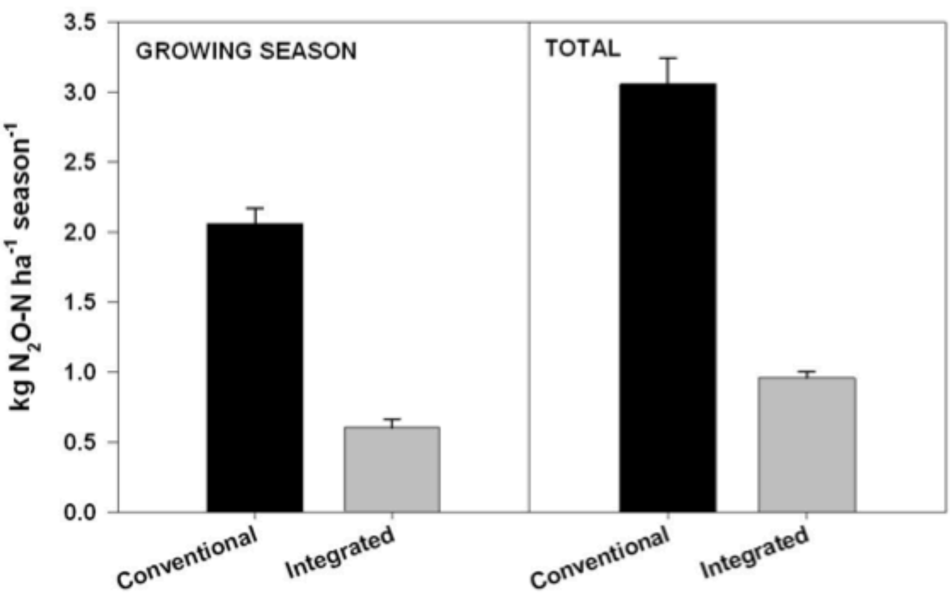
Garland et al. (2011) reported N_2O emissions in the first year following a vineyard's conversion from conventional to no tillage. Over the growing season, N_2O emissions were no different in no-till plots than in conventionally tilled plots, although the mean emissions in the row and under the vine in the no-till plots were greater than in conventional-till plots.

Two studies in California tomato systems report conservation tillage effects on N_2O emissions. Kallenbach et al. (2006) examined the effects of tillage (conservation versus conventional), irrigation (furrow irrigation versus subsurface drip), and cover cropping (winter legume versus no cover crop) treatments on N_2O emissions. Overall, they found no cumulative difference in emissions due to tillage, although there were differences related to interactive effects of irrigation and cover cropping (discussed below). In the second report, Kennedy (2012) examined emissions from two different tomato-cropping systems, conventional (sidedress fertilizer injection, furrow irrigation, standard tillage, winter fallow) and integrated (fertigation, subsurface drip irrigation, reduced tillage, winter cover crop). These numerous factors cumulatively reduced N_2O emissions in the integrated system compared with the conventional system by 0.65 t CO_2e ha^{-1} yr^{-1} (Figure 3).

Another published study examined reduced tillage in California (Kong, Fonte, van Kessel, and Six 2009). The authors examined maize under three management systems, focusing mainly on soil C and N dynamics and soil aggregation. N_2O emissions data are reported, but samplings were too infrequent to extrapolate reliable N_2O emissions rates. Likewise, Steenwerth and Belina (2010) compared the effects of tillage under grape vine rows versus herbicide application on N_2O emissions in a vineyard. Herbicide application produced 50% more N_2O emissions than the tillage treatment within the first 1.5 days, after which N_2O emissions were negligible in both treatments. The limited sampling restricted extrapolation to annual rates.

Also reported in Table 11 are modeled results from De Gryze, Catala, and Howitt (2009) and De Gryze (2010). The reported N_2O emissions are based on predictions from the DAYCENT model. These modeled predictions generally showed slight increases in N_2O emissions, depending on the crop. Because so little California field data exist to calibrate and validate these model predictions, these values likely provide a general emissions framework rather than robustly constrained values.

Figure 3. Cumulative N_2O Emissions in Tomatoes under Conventional and Integrated Management in California



Source: Figure reproduced from Kennedy (2012).
Note: The left panel shows emissions from the growing season; the right panel shows total emissions over the calendar year.

Cover Crops and Organic Amendments

Substituting mineral nitrogen fertilizer with organic-based inputs is another potential strategy for reducing GHG emissions in California. Organic fertility sources are typically less prone to leaching and nutrient loss than fertilizers in mineral (inorganic) forms (Seiter and Horwath 2004; Drinkwater and Snapp 2007). Organic fertility sources are generally slower to turn over and become available to plants (i.e., slow release) than mineral fertilizers (i.e., fast release). This slower cycling can ultimately lead to greater nutrient-use efficiencies in systems that use organic sources (Crews and Peoples 2004; Drinkwater and Snapp 2007).

Cover crops and organic amendments are two ways to increase organic fertility. Cover crops are a special case: they are an organic amendment planted and grown in the field and not brought in from off site. Organic amendments include any plant- or animal-based residue, such as manure, compost, or biosolids.

Cover crops

Cover crops are a wide-ranging category of crops that are typically not harvested but instead returned to the soil through mowing or incorporation with tilling. Cover crops can be planted any time of year and occupy a wide range of functionality (Snapp et al. 2005). Cover crop uses include planting of a winter legume (e.g., Australian winter pea, hairy vetch) to fix nitrogen and build soil organic matter (Kallenbach, Rolston, and Horwath 2010); planting of rye in the fall to suppress weeds, build soil organic matter, and scavenge excess soil nutrients after harvest (Shipley, Messinger, and Decker 1992); planting of mustard to suppress pests and attract beneficial insects (Matthiessen and Kirkegaard 2006); and planting of sorghum-sudangrass in the summer to break up compacted soil and build organic matter (Wolf 1997).

In California, cover crops may also have potential to decrease GHG emissions by sequestering C in soil (i.e., building organic matter) and increasing the efficiencies of N fertilization (i.e., scavenging for residual soil nutrients not taken up by the cash crop). Leguminous cover crops, in particular, may increase direct field emissions by increasing available soil nitrogen through biological N fixation, and they may reciprocally decrease indirect emissions by reducing the need for external N fertilizer inputs. Cover crops can also add to emissions if additional energy is required for planting, mowing, plowing, or irrigating.

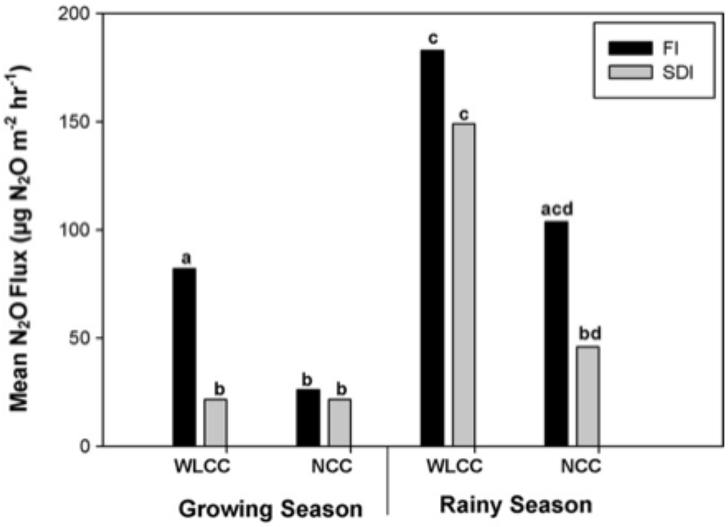
Field Studies

Only a few studies in California have examined the effects of cover cropping on GHG emissions (Table 12). Kallenbach, Rolston, and Horwath (2010) quantified N_2O emissions with cover crop and irrigation practices in a tomato-cropping system in California. Treatments included winter legume cover crop with furrow irrigation, winter legume cover crop with subsurface drip irrigation, no cover crop with furrow irrigation, and no cover crop with subsurface drip irrigation. Kallenbach, Rolston, and Horwath (2010) found the largest reductions in subsurface drip irrigation (discussed below), but seasonal differences in N_2O emissions were influenced by cover crops (Figure 4). Averaged across irrigation practices, the presence of a leguminous cover crop increased N_2O emissions by 1.69 CO_2e ha^{-1} yr^{-1}.

Table 12. Mitigation Potential Reported in Cover Cropping Studies in California

Source	Data Type	Crop	Cover Crop	N_2O Mitigation Potential ($t\ CO_2e\ ha^{-1}\ yr^{-1}$)
		No cover crop → Winter cover crop		
Kallenbach et al. (2010)	Field	Tomato	Legume	-1.69
Steenwerth and Belina (2008)	Field	Grape	Grass	-0.05
Kennedy (2012)	Field	Tomato	Grass	0.65
Smukler et al. (2012)	Field	Tomato	Mustard	-0.03
De Gryze et al. (2009)	Modeled	Tomato	Legume	-0.03
		Alfalfa		-0.05
		Corn	Legume	-0.12
		Rice	Legume	0.30
		Wheat		-0.03
		Safflower	Legume	-0.16
		Sunflower	Legume	0.00
		Cotton	Legume	0.22
		Melon	Legume	-0.11

Figure 4. Mean N_2O Emissions in California Tomatoes with Two Types of Irrigation and a Cover Crop Treatment



Source: Figure reproduced from Kallenbach et al. (2010).
Note: FI = furrow irrigation; SDI = subsurface drip irrigation; WLCC = winter legume cover crop; NCC = no cover crop.

In a Chardonnay vineyard in California, Steenwerth and Belina (2008) examined the effects of cover cropping versus cultivation on N dynamics and N_2O production in the alleys between the grapevine rows. Cover crops included Trios 102 (*Triticale x Triosecale*) and Merced Rye (*Secale cereale*) planted in the fall, and the cultivation treatment was tilled every two months. Averaged across cover crop treatments, cover cropping increased annual N_2O emissions by 0.05 kg CO_2e ha^{-1} yr^{-1} compared with cultivation. However, relative to annual cropping systems, N_2O emissions were found to be much lower in these perennial systems. Steenwerth and Belina (2008) also found that N_2O efflux was sensitive to spring and fall precipitation, as evidenced by the increase in emissions during this period.

Two additional field studies, Kennedy (2012) and Smukler, O'Geen, and Jackson (2012) had challenging experimental designs that limit how much information can be drawn from them with absolute certainty. Kennedy (2012) examined emissions from two different tomato-cropping systems, conventional (sidedress fertilizer injection, furrow irrigation, standard tillage, winter fallow) and integrated (fertigation, subsurface drip irrigation, reduced tillage, winter cover crop). These numerous factors cumulatively reduced N_2O emissions in the integrated system compared with the conventional system by 0.65 t CO_2e ha^{-1} yr^{-1} (Table 12). Smukler, O'Geen, and Jackson (2012) surveyed an organic farm and found that in fields that were cover cropped, there was a slight increase in N_2O emissions with a mustard cover crop of 0.03 t CO_2e ha^{-1} yr^{-1} (Table 12).

In a modeled study, De Gryze, Catala, and Howitt (2009) reported modeled predictions of N_2O emissions based on the presence of a winter legume in various crops in California. They found slight increases in N_2O emissions in all crops except rice, sunflower, and cotton (Table 12). The exact reasons for this finding may reflect DAYCENT model interactions with soil type and residual soil N dynamics.

