Final Report

Improving DNDC Modeling Capability to Quantify Mitigation Potential of Nitrous Oxide from California Agricultural Soils

(Contract Number: 14-306)

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Prepared for the California Air Resources Board and the California Environmental Protection Agency

September 6, 2017

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Acknowledgement

We thank Martin Burger, William Horwath, David Smart, Johan Six, Dave Goorahoo, and Cynthia Kallenbach for providing N_2O flux data to facilitate the model tests. We gratefully acknowledge Dr. Lei Guo (California Air Resource Board), Pete Ingraham (Applied GeoSolutions), and Beth Ziniti (Applied GeoSolutions) for assisting database preparation, statistical analyses, and regional simulations.

This Report was submitted in fulfillment of contract 14-306 Improving DNDC Modeling Capability to Quantify Mitigation Potential of Nitrous Oxide from California Agricultural Soils by Institute for the Study of Earth, Oceans and Space, University of New Hampshire under the sponsorship of the California Air Resources Board. Work was completed as of July 2017.

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Abstract

This project refined a biogeochemical model, DeNitrification-DeComposition (DNDC), so that it can be used to quantify nitrous oxide (N_2O) emissions as well as N_2O mitigation potentials under California conditions. Specifically, we (1) compiled N_2O measurements from California fields across a wide range of crops and farming management practices (FMPs); (2) refined DNDC and tested the model against the collected data to verify the model's ability of representing diverse crops and management practices in California; (3) updated a California-specific GIS databases for statewide greenhouse gases (GHG) modeling; (4) estimated N_2O emissions from California croplands; and (5) assessed efficiency of alternative FMPs in mitigating N_2O emissions. We improved DNDC in the following aspects: we (1) offered two irrigation simulation options for the DNDC regional mode: an irrigation index and irrigation event; (2) compiled irrigation management data into the California-specific database and added the capacity of varying irrigation water depth with county air temperatures; (3) expanded the database by including more cropping systems and multi-years information of climate and crop area; and (4) improved manure parameterization to reflect application of slurry manure in California croplands. Besides these improvements, we also updated the fertilization and crop residue returns in the database.

We verified DNDC against the N_2O measurements collected across a range of California cropping systems. The DNDC simulations matched observed N_2O peaks, which primarily responded to fertilization and/or irrigation. Altogether, we tested DNDC against 52 cases to verify its applicability for quantifying N_2O emissions from different cropping systems in California. The correlation between the DNDC-modeled and measured annual/seasonal N_2O emissions is significant with an $R^2$of 0.87, a slope of 1.00, and a P of < 0.001, indicating that DNDC reliably predicted the N_2O emissions from the cropping systems. We used the validated DNDC and the updated database to simulate historical N_2O emissions from California croplands. The simulated annual N_2O emissions from California croplands ranged between 3.49×10^3 and 6.37×10^3 metric ton (MT) N yr^{-1} with a mean annual emissions of 5.23×10^3 MT N yr^{-1} from 2000 to 2015. The estimates further indicated that (1) the direct N_2O emissions from California croplands showed a significant decreasing trend since 2002 primarily due to significant reductions of croplands area and N inputs as well as N_2O emission rate; (2) major contributing crops of N_2O were corn, non-legume hay, alfalfa, and cotton; and (3) the counties with substantial N_2O emissions are San Joaquin, Fresno, and Tulare. Additional DNDC simulations were carried out to assess uncertainties of the N_2O estimates. Uncertainty analyses were performed for (1) soil properties, (2) irrigation water depth, and (3) management event scheduling, using the 2012 activity database. The largest uncertainties of the DNDC N_2O estimates would arise from soil properties. The range of the DNDC N_2O estimate would vary between 3965 Mg N and 7799 Mg N. The efficiency of different FMPs on mitigating N_2O emissions was assessed by conducting a series of simulations with varying FMPs and comparing the simulations under alternative FMP scenarios against the baseline simulation. We set eight alternative scenarios by exclusively modifying a FMP applied under the baseline scenario, including nitrogen application, application of nitrification inhibitor, tillage, planting of cover crop, or irrigation management, to investigate impacts of each management practice on N_2O emission. The practices identified with relative high mitigation efficiency (> 20% reduction) included combing N rate reduction by 15% and application of nitrification inhibitors, planting non-leguminous cover crops, surface drip irrigation, and subsurface drip irrigation.

Executive Summary

Background

Nitrous oxide (N_2O) is one of the most important greenhouse gases (GHGs). It significantly contributes to global warming due to its high global warming potential (298 kg carbon dioxide per kg N_2O at a time horizon of 100 years; IPCC, 2013), and also leads to deterioration of the atmospheric environment by depleting ozone (Ravishankara et al., 2009). During the recent three decades, the concentration of N_2O in atmosphere was continually increasing at a rate of 0.73 ppbv (10^{-9}) yr^{-1} or 0.2-0.3% yr^{-1}, primarily due to accelerated emissions from agriculture soils (IPCC, 2013). Globally, agricultural sources of N_2O emissions are approximately 4.1 Tg (10^{12} g) N-N_2O yr^{-1} (IPCC, 2013; Syakila and Kroeze, 2011), which are primarily attributed to the use of synthetic nitrogen (N) fertilizers and organic manure (Davidson, 2009).

With the passage of the Global Warming Solutions Act of 2006 (AB32), which aims to reduce GHGs emissions from California to 1990 levels by 2020, California has rapidly made efforts to quantify and mitigate GHGs. A number of field studies have been performed to characterize GHGs, in particular, N_2O emissions from typical California cropping systems in recent years (e.g., Garland et al., 2011, 2014; Burger and Horwath, 2012; Steenwerth et al., 2010; Kennedy et al., 2013; Smart et al., 2011). The current project built off the earlier efforts to improve and apply a process-based biogeochemical model DNDC to extrapolate the N_2O measurements at specific sites or during specific periods to larger regions or over extended time spans, and thus to enable quantification of mitigation potentials of alternative farming management practices to reduce N_2O emissions from California croplands. Finally, this project provided necessary tools and database to improve California inventory of N_2O emissions from agricultural soil management, the major source of N_2O emissions in California.

Methods and Results

We improved the DNDC package to assess N_2O emissions and mitigation potentials under various California conditions in the following areas: we (1) offered two irrigation simulation options for the DNDC regional mode: an irrigation index and irrigation event; (2) compiled irrigation management data (i.e. water amount, frequency, irrigation method) into the California-specific database and added the capacity of varying irrigation water depth of crops with county air temperatures; (3) expanded the California-specific database by including more cropping systems (i.e. spinach, garlic, celery, squash, spring wheat, and strawberries) and multi-years (2000 to 2015) information of climate and crop area; and (4) improved manure parameterization to reflect application of wet (slurry) manure in California croplands.

We verified the DNDC model against field measurements of N_2O emissions collected across a range of California cropping systems. In a previous project, DNDC simulations of N_2O emissions from California croplands have been tested against field N_2O measurements from several cropping systems (alfalfa, winter wheat, vineyard, almond orchard, tomato, and rotation of row crops) representing a range of environmental conditions and farming management practices in California agriculture (Li et al., 2014). In this project, we tested DNDC further against N_2O emissions from several other cropping systems, including corn, lettuce, and cotton, as a complement for the previous study. The DNDC simulations produced similar patterns of daily N_2O fluxes as observed in the fields, which were usually induced by fertilization, fertigation, or irrigation. The simulated impacts of the various treatments on N_2O emissions were also generally comparable with the measurements. Altogether, we compared DNDC simulations against 52 cases to test its applicability for quantifying N_2O emissions from different cropping systems in California. The correlation between the DNDC-modeled and measured annual/seasonal N_2O emissions is significant with an R^2 of 0.87, a slope of 1.00, and a $P < 0.001$ (Figure A1), indicating that the DNDC model reliably predicted the seasonal and annual N_2O emissions from the tested cropping systems without statistical biases. DNDC also performed more favorably than the IPCC Tier 1 Emission Factor (EF) approach. The EF-derived regression showed an R^2 of 0.01 and a slope of 0.84 (Figure E1).

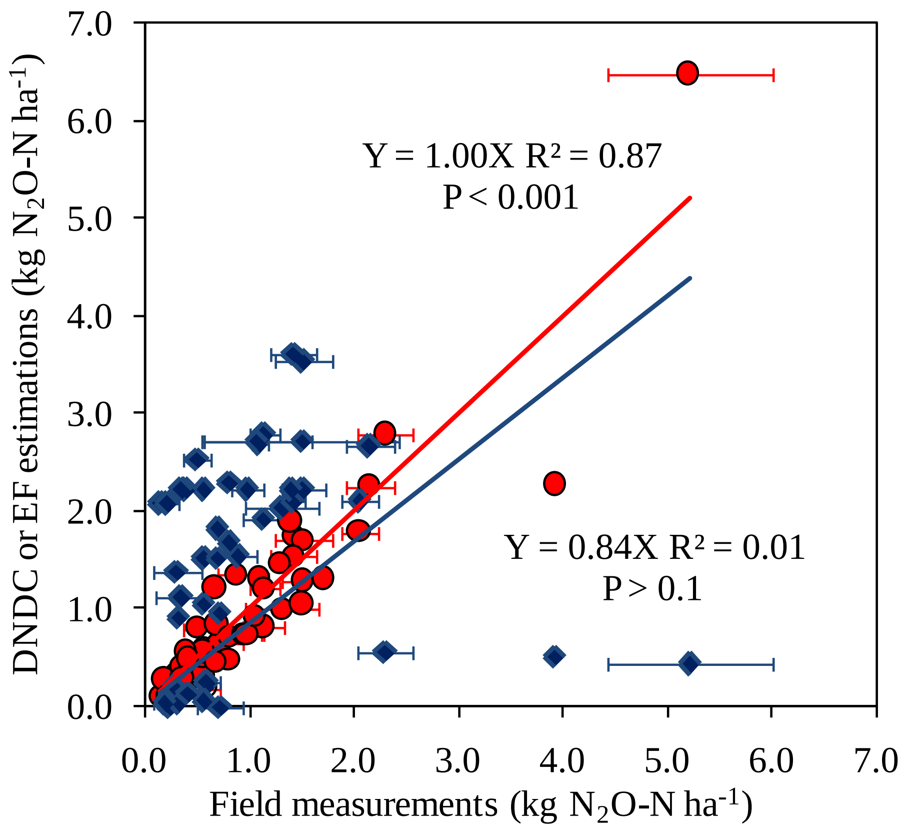

Figure E1. Comparison of the DNDC simulated (red circle) and EF calculated (blue diamond) seasonal or annual cumulative N_2O emissions against the field measurements for all the tested cropping systems in California. The functions shown describe the regression lines. The horizontal bars indicate standard errors of replicate field measurements (n = 3 to 6, depending on crop systems). The field data were collected at 13 sites located in 8 counties in California, and covered major cropping systems, including alfalfa, corn, cotton, wheat, tomato, lettuce, almond orchard, and vineyard.

Based on the model validation results that DNDC is capable of accurate modeling N_2O emissions across the cropping systems with various farming management practices, the model was applied to develop N_2O inventory for California croplands. Regional simulations were conducted by linking DNDC to a California-specific database containing temporal and spatial information on weather, crop, soil, and farming management practices in 58 counties of California from 2000 to

2015. As irrigation is one of the most important factors impacting N_2O emissions and irrigation practices are highly diversified in California within and among different types of crops, we introduced an 'event-based' irrigation option into the DNDC region mode by creating new interfaces and a new database with the historical information of irrigation management practices, including method, water amounts, frequency, and soil depth of water supplied. The irrigation methods included in DNDC are flooding irrigation, sprinkler irrigation, drip irrigation, subsurface drip irrigation, and cover of plastic film over soil surface. The historical information we developed included detailed irrigation method changes from 2000 to 2015 for each of the crops based on the California Department of Water Resources’ Irrigation Method Survey (CDWR, 2015). The improvement in the DNDC capacity of simulating 'event-based' irrigation in the region mode and the detailed information on irrigation practice change in California would significantly improve the N_2O emissions estimates for California.

The simulated annual N_2O emissions from California croplands ranged between 3.49×10^3 (in 2015) and 6.37×10^3 (in 2002) metric ton (MT) N yr^{-1} (or 1.63 to 2.98 Tg CO_2 equivalents yr^{-1} using the IPCC Fourth Assessment Report 100-year global warming potential of 298 kg CO_2-equivalents kg^{-1} for N_2O) from 2000 to 2015. The mean annual N_2O emissions were 5.23×10^3 MT N yr^{-1} (or 2.45 Tg CO_2 equivalents yr^{-1}) across the simulated 16 years. Based on these results, 0.70% to 1.08% of the N in synthetic fertilizers and crop residues applied into California croplands was emitted as N_2O during 2000 to 2015. The average fraction of the N emitted as N_2O was 0.93% from 2000 to 2015. The modeled inventory results further indicated that (1) the direct N_2O emissions from California croplands showed a significant decreasing trend primarily due to significant reductions of croplands area and associated N inputs as well as N_2O emission rate (due to presumably the large scale change from flooding irrigation to sprinkler or drip irrigation; Figure E2); (2) most of the N_2O emissions were from hay and field crops, and the crops with substantial contribution to state total N_2O emissions were corn (18.4%), non-legume hay (18.1%), alfalfa (9.4%), and cotton (7.0%); and (3) the counties with substantial N_2O emissions were primarily located in the Central Valley of California with San Joaquin, Fresno, and Tulare estimated as the top three counties with the high N_2O emissions (Figure E3).

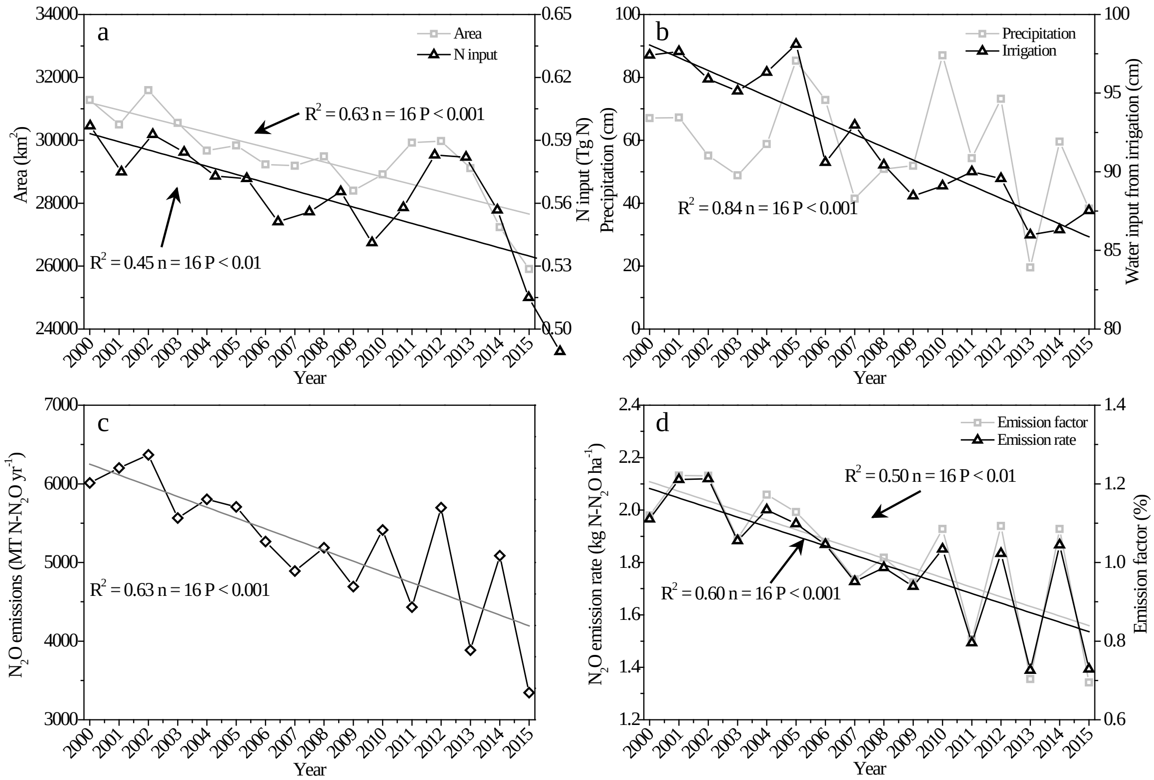

Figure E2. Dynamics of croplands area and nitrogen (N) input from synthetic fertilizers and crop residues (a), annual precipitation and water input from irrigation (b), annual state N_2O emissions (c), and emission rates and Emission Factors (EFs) of N_2O. The EFs in the panel (d) were the fractions of N input from synthetic fertilizers and crop residues emitted as N_2O.

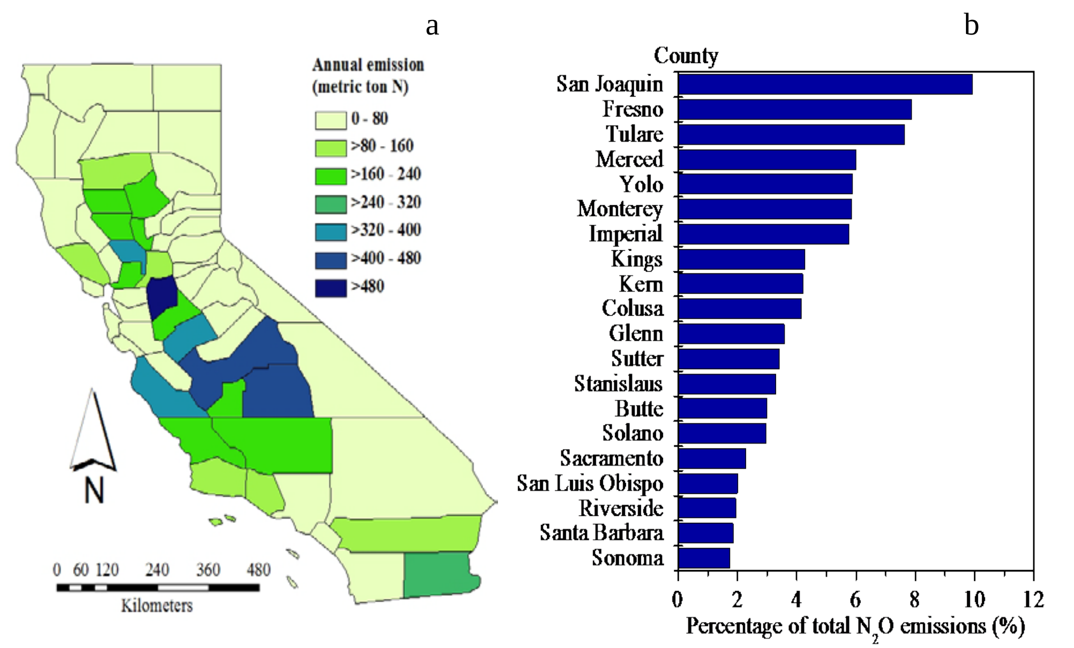

Figure E3. DNDC simulated annual N_2O emissions from different counties in California (a) and a ranking of the top 20 counties on N_2O emission (b).

We conducted statistical analysis to evaluate DNDC uncertainty using the validation results. Differences between 52 paired field observations and DNDC modeled emissions are calculated and analyzed for bias, trends in variability across the range of total emissions, and differences by crop type. There is no significance bias in the DNDC modeled total emissions, although on average, the model slightly underestimated measured total emissions, and in a logarithm scale, the DNDC appears to underestimate the lower measured emissions. Furthermore, there is a trend of increasing variability with increasing total N_2O emissions. There were no apparent differences in model performance by crop type, but sample sizes were small and/or uneven for all types. We also assessed the impact of uncertainties in the activities database, including soil properties, irrigation water depth, and scheduling of management events, on modeled N_2O emission estimates. The results showed that the largest source of uncertainty of the state total estimates of N_2O comes from uncertainties of soil properties. The range of total N_2O emissions varied from 70% to 137% of the baseline value, which was obtained using area-weighted average soil property values.

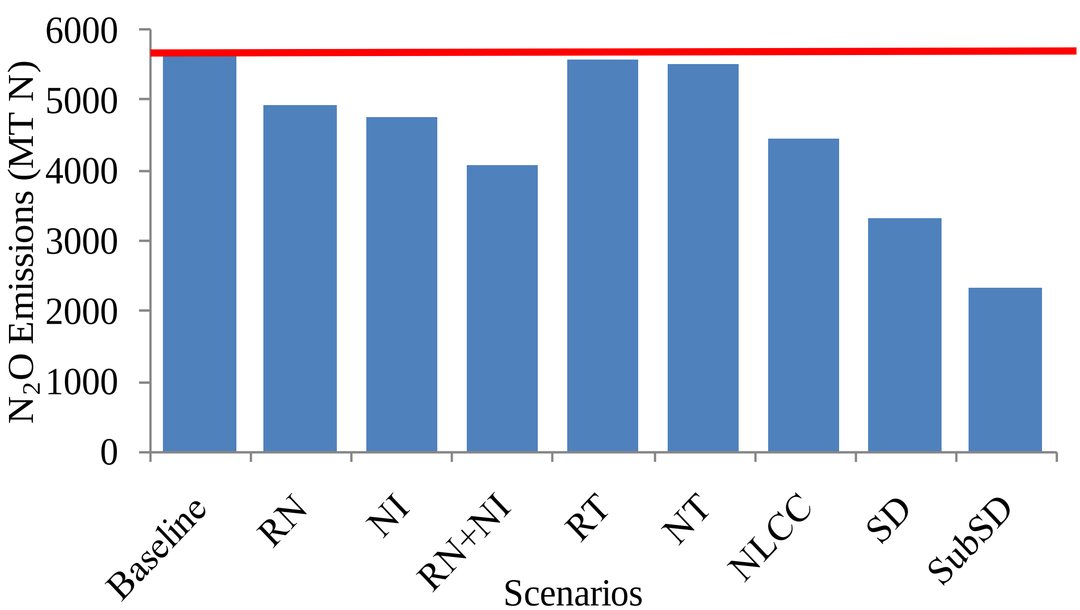

Figure E4. Simulated annual total N_2O emissions from California croplands under the baseline and alternative scenarios. RN: reducing nitrogen fertilization by 15%; NI: applying nitrification inhibitor for all ammonium based fertilizers; RN+NI: combining reduction of nitrogen fertilization and application of nitrification inhibitor; RT: converting the baseline tillage into reduced tillage; NT: converting the baseline tillage into no tillage; NLCC: planting non-leguminous cover crops in winter seasons; SD: applying surface drip irrigation; SubSD: applying subsurface drip for irrigation.

