Chapter 12

Discerning Agricultural Management Effects on Nitrous Oxide Emissions from Conventional and Alternative Cropping Systems: A California Case Study

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Several decades of research have provided crucial understanding of the production of nitrous oxide (N\textsubscript{2}O) from agricultural soils and the major environmental and managerial factors that play a role in the generation of this potent greenhouse gas (GHG). Due to the increase in demand for food production and the concomitant increase in use of N fertilizers to meet this demand, it is more than ever important to quantify the effects of the different factors contributing to N\textsubscript{2}O emissions and produce detailed, accurate and reliable annual N\textsubscript{2}O emission budgets for current and alternative agricultural systems. Within the diverse cropping systems of California, annual budgets are missing or incomplete for some of the state’s more important, high acreage cash crops such as grape and nut crops. Recent research, documented within this paper, highlights the difference in N\textsubscript{2}O emissions between conventional and alternative management practices in perennial and annual cropping systems of California. We observed measureable differences in N\textsubscript{2}O emissions between standard and conservation irrigation techniques used in a Northern...
California almond orchard. Sub-surface drip irrigation had lowered emissions of N$_2$O (0.006± 0.001 kg N$_2$O-N ha$^{-1}$) compared to surface drip (0.08 ± 0.021 kg N$_2$O-N ha$^{-1}$) following a four-day fertigation event. In a Northern California vineyard, although not statistically different, standard tillage (ST) led to less N$_2$O emissions compared to no tillage (NT)/conservation tillage (CT) practices, where cumulative emissions were 0.13 ± 0.021 kg N$_2$O-N ha$^{-1}$ season$^{-1}$ in the ST system as compared to 0.19 ± 0.017 kg N$_2$O-N ha$^{-1}$ season$^{-1}$ from the NT system. We also show that the use of pyrolyzed agricultural wastes (biochar) as a soil amendment has the ability to reduce N$_2$O emissions associated with fertigation peaks by approximately 41%, however, overall cumulative emissions were not statistically different between the biochar amended soils and control soils. Finally, we recommend based on our studies that future investigations in California should include longer term and more robust sampling to be able to create more accurate future emission budgets and mitigate GHG emissions from both vegetable and perennial crops.

Introduction

During the last century, the impact of anthropogenic activities upon the global nitrogen (N) cycle have led to increased emissions of reactive forms of N to the atmosphere, which has affected climate systems through production of air pollutants, including nitrous oxide (N$_2$O) (1). The increase of N$_2$O in the atmosphere is currently of increasing concern due to its high radiative forcing potential, at approximately 300 times greater than carbon dioxide (CO$_2$), and its role in stratospheric ozone depletion (2, 3). Soils are the principal source of N$_2$O, with agricultural soils representing the single largest source of anthropogenic N$_2$O production (1, 4). Nitrous oxide accounts for approximately 6% of total anthropogenic greenhouse gas (GHG) emissions (5). According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report:Climate Change 2007, direct and indirect emissions of N$_2$O from agricultural ecosystems to the atmosphere contribute approximately 6 Tg N yr$^{-1}$. However, it has been suggested that emissions can be reduced by approximately 0.5 Tg N$_2$O-N yr$^{-1}$ through improved fertilizer management and alternative irrigation and crop management techniques (6).

Nitrous oxide is primarily produced from the microbial processes of denitrification and nitrification and is affected by many different factors, both environmental and managerial and their interactions (7). Nitrification is the aerobic process in which ammonium (NH$_4^+$) is oxidized to nitrite (NO$_2^-$) and further oxidized to nitrate (NO$_3^-$) (8). Denitrification is an anaerobic process in which NO$_3^-$ is reduced to N$_2$O and dinitrogen gas (N$_2$) and it is dependent upon many factors including soil pH, degree of anaerobicity of soil, soil C content, NO$_3^-$ content and water content (9, 10). The greatest rates of N$_2$O
emissions from soils tend to be associated with the denitrification pathway whereas nitrification-derived N₂O flux rates are smaller (11). However, more often than not, conditions favorable for the nitrification process tend to be more common, i.e., greater soil aeration, lower WFPS, good soil drainage and more aerobic conditions (11, 12).