Overall, these studies show a general trend in increasing N_2O emissions with a winter cover crop. Something to possibly glean from these studies is that the type of cover crop may have an effect on N_2O emissions. For example, using a nitrogen-fixing legume may introduce and increase available soil N and therefore lead to increases in N_2O emissions. In contrast, a winter grass may rapidly take up available soil

N and have a greater chance of reducing N_2O emissions. Unfortunately, lack of empirical data limits the conclusions that can be drawn at this point.

Organic Amendments

Apparently only one field study has examined N_2O emissions with organic amendments in California. Burger et al. (2005) examined emissions in tomatoes under an organic system (cover crops and animal manure) and a conventional system (inorganic fertilizer). They found the highest emissions fluxes occurred after fertilizer incorporation, in both organic (0.94 mg N_2O-N m^{-2} h^{-1}) and conventionally managed soils (2.12 mg N_2O-N m^{-2} h^{-1}). However, the number of sampling periods was too infrequent to allow estimation of seasonal or annual emissions rates. A long-term cropping system N-use efficiency study showed organically managed 4-year rotation lost only 4.5% of the N applied as manure over a 10-year period in northern California (Poudel, Horwath, Mitchell, and Temple 2001). In contrast, a long-term cropping system N-use efficiency study showed that an organically managed 2-year rotation lost only 65% of the N applied as manure over a 10-year period in northern California (Horwath, unpublished). The intensity (every year versus every two years in the four-year rotation) of manure application in the two-year rotation resulted in substantial N losses through leaching and likely denitrification. There was no interaction of conservation and manure additions on N losses compared with conventional tillage. It is therefore necessary to evaluate the intensity (crop rotation, manure application frequency, and so on) of manure additions to understand potential losses of N as N_2O.

Table 13. Mitigation Potential Reported in Organic Amendment Studies in California

Study	Data Type	Crop	N_2O Mitigation Potential ($t\ CO_2e\ ha^{-1}\ yr^{-1}$)
		Synthetic N fertilizer → Organic amendments	
Burger et al. (2005)[a]	Field	Tomato	Insufficient data
De Gryze et al. (2009)[a]	Modeled	Alfalfa	0.00
		Corn	0.23
		Rice	0.89
		Tomato	0.07
		Wheat	0.29
		Safflower	0.26
		Sunflower	-0.04
		Cotton	0.02
		Melon	0.07
		Synthetic → Solid Organic	
Aguilera et al. (201b)[2]	Field & Model	Multiple Crops	0.40
		Synthetic/Organic Mixture → Solid Organic	
Aguilera et al. (2013)[b]	Field & Model	Multiple Crops	0.56
		Liquid Organic → Solid Organic	
Aguilera et al. (2013)[b]	Field & Model	Multiple Crops	0.84

[a] California-specific study.
[b] Results are from a meta-analysis representing the mean from 27 studies, including 26 field studies and 1 modeled study, in Mediterranean climates across many cropping systems.

In a modeling study mentioned above, De Gryze, Catala, and Howitt (2009) reported the mitigation potential of various California crops (Table 13) under conventional and organic practices. These modeled results show that supplementing mineral fertility sources with manure reduced emissions in all crops except alfalfa and sunflower. The authors did not speculate on the reasons for increased emissions in sunflower, but it could result from the manure containing a large amount of readily available C, which stimulates microbial processes (Bouwman, Boumans, and Batjes 2002a; Stehfest and Bouwman 2006). However, the paucity of observations makes it difficult to predict the interaction of conservation tillage and organic amendments on N_2O emissions. These modeled results show that combining farming practices (particularly combining conservation tillage with manure application or winter cover cropping with manure application) yielded the largest reductions in GHG emissions, but further research is required to better understand the practices' combined effect on N_2O emissions.

A meta-analysis of all studies available in Mediterranean climates shed additional insight into organic amendment management. Aguilera et al. (2013) found that solid organic amendments yield lower N_2O emissions than even untreated fields and that liquid organic slurries yield the highest emissions. Aguilera et al. (2013) suggested that these findings reflect comparatively high rates of N mineralization and high concentrations of NH_4^+. Switching to solid organic amendments could reduce emissions by 0.40, 0.56, 0.84, and 0.03 t CO_2-e ha^{-1} yr^{-1} on synthetic, synthetic/organic mixtures, liquid organic, and untreated fields, respectively.

Rice Management

Flooded rice cultivation coupled with various winter water and residue management regimes has unique and important effects on emissions of both CH_4 and N_2O. Therefore, this report assesses rice cultivation separately from California's other major crops.

In response to California's Rice Straw Burning Act of 1991, which was passed to improve air quality in the fall in the Sacramento Valley, rice growers have largely shifted their post-harvest management away from straw burning and toward a combination of residue incorporation and winter flooding to facilitate the breakdown of rice straw in the soil (Hill, Williams, Mutters, and Greer 2006). Farmers' efforts to comply with the air quality regulation have also had important economic and environmental tradeoffs, such as increased post-harvest costs and CH_4 emissions (Hill, Williams, Mutters, and Greer 2006; Haden et al. 2013). At present, CH_4 from California rice production accounts for approximately 0.1% of total anthropogenic GHG emissions and less than 1% of agricultural emissions statewide (CARB 2011).

When a rice field is flooded, the soil becomes progressively more anaerobic as the oxygen level and redox potential both decline over time. In the absence of oxygen, decomposition of crop residues and other organic materials is facilitated by anaerobic bacteria that generate CH_4 rather than CO_2 (Horwath 2011). The increased efflux of CH_4 has important implications for climate change, because CH_4 has a global warming potential that is more than 20 times higher than CO_2 over a 100-year time horizon (IPCC 2006). Gaseous CH_4 is released to the atmosphere either through the rice plant itself (e.g., transported through aerenchyma), direct losses from soil via ebullition, and degassing during drainage. Various soil properties such as temperature, texture, chemical content (e.g., C, Fe, NH_4), and redox status can also affect the rate of CH_4 efflux (Kirk 2004). Emissions of N_2O following fertilizer applications also occur during rice cultivation; however, the rate of efflux and the fraction of applied N lost as N_2O (i.e., the N_2O emissions factor) tend to be lower for rice than for crops grown under aerobic soil conditions (IPCC 2006; Linquist et al. 2012a, b).

A recent review of emissions from global rice systems suggests that approximately 89% of the systems' total global warming potential is attributed to CH_4; the remaining 11% comes from N_2O (Linquist et al. 2012b). Practices such as mid-season drainage or flooding period reduction can reduce CH_4 emissions from rice but also promote higher N_2O emissions that offset some of the total emissions reductions (Hou et al. 2000; Johnson-Beebout, Angeles, Alberto, and Buresh 2009). However, most studies that consider both CH_4 and N_2O have found that some form of mid-season drainage still yields a net reduction in GHG emissions (Zou et al. 2005; Linquist et al. 2012b). The countervailing differences in the rate of efflux for CH_4 and N_2O during wetting and drying cycles must each be considered when examining how agricultural management might affect overall emissions from rice cultivation.

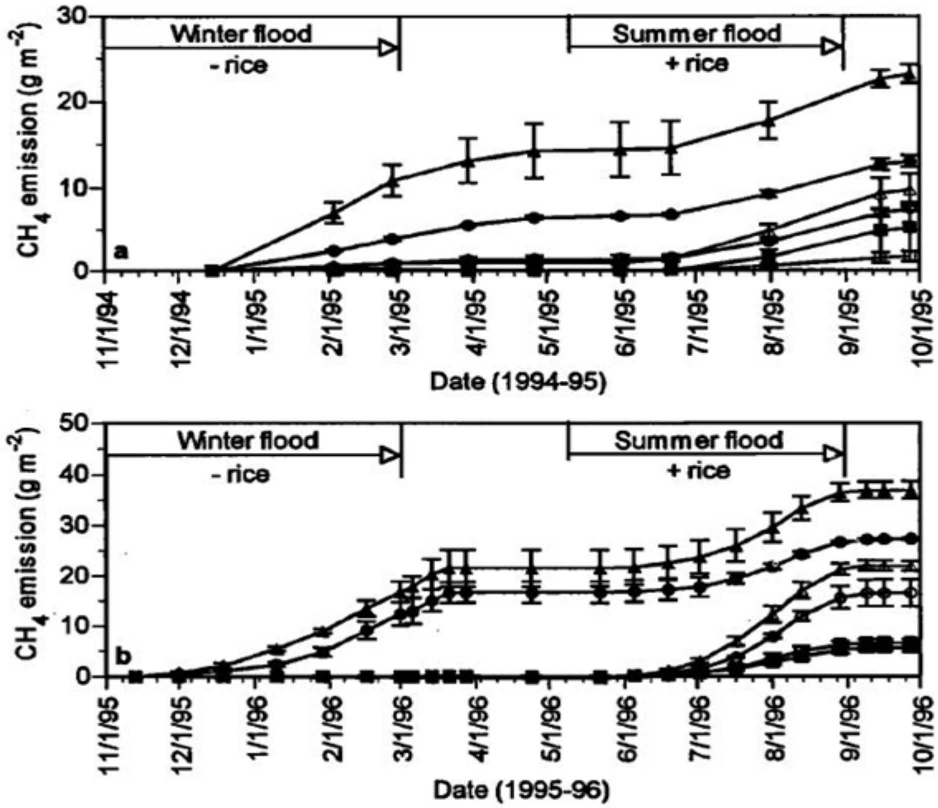
Field Studies

Several field studies conducted in California' Sacramento Valley in the early 1980s were among the first experiments in the world to measure CH_4 from rice paddies (Cicerone and Shetter 1981; Cicerone, Shetter, and Delwiche 1983; Cicerone, Delwiche, Tyler, and Zimmerman 1992). In response to restrictions on straw burning, several studies during the 1990s also examined the effects of new residue incorporation and winter flooding regimes on CH_4 emissions (Bossio, Horwath, Mutters, and van Kessel 1999; Fitzgerald, Scow, and Hill 2000). Bossio, Horwath, Mutters, and van Kessel (1999) measured notably higher CH_4 emissions during the growing season from plots that had incorporated rice straw following harvest during the previous four seasons (88.7–95.2 kg CH_4-C ha^{-1} yr^{-1}), as compared with plots where straw was burned (16.3–22.5 kg CH_4-C ha^{-1} yr^{-1}). Winter flooding did not have a prominent effect on CH_4 emissions during the growing season; however, because Bossio, Horwath, Mutters, and van Kessel (1999) did not report data for the winter period, it is likely that they did not fully capture the effects of winter flooding on annual CH_4 emissions. Fitzgerald, Scow, and Hill (2000) found similar effects of straw incorporation and straw rolling on cumulative annual CH_4 emissions relative to straw burning treatments (Figure 5). They also observed that a significant fraction of the total annual CH_4 emissions (up to 50%) occurred during the winter flooding period following straw incorporation or rolling (Fitzgerald, Scow, and Hill 2000). Devêvre and Horwath (2000) confirmed that colder winter temperatures were not as important as the presence of rice straw in affecting CH_4 emissions. This finding highlights the importance of measuring emissions throughout the fallow period, particularly if winter flooding is part of the post-harvest straw management regime. Mitigation potential estimates based on these California studies are presented in Table 14.

