A. PROJECT INFORMATION

Final Report: July 2015-December 2018

Agmt #15-0356-SA

Quantifying N_2O Emissions under Different On-farm Irrigation and Nutrient Management BMPs that Reduce Groundwater Nitrate Loading and Applied Water

California Department of Food and Agriculture Fertilizer Research and Education Program

FY2015-16 special Call for Proposals

Project Leader

Arlene Haffa, PhD, MS, Associate Professor of Biochemistry and Microbiology, School of Natural Sciences, California State University, Monterey Bay, 100 Campus Center, Seaside, CA 93955 (831) 582-4695, ahaffa@csumb.edu

Co-Project Leaders

Jason Dexter, MS, Field Research Scientist, Cooperative for Research in Earth Science and Technology, NASA Ames Research Center and School of Natural Sciences, California State University, Monterey Bay, 831-582-5028- jdexter@csumb.edu

William Horwath, PhD, Professor of Soil Biogeochemistry, Department of Land, Air and Water Resources, UC Davis, 3226 Plant & Environmental Science Building One Shields Ave. Davis, California 95616-8626 530-754-6029, wrhorwath@ucdavis.edu

Forrest Melton, MS, Senior Research Scientist, Cooperative for Research in Earth Science and Technology, NASA Ames Research Center and School of Natural Sciences, California State University, Monterey Bay, 831-917-6076. fmelton@csumb.edu

Stefanie Kortman, MS Graduate Student Researcher, Environmental Science, School of Natural Sciences, California State University, Monterey Bay, 100 Campus Center, Seaside, CA 93955 skortman@csumb.edu

B. OBJECTIVES:

The primary objective of this project was to quantify N_2O emission rates from Central CA's commodity crops and examine the key biophysical drivers to ammonia (NH_3) oxidation as percent O_2 is reduced. These data will be used in conjunction with data obtained from other projects that are evaluating alternative management practices aiming to reduce total applied irrigation and NO_3^- leaching to improve N-cycle models that can be integrated into low cost management tool applications (e.g. Satellite Irrigation Management Support (SIMS) and CropManage (CM)).

Specific Objectives:

1) Estimate annual direct and indirect N_2O emissions in conjunction with NO_3^- leaching data obtained from NLGCA study, and assess their respective N system loss under the BMPs relative to estimated standard practice.
2) Quantify idle period direct and indirect N_2O flux to improve annual GHG estimates under standard and alternative management practices given measured meteorological conditions.
3) Quantify yields and input costs under the BMPs relative to standard practice to provide demonstration projects conducted with leading industry partners to evaluate the effectiveness of the BMPs for reducing N_2O and nitrate losses and sustaining yields while potentially reducing production costs.
4) Characterize cultivation, cropped and idle period N_2O emissions under BMPs relative to standard practice to provide linkages between crop biomass status, biophysical parameters and emission rates during both cropped and idle periods.
5) Quantify N_2O from NH_3 oxidation as a function of O_2 concentration under standard versus BMPs for the purpose of fine tuning irrigation and fertigation management.
6) Engage in outreach and education activities and education

C. ABSTRACT:

As a greenhouse gas (GHG), nitrous oxide (N_2O) is 300 times more effective than carbon dioxide at warming the atmosphere, while 75% of N_2O emissions in the U.S. are emitted by agriculture soil management, namely through nitrogen (N) fertilizer application. In efforts to provide user friendly tools to allow farmers to optimize and efficiently quantify water usage and fertilizer applications, University of California Cooperative Extension (UCCE) developed the CropManage irrigation and nitrogen scheduling tool that provides real time evapotranspiration (ETc) based irrigation recommendations and fertilizer recommendations on a per field basis. In this study, field trials were conducted on commercial farms in the Salinas Valley to quantify the benefits of using these tools to support best management practices (BMPs) for irrigation and nutrient management in strawberries, broccoli and lettuce. This work was performed to develop a more complete understanding of the overall nitrogen budget to inform ways that management changes can be implemented to achieve effective N_2O abatement without yield losses. Field scale trials were implemented on commercial farms in the Salinas Valley using the CropManage irrigation and nitrogen scheduling tool that provides real time evapotranspiration (ETc) based irrigation recommendations and fertilizer recommendations on a per field basis (Cahn 2015). CropManage was used to calculate the 100% and 130% ETc (referred to as CM and 130, respectively) replacement requirements prior to each irrigation event in commercial strawberries (2015-2016) and lettuce followed by broccoli (2017) grown in a replicated randomized split-block design with four replicates each. Broccoli (2016) was monitored in a split block field trial with a comparison between 100% ETc (CM) and the Grower Practice

(GP). Direct N_2O emissions were monitored on average twice weekly using static chambers placed between plants. N_2O was determined using a Shimadzu Gas Chromatograph. Vadose zone leachate was collected from G3 Passive Capillary Lysimeters weekly and analyzed for nitrate (NO_3^-) on a Lachat flow-through injection analyzer 8500. The vadose zone flux and subsurface flow aspect of this study has been partly supported through NLGCA (PI: Melton). In all trials yields were measured following standard commercial grower practices.

D. INTRODUCTION:

As a greenhouse gas (GHG), nitrous oxide (N_2O) is 300 times more effective than carbon dioxide at warming the atmosphere, while 75% of N_2O emissions in the U.S. are emitted by agriculture soil management, namely through nitrogen (N) fertilizer application (Denman et al., 2007). Thus, this sector is the largest contributor to non-CO_2 emissions, and N_2O output as a result of increased agricultural activity is expected to increase 5% by 2020 (US Dept. of State, 2007). In Mediterranean climates, such as California (CA), row crop production and soil management account for a majority of the total N_2O emissions (ARB, 2010), making agriculture a vital sector for potential GHG abatement.

Common agronomic practices that enhance N_2O production include fertilizer application, irrigation management, and tillage (Mosier and Hutchinson 1981; Smith and Conen 2004; DeGryze et al., 2009; Lee et al. 2009; Kallenbach et al., 2010), but researchers lack a fundamental understanding of how management changes can be implemented in localized agroecosystems to achieve effective N_2O abatement. Most soil GHG studies in the U.S. are from the Midwestern corn-belt region and focus on direct N_2O emissions from soil (e.g. Parkin and Kaspar 2006; Petersen et al. 2006; Chapuis-Lardy et al. 2009; Venterea et al. 2010). Very few have assessed both direct and indirect N_2O emissions due to row crop soil management (Mosier and Zhaoliang, 2000; Maharjan et al., 2014), and none represent CA growing conditions. Current Intergovernmental Panel on Climate Change (IPCC) estimates of indirect N_2O emissions from row-crops are determined by using an estimation of soil nitrate (NO_3^-) leachate to gaseous N_2O conversion factor (De Klein et al., 2007). There is potential for evapotranspiration-based (ET-based) irrigation to mitigate direct and indirect N_2O emissions as a result of improved crop nitrogen uptake and reductions in N application, groundwater nutrient loading, and reduced tile drain effluent. Nearly 60% of the 369,187 cropped acres in Monterey County utilize drip irrigation to control the delivery of crop water and nitrogen (N) fertilizer application. Through the integration of low-cost nutrient and irrigation co-management, Suddick et al., (2011) estimates cumulative direct emission N_2O emissions in California can be reduced by 0.5 of the ~6 Tg N_2O-N yr^{-1}.