The efficiency of different FMPs on mitigating N_2O emissions was assessed by conducting a series of simulations with varying FMPs for all cropping systems included in the database. The simulations under alternative management practice scenarios were compared against the baseline simulation. We modeled eight alternative scenarios by exclusively modifying a farming management practice applied under the baseline scenario, including nitrogen application, application of nitrification inhibitor, tillage, planting of cover crop, or irrigation management, to investigate impacts of each management practice on N_2O emission. The practices identified with relative high N_2O mitigation efficiency (> 20% reduction) included combining N rate reduction by 15% and application of nitrification inhibitors, planting non-leguminous cover crops, surface drip irrigation, and subsurface drip irrigation (Figure E4). In addition, these practices did not adversely affect the simulated crop yields and emissions of CO_2 and CH_4.

Conclusions: The DNDC package has been refined to assess N_2O emissions and mitigation potentials under various California conditions. Through the thorough comparison of DNDC with field observations, we concluded that the DNDC model reliably predicted the seasonal and annual N_2O emissions from the tested cropping systems. The simulated annual N_2O emissions from California croplands ranged between 3.49×10^3 (in 2013) and 6.37×10^3 (in 2002) metric ton (MT) N yr^{-1} (or 1.63 to 2.98 Tg CO_2 equivalents yr^{-1} by using the IPCC Fourth Assessment Report 100-year global warming potential of 298 kg CO_2-equivalents kg^{-1} for N_2O) from 2000 to 2015.The practices identified with relative high mitigation efficiency (> 20% reduction) included combining N rate reduction by 15% and application of nitrification inhibitors, planting non-leguminous cover crops, surface drip irrigation, and subsurface drip irrigation. The DNDC-based package and the simulations conducted in this project can support development of N_2O inventory and mitigation strategies for California.

Future Work: Potential further improvements in the California specific modeling system would include modeling N_2O emissions from manure sources and improving the regional database to reduce the uncertainty of the simulations. Additional studies are necessary to better constrain manure management activity for incorporating N derived from manure sources into the DNDC regional database, and further testing against field data. The uncertainty of the simulations could also be reduced by improving the regional database from the current county to sub-county scale with a better represented combination between cropping systems and soil properties.

1. Introduction

1.1 Background

Nitrous oxide (N_2O) is one of the most important greenhouse gases (GHGs). It significantly contributes to global warming due to its high global warming potential (298 kg carbon dioxide per kg N_2O at a time horizon of 100 years; IPCC, 2013), and also leads to deterioration of the atmospheric environment by depleting ozone (Ravishankara et al., 2009). During the recent three decades, the concentration of N_2O in atmosphere was continually increasing at a rate of 0.73 ppbv (10^{-9}) yr^{-1} or 0.2-0.3% yr^{-1}, primarily due to accelerated emissions from agriculture soils (IPCC, 2013). Globally, agricultural sources of N_2O emissions are approximately 4.1 Tg (10^{12} g) N-N_2O yr^{-1} (IPCC, 2013; Syakila and Kroeze, 2011), which are primarily attributed to the use of synthetic nitrogen (N) fertilizers and organic manure (Davidson, 2009).

With the passage of the Global Warming Solutions Act of 2006 (AB32), which aims to reduce GHGs emissions from California to 1990 levels by 2020, California has rapidly made efforts to quantify and mitigate GHGs. In recent years, several field studies have been performed to characterize GHGs, in particular, N_2O emissions from typical California cropping systems (e.g., Garland et al., 2011, 2014; Burger and Horwath, 2012; Steenwerth et al., 2010; Kennedy et al., 2013; Smart et al., 2011). The current project built off the earlier efforts to improve and apply a process-based biogeochemical model DNDC to extrapolate the N_2O measurements at specific sites or during specific periods to larger regions or over extended time spans, and thus to enable quantification of mitigation potentials of alternative farming management practices to reduce N_2O emissions from California croplands. Finally, this project provided necessary tools and database to improve California inventory of N_2O emissions from agricultural soil management, the major source of N_2O emissions in California.

1.2 N_2O Emissions from Soils and Mitigation

N_2O emissions from soils are primarily produced through microbial-mediated nitrification and denitrification, and are subject to controls involving interactions of numerous environmental factors, such as concentrations of mineral N, availability of dissolvable organic carbon (DOC), redox potential, and temperature (e.g., Robertson and Groffman, 2007; Butterbach-Bahl et al., 2013). N_2O production is tightly linked with soil carbon dynamics in nature. For example, many researchers have measured N_2O fluxes from several contiguous plots under similar climate and management conditions, the higher N_2O emissions were mostly observed at the plots with higher soil organic carbon (SOC) contents. Among the observations, organic soils consistently emitted relative high N_2O fluxes (Bremner and Shaw, 1958; Bowman and Focht, 1974; Burford and Bremner, 1975; Mosier et al., 1991; Vinther, 1992). The temporal and spatial variability of these controlling factors results in enormous heterogeneity in N_2O fluxes (e.g., Bouwman et al., 2002; Groffman et al., 2009). Therefore, it is impractical to quantify N_2O emissions from croplands and identify effective options for N_2O mitigation based on field measurements alone.

Because N_2O emissions are strongly affected by field management practices (FMPs) that control the environmental factors influencing N_2O production and consumption, improving FMPs has a high potential to mitigate N_2O emissions from croplands. For example, numerous studies have demonstrated that N_2O emissions can be reduced by improving application of N fertilizers and increasing N use efficiency of crops, although the mitigation efficiency is highly variable across different cropping systems or regions (e.g., Eagle and Olander, 2012; Syder et al., 2009). In addition, improved irrigation management and/or manure application have been considered as potential measures for N_2O mitigation because they are directly coupled with one or several environmental factors regulating N_2O production, consumption, and/or emission (Aguilera et al., 2013; Eagle and Olander, 2012). However, quantitative assessments of the mitigation efficiency of alternative management regimes are rare at large regional or national scales although these assessments are necessary for developing effective mitigation strategies (e.g., Bouwman et al., 2002; Smith et al., 2008; Venterea et al., 2012).

1.3 Role of Agriculture in Greenhouse Gas Mitigation

Agricultural activities are responsible for approximately 50% of global atmospheric inputs of CH_4 and agricultural soils are responsible for 75% of global N_2O emissions (Scheehle and Kruger, 2005; USEPA, 2005), and thereby represent a significant opportunity for greenhouse gas mitigation through reductions of CH_4 and N_2O emissions, as well as through soil carbon sequestration (Oenema et al., 2001). Recently, significant investments are being made in assessing carbon sequestration in agricultural soils due to the potential for trading carbon credits coupled with significant environmental benefits through improved soil quality, soil fertility, and reduced erosion potential. Changes in farming management practices, such as tillage, fertilization, irrigation, cover cropping, and manure amendment, are currently being evaluated for their potential in mitigating greenhouse gases emitted from the agricultural sector. For example, it has been widely reported that replacing conventional tillage with no-till results in SOC storage (Lal et al. 1999, Smith et al. 2000). The carbon sequestration potential of agricultural lands is being studied with experimental or modeling approaches in many recent or ongoing research projects. Most of the published research focused only on the soil C dynamics with little attention placed on other greenhouse gases, namely N_2O and CH_4, which may offset gains in carbon sequestration if not managed properly. Few of the reports assessed the impacts of the C sequestration induced by the management alternatives on the coupled N_2O or CH_4 emissions from the same lands.

1.4 California Agriculture and Greenhouse Gas Emissions

California agriculture is extremely diverse consisting of over 400 commodities across a wide range of landscape and geographical conditions (NASS, 2012). There are approximately 3.4 million ha of harvested croplands, 34% of which are orchards and vineyards, 23% are alfalfa and hay, and 14% are devoted to vegetable crops. Agricultural management practices, such as tillage, fertilization, and irrigation are highly variable as well, although they are generally characterized as intensive because of common standard tillage operations, high rates of N fertilizer application, and intensive furrow irrigation on the majority of croplands (Suddick et al., 2010). For example, over 90% of California vineyards and orchards are irrigated and fertilized using micro-irrigation systems (Smart et al., 2011), although many orchard growers often flood following harvest, while field crops are usually flood irrigated (Tindula et al., 2013) and fertilized through surface spraying, injection, or broadcast. The wide variation in the type of cropping systems and FMPs could further exacerbate the temporal and spatial variability of N_2O emissions from croplands, thus making the quantification N_2O emissions from California a challenging task (De Gryze et al., 2011).

California agriculture emits CH_4 and N_2O from various agricultural sources, including enteric fermentation, agricultural soil management, rice paddy cultivation, and manure management. In 2007, agriculture in California generated approximately 32.94 Tg (10^{12} g or 1 million metric tons) carbon dioxide equivalents (CO_2 eq.) of GHG emissions, which is approximately 7% of the state's total emissions. N_2O and CH_4 accounted for significant fraction of emissions. Managed agricultural soils were the dominant source of N_2O (8.34 Tg CO_2 eq.). Enteric fermentation (9.7 Tg CO_2 eq.) and manure management (10.22 Tg CO_2 eq.) were the dominant agricultural sources of CH_4 (California Air Resources Board, 2013). Direct emissions of N_2O from agricultural soils accounted for 6.44 Tg CO_2 eq., with indirect N_2O emissions accounting for 1.90 Tg CO_2 equivalents. These emission inventories were developed by using emission factor approaches as specified in IPCC guidelines, with some California specific emission factors. Simple regression approaches, such as Emission Factor (EF) methods (e.g., Bouwman, 1996), are useful tools to estimate N_2O emissions at regional or global scales (e.g., Stehfest and Bouwman, 2006; Syakila and Kroeze, 2011). However, such approaches would become less accurate at finer temporal and spatial scale because they usually ignore some natural or management factors, which are critical for N_2O production (Butterbach-Bahl et al., 2013; Chen et al., 2008). By neglecting specifics of farming management practices, simple empirical methods may not be suitable for identifying mitigation opportunities for N_2O emission (Butterbach-Bahl et al., 2013; Giltrap et al., 2010).

1.5 Process-based Models and Agricultural Mitigation of Greenhouse Gases

Based on the experimental observations as well as biogeochemical analysis, DOC and available N have been recognized as two important factors affecting soil N_2O emissions, although not exclusively. Soil temperature, moisture, pH, redox potential, and other substrate concentrations can also affect N_2O production and consumption. These soil environmental factors are driven by a group of primary drivers (e.g., climate, topography, soil properties, vegetation, and anthropogenic activity) on the one hand, and drive a series of biochemical or geochemical reactions, which determine N_2O production and consumption, on the other hand. The complex interactions among the primary drivers, soil environmental factors, and the biogeochemical reactions result in the observed highly variable N_2O fluxes. For example, different tillage practices could simultaneously affect soil temperature, moisture, redox potential and soil DOC and available N content. These affected factors will simultaneously and collectively alter the rates of decomposition, nitrification, denitrification, and substrate diffusion, which in turn collectively determine N_2O emission. Process-based modeling is a useful solution to bring the complex system into a calculable framework. During the last decade, many process-based models (e.g., CASA, CENTURY, Roth-C, N-EXPERT, etc.) were developed focusing on soil C and N dynamics including N_2O emissions. Process-based models have usually considered both natural factors and FMPs regulating N_2O emissions from soils, and therefore provide a method for quantifying N_2O emissions and seeking effective options for N_2O mitigation (Butterbach-Bahl et al., 2013; Chen et al., 2008; Giltrap et al., 2010). The Denitrification-Decomposition (DNDC) model is one of the process-based modeling efforts. DNDC was constructed based on four basic concepts, i.e., biogeochemical abundance, field, coupling, and cycling. DNDC consists of six sub-models (i.e., soil climate, crop growth, decomposition, nitrification, denitrification, and fermentation). The six interacting sub-models include fundamental factors and reactions, which integrate C and N cycles into a computing system (Li et al., 1992, 1994; Li 2000). DNDC has been validated against numerous datasets observed worldwide. During the last several years, DNDC has been independently tested by researchers in many countries and applied for their national C sequestration and N_2O inventory studies (Giltrap et al., 2010). DNDC predicts N_2O emissions by tracking the reaction kinetics of nitrification and denitrification across climatic zones, soil types, and management regimes. With its prediction capacity of both SOC and N_2O, DNDC is also ready to serve offset analyses between C sequestration and N_2O emissions for agro-ecosystems. DNDC can also integrate GIS data for regional assessments, therefore are suitable for extending site scale N_2O data into large scale N_2O emissions.

This project (1) improved the DNDC package to assess N_2O emissions and mitigation potentials under various California conditions; (2) compiled N_2O flux data measured at the crop fields across a wide range of management conditions in California; (3) utilized the measured N_2O data to validate DNDC on quantifying agricultural N_2O emissions in California; (4) developed a California specific GIS databases including climate, soil and agricultural management practices for statewide GHG modeling; (5) estimated N_2O emissions from California croplands; and (6) assessed efficiency of alternative management in mitigating N_2O emissions.

2. Model Tests

In a previous project (Calibrating, validating, and implementing process models for California agriculture greenhouse gas emissions; project number: 10-309), DNDC simulations of N_2O emissions from California croplands have been tested against field measurements of N_2O emissions from several cropping systems (alfalfa, winter wheat, vineyard, almond orchard, tomato, and rotation of row crops) representing a range of environmental conditions and farming management practices in California agriculture (Li et al., 2014). In this project, we improved manure parameterization to reflect application of slurry manure in California croplands and further tested DNDC against N_2O emissions from several other cropping systems, including corn, lettuce, and cotton, as a complement for the previous study. This task entailed compiling existing field data on N_2O emissions. In addition to the baseline treatments with conventional FMPs, we also tested the N_2O emissions simulated under alternative fertilization for corn and lettuce. These tests indicated DNDC is well suited for quantifying N_2O emissions and its mitigation potential for the diverse cropping systems of California.

2.1 Site and Cropping System Descriptions

Field data used to support the model tests were collected at four sites located in four counties in California. The study sites generally experience a Mediterranean climate that consists of hot dry summer and wet cool winter. Table 1 summarizes general characteristics and soil properties of the tested fields.

All field experiments included a treatment representing typical FMPs in the local area. In addition, treatments of different N fertilization were set in the lettuce system to investigate the impacts of N application rate on N_2O emissions (Table 1). To quantify the impacts of different forms of N fertilizers and nitrification inhibitor on N_2O emissions from corn, the experiment measured emissions under seven treatments with different applications of N fertilizers and nitrification inhibitor (Table 1). Additional details regarding the FMPs performed at the sites are summarized in Table 1, and were described by Burger and Horwath (2012), Burger et al. (2015), and Mahal et al. (2014).

The field measurements of N_2O fluxes were performed using the vented static chamber method (Hutchinson and Mosier, 1981). For the lettuce and corn systems, N_2O fluxes were usually measured daily or once every two days following events such as tillage, fertilization, precipitation, irrigation, or harvest, until the high N_2O fluxes induced by the event receded to background levels. For other periods, the measurements of N_2O fluxes were performed less frequently, but fluxes were usually measured with a frequency of higher than once every two weeks. For the cotton system, the measurements of N_2O fluxes were performed with a frequency of monthly. Seasonal or annual total N_2O emissions were generally available in these field studies, and were calculated by linear interpolation of the measured daily fluxes (Garland et al. 2011, 2014; Burger and Horwath, 2012). When measuring the N_2O fluxes, local climate, soil properties, crop yield or above-ground biomass, and FMPs were often recorded as well. The technical details regarding the N_2O measurements, and the relevant auxiliary variables were described by Burger and Horwath (2012), Burger et al. (2015), and Mahal et al. (2014).

Table 1. General characteristics and soil properties of study fields where measurements of N_2O fluxes were used for model tests in this project.

County	Period[a]	Crop type	T[b]	Soil texture	Clay (%)	BD[c]	pH	SOC[d]	Ref.[g]
Fresno	Apr. 2012-Nov. 2012	Cotton		Sandy loam	9	1.40	6.8	8.0	(1)
Kings	May 2012-Oct. 2012	Cotton		Sandy loam	9	1.40	7.0	9.8	(1)
Monterey	June 2009-Mar. 2011	Lettuce	DNF-1[e]	Loam	17	1.58	7.6	12.7	(2)
Yolo	May 2012-Oct. 2012	Corn	DNF-2[f]	Loam	22	1.36	7.0	7.4	(3)

[a]Period during which measurements of N_2O fluxes were used for model tests.
[b] T, treatments included in the field studies.
[c] BD, bulk density (g cm^{-3}).
[d] SOC, content of soil organic carbon (g C kg^{-1} dry soil).
[e] DNF-1, different nitrogen fertilization. Measurements of N_2O fluxes under five treatments were used for model tests. The treatments included different practices of nitrogen fertilization, with 336, 252, 168, 84, and 11 kg UAN32-N ha^{-1} applied during the lettuce growing season. UAN32: $(NH_2)_2CO{\bullet}NH_4NO_3$. Details of the treatment setting are described by Burger and Horwath (2012).
[f] DNF-2, different nitrogen fertilization. Measurements of N_2O fluxes under seven treatments were used for model tests. The treatments included different practices of nitrogen fertilization and nitrification inhibitor, with 222 (aqua ammonia + 8-24-6), 222 (aqua ammonia + 8-24-6 + the nitrification inhibitor G77), 222 (UAN + 8-24-6), 222 (UAN + 8-24-6 + urease and nitrification inhibitor AgrotainPlus™), 222 (UAN + 8-24-6 + G77), 222 (calcium nitrate + 8-

24-6), and 20 (8-24-6) kg N ha^{-1} applied during the wheat growing season. Details of the fertilization treatments are described by Burger et al., (2015).
[g](1) Mahal, (2014); (2) Burger and Horwath, (2012); (3) Burger et al., (2015).

2.2 DNDC Validation Tests

Field data, including measurements of N_2O fluxes, as well as soil properties and FMPs were acquired from the respective researchers (Burger and Horwath, 2012; Burger et al., 2015; Mahal, 2014) to test the DNDC model. Daily meteorological data, including maximum and minimum air temperatures, precipitation, and solar radiation were derived from either on-site measurements or local meteorological stations. Primary soil input parameters, including soil texture, clay fraction, bulk density, pH, SOC content, were determined based on on-site measurements. FMPs applied in each treatment of the tested sites included planting and harvest dates, tillage, fertilization, irrigation, and cultivation and incorporation of cover crop, and were derived from field records. We set up the input parameters of FMPs by strictly following field records in order to represent all variations in FMPs in the simulations. The phenological and physiological parameters related to crop growth were estimated either by referring on-site observations or using model defaults that were derived from a large collection of literature values. No site specific modifications were performed if not mentioned above. The modeled N_2O fluxes were compared against the measured records.

The modeled daily N_2O fluxes were compared with the corresponding observations. Figures1 and 2 provide examples regarding how the modeled and measured daily N_2O fluxes were compared. At the lettuce field, peaks of N_2O fluxes were often simulated on days following events of fertigation, sprinkler irrigation, and heavy rainfall under conventional FMPs with N application rate of 252 kg N ha^{-1} (Figure 1). The DNDC simulations were similar with the observed peaks of daily N_2O fluxes, although the magnitudes of the simulated peaks were not fully consistent with the observations. The simulations were also comparable with the observations at the corn field, predicted similar N_2O peaks, which were usually induced by fertilization or irrigation (Figure 2). All the figures of daily comparisons for the tested cases are shown in Appendix A.

The rate of N application substantially affected the N_2O emissions from the lettuce field. DNDC simulations showed an increase trend in N_2O emission along with increasing N application rate, which was consistent with the field measurements (Table 2). Of the 10 studied treatment-year combinations, the observed annual total N_2O emissions varied from 0.58 to 1.51 kg N_2O-N ha^{-1}. The simulations of annual N_2O emissions varied from 0.19 to 1.70 kg N_2O-N. The values of Root Mean Square Error (RMSE) between the modeled and observed annual cumulative N_2O emissions ranged from 6% to 68% across the 10 lettuce field cases. The DNDC results regarding impacts of different treatments on N_2O emissions from the corn fields were also generally consistent with the measurements (Table 2).