One of the primary limitations of the studies by Bossio, Horwath, Mutters, and van Kessel (1999) and Fitzgerald, Scow, and Hill (2000) is that N_2O was not included in their field measurements. This lack of data on N_2O emissions makes it difficult to fully evaluate (and model) the net impact of various management practices on total emissions from rice in California. To address this gap in data, several recent field experiments that account for both CH_4 and N_2O have been conducted in the Sacramento Valley since 2008 (Linquist, van Kessel, and Hill 2010; Burger and Horwath 2012; Pittelkow et al., in review). A study has also been initiated to evaluate GHG emissions from Histosols (peat soils) in the Sacramento–San Joaquin Delta and the potential for rice production to slow the process of aerobic decomposition and subsidence, which occurs when peat soils are drained, showing significant N_2O production associated with draining events (Horwath, personal communication). These studies have yet to be published in the peer-reviewed literature, thus only the preliminary results are discussed here. Consequently, no calculations of mitigation potential were carried out on these forthcoming studies.

From these recent California studies, several useful findings have begun to emerge. Most notably, a two-year study examining a conventional water-seeded, continuously flooded system found that reductions in yield-scaled global warming potential (kg CO_2e Mg^{-1} grain) can be obtained by efforts to optimize grain yields at currently recommended N rates (Linquist, van Kessel, and Hill 2010; Pittelkow et al., in review).

Figure 5. Cumulative Methane Emissions from Rice in (a) 1994–1995 and (b) 1995–1996



Source: Fitzgerald et al. (2000).
Note: Winter was fallow (- rice). Summer was vegetated (+ rice). Error bars are the standard error of the treatment means. Note difference in y axes between the top and bottom panels. Solid squares = winter flooded and straw burned; solid circles = winter flooded and straw incorporated; solid triangles = winter flooded and straw rolled; open squares = no winter flood and straw burned; open circles = no winter flood and straw incorporated; open triangles = no winter flood and straw rolled.

Table 14. Estimated CH_4 Mitigation Potential of Various California Rice Straw and Water Management Regimes

Source	Data Type	Crop	CH_4 Mitigation Potential (t CO_2e ha^{-1} yr^{-1})
Straw incorporated with winter flood → straw removed or burned with no winter flood			
Bossio et al. (1999)	Field	Rice	1.39
Fitzgerald et al. (2000)	Field	Rice	2.52
Straw incorporated with winter flood → Straw removed or burned with winter flood			
Bossio et al. (1999)	Field	Rice	1.52
Fitzgerald et al. (2000)	Field	Rice	2.32
Straw incorporated with winter flood → Straw incorporated with no winter flood			
Bossio et al. (1999)	Field	Rice	-0.13
Fitzgerald et al. (2000)	Field	Rice	1.29

Recent studies also suggest that GHG emissions reductions can be achieved by adopting a drill-seeded establishment approach combined with either a conventional tillage or stale seedbed approach. Drill-seeding tends to reduce CH_4 emissions by delaying the onset of permanent flood during the growing season, but it increases N_2O emissions relative to the conventional water-seeded system (Assa and Horwath 2009; Burger and Horwathm 2012). Assa and Horwath (2009) measured a 30–35% reduction in CH_4 emissions under the drill-seeded stale seedbed system relative to the water-seeded conventional tillage system. In field experiments where rice was established through water-seeding, the EF for N_2O (i.e., the percentage of applied N lost as N_2O) ranged from 0.12–0.61%, whereas the EF range for drill-seeded treatments (0.54–0.74 %) was consistently higher (Burger and Horwath 2012; Linquist, van Kessel, and Hill 2010). Despite the tradeoffs between CH_4 and N_2O, these preliminary findings indicate that net reductions in total GHG emissions are possible with drill-seeding. Lower grain yields under the drill-seeded stale seedbed system are the primary economic drawback to this approach (Burger and Horwath 2012; Assa and Horwath 2009; Linquist, van Kessel, and Hill 2010).

These ongoing efforts to assess the effects of N rate, establishment method, and winter residue management on net GHG emissions per unit area (kg CO_2e ha^{-1}) and ton of grain (kg CO_2e Mg^{-1} grain) in water-seeded, drill-seeded, and state seedbed systems will provide data for a more complete analysis for California in the near future.

Literature Summary

The 10 management activities discussed above have been summarized in tables 15 and 16. Table 15 lists the specific studies by management activity that this report has used to assess mitigation potential. Twenty published studies evaluate the effects of management activities on GHG emissions in California croplands. Given the diversity of soil types, climates, landscapes, cropping systems, and management practices, these studies represent a very limited amount of information relative to that required to make informed comprehensive policy decisions for GHG reductions in California croplands.

Findings from studies conducted outside California could be applied to California croplands. This report attempts to assess the uncertainty associated with such an endeavor (Table 15). Several of its sections (e.g., N fertilizer source, N fertilizer efficiency enhancers) already rely heavily on studies conducted outside California. This expanded geographic boundary was necessary given that virtually no studies from California exist on particular management strategies. This report also explores the limited number studies available from other Mediterranean climates in the world. These studies provide additional information, but they represent a small fraction of the total published studies on effects of management practices on GHG emissions in croplands.

Where possible, the biophysical mitigation potential values for each management practice were calculated (Table 16). Specifically, they were calculated as the minimum, mean, and maximum of all values reported in the tables in this literature review with respect to each management activity. Management activities that do not report a value (--) could not be calculated for one or more of the following reasons: (1) the activities were too complex to reasonably constrain (e.g., "Farmland Preservation," "Expansion of Perennial Crops"), measurements were based on a continuous rather than a discrete scale (e.g., "N Fertilizer Source"), or California-specific data were lacking (e.g., "N Fertilizer Timing and Placement," "N Fertilizer Efficiency Enhancers").

As discussed below, the relative mitigation potential indicates that two activities, the preservation of farmland and expansion of perennial crops, hold the most potential for mitigating greenhouse gases in California croplands. Two other management activities, better management of nitrogen fertility and improved irrigation practices, could have marked impacts on emissions in California croplands.

Table 15. Greenhouse Gas Emissions Studies Conducted in California Croplands for Various Management Activities

Management Activity	Number of Studies	Uncertainty with Extrapolating Outside Studies to California[a]	References
Farmland Preservation	2	Low – Medium	Haden et al. (2013); Wheeler et al. (2013)
Expansion of Perennial Crops	5	Medium – High	Alfalfa (Burger and Horwath 2012); Almond (Smart et al. 2006; Schellenberg et al. 2012; Alsina et al. 2013); Grape (Garland et al. 2011)
N Fertilizer Rate	2	Low	Almond (Smart et al. 2006); Lettuce, Tomato, and Wheat (Burger and Horwath 2012)
N Fertilizer Source	1	Low – Medium	Almond (Schellenberg et al. 2012)
N Fertilizer Timing and Placement	0	Low	--
N Fertilizer Efficiency Enhancers[b]	0	Low	--
Irrigation Practices	3	Medium	Almond (Alsina et al. 2013); Tomato (Kallenbauch et al. 2010; Kennedy 2012)
Conservation Till or No-till	7	High	Maize, Sunflower, Chickpea (Lee et al. 2009; Kong et al. 2009); Tomato (Kallenbauch et al. 2010; Kennedy 2012); Grape (Steenwerth and Belina 2010; Garland et al. 2011); 9 modeled crops (De Gryze et al. 2009)
Cover Crops and Organic Amend.	6	Medium	Tomato (Burger et al. 2005; Kallenbauch et al. 2010; Kennedy 2012; Smukler et al. 2012); Grape (Steenwerth and Belina 2008); 9 modeled crops (De Gryze et al. 2009)
Rice Management	5	Medium	Rice (Bossio et al., 1999; Fitzgerald et al. 2000; Linquist et al. 2010; Burger and Horwath (2012); Pittelkow et al. (in review)

[a] Uncertainty with extrapolating studies conducted outside California to the California landscape is intended to reflect the relative confidence with which findings of these studies can be applied to California croplands. The low-medium-high ratings are based on a variety of relevant factors associated with each management activity.
[b] N fertilizer efficiency enhancers include polymer-coated fertilizers, nitrification inhibitors, and urease inhibitors.

Table 16. Summary of Biophysical Mitigation Potential for Various Management Activities in California Croplands

Management Activity	Predominant Gases Involved	Biophysical Mitigation Potential[a] ($t\ CO_2e\ ha^{-1}\ yr^{-1}$) Min	Mean	Max	Relative Mitigation Potential[b]
Farmland Preservation	CO_2, N_2O, CH_4	--	--	--	High
Expansion of Perennial Crops	CO_2 N_2O	--	--	--	Medium
N Fertilizer Rate	N_2O	--	--	--	Medium
N Fertilizer Source	N_2O	-0.16	0.33	1.85	Low – Medium
N Fertilizer Timing and Placement	N_2O	--	--	--	Low – Medium
N Fertilizer Efficiency Enhancers[c]	N_2O	--	--	--	Low – Medium
Irrigation Practices	N_2O	0.31	0.78	1.26	Low – Medium
Conservation Till or No-till	N_2O	-0.69	0.04	0.65	Low
Cover Crops and Organic Amend.	N_2O	-1.69	0.03	0.89	Low
Rice Management	CH_4, N_2O	-0.13	1.49	2.52	Low - Medium

[a] Biophysical mitigation potential values were calculated as the minimum, mean, and maximum of all values reported in the tables above with respect to management activity. Management activities that do not report a value (--)could not be calculated for one or more of the following reasons: (1) the activities were too complex to reasonably constrain (e.g., "Farmland Preservation," "Expansion of Perennial Crops"), measurements were based on a continuous rather than a discrete scale (e.g., "N Fertilizer Source"), or California-specific data were lacking (e.g., "N Fertilizer Timing and Placement," "N Fertilizer Efficiency Enhancers").

[b] The relative mitigation potential is intended assess the possible impact that a particular management practice could have on emissions reduction on an annualized per unit area basis relative to other management activities. Each category is defined as follows: Low (<1 $t\ CO_2e\ ha^{-1}\ yr^{-1}$), Medium (1-5 $t\ CO_2e\ ha^{-1}\ yr^{-1}$), High (>5 $t\ CO_2e\ ha^{-1}\ yr^{-1}$).

[c] N fertilizer efficiency enhancers include polymer-coated fertilizers, nitrification inhibitors, and urease inhibitors.

KEY FINDINGS

- Agriculture contributes approximately 7% of California's total GHG emissions; less than 3% coming from croplands.

- Relatively few field studies conducted in California rigorously examine GHG emissions from changes in agricultural management activities and practices. Thus, more research could inform future management and policy alternatives.

- Becuse average GHG emissions from urban land uses are orders of magnitude higher than those from California croplands (approximately 70 times higher per unit area), farmland preservation, more than any of the other management activity, will likely have the single greatest impact in stabilizing and reducing future emissions across multiple land use categories.

- More than half of California croplands are devoted to perennial agriculture; a relatively large proportion (34%) is in orchards and vineyards. These perennial systems likely mitigate a relatively large amount of GHG emissions when converted to annual crops (ranging from 2.92 to 5.24 $t\ CO_2e\ ha^{-1}\ yr^{-1}$ (Eagle et al. 2012)), but the magnitude of emissions reduction remains uncertain. However, biomass C storage is temporary; an equilibrium between production and decomposition is quickly established.