The addition of synthetic fertilizers is a major source of N₂O production; it is estimated that approximately 1.25% of all N fertilizer (both inorganic and organic forms) added to soils is emitted as N₂O (1). Nonetheless, recent reviews have shown that emissions factors can vary from 0.1 to 7.0% from both natural and agricultural soils (13). The production of both natural and fertilizer-derived N₂O from agricultural soils is again largely dependent upon management practices, including fertilizer and irrigation timing, microbial processes, local climate conditions and soil properties, including soil water and N dynamics, thus making the quantification of annual N₂O emissions from specific cropping systems a challenging task.

It is well documented that agriculture is a substantial source of GHG emissions worldwide, but that also a potential for GHG reductions currently exists within agriculture (14–16). Consequently, assessing annual emission budgets is a necessary task in order to determine the current impact that agriculture has on climate, to estimate the future potential mitigation of climate change related to anthropogenic increases of GHG’s in the atmosphere, and to ensure future food security while reducing the agricultural impact on GHG concentrations in the atmosphere.

Determining annual N₂O budgets is often difficult due to the high spatial and temporal variability of N₂O fluxes (17). Process based biogeochemical models, such as the denitrification decomposition model (DNDC) (18) and the daily time step version of the CENTURY model (DAYCENT) (19), have been used to estimate GHG emissions by simulating crop growth and soil carbon (C) and nitrogen (N) dynamics as related to, agricultural management, soil properties, and climate. These biogeochemical models, however, still contain substantial uncertainty in their estimations of N₂O emission arising from different soil conditions and management practices across spatial and temporal scales. For the State of California, this is particularly true, due to its wide variation in soils and cropping system types. Research on the effects of both conventional and alternative management practices on N₂O emissions are lacking for California, especially for vegetable and perennial cropping systems such as vineyards and nut orchards (20). Furthermore, until recently there was very little ground-based field data available to quantify the interactions and impacts of irrigated farming with alternative practices on soil C and N dynamics and GHG emissions (15). Therefore, further research is necessary if climate change mitigation measures are to be realized in the future.

The objectives of this paper are to (1) discern the state of knowledge for factors from both alternative and conventional cropping systems that contribute to N₂O emissions from vegetable and perennial cropping systems in California, (2) evaluate current methodologies, and (3) make recommendations towards GHG mitigation strategies for Californian agriculture.
California: A Case Study

California has a wide range of climatic regions and ecosystems (e.g., croplands, forests, coastal margins, mountainous areas, and desert). California agriculture is incredibly diverse because of its varied mesoclimates that allow for a wide variety of annual (i.e., vegetables and cereals) and high-value specialty perennial crops, such as citrus, nuts, stone fruits, and wine and table grapes. California accounts for approximately 43% of the vegetable and fruit production and 42% of nut production in the United States (21). Despite the apparent importance of agriculture within California there is little data on GHG emissions from Californian agricultural lands (e.g., (20, 22, 23)).

California is the 10th largest emitter of GHG’s in the world, accounting for approximately 493 million metric tons of CO₂ equivalents per annum (22). Within California, it is estimated that agricultural and forestry practices contribute to approximately 8% of the total GHG emissions, of which over 50% are accounted for by N₂O (22). Consequently, addressing GHG emissions reductions potentials within California agriculture is vital to developing and implementing alternative management strategies, such as conservation tillage practices, cover cropping, organic management, residue management strategies, biochar additions, reduced synthetic N fertilizer input, using improved N sources (e.g. nitrification inhibitors and poly-coated urea), and state-of-the-art irrigation systems. These practices likely provide an opportunity to reduce GHG emissions and partly address climate change issues both locally and globally. Currently agricultural management practices within California are highly intensive because the vast majority of crop acreage is cultivated using standard tillage (ST) operations, high inputs of synthetic N fertilizers, and intensive irrigation schedules (20).

Effects of Tillage and Cover Cropping on N₂O Fluxes

The mechanical disturbance of soil by agriculture practices, through tillage and tractor compaction of soil, significantly influences gas fluxes (24). Standard tillage (ST) is known to stimulate mineralization of both C and N present within soils. Furthermore, it is thought that tillage can temporarily reduce competition between plants roots and microbial communities for N and thus potentially increase N₂O emissions (11). In an intensively managed vegetable system in Northern California, the net mineralization of N and the accumulation of NO₃⁻ markedly increased for several days following standard rotor tillage operations of the soil surface, which in turn could be associated with observed higher rates of denitrification and hence greater N₂O emissions (25).