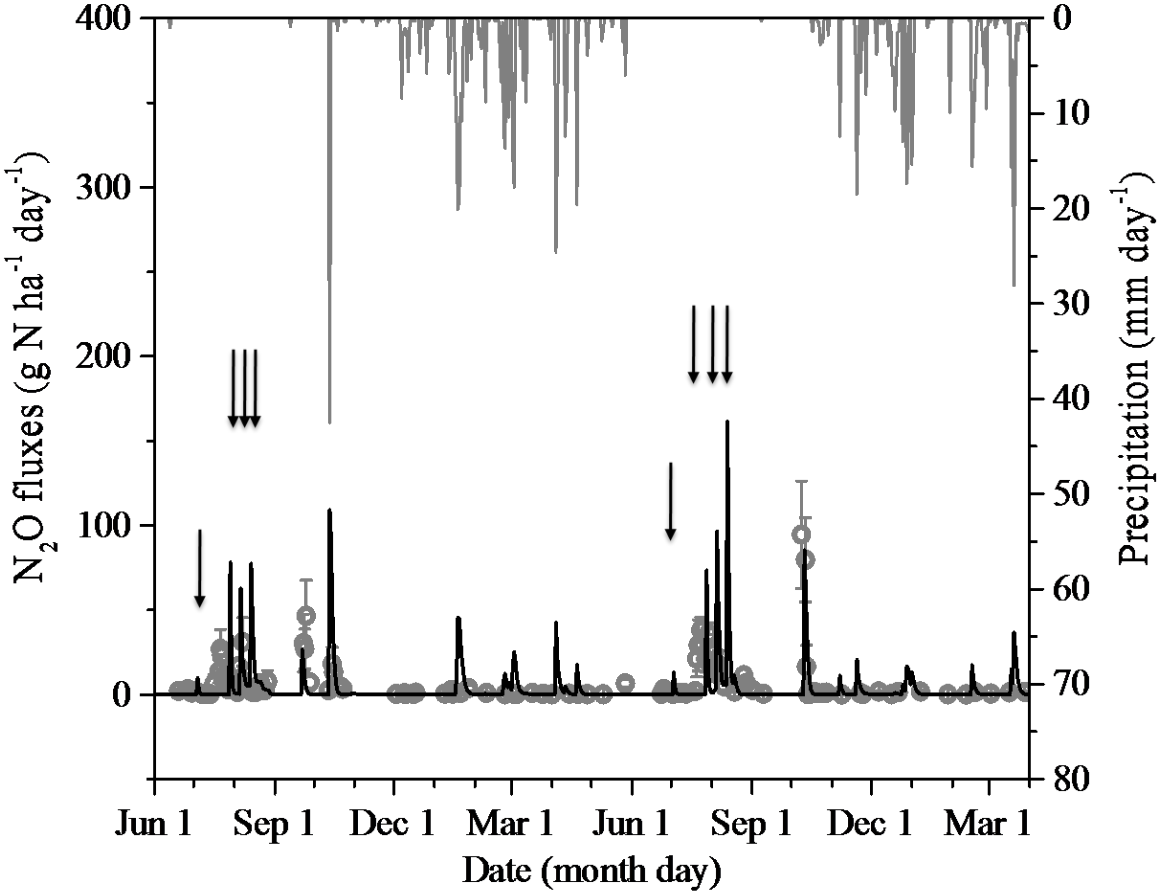

Figure 1. Precipitation (grey line), and simulated (dark line) and measured (dots) daily N_2O fluxes from a lettuce field under conventional nitrogen fertilization. N fertilizers were applied into the field at a rate of 252 kg N ha^{-1} during each growing season. The arrows indicate the dates of fertigation events. The fields were irrigated many times with small amount of water each time by using drip irrigation systems, and the dates of irrigation events are not shown for the reason of clarity. The measurements are the means, and the vertical bars indicate standard errors of replicates (n = 4).

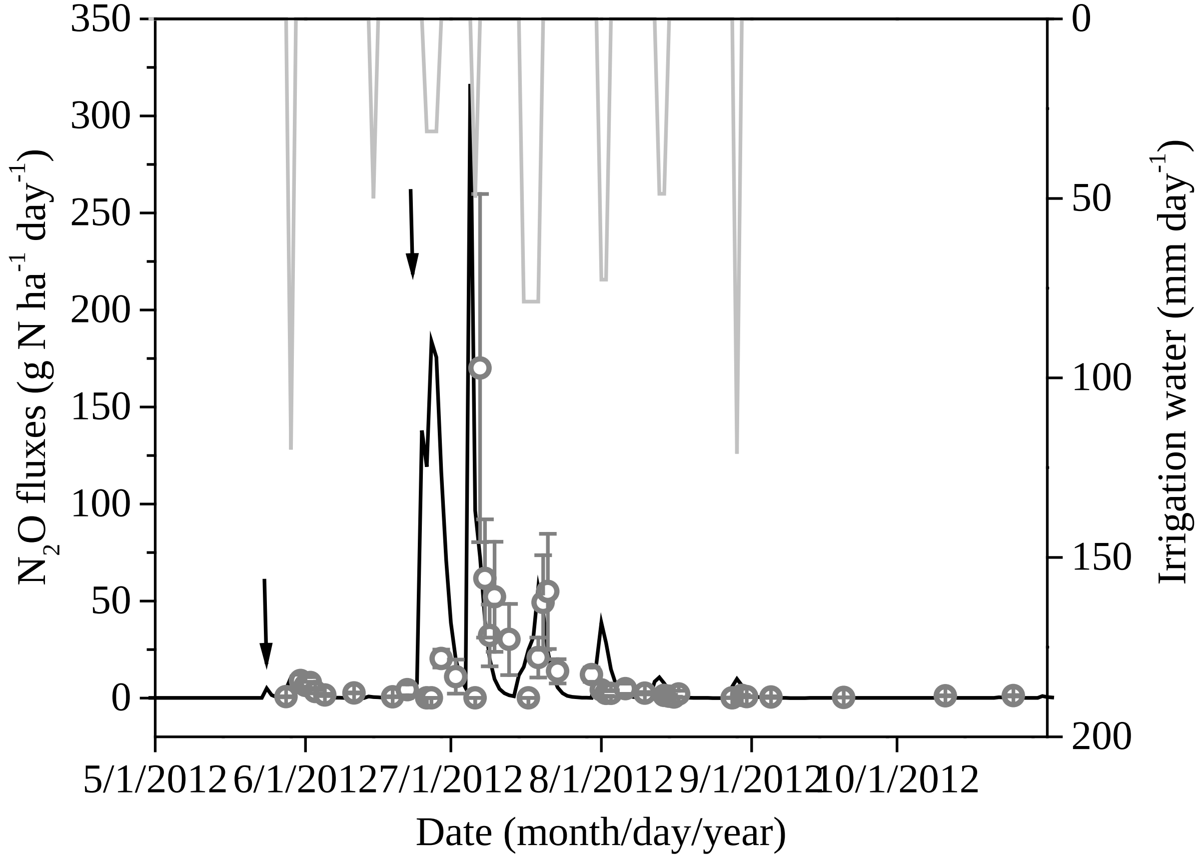

Figure 2. Measured (dots) and simulated (line) daily N_2O fluxes from a corn field under the application of anhydrous ammonia fertilizers. An example showing that significant N_2O fluxes were induced by fertilization or irrigation in both the simulations and field observations. The fields were irrigated by using furrow method.

Table 2. Comparisons between the simulated (S) and observed (O) seasonal or annual N_2O emissions.

Period[a]	Cropping system	T[b]	O[c]	SE[c]	S	RMSE
June 2009 - May 2011	Lettuce	366N (UAN32)	1.51	0.27	1.7	13%
		252N (UAN32)	1.09	0.08	1.31	20%
		168N (UAN32)	0.69	0.07	0.84	22%
		84N (UAN32)	0.71	0.07	0.63	11%
		11N (UAN32)	0.58	0.05	0.51	12%
June 2010 - May 2011	Lettuce	366N (UAN32)	1.42	0.22	1.54	8%
		252N (UAN32)	1.14	0.14	1.21	6%
		168N (UAN32)	1.13	0.2	0.82	27%
		84N (UAN32)	0.56	0.03	0.31	45%
		11N (UAN32)	0.59	0.13	0.19	68%
May 2012 - Oct. 2012	Corn	NH_3	1.51	0.21	0.14	15%
May 2012 - Oct. 2012		NH_3 + G77	1.39	0.08	0.2	37%
May 2012 - Oct. 2012		UAN	0.97	0.15	0.21	24%
May 2012 - Oct. 2012		UAN + G77	0.56	0.05	0.3	0%
May 2012 - Oct. 2012		UAN + AP	0.39	0.03	0.19	44%

May 2012 - Oct. 2012		Nitrate	0.35	0.06	0.28	20%
May 2012 - Oct. 2012		Control	0.27	0.06	0.6	78%
Apr. 2012 - Nov. 2012	Cotton	N168	0.8	N/A	0.486	39%
May 2012 - Oct. 2012	Cotton	N153	0.681	N/A	0.462	32%

[a]Period during which measurements of N_2O fluxes were used for model tests.
[b] T, treatments included in the field studies. Details of the treatment setting were described by Burger and Horwath (2012), Burger et al. (2015), and Mahal et al. (2014).
[c]Observed data with standard error (SE) of the field measurements are reported in Burger and Horwath (2012), Burger et al. (2015), and Mahal et al. (2014).

Through this project and the previous project (Calibrating, validating, and implementing process models for California agriculture greenhouse gas emissions; project number: 10-309), we validated DNDC against 52 cases to document the model's applicability for quantifying N_2Oemissions from different agricultural systems in California. These field cases covered a wide range of environmental conditions and FMPs in California croplands, and therefore are representative of a range of typical cropping systems in California, including hay, cereal crops, vegetable, vineyard, and perennial orchards. Figure 3 shows the results of all these model tests. The correlation between the DNDC-modeled and measured annual/seasonal N_2O emissions is significant with an R^2 of 0.87, a slope of 1.00, and a $P < 0.001$ (Figure 3). The results indicate that the DNDC model reliably predicted the seasonal and annual N_2O emissions from the tested cropping systems.

We also calculated the seasonal or annual N_2O emissions using the EF approach (Tier 1; IPCC, 2006), which was used in the development of the California inventory of N_2O from agricultural soil management (e.g., CARB, 2011, 2016). The estimates of N_2O emissions based on the EF approach were compared against the field measurements and the DNDC simulations to assess if the use of the process-based model, such as DNDC, can improve the N_2O inventory in California. The EF-based seasonal or annual N_2O emissions were calculated as:

$$N_2O_D = (\mathrm{N_{SF}} + \mathrm{N_{CR}}) * \mathrm{EF_1}$$

where N_2O_D is direct N_2O emissions (kg N_2O-N) from agricultural managed soils; N_{SF} is amount of synthetic fertilizer N (kg N) applied to soils based on field records; N_{CR} is amount of N in crop residues (kg N) returned to soil; and EF_1 is emission factor for N_2O emissions from N inputs (kg N_2O-N kg^{-1} N), which was set as 0.01 by following CARB (2011, 2016). Note that amounts of N from organic fertilizers and managed manure were zero based on the field records.

The EF-derived regression showed an R^2 of 0.01 and a slope of 0.84 without significant correlation between the EF-derived and observed N_2O emissions (Figure 3). The EF method showed obvious discrepancies in estimating N_2O emissions from some systems. For example, the EF approach underestimated the N_2O emissions from alfalfa fields and vineyard in Colusa County, where the high N_2O emissions may be partially attributable to planting of the leguminous crops capable of fixing atmospheric nitrogen gas (N_2) and/or intensive irrigations, rather than solely to N fertilizer application (Burger and Horwath, 2012; Burger et al., 2016; Garland et al., 2014). The capability of DNDC to capture impacts of factors other than the N fertilizer application on N_2O emissions is important not only in improving inventory estimates but also essential for identifying mitigation options that can be used to reduce N_2O emissions from agricultural soil management.

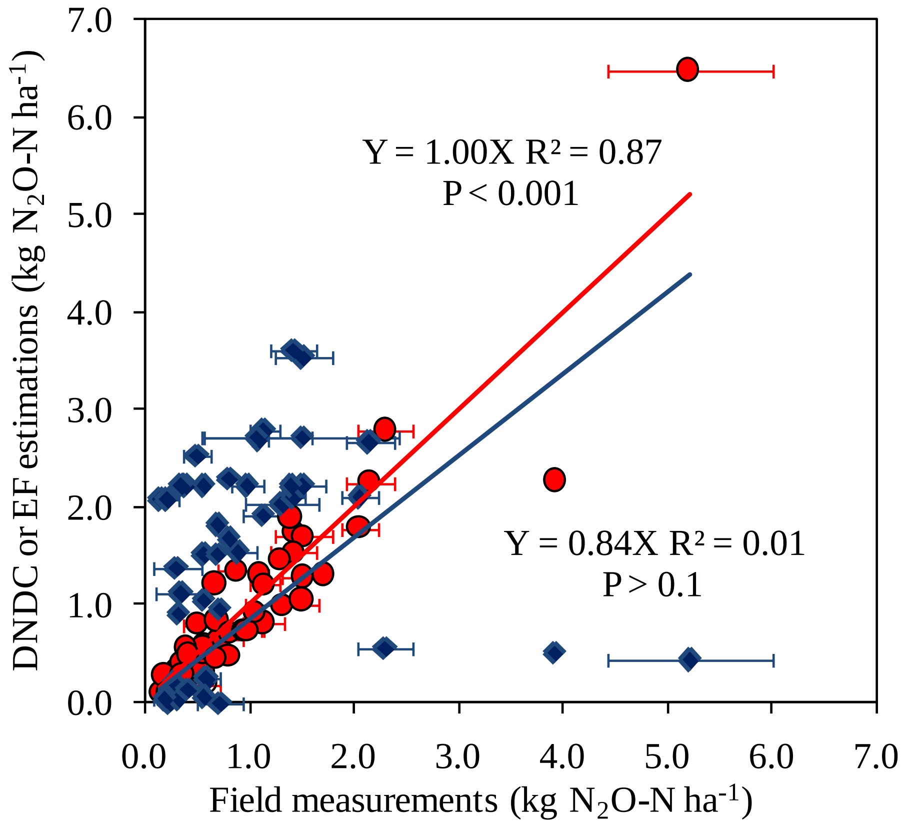

Figure 3. Comparison of the DNDC simulated (red circle) and EF calculated (blue diamond) seasonal or annual cumulative N_2O emissions against the field measurements for all the tested cropping systems in California. The functions shown describe the regression lines. The horizontal bars indicate standard errors of replicate field measurements (n = 3 to 6, depending on crop systems). The field data were collected at 13 sites located in 8 counties in California, and covered major cropping systems, including alfalfa, corn, cotton, wheat, field crop rotation, tomato, lettuce, almond orchard, and vineyard. The field data showed were provided by Martin Burger, William Horwath, David Smart, Johan Six, Dave Goorahoo, and Cynthia Kallenbach. The technical details regarding the N_2O measurements, and the relevant auxiliary variables were described by Garland et al. (2011, 2014), Burger and Horwath (2012), Burger et al. (2015), Steenwerth et al. (2010), Kennedy et al. (2013), Smart et al. (2011), Lee et al. (2009), Kallenbach et al. (2010), and Mahal (2014).

3. Direct N_2O Emissions from California Croplands

We improved and applied the DNDC model to quantify direct N_2O emissions from California croplands. The improvements made for this regional simulation include (1) offering two irrigation simulation options for the DNDC regional mode: an irrigation index and irrigation event; (2) compiling irrigation management data (i.e. water amount, frequency, irrigation method) into the California-specific database and added the capacity of varying irrigation water depth of crops with county air temperatures; (3) developing the California-specific database including major cropping systems and multi-years (2000 to 2015) information of climate and crop area; and (4) updating California-specific GIS database in fertilization and crop residue returns. To get the emission estimate of a given year, DNDC was run for three consecutive years from two years prior to initialize the model to allow the distribution of carbon and nitrogen speciation in soil to match closely field conditions, and the results for the third year were taken as the emission estimate for the given year. These results represent direct N_2O emissions from fertilizer N uses and crop residues because we excluded croplands in dairy and organic farms for simulations (please refer the section 3.1 for details).

3.1 Database Construction

To simulate N_2O emissions from California croplands, we created a California specific database containing all input information required by the DNDC model. The input information in the database include: (1) daily meteorological data, (2) land area of different crop types (n = 53), (3) soil properties, and (4) farming management practices. The basic unit adopted for organizing the database is county, which has been frequently chosen for regional simulations of greenhouse gas emissions (e.g., Del Grosso et al., 2006; Li et al., 2005). Farming management data, covering planting and harvest dates, tillage, fertilization, irrigation, and residue management, were developed for each crop type largely from open literatures, surveys, as well as personal communications with researchers, growers, and University of California Cooperative Extension staff.

Crop areas. Statewide crop total areas were obtained from NASS (National Agricultural Statistics Service) QuickStats (https://quickstats.nass.usda.gov/). County level crop area data were directly from QuickStats for census years (USDA, 2004; 2009). For non-census years, statewide totals of crop area were allocated to the counties based on the crop area fraction of a county for each crop as interpolated from census years prior 2012, or as reported in the California Department of Agriculture's (CDFA's) County Agricultural Commissioners' reports (https://www.nass.usda.gov/Statistics_by_State/California/Publications/AgComm/Detail/) after 2012. Due to lack of data regarding application of livestock manure (primarily dairy manure in California), croplands in dairy and organic farms were excluded. To remove croplands in dairies receiving manure application, the total dairy cropland area in each county was obtained from the spatial data provided by the State Water Resource Control Board (Kris Sisk and Lisa Wilson, 2015; personal communication). The types of crop planted and the associated planting areas were obtained from 10% sampling of the 2013 Annual Dairy Reports for the Central Valley. The organic farm areas and associated crops were obtained from the reports of "Statistical Review of California's Organic Agriculture" (http://aic.ucdavis.edu/research1/organic.html) of the University of California at Davis (UCD). Table 3 provides historical cropland areas included in the database. The total cropland areas simulated ranged between 2590.6 and 3159.2 × 10^3 ha across 2000 to 2015 (Table 3), representing an average of 91.9% of total California croplands (89.4% to 93.7%).

Soil data. Soil data were from the U.S. Department of Agriculture's (USDA's) SSURGO soil database (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx) (NRCS, 2015). Key soil data required by DNDC for a regional simulation, including bulk density, clay content, SOC content, and pH, were extracted. We overlaid the SSURGO map units with the regions of agricultural landuse developed by California Department of Water Resources (CDWR, 2015) and then calculated the area-weighted means of the four soil properties (Figure 4) for each county. The area-weighted means of the soil properties were used as "representative" soil values for simulating "representative" N_2O emissions from California croplands and for assessing impacts of alternative management on GHG emissions. In addition, we determined the minimum and maximum values of soil properties for each county to support the ‘‘most sensitive factor’’ method (Li et al., 2005; Li, 2007) for quantifying potential uncertainties of N_2O emissions resulted from variability of the soil properties.

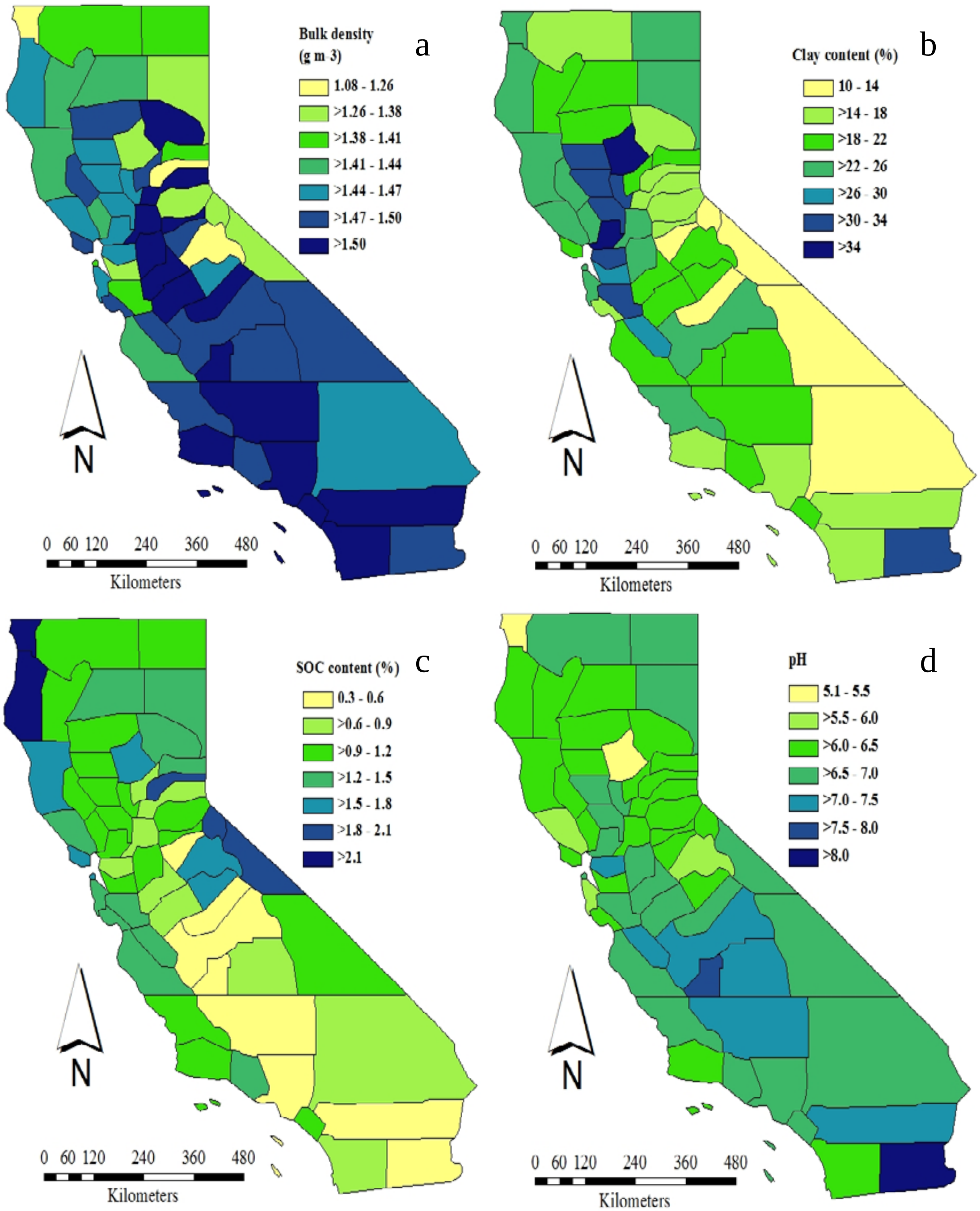

Figure 4. County values of key soil input parameters: bulk density (a), clay content (%), SOC content (%), and pH. The data shown are the "representative" soil properties calculated by weighting soil properties in Soil Survey Geographic database with the cropland area in each county.