- Increasing N fertilizer rates generally leads to increases in N_2O emissions. However, N fertilization is imperative to maintain the productivity of California cropping systems. An arbitrary reduction of N fertilization rates is often not economically feasible for growers and has large implications for state, national, and global food security. Efforts to increase N-use efficiency by avoiding N rates that greatly exceed those required for economically optimum yields offers moderate potential to reduce N_2O emissions—a particular concern given rapid adoption of micro-irrigation practices that necessitate reassessment of N fertilizer rates. Likewise, calculations of yield-scaled emissions should be more frequently employed to evaluate N_2O emissions relative to the productivity of the cropping system.

- Substituting a lower-emitting N fertilizer source offers moderate potential to reduce N_2O emissions (-0.16 to 1.85 t CO_2e ha^{-1} yr^{-1}). However, very little information on California-specific cropping systems exists. The best solutions would provide comparably priced fertilizers that require no major modifications to current management practices.

- Field experiments examining the effects of N placement and timing have not been conducted for California cropping systems.

- Moderate reductions in N_2O emissions are possible with N fertilizer efficiency enhancers, such as polymer-coated fertilizers (35%), nitrification inhibitors (38%), and urease inhibitors (10%). These products can enhance the efficiency of N fertilizers by helping match N availability with crop demand. However, these products are not widely used in California cropping systems due to concerns regarding their cost. Their efficacy in micro-irrigation systems is likely diminished, because N-use efficiency is increased by fertigation.

- Irrigation technologies such as sub-surface drip irrigation offer opportunities to moderately reduce N_2O emissions (0.31 to 1.26 t CO_2e ha^{-1} yr^{-1}) with co-benefits of improved yield and water use for some cropping systems.

- Conservation tillage practices have had very poor adoption rates in California relative to other regions in the United States. Although these practices generally provide a number of agronomic and environmental benefits, their potential to mitigate GHG emissions in California—studies show ranges from -0.69 to 0.65 t CO_2e ha^{-1} yr^{-1}—are highly uncertain.

- Cover crops and organic amendments' effect on emissions are not well understood in California. These crops and amendments offer opportunities to reduce synthetic N inputs and increase internal nutrient cycling efficiencies, but they may also increase direct N_2O emissions (in particular, leguminous cover crops). Limited studies demonstrate that N_2O mitigation potential ranges from -1.69 to 0.89 t CO_2e ha^{-1} yr^{-1}.

- Emissions from California rice cultivation are approximately 0.01% of total statewide emissions; thus, the overall scope for emissions reductions is relatively low. However, strategies to reduce emissions from rice cultivation (e.g., straw removal, drill seeding, reduced duration of flooding in the season, or winter fallow) offer low to moderate potential to reduce CH_4 emissions per unit area (-0.13 to 2.52 t CO_2e ha^{-1} yr^{-1}). Constraints to straw removal include baling costs and a limited market for rice straw. Comparatively low yields in drill-seeded systems are also an important drawback.

INFORMATION NEEDED TO ASSESS TOTAL MITIGATION POTENTIAL

To evaluate the scope for implementation of various GHG management activities and to develop potential offset protocols for the agricultural sector in California, policy makers need the information described in Table 17. They also need to better understand the practical barriers that limit adoption of GHG-mitigating activities and the policies that might facilitate their implementation. These issues and the availability of relevant information are examined below in the context of each management activity. Where accurate information is still lacking, an effort was made to identify the most important data and knowledge gaps.

Table 17. Key Information Needed to Assess Mitigation Potential for Management Activities in California Croplands

Information Needs
What is the current acreage where greenhouse gas management activity is already used?
What is the relative proportion of acreage that a management activity is practiced for a given crop type?
What is the recent rate of adoption—by crop and overall—for various management activities?
What is the total statewide acreage—by crop and overall—where future adoption is possible?
What is a realistic estimate of the acreage—by crop and overall—where future adoption is likely?
Is adoption (or disadoption) driven more by market or policy factors?
What are the main technical, economic, and social barriers to adoption?

Farmland Preservation

With the passing of the Sustainable Communities and Climate Protection Act of 2008 (SB 375) by the California legislature, efforts to reduce GHG emissions by promoting compact growth and farmland preservation are increasingly being integrated into regional development and transportation plans. However, the total amount of current farmland preserved (or likely to be preserved in the future) under these plans has not been rigorously estimated statewide. Several general plans adopted by municipal governments now require a set amount of farmland to be put into a permanent agricultural easement when any existing farmland is converted to urban land uses. For example, in the unincorporated areas of Stanislaus County, one acre of farmland must be put into a permanent agricultural easement for each acre of new urban or industrial development (Stanislaus County 2007). Likewise, the cities of Davis and Hughson require a 2:1 “land mitigation” ratio of farmland preservation to new urban development, and in certain circumstance may require ratios greater than 2:1 (City of Davis 2013; City of Hughson 2012). With legal precedence for these farmland preservation policies already established in California, other local governments are likely to consider adopting a similar approach in their regional development plans. Additional research on these land use policies will be needed to further assess their impact on regional GHG emissions across multiple land use types.

Expansion of Perennial Crops

Acreage of perennial crops, such as fruits and nuts, grapes, and irrigated hay and alfalfa have been increasing overall in California over the past several decades (UCAIC 2009). This expansion has come at the expense of some field crops, such as cotton and small grains. The management and permanence of perennial crops varies widely among species as well as among broad function groups (e.g., tree, shrubs, or herbaceous). This crop management, coupled with plant life strategy, plays an important role in total C inventories in these agroecosystems (soil and biomass), and the relative amount of emitted greenhouse gases (Williams et al. 2011). Despite perennial crops’ large potential to reduce GHG emissions in California, only 5 published studies document these emissions (Table 15).

N Fertilizer Rate

Nitrogen fertilization concurrently drives agricultural productivity and N_2O emissions. As discussed above, yield-scaled emissions provide a useful metric to account for GHG emissions relative to productivity. Greater use of this approach will help agricultural researchers and practitioners identify optimum N fertilization rates for a given system. In reality, identifying these rates is challenging, because soil N dynamics are influenced by interacting factors such as weather, soil properties, site history, and individual management. Furthermore, getting an accurate assessment of actual N fertilization application rates is equally challenging, because growers decide these rates on the basis of information from a variety of sources (e.g., soil tests, academic and industry recommendations, previous management and experience, and perceived yield potential of fields). Because N fertilizer often represents a substantial input cost, growers already have an incentive to minimize N fertilization needs. They will almost always associate any reduction in an established fertilizer application rate with risk of yield reduction. A number of avenues will be necessary to optimize N fertilization, including (1) scientific studies that determine optimal N rates with ever-changing plant genetics, management, and climate; (2) better tools that allow for real-time monitoring of crop nutritional status, and (3) better education and training of growers striving to optimize N inputs.

N Fertilizer Timing and Placement

Because no California-based studies have specifically examined these strategies as a means to reduce N_2O emissions, additional data on farmer adoption would not facilitate development of offset protocols at this time. However, use of fertilizer efficiency enhancers and various fertigation technologies have important implications for both the timing and placement of N fertilizers. Consequently, trends in the adoption of these related technologies, which are described below, are likely to also be key drivers of improved timing and placement.

N Fertilizer Efficiency Enhancers

The meta-analyses examined in this report suggests that use of N fertilizer efficiency enhancers can yield significant reductions in N_2O emissions and that polymer-coated fertilizers and nitrification inhibitors may reduce N_2O flux by an average of 35% and 38%, respectively, even when N rates are held constant (Akiyama, Yan, and Yagi 2010). Additional N_2O reductions would also be achieved if improvements in N use efficiency facilitated a moderate reduction in N rate. At present, the use of N fertilizer efficiency enhancers, polymer-coated fertilizers, and nitrification inhibitors in California and elsewhere is extremely low due to their high cost relative to conventional mineral fertilizers (Trenkel 2010; R. Smith, personal communication 2013). Data on use of these products in California is unavailable (R. Smith, personal communication 2013). However, recent reports indicate that a combination of declining production costs and increasing manufacturing capacity are gradually reducing the cost of these fertilizer products (Trenkel 2010). Several commercial products are available for a moderate price premium. If these production trends continue, the relative profitability of N efficiency enhancers is likely to increase as the price of N fertilizers and grain rise in the global market (Laboski 2006).

Irrigation Practices

As noted above, innovative water management technologies such as drip and micro-sprinkler irrigation have potential to reduce N_2O emissions relative to conventional furrow and flood irrigation. Recent surveys of irrigation methods in California also indicate that an increasing number of growers are using drip and micro-sprinkler irrigation, particularly for higher-value perennial and annual vegetable crops (Tindula, Orang, and Snyder 2013; Orang, Matyac, and Snyder 2008). For example, as of 2010, either drip or micro-sprinkler irrigation was used on more than 70% of almond, vineyard, and subtropical orchard crop acreage in California. These low-volume irrigation technologies are used on about 40% of existing acreage planted in deciduous trees such as walnuts (Tindula, Orang, and Snyder 2013) and are also increasingly used in processing tomatoes (63%), fresh market tomatoes (45%), onions (42%), cucurbits (39%), and other truck crops (35%). In some circumstances, drip and micro-sprinklers can be used to irrigate various grain and field crops; however, the cost of these technologies limits their feasibility in these lower-value crops (e.g., drip or micro-sprinklers are used on only 0–15% of current acreage planted in field crops). Research in California should thus focus on overcoming the remaining economic and technical barriers to the technologies' adoption in grain and field crop systems. This adoption has been driven almost entirely by market forces related to higher yields and more efficient water and fertilizer use; possible reductions in N_2O emissions are one of several important (albeit unintended) environmental co-benefits. Policies and incentives that help to stimulate adoption of these irrigation technologies are likely to be beneficial from both climate change mitigation and adaptation standpoints (Haden et al. 2012).

Conservation Tillage and No Tillage

Conservation tillage is practiced on 23% of total U.S. cropland (Triplett and Dick 2008) but on less than 2% of California cropland. The low rate of adoption in California suggests substantial barriers to use of conservation and no tillage systems in the state (Mitchell et al. 2009). One barrier is indicated in a meta-analysis by van Kessel et al. (2013) showing that no-till and reduced-till systems had 5% lower yields than conventionally tilled systems across all climates; differences were more pronounced in dry climates (11% yield reduction). Haden et al. (2013) indicated another barrier to adoption: conservation tillage may not be compatible with California's comparatively complex annual crop rotations. Although conservation tillage could be practiced in California's various perennial vineyard and orchard cropping systems, its current rate of adoption and possible tradeoffs there have not been adequately examined in the scientific literature. Given California farmers' lack of interest in conservation tillage, other management practices discussed in this report might hold greater potential for early adoption.

Cover Crops and Organic Amendments

Information on the extent to which cover crops and organic amendments are used in California is limited. An informal grower survey on cover crops in California vineyards in 1997 found that of the 770,338 acres planted in vineyards across the state, approximately 124,144 acres (16%) had cover crops (Ingles 1998). In another informal survey—this time of tomato and safflower growers from five California counties (Yolo, Solano, Sutter, San Joaquin, Colusa) in 1994—found that 34 of 119 growers (29%) were using cover crops (Ridgely and Van Horn 1995). Organic growers planted cover crops at much higher rates (68%) than conventional growers (8%). Of those growers who plant cover crops, 69% do so only in the winter. Growers cited three main reasons for not growing cover crops: (1) they were unable to incorporate cover crops in time for spring planting, (2) they had the option to plant a cash crop with a direct economic benefit instead, and (3) they found the overall cost of growing cover crops too high (Ridgely and Van Horn 1995). These barriers hinder cover crop adoption across the country (Snapp et al. 2005).

