Final Report

for Project

Calibrating, Validating, and Implementing Process Models for California Agriculture Greenhouse Gas Emissions

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Project PI

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ABSTRACT

The goal of the project is to build up a modeling tool to quantify soil greenhouse gases emitted from agricultural production in California under current climate, soil and management conditions.

To approach the goal, we conducted (1) field data collection and analysis, (2) model calibration, validation and comparison tests, (3) regional simulation and (4) tools to help ARB update crop acreages, management practices and other DNDC inputs on an annual basis. As nitrous oxide (N_2O) is the major greenhouse gas for CA agricultural production, the above listed activities were implemented with a focus on N_2O emissions.

The field measurements were conducted for quantifying N_2O fluxes from 10 agricultural sites in CA by groups led by Drs. Dave Smart, Johan Six, Cynthia Kallenbach and William Horwath. The crops planted at the sites included grapes, almond, tomato, alfalfa, winter wheat and other row crops planted, which well represented the major crop types across the agricultural regions in CA. At each of the sites, alternative farming practices were applied, which included different crop rotation sequences, standard tillage vs. reduced till, furrow irrigation vs. drip irrigation, different rates of fertilizer application, with vs. without winter cover crop etc. N_2O fluxes were measured at the sites with static chambers during the time period from 2003-2011. The final results consisted of 40 datasets at the field-year basis. The measured 40 datasets of daily N_2O fluxes were provided to serve model tests.

The Denitrification-Decomposition or DNDC model was adopted as a core model in the project. Calibrations were conducted for the crop parameters of DNDC to ensure the model was able to correctly simulate the crop growth and yields that are crucial for correctly modeling soil water and N dynamics for the tested fields. With the calibrated crop parameters, DNDC simulated all the 40 measured datasets. The modeled N_2O fluxes were compared with observations for all the 40 datasets. Results from the comparisons indicated that the correlation between the modeled and measured N_2O fluxes was high ($p<0.01$) upon annual basis.

To further confirm the applicability of DNDC for the CA agricultural N_2O emissions, DNDC was compared with another two well documented and widely applied models, DAYCENT and IPCC Approach, based on their performances against a same group of N_2O datasets measured in CA. Due to the limited capacity of DAYCENT for modeling perennial crops and drip irrigation (personal communication from Juhwan Lee who has long-term experience working with DAYCENT and was in charge of the DAYCENT implementation in the project), only 25 of the 40 datasets provided by the field researchers could be simulated by DAYCENT and hence served the model comparison. DNDC and DAYCENT were compared based on their simulated daily and annual N_2O fluxes. The comparisons on the daily basis were conducted by integrating the DNDC- and DAYCENT-modeled daily N_2O fluxes into a same chart without statistical calculations for each case. The lack of statistical results was due to the scarcity of the field data as well as the timing lags between the measured and modeled N_2O emission episodes that has

inhibited utilization of most popular statistical tools. On the annual basis, under the exponential and linear interpolation methods, the performances of both DNDC and DAYCENT were better than that of IPCC approach. Under the exponential interpolation method, the correlation between the measured and the DNDC-modeled annual/seasonal N_2O emissions is very significant (R^2=0.80, slope=0.97 and p=0.001); the correlation between the measured and the DAYCENT-modeled annual/seasonal N_2O emissions is not significant (R^2=0.005, slope=0.10). Under the linear interpolation method, the correlation between the measured and the DNDC- or DAYCENT-modeled annual/seasonal N_2O emissions is low (DNDC: R^2=0.21; DAYCENT: R^2=0.25).

Regional simulation of emissions from fertilizer use was conducted by linking DNDC to a GIS database which held all the input information of weather, soil, crop type and farming management practices for all the 3,806,481 hectares of cropland in 58 counties in CA. DNDC simulates not only N_2O fluxes but also the major pools and fluxes of C or N in agroecosystems, which include methane (CH_4) and carbon dioxide (CO_2) fluxes. The modeled results provided an opportunity to assess a whole span of greenhouse gas (GHG) emissions from the agricultural lands in CA. In addition, DNDC quantifies uncertainty of the modeled GHG fluxes based on the uncertainties in combination of cropping systems and soil properties at county scale. The GHG fluxes reported in this report are presented as a median with a variation range.