Over the past few decades, ST operations have decreased in favor of no-tillage or reduced tillage practices in the United States (26). Reducing tillage intensity has been cited as a sustainable practice because it reduces fossil fuel usage and labor needs. It also enhances certain aspects of soil quality such as reduced erosion, increased soil C content and improved water retention (27, 28). Increases in soil C can also offset increases in atmospheric CO₂ (29), however, the interaction between tillage practices and soil conditions and their influence on other potent GHG’s such as N₂O and methane (CH₄) are still inconclusive (20, 30).
In California, there is a shortage of information regarding conservation tillage practices, especially within perennial systems such as vineyards that cover a huge acreage of the state’s cropped land. One reason for the lack of information is the low (10%) land area where CT is supported (31). Consistent with other studies that have observed the initial increase in N$_2$O emissions under newly converted CT systems (4, 30), growing season N$_2$O emissions from a corn-tomato system under minimum tillage following one year after conversion from standard tillage operations, were greater than those from a standard tilled corn-tomato system on a fine textured soil under California conditions (Davis, CA) (32). Based on the compilation of data and extensive literature review (30), it has been predicted that following the initial conversion of annual agricultural systems to CT from ST, N$_2$O emissions would decrease after several years if the practice was maintained in the long term. These studies do not include perennial ecosystems; furthermore, many model predictions and inventories have also shown a distinct lack of information for perennial systems.

In vineyard systems where cover cropping combined with CT is utilized to reduce the use of synthetic N fertilizers, cover crops can provide habitats for beneficial insects and increase soil quality and soil C (33–36). However, it still remains largely unknown what the effect of cover cropping and CT has upon GHG production and consumption, particularly N$_2$O. Increased emissions from cover cropped vineyard systems [i.e., Trios 102 (Triticale x Triosecale), (‘Trios’), Merced Rye (Secale cereale)] as compared to non-cover cropped vineyards (i.e., tilled, bare soil) have been documented in California (Monterey County; (37)). Nonetheless, this is only one study and so making any future generalizations regarding the effect of CT and cover crops on N$_2$O emissions from vineyards needs to be done cautiously. A more recent study (38) assessed direct N$_2$O emissions following the transition from ST to CT in a cover cropped Northern California vineyard over a single growing season. Using static closed chambers, frequent measures of N$_2$O were completed both in the vine and tractor row following significant management events, such as irrigation, fertilization, and cover crop mowing and incorporation, as well as weather events such as precipitation. Measurements lasted a full seven to ten days following irrigation, fertilization, precipitation or vineyard floor management events respectively (38). Cumulative N$_2$O emissions in the CT system were 0.19 ± 0.017 kg N$_2$O-N ha$^{-1}$ season$^{-1}$ in the vine row and 0.11 ± 0.018 kg N$_2$O-N ha$^{-1}$ in the tractor row and were greater, but not significantly, compared to 0.13 ± 0.021 kg N$_2$O-N ha$^{-1}$ in the vine row and 0.07 ± 0.041 kg N$_2$O-N ha$^{-1}$ in the tractor row of the ST system (38) (Figure 1). Compared to other studies of irrigated agricultural systems in similar Mediterranean climates, the total cumulative emissions for the vineyard were much lower primarily due to the relatively small amount of N fertilizer added (5 kg N ha$^{-1}$ season$^{-1}$) and the drip irrigation system, which results in high N and water use efficiency and thus reduced N$_2$O emissions (38). Moreover, fertilization even at such low amounts still had the largest impact upon N$_2$O emissions under vine rows over the growing season, while cover crop mowing and residue incorporation had the greatest influence within tractor rows (Figure 2). Hence, management events play a significant role in N$_2$O emissions from vineyards (37, 38).
Unfortunately in order to reliably predict future GHG emissions from vineyards and other perennial crops within California and to develop future best management practices to reduce emissions and sustain future crop production practices, longer term studies and the influence of winter precipitation patterns are needed to estimate accurate and complete budgets of N\textsubscript{2}O within California cropping systems.