Rice Management

CH_4 and N_2O emissions from rice production contribute less than 1% to total statewide agricultural emissions. Therefore, the overall scope for significantly reducing these emissions through the various water and crop residue management activities described above is comparatively low. Emissions data for rice cropping practices are more robust than those for other cropping practices, and farmers' use of rice cropping practices are reasonably well-documented. For example, more than 96% of rice is managed under the continuous flooding and water-seeded regime; more than half of these acres employ some form of straw incorporation and winter flooding (CARB 2011; Haden et al. 2013). In contrast, less than 4% of California acres are dry seeded each year, and on only 2–6% of acres do farmers bale and remove straw (CARB 2011). Comparatively low yields from dry-seeded systems and poor market opportunities for baled rice straw are the main constraints to adoption of a water-seeded regime. Moreover, the Rice Cultivation Project Protocol (CAR 2011) currently under review by the California Air Resources Board shows in detail the type of information needed to develop scientifically rigorous biogeochemical models (e.g., the DeNitrification DeComposition Model) that are validated for California production conditions (CARB 2011). While this prototype offset protocol includes only a limited selection of eligible management activities (e.g., dry seeding with delayed flooding, post-harvest straw baling and removal), it shows what is required to ensure that mitigation projects meet the criteria of being real, permanent, quantifiable, verifiable, enforceable, and additional (Niemeier and Rowan 2009). It also highlights potential opportunities to financially incentivize the adoption of mitigation practices if sufficient local data eventually becomes available for other crops and management practices.

RESEARCH PRIORITIES AND RECOMMENDATIONS

This report has outlined information gaps regarding N_2O, CH_4, and CO_2 emissions from agricultural croplands in California. The paucity of information on GHG emissions in California agriculture is in part a result of the state's diverse crops (annual versus perennial) and rotations (vegetables versus grain) and its unique management practices (e.g., irrigation, intensive tillage), which make for sparse datasets for individual crops. Many study results from which this report draws data and inferences are of grain-based cropping systems. The IPCC's proposed emissions factor for N_2O production from fertilizer N applications (IPCC 2006, 2007) relies heavily on data from these systems—particularly those in temperate climates in the northern hemisphere. As shown in the reported studies above, diversity of crops, irrigation practices, fertilizer management, and so on strongly influence emissions factors; therefore, unique emissions factors are likely needed for each crop and cropping system.

Better understanding of N_2O, CH_4, and CO_2 emissions in California agriculture requires research on the following:

- Impacts of farmland loss on GHG emissions across major land use types and policies that reduce urbanization of landscapes.
- Inventories of C stocks and GHG emissions in California's vine and woody perennial crops.
- Ways in which tillage, residue management, irrigation management, and cropping system influence C cycling and sequestration in agricultural soils.
- Efficient use of nitrogen fertilizers in California.
    - Site- and crop-specific N-rate yield and emission trials to optimize yield-scaled emissions factors.
    - Optimal fertigation, particularly that associated with micro-irrigation technologies.
    - Best fertilizer stabilizers, such as nitrification inhibitors, for micro-irrigation and perennial crops.
- Development and implementation of drip and microsprinkler irrigation technologies across lower-value crops and perennial systems, particularly alfalfa.
- Ammonia oxidation-related pathways and appropriate management practices to reduce emissions across a range of soil conditions.
- Off-season emissions' contribution to total annual emissions.
- Fertilizer types, rates, and application methods to reduce N_2O emissions across all crops.
- Effect of cover crops (legumes versus grasses) on the behavior of fertilizers and residual soil N.
- Effect of soil disturbance by tillage and compaction on soil conditions leading to N_2O emissions.
- Influence of alternative fertilizer sources such food processing wastes.
- Ways in which crop establishment and the management of water, residue, and fertilizers effect CH_4 and N_2O emissions in rice cropping systems.

- Optimization of biogeochemical models to better estimate N_2O emissions across diverse crops and crop rotations, particularly those containing perennials.
- Improved measurement technologies and modeling approaches to apply field-based GHG measurements to larger spatial scales (e.g., landscape, regional, national).

This list of research needs illustrates the complexity of N fertilizer use in agriculture. It also suggests that reducing N_2O emissions from agriculture requires university extension services and the producers, manufacturers, and distributers of fertilizers to jointly promote efficient use of fertilizer N and adoption of other GHG mitigation strategies. To that end, this report recommends the following:

- A standardized approach to developing nutrient management plans and user-friendly tools (e.g., computer programs and applications for smart phones and tablets) that help growers identify the most efficient nutrient application practices.
- Greater efforts by university extension services—and less reliance on fertilizer suppliers—to provide unbiased information to growers on nutrient management plans and N fertilizer application rates.
- Greater responsibility on the part of commodity groups to promote sustainable and efficient N fertilizer use.
- Reinvigoration of the alliance of the Agricultural Experiment Station, commodity groups, and food processors to promote efficient use of N fertilizers.

REFERENCES

Abdalla, M., B. Osborne, G. Lanigan, D. Forristal, M. Williams, P. Smith, and M.B. Jones. 2013. “Conservation Tillage Systems: A Review of Its Consequences for Greenhouse Gas Emissions.” *Soil Use and Management*: in press. doi:10.1111/sum.12030.

Aguilera, E., L. Lassaletta, A. Sanz-Cobena, J. Garnier, and A. Vallejo. 2013. “The Potential of Organic Fertilizers and Water Management to Reduce N_2O Emissions in Mediterranean Climate Cropping Systems. A Review.” *Agriculture, Ecosystems & Environment* 164 (January 1): 32–52. doi:10.1016/j.agee.2012.09.006.

Akiyama, H., X. Yan, and K. Yagi. 2010. “Evaluation of Effectiveness of Enhanced-Efficiency Fertilizers as Mitigation Options for N_2O and NO Emissions from Agricultural Soils: Meta-Analysis.” *Global Change Biology* 16 (6): 1837–1846. doi:10.1111/j.1365-2486.2009.02031.x.

Alsina, M.M., A.C. Fanton-Borges, and D.R. Smart. 2013. “Spatiotemporal Variation of Event-Related N_2O and CH_4 Emissions during Fertigation in a California Almond Orchard.” *Ecosphere* 4 (1) (January 1): 1–21. doi:10.1890/ES12–00236.1.

Alvarez, R. 2005. “A Review of Nitrogen Fertilizer and Conservation Tillage Effects on Soil Organic Carbon Storage.” *Soil Use and Management* 21 (1): 38–52. doi:10.1111/j.1475-2743.2005.tb00105.x.

Angers, D.A., and N.S. Eriksen-Hamel. 2008. “Full-Inversion Tillage and Organic Carbon Distribution in Soil Profiles: A Meta-Analysis.” *Soil Science Society of America Journal* 72 (5): 1370–1374. doi:10.2136/sssaj2007.0342.

Appel, T. 1998. “Non-Biomass Soil Organic N–the Substrate for N Mineralization Flushes Following

Soil Drying–Rewetting and for Organic N Rendered CaCl2-Extractable Upon Soil Drying." *Soil Biology and Biochemistry* 30 (10–11) (September): 1445–1456. doi:10.1016/S0038-0717(97)00230–7.

Archer, D.W., J.L. Pikul Jr., and W.E. Riedell. 2002. "Economic Risk, Returns and Input Use under Ridge and Conventional Tillage in the Northern Corn Belt, USA." *Soil and Tillage Research* 67 (1) (August): 1–8. doi:10.1016/S0167–1987(02)00016–8.

Assa, Y., and W. Horwath. 2009. *Report on Greenhouse Gas Emissions Study at Biggs, CA Rice Experiment Station Conducted in May 2008–May 2009.* University of California, Davis.

Baker, J.M., T.E. Ochsner, R.T. Venterea, and T.J. Griffis. 2007. "Tillage and Soil Carbon Sequestration: What Do We Really Know?" *Agriculture Ecosystems & Environment* 118 (1-4): 1–5.

Bolan, N.S., S. Saggar, J. Luo, R. Bhandral, and J. Singh. 2004. "Gaseous Emissions of Nitrogen from Grazed Pastures: Processes, Measurements and Modelling, Environmental Implications, and Mitigation." *Advances in Agronomy* Volume 84: 37–120.

Bossio, D.A., W.R. Horwath, R.G. Mutters, and C. van Kessel. 1999. "Methane Pool and Flux Dynamics in a Rice Field Following Straw Incorporation." *Soil Biology and Biochemistry* 31 (9) (August): 1313–1322. doi:10.1016/S0038-0717(99)00050–4.

Bouwman, A.F., L.J.M. Boumans, and N. H. Batjes. 2002a. "Emissions of N_2O and NO from Fertilized Fields: Summary of Available Measurement Data." *Global Biogeochemical Cycles* 16 (4): 1–13. doi:10.1029/2001GB001811.
Bouwman, A.F., L.J.M. Boumans, and N. H. Batjes. 2002b. "Modeling Global Annual N_2O and NO Emissions from Fertilized Fields." *Global Biogeochemical Cycles* 16 (4): 1–9. doi:10.1029/2001GB001812.

Breitenbeck, G.A., A.M. Blackmer, and J.M. Bremner. 1980. "Effects of Different Nitrogen Fertilizers on Emission of Nitrous Oxide from Soil." *Geophysical Research Letters* 7 (1): 85–88. doi:10.1029/GL007i001p00085.

Breitenbeck, G.A., and P. Bremner. 1986. "Effects of Rate and Depth of Fertilizer Application on Emission of Nitrous Oxide from Soil Fertilized with Anhydrous Ammonia." *Biology and Fertility of Soils* 2 (4) (August): 201–204. doi:10.1007/BF00260844.

Bremner, J.M., G.A. Breitenbeck, and A.M. Blackmer. 1981. "Effect of Anhydrous Ammonia Fertilization on Emission of Nitrous Oxide from Soils." *Journal of Environmental Quality* 10 (1): 77–80. doi:10.2134/jeq1981.00472425001000010017x.

Burger, M., L.E. Jackson, E.J. Lundquist, D.T. Louie, R.L. Miller, D.E. 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 (2): 109–118.

Burger, M., and R. Venterea. 2011. "Effects of Nitrogen Fertilizer Types on Nitrous Oxide Emissions." In *Understanding Greenhouse Gas Emissions from Agricultural Management* 1072: 179–202. ACS Symposium Series. American Chemical Society. http://dx.doi.org/10.1021/bk–2011–1072.ch011.

Burger, M., and W.R. Horwath. 2012. *Assessment of Baseline Nitrous Oxide Emissions in California Cropping Systems.* Sacramento, CA: California Air Resources Board.

Burton, D.L., X. Li, and C.A. Grant. 2008a. "Influence of Fertilizer Nitrogen Source and Management Practice on N_2O Emissions from Two Black Chernozemic Soils." *Canadian Journal of Soil Science* 88 (2) (May): 219–227. doi:10.4141/CJSS06020.

Burton, D.L., B.J. Zebarth, K.M. Gillam, and J.A. MacLeod. 2008b. "Effect of Split Application of Fertilizer Nitrogen on N2O Emissions from Potatoes." *Canadian Journal of Soil Science* 88 (2) (May): 229–239. doi:10.4141/CJSS06007.

CDFA (California Department of Food and Agriculture). 2007. *Fertilizer Tonnage Reports 2002–2007*. Sacramento, CA: California Department of Food and Agriculture.