The modeled annual emissions of N_2O, CH_4 and CO_2 from CA were 0.0072 ± 0.0041Tg N, 0.066 ± 0.048 Tg C and -1.58 ± 2.58 Tg C, respectively (1 Tg = $1x10^{12}$ g or 1 million metric tons). The global warming potentials (GWPs) of the N_2O, CH_4 and CO_2 emissions from CA were 3.49 ± 2.02, 2.19 ± 1.59 and -5.79 ± 9.46 Tg CO_2 equivalent yr^{-1}, respectively with a sum of -0.113 ± 10.39 Tg CO_2 equivalent yr^{-1}. The modeled N_2O emission (3.49 ± 2.02 Tg CO_2 equivalent yr^{-1}) is comparable with the 2011 N_2O emission from chemical fertilizer use (3.66 Tg carbon dioxide equivalent yr^{-1}) formerly reported by CA Air Resource Board (ARB).

The modeled results indicate that (1) N_2O is the leading GHG from the CA agricultural soils, (2) CH_4 emitted from CA rice production also makes non-negligible contribution to the warming effect, (3) the CA agricultural soils seem sequestering C although the magnitude is highly uncertain (± 9.46 Tg CO_2 equivalent yr^{-1}), and (4) the entire CA agriculture seems close to a neutral status regarding its contribution to global warming (-0.113 Tg CO_2 equivalent yr^{-1}) although the uncertainty is large (± 10.39 Tg CO_2 equivalent yr^{-1}). The uncertainty could be reduced if the spatial databases can be improved by refining the simulated unit from the current county to sub-county scale with better specified combinations between cropping systems and soil properties. The modeled results indicate that the major N_2O emitter crops are cotton (14%), corn 14%), rice (13%); the CH_4 emitter is solely rice; the major CO_2 emitters are cotton (37%), tomato (21%) and pasture (10%); and the major CO_2 sequestering crops are alfalfa (44%), grape (25%) and corn (15%).

Another major product from the project is a modeling tool package including the latest version of DNDC which has been calibrated and validated with the CA-measured N_2O data, the updated CA agricultural database which provides input information of weather, soil, crop type and acreage, and farming management practices to support the model application at site or regional scale. The tool possesses the standard interface of DNDC that allow users to easily conduct site or regional simulations for inventory or mitigation studies. The modeling package includes spreadsheet tools and scripts for easy updating of crop acreages, management and daily weather inputs on a regular basis for annual updates of statewide emission estimates.

EXECUTIVE SUMMARY

Background: The California Global Warming Solutions Act of 2006 has legislated GHG emission reductions such that 2020 emission levels are at or below 1990 levels. Mandatory GHG emission reductions are now set in law for the first time in the US. In response to this Act, a Climate Action Team (CAT) was created to identify Discrete Early Actions to reduce emissions and meet the 2020 targets. The 2006 CAT report identified the use of cover crops and conservation tillage as strategies for sequestering soil carbon in California croplands. A challenge with the development of GHG emission reduction policies, particularly market-based policies, is the need to accurately and transparently conduct full GHG accounting to quantify net emission reductions, especially given the strong linkage between soil carbon content and trace gas emissions (e.g., nitrous oxide and methane). In addition, California is now exploring the development of various GHG emission reduction strategies including the potential use of market-based mechanisms to create incentives for producers to adopt voluntary GHG emission practices.

The 2007 California Census of Agriculture reported 3,806,481 hectares of croplands in the state, with 3,243,964 hectares irrigated and 3, 088, 978 hectares of it harvested (USDA, 2009). California agriculture emits methane (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 (1 Tg = $1x10^{12}$ g or 1 million metric tons) carbon dioxide equivalent (CO_2 eq.) of GHG emissions, which is approximately 7% of the state's total emissions (California Air Resources Board, 2013). N_2O and CH_4 accounted for significant fraction of emissions. Application of chemical fertilizers and manure to agricultural soils were the dominant source of N_2O (6.44 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). These emission inventories were developed using emission factor approaches as specified in IPCC guidelines, with some California specific emission factors.