Irrigation and Fertilization Effects on \textsubscript{N\textsubscript{2}}O Fluxes

Two of the main limiting factors affecting agricultural crop production within arid and semi-arid regions are water and N. Both of these factors are intrinsically linked to the production of \textsubscript{N\textsubscript{2}}O emissions from soils in agricultural ecosystems. Irrigation not only stimulates plant growth, which in turn can enhance C storage in soils through increases in yields (15), but it can also accelerate microbial turnover of C and N (39), thereby increasing the potential for \textsubscript{N\textsubscript{2}}O production. Many studies have assessed net \textsubscript{N\textsubscript{2}}O fluxes under different cropping systems (13), and it has been shown that there is a strong relationship between irrigation and the stimulation of \textsubscript{N\textsubscript{2}}O production (40). However, limited data is available for irrigated agriculture for such diverse regions like California where there are many different types of irrigation systems utilized within the various cropping systems of California (41).
Figure 2. Seasonal N₂O flux rates from a) standard tillage (ST) vine b) standard tillage (ST) row c) conservation tillage (CT) vine and d) conservation tillage (CT) row. Error bars represent the standard error between replicates (34).

Of the 5023 Mha dedicated to global agriculture, where approximately 28% is devoted to cropland (1405 Mha) (42) 18% of the total, receives additional water through irrigation (43). In the semi-arid and arid climate of California, where evaporative demands are high and the annual precipitation is low to non-existent during the hot summer growing season, irrigation is essential to maintain adequate crop yields. Approximately 76% of the total cropland area within California is currently under irrigation (44). In semi-arid and arid regions, like those observed in California, the soils are often low in available nutrients and have low microbial activity when dry (45, 46). However, following soil moistening, especially after irrigation events, the microbial population within the soil greatly increases and N mineralization takes place at a rapid rate (47, 48). Furthermore, after irrigation and soil water saturation, anaerobic micro sites can occur through the high rate of oxygen consumption from intense microbial respiration when oxygen demands...
exceed supply (49). This supports the microbial process of denitrification, but only if there is sufficient organic C and NO₃⁻ available (8, 17). In addition, these wet-dry cycles that often accompany irrigation events are known to affect soil microbial processes and subsequently C and N cycling, as well as the diffusivity of soil gases, which regulate both the production and consumption of N₂O between the soil and atmosphere interfaces (50), and thus strongly influences both nitrification and denitrification rates of N₂O from the soil.

When N₂O emissions were measured from irrigated tomato crops within California’s Central Valley, elevated N₂O emissions following irrigation during the cropping season occurred when WFPS was above 60% through the process of denitrification (40). This is consistent with previous studies which show that denitrification becomes a highly significant source of N₂O once soils have exceeded field capacity or have a WFPS in the range of 60-90% (9, 51–53). The elevated N₂O emissions lasted for two days following the wetting event and declined as the top 15 cm of the soil surface dried out quickly (40). During the cropping season, N₂O was clearly controlled by irrigation and evapotranspiration (drying) rates, especially in quickly drying soils. In a California vineyard (Monterey County), N₂O emissions were measured after N fertilization (31.8 kg N ha⁻¹; ammonium nitrate urea solution 32-0-0: 45.2%NH₄NO₃ and 34.8% urea by weight) using a drip system (fertigation) within the vine row. The soil that received herbicide to control weed cover over a five-year period had greater N₂O emissions over a 3-day period than the soil that was cultivated for the same duration (54). The cultivated soil had slightly greater organic matter content and microbial biomass than the herbicide treated soil, suggesting that greater weed presence in the cultivated soil contributed to greater N retention due to inorganic N uptake by the weeds. Furthermore, we suggest that the greater presence of weeds in the cultivated soils also provided labile soil C substrates that could facilitate greater conversion of N₂O to N₂ (55).