CAR (Climate Action Reserve). 2011. *Rice Cultivation Project Protocol.* Los Angeles, CA: Climate Action Reserve.

CARB (California Air Resources Board). 2011. *California Greenhouse Gas Emissions Inventory: 2000–2009.* Sacramento, CA: California Air Resources Board, California Environmental Protection Agency. Available from http://www.arb.ca.gov/cc/inventory/data/data.htm.

Cicerone, R.J., C.C. Delwiche, S.C. Tyler, and P.R. Zimmerman. 1992. "Methane Emissions from California Rice Paddies with Varied Treatments." *Global Biogeochemical Cycles* 6 (3): 233–248. doi:10.1029/92GB01412.

Cicerone, R.J., J.D. Shetter, and C.C. Delwiche. 1983. "Seasonal Variation of Methane Flux from a California Rice Paddy." *Journal of Geophysical Research: Oceans* 88 (C15): 11022–11024. doi:10.1029/JC088iC15p11022.

Cicerone, R.J., and J. D. Shetter. 1981. "Sources of Atmospheric Methane: Measurements in Rice Paddies and a Discussion." *Journal of Geophysical Research: Oceans* 86 (C8): 7203–7209. doi:10.1029/JC086iC08p07203.

City of Davis. 2013. *Davis Municipal Code 40A.O3.025 Agricultural Land Mitigation Requirments.* Davis, California. Available from http://qcode.us/codes/davis/.

City of Hughson. 2012. *Farmland Preservation Program.* Hughson, California. Available from http://hughson.org/wp-content/uploads/2012/03/1–Exhibit–A–Hughson–Farmland–Preservation-Program–_2_.pdf.

Crews, T.E, and M.B Peoples. 2004. "Legume versus Fertilizer Sources of Nitrogen: Ecological Tradeoffs and Human Needs." *Agriculture, Ecosystems & Environment* 102 (3) (May): 279–297. doi:10.1016/j.agee.2003.09.018.

Dalal, R.C., W. Wang, G.P. Robertson, and W.J. Parton. 2003. "Nitrous Oxide Emission from Australian Agricultural Lands and Mitigation Options: A Review." *Soil Research* 41 (2) (January 1): 165–195.

De Gryze, S., R. Catala, and R. Howitt. 2009. *Assessment of Greenhouse Gas Mitigation in California Agricultural Soils.* Prepared by the University of California–Davis for the California Energy Commission Public Interest Energy Research Program. Available from http://www.energy.ca.gov/2008publications/CEC-500-2008-039/CEC-500-2008-039.PDF.

De Gryze, S., A. Wolf, S.R. Kaffka, J. Mitchell, D.E. Rolston, S.R. Temple, J. Lee, and J. Six. 2010. "Simulating Greenhouse Gas Budgets of Four California Cropping Systems under Conventional and

Alternative Management." *Ecological Applications* 20 (7) (February 8): 1805–1819. doi:10.1890/09–0772.1.

Devêvre, O.C., and W.R. Horwáth. 2000. "Decomposition of Rice Straw and Microbial Carbon Use Efficiency Under Different Soil Temperatures and Moistures." *Soil Biology and Biochemistry* 32 (11–12) (October 1): 1773–1785. doi:10.1016/S0038–0717(00)00096–1.

Drinkwater, L.E., and S.S. Snapp. 2007. "Nutrients in Agroecosystems: Rethinking the Management Paradigm." In *Advances in Agronomy*, vol. 92, edited by Donald L. Sparks, 163–186.

Dusenbury, M.P., R.E. Engel, P.R. Miller, R.L. Lemke, and R. Wallander. 2008. "Nitrous Oxide Emissions from a Northern Great Plains Soil as Influenced by Nitrogen Management and Cropping Systems." *Journal of Environment Quality* 37 (2): 542. doi:10.2134/jeq2006.0395.

Duxbury, J.M., D.R. Bouldin, R.E. Terry, and R.L. Tate. 1982. "Emissions of Nitrous Oxide from Soils." *Nature* 298 (5873) (July 29): 462–464. doi:10.1038/298462a0.

Eagle, J.E., L.R. Henry, L.P. Olander, K. Haugen-Kozyra, N. Millar, and G.P. Robertson. 2012. "Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States." *A Synthesis of the Literature.* Technical Working Group on Agricultural Greenhouse Gases (T-AGG) Report. http://nicholasinstitute.duke.edu/ecosystem/land/TAGGDLitRev.

Engel, R., D.L. Liang, R. Wallander, and A. Bembenek. 2010. "Influence of Urea Fertilizer Placement on Nitrous Oxide Production from a Silt Loam Soil." *Journal of Environment Quality* 39 (1): 115–125. doi:10.2134/jeq2009.0130.

Fearnside, P.M. 2000. "Global Warming and Tropical Land-use Change: Greenhouse Gas Emissions from Biomass Burning, Decomposition and Soils in Forest Conversion, Shifting Cultivation and Secondary Vegetation." *Climatic Change* 46 (1–2) (July 1): 115–158. doi:10.1023/A:1005569915357.

Fierer, N., and J.P. Schimel. 2002. "Effects of Drying–Rewetting Frequency on Soil Carbon and Nitrogen Transformations." *Soil Biology and Biochemistry* 34 (6) (June): 777–787. doi:10.1016/S0038–0717(02)00007–X.

Fitzgerald, G.J., K.M. Scow, and J.E. Hill. 2000. "Fallow Season Straw and Water Management Effects on Methane Emissions in California Rice." *Global Biogeochemical Cycles* 14 (3): 767–776. doi:10.1029/2000GB001259.

FMMP (Farmland Mapping and Monitoring Program). 2008. *Statewide Change, 1984 and 2008.* Sacramento, CA: California Department of Conservation. Available from http://www.conservation.ca.gov/dlrp/fmmp/trends/Pages/Index.aspx.

———. 2013. Farmland Mapping and Monitoring Program. *Yolo County Change, 1992 and 2008.* Sacramento, CA: California Department of Conservation.

Frye, W.W. 1984. "Energy Requirement in No–Tillage." In *No–Tillage Agriculture Principles and Practices*, 127–151. New York, NY: Van Nostrand Reinhold.

Fujinuma, R., R.T. Venterea, and C. Rosen. 2011. "Broadcast Urea Reduces NO but Increases NO Emissions Compared with Conventional and Shallow-Applied Anhydrous Ammonia in a Coarse–Textured Soil." *Journal of Environment Quality* 40 (6): 1806. doi:10.2134/jeq2011.0240.

Garland, G.M., E. Suddick, M. Burger, W.R. Horwath, and J. Six. 2011. "Direct N_2O Emissions Following Transition from Conventional Till to No-Till in a Cover-Cropped Mediterranean Vineyard (Vitis Vinifera)." *Agriculture, Ecosystems & Environment* 144 (1) (November): 423–428. doi:10.1016/j.agee.2011.11.001.

Grandy, A.S., G.P. Robertson, and K.D. Thelen. 2006. "Do Productivity and Environmental Trade-offs Justify Periodically Cultivating No–Till Cropping Systems?" *Agronomy Journal* 98 (6): 1377–1383. doi:10.2134/agronj2006.0137.

Grandy, A.S., and G.P. Robertson. 2006. "Aggregation and Organic Matter Protection Following Tillage of a Previously Uncultivated Soil." *Soil Science Society of America Journal* 70 (4): 1398. doi:10.2136/sssaj2005.0313.

Grant, R.F., E. Pattey, T.W. Goddard, L.M. Kryzanowski, and H. Puurveen. 2006. "Modeling the Effects of Fertilizer Application Rate on Nitrous Oxide Emissions." *Soil Science Society of America Journal* 70 (1): 235. doi:10.2136/sssaj2005.0104.

Haden, V.R., M. Dempsey, S. Wheeler, W. Salas, and L.E. Jackson. 2013. "Use of Local Greenhouse Gas Inventories to Prioritise Opportunities for Climate Action Planning and Voluntary Mitigation by Agricultural Stakeholders in California." *Journal of Environmental Planning and Management*. doi:10.1080/09640568.2012.689616.

Haden, V.R., M.T. Niles, M. Lubell, J. Perlman, and L.E. Jackson. 2012. "Global and Local Concerns: What Attitudes and Beliefs Motivate Farmers to Mitigate and Adapt to Climate Change?" *PLoS ONE* 7 (12) (December 26): e52882. doi:10.1371/journal.pone.0052882.

Halvorson, A.D., and S.J. Del Grosso. 2013. "Nitrogen Placement and Source Effects on Nitrous Oxide emissions and yields of irrigated corn." *Journal of Environmental Quality* 42, 312–322.

Halvorson, A.D., S.J. Del Grosso, and F. Alluvione. 2010. "Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated No-Till Corn." *Journal of Environment Quality* 39 (5): 1554. doi:10.2134/jeq2010.0041.

Hanson, B., and W.D Bendixon. 2000. "Patterns of Soil Moisture, Soil Salinity, and Soil Nitrate under Drip Irrigation of Row Crops." In *Proceedings of the 2000 National Conference and Exhibition: Water–Essential for Life*. Melbourne, Australia.

Hanson, B., and D. May. 2007. "The Effect of Drip Line Placement on Yield and Quality of Drip–Irrigated Processing Tomatoes." *Irrigation and Drainage Systems* 21 (2) (May 1): 109–118. doi:10.1007/s10795–007–9023–5.

Hill, J.E., J.F. Williams, R.G. Mutters, and C.A. Greer. 2006. "The California Rice Cropping System: Agronomic and Natural Resource Issues for Long-term Sustainability." *Paddy and Water Environment* 4 (1) (March 1): 13–19. doi:10.1007/s10333–005–0026–2.

Horwath, W.R. 2011. "Greenhouse Gas Emissions from Rice Cropping Systems." In *Understanding Greenhouse Gas Emissions from Agricultural Management*, 1072: 67–89. ACS Symposium Series. American Chemical Society. Available from http://dx.doi.org/10.1021/bk–2011–1072.ch005.

Hou, A.X., G.X. Chen, Z.P. Wang, O. Van Cleemput, and W.H. Patrick. 2000. "Methane and Nitrous

Oxide Emissions from a Rice Field in Relation to Soil Redox and Microbiological Processes." *Soil Science Society of America Journal* 64 (6) (November 1): 2180–2186. doi:10.2136/sssaj2000.6462180x.

Hultgreen, G., and P. Leduc. 2003. *The Effect of Nitrogen Fertilizer Placement, Formulation, Timing, and Rate on Greenhouse Gas Emissions and Agronomic Performance.* Final Report Project No. 5300G, ADF#19990028. Sacramento, CA: Department of Agriculture and Food.

Ingles, C. 1998. *Cover Cropping in Vineyards: A Grower's Handbook.* Publication 3338. Davis, CA.: University of California Division of Agriculture and Natural Resources.

IPCC (International Panel on Climate Change). 1995. *IPCC Second Assessment: Climate Change 1995.* Intergovernmental Panel on Climate Change.

———. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories.* Japan: Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Program.

———. 2007. *Climate Change 2007: Synthesis Report.* Contribution of Working Groups I, II and III to the Fourth Assessment. Cambridge, UK: Intergovernmental Panel on Climate Change.

———. 2013. *Climate Change 2013: The Physical Science Basis.* Working Group I Contribution to the IPCC Fifth Assessment Report. Intergovernmental Panel on Climate Change.