Meteorological data. Daily meteorological data (maximum and minimum air temperatures, precipitation, and solar radiation) from 1998 to 2015 were derived from the DAYMET model, the Daily Surface Weather and Climatological Summaries (https://daymet.ornl.gov/) (Thornton et al., 2015). DAYMET climate data are available for the United States at 1-km^2 resolution, and the data from the 1-km^2 cell that was closest to the area-weighted geographical center of croplands in each county were used to drive the DNDC model. California generally experiences a Mediterranean climate consisting of hot dry summers and wet cool winters, although meteorological conditions were varied across different counties.

N fertilizer use. There was no discernable trend in N fertilizer application rates from 2000 to 2015, so a static N use rate for each crop was used for the 2000 to 2015. N fertilizer use rates, types, and schedules were developed based on the "Cost and Return Studies" of the University of California, Davis (UCD, 2016) and literature reviews (for example, Rosenstock et al., 2012). Table 3 provides total N fertilizer uses in California croplands over 2000-2015.

Irrigation practices. The DNDC model developed for this project offers two options for defining irrigation practices for regional simulations: the irrigation index and irrigation event. The irrigation-event mode was used for simulating direct N_2O emissions from California croplands to better reflect irrigation management diversity in California and capture impacts of irrigation method on N_2O emissions. Information collected to support this mode included irrigation method, water depth, and schedule.

The irrigation methods for each crop were assumed to change overtime according to the CDWR's Irrigation Method Survey for 1991, 2000, and 2010 (http://www.water.ca.gov/landwateruse/surveys.cfm) (CDWR, 2016). The four irrigation methods considered were surface gravity irrigation, sprinkler irrigation, surface drip, and subsurface drip. State-wide surveys of irrigation methods (Orang et al., 2008; Tindula et al., 2013) demonstrated that low-volume irrigation has increased in all investigated crop types in California, including hay, field crops, vegetable, melon, and berries (VMB), orchard, and vineyard, while surface irrigation has declined for these crop types from 2001 to 2010. However, the fraction of corresponding irrigation methods for each type of crops is not available in each year, therefore we estimated the fraction of each year by using linear interpolation for 2000 to 2010 and extrapolation for 2011 to 2015 (Figure 5). Appendix B lists fractions of historical irrigation methods for the crops from 2000 to 2015.

The most common irrigation method and irrigation water depth for each crop were first determined from the "Cost and Return Studies" of UCD (2016). The baseline irrigation depth was then varied using the ratios of 1.58, 1.27, 1.06, and 1.0 for surface gravity irrigation, sprinkler irrigation, surface drip, and subsurface drip, respectively, consistent with the reported water use efficiencies of the four irrigation methods of 60%, 75%, 90%, and 95% for surface gravity irrigation, sprinkler irrigation, surface drip, and subsurface drip, respectively (Brouwer et al., 1989). The final irrigation depth was further adjusted for each county based on the ratio of the county's annual mean air temperature to the state-mean air temperature so that more irrigation water would be applied for counties with a higher air temperature. The frequency of surface gravity irrigation was set at 7 to 10 times per growing season (UCD, 2016) and was increased to once every four days for sprinkler irrigation and every other day for surface and subsurface drip irrigation. These irrigation frequencies were considered best representative of the actual practices (Johnson and Cody, 2015; UCD, 2016).

Table 3. Total land areas (unit: 1000 hectares) for simulating direct N_2O emissions, N inputs (unit: 10^6 kg N) from synthetic fertilizers and crop residue return, subdivided by crop categories.

Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Cropland area																
Hay	689.6	701.3	787.8	733.5	727.0	738.4	758.5	716.7	737.2	696.4	675.0	636.4	672.5	643.8	604.3	524.2
Field crops	1031.0	941.1	906.1	910.2	939.2	844.9	767.3	802.1	811.2	723.5	778.3	886.7	837.2	752.2	566.1	507.1
VMB[a]	481.8	466.5	491.1	472.5	471.2	470.7	464.3	450.5	438.7	435.5	439.1	436.5	443.5	442.3	446.4	438.3
Orchard	599.7	608.9	641.5	617.0	606.2	616.4	622.8	642.3	655.8	677.2	690.8	724.1	735.8	758.5	775.3	792.6
Vineyard	326.2	332.4	332.6	322.1	223.6	313.5	310.8	307.7	305.6	307.4	308.7	308.8	308.6	314.9	331.7	328.4
Total	3128.4	3050.2	3159.2	3055.3	2967.1	2983.9	2923.7	2919.4	2948.5	2840.0	2891.8	2992.8	2997.4	2911.6	2723.8	2590.6
N from synthetic fertilizers																
Hay	48.3	50.7	55.0	51.3	52.8	55.2	56.0	55.9	56.2	53.0	52.9	50.9	55.2	50.3	46.3	38.4
Field crops	205.4	186.4	180.7	185.4	188.0	170.2	152.1	164.1	172.0	150.4	160.2	184.2	175.3	153.2	113.9	100.9
VMB	100.5	98.2	103.5	99.8	99.1	99.8	98.2	94.7	92.6	91.8	92.7	92.2	93.9	93.3	94.3	92.5
Orchard	108.2	110.7	117.1	113.6	112.1	114.7	116.9	121.1	124.3	129.0	132.0	139.2	142.9	146.9	150.9	154.8
Vineyard	14.7	15.0	15.0	14.5	10.1	14.1	14.0	13.8	13.8	13.8	13.9	13.9	13.9	14.2	14.9	14.8
Total	477.0	461.1	471.2	464.6	462.1	454.0	437.3	449.7	458.8	438.0	451.8	480.4	481.2	457.8	420.4	401.4
N from crop residue return																
Hay	57.1	55.1	62.1	61.0	53.8	59.8	58.8	52.1	54.2	52.2	51.0	44.6	45.8	45.5	46.4	41.8
Field crops	26.6	23.9	22.3	22.1	22.2	20.7	18.3	19.9	19.4	16.3	20.8	22.5	21.0	19.3	13.8	11.5
VMB	21.6	20.9	21.3	21.5	21.7	22.1	21.5	19.5	18.9	19.3	19.0	18.9	18.2	18.7	19.1	18.9
Orchard	12.2	11.3	13.2	12.6	11.5	12.7	12.9	12.3	11.9	13.0	12.9	14.2	13.3	13.1	12.7	13.2
Vineyard	2.4	2.6	2.5	2.5	1.6	2.5	2.4	2.4	2.2	2.4	2.4	2.4	2.4	2.4	2.6	2.4
Total	119.9	113.8	121.5	119.7	110.8	117.8	113.9	106.2	106.6	103.2	106.1	102.6	100.8	98.9	94.6	87.8

[a]The 'VMB' indicates vegetable, melon, and berries.

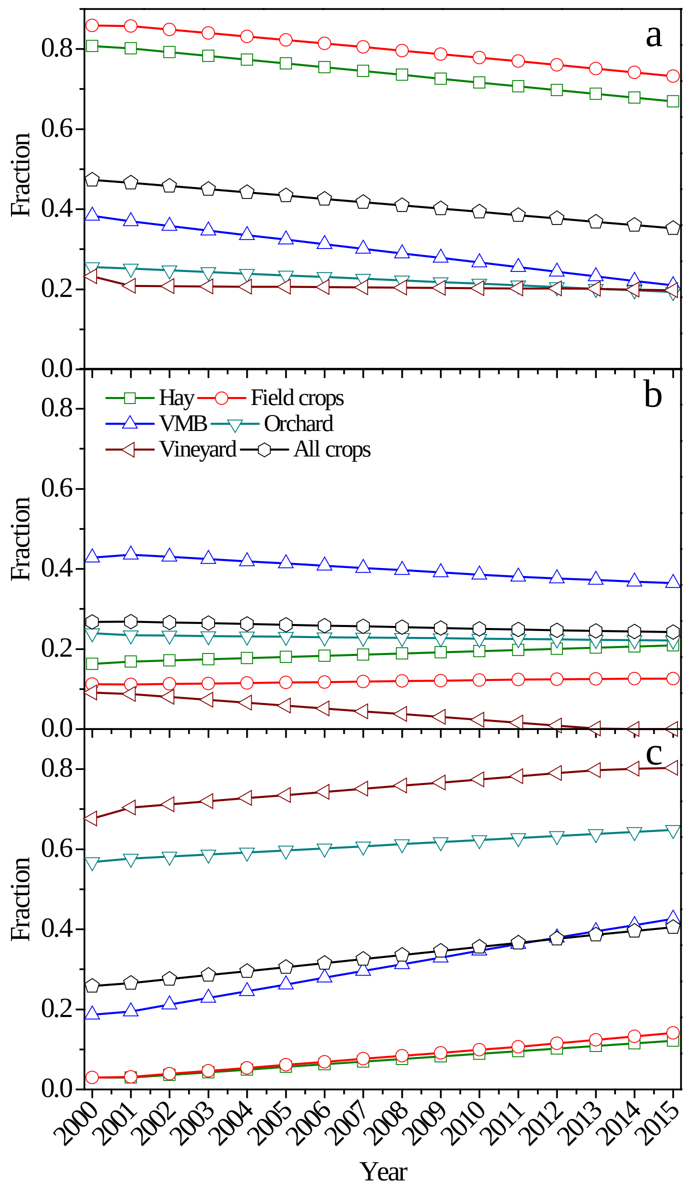

Figure 5. Fractions of surface (a), sprinkler (b), and low-volume (c) irrigations for hay, field crops, vegetable, melon, and berries (VMB), orchard, vineyard, and all crops from 2000 to 2015. Data were from Orang et al. (2008) and Tindula et al. (2013) for 2001 and 2010, and were determined by linearly interpolating the survey data of 1991, 2001, and 2010. The data showed a trend of increasing in low-volume irrigation and decreasing in surface irrigation in all investigated crop types.

3.2 Baseline N_2O Calculation

Because irrigation management practices are extremely diversified in California, covering practices from surface flooding to precise drip irrigation for an individual type of crops (Orang et al., 2008; Tindula et al., 2013), we did not use one irrigation practice for an individual type of crops. Instead, we set four scenarios of irrigation methods (i.e., surface gravity, sprinkler, drip, and subsurface drip) for each crop type and conducted DNDC simulations under these four scenarios. As Table 4 lists, the simulations of N_2O emissions were different across different scenarios of irrigation methods. Therefore, it is advantageous to simulate N_2O emissions under different irrigation methods to capture impacts of irrigation method on N_2O emissions. We then calculated the baseline N_2O emissions under the actual distribution of irrigation management by weighting the results of the individual simulations under the four scenarios using the fraction of the corresponding irrigation methods for each type of crops (Appendix B). The setting of irrigation scenarios ensures a comparison of N_2O emissions under alternative irrigation management, and the calculation of the baseline N_2O emissions represent as closely as possible of N_2O emissions under actual irrigation management practices in California. The setting of the four scenarios of irrigation management practices was described in the previous section in details.

Table 4. Area, amount of fertilizer N, and N_2O emissions under baseline and four different scenarios of irrigation management for the simulated crop types. The simulations in 2012 were used as an example to demonstrate the impacts of irrigation scenarios on N_2O emissions. Baseline N_2O emissions were calculated by weighting the simulations in 2012 under the four scenarios of irrigation management with fractions of corresponding irrigation methods for each crop type in 2012.

Crop type	Area (ha)	Fertilizer (MT N)	N_2O emissions (MT N yr^{-1})				
			Baseline	Surface gravity	Sprinkler	Surface Drip	Subsurface Drip
Alfalfa	359115.8	6033.1	452.3	535.1	189.8	172.4	164.6
Almonds	325182.8	72841.0	363.2	628.9	476.1	390.8	203.2
Apples	5647.6	266.0	2.2	2.9	2.0	1.9	1.7
Apricots	3714.7	312.4	1.6	2.4	1.4	1.1	0.9
Artichokes	2700.6	650.8	5.5	12.5	4.6	3.0	1.9
Asparagus	4113.8	415.1	2.6	4.5	2.3	2.1	1.8
Avocados	19308.2	3568.2	12.2	20.9	20.6	12.6	7.6
Barley	29696.5	2963.7	48.7	51.8	39.5	37.0	35.9
Beets	11743.2	2466.1	21.2	24.9	6.0	5.5	1.4
Berries	16285.5	2915.1	31.6	80.6	22.8	14.0	11.8
Broccoli	40562.7	7950.3	83.7	221.5	57.6	40.3	24.4
Cabbage	5011.0	1373.0	18.0	57.6	8.5	6.9	3.9
Carrots	19736.0	5526.1	17.6	46.8	12.1	9.0	4.5
Cauliflower	13281.0	3652.3	23.5	46.4	21.9	15.8	8.2
Celery	3085.4	836.8	12.4	29.3	8.0	8.3	6.5
Cherries	13102.6	896.2	4.4	9.2	2.6	2.2	1.9
Cotton	144834.0	29401.3	253.1	347.5	62.7	62.1	28.1
Dates	1776.2	490.2	0.7	1.1	1.1	1.0	0.1
Dry beans	22776.1	2300.4	86.4	104.2	48.5	51.3	41.6
Figs	2114.6	237.0	0.5	1.2	0.8	0.6	0.3
Garlic	8170.1	2314.6	8.9	23.8	7.5	7.0	4.9
Grain corn	80617.7	23475.9	643.5	765.1	346.2	313.9	174.2
Grapes	308573.8	13885.8	321.6	468.2	286.5	284.8	284.3

Green beans	7535.9	1085.2	16.7	18.8	14.1	10.5	9.9
Lemons	16832.7	2390.2	8.8	21.0	11.4	10.4	4.7
Lettuce	92023.1	19416.9	189.0	230.6	187.1	174.0	160.0
Melons	26699.7	5233.1	51.8	81.4	26.5	21.7	16.5
Non-legume hay	313334.3	49193.5	1004.4	1230.8	923.5	311.2	237.4
Oats	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Olives	14469.6	1620.6	15.1	24.1	23.1	18.6	7.5
Onions	16169.0	3912.9	15.9	43.3	12.9	13.4	7.9
Other citrus	84337.5	10457.8	33.6	75.1	45.3	41.7	16.2
Other fruits	11971.3	2023.2	7.1	9.9	8.2	6.8	2.1
Other nuts	105253.9	23682.1	187.9	151.1	319.2	208.2	59.5
Other vegetables	24872.1	5248.0	28.2	38.8	26.8	24.7	22.6
Peach	24554.8	4149.8	18.6	25.8	20.9	17.3	6.6
Pears	4412.8	789.9	3.0	5.0	2.3	2.2	1.9
Peppers	10336.8	3183.7	12.4	23.4	10.8	8.6	7.1
Pistachios	73196.5	14346.5	44.1	63.7	69.9	62.8	8.6
Plums	8597.9	1203.7	4.7	7.6	4.4	3.9	1.5
Potatoes	16235.8	3815.4	12.4	55.5	11.6	12.3	9.1
Prunes	21287.2	3576.3	19.3	23.9	23.0	19.4	8.0
Rice	224876.0	32157.3	305.5	305.5	305.5	305.5	305.5
Safflowers	19583.0	2193.3	11.5	12.3	10.7	9.3	9.3
Silage corn	117838.2	32334.8	586.4	586.4	851.7	135.9	53.3
Sorghum	12156.5	1908.6	13.8	12.3	32.6	4.9	1.6
Spinach	8486.6	1329.8	13.0	15.0	12.3	12.6	12.4
Spring wheat	71120.8	23896.6	199.6	208.2	239.4	94.2	43.4
Squash	5365.1	1738.3	22.0	35.5	9.8	8.5	6.0
Sunflowers	20133.4	2031.5	27.4	31.5	24.6	18.9	11.4
Sweet potatoes	6185.0	872.1	4.3	26.8	3.9	3.6	2.8
Tomatoes	116597.3	22386.7	181.3	295.6	181.3	157.3	130.0
Winter wheat	81813.5	20207.9	244.0	261.5	195.3	170.8	167.6
Alfalfa	359115.8	6033.1	452.3	535.1	189.8	172.4	164.6

3.3 Baseline Inventory of N_2O Emissions from California Croplands

The simulated annual N_2O emissions from California croplands ranged between 3.49×10^3 (in 2015 with a cropland area of 2.59×10^6 ha) and 6.37×10^3 (in 2002 with a cropland area of 3.16 $\times 10^6$ ha) metric ton (MT) N yr^{-1} (or 1.63 to 2.98 Tg CO_2 equivalents yr^{-1} by using the IPCC Fourth Assessment Report 100-year global warming potential of 298 kg CO_2-equivalents kg^{-1} for N_2O) from 2000 to 2015 (Figure 6). The mean annual N_2O emissions were 5.23×10^3 MT N yr^{-1} (or 2.45 Tg CO_2 equivalents yr^{-1}) across the simulated 16 years (Table 5). Based on the DNDC simulations, 0.70% (in 2013 and 2015) to 1.08% (in 2001 and 2002) of the N inputs from synthetic fertilizers and crop residues applied into California croplands were emitted as N_2O during 2000 to 2015. The average fraction of the N emitted as N_2O was 0.93% from 2000 to

2015. We compared the DNDC predictions with the CARB reported N_2O emissions based on the Tier 1 EF methodology (CARB, 2016). The appropriate categories for the comparison include N_2O emissions from N inputs through applications of synthetic fertilizers and crop residues. The sum of the N_2O emissions from these two categories was 2.86 Tg CO_2 equivalents on an average basis from 2000 to 2014 in the CARB inventory (CARB, 2016). This value is slightly higher than the N_2O emissions calculated based on the DNDC simulations (averaged as 2.50 Tg CO_2 equivalent yr^{-1} from 2000 to 2014). The average of the DNDC-based EFs (0.94% across 2000 to 2014) was also comparable with the CARB used value (1.00%).

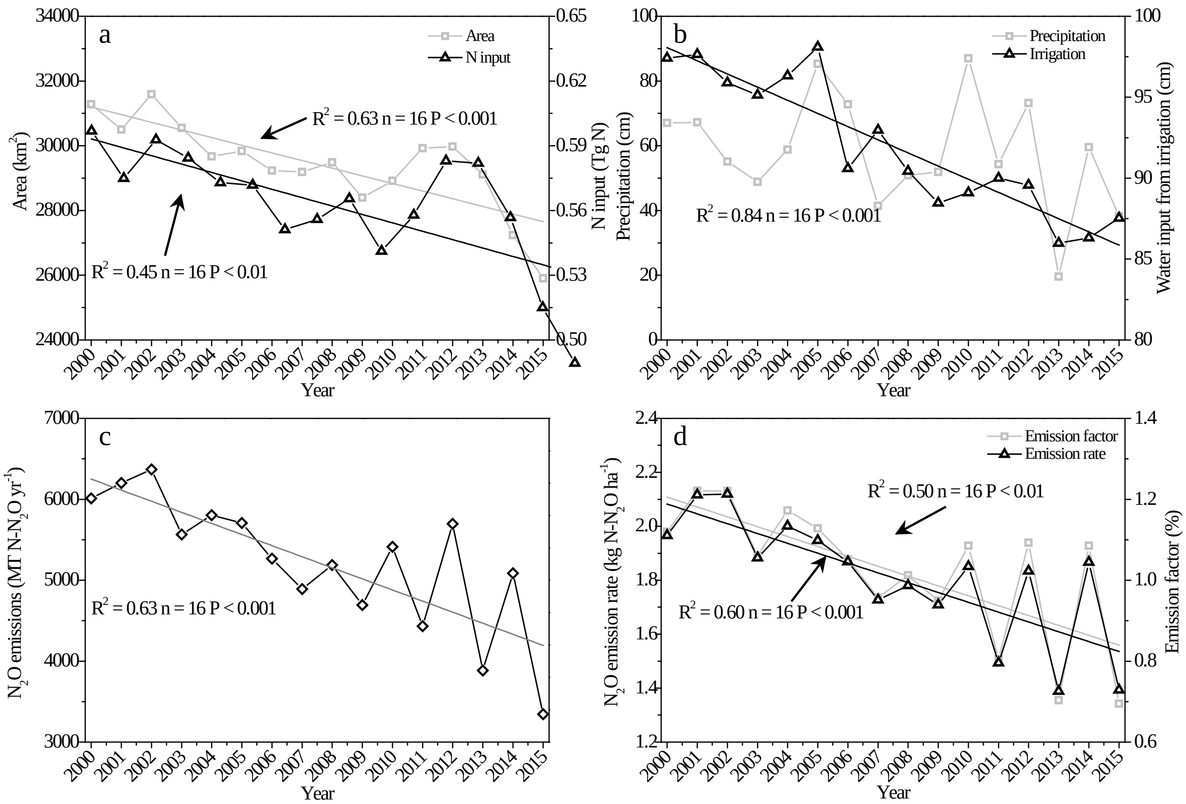

Figure 6. Dynamics of croplands area and nitrogen (N) input from synthetic fertilizers and crop residues (a), annual precipitation and water input from irrigation (b), annual state N_2O emissions (c), and emission rates and Emission Factors (EFs) of N_2O (d) from 2000 to 2015. The EFs in the panel (d) were the fractions of N input from synthetic fertilizers and crop residues emitted as N_2O. The statistical information is for the corresponding regression lines. The DNDC simulations showed significant decreasing trends in croplands area, N input, water input from irrigation, state N_2O emissions, N_2O emission rate, and EF from 2000 and 2015.