It is important to predict the impact of irrigation practices on soil N turnover and mineralization as well as to optimize management practices in order to reduce the losses of N to the environment. In California, four major types of irrigation (i.e. flood, (including furrow), surface drip, micro-sprinkler and sub-surface drip irrigation) are utilized. Alternative and sustainable management practices are being advocated with increasing political pressures to reduce and mitigate GHG emissions from agriculture. The use of sub-surface drip (SSD) over surface drip (SD) or micro-sprinkler (MS) irrigation has been postulated to be the most efficient irrigation practice with a great potential to reduce water usage, increase nutrient efficiency and to reduce both N₂O and CO₂ emissions (56). The SSD technology is an improvement over SD irrigation, where the water needs of the crop can be met and delivered to the root system directly in a timely manner with minimum losses (57). Many of California’s fruit and nut growers are already implementing more efficient irrigation systems such as SD and MS over flood and furrow. There is also a trend for growers to switch from lower value field crops to the more high value specialty crops such as almonds and wine grapes, of which the former used to be irrigated using flood or furrow (58). A Central Valley study in a split plot tomato field trial that compared the effect of SSD or furrow irrigation on event based N₂O emissions with or without a winter legume
cover crop, observed that SSD decreased N\textsubscript{2}O emissions by half compared to the furrow irrigation regardless of the presence or absence of a winter cover crop (41). Despite this, there is still little to no data related to the effect of irrigation type on N\textsubscript{2}O emission from soils in California perennial systems. One short-term study (Figure 3) shows the diurnal pattern of N\textsubscript{2}O following 36 hours after an irrigation event where no fertilizer was added to a Northern California almond orchard. The almond orchard was situated in Colusa County at the Nickels Soil Laboratory where three different irrigation systems, SD, MS and SSD, were utilized; static closed chambers were placed directly under the irrigation systems in the tree row as well as in the tractor row in order to obtain representative fluxes occurring from soil wetting. Diurnal fluctuations in emissions are often attributed to fluctuation in soil temperatures. However, there was no significant diurnal pattern observed within the almond study, most likely due to the high spatial variability of the replicates within the field (59). Nevertheless, N\textsubscript{2}O emissions did vary over the 36 hour time period following irrigation, thus highlighting the high degree of variability in N\textsubscript{2}O emissions over relatively small time scales and demonstrating the importance of consistent measurements over a similar time of day in order to measure representative fluxes for the system. The SSD irrigation system led to lower emissions on the whole compared to SD and MS irrigation treatments, which corroborates previous research showing that SSD is a highly efficient irrigation system that is precise at delivering water directly beneath the crop roots to a relatively small area. By doing so, SSD restricts microbial activity (41) and anaerobic microsite development, thereby limiting denitrification (17). The SD and MS irrigation practices led to slightly higher N\textsubscript{2}O fluxes due to the greater delivery of water to the soil and, therefore, surplus of water.

Fertigation is a more effective and cost-saving way of supplying a crop with its nutrient needs and provides flexibility in the fertilization practice since fertilizers can be added directly to the active crop root zone (60). Emissions of N\textsubscript{2}O were measured for four days after 50 kg N ha\textsuperscript{-1} in the form of urea nitrate (UN 32) was added to the Nickels Soil Laboratory almond orchard in California through three different irrigation systems (SD, MS and SSD) (Figure 4). The SD irrigation system emitted greater fluxes of N\textsubscript{2}O compared to both the MS and SSD systems within the tree row. Generally, in the zone directly under the SD emitter, localized anaerobic conditions can occur following an irrigation event (61). Such anaerobic conditions will reduce the oxygen in the soil and thus provide optimum conditions for denitrification. A previous study (62) observed during SD irrigation increased NH\textsubscript{4}\textsuperscript{+} concentrations in soils due to mineralization of partially dried soils; in turn NO\textsubscript{3}\textsuperscript{-} decreased as soils saturated following irrigation and was thought to be lost as N\textsubscript{2}O or N\textsubscript{2} due to the more anaerobic soil conditions. For the Nickels almond study, emissions were most likely produced through the denitrification process, as surface applied urea is expected to stimulate more denitrifying activity within the upper soil layers (62).
Figure 3. Diurnal changes in $N_2O$ emissions from three different irrigation systems in a Northern California almond orchard following 36 hours after irrigation without fertilization. Error bars represent standard error of the mean (n=4).

Figure 4. $N_2O$ emissions for four days following N fertilization of urea nitrate (UN32) in both the tree and tractor rows of a Northern California almond orchard. Error bars represent standard error of the mean (n=4).
Previous research has shown that the evolution of a N₂O peak following a management event such as fertigation tends to be relatively short-lived, lasting only a couple of days to a couple of weeks (11). N₂O emissions after the four days following the fertigation event in the almond orchard were still elevated in the SD irrigation treatment, indicating that future studies should continue with field measurements until the N₂O flux returns to background levels to ensure complete measurements of the peak flux and improve accuracy of annual budgets. Total cumulative emissions over the four day period were observed to be significantly lower in the SSD system compared to the other two irrigation treatments (Figure 5). Congruent with earlier studies, SSD is a highly efficient irrigation method which limits the losses of N fertilizers (56) and reduces N₂O emissions from soils leaving less N available to be transformed to N₂O by microbial processes (41).