Jackson, L.E., V.R. Haden, A.D. Hollander, H. Lee, M. Lubell, V.K. Mehta, A.T. O'Geen, M. Niles, J. Perlman, D. Purkey, W. Salas, D. Sumner, M. Tomuta, M. Dempsey, and S.M. Wheeler. 2012. *Adaptation Strategies for Agricultural Sustainability in Yolo County, California.* CEC–500–2012–032. Sacramento, CA: California Energy Commission.

Johnson-Beebout, S.E., O.R. Angeles, M.C.R. Alberto, and R.J. Buresh. 2009. "Simultaneous Minimization of Nitrous Oxide and Methane Emission from Rice Paddy Soils Is Improbable Due to Redox Potential Changes with Depth in a Greenhouse Experiment Without Plants." *Geoderma* 149 (1–2) (February 15): 45–53. doi:10.1016/j.geoderma.2008.11.012.

Kallenbach, C., W.R. Horwath, Z. Kabir, J. Mitchell, and D. Rolston. 2006. *Use of Conservation Tillage, Subsurface Drip Irrigation and Cover Cropping to Reduce Soil Carbon and Nitrogen Emissions and Sequester Soil Carbon.* University of California, Davis: Kearney Foundation of Soil Science. Available from
http://kearney.ucdavis.edu/OLD%20MISSION/2004_Final_Reports/2004221Horwath_FINALkms.pdf.

Kallenbach, C.M., D.E. Rolston, and W.R. Horwath. 2010. "Cover Cropping Affects Soil N_2O and CO_2 Emissions Differently Depending on Type of Irrigation." *Agriculture, Ecosystems & Environment* 137 (3–4) (May 15): 251–260. doi:10.1016/j.agee.2010.02.010.

Kennedy, T.L. 2012. *Nitrous Oxide Emissions from California Tomato Cropping Systems under Conventional and Alternative Management.* M.S., University of California, Davis.

Kirk, G. 2004. *The Biogeochemistry of Submerged Soils*. Chichester, UK: John Wiley & Sons.

Kong, A.Y.Y., S.J. Fonte, C. van Kessel, and J. Six. 2009. "Transitioning from Standard to Minimum Tillage: Trade-offs between Soil Organic Matter Stabilization, Nitrous Oxide Emissions, and N Availability in Irrigated Cropping Systems." *Soil and Tillage Research* 104 (2) (July): 256–262. doi:10.1016/j.still.2009.03.004.

Kravchenko, A.N., and G.P. Robertson. 2011. “Whole-Profile Soil Carbon Stocks: The Danger of Assuming Too Much from Analyses of Too Little.” *Soil Science Society of America Journal* 75 (1): 235. doi:10.2136/sssaj2010.0076.

Laboski, C. 2006. “Does It Pay to Use Nitrification and Urease Inhibitors?” In *Proceedings of the 2006 Wisconsin Fertilizer, Aglime & Pest Management Conference,* vol. 45.

Lee, J., J.W. Hopmans, C. van Kessel, A.P. King, K.J. Evatt, D. Louie, D.E. Rolston, and J. Six. 2009. “Tillage and Seasonal Emissions of CO_2, N_2O and NO across a Seed Bed and at the Field Scale in a Mediterranean Climate.” *Agriculture, Ecosystems & Environment* 129 (4) (February): 378–390. doi:10.1016/j.agee.2008.10.012.

Linquist, B.A., M.A. Adviento-Borbe, C.M. Pittelkow, C. van Kessel, and K.J. van Groenigen. 2012. “Fertilizer Management Practices and Greenhouse Gas Emissions from Rice Systems: A Quantitative Review and Analysis.” *Field Crops Research* 135 (August 30): 10–21. doi:10.1016/j.fcr.2012.06.007.

Linquist, B.A., K.J. van Groenigen, M.A. Adviento-Borbe, C.M. Pittelkow, and C. van Kessel. 2012. “An Agronomic Assessment of Greenhouse Gas Emissions from Major Cereal Crops.” *Global Change Biology* 18 (1): 194–209. doi:10.1111/j.1365-2486.2011.02502.x.

Linquist, B.A., C. van Kessel, and J. Hill. 2010. “Annual Report Comprehensive Research on Rice: Improving Fertilizer Guidlines for California’s Changing Rice Climate.” Yuba City, CA: California Rice Research Board. Available from http://www.carrb.com/10rpt/2010%20RM4%20Linquist.pdf.

Maharjan, B., and R.T. Venterea. 2013. “Nitrite Intensity Explains N Management Effects on N_2O Emissions in Maize.” *Soil Biology and Biochemistry* 66 (November): 229–238. doi:10.1016/j.soilbio.2013.07.015.

Matthiessen, J.N., and J.A. Kirkegaard. 2006. “Biofumigation and Enhanced Biodegradation: Opportunity and Challenge in Soilborne Pest and Disease Management.” *Critical Reviews in Plant Sciences* 25 (3): 235–265. doi:10.1080/07352680600611543.

McSwiney, C.P., and G.P. Robertson. 2005. “Nonlinear Response of N_2O Flux to Incremental Fertilizer Addition in a Continuous Maize (Zea Mays L.) Cropping System.” *Global Change Biology* 11 (10): 1712–1719. doi:10.1111/j.1365–2486.2005.01040.x.

Minoshima, H., L.E. Jackson, T.R. Cavagnaro, S. Sánchez-Moreno, H. Ferris, S.R. Temple, S. Goyal, and J.P. Mitchell. 2007. “Soil Food Webs and Carbon Dynamics in Response to Conservation Tillage in California.” *Soil Science Society of America Journal* 71 (3): 952. doi:10.2136/sssaj2006.0174.

Mitchell, J.P., G. S. Pettygrove, S. Upadhyaya, A. Shrestha, R. Fry, R. Roy, P. Hogan, and K. Hembree. 2009. *Classification of Conservation Tillage Practices in California Irrigated Row Crop Systems.* Publication 8364. Davis, CA: University of California Division of Agriculture and Natural Resources. anrcatalog.ucdavis.edu/pdf/8364.pdf.

Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 2006. “Net Global Warming Potential and Greenhouse Gas Intensity in Irrigated Cropping Systems in Northeastern Colorado.” *Journal of Environment Quality* 35 (4): 1584–1598. doi:10.2134/jeq2005.0232.

Mulvaney, R.L., S.A. Khan, and C.S. Mulvaney. 1997. “Nitrogen Fertilizers Promote Denitrification.”

Biology and Fertility of Soils 24 (2) (February 1): 211–220. doi:10.1007/s003740050233.

Murray, B.C., and J.S. Baker. 2011. "An Output-Based Intensity Approach for Crediting Greenhouse Gas Mitigation in Agriculture: Explanation and Policy Implications." *Greenhouse Gas Measurement and Management* 1 (1): 27–36. doi:10.3763/ghgmm.2010.0004.

NASS (National Agricultural Statistics Service). 2011. *California Agricultural Statistics 2010 Crop Year.* Washington, DC: National Agricultural Statistics Service, USDA. Available from www.nass.usda.gov/ca.

Niemeier, D., and D. Rowan. 2009. "From Kiosks to Megastores: The Evolving Carbon Market." *California Agriculture* 63 (2) (April): 96–103. doi:10.3733/ca.v063n02p96.

Oenema, O., G. Velthof, and P. Kuikman. 2001. "Technical and Policy Aspects of Strategies to Decrease Greenhouse Gas Emissions from Agriculture." *Nutrient Cycling in Agroecosystems* 60 (1–3) (July 1): 301–315. doi:10.1023/A:1012601113751.

Olander, L.P., K. Haugen-Kozyra, S. Del Grosso, D. Malin, K. Paustian, and W. Salas. 2011. *Using Biogeochemical Process Models to Quantify Greenhouse Gas Mitigation from Agricultural Management Projects.* Technical Working Group on Agricultural Greenhouse Gases Supplemental Report. Durham, NC: Nicholas Institute, Duke University.

Orang, M., J.S. Matyac, and R. Snyder. 2008. "Survey of Irrigation Methods in California in 2001." *Journal of Irrigation and Drainage Engineering* 134 (1): 96–100. doi:10.1061/(ASCE)0733–9437(2008)134:1(96).

Pittelkow, C., M.A. Adviento-Borbe, J. Hill, J. Six, C. Van Kessel, and B. Linquist. In Review. "Yield-Scaled Global Warming Potential of Annual Nitrous Oxide and Methane Emissions from Continuously Flooded Rice Systems in Response to Nitrogen Input."

Poudel, D.D., W.R. Horwath, J. Mitchell, and S.R. Temple. 2001. "Impacts of Cropping Systems on Soil Nitrogen Storage and Loss." *Agricultural Systems* 68: 253–268.

Ridgely, A.M. and M. Van Horn. 1995. *Survey of Annual Crop Growers Regarding Cover Crops: Summary of Final Report to UC Sustainable Agriculture Research and Education Program.* Available from http://www.sarep.ucdavis.edu/newsletters/archive.

Robertson, G.P, E.A. Paul, and R.R. Harwood. 2000. "Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere." *Science* 289 (5486) (September 15): 1922–1925. doi:10.1126/science.289.5486.1922.

Rochette, P., D.A. Angers, G. Bélanger, M.H. Chantigny, D. Prévost, and G. Lévesque. 2004. "Emissions of N2o from Alfalfa and Soybean Crops in Eastern Canada." *Soil Sci. Soc. Am. J.* 68 (2) (March): 493–506.

Ruser, R., H. Flessa, R. Russow, G. Schmidt, F. Buegger, and J.C. Munch. 2006. "Emission of N_2O, N_2 and CO_2 from Soil Fertilized with Nitrate: Effect of Compaction, Soil Moisture and Rewetting." *Soil Biology and Biochemistry* 38 (2) (February): 263–274. doi:10.1016/j.soilbio.2005.05.005.

Schellenberg, D.L., M.M. Alsina, S. Muhammad, C.M. Stockert, M.W. Wolff, B.L. Sanden, P.H. Brown, and D.R. Smart. 2012. "Yield-Scaled Global Warming Potential from N_2O Emissions and CH_4 Oxidation for Almond (Prunus Dulcis) Irrigated with Nitrogen Fertilizers on Arid Land." *Agriculture, Ecosystems &*

Environment 155 (July 15): 7–15. doi:10.1016/j.agee.2012.03.008.

Schmidt, M.W.I., M.S. Torn, S. Abiven, T. Dittmar, G. Guggenberger, I.A. Janssens, M. Kleber, I. Kogel-Knabner, J. Lehmann, D.A.C. Manning, P. Nannipieri, D.P. Rasse, S. Weiner, and S.E. Trumbore. 2011. “Persistence of Soil Organic Matter as an Ecosystem Property.” *Nature* 478 (7367) (October 5): 49–56. doi:10.1038/nature10386.

Seiter, S., and W. Horwath. 2004. “Strategies for Managing Soil Organic Matter to Supply Plant Nutrients.” In *Soil Organic Matter in Sustainable Agriculture*, vol. 20042043, edited by Fred Magdoff and Ray Weil. Boca Raton, FL: CRC Press. Available from http://www.crcnetbase.com/doi/abs/10.1201/9780203496374.ch9.

Shipley, P.R., J.J. Messinger, and A.M. Decker. 1992. “Conserving Residual Corn Fertilizer Nitrogen with Winter Cover Crops.” *Agronomy Journal* 84 (5): 869–876. doi:10.2134/agronj1992.00021962008400050020x.