The legislation passed in California creates a clear need for a system that identifies and quantifies agricultural carbon sequestration and greenhouse gas mitigation opportunities. A tool which is capable of quantifying carbon sequestration and N_2O and CH4 emissions is crucially important for fulfilling the mitigation tasks. This project was to take a step towards this direction.

Methods and Results: Forty datasets of measured daily N_2O fluxes were provided by Dave Smart, Johan Six, Cynthia Kallenbach and William Horwath of UC-Davis. The datasets covered a wide range of crop types in California, including vineyard, almond, tomato, wheat, corn, sunflower, beans, alfalfa and cover crops. The field data also covered routine and alternative farming management practices utilized in CA. The field data were utilized to calibrate and then independently validate the process-based biogeochemistry model, Denitrification-Decomposition or DNDC. The calibration was performed to set the model input crop parameters for varieties grown in California to ensure that the modeled crop growth had correct effects on the soil climate and carbon (C) and nitrogen (N) dynamics. No internal parameters in DNDC were calibrated leaving the biogeochemical processes embedded in DNDC unchanged. This is critically important for independent validations across different climatic zones, soil types and management regimes for a target domain. The modeled N_2O fluxes for the 40 datasets were compared against measured data at annual basis with encouraging results. The correlation between the measured and DNDC-modeled annual/seasonal N_2O emissions was very significant with $p<0.01$ ($R^2=0.80$, slope=0.97, p=0.001). Table A and Figure A show measured and modeled annual/seasonal N_2O fluxes for the 40 tested datasets. It is important to note that the estimate of measured annual/seasonal N_2O flux was derived based on extrapolation of a set of daily measured fluxes by interpolating between measurements. As a method traditionally utilized in DNDC studies, the exponential interpolation approach was adopted in the project to convert the measured discontinuous daily N_2O fluxes to annual/seasonal total N_2O emission. However, in the study, we also applied another option, the linear interpolation method, for comparison. The results from the two interpolating methods are all shown in this report.

Table A. Comparison of DNDC-modeled annual/seasonal N_2O fluxes (g N ha^{-1}) with measured N_2O fluxes (g N ha^{-1}) for 40 site-year datasets from agricultural fields in California (Field data from Dave Smart, Johan Six, Cynthia Kallenbach and William Horwath)

Data source	Land-use	Year	Location/treatment	Modeled N2O flux	Measured N2O flux (mean)	Measured N2O flux (STD)
Dave Smart	Vineyard	2009	Drip area	115	145	44
		2010	Drip area	243	199	116
		2009	Alley area	85	113	21
		2010	Alley area	368	101	13
Johan Six	Almond	2010	Tree row	271	297	40
		2010	Tractor row	89	116	35
Johan Six	Tomato (Field-10)	2010	Berm	183	240	20
		2010	Furrow	296	309	146
Johan Six	Tomato (Field-31)	2010	Berm	183	371	162
		2010	Furrow	734	940	280
Johan Six	Wheat (Field 74)	2003	Standard till	98	148	57
	Corn	2004	Standard till	920	1056	525
	Sunflower	2005	Standard till	324	305	235
	Beans	2006	Standard till	279	181	106
	Wheat	2003	Reduced till	105	214	112
	Corn	2004	Reduced till	1054	1496	928
	Sunflower	2005	Reduced till	413	351	254
	Beans	2006	Reduced till	487	412	180
Johan Six	Vineyrad	2009	Vine	113	140	13
		2010	Vine	222	203	150
		2009	Row	1294	1150	323
		2010	Row	435	594	377
Synthia Kallenbach	Tomato/cover crop	2006	DI-NCC	295	359	217
		2006	DI-WLCC	1461	1298	670
		2006	FI-NCC	1310	1714	1381
		2006	FI-WLCC	1216	665	512
William Horwath	Alfalfa	2010	5-year old	2760	253	63
		2011	5-year old	5490	5304	1374
		2010	1-year old	567	429	113
		2011	1-year old	1579	1437	293
William Horwath	Winter wheat	2010	0 kg N/ha (fertilizer rate)	1	27	
		2011	0 kg N/ha (fertilizer rate)	100	189	31
		2010	91 kg N/ha	44	17	
		2011	91 kg N/ha	348	347	72
		2010	151 kg N/ha	76	28	
		2011	151 kg N/ha	528	426	95
		2010	203 kg N/ha	98	175	
		2011	203 kg N/ha	705	881	265
		2010	254 kg N/ha	1677	1876	
		2011	254 kg N/ha	1282	724	