The adoption of SSD irrigation systems within California is slow and represents less than 15% of all irrigation systems utilized within California (41). SSD irrigation requires maintenance and can be costly at initial installation. However, SSD has demonstrated the capacity to reduce N₂O emissions, and with the increased nutrient and water use efficiency the method provides, future adoption should be considered in perennial crops.

![Figure 5](image-url)

**Figure 5.** Cumulative emissions from a fertigation event under three different irrigation systems within a Northern California almond orchard. Error bars represent the cumulative error of the mean (n=4).
Soil Amendments and Residue Management

In agriculture the use of organic amendments (e.g. manures, composts and mulches) can lead to the accumulation of soil organic carbon (SOC) by improving aggregation, reducing the need for synthetic N fertilizer additions and simultaneously providing crops with adequate nutrients. Nethertheless, in agricultural soils, inputs of N from fertilization, composts, manures, post harvest residues or similar soil amendments are major contributors to N₂O emissions (63, 64). Emissions of N₂O have been found to be greater when the amendment or residue has a lower C:N ratio (63, 65, 66), leading not only to increases in N₂O emissions but also fast rates of NO₃⁻ leaching (67). Conversely, previous studies have reported that many factors can complicate the relationship between residue input and N₂O fluxes (68). The main confounding factors are crop type, the biogeochemical composition of the residue and amendment, tillage regimes, soil moisture, pH, climate and the time of year residue was incorporated (see review (68)).

In light of future mitigation of climate related changes through increases in GHG emissions to the atmosphere, the use of pyrolyzed biomass, termed biochar, as a soil amendment has recently been reported to have beneficial effects by improving soil quality, increasing C sequestration and potentially reducing N₂O emissions from soils (69–71). Biochar is produced when green wastes, such as orchard pruning’s and nut shells, are gasified in the absence of oxygen in a process termed pyrolysis. The pyrolysis process produces a renewable energy source from the biomass itself in the form of a gas or other byproducts (e.g. bio-oil) which can be used instead of fossil fuels. The addition of biochar produced from green waste biomass into agricultural soils, may provide a significant terrestrial sink of C in soils, enhance soil quality, reduce greenhouse gas emissions, and provide an environment which promotes a healthy soil food web.

Previous research has indicated a decrease in N₂O emissions following the application of biochar to soils (72, 73). In a short term, small field scale study in a lettuce crop production system in Yolo County, California, biochar derived from a high temperature (950 °C) gasification pyrolysis of waste walnut shells was applied to the soil (Figure 6). The treatments included a control (no amendment), compost (5 t ha⁻¹), and biochar (5 t ha⁻¹). All treatments received fertilizer (250 kg N ha⁻¹) in pellet form and were subject to surface drip irrigation. N₂O emissions were measured daily (Figure 6) using the static closed chamber method until the lettuce was ready to harvest. Total cumulative emissions over the whole experiment were highest from the compost plots (Figure 7). Compost can increase C availability and the soil anaerobicity when the porosity of the compost amended soil is low, and has a relatively small particle size (74), thus enhancing the potential to release N₂O through denitrification pathways compared to non-compost amended soils (75). Furthermore, the addition of C from the compost amendment would be more readily available for utilization by micro-organisms compared to the biochar amendment, which would increase denitrification rates and subsequently increase in emissions of N₂O (76).
Figure 6. $N_2O$ emissions following the application of 5 t/ha high temperature (950 °C) walnut shell biochar or compost amendments to small field plots following a lettuce rotation.
Figure 7. Cumulative N\textsubscript{2}O emissions following the application of biochar or compost to soil under lettuce. Error bars represent the standard cumulative error of the mean for the three treatments.