The co-benefits of reduced applied water and NO_3^- leaching present both economic and environmental implications for best management practice (BMPs) implementation in CA and beyond. Monterey and Santa Cruz counties alone secured $5.1 billion in farm receipts in 2013, but faced challenges associated with nutrient and cultivation-intensive production of diverse specialty crops (MCCR, 2013). There is a significant need within each region and the state for cost-effective BMPs to protect air and water quality for agricultural sustainability improvements and for long term resource availability (Letey and Vaghan, 2013).

To maximize the understanding and effectiveness of BMPs, the N_2O field-scale demonstration studies are being concurrently run with annual NO_3^- leaching pathway analysis and tile drain effluent studies quantifying the benefits of on-farm BMPs for reduction in N losses from agricultural systems. The vadose zone flux and subsurface flow study has been partly supported through NLGCA (PI: Melton). Study co-location has advanced the understanding of the driving processes of N_2O emissions as they relate to soil water content, drainage and tile drain effluent. The current literature lacks studies that robustly characterize direct N_2O emissions in drip irrigated fields in correlation with NO_3^- losses below the root zone, and this study should help improve BMPs aimed at reducing N_2O emissions in conjunction with less NO_3^- leaching and surface runoff (Viers et al., 2012).

E. WORK DESCRIPTION:

The following tasks were proposed. Detailed methodologies are included below the list.

Task 1: Planning Meet with other project team members, growers and cooperators to coordinate work plan and field logistics. Evaluation of crop rotation and field research site.

Status: Completed ~ Strawberries October 2015, 1st Broccoli Trial March of 2016, Lettuce/Broccoli Rotation February 2017, Fallow period sampling October 2017.

Task 2: Field Preparation – deployment and installation of data collection equipment

Status: Completed ~ Strawberries October 2015, 1st Broccoli Trial March of 2016, Lettuce/Broccoli Rotation April 2017 and August 2017, Fallow period sampling November 2017.

Task 3a: Strawberry growing season: direct and indirect N_2O emission sampling (This task was added after the grant was awarded). At the end of the strawberry trial the partner-grower communicated plans to plant a cover crop.

Status: Completed October 2016.

Task 3b: Lettuce growing season: direct and indirect N_2O emission sampling

Status: Completed June 2017.

Task 4: Broccoli growing season: direct and indirect N_2O emission sampling

Status: Completed year one October 2016, Year two November 2017.

Task 5. Fallow period sampling This trial was in collaboration with colleagues at UCCE (R. Smith) and UCSC (J. Muramoto) and had supplemental funding from the CSU ARI CSUMB Campus allocation to also study how supplemental carbon alters nitrogen immobilization. This data was intended to provide indirect N_2O emission estimates during the fallow period.

Status: No data was obtained, as there was no rain during the fallow period (November 2017- February 2018), and thus no samples to collect.

Task 6. GHG and soils laboratory processing and analysis CSUMB processed the GHG samples from all sites, and UC Davis has processed soil samples from the strawberry and the lettuce/broccoli trials to quantify N_2O emissions from NH_3 oxidation as a function of oxygen concentration.

Status: Completed June 2018.

Task 7. Outreach presentation of plans & then results at conferences and grower meetings

Status: Completed October 2018 The specifics are outlined in Section H: Outreach Activities.

Task 8. Analysis and Processing of Field Data

Status: Completed December 2018

Task 9. Milestone 1: Report summarizing Y1 completed research

Status: Completed July 2016

Task 10. Milestone 2: Completion of report summarizing Y1 & Y2 findings from field data

Status: Completed July 2017

Task 11. Milestone 3: Final project report completed and submitted to CDFA.

Status: Completed January 2019

In addition to these CDFA-funded tasks, a USDA-NIFA Non-Land Grant Colleges of Agriculture award (PI Melton) supported research to quantify annual NO_3^- leaching, and NO_3^- effluent discharge on these fields using irrigation BMPs under 100% ETc and fertilizer management, and quantify the benefits of on-farm BMPS for reduction of N losses from agricultural systems. UCCE funding supported CropManage, some soil nitrate testing, and yield analysis. Grower partners provided all ranch management including cropping, irrigation, fertigation, field workers, and harvest crews.

Experimental Design Commercial farm locations were selected so both CropManage and 130% ETc and N-replacement-based irrigation and nutrient management treatments could be established as either a randomized complete block design or a split block design on the same soil type. For this demonstration study, it was not possible to implement a control treatment with no fertilizer applied due to loss of crop and resulting grower economic burden. The treatments followed CropManage recommendations for applied irrigation and N in strawberries and a lettuce/broccoli rotation following 100% of ETc and N replacement (ET 100) and 130% of ETc and N (ET 130), where ET 100 represents the BMP for that particular crop. In the 2016 broccoli trial, irrigation and nutrient management treatments were based on CropManage recommendations for 100% ETc-based irrigation, as well as an independent grower practice. Soil N_2O emissions monitoring of strawberry, lettuce, and broccoli were conducted at a frequency according to expected N_2O activity, and within the constraints of budgeting and staff. Emissions were measured more intensively around activities that enhance N_2O production, i.e. irrigation, fertilization, and precipitation (Mosier and Hutchinson 1981; Smith and Conen 2004; Chapuis-Lardy et al. 2009; Lee et al. 2009), and less frequently, but at minimum weekly, during times when emissions are expected to be lower, but still contribute to more accurate annual emissions estimates (Parkin, 2008). Environmental variables and NO_3^- leaching were measured simultaneously with N_2O monitoring, and continuously where applicable (i.e. soil moisture sensors, lysimeters, soil temperature, EC). The goal was to capture at least 50% of all applied irrigation events to have a robust data set from which to compare treatment effects on NO_3^- leaching and N_2O emissions. Experimental design has been explicitly developed to assess potential treatment differences in N_2O emissions using repeated measures analysis (Kravchenko and Robertson, 2015).

Direct N_2O Flux Measurements and Gas Chromatograph Analysis Direct N_2O emissions were measured using portable, vented non-flow through non-steady-state gas chamber methods described by Parkin and Venterea (2010) and Rochette and Eriksen-Hammel (2008). Following the recommendations from Morris et al. (2013), replicate chambers were installed in each of four treatment replicated plots for the strawberry and lettuce trials, and in each plot for the split-block design in broccoli. Gas chambers are made of either 10 or 25 cm diameter PVC, with a base and cap that cover a total surface area of 0.08 m^2 or 0.05 m^2. After irrigation/fertigation bases were inserted to 5 or 8 cm depths in the soil and left for 2-24 hours before sampling to allow for settling out of soil disturbance-related impacts on soil gas movement. Bases were inserted in the crop beds between plants and within the wetted area of the surface drip tape. Sampling occurred at minimum once per week, and most weeks twice per week. During sampling, chamber caps are attached to the bases with a rubber sleeve. The caps are wrapped in reflective mylar tape and have septum-lined vent ports fitted with tubes (4.8 mm dia., 10 cm long). Four discrete headspace gas samples were collected at regular intervals over 36 minutes (0, 12, 24, 36 mins) for 10 cm diameter PVC, and for 45 minutes (0, 15, 30, 45 mins) for 25 cm diameter chambers. We collected headspace samples by inserting a needle attached to a 20-mL polypropylene syringe (Becton Dickinson, Rutherford, NJ) into the sampling port in the caps. Samples were immediately transferred to 12 mL pre-evacuated glass Exetainer vials (Labco Ltd., High Wycombe, UK) and stored until analysis by gas chromatograph within two weeks. Several ambient air samples were collected during each sampling event to be used as a quality control to assess potential soil disturbance during initial chamber cap placement (Rochette and Eriksen-Hammel 2008).