We quantified contributions of different crop categories on state total N_2O emissions. Most of the N_2O emissions were from the categories of hay and field crops with inter-annual variations for their contributions (Figure 7). On a multi-year average basis, 27.5% and 41.6.0% of the state total N_2O emissions were from the hay and field crops, respectively, primarily due to their large contributions in total cropland area and N input. The contributions of the VMB, orchard, and vineyard in the state total N_2O emissions were 15.6%, 10.5%, and 4.8%, respectively.

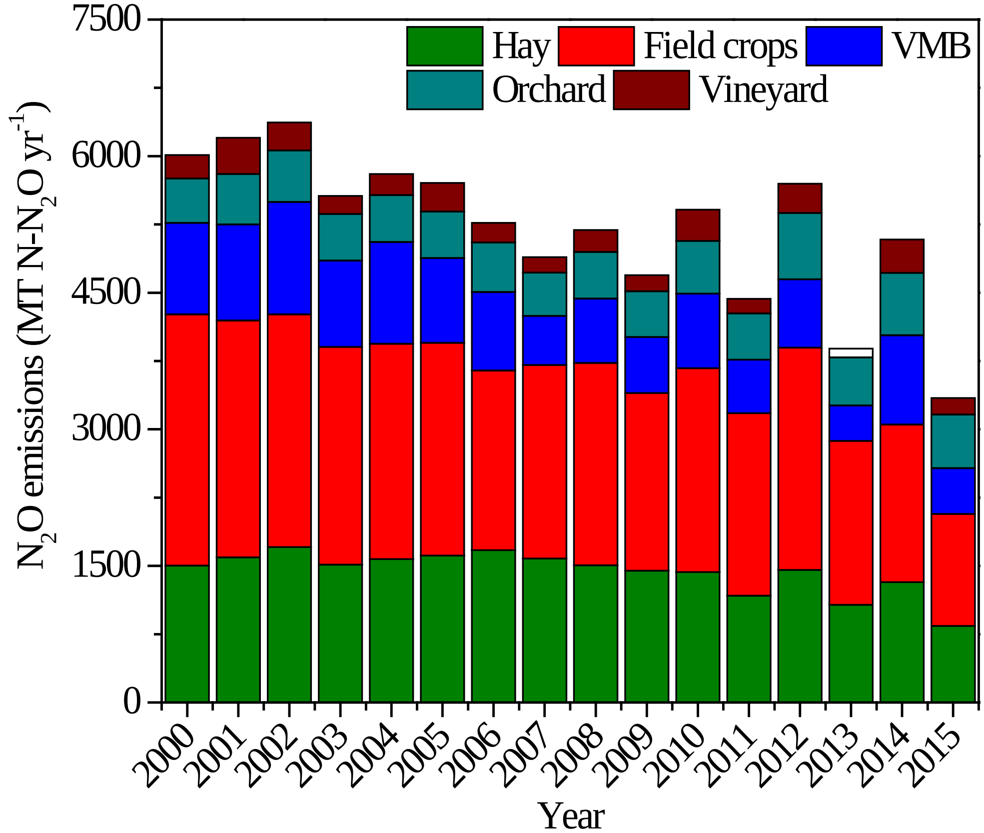

Figure 7. N_2O emissions of different crop categories from 2000 to 2015.

We also summarized crop type-sorted N_2O emissions from California croplands based on the multi-year simulations (Table 5). The crop types with substantial contribution to state total N_2O emissions were corn (18.4%; including grain corn and silage corn), no legume hay (18.1%), alfalfa (9.4%), and cotton (7.0%). The corn fields were the largest source of the N_2O emissions in California cropping systems over the simulated 16 years primarily because of the large area, high synthetic N input, and high water input resulted from the large fraction of surface gravity irrigation. The hay fields, including non-legume hay and alfalfa, were also predicted as large sources primarily because of the large area and high percentage of surface gravity irrigation, which together with the relative long growing seasons for the hay resulted in high water input.

Table 5. Average total land areas for simulating direct N_2O emissions, N input (unit: MT N) from synthetic fertilizers and crop residue return, N_2O emissions, rate of N_2O emissions, and emission factor (EF), and changes of the land areas, N input (unit: MT N), and N_2O emissions from 2000 to 2015.

	Mean of 2000 to 2015					Change from 2000 to 2015		
Crop type	Area	N input	N_2O	N_2O rate	EF	Area	N input	N_2O
	km^2	MT N	MT N	kg N ha^{-1}	%	km^2	MT N	MT N
Alfalfa	4035.2	57024	491.2	1.22	0.86	-1150.0	-16853	-228.0
Almonds	2677.8	62407	204.7	0.76	0.33	1515.0	35255	68.3
Apples	86.1	513	2.5	0.29	0.48	-106.2	-621	-2.8
Apricots	46.1	432	2.0	0.44	0.47	-32.0	-300	-2.0
Artichokes	29.7	752	6.9	2.31	0.91	-10.7	-270	-3.6
Asparagus	81.3	822	5.2	0.65	0.64	-106.0	-1073	-9.7
Avocados	222.7	4284	18.8	0.85	0.44	-37.8	-725	-6.4
Barley	251.7	3332	37.7	1.50	1.13	-294.9	-3883	-46.2
Dry beans	260.7	3339	80.1	3.07	2.40	-274.5	-3609	-72.8
Green beans	83.1	1471	17.6	2.11	1.19	-66.8	-1209	-16.9
Beets	149.5	3641	21.6	1.45	0.59	-66.7	-1641	-29.6
Berries	151.5	3571	41.1	2.72	1.15	66.1	1572	13.7
Broccoli	463.1	11159	126.3	2.73	1.13	-76.2	-1815	-61.0
Cabbage	66.4	2216	29.5	4.43	1.33	-24.9	-829	-21.3
Carrots	214.0	6569	25.5	1.19	0.39	-42.8	-1291	-8.0
Cauliflower	132.7	3733	27.5	2.07	0.74	-21.3	-598	-10.4
Celery	59.4	2935	32.8	5.52	1.12	-58.1	-2897	-36.8
Cherries	107.1	853	3.4	0.32	0.40	42.9	331	-0.5
Other citrus	898.2	14309	39.8	0.44	0.28	-14.6	-1030	-12.0
Grain corn	679.2	25013	537.1	7.91	2.15	-594.9	-21902	-569.1
Silage corn	869.0	25669	425.1	4.89	1.66	199.0	5908	109.4
Cotton	1928.3	43153	366.5	1.90	0.85	-3063.3	-68473	-705.3
Dates	20.3	958	0.8	0.37	0.08	19.3	966	0.4
Figs	35.5	411	1.0	0.28	0.24	-26.9	-312	-1.2
Other fruits	72.2	1384	4.8	0.67	0.35	122.8	2351	8.0
Garlic	97.1	3182	12.0	1.24	0.38	-24.5	-783	-12.2
Grapes	3114.4	16395	248.8	0.80	1.52	21.4	89	-75.4
Lemons	188.2	4607	12.9	0.69	0.28	-13.3	-420	4.3
Lettuce	844.1	18988	148.6	1.76	0.78	-111.1	-2594	-124.1
Melons	257.0	5812	45.0	1.75	0.77	-94.5	-2156	-37.3
No legume hay	2866.4	47342	946.8	3.30	2.00	-504.9	-8296	-434.6
Other nuts	902.7	21657	155.5	1.72	0.72	390.2	9395	52.7

Oats	19.8	214	0.8	0.39	0.36	-23.7	-247	-0.5
Olives	136.5	1660	12.3	0.90	0.74	-7.7	-84	-0.4
Onions	171.5	4705	21.4	1.25	0.45	20.2	509	-18.7
Peach	354.3	6785	26.2	0.74	0.39	-276.0	-5283	-22.4
Pears	59.6	1266	3.5	0.59	0.28	-37.3	-826	-2.8
Peppers	103.9	3369	11.5	1.10	0.34	-0.7	-16	-7.4
Pistachios	541.5	11397	33.2	0.61	0.29	638.5	13438	38.0
Plums	122.3	1864	7.2	0.59	0.39	-86.8	-1318	-4.3
Potatoes	150.6	3797	11.5	0.77	0.30	-39.1	-984	-4.4
Prunes	257.2	5052	20.8	0.81	0.41	-161.0	-3124	-15.7
Rice	2117.3	33107	320.3	1.51	0.97	-511.9	-8491	-42.6
Safflowers	271.3	3457	13.9	0.51	0.40	-148.3	-1877	-5.5
Sorghum	87.6	1863	10.3	1.18	0.55	204.6	4297	19.7
Spinach	92.0	1502	14.4	1.56	0.96	-25.1	-402	-16.0
Squash	48.0	1703	18.6	3.87	1.09	-12.0	-425	-5.1
Sunflowers	130.8	1394	14.2	1.08	1.02	65.8	698	4.4
Sweet potatoes	50.1	786	3.7	0.73	0.47	24.1	383	0.5
Tomatoes	1283.4	35095	191.2	1.49	0.54	-35.2	-429	-142.8
Other vegetables	176.5	3967	24.9	1.41	0.63	204.0	4620	18.9
Spring wheat	481.9	16688	143.2	2.97	0.86	-1.1	-81	7.8
Winter wheat	880.4	24329	199.7	2.27	0.82	-728.9	-20236	-198.9
Total	29427.2	561936.1	5222.0	1.85	0.93	-5378.1	-107589.7	-2668.4

Figure 8 shows the means of the simulated N_2O emissions from 2000 to 2015 in each county of California as well as a ranking of individual counties in N_2O emission. The simulations of total N_2O emissions highly varied between 0.0 and 519.1 MT N yr^{-1} across different counties. San Joaquin was estimated to be the county with the highest N_2O emissions, and, on average, accounted for 9.9% of the state total N_2O emissions from 2000 to 2015. Fresno and Tulare contributed 7.9% and 7.6%, respectively, ranked as the second and third emitting county. The counties with substantial N_2O emissions were primarily located in the Central Valley of California due to large crop acreages. The DNDC results also indicate that the spatial variations of the total N_2O emissions were jointly influenced by the variations of the cropland area and associated fertilizer N application as well as the N_2O emission rates per area due to the variations of climate, soil properties, and FMPs across different counties. The simulated direct N_2O emissions tend to be high in regions receiving large amounts of N fertilizers and water through precipitation and/or irrigation and with fine-textured soils that are high in organic matter. Most of these factors regulating the N_2O variability have not been well considered by the EF methodology, but may provide potential options for N_2O mitigation in addition to improve application of N fertilizers and increase N use efficiency.

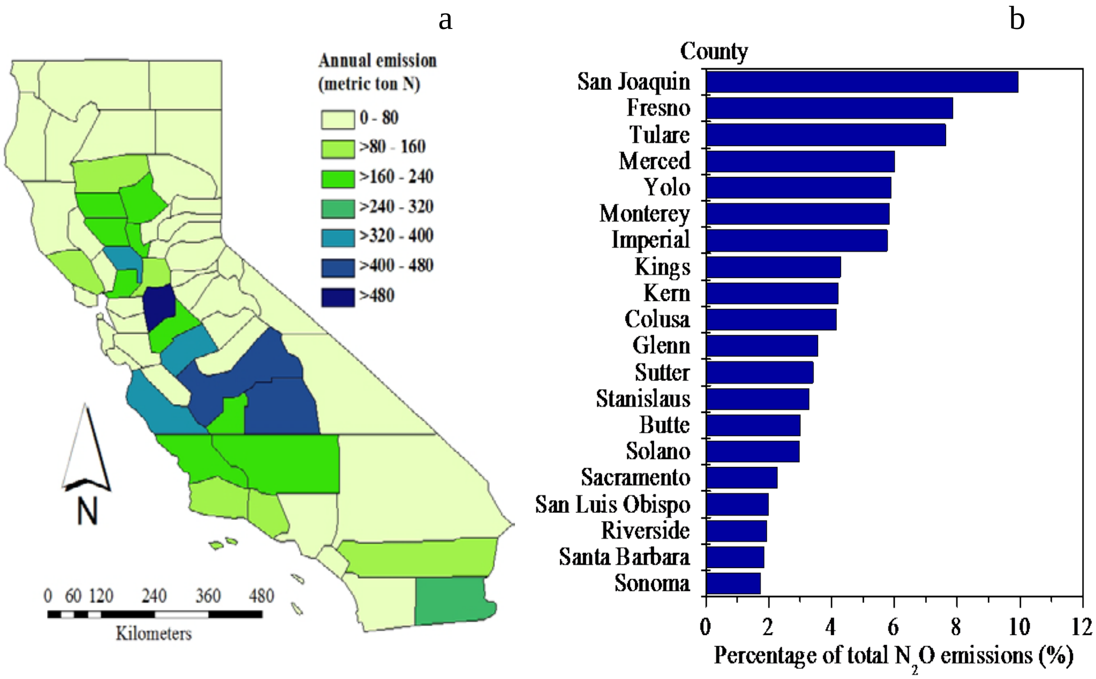

Figure 8. DNDC simulated annual N_2O emissions from different counties in California (a) and a ranking of the top 20 counties on N_2O emission (b). The data in the panel (a) were the mean annual N_2O emissions from 2000 to 2015. The sum of the N_2O emissions from these 20 counties was over 80% of the simulated state total N_2O emission.

3.4 Temporal Trend of N_2O Emissions

The simulated direct N_2O emissions from California croplands showed a significant decreasing trend from 2000 to 2015 ($P < 0.001$) although large inter-annual variations appeared (Figure 6c). The N_2O emissions reduced by 2.67×10^3 MT N yr^{-1} from 2000 to 2015. The decreasing of the N_2O emissions was primarily due to significant reductions of (1) croplands area and N inputs ($P < 0.001$, Figure 6a) and (2) N_2O emission rate ($P < 0.01$, Figure 6d) and EF ($P < 0.05$, Figure 6d). The total area and N inputs in California cropland decreased by 5378.1 km^2 and 107590 MT N, respectively, from 2000 to 2015. DNDC also simulated the significant declining trends for the N_2O emission rate and EF (Figure 6d). The decreasing trends largely resulted from the changes in irrigation management practices from 2000 to 2015 – the trend that more croplands irrigated by low-volume irrigation and less croplands irrigated by relatively high-volume surface methods (Figure 5) and the resulted reduction of water input from irrigation (Figure 6b) could reduce N_2O emission rate because of the relative lower N_2O emissions under low-volume irrigation management (Table 4).

As Figure 9 shows, we estimated a decreasing trend in the N_2O emissions between 2000 and 2015 for most of the counties in California. Fresno was the county with the largest N_2O reduction between 2000 and 2015, and accounted for 14.4% of the state total N_2O reduction. San Joaquin and Yolo contributed 11.4% and 10.4% of the state total N_2O reduction, respectively, ranked as the second and third county with N_2O decreasing, and followed by Monterey (8.2%) and Kern (7.0%).

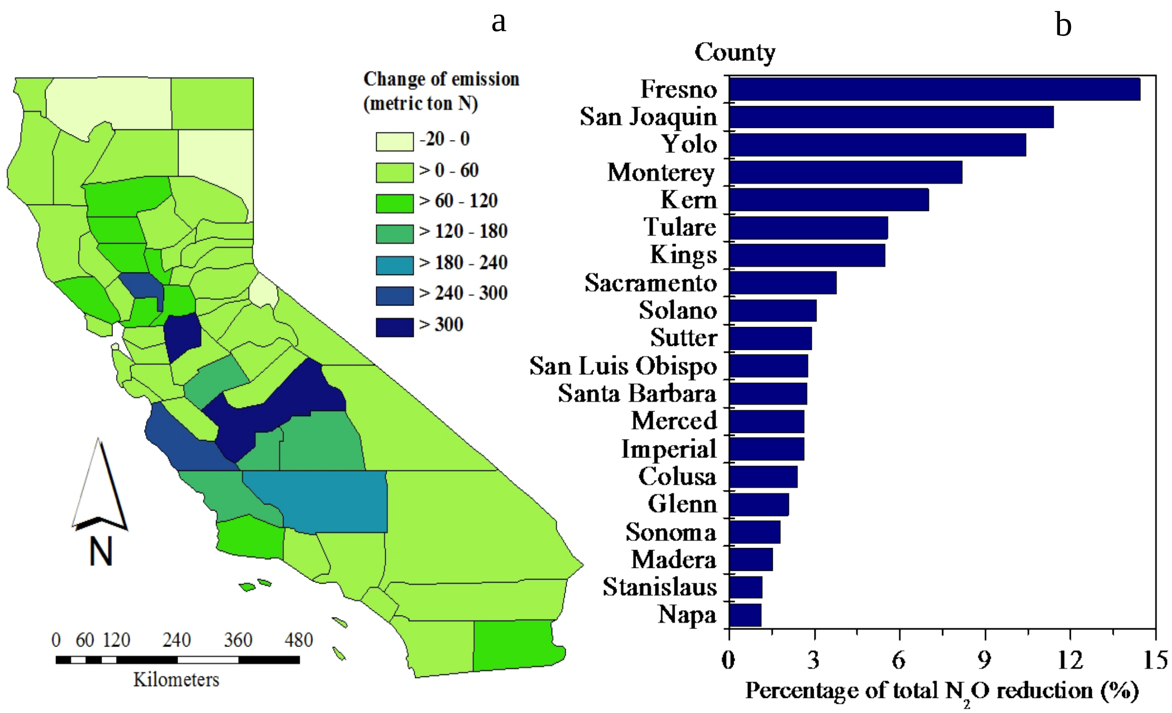

Figure 9. Changes of annual N_2O emissions for different counties in California (a) and a ranking of the top 20 counties showed N_2O reduction (b). The data in the panel (a) were calculated by subtracting the 2000's N_2O emissions with the 2015's emissions, and showed a reduction trend between 2000 and 2015 for most counties. The sum of the N_2O reduction from these 20 counties was over 80% of the simulated state total N_2O reduction.

4. Uncertainty Analysis

Uncertainty analyses were performed to evaluate uncertainties of the DNDC simulated N_2O emissions from the tested crop fields and the whole California croplands.

We conducted statistical analysis to evaluate DNDC uncertainty using the results from the model tests (Section 2). Differences between 52 paired field observations and DNDC modeled N_2O emissions were calculated and analyzed for bias, trends in variability across the range of total emissions, and differences by crop type.

First, we investigated the differences between modeled and measured seasonal or annual N_2O emissions. We calculated the residuals as the measured emissions minus the modeled emissions with negative residuals representing overestimates of DNDC and positive values representing underestimates of DNDC. The residuals have a roughly symmetric distribution with a slightly positive mean (Figure 10). However, there is no significant bias in the DNDC modeled total N_2O emissions. We calculated a non-parametric prediction interval for new residuals (i.e. differences between a new measured and modeled observation) by looking at the range of ordered residuals and assigning the probability based on assuming each residual has equal probability to be the minimum or maximum. There is about a 96% chance a new residual will fall between -1.3 and

1.6 kg N_2O-N ha^{-1}, the minimum and maximum residuals. And there is a 90% chance a new residual will fall between -0.07 and 0.12 kg N_2O-N ha^{-1}.

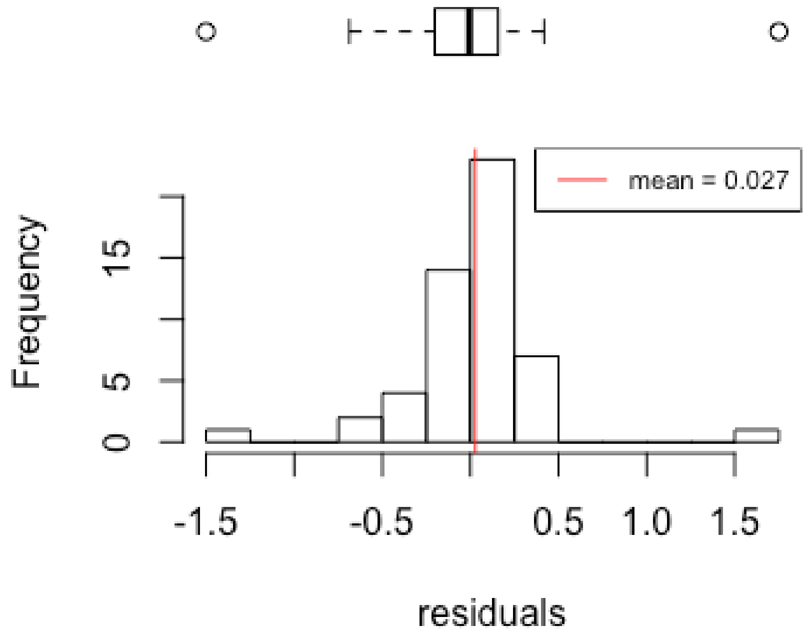

Figure 10. Distribution of the residuals between the modeled and measured N_2O emissions.