N\textsubscript{2}O emissions were significantly reduced by approximately 41\% in biochar amended soils during the initial N\textsubscript{2}O peak after fertilization as compared to compost and control plots (Figure 6). The N\textsubscript{2}O emissions may have been reduced in the biochar amended soils due to the possible adsorption and retention of NH\textsubscript{4}\textsuperscript{+} in the soil through increased oxidative reactions on the biochar surface, thus reducing the amount of N available for nitrification and denitrification (71, 77). Despite the obvious reduction in N\textsubscript{2}O in biochar plots at the start of the experiment, cumulative emissions (Figure 7) were not significantly different from control plots, but were lower than compost amended soils. The N\textsubscript{2}O emissions following the application of biochar to soils is still relatively understudied and data is contradictory depending upon biochar feedstock and the interactions of local soil conditions with rates of biochar application (77). For instance, a previous and contrasting study (71) observed that, following the application of biochar, N\textsubscript{2}O fluxes were inconsistent, variable and appearing to increase early within the experiment as compared to controls. However, as the experiment progressed, reductions in emissions of N\textsubscript{2}O were most likely due to the increased aging of the biochar soil surface, thus increasing the capacity for the biochar to absorb available N in the soils (71). The potential for this new technology to be applied to agricultural soils is still in its infancy, requiring future research to ensure that the application of biochar does have the capacity to reduce N\textsubscript{2}O emissions, or at least not increase N\textsubscript{2}O emissions.
Methodology Evaluation

Despite the numerous studies investigating N\textsubscript{2}O emissions from agricultural ecosystems and the controlling environmental and management factors, it is still difficult to predict and constrain future emissions under field conditions. This is primarily due to the facts that microbial processes of denitrification and nitrification have very specific optimum conditions that change both spatially and temporally within the soil, and that there is a high uncertainty in N\textsubscript{2}O monitoring data related to the quality and quantity of field measurements. Many studies have only measured N\textsubscript{2}O fluxes from the field level either weekly or biweekly, while some studies have measured the fluxes more intensively by measuring either once per day or every couple of days with more frequent sampling occurring over periods where management events such as fertilization occurs (78). The difference in sampling frequency can increase uncertainty and reliability of estimates of N\textsubscript{2}O emissions occurring from agricultural soils (79). For example, a previous study (80) observed a 20% overestimation in total annual emissions from sampling done on a weekly basis as opposed to total emissions calculated on a daily basis. Consequently, the lack of intensive data and the resulting substantial uncertainty around estimates of N\textsubscript{2}O emissions for the major irrigated crops in California is definitely a pressing issue that needs to be resolved.

N\textsubscript{2}O fluxes are commonly determined through the static closed chamber field technique, which is utilized in research primarily due to the relative simplicity and ability to allow process based studies of N\textsubscript{2}O (81). A significant problem associated with this technique is the relatively small area of the soil surface covered by a single chamber. This renders extrapolation to whole field scale difficult due to the high spatial variability associated with N\textsubscript{2}O emissions (82). In order to ameliorate this issue, the number of static chambers employed at each field site would need to be increased. Furthermore, in order to constrain accurate and reliable N\textsubscript{2}O budgets, measurements need to be taken more frequently, especially during management and precipitation events that greatly influence N\textsubscript{2}O fluxes. This will facilitate the assessment of precise N\textsubscript{2}O emission patterns crucial for the calibration and validation of process based biogeochemical models needed to dependably predict annual N\textsubscript{2}O emission budgets. Consequently, the full characterization of N\textsubscript{2}O fluxes from agricultural soils in California requires a great effort spatially, and with near continuous field measurements similar to those conducted in previous studies (83, 84); this effort becomes a laborious and expensive, but very necessary, endeavor.

Previously reported coefficients of variation for N\textsubscript{2}O fluxes from agricultural soils have ranged from 100-900% (85), -40-70% (13, 86) and -30-300% (87), thus showing the great variation within agriculture. Given the lack of data for California crops, the studies presented within this paper are a first contribution to the data pool for N\textsubscript{2}O emissions occurring from perennial crops within California. The study by Garland et al (38) clearly shows the high temporal variability over a single growing season in a Northern Californian vineyard and highlights the N\textsubscript{2}O peak evolution following significant management events such as tillage and fertilization. Furthermore, this study provides a more fundamental understanding of the effects of alternative management strategies on N\textsubscript{2}O emissions that may
not have been realized if measurements were less frequent. The Garland et al (38) study and others (37, 54) are instrumental in reducing the uncertainty and variation surrounding N₂O fluxes from agriculture.