Beginning in late May (05/23/16), the N_2O monitoring scheme was changed in strawberries to better reflect field conditions with surface drip. The soil within the chamber bases was not receiving comparable irrigation compared to soil outside the base. This observation was confirmed by data from *in situ* soil moisture probes placed at two different locations (above and below the plant) both inside and outside one chamber base in each treatment. Following this finding 10 cm diameter PVC gas chambers covering a surface area of 0.01 m^2 were used.

N_2O samples were analyzed at CSUMB with a Shimadzu GC-2014 gas chromatograph equipped with an electron capture detector and integrated with a headspace autosampler (AOC 5000). The GC is calibrated during each sample batch with analytical-grade gas standards (Air Liquide Gases LLC, Plumsteadville, PA). Gas sample analysis is assessed for quality by including in each GC batch a standard sample that was transported and stored with field samples. These field sampling and GC analysis methods have been developed and used for previous research supported by ARI, CARB, and USDA.

Gas flux was determined from the rate of change of chamber gas concentration, chamber volume, and soil surface area. The change in chamber headspace N_2O gas concentration as a function of time is be represented by regression analysis, where the slope of the line is the flux rate (Parkin and Venterea, 2010; Rochette and Bertrand, 2008). The HMR package (Pedersen et al. 2001) available on the R open-source statistical program (R Development Core Team) was used to determine the type of regression from which the GHG flux should be calculated (e.g. linear or nonlinear). The HMR package uses a best-fit model selection process to recommend a specific data analysis to calculate gas flux: non-linear regression (Hutchinson-Mosier Regression, or HMR), linear regression, or zero flux. HMR results are given in volume per area per time units (μL N m^{-2} s^{-1}), and the Ideal Gas Law and air temperatures taken during sampling were used to convert from volumetric to mass based units (μg N m^{-2} s^{-1}). Cumulative area-based fluxes were estimated by taking the N_2O fluxes measured on each sampling day and applying trapezoidal integration of flux vs. time.

Environmental Variables Environmental variables that are known to influence N_2O production were measured and recorded. UCCE collaborators monitored soil nitrate with nitrate quick tests and supplementary laboratory analysis, while our NASA collaborators maintained soil moisture sensor networks, flow meters and MET stations to monitor soil parameters, applied water, air temperature, and precipitation. CSUMB collected bulk density samples to 0-32cm depth with soil cores, and oven-dried the soil at 105ºC. Soil % water filled pore space (WFPS) and soil temperature were measured with *in situ* 10HS and 5TE soil probes (Meter Group, Pullman, WA) as described above, and thermocouples (Omega Engineering) were used to measure air temperature in chamber headspace.

Soil Water Nitrate Concentrations To advance the understanding of how water movement through the vadose zone is related to N_2O emissions and N cycling, NO_3^--N leachate concentrations were analyzed and used to calculate treatment total loads, quantify spatially variable vadose-zone NO_3^--N flux, and drainage accuracy and precision data. These data were obtained by additional grants awarded to CSUMB and NASA.

Yield and Plant Nitrogen Content Other funding sources at UCCE and the commercial growers supported the full scope of this proposal. This included the assessment of crop yields and biomass for each treatment to determine total N removal and uptake by the crop, as well as to calculate N use efficiency. Yields for strawberries, broccoli and lettuce were recorded at harvest by weight, carton, and count for each crop grown, following protocols developed by UCCE for ongoing research. Sub-samples of each field were selected for careful collection and measurement, and were compared against overall yield recorded by the commercial grower. Yield-based N_2O emissions (g N Mg^{-1} yield) were calculated by dividing the cumulative area-based N_2O emissions by marketable crop yield.

Data Analysis and Statistics Direct N_2O emissions based on cumulative area-based fluxes were analyzed for alternative and standard irrigation treatments, and according to crop yield. Mean cumulative area-based N_2O fluxes were calculated for each sampling date and time from the arithmetic mean of measurements made from each replicate chamber in a treatment. Growing season and annual emissions estimates for each treatment were determined by trapezoidal integration between mean field measurements, where fluxes are assumed to change linearly between measurements. Yield-based N_2O emissions were calculated by dividing cumulative area-based emissions by marketable crop yield for each crop type.

Indirect N_2O emissions from NO_3^- leaching were estimated using established IPCC emissions factors (De Klein et al., 2006). These emissions factors (EF) estimate the percent of leached NO_3^- converted to gaseous N_2O and transported into groundwater and surface drainage, rivers, and estuaries (EF_5= 0.05, 0.75, and 2.5% nitrate leached). Indirect emissions are calculated by multiplying the N_2O emissions factors by cumulative N_2O emissions for each treatment and crop. Combined direct and indirect emissions were be calculated by summing the direct and indirect estimates for each treatment.

Differences between mean cumulative N_2O emissions across treatments for each crop were evaluated using one-way ANOVA ($P < 0.05$). Prior to ANOVA normality (Shapiro-Wilk test) and equality of variance (Levene's test) were assessed; non-normal data were log-transformed before analysis and re-tested to ensure they met the assumptions. Where flux data transformations did not significantly improve normality, untransformed data were used in the ANOVA as this statistical test is not as sensitive to deviations from normality. Relationships between N_2O fluxes and %WFPS and soil temperature were tested using Pearson's or Spearman's correlation, the former used when both variables satisfied assumptions of normality and the latter when at least one variable did not.

Microbial Nitrification and Denitrification Lab incubations were carried out to determine the driving forces of N_2O production in strawberries and lettuce/broccoli 2017 soils. Incubations were not performed on Broccoli 2016 soil due to lack of differences in applied water and fertilizer between treatments and because the alternative treatment was not ET 130. Traditionally, high rates of N_2O emissions have been associated with denitrification by heterotrophic bacteria (Firestone and Davidson 1989), whereby nitrate is reduced to dinitrogen gas with N_2O as byproduct, occurring mainly under conditions of high soil water content (Bateman and Baggs 2005). However, previous research at the field and lab scale has shown that nitrification can be a significant source of N_2O after ammoniacal fertilizer additions (Bremner and Blackmer 1978, Zhu et al. 2013, Huang et al. 2014). Here, the effects of different fertilizer N sources with and without nitrification inhibitor on N_2O production were assessed.