We also compared the residuals by crop type by using both the original and logarithm scales of the residuals (Figure 11). The results suggest that the model overestimated the measured annual N_2O emissions for the alfalfa on the original scale. And on the logarithm scale, the model overestimated the measured annual or seasonal N_2O emissions for alfalfa and bean. However, sample sizes are uneven and small for several crop types (e.g., alfalfa and bean). Thus, it is difficult to justify model performance by crop type.

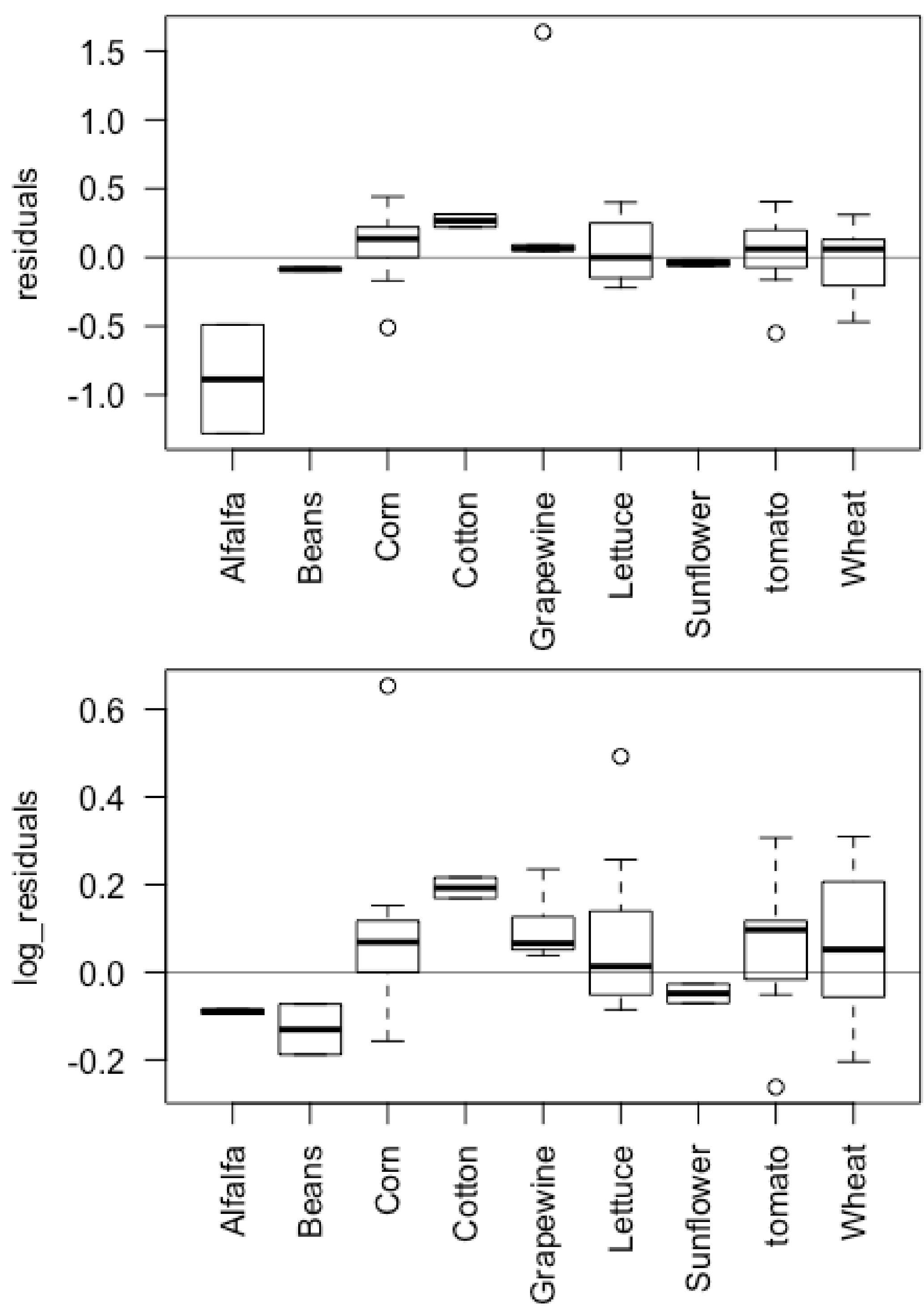

Figure 11. Crop sorted residuals between the modeled and measured N_2O emissions.

Next, we investigated the differences between the modeled and measured changes in N_2O emissions due to changes in management. In particular, we considered two types of changes, differences and percentage changes (ratios), and two sources for the changes, N_2O change due to change in nitrogen rate (N rate) and differences in the form of the nitrogen used.

Only lettuce and winter wheat were used to investigate the changes in N_2O emissions due to differences in nitrogen rates of which there were a total of 36 observations regarding the changes in N_2O emissions from the two sites (one for winter wheat and the other for lettuce) each having either two treatments or covering two time periods. Residuals in difference change were calculated as measured minus modeled changes in N_2O emissions due to differences in nitrogen rates, and the mean of these residuals is -0.17 kg N_2O-N ha^{-1}, which indicates the model slightly overestimated the N_2O changes due to differences in N rates on average. However, the simulated changes were significantly correlated with the observed changes without statistical bias. It also appears reasonable that this estimate of residuals does not depend on the emission differences (Figure 13). For the percent changes in N_2O emissions due to N rate changes, DNDC model appears to overestimate the measured percent changes (Figure 12). The percent change overestimation bias appears worst for relatively large modeled percent changes (red dots in the Figure 12). These more biased observations, however, only occur for the time period of Nov. 2009 - May 2010 for Winter wheat and the treatment in the second year of Lettuce.

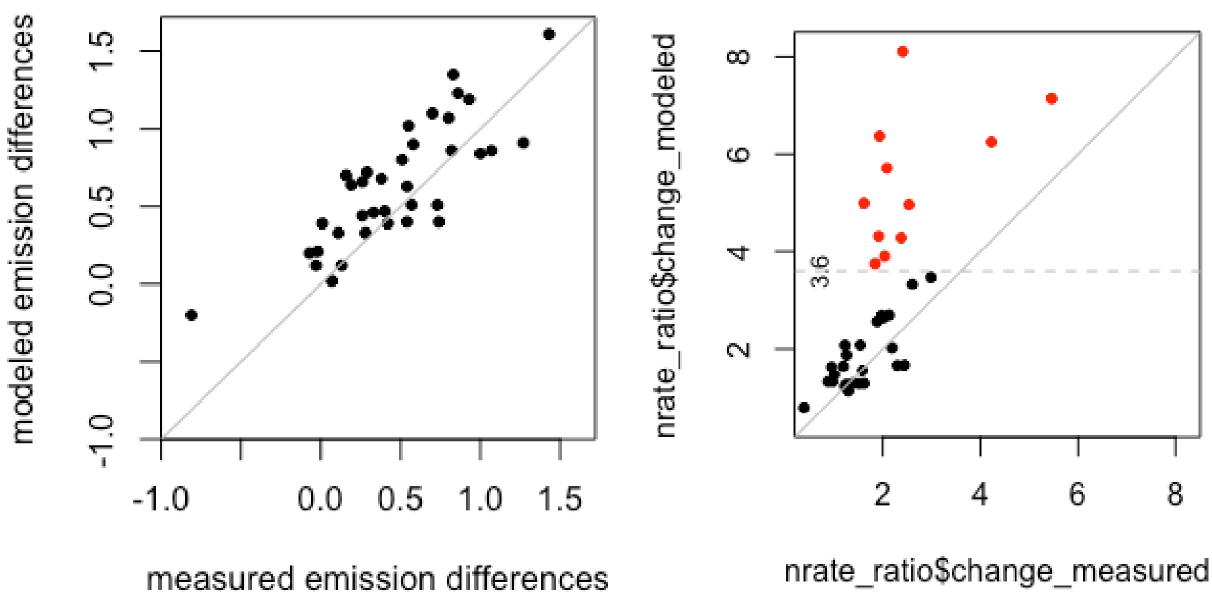

Figure 12. Comparisons between the modeled and measured N_2O changes due to change in nitrogen rate.

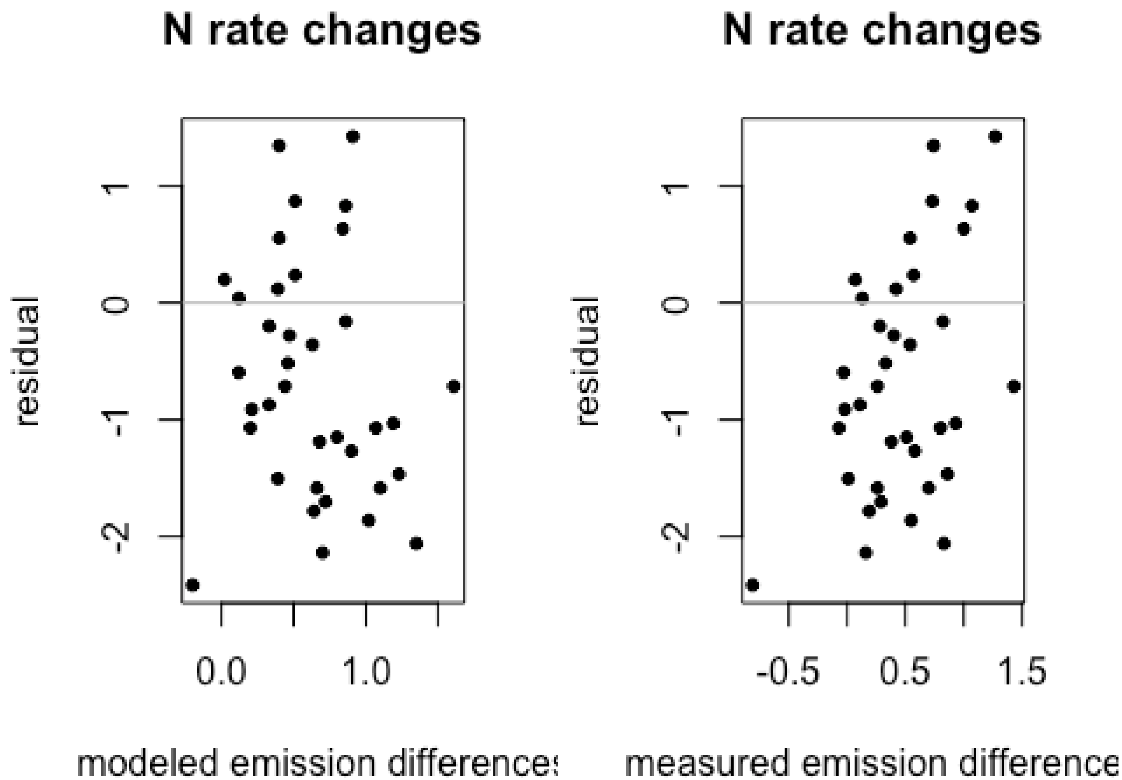

Figure 13. The residuals between the modeled and measured N_2O changes due to change in nitrogen rate.

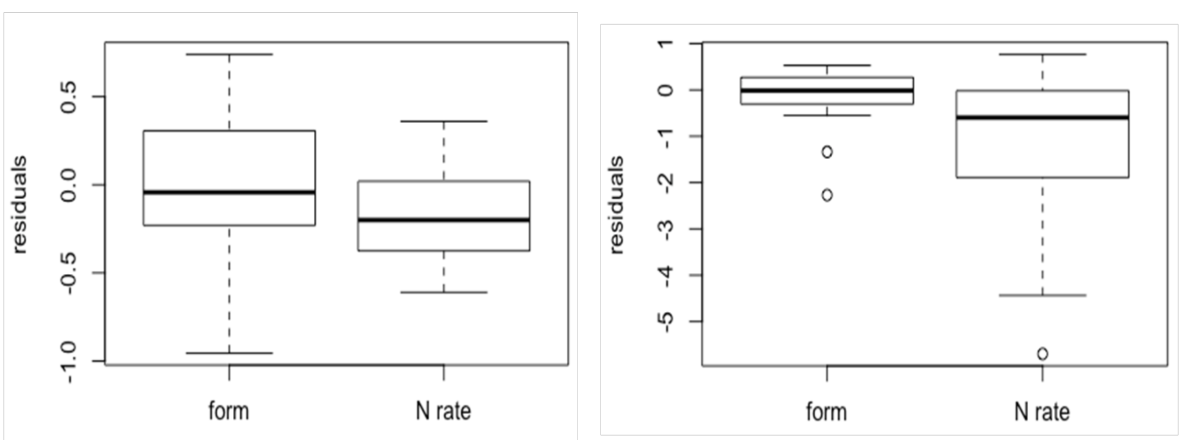

Figure 14. Comparing nitrogen form and rate changes. Left: Difference changes (units kg N-N_2O ha^{-1}). Right: Percent changes.

We used a total of 61 observations (36 N rate changes and 25 N form changes) to investigate the differences between the modeled and measured changes in N_2O emissions due to differences in the form of the nitrogen used. The alfalfa observations, and observations that change both N rate and form were excluded from this analysis. The changes in N_2O emissions due to N form changes appear slightly more variable compared to the N rate changes, but the mean of residues was close to zero. When we compare the percent change residuals due to a N rate change vs a change in N form, excluding alfalfa and changes due to both N form and rate, it appears N form changes are less bias than N rate changes and form percent changes are less variable (Figure 14).

To assess uncertainties of the N_2O emission estimates associated with uncertainties in the activities database, we performed uncertainty analyses for (1) soil properties, (2) irrigation water depth, and (3) scheduling of management events. All uncertainty analyses were performed using the 2012 activities database.

The uncertainties for soil properties were performed using the minimum and maximum soil property values as derived from the SSURGO soil database using the approach of the ‘‘Most Sensitive Factor’’ method (Li et al., 2005; Li, 2007). This analysis provided the range of potential N_2O emissions due to variability of the most sensitive soil property. The uncertainties for irrigation water depth were performed by changing the amount of water applied with +/- 25% of the default value. Finally, the uncertainties for management practice scheduling were performed by changing the dates of all management events (planting and harvest, irrigation, fertilizer application, and tillage) within a five-week window before and after of the respective default dates. The results of all uncertainty analyses are summarized in Table 6.

Table 6. Total N_2O emissions (Mg N) for 2012 as affected by uncertainties of input parameters.

Parameter	Average	Minimum (%Average)	Maximum (%Average)
Soil properties	5697	3965 (69.6%)	7799 (137%)
Irrigation water depth	5697	4773 (83.8%)	6450 (113%)
Management practice scheduling	5697	5460 (96.0%)	5749 (101%)

The largest uncertainties of the inventory estimates of N_2O would arise from uncertainties of soil properties with the SOC being the most sensitive factor. The range of the DNDC emission estimate would vary between 3965 Mg N (1.86 MMT CO_2 eq.) and 7799 Mg N (3.65 MMT CO_2 eq.) with the most likely value of 5697 Mg N (2.67 MMT CO_2 eq.). In other words, the estimated N_2O emissions would vary between 70% and 137% of the baseline value, which was obtained with area-weighted average soil property values.

5. Impacts of Alternative Management on N_2O Emissions

5.1 Alternative Management Practices

To quantify impacts of FMPs on the N_2O emissions from California croplands and the mitigation efficiency of FMPs, a series of DNDC simulations were conducted by varying FMPs for all the cropping systems included in the database. The simulations under alternative management practice scenarios were compared against the baseline simulation. All the simulations under the alternative scenarios were conducted by using the activity data in 2012.

Alternative scenarios were simulated by exclusively changing a single farming management practice from the baseline scenario. We tested eight alternative scenarios by exclusively modifying a farming management practice applied under the baseline scenario, including nitrogen application, application of nitrification inhibitor, tillage, planting of cover crop, or irrigation management, to investigate impacts of each management practice on N_2O emission. The eight alternative scenarios were as follows (Table 7): (1) reducing the amount of nitrogen fertilization by 15% (RN); (2) applying nitrification inhibitor for all ammonium based fertilizers (NI); (3) combining reduction of nitrogen fertilization (The scenario 1) and application of nitrification inhibitor (RN+NI); (4) converting the tillage practices in the baseline into reduced tillage (RT); (5) converting the tillage practices in the baseline into no tillage (NT); (6) planting non-leguminous cover crops in winter seasons (NLCC); (7) applying surface drip method for irrigation (SD); and (8) applying subsurface drip for irrigation (Subs).

Table 7. The settings of alternative scenarios.

Scenarios	Farming management practices
RN	Reduced nitrogen application by 15%.
NI	Applying nitrification inhibitor for all applications with ammonium based fertilizers.
RN+NI	A combination of RN and NI.
RT	Reduced tillage; the soil was tilled to a 10 cm depth for those tillage events with a deeper tilling depth.
NT	No tillage; no tillage practice for all simulated cropping systems.
NLCC	Cultivation of non-leguminous cover crops during winter seasons, and cover crops were incorporated into soils in Spring.
SD	Surface drip; a decrease in total irrigation water and an increase in irrigation frequency for all simulated cropping systems.
SubSD	Subsurface drip; a decrease in total irrigation water and an increase in irrigation frequency for all simulated cropping systems; water was applied at a depth of 15 cm below surface.

The DNDC was run for baseline and alternative scenarios. For the simulations under each scenario, a single farming management practice change was evaluated (i.e., tillage, fertilization, irrigation, or cover cropping), but other conditions (i.e., climate, soil, crop type, and other practices) were kept the same under the different scenarios. Note that DNDC was run four times using four different irrigation management settings for all the scenarios excluding SD and SubSD and the N_2O emissions under the actual distribution of irrigation management were calculated by weighting the results of the individual simulations under the four irrigation management settings using the fraction of the corresponding irrigation methods for each type of crops. For the SD and SubSD scenarios, DNDC was run one time using the surface and subsurface drip irrigation methods, respectively. For all the scenarios, the DNDC was run for three years from 2010 to 2012, and the modeled state annual N_2O emissions in 2012 were used for analysis.

5.2 Impacts of Alternative Management on N_2O Emissions

Figure 15 shows the simulated annual total N_2O emissions from California croplands under the baseline and alternative scenarios. The modeled state total annual N_2O emission was 5697.2 MT N under the baseline scenario by using the activity data in 2012.

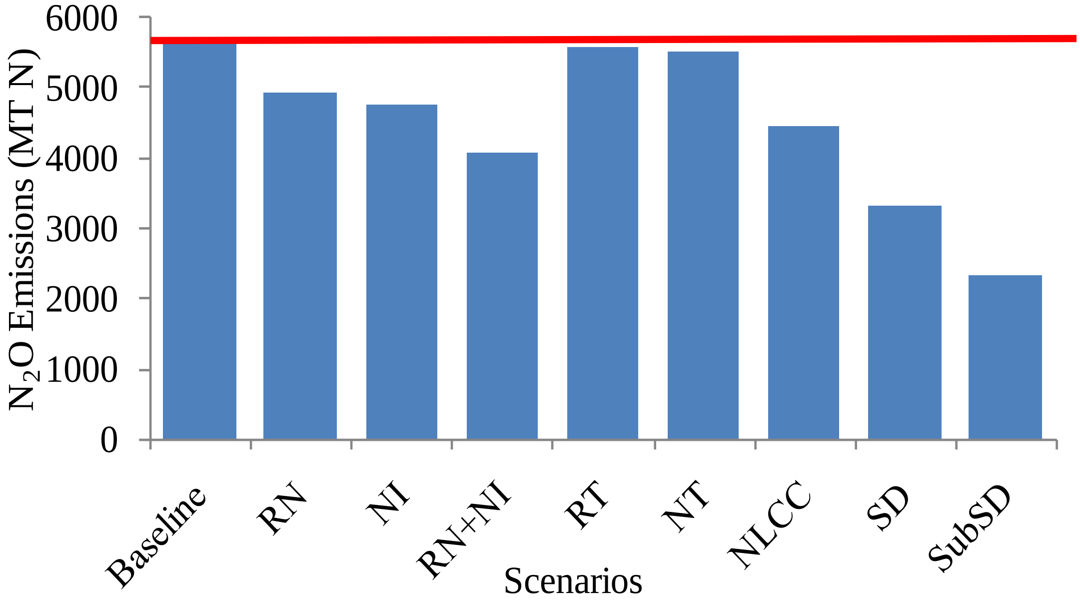

Figure 15. Simulated annual total N_2O emissions from California croplands under the baseline and alternative scenarios.

All changes in FMPs under the alternative scenarios affected N_2O emissions. Reducing N application rate would reduce concentrations of soil mineral N, and thus the N_2O emissions, especially for cropping systems with intensive N inputs. Compared to the baseline, a decrease of N application rate by 15% reduced the annual N_2O emissions by 13.2%. DNDC also simulated a decrease of N_2O emissions by using nitrification inhibitor. The state total N_2O emission simulated under the NI scenario was reduced by 16.3% (Figure 15). Nitrification inhibitors can block or control conversion of NH_4^+ to NO_2^-, and subsequently to NO_3^-. This function helps to keep N in the NH_4^+ form for a longer time, enhance NH_4^+ uptake by crops, and mitigate N_2O emission from both nitrification and denitrification processes (Shoji et al., 2001; Wolt, 2004; Helena et al., 2012; Kleineidam et al., 2011). As a result, DNDC simulated a reduction in N_2O emission under NI. For the scenario of RN+NI, DNDC showed a reduction of 28.4% in N_2O emission, indicating that the strategy combing N rate reduction and application of nitrification inhibitors would effectively mitigate the N_2O emissions from California crop fields.