We have also demonstrated that not only are N₂O emissions highly variable over a seasonal timescale, emissions are also highly variable on the much smaller diurnal time scale. N₂O fluxes from Nickels Soil Laboratory almond orchard varied greatly over a 36 hour time period. A future recommendation for N₂O research would be to monitor N₂O fluxes over shorter timescales and multiple times a day, especially during times of intensive management and weather events. This of course would require a huge manual effort; therefore deployment of automated static chambers with the ability to sample multiple times a day for extended time periods are one option to monitor diurnal changes in N₂O emissions from agricultural soils. In addition, other techniques such as micro-meteorological methods have a large spatial footprint and can be employed to monitor near continuous observation in time (88). Both techniques require expensive equipment for data collection and analysis.

Potential Mitigation Measures

Currently a variety of mitigation options exist to reduce GHG emissions occurring from agricultural soils. Improvements to agronomic practices such as N fertilization, nutrient and water use efficiency (e.g. use of reclaimed municipal waste water), and residue management (e.g. green manures) represent the major mitigation options to reduce GHG’s. Furthermore, the use of enhanced-efficiency N fertilization techniques, such as nitrification inhibitors and poly coated urea, are also potential mitigation options; they have been shown to reduce N₂O emissions by almost 40% (89) compared to conventional N fertilizers such as urea (90, 91). However, there is still a lack of data for many of the mitigation options available within California agriculture and it is still challenging to predict the interactions between mitigation options under specific field conditions in California. Therefore, we suggest that potential practices must be evaluated first on an individual basis in order to understand the change in management and land-use with interactions within local soil conditions. Subsequently, mitigation options should also be assessed in combination to ensure that one mitigation strategy paired together with another practice does not enhance emissions. It therefore seems appropriate that a mixture of mitigation management options would be better to constrain emissions from agriculture.

Process based biogeochemical models combined with field based measurements will be able to evaluate future scenarios and management options best for reducing GHG’s. Furthermore, a whole system based approach that evaluates the overall long term production viability goals of the crop in conjunction with GHG reduction goals is the way forward in order to adapt and mitigate climate change and to maintain future food security and agricultural sustainability. The data presented within this paper supports the suggestion that both environmental and soil conditions in conjunction with agricultural management practices are critical in controlling the release of N₂O from
agricultural soils in California. Water and N are clearly two of the most important factors affecting N₂O emissions; therefore, an improvement in N fertilizer and irrigation efficiency is needed. The type and placement of N fertilizers deeper within the soil layer using SSD irrigation, reducing unnecessary irrigations, and using controlled timing of irrigations while satisfying minimum crop N and water requirements to maintain sufficient yields and quality are potential mitigation options that will reduce N₂O emissions (5, 92, 93). Furthermore, the addition of biochar to soils could also reduce atmospheric concentrations of CO₂ through C sequestration in soils as well as mitigating N₂O produced from soils, while enhancing crop productivity and improving soil quality.

**Conclusion**

This paper highlights both the high degree of spatial and temporal variability of N₂O emissions from agricultural soils in California and the significant influence of management (e.g., irrigation and fertilization) upon these emissions. Despite the current emerging data for California, there is still an urgent need to collect more frequent measurements. Furthermore, integration of all methods of collection, reporting and modeling in order to reduce uncertainty around estimates of N₂O emissions is pertinent. Agricultural mitigation measures must also be in cohesion with other sociological and economic development strategies to succeed. Not only the reduction in GHG emission should be taken into account when assessing alternative and conservation management practices, as most of these practices have associated co-benefits (e.g., reduced costs, improved soil health, enhanced biodiversity) that are also highly valuable in their own right and will be necessary for the future sustainability of California agriculture. There is a great potential for California agriculture to reduce GHG emissions and be involved in the future development and implementation of alternative management practice. However, all alternative practices must also be evaluated for any potential negative impacts such as reduced yields and crop quality. Also, if California is to succeed in meeting its climate change and GHG reduction goals there is a definite need for a synergy to exist between current technologies and socio-economic sectors and pave the way for forthcoming policies to effectively tackle the complex issue of climate change.

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References


42. FAOSTAT, 2006. Agricultural data.


44. USDA Economic Research Service Fact Sheet, California, updated 9/10/10.