The soil was collected for ET 100 and ET 130 treatments by taking cores to 15 cm depth. The soils were pre-incubated for seven days at a moisture content of 40% of water holding capacity. Microcosms were prepared with 20 g (dwt.) soil in 160-mL vials equipped with rubber septa that allowed removal of headspace gas from the vials. The soils were brought to a moisture content of 65% of water holding capacity and amended with either aqua ammonia or potassium nitrate, so that each N fertilizer treatment had a total of 100 mg N kg^{-1}. The control treatment had a concentration of 25 or 32 mg N kg^{-1} nitrate and trace amount of NH_4^+ (<1 mg N kg^{-1}) in the two. The aqua ammonia treatment received 100 mg N kg^{-1} as NH_3 and the nitrate treatment received 75 or 68 mg N kg^{-1} as KNO_3. In each treatment (control, aqua ammonia, nitrate), one half of microcosms were treated with acetylene to inhibit nitrification immediately after adding the N fertilizers or deionized water (control) by injecting pure acetylene (C_2H_2) into the headspace of the vials to bring the concentration of the head space to 0.01% acetylene. The incubation was carried out over 36 hours at room temperature. There were 3 replicates per treatment.

F. Data/Results:

Crop yields for each crop/field were comparable for ET 100 and ET 130 or GP treatments. Cumulative area-based direct N_2O emissions were lower for ET 100 treatments in 2016 broccoli and romaine lettuce (Table 1). Yield based emissions followed this same trend. Peak emissions occurred at all sites following higher rates of N application (Figures 1). The 2016 broccoli trial Grower Practice had the highest daily, cumulative and yield-scaled N_2O emissions. Results of one-way ANOVA indicate there were no statistically significant differences in cumulative N_2O emissions between treatments in different crops/fields, except for Broccoli 2016 (α= 0.05, p= 0.0168, F= 6.19).

Table 1. Results for yield, cumulative direct and yield-based N_2O emissions (standard error in parentheses), NO_3^- leaching, indirect emissions, and sum of direct and indirect emissions (DI) for each crop and treatment. Yields are based on marketable yield. Leaching data and associated indirect emissions for

strawberries are presented with caution do to potential instrument deployment issues that may have resulted in inaccurate estimates.

Treatment and Crop Type	Yield	Cumulative direct N_2O emissions	Yield-scaled N_2O emissions	NO_3^- leaching	Indirect Emissions kg N ha^{-1}			DI Emissions kg N ha^{-1}		
	Mg ha^{-1}	kg N ha^{-1}	g N Mg^{-1} yield	kg N ha^{-1}	EF_5 0.05	EF_5 0.75	EF_5 2.5	Sum DI EF_5 0.05	Sum DI EF_5 0.75	Sum DI EF_5 2.5
ET 100 Strawberries	94	2.2 (0.003)	18	65	0.03	0.49	1.62	1.76	2.21	3.34
ET 130 Strawberries	93	2.1 (0.003)	22	111	0.06	0.83	2.78	2.06	2.84	4.79
ET 100 Broccoli (2016)	13	3.7 (0.16)	291	31	0.02	0.23	0.78	3.41	3.63	4.18
GP Broccoli (2016)	15	5.7 (0.27)	374	32	0.02	0.24	0.79	4.73	4.96	5.51
ET 100 Romaine Lettuce	75	0.5 (0.03)	9	10	0.01	0.08	0.26	0.46	0.54	0.72
ET 130 Romaine Lettuce	75	0.6 (0.03)	11	39	0.02	0.29	0.98	0.58	0.85	1.54
ET 100 Broccoli (2017)	18	3.5 (0.06)	186	62	0.03	0.47	1.56	3.51	3.95	5.04
ET 130 Broccoli (2017)	18	3.0 (0.04)	153	76	0.04	0.57	1.90	3.03	3.56	4.89

Direct plus indirect (DI) emissions for all crops/fields are presented in Table 1 with the three different scenarios of indirect emissions as described in De Klein et al. 2006, using EF_5 of 0.05% (lower limit), 0.75% (default value), and 2.5% (upper limit), which represent the percentage of nitrate leachate that could be transformed into N_2O emissions in downstream-from-farm aquatic environments (i.e. drainage ditches, ponds, streams, wetlands). Leaching estimates for strawberries are presented with a caution as detailed scrutiny of the results from individual lysimeter instruments suggest potential deployment and/or maintenance issues that may have resulted in inaccurate estimates. Thus, because the indirect emissions are derived from these values, they are not precise.

For all treatments EF_5 values for 0.05 and 0.75% account for a fraction of DI emissions, and ET 100 treatments had lower DI emissions than alternative management for all crops except broccoli (2017), which had very similar DI values. Indirect emissions were lower for ET 100 treatment for all trials. The range of indirect emissions estimates under $EF_5 = 2.5$ vary from 13% (for GP Broccoli) to 163% (ET 130 Romaine) of cumulative direct N_2O emissions, and five out of eight of the indirect estimates were over 50% of direct emissions.

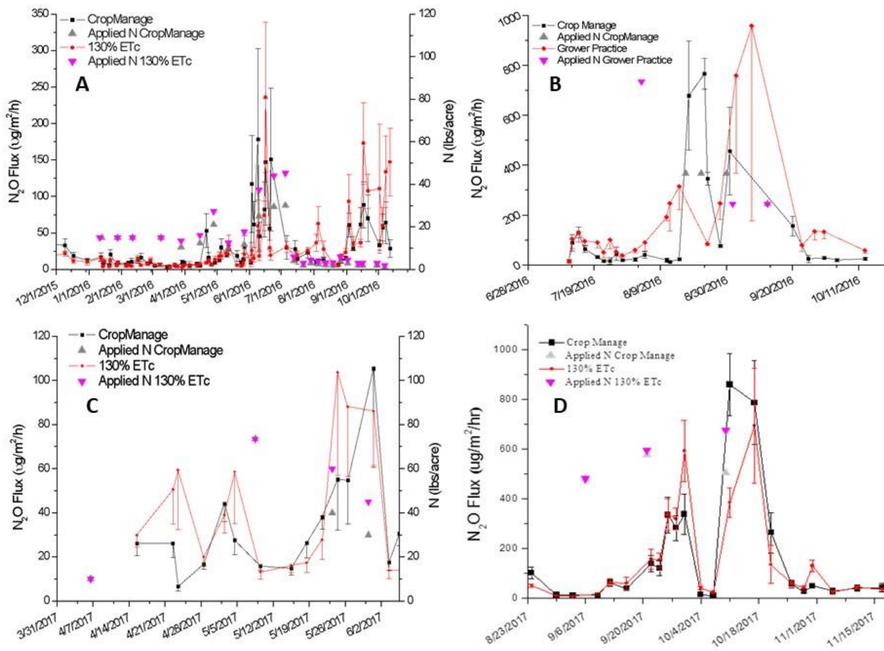

Figure 1. Direct mean daily N_2O fluxes (µg/m^2/h) and N applications (lbs N/acre) for ET 100/CropManage and alternative treatments (ET 130/130% ETc, or Grower Practice/GP) in strawberries (A), broccoli 2016 (B), and lettuce (C), and broccoli 2017 (D). Peak fluxes occurred at all sites following fertilizer application.