Compared to the tillage practices applied in the baseline, we did not notice obvious mitigation efficiencies for RT and NT during the three-year period of simulation. Reduced or no tillage only slightly reduced the statewide total N_2O emission by 2% and 3%, respectively (Figure 15).

Changing cover crop management is also a practice that can influence N_2O emissions substantially. Compared with the baseline, the simulated state total N_2O emission was reduced by 21.6% by planting non-leguminous cover crops if all other factors and management remain unchanged (Figure 15). The DNDC simulations indicated that the N_2O reduction by planting non-leguminous cover crops is primarily due to immobilization of soil residual N through N uptake by the cover crops, which would lead to a low availability of soil mineral N during winter rainy season in California.

Finally, irrigation practices substantially affected N_2O emissions, and the simulated N_2O emissions under low-water irrigations were generally lower than those receiving high-water irrigations. Compared to surface gravity irrigation, the N_2O emissions were reduced by 29% (5.24×10^3 vs. 7.41×10^3 MT N yr^{-1}), 55% (3.33×10^3 vs. 7.41×10^3 MT N yr^{-1}), and 68% (2.34×10^3 vs. 7.41×10^3 MT N yr^{-1}), respectively, by using sprinkler, surface, and subsurface drip irrigation. The DNDC results therefore showed a high potential in N_2O mitigation by using surface or subsurface drip irrigation with more frequent (once every two days vs. several times across a growing season) but lower water input (69% and 62% of the total irrigated water amount for surface or subsurface drip irrigation, respectively) in comparison with surface gravity irrigation. This conclusion is consistent with earlier studies (e.g., Aguilera et al., 2013; Sánchez-Martín et al., 2008), which reported mitigating effects of low-volume irrigation as compared to high-volume irrigation in Mediterranean cropping systems. By considering the N_2O emissions under actual irrigation management in 2012 as the baseline, we estimated that the potential of mitigating N_2O emissions by using surface or subsurface drip irrigation is 41% or 59%, respectively, although the potentials varied across different crop types (Table 4). Irrigation practices affected the N_2O emissions primarily through influencing soil water content and oxygen status. The model simulated relative higher N_2O emissions under practices of flood irrigation primarily because of transiently created near-water-saturation in soils after each irrigation event, which in combination with warm temperature during summer and relative high content of soil nitrate produced during periods without irrigation, could lead to optimal conditions for denitrification and N_2O production (Davidson and Verchot, 2000). On the contrary, lower N_2O emissions simulated under practices of low-volume irrigation (e.g., drip irrigation) were due to relatively drier soil conditions associated with low amount of water applied and limited water distribution in soil profiles (e.g., Kallenbach et al., 2010) in each irrigation event, which could restrict N_2O production through denitrification, a pathway favored by anaerobic conditions.

DNDC simulated not only N_2O fluxes but also the major pools and fluxes of C or N in agro-ecosystems, which include crop yield, methane (CH_4) and CO_2 fluxes. The modeled results provided an opportunity to assess the impacts of FMPs on the crop yields and a whole span of GHG emissions from California croplands. As Figure 16a illustrates, all the changes in FMPs under the alternative scenarios did not obviously affect the crop yields. Applying the practices with relative high N_2O mitigation efficiency (> 20% reduction) did not obviously increase the CO_2 and CH_4 emissions (Figure 16b and c). In addition, the simulated state total soil C sequestration was increased by 97% and the simulated total CH_4 emission was decreased by 14% for the scenario of planting non-leguminous cover crops (NLCC) if all other factors and management remain unchanged (Figure 16b and c). The DNDC simulations demonstrate that the mitigations of CO_2 and CH_4 emissions by planting non-leguminous cover crops were primarily due to C input by the cover crops, which led to increased soil carbon sequestration and CH_4 oxidation activity in uplands. By taking N_2O, CH_4, and soil C sequestration into considerations, planting non-leguminous cover crops showed the highest efficiency for mitigating the net GHG emissions from California croplands compared to the baseline (Figure 16d).

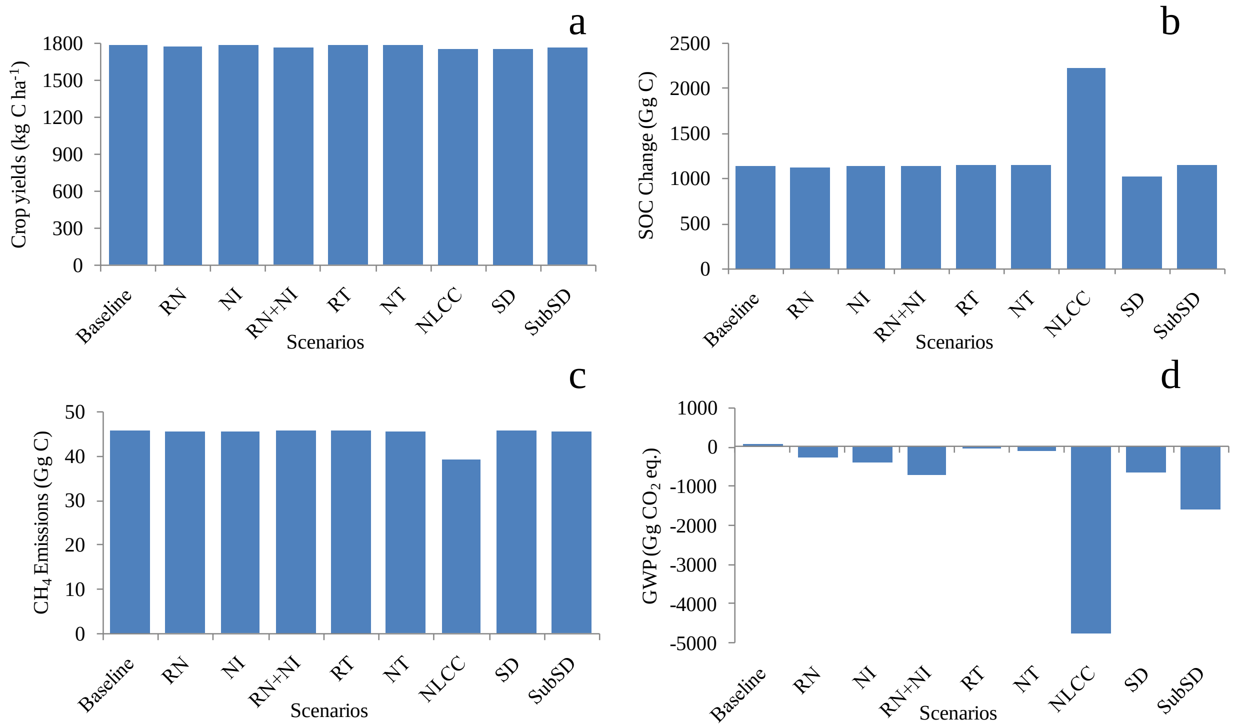

Figure 16. Simulated crop yields (a), soil organic carbon sequestrations (b), CH_4 emissions (c), and net emissions of greenhouse gases (d) from California croplands under the baseline and alternative scenarios. The crop yields in the panel (a) are area-weighted average values and emissions or sequestrations of GHG in the panels (b-d) are state total values with the unit of Gg (10^9 g) C or CO_2 equivalent.

In summary, we quantified impacts of FMPs on the N_2O emissions from California croplands, and the practices identified with relative high mitigation efficiency (> 20% reduction) included combining N rate reduction by 15% and application of nitrification inhibitors, planting non-leguminous cover crops, surface drip irrigation, and subsurface drip irrigation. In addition, these practices did not adversely affect the simulated crop yields and emissions of CO_2 and CH_4.

6. Technology Transfer of DNDC Modeling System to CARB

The project held a series of discussions and meetings with CARB staff regarding how to transfer the DNDC modeling system to CARB staff in a way that would make it relatively easy to make routine updates to the DNDC input data to facilitate statewide simulations. The traditional approach for regional modeling with DNDC is to use DNDC in regional mode where spatially explicit information on DNDC inputs are provided in tab-delimited text input files. It was decided that using the DNDC region mode as a basis to develop an easily-to-use tool as this is the easiest approach. Therefore, this task would focus on development of tools to make updating county scale regional mode inputs and post-processing outs easier.

To facilitate DNDC simulations using the county-scale California crops regional database, we created a tool that allows customization of the database, creates regional format input files, retrieves and converts DAYMET weather data, and processes simulation output files. Database enhancement is completed via a formatted Microsoft Excel spreadsheet (a commonly available and widely used format for day-to-day data storage). Data retrieval and processing is completed via python script-based tools.

We delivered the new DNDC system and related tool to CARB. For requesting the DNDC system and technical support, please contact Dr. Lei Guo at:

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6.1 Inputs Processing

The DNDC regional database format for simulating N_2O emissions from California croplands includes the following 10 input files:

- Site information
- Crop area
- Crop parameters
- Fertilization
- Flooding for wetland crops (i.e. rice)
- Irrigation
- Manure applications
- Plant and harvest dates
- Residue Management
- Tillage

In addition, regional simulations can be started using saved input data describing the parameters of the simulation with DNDC's .DRD format files (Appendix C). We have created a spreadsheet with a set of tables based on the input text files (Appendix D). These tables allow a user to make changes to any existing crop or aspect of crop management within any county by either searching or filtering the table of interest. In addition, we have included a table that allows a user to specify the overall parameters of a simulation including the duration (years), which counties and/or crops to include and/or not include, which irrigation method (either surface furrow, sprinkler, surface drip, and subsurface drip) to use for simulations, and how to simulate greenhouse gas emission flux (either methane, nitrous oxide, change of SOC) and irrigation (either with or without irrigation). All input parameters from 2000 to 2015 have been included in the spreadsheet (Appendix D), so that CARB staff can directly use these inputs to conduct the simulations from 2000 to 2015.

Once changes to the spreadsheet are made and saved, Python script-based tools will allow a user to create a new set of input and DRD files (Appendix E). These files can then be used to start a simulation via the DNDC GUI.

6.2 Outputs Processing

DNDC regional mode returns output files with annual per hectare results in native units (e.g. nitrous oxide emissions are returned in units of kg N ha^{-1} yr^{-1}) under different irrigation scenarios. For each county and each crop, the Python script-based tool calculates the baseline N_2O emissions under the actual distribution of irrigation management by weighting the results of the individual simulations under the four scenarios using the fraction of the corresponding irrigation methods for each type of crops (Appendix E). Post-processed results are returned in .CSV format to facilitate import into Microsoft Excel or other spreadsheet processing software for additional analyses.

7. Recommendations

Potential further improvements in the California specific modeling system would include modeling N_2O emissions from manure sources and improving the regional database to reduce the uncertainty of the simulations. We conducted DNDC simulations to quantify direct N_2O emissions from California croplands during 2000 to 2015. These results only represent direct N_2O emissions from fertilizer N uses and crop residues because we excluded croplands in dairy and organic farms from simulations. Based on the CARB inventory (CARB, 2016), approximately 0.25 Tg N was applied to California crop fields as managed manure in 2002 resulting in 1.08 Tg CO_2 equivalents $yr^{-1}$for direct N_2O emissions, although only about 6% of cropland were in dairy and organic farms. Therefore, livestock manure applied into croplands represents an important sector where N_2O emissions should be reliably quantified and mitigation efforts should be focused on. DNDC includes comprehensive biogeochemical processes simulating manure transformations and parameterizations of manure management practices (Li et al., 2012), has been improved to reflect manure application in California croplands, and can potentially quantify N_2O emissions and mitigation potential from managed manure. Additional studies are necessary to better constrain manure management activity for incorporating N from manure into the DNDC regional database, and the model needs to be tested against field data of N_2O emissions from manure in California. We also calculated uncertainties in the simulated baseline N_2O emissions as a range of 70% to 137% of the baseline value due to potential variability of soil properties based on the activity data in 2012. The uncertainty of the simulations could be reduced by improving the regional database through refining the database unit from the current county to sub-county scale with better specified combinations between cropping systems and soil properties.

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Glossary of Terms, Abbreviations, and Symbols

BD	Bulk density
C	Carbon
CARB	California air resources board
CDWR	California department of water resources
CH_4	Methane
CO_2	Carbon dioxide
CO_2 eq.	Carbon dioxide equivalents
DNDC	The denitrification decomposition model
DNF	Different nitrogen fertilization
DOC	Dissolved organic carbon
EF	Emission factor
FMPs	Farming management practices
G77	Reacted dicyandiamide and N-(n-butyl)-thiophosphoric triamide
Gg	Gigagram, 10^9 g
GHGs	Greenhouse gases
GIS	Geographic information system
ha	Hectare
GWP	Global warming potential
IPCC	Intergovernmental panel on climate change
kg	Kilogram, 10^3 g
Mg	Megagram, 10^6 g
MMT	Million metric ton
MT	Metric ton
n	Number
N	Nitrogen
N_2O	Nitrous oxide
NASS	National agricultural statistics service
NH_3	Aqua ammonia
NH_4^+	Ammonium
NI	Nitrification inhibitor
NLCC	Cultivation of non-leguminous cover crops
NO_2^-	Nitrite
NO_3^-	Nitrate
NT	No tillage
O	Observations
ppbv	Parts per billion by volume
R^2	Coefficient of determination
RMSE	Root mean square error
RN	Reduced nitrogen application
RN+NI	A combination of reduced nitrogen and applying nitrification inhibitor
RT	Reduced tillage
S	Simulations
SD	Surface drip
SE	Standard error
SOC	Soil organic carbon

SubSD	Subsurface drip
T	Treatment
Tg	Teragram, 10^{12} g
UAN	Urea ammonium-nitrate
UCD	University of California at Davis
USDA	United States Department of Agriculture
VMB	Vegetable, melon, and berries
yr	Year

Appendix A. Daily DNDC Model Validation Results

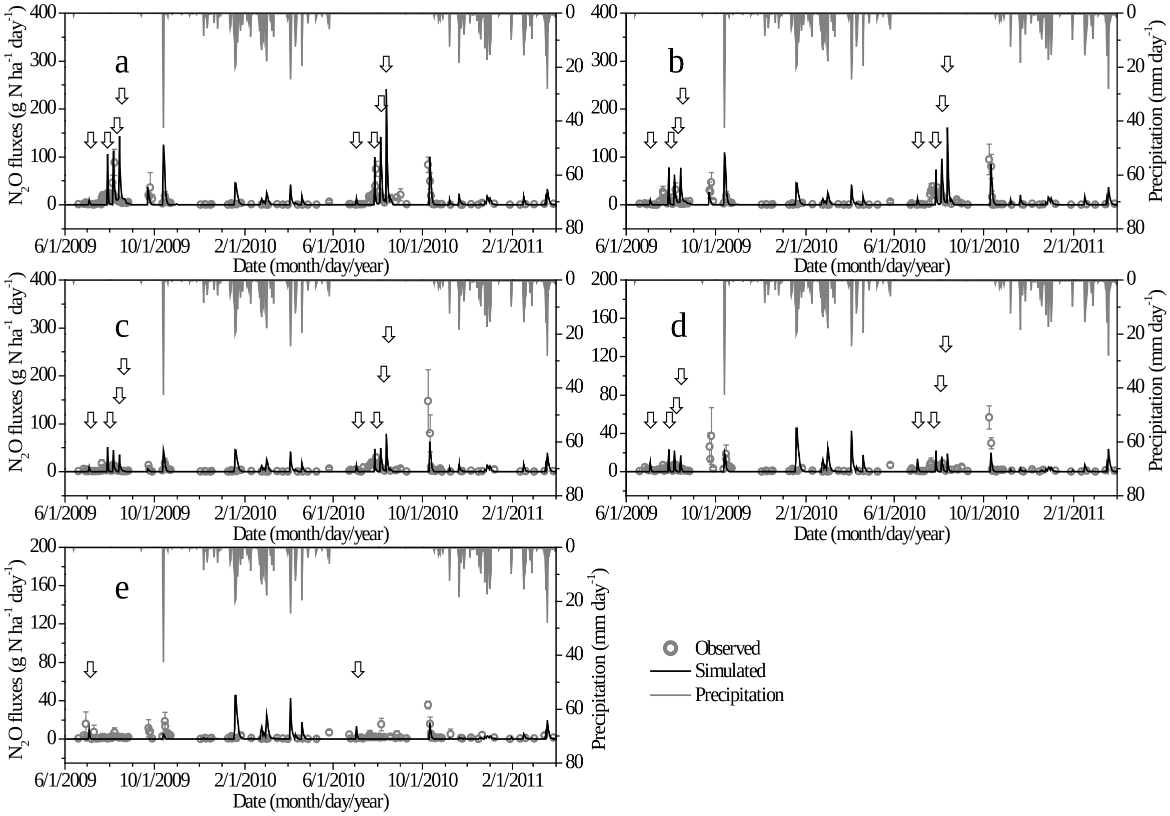

Figure A1. Precipitation, and simulated and measured daily N_2O fluxes from lettuce fields under different nitrogen fertilization. N fertilizers were applied in the fields at rates of (a) 336, (b) 252, (c) 168, (d) 84, and (e) 11 kg N ha^{-1} during each growing season. The arrows indicate the dates of fertigation events. The fields were irrigated many times with small amount of water each time by using drip irrigation systems, and the dates of irrigation events are not shown for the reason of clarity. The measurements are adopted from Burger and Horwath (2012) and are the means, and the vertical bars indicate standard errors of replicates (n = 4). Note that the vertical axis scales for N_2O fluxes in panels a to c are different with the scales in panels d and e.

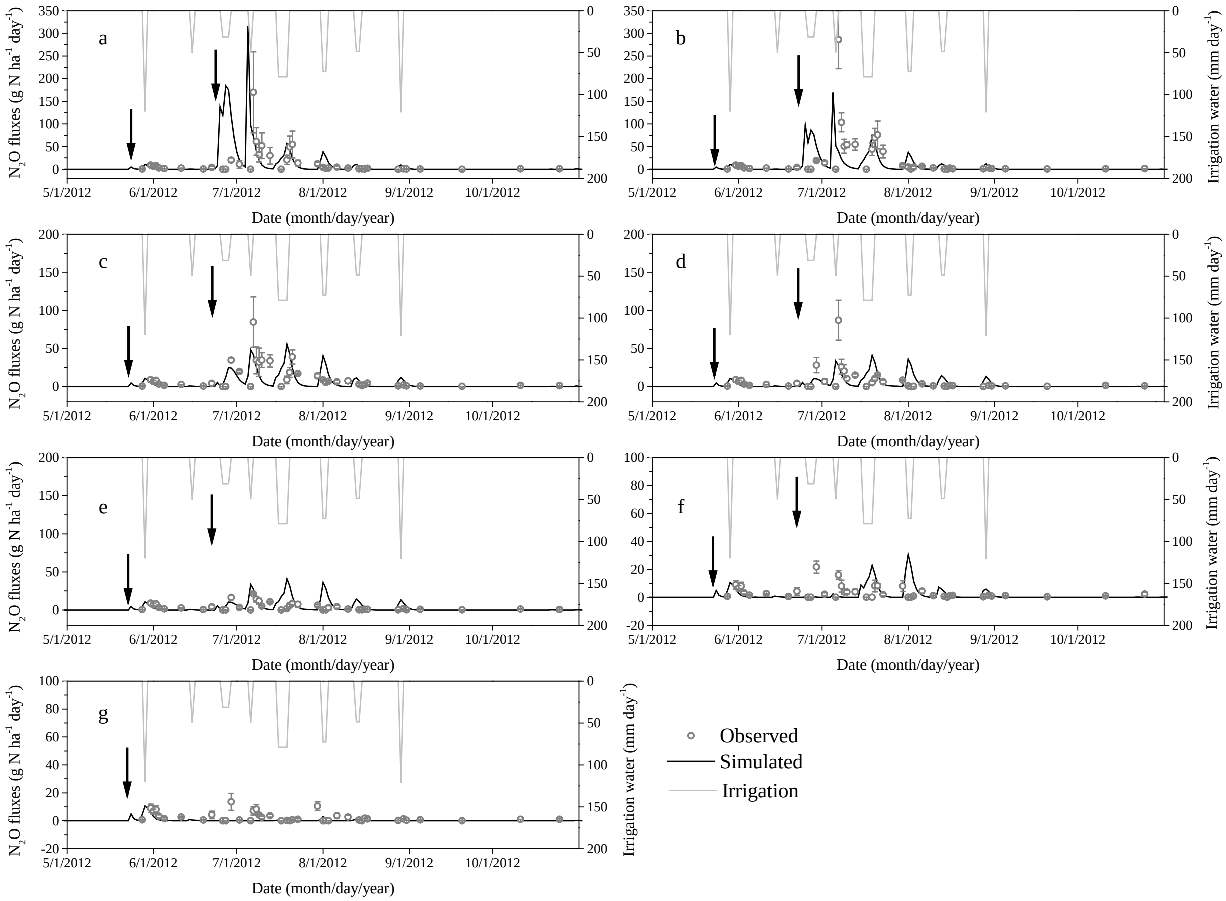

Figure A2. Irrigation, and simulated and measured daily N_2O fluxes from corn fields under different treatments. The treatments included different practices of nitrogen fertilization and nitrification inhibitor, with 222 (a; aqua ammonia + 8-24-6), 222 (b; aqua ammonia + 8-24-6 + the nitrification inhibitor G77), 222 (c; UAN + 8-24-6), 222 (d; UAN + 8-24-6 + G77), 222 (e; UAN + 8-24-6 + urease and nitrification inhibitor AgrotainPlus™), 222 (f; calcium nitrate + 8-24-6), and 20 (g; 8-24-6) kg N ha^{-1} applied during the wheat growing season. Details of the fertilization treatments were described by Burger et al., (2015).The measurements are the means, and the vertical bars indicate standard errors of replicates (n = 3). Note that the vertical axis scales for N_2O fluxes are different for different panels.