Six, J., E.T. Elliott, and K. Paustian. 1999. “Aggregate and Soil Organic Matter Dynamics Under Conventional and No–tillage Systems.” *Soil Science Society of America Journal* 63 (5) (September 1): 1350–1358. doi:10.2136/sssaj1999.6351350x.

Six, J., E.T. Elliott, K. Paustian, and J.W. Doran. 1998. “Aggregation and Soil Organic Matter Accumulation in Cultivated and Native Grassland Soils.” *Soil Science Society of America Journal* 62 (5): 1367–1377. doi:10.2136/sssaj1998.03615995006200050032x.

Six, J., S.M. Ogle, F.J. Breidt, R.T. Conant, A.R. Mosier, and K.Paustian. 2004. “The Potential to Mitigate Global Warming with No–Tillage Management Is Only Realized When Practised in the Long Term.” *Global Change Biology* 10 (2): 155–160. doi:10.1111/j.1529–8817.2003.00730.x.

Smart, D. 2009a. *Carbon Sequestration Opportunities and Greenhouse Gas Production in Almond Orchards.* Research Report for Almond Board of California. Available from http://www.almondboard.com/PR/U.2008.08-AIR2-Smart.Smart.Carbon%20Sequestration%20Opportunities%20and%20Greenhouse%20Gas%20Production%20in%20Almond%20Orchards%20%28Continuation%20of%2007-ENVIR5-Smart%29.pdf

———. 2009b. *Evaluating Nitrogen Use Efficiency in Almond Using an Isotopic Tracer Approach.* Research Report for Almond Board of California. Available from http://www.almondboard.com/PR/A.2008.08-AIR4-Smart.Smart.Evaluating%20Nitrogen%20Use%20Efficiency%20in%20Almond%20Using%20an%20Isotopic%20Tracer%20Approach.pdf

———. 2010. *Nitrous Oxide Emissions from an Almond Orchard.* Research Report for Almond Board of California.Available from http://www.almondboard.com/PR/U.2009.09-AIR2-Smart.Smart.Nitrous%20Oxide%20Emission.pdf.

———. 2011. *Constraining Greenhouse Gas Emissions from Almond Orchards for Two Nitrogen Fertilizer Sources and Three Microirrigation Systems.* Research Report for Almond Board of California. Available from http://www.almondboard.com/PR/A.2010.10-AIR2-Smart.Smart.Constraining%20Greenhouse%20Gas%20Emissions%20from%20Almond%20Orchards%20for%20Two%20Nitrogen%20Fertilizer%20Sources%20and%20Three%20Microirrigation%20Systems.pdf

———. 2012. *Greenhouse Gas Emissions from Almond Orchard Floors and Measuring Nitrogen Mobilization Using an Isotopic Approach.* Research Report for Almond Board of California. Available from http://www.almondboard.com/PR/A.2011.11-AIR2-Smart.Smart.Constraining%20Greenhouse%20Gas%20Emission%20from%20Orchards%20Measuring%20Nitrogen%20Mobilization%20Using%20Isotopic%20Approach.pdf

Smart, D.R., M.M. Alsina, M.W. Wolff, M.G. Matiasek, D.L. Schellenberg, J.P. Edstrom, P.H. Brown, and K.M. Scow. 2011. "N_2O Emissions and Water Management in California Perennial Crops." Available from http://ucanr.org/sites/scri/files/140106.pdf.

Smart, D.R., E. Suddick, and T. Pritchard. 2006. *Control of Greenhouse Gas Emissions from California Vineyards by Soil Carbon and Water and Its Policy Implications: Final Report to Kearney Foundation of Soil Science.*

Smukler, S.M., A.T. O'Geen, and L.E. Jackson. 2012. "Assessment of Best Management Practices for Nutrient Cycling: A Case Study on an Organic Farm in a Mediterranean-Type Climate." *Journal of Soil and Water Conservation* 67 (1) (January 1): 16–31. doi:10.2489/jswc.67.1.16.

Snapp, S.S., S.M. Swinton, R. Labarta, D. Mutch, J.R. Black, R. Leep, J. Nyiraneza, and K. O'Neil. 2005. "Evaluating Cover Crops for Benefits, Costs and Performance Within Cropping System Niches." *Agron. J.* 97 (1) (January): 322–332.

Snyder, C.S., T.W. Bruulsema, T.L. Jensen, and P.E. Fixen. 2009. "Review of Greenhouse Gas Emissions from Crop Production Systems and Fertilizer Management Effects." *Agriculture, Ecosystems & Environment* 133 (3–4) (October): 247–266. doi:10.1016/j.agee.2009.04.021.

Stanislaus County. 2007. *Farmland Mitigation Program Guidelines: Appendix B.* Modesto, California. Available from http://www.co.stanislaus.ca.us/planning/pl/gp/gp-ag-element-b.pdf.

Steenwerth, K.L., and K.M. Belina. 2008. "Cover Crops and Cultivation: Impacts on Soil N Dynamics and Microbiological Function in a Mediterranean Vineyard Agroecosystem." *Applied Soil Ecology* 40 (2) (October): 370–380. doi:10.1016/j.apsoil.2008.06.004.

———. 2010. "Vineyard Weed Management Practices Influence Nitrate Leaching and Nitrous Oxide Emissions." *Agriculture, Ecosystems & Environment* 138 (1–2) (June 15): 127–131. doi:10.1016/j.agee.2010.03.016.

Stehfest, E., and L. Bouwman. 2006. "N2O 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 (3) (July 12): 207–228. doi:10.1007/s10705-006-9000–7.

Tenuta, E.G., and M. Beauchamp. 2003. "Nitrous Oxide Production from Granular Nitrogen Fertilizers Applied to a Silt Loam Soil." *Canadian Journal of Soil Science* 83 (5) (November): 521–532. doi:10.4141/S02–062.

Thornton, F.C., B.R. Bock, and D.D. Tyler. 1996. "Soil Emissions of Nitric Oxide and Nitrous Oxide from Injected Anhydrous Ammonium and Urea." *Journal of Environmental Quality* 25 (6): 1378–1384.

Tindula, G., M. Orang, and R. Snyder. 2013. "Survey of Irrigation Methods in California in 2010." *Journal of Irrigation and Drainage Engineering* 139 (3): 233–238. doi:10.1061/(ASCE)IR.1943–

4774.0000538.

Trenkel, M.E. 2010. *Slow– and Controlled-Release and Stabilized Fertilizers: An Option for Enhancing Nutrient Use Efficiency in Agriculture.* Paris, France: International Fertilizer Industry Association.

Triplett, G.B., and W.A. Dick. 2008. "No-Tillage Crop Production: A Revolution in Agriculture!" *Agronomy Journal* 100 (Supplement_3): S–153. doi:10.2134/agronj2007.0005c.

UCAIC. 2009. *The Measure of California Agriculture.* University of California Agricutural Issues Center.

USDA–ERS (U.S. Department of Agriculture Economic Research Service). 2012. *ARMS Farm Financial and Crop Production Practices: Tailored Reports.* Washington, DC: USDA–ERS.

Van Groenigen, J.W., G.L. Velthof, O. Oenema, K.J. Van Groenigen, and C. Van Kessel. 2010. "Towards an Agronomic Assessment of N_2O Emissions: A Case Study for Arable Crops." *European Journal of Soil Science* 61 (6): 903–913. doi:10.1111/j.1365–2389.2009.01217.x.

Van Kessel, C., R. Venterea, J. Six, M.A. Adviento-Borbe, B.A. Linquist, and K.J. van Groenigen. 2013. "Climate, Duration, and N Placement Determine N_2O Emissions in Reduced Tillage Systems: A Meta–Analysis." *Global Change Biology* 19 (1): 33–44. doi:10.1111/j.1365–2486.2012.02779.x.

Veenstra, J.J., W.R. Horwath, and J.P. Mitchell. 2007. "Tillage and Cover Cropping Effects on Aggregate-Protected Carbon in Cotton and Tomato." *Soil Sci. Soc. Am. J.* 71 (2) (March): 362–371.

Venterea, R.T., M. Burger, and K.A. Spokas. 2005. "Nitrogen Oxide and Methane Emissions Under Varying Tillage and Fertilizer Management." *Journal of Environment Quality* 34 (5): 1467–1477. doi:10.2134/jeq2005.0018.

Venterea, R.T., M.S. Dolan, and T.E. Ochsner. 2010. "Urea Decreases Nitrous Oxide Emissions Compared with Anhydrous Ammonia in a Minnesota Corn Cropping System." *Soil Science Society of America Journal* 74 (2): 407. doi:10.2136/sssaj2009.0078.

Venterea, R.T., and D.E. Rolston. 2000. "Nitric and Nitrous Oxide Emissions Following Fertilizer Application to Agricultural Soil: Biotic and Abiotic Mechanisms and Kinetics." *Journal of Geophysical Research: Atmospheres* 105 (D12): 15117–15129. doi:10.1029/2000JD900025.

Wagner-Riddle, C., and G.W. Thurtell. 1998. "Nitrous Oxide Emissions from Agricultural Fields during Winter and Spring Thaw as Affected by Management Practices." *Nutrient Cycling in Agroecosystems* 52 (2-3) (October 1): 151–163. doi:10.1023/A:1009788411566.

Wagner-Riddle, C., G.W. Thurtell, K.M. King, G.E. Kidd, and E.G. Beauchamp. 1996. "Nitrous Oxide and Carbon Dioxide Fluxes from a Bare Soil Using a Micrometeorological Approach." *Journal of Environmental Quality* 25 (4): 898–907. doi:10.2134/jeq1996.00472425002500040035x.

West, T.O., and W.M. Post. 2002. "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis." *Soil Science Society of America Journal* 66 (6): 1930–1946.

West, Tristram O., and G. Marland. 2002. "A Synthesis of Carbon Sequestration, Carbon Emissions, and Net Carbon Flux in Agriculture: Comparing Tillage Practices in the United States." *Agriculture, Ecosystems & Environment* 91 (1–3) (September): 217–232. doi:10.1016/S0167–8809(01)00233–X.

Williams, J.N., A.D. Hollander, A.T. O'Geen, L.A. Thrupp, R. Hanifin, K. Steenwerth, G. McGourty, and L.E. Jackson. 2011. "Assessment of Carbon in Woody Plants and Soil Across a Vineyard-woodland Landscape." *Carbon Balance and Management* 6 (1) (November 9): 11. doi:10.1186/1750–0680–6–11.

Wolf, D. 1997. *Soil Compaction: Crop Response and Remediation.* Ithaca, NY: Cornell University, Department of Fruit and Vegetable Science.

Zhu, X., M. Burger, T.A. Doane, and W.R. Horwath. 2013. "Ammonia Oxidation Pathways and Nitrifier Denitrification Are Significant Sources of N_2O and NO under Low Oxygen Availability." *Proceedings of the National Academy of Sciences* (April 1): 201219993. doi:10.1073/pnas.1219993110.

Zou, J., Y. Huang, J. Jiang, X. Zheng, and R.L. Sass. 2005. "A Three-Year Field Measurement of Methane and Nitrous Oxide Emissions from Rice Paddies in China: Effects of Water Regime, Crop Residue, and Fertilizer Application." *Global Biogeochemical Cycles* 19 (2). doi:10.1029/2004GB002401.

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