Soil WFPS and temperature were generally lower in ET 100 treatments compared to alternative treatments (Figure 2). Results of correlation tests (Table 2) indicate soil variables % water filled pore space (WFPS) and soil temperature were not generally related to N_2O flux across treatments or fields; most relationships were non-significant, and those that were significant were weak or moderate. ET 100 treatments were significantly correlated with WFPS across three of the trials; however, two of the correlations were negative and weak. In strawberries, soil temperature had a weak to moderate positive correlation with emissions for both treatments. The most notable predictor was WFPS for both ET 100 and ET 130 in Broccoli 2017 with had a moderate positive correlation with N_2O flux ($r = 0.591$ and $r = 0.564$, respectively). There were no significant correlations for Lettuce. These results suggest there may be unexplored predictors and/or relationships that are driving N_2O production in these systems.

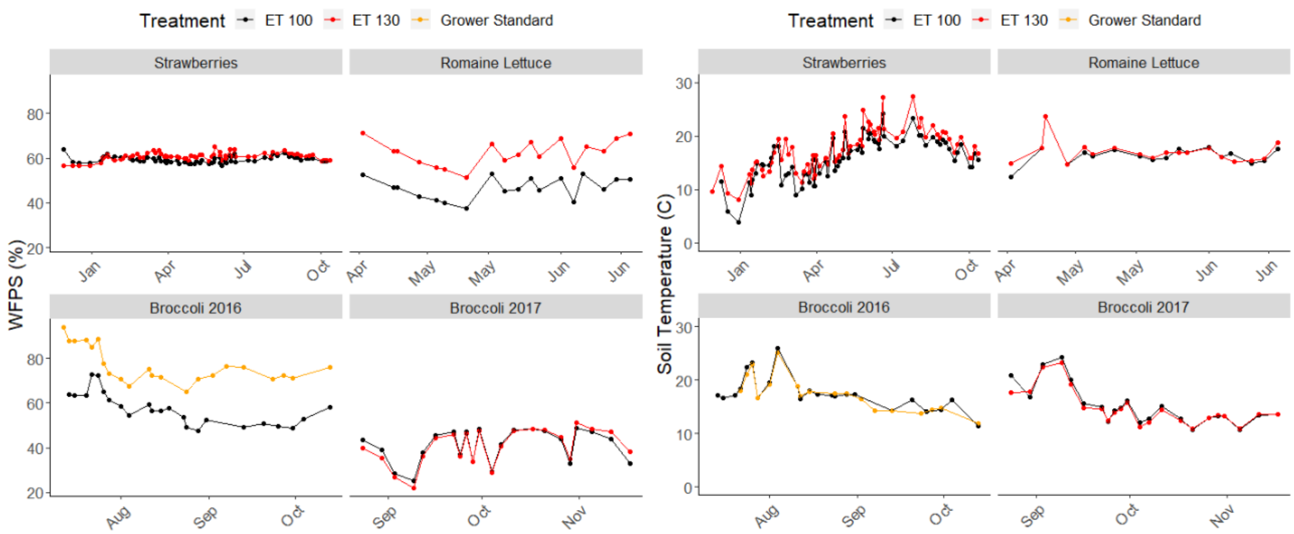

Figure 2. Respective mean percent soil water filled pore space (WFPS) and mean soil temperature at 0-15 cm depth during the times for N_2O sampling for all crops/fields. WFPS was almost always lower for ET 100 vs alternative practice, while soil temperature was generally the same for both treatments except in Strawberries where it was higher in ET 100.

Table 2. Pearson and Spearman correlation coefficients (r) representing relationships between N_2O flux and predictor soil variables % water filled pore space (WFPS) and soil temperature across all fields and separated by management. There were not consistent significant relationships between soil variables and gas flux for any one treatment type or field, and in some cases the relationship was a negative one (WFPS for ET 100 in strawberries and broccoli 2016).

	Strawberries		Broccoli 2016		Lettuce		Broccoli 2017	
	ET 100	**ET 130**	**ET 100**	**GS**	**ET 100**	**ET 130**	**ET 100**	**ET 130**
WFPS	<u>-0.336**</u>	<u>0.0860</u>	<u>-0.422*</u>	<u>-0.100</u>	0.156	0.125	0.591**	0.564**
Soil Temperature	<u>0.426***</u>	<u>0.564***</u>	<u>-0.104</u>	-0.213	<u>0.209</u>	0.336	-0.245	-0.390

*, **, *** refers to significance at $p<0.05$, $p<0.01$, and $p<0.001$, respectively. NS = not significant, underlined = Spearman test.

Lab incubations were carried out to determine the driving forces of N_2O production in and lettuce/broccoli 2017 soils. The effects of soil moisture content and fertilizer N source were evaluated with and without nitrification inhibitor on N_2O production. The incubation showed that in both treatments, the majority of the N_2O production was due to nitrification. Compared to the nitrate treatments, the application of aqua ammonia had higher N_2O production. Moreover, the nitrification inhibitor (C_2H_2) reduced N_2O production to the control levels in both fertilizer treatments.

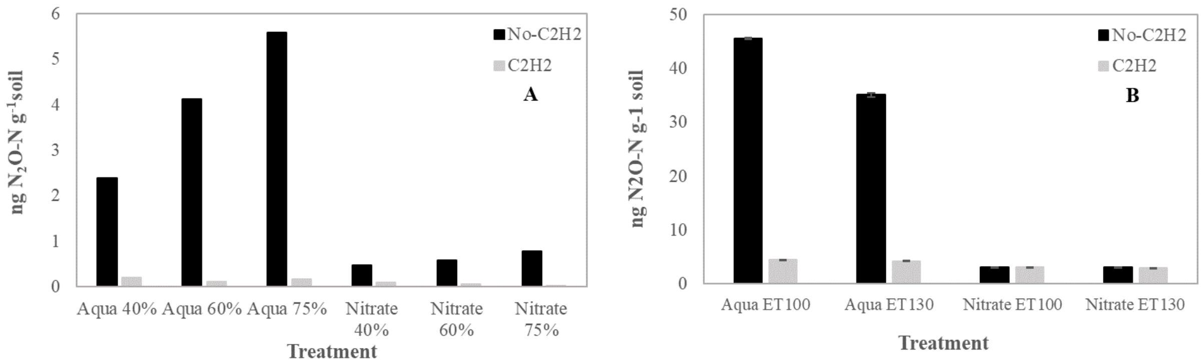

Figure 3. Nitrous oxide production from strawberry (A) and lettuce/broccoli (B) soil during 36 hour incubation with/without acetylene (C_2H_2) to inhibit nitrification. Vertical bars represent standard error (n = 3). In both treatments, the majority of the N_2O production was due to nitrification.

G. Discussion and Conclusions

Across sites and crop types, 100 ET-based management maintained comparable yields and minimized NO_3^- leaching and indirect N_2O emissions compared to alternative practices.