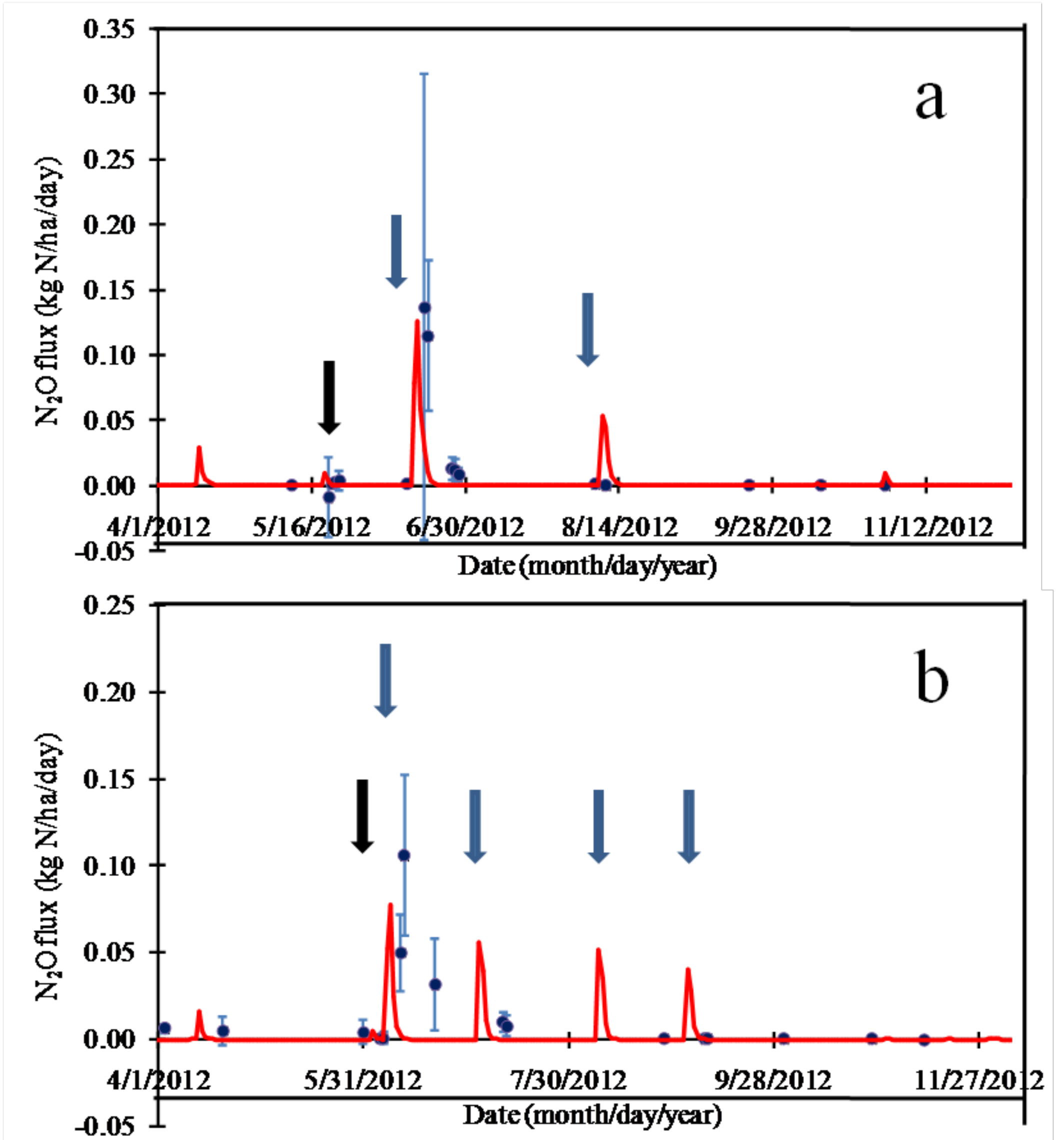

Figure A3. Measured and simulated daily N_2O fluxes from two cotton fields in the counties of Kings (a) and Fresno (b), respectively. The black arrows indicate the dates of fertilization. The blue arrows indicate the dates of irrigation. Both the model and field measurements demonstrate significant N_2O fluxes after the irrigation events, especially the first irrigation after fertilization.

Appendix B. Percentages of Different Irrigation Methods for the Simulated Crops

Category	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Surface gravity																
Alfalfa	0.81	0.80	0.80	0.80	0.79	0.79	0.79	0.78	0.78	0.77	0.77	0.77	0.76	0.76	0.76	0.75
Almonds	0.19	0.19	0.19	0.18	0.17	0.17	0.16	0.15	0.15	0.14	0.13	0.13	0.12	0.11	0.11	0.10
Apples	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.30
Apricots	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.30
Artichokes	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.18
Asparagus	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.18
Avocados	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.03
Barley	0.87	0.87	0.86	0.85	0.84	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76	0.75	0.74
Beets	0.99	1.00	0.98	0.97	0.95	0.94	0.92	0.90	0.89	0.87	0.85	0.84	0.82	0.81	0.79	0.72
Berries	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.72
Broccoli	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.77
Cabbage	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.18
Carrots	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.18
Cauliflower	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.18
Celery	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.18
Cherries	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.18
Cotton	0.94	0.94	0.92	0.89	0.87	0.85	0.82	0.80	0.78	0.75	0.73	0.71	0.68	0.66	0.64	0.18
Dates	0.10	0.10	0.10	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	0.03	0.03	0.30
Dry beans	0.57	0.57	0.58	0.59	0.60	0.61	0.62	0.63	0.64	0.65	0.66	0.68	0.69	0.70	0.71	0.03
Figs	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.74
Garlic	0.44	0.44	0.41	0.38	0.35	0.33	0.30	0.27	0.25	0.22	0.19	0.16	0.14	0.11	0.08	1.00
Grain corn	0.88	0.87	0.86	0.85	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76	0.75	0.75	0.61
Grapes	0.23	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.02
Green beans	0.57	0.57	0.58	0.59	0.60	0.61	0.62	0.63	0.64	0.65	0.66	0.68	0.69	0.70	0.71	0.03
Lemons	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.30
Lettuce	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.05

Melons	0.51	0.45	0.46	0.46	0.47	0.48	0.48	0.49	0.49	0.50	0.50	0.51	0.52	0.52	0.53	0.20
No legume hay	0.86	0.85	0.83	0.82	0.80	0.78	0.76	0.75	0.73	0.71	0.69	0.68	0.66	0.64	0.62	0.61
Oats	0.87	0.87	0.86	0.85	0.84	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76	0.75	0.03
Olives	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.18
Onions	0.44	0.44	0.41	0.38	0.35	0.33	0.30	0.27	0.25	0.22	0.19	0.16	0.14	0.11	0.08	0.53
Other citrus	0.10	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.30
Other fruits	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.74
Other nuts	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.03
Other vegetables	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.05
Peach	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.30
Pears	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.30
Peppers	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.18
Pistachios	0.19	0.19	0.19	0.18	0.17	0.17	0.16	0.15	0.15	0.14	0.13	0.13	0.12	0.11	0.11	0.10
Plums	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.30
Potatoes	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Prunes	0.34	0.34	0.33	0.33	0.33	0.33	0.32	0.32	0.32	0.32	0.31	0.31	0.31	0.31	0.30	0.30
Rice	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Safflowers	0.58	0.58	0.57	0.57	0.56	0.56	0.56	0.55	0.55	0.55	0.54	0.54	0.53	0.52	0.51	0.50
Silage corn	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.61
Sorghum	0.86	0.85	0.83	0.82	0.80	0.78	0.76	0.75	0.73	0.71	0.69	0.68	0.66	0.64	0.62	0.18
Spinach	0.38	0.36	0.35	0.33	0.32	0.31	0.30	0.28	0.27	0.26	0.24	0.23	0.22	0.20	0.19	0.53
Spring wheat	0.87	0.87	0.86	0.85	0.84	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76	0.75	0.61
Squash	0.46	0.45	0.46	0.46	0.47	0.48	0.48	0.49	0.49	0.50	0.50	0.51	0.52	0.52	0.53	0.02
Sunflowers	0.86	0.85	0.83	0.82	0.80	0.78	0.76	0.75	0.73	0.71	0.69	0.68	0.66	0.64	0.62	0.12
Sweet potatoes	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.18
Tomatoes	0.69	0.68	0.64	0.60	0.56	0.52	0.49	0.45	0.41	0.37	0.33	0.29	0.25	0.20	0.16	0.74
Winter wheat	0.87	0.87	0.86	0.85	0.84	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76	0.75	0.74
Sprinkler																

Alfalfa	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Almonds	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.15	0.15	0.15	0.16
Apples	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25
Apricots	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25
Artichokes	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42
Asparagus	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42
Avocados	0.13	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.16
Barley	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14
Beets	0.01	0.00	0.00	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.09
Berries	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.09
Broccoli	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.05
Cabbage	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42
Carrots	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42
Cauliflower	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42
Celery	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42
Cherries	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.42
Cotton	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.42
Dates	0.13	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.25
Dry beans	0.43	0.43	0.41	0.38	0.36	0.33	0.31	0.28	0.26	0.24	0.21	0.19	0.16	0.14	0.11	0.16
Figs	0.13	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.01
Garlic	0.56	0.56	0.54	0.52	0.51	0.49	0.47	0.45	0.43	0.41	0.39	0.37	0.35	0.33	0.31	0.00
Grain corn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.09
Grapes	0.09	0.09	0.08	0.07	0.07	0.06	0.05	0.04	0.04	0.03	0.02	0.02	0.01	0.00	0.00	0.17
Green beans	0.43	0.43	0.41	0.38	0.36	0.33	0.31	0.28	0.26	0.24	0.21	0.19	0.16	0.14	0.11	0.16
Lemons	0.13	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.25
Lettuce	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.30
Melons	0.21	0.24	0.22	0.21	0.19	0.18	0.16	0.15	0.13	0.12	0.11	0.09	0.08	0.06	0.05	0.00
No legume hay	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.16	0.16	0.16
Oats	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.16
Olives	0.13	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.42

Onions	0.56	0.56	0.54	0.52	0.51	0.49	0.47	0.45	0.43	0.41	0.39	0.37	0.35	0.33	0.31	0.03
Other citrus	0.13	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.16	0.16	0.25
Other fruits	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.14
Other nuts	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.16
Other vegetables	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.30
Peach	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25
Pears	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25
Peppers	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.42
Pistachios	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.15	0.15	0.15	0.16
Plums	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25
Potatoes	0.91	0.91	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.76
Prunes	0.32	0.31	0.30	0.30	0.30	0.29	0.29	0.28	0.28	0.28	0.27	0.27	0.26	0.26	0.25	0.25
Rice	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Safflowers	0.28	0.28	0.30	0.32	0.33	0.35	0.37	0.39	0.41	0.43	0.44	0.46	0.47	0.48	0.49	0.50
Silage corn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16
Sorghum	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.16	0.16	0.42
Spinach	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.42	0.03
Spring wheat	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.16
Squash	0.24	0.24	0.22	0.21	0.19	0.18	0.16	0.15	0.13	0.12	0.11	0.09	0.08	0.06	0.05	0.76
Sunflowers	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.16	0.16	0.00
Sweet potatoes	0.91	0.91	0.90	0.89	0.88	0.87	0.86	0.84	0.83	0.82	0.81	0.80	0.79	0.78	0.77	0.42
Tomatoes	0.29	0.30	0.27	0.24	0.21	0.18	0.16	0.13	0.10	0.07	0.04	0.01	0.00	0.00	0.00	0.14
Winter wheat	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14
Drip																
Alfalfa	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.07
Almonds	0.69	0.69	0.70	0.70	0.71	0.71	0.71	0.72	0.72	0.72	0.73	0.73	0.73	0.74	0.74	0.74
Apples	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.45
Apricots	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.45
Artichokes	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40

Asparagus	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
Avocados	0.77	0.77	0.78	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.80	0.80	0.80	0.80	0.80	0.81
Barley	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.11	0.11
Beets	0.00	0.00	0.01	0.03	0.04	0.05	0.06	0.08	0.09	0.10	0.12	0.13	0.14	0.15	0.17	0.19
Berries	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.19
Broccoli	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.18
Cabbage	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
Carrots	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
Cauliflower	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
Celery	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
Cherries	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.40
Cotton	0.01	0.01	0.03	0.05	0.07	0.09	0.11	0.13	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.40
Dates	0.77	0.77	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.80	0.80	0.80	0.80	0.81	0.81	0.45
Dry beans	0.00	0.00	0.01	0.03	0.04	0.06	0.07	0.08	0.10	0.11	0.12	0.14	0.15	0.17	0.18	0.81
Figs	0.77	0.77	0.78	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.80	0.80	0.80	0.80	0.80	0.25
Garlic	0.00	0.00	0.05	0.09	0.14	0.19	0.23	0.28	0.33	0.37	0.42	0.46	0.51	0.56	0.60	0.00
Grain corn	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.22	0.23	0.24	0.30
Grapes	0.68	0.70	0.71	0.72	0.73	0.74	0.74	0.75	0.76	0.77	0.77	0.78	0.79	0.80	0.80	0.81
Green beans	0.00	0.00	0.01	0.03	0.04	0.06	0.07	0.08	0.10	0.11	0.12	0.14	0.15	0.17	0.18	0.81
Lemons	0.77	0.77	0.78	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.80	0.80	0.80	0.80	0.80	0.45
Lettuce	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.65
Melons	0.28	0.31	0.32	0.33	0.34	0.35	0.35	0.36	0.37	0.38	0.39	0.40	0.41	0.42	0.42	0.80
No legume hay	0.02	0.02	0.04	0.05	0.07	0.08	0.10	0.11	0.13	0.14	0.16	0.17	0.19	0.20	0.22	0.23
Oats	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.11	0.81
Olives	0.77	0.77	0.78	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.80	0.80	0.80	0.80	0.80	0.40
Onions	0.00	0.00	0.05	0.09	0.14	0.19	0.23	0.28	0.33	0.37	0.42	0.46	0.51	0.56	0.60	0.43
Other citrus	0.77	0.77	0.78	0.78	0.78	0.78	0.79	0.79	0.79	0.79	0.80	0.80	0.80	0.80	0.80	0.45
Other fruits	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.11
Other nuts	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.81

Other vegetables	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.65
Peach	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.45
Pears	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.45
Peppers	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40
Pistachios	0.69	0.69	0.70	0.70	0.71	0.71	0.71	0.72	0.72	0.72	0.73	0.73	0.73	0.74	0.74	0.74
Plums	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.45
Potatoes	0.08	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.22
Prunes	0.34	0.35	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.41	0.41	0.42	0.43	0.44	0.44	0.45
Rice	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Safflowers	0.15	0.15	0.13	0.12	0.10	0.09	0.07	0.06	0.04	0.03	0.01	0.00	0.00	0.00	0.00	0.00
Silage corn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23
Sorghum	0.02	0.02	0.04	0.05	0.07	0.08	0.10	0.11	0.13	0.14	0.16	0.17	0.19	0.20	0.22	0.40
Spinach	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.43
Spring wheat	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.11	0.23
Squash	0.30	0.31	0.32	0.33	0.34	0.35	0.35	0.36	0.37	0.38	0.39	0.40	0.41	0.42	0.42	0.22
Sunflowers	0.02	0.02	0.04	0.05	0.07	0.08	0.10	0.11	0.13	0.14	0.16	0.17	0.19	0.20	0.22	0.88
Sweet potatoes	0.08	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.40
Tomatoes	0.02	0.02	0.09	0.16	0.22	0.29	0.36	0.43	0.50	0.56	0.63	0.70	0.75	0.80	0.84	0.11
Winter wheat	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.11	0.11

Note: Data were summarized from the studies by Orang et al. (2008) and Tindula et al. (2013) for the years of 2001 and 2010 (available at CDWR, (2016b)). For other years without the survey data, the fractions of irrigation methods were determined by linear interpolation (2001-2009) or extrapolation (2011-2015) of the survey data. The data showed a trend of increasing in low-volume (drip and subsurface drip) irrigation and decreasing in surface irrigation in all investigated crop types between 2000 and 2015.

Appendix C. An Example of a '.DRD' File for Conducting DNDC Regional Simulations

```
CA
C:\DNDC\Database\California\GIS\CA_ClimateSoil.txt
n2o-2015-furrow
0
2 0 3 2013
1
58 58 1
0

3

370.000000 0.000000 1.000000
1.000000 1.000000 1.000000
1 0 0
1.000000 1.000000 1.000000
1.000000 1.000000 0.000000 0.000000 0.000000
1 0 0 0 0

370.000000 0.000000 1.000000
1.000000 1.000000 1.000000
1 0 0
1.000000 1.000000 1.000000
1.000000 1.000000 0.000000 0.000000 0.000000
1 0 0 0 0

370.000000 0.000000 1.000000
1.000000 1.000000 1.000000
1 0 0
1.000000 1.000000 1.000000
1.000000 1.000000 0.000000 0.000000 0.000000
1 0 0 0 0
```

Appendix D. A Spreadsheet Including Input Data for Simulating N_2O Emissions from California Croplands

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	*1=yes, simulate this unit, 0=no, do not simulate this county*	*county ID*	*county name*	*county FIPS code*	*Latitude (decimal degrees)*	*Longitude (decimal degrees)*	*nitrogen deposition (mg/L)*	*soil organic carbon fraction, maximum value for county*	*soil organic carbon fraction, minimum value for county*	*clay fraction, maximum value for county*	*clay fraction, minimum value for county*	*pH, maximum value for county*	*pH, minimum value for county*	*bulk density (g/cm3), maximum value for county*	*bulk density (g/cm3), minimum value for county*
2	simulate	county_id	county	FIPS	lat	lon	N dep.	SOC max	SOC min	clay max	clay min	pH max	pH min	dens. max	dens. min
3	1	1	Alameda	6001	37.69	-121.75	0.98	0.010	0.010	0.28	0.28	6.45	6.45	1.38	1.38
4	1	2	Alpine	6003	38.78	-119.77	0.20	0.019	0.019	0.14	0.14	6.47	6.47	1.34	1.34
5	1	3	Amador	6005	38.41	-120.88	0.98	0.010	0.010	0.15	0.15	6.12	6.12	1.53	1.53
6	1	4	Butte	6007	39.55	-121.81	0.24	0.016	0.016	0.37	0.37	5.28	5.28	1.35	1.35
7	1	5	Calaveras	6009	38.16	-120.67	0.42	0.005	0.005	0.13	0.13	6.37	6.37	1.47	1.47
8	1	6	Colusa	6011	39.16	-122.07	0.98	0.011	0.011	0.30	0.30	6.60	6.60	1.44	1.44
9	1	7	Contra-Costa	6013	37.94	-121.66	0.98	0.008	0.008	0.33	0.33	7.06	7.06	1.46	1.46
10	1	8	Del-Norte	6015	41.88	-124.16	0.38	0.069	0.069	0.24	0.24	5.12	5.12	1.08	1.08
11	1	9	El-Dorado	6017	38.73	-120.91	0.98	0.012	0.012	0.17	0.17	6.05	6.05	1.38	1.38
12	1	10	Fresno	6019	36.57	-120.11	0.23	0.006	0.006	0.24	0.24	7.15	7.15	1.48	1.48
13	1	11	Glenn	6021	39.58	-122.12	0.98	0.009	0.009	0.30	0.30	6.27	6.27	1.45	1.45
14	1	12	Humboldt	6023	40.66	-124.17	0.21	0.023	0.023	0.23	0.23	6.13	6.13	1.46	1.46
15	1	13	Imperial	6025	32.94	-115.45	0.57	0.003	0.003	0.32	0.32	8.09	8.09	1.50	1.50
16	1	14	Inyo	6027	37.16	-118.30	0.47	0.009	0.009	0.12	0.12	6.76	6.76	1.47	1.47
17	1	15	Kern	6029	35.43	-119.29	0.47	0.003	0.003	0.19	0.19	7.33	7.33	1.52	1.52
18	1	16	Kings	6031	36.13	-119.76	0.47	0.006	0.006	0.18	0.18	7.57	7.57	1.52	1.52
19	1	17	Lake	6033	38.99	-122.79	0.21	0.011	0.011	0.22	0.22	6.42	6.42	1.49	1.49

counties | crop_systems | crops | crop_area | irrigation_fraction | crop_parameters | cropping | tillage | fertilizer | organic_amendment | flooding | irrigation_event

Appendix E. An Example of Using Python Script-based Tools to Create DNDC Input Files and Post-process Simulations

Administrator: Command Prompt

```
C:\DNDC>CD project

C:\DNDC\project>python inputs.py

SIMULATION PARAMETERS:
    path_xlsx        : C:\DNDC\project\database.xlsx
    path             : C:\DNDC\
    database_name    : California
    database_prefix  : CA
    major_concern    : n2o
    year             : 2015
    years            : 3


read-in database
"ClimateSoil" table
"CropParameter" table
all other management tables
irrigation fraction CSV
DRD files

C:\DNDC\project>
```

Administrator: Command Prompt

```
C:\DNDC\project>python results.py

SIMULATION PARAMETERS:
    path             : C:\DNDC\
    database_name    : California
    database_prefix  : CA
    major_concern    : n2o
    year             : 2015
    years            : 3


read-in irrigation fraction
extract raw results
weight results by irrigated fractions
write weighted results

C:\DNDC\project>
```