Strawberry and lettuce/broccoli lab incubation findings that nitrification was the dominant source of N_2O production are consistent with observed fluxes where WFPS was <70% throughout a majority of the two crop seasons, which is below the optimal range of 70-90% WFPS for denitrification (Bateman and Baggs 2005). Peak fluxes occurred following fertilizer application that included ammonium, and previous research at the field and lab scale has shown that nitrification can be a significant source of N_2O after ammoniacal fertilizer additions (Bremner and Blackmer 1978, Zhu et al. 2013, Huang et al. 2014).

Results indicate a significant difference in cumulative N_2O emissions between treatments only for the Broccoli 2016 study, which did not have an ET 130 treatment but rather had the grower practice as the alternative management to ET 100. While there was little to no difference in the amount of applied fertilizer and irrigation between the ET 100 and GS treatments at this trial, the scheduling of irrigation and fertilizer application through drip tape was very different. There were about one third of irrigation events where the grower applied water over longer periods of time compared to ET 100 treatment, from less than one to up to 12 hours more, and more often than not several hours. We are continuing to analyze data to learn if timing and duration of irrigation can explain the differences in N_2O emissions.

The lack of differences in N_2O emissions could be explained by greater amounts of irrigation and subsequent drainage in ET 130 treatments, where more rapid transport of NO_3^- through the well-drained soils in this study could have removed NO_3^- from the upper soil profile before microbes could transform it into measurable emissions from the soil surface. Additionally, all fields and crops maintained WFPS below 70% for a majority- if not all- the time throughout the respective study periods, which would have limited denitrification and associated N_2O production.

Indirect emissions due to NO_3^- leaching accounted for 14 to 63% of DI emissions for EF_5 of 2.5%, where six of the eight results were over 30%. If accounted for in N_2O inventory calculations, these indirect estimates would add substantially to emissions estimates from farm management practices. Marharjan et al. (2014) had similar findings, and we echo the authors' assertion the wide range of uncertainty in currently available indirect emissions factors reinforces the important need for improvements in this area.

We are building upon this work with a more rigorous principal component analysis (PCA) of these data which includes explanatory variables with known impact on N_2O emissions and are potentially highly correlated. This process will quantify what proportion of variation in N_2O emissions is in each of the many factors that we include in the model and will help identify subsets of variables that are highly correlated with each other, thus providing a deeper understanding into the complex interactions between farm management, soil processes, and N_2O emissions.

This study provides insights into the benefits of using the CropManage ET-based irrigation and fertilizer management decision support tool. These results demonstrate the efficacy of a 100% ET_c and N application regime at producing comparable yield to grower practice and 130% ET_c and N management. Additionally, reductions in nitrate leaching, direct and indirect N_2O emissions associated with more efficient irrigation and nutrient management invariably reduce costs associated with water and N fertilizer use, helping farmers maintain a viable business while produce healthy crops at industry-standard competitive yields.

H. Project Impacts:

This project was successful at helping to quantify nitrous oxide emissions under on-farm best management practices, and with excess irrigation and fertilizer application. Because of the collaborations and other funding from NASA ARC-CREST and the UCCE these data can be used to create a more complete understanding of the total nitrogen budget in specialty crops relevant to the central coast of California (broccoli, lettuce, and strawberries). Throughout the study we were able to have strong industry and research interactions. One of the main takeaways for us was that reducing irrigation and fertilizer use to the CropManage 100% ETc recommendations did not result in any loss of crop yields. In fact, we found after the 2nd year that we needed to explicitly ask the grower partners to apply excess irrigation and water because they were adopting the more conservative usage practices. We did not expressly look at types of N inputs, and thus do not have complete data, but it appears that there is an inverse relationship between nitrate application and nitrous oxide emissions. When ammoniacal fertilizer was applied there were much greater nitrous oxide emissions. This deserves further study.

I. Outreach Activities Summary

Event 1: 49th Annual American Geophysical Union Meeting

Date/Location: December 2015, San Francisco

Participants/audience: ~24,000 Scientists, Industry, and Technology Researchers

Effectiveness: The poster presentation provided for networking with others interested in monitoring nitrogen and moisture dynamics in soil, and was well-received.

Event 2: UCCE Irrigation and Nutrient Management Workshop

Date/Location: December 2015, Salinas

Participants/audience: ~20 growers, extension specialists, and researchers

Effectiveness: The workshop covered CropManage Training and facilitated dialogue with growers about BMPs.

Event 3: EcoFarm Conference

Date/Location: January 2016, Pacific Grove

Participants/audience: ~2000 Growers, Industry Representatives, Scientists

Effectiveness: The event provided in-depth information on issues and opportunities facing the organic farming industry in standard plenary talks and poster sessions. The setting also allowed for many small group gatherings over dinner, at break-out sessions, and at industry demonstration booths.

Event 4: Soils Class Demonstration Day in Strawberries

Date/Location: March 28, 2016, Aromas

Participants/audience: 23 students, several growers and researchers

Effectiveness: Students met growers and learned about commercial grower partnerships crucial to conduct this study. Details of the goals and experimental design of this study were explained, and students participated in field sampling for soil nitrous oxide emissions. A follow-up lecture was given with results, and discussion was facilitated for students to apply knowledge of soil processes to interpret results and understand limitations and benefits of on-farm experiments.

Event 5: Field Demonstration Day at the Strawberry Site

Date/Location: July 2016, Aromas

Participants/audience: 10 ranch managers and scientists (industry and CSUMB)

Effectiveness: The meeting was effective at providing a mid-study update in order to prepare for the upcoming harvest. Preliminary data was shared which provided for an opportunity for the grower partner to ask questions, and become informed.

Event 6: CDFA FREP/WPHA Annual Conference

Date/Location: October 2016, Modesto

Participants/audience: ~1000 Growers, Biotech Industry, and Scientists

Effectiveness: The poster was effective at generating a lot of conversations and interest.

Event 7: Soils Class Demonstration Day in Lettuce

Date/Location: April 2017, Gonzalas

Participants/audience: 22 students, several growers and researchers

Effectiveness: Students met growers and learned about commercial grower partnerships crucial to conduct this study. Details of the goals and experimental design of this study were explained, and students participated in field sampling for soil nitrous oxide emissions. A follow-up lecture was given with results, and discussion was facilitated for students to apply knowledge of soil processes to interpret results and understand limitations and benefits of on-farm experiments.

Event 8: California State University, Agricultural Research Initiative Meeting

Date/Location: September 2017, Sacramento

Participants/audience: 100 scientists, students, and administrators

Effectiveness: This grant and the collaborative funds were used to present one talk and two posters. The data was very well-received. One of the goals of the meeting was to generate cross-CSU campus collaborations and the format was conducive to this.

Event 9: Greater Vision Water Forum

Date/Location: October 2017, Seaside

Participants/audience: 500 scientists, students, agency professionals and commercial growers

Effectiveness: This event was very interdisciplinary, but the idea of using on-farm BMPs to mitigate climate change effects was found to be very interesting to many participants. The poster presenter was an undergraduate student, and this helped to promote their identity as a scientist.

Event 10: Monterey Peninsula College, Gentrain Forum

Date/Location: October 2017, Monterey

Participants/audience: 100 community members

Effectiveness: The talk created a lot of community interest. There were many questions surrounding research in agricultural settings, and a general sense of appreciation for the industry partners who have teamed up with CSUMB, NASA, and the UCCE to make the world a better place.

Event 11: Grower Meeting and Data Update

Date/Location: October 2017, Spreckles

Participants/audience: ~20 scientists, students, and commercial growers

Effectiveness: The lettuce nitrogen dynamics data was very well-received by the commercial partners.

Event 12: 50th Annual American Geophysical Union Meeting

Date/Location: December 2017, New Orleans, LA

Participants/audience: ~24,000 Scientists, Industry, and Technology Researchers

Effectiveness: The NASA staff presented the joint CSUMB data. While agricultural sciences are not the primary topic of the AGU, the sheer size of the conference allowed for many good interactions.

Event 13: Grower Meeting and Data Update

Date/Location: March 2018, Spreckles

Participants/audience: ~15 scientists, students, and ranch managers

Effectiveness: The data from the broccoli trial was presented to the industry partner.

Event 14: CSU Research Advocacy to State Legislative Staff

Date/Location: June 2018, Sacramento

Participants/audience: Several students, and ~40 state policy makers

Effectiveness: The presentation highlighted the importance of research in the CSU System and the positive impacts on student success. One of the primary missions of the CSU is to provide CA with a quality workforce, and the importance of agricultural research was highlighted.

Event 15: CSU Climate Change Conference

Date/Location: July 2018, Virtual host Long Beach Chancellor's Office

Participants/audience: ~50 scientific presentations, >100 real-time participants

Effectiveness: The presentation was part of a panel discussion and generated a lot of great discussion.

Event 16: CDFA FREP/WPHA Annual Conference

Date/Location: July 2018, Seaside

Participants/audience: ~1000 Growers, Biotech Industry, and Scientists

Effectiveness: The talk and poster were effective at generating a lot of conversations and interest.

Event 17: CDFA FREP/WPHA Blog

Date/Location: August 2018

Participants/audience: CDFA list serve

Event 18: CSU Board of Trustees Meeting

Date/Location: September 2018, Long Beach

Participants/audience: CSU Board of Trustees, General Public

Effectiveness: The presentation highlighted the importance of research in the CSU System and the positive impacts on student success. One of the primary missions of the CSU is to provide CA with a quality workforce, and the importance of agricultural research was highlighted.

J. Factsheet/Database Template:

1. Project Title Quantifying N_2O Emissions under Different On-farm Irrigation and Nutrient Management BMPs that Reduce Groundwater Nitrate Loading and Applied Water

2. Grant Agreement Number 15-0356-SA

3. Project Leaders

Arlene Haffa, PhD, MS, Associate Professor of Biochemistry and Microbiology, School of Natural Sciences, California State University, Monterey Bay

William Horwath, PhD, Professor of Soil Biogeochemistry, Department of Land, Air and Water Resources, UC Davis.

Forrest Melton, MS, Senior Research Scientist, NASA Ames Research Center and School of Natural Sciences, California State University, Monterey Bay

Stefanie Kortman, MS Graduate Student, School of Natural Sciences, California State University, Monterey Bay

4. Start Year/End Year 2015-2018

5. Location CSUMB, three commercial farms in Salinas and Pajaro Valleys

6. County Monterey

7. Highlights

1) Crop yields for strawberries, lettuce, and multiple broccoli trials were comparable using 100% and 130% of recommended evapotranspiration (drip) irrigation treatments.
2) Cumulative area-based direct nitrous oxide (N_2O) emissions were lower for the 100% treatments in 2016 broccoli and romaine lettuce. Yield based emissions followed this same trend.
3) Peak emissions occurred at all sites following higher rates of N application.
4) The 2016 broccoli trial Grower Practice had the highest daily, cumulative and yield-scaled N_2O emissions. Results of one-way ANOVA indicate there were no statistically significant differences in cumulative N_2O emissions between treatments in different crops/fields, except for Broccoli 2016 (α= 0.05, p= 0.0168, F= 6.19).
5) Indirect nitrous oxide emissions estimates were lower for 100% treatments in all trials.

8. Introduction There are economic and environmental sustainability challenges associated with the nutrient intensive production of specialty crops grown in the Pajaro and Salinas Valleys. Nitrate-N fertilizer applications in excess of crop use uptake may result in additional irrigation and fertilizer costs, N_2O gas emissions to the atmosphere, and nitrate (NO_3^-) leaching to groundwater. N_2O is 300 times more effective than carbon dioxide at warming the atmosphere, and the majority of N_2O in the U.S. is emitted by agriculture soils. N_2O is produced by microorganisms that convert available nitrogen to N_2O gas as a bi-product of metabolic processes. Direct emissions are a release of gas from the soil, and indirect emissions occur when leached NO_3- is transformed into N_2O in downstream aquatic environments (De Klein et al., 2006). Few studies address both direct and indirect N_2O emissions due to row crop soil management. We are evaluating the potential for evapotranspiration-based (ET-based) irrigation to mitigate N_2O emissions and NO_3- leaching as a result of improved crop N uptake. The goal is to assist growers in optimizing water and fertilizer use in a way that reduces crop production costs while minimizing losses of excess N to the environment.

9. Methods/Management

- Establish standard and alternative irrigation management treatments in split-block designed strawberry and subsequently lettuce-broccoli crop rotations
- Measure direct soil N_2O emissions and total applied water from these cropping systems
- Estimate direct and indirect N_2O emissions in conjunction with NO_3^- leaching data
- Quantify direct and indirect N_2O emissions in relation to yield quantity and quality differences, input costs and total water applied
- Characterize N_2O emissions based on environmental factors
- Analyze the pathway of N transformation in soil through physical NH_3 oxidation due to water and oxic/pH conditions

10. Findings

Across sites and crop types, 100 ET-based management maintained comparable yields and minimized NO_3^- leaching and indirect N_2O emissions compared to alternative practices. Strawberry and lettuce/broccoli lab incubation findings that nitrification was the dominant source of N_2O production are consistent with observed fluxes where WFPS was <70% throughout a majority of the two crop seasons, which is below the optimal range of 70-90% WFPS for denitrification (Bateman and Baggs 2005). Peak fluxes occurred following fertilizer application that included ammonium, and previous research at the field and lab scale has shown that nitrification can be a significant source of N_2O after ammoniacal fertilizer additions (Bremner and Blackmer 1978, Zhu et al. 2013, Huang et al. 2014).

Results indicate a significant difference in cumulative N_2O emissions between treatments only for the Broccoli 2016 study, which did not have an ET 130 treatment but rather had the grower practice as the alternative management to ET 100. While there was little to no difference in the amount of applied fertilizer and irrigation between the ET 100 and GS treatments at this trial, the scheduling of irrigation and fertilizer application through drip tape was very different. There were about one third of irrigation events where the grower applied water over longer periods of time compared to ET 100 treatment, from less than one to up to 12 hours more, and more often than not several hours.

Similar N_2O emissions could be explained by greater drainage in ET 130 treatments, with greater transport of NO_3^- through the well-drained soils, removing NO_3^- from the upper soil profile before microbial transformation. Additionally, all fields and crops maintained WFPS below 70% for a majority of the time, which would have limited denitrification and associated N_2O production.

Indirect emissions due to NO_3^- leaching varied from a small fraction of DI emissions for EF_5 of 0.05 and 0.75% to a range of 14 to 63% for EF_5 of 2.5%. The wide range of uncertainty in currently available indirect emissions factors reinforces the important need for improvements in this area. As these indirect emissions estimates represent the percentage of nitrate leachate that could be transformed into N_2O emissions in downstream-from-farm aquatic environment, it is essential that lysimeter measurements accurately reflect field conditions. The passive capillary lysimeters used required invasive and labor-intensive installation that inevitably disturbs the soil. While we implemented these highly technical devices with utmost care, there are limitations to the function of the lysimeters in high-turnover agriculture systems. Thus, we present leaching estimates with a caution not to interpret these- and associated indirect emissions- results as canonical.

Lab incubations determined the driving forces of N_2O production in the soils. The effects of soil moisture content and fertilizer N source were evaluated with and without nitrification inhibitor on N_2O production. The majority of the N_2O production was due to nitrification. Compared to the nitrate treatments, the application of aqua ammonia had higher N_2O production. Moreover, the nitrification inhibitor (C_2H_2) reduced N_2O production to the control levels in both fertilizer treatments. This suggests that for these fields ammoniacal fertilizer additions may be an important driver of N_2O production, and nitrate-based fertilizer application could potentially minimize N_2O emissions. Future studies should investigate how N_2O fluxes respond to fertilizers with different N-compositions.

This study validates the benefits of using CropManage as a decision support tool for irrigation and nutrient management of strawberries, lettuce, and broccoli in the Central Coast. These results demonstrate the efficacy of a 100% ETc and N application regime at producing comparable yield to grower practice and 130% ETc and N management. Additionally, reductions in direct and indirect N2O emissions and NO_3- leaching, associated with more efficient irrigation and nutrient management invariably reduce costs associated with water and N fertilizer use, helping farmers maintain a viable business while producing healthy crops at industry-standard competitive yields.

References

Bateman, E.M. and E J. Baggs. 2005. Contributions of nitrification and denitrification to N_2O emissions from soils at different water-filled pore space. Biol. Fert. Soils. 41: 379–88.

Bremner J.M. and A.M. Blackmer 1978. Nitrous oxide emission from soils during nitrification of fertilizer nitrogen. Science 199:295-296.

Cahn, M., Hartz, T., Smith, R., Noel, B., Johnson, L., & Melton, F. 2015. CropManage: An online decision support tool for irrigation and nutrient management. Proceedings of the 2015 Western Nutrient Management Conference, Vol. 11, Reno, NV.

CEC (California Energy Commission). 2006. Inventory of California Greenhouse Gas Emissions and Sinks: 1990-2004 [Internet]. Available from: http://www.energy.ca.gov/2006publications/CEC-600-2006-013/CEC-600-2006-013-SF.PDF

De Gryze S, Albarracin MV, Catala-Luque R, Howitt RE, Six J. 2009. Modeling shows that alternative soil management can decrease greenhouse gases. California Agriculture 63(2): 84-90.

De Klein, C., R.S.A. Novoa, S. Ogle, K.A. Smith, P. Rochette, T.C. Wirth, et al. 2006. N_2O emissions from managed soils and CO_2 emissions from lime and urea application. In: S. Eggleston et al., editors, 2006 IPCC guidelines for national greenhouse gas inventories. Vol. 4. Agriculture, forestry and other land use. Inst. Global Environ. Strategies, Hayama, Japan.

Denman, K.L., G. Brasseur, and A. Chidthaisong. 2007. Couplings between changes in the climate system and biogeochemistry. In: S. Solomon et al., editors, Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge, UK. p. 500–587

Firestone, M.K. and E.A. Davidson. 1989. Microbiological basis of NO and N_2O production and consumption. In: Andreae, M.O. and D.S. Schimel, editors, Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere. Wiley, New York, p. 7-21.

Huang, T., B. Gao, X. Hu, X. Lu, R. Well, P. Christie, L.R. Bakken, and X. Ju. 2014. Ammonia oxidation as an engine to generate nitrous oxide in an intensively managed calcareous Fluvo-aquic soil. Sci. Rep. 4:3950: 1–9.

Kallenbach CM, Rolston DE, Horwath WR. Cover cropping affects soil N_2O and CO2 emissions differently depending on type of irrigation. 2010. Agriculture, Ecosystems and Environment 137:251-260.

Kravchenko AN, Robertson GP. Statistical Challenges in Analyses of Chamber-Based Soil CO_2 and N_2O Emissions Data. 2015. Soil Sci. Soc. Am. J. 79:200–211.

Lee J, Hopmans J, van Kessel C, King AP, Evatt KJ, Louie D, Rolston DE, Six J. 2009. Tillage and seasonal emissions of CO2, N2O and NO across a seed bed and at field scale in a Mediterranean climate. Ag, Ecosyst. And Enviro. 129:378-390.

Letey, J. and P. Vaughan. 2013. Soil type, crop and irrigation technique affect nitrogen leaching to groundwater. California Agriculture **67**:231-241.

Maharjan, B., Venterea, R. T. & Rosen, C. Fertilizer and irrigation management effects on nitrous oxide emissions and nitrate leaching. *Agron. J.* **106,** 703–714 (2014).

Mosier AR, Hutchinson GL. 1981. Nitrous oxide emissions from cropped fields. J. Environ. Qual. 10:169-173.

Parkin TB, Kaspar TC. 2006. Nitrous oxide emissions from corn-soybean systems in the midwest. Journal of Environmental Quality 35(4):1496-1506.

Parkin TB. 2008. Effect of sampling frequency on estimates of cumulative nitrous oxide emissions. Journal of Environmental Quality 37:1390-1395.

Parkin, T.B. and Venterea, R.T. 2010. Sampling Protocols. Chapter 3. Chamber-Based Trace Gas Flux Measurements. IN Sampling Protocols. R.F. Follett, editor. p. 3-1 to 3-39. Available at: www.ars.usda.gov/research/GRACEnet

Petersen SO, Regina K, Pollinger A, Rigler E, Valli L, Yamulki S, Esala M, Fabbri C, Syvasalo E, Vinther FP. 2006. Nitrous oxide emissions from organic and conventional crop rotations in five european countries. Agriculture, Ecosystems and Environment. 112(2-3): 200-206.

Rochette P, Eriksen-Hamel NS. 2008. Chamber measurements of soil nitrous oxide flux: are absolute values reliable? Soil Sc. Soc. Am. J. 72:331-342.

Smith KA, Conen F. 2004. Impacts of land management on fluxes of trace greenhouse gases. Soil Use and Management. 20:255-263.

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. Proc. Natl. Acad. Sci. U.S.A. 110(16):6328–6333.