Statistical results: R^2=0.80, slope=0.97, p=0.001

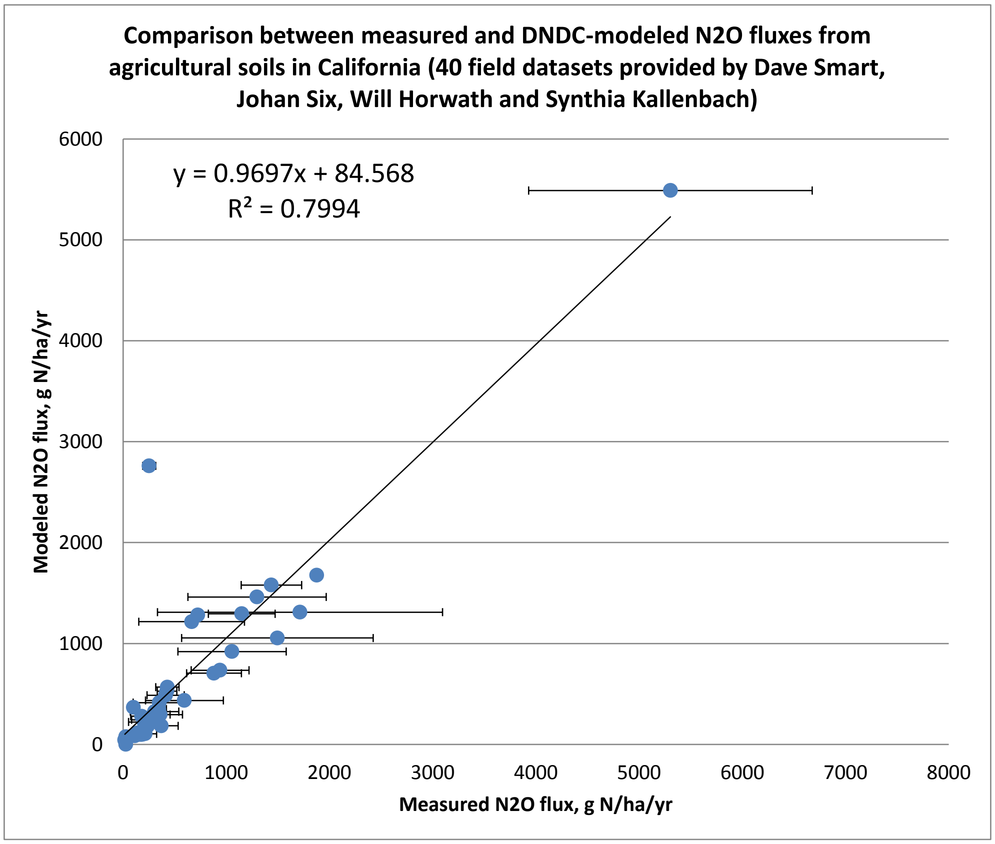

Figure A. Comparison between DNDC-modeled and measured annual or seasonal N_2O fluxes for 40 site-year datasets from agricultural fields in California (R^2=0.80, slope=0.97, p=0.001)

In addition, to further confirm the applicability of DNDC for the CA agricultural N_2O emissions, DNDC was compared with another two well documented and widely applied models, DAYCENT and IPCC Approach, based on their performances against a same group of N_2O datasets measured in CA. Due to the limited capacity of DAYCENT for modeling perennial crops and drip irrigation (pers comm. Juhwan Lee who has long-term experience in working with DAYCENT and was in charge of the DAYCENT implementations in the project), only 25 of the 40 datasets provided by the field researchers were utilized to serve the model comparison. DNDC and DAYCENT were compared based on their simulated daily and annual N_2O fluxes. The comparisons on the daily basis were conducted by integrating the DNDC- and DAYCENT-modeled daily N_2O fluxes into a same chart without statistical calculations for each case. The lack of statistical results was due to the scarcity of the field data as well as the timing lags between the measured and modeled N_2O emission episodes that has inhibited utilization of most popular statistical tools. On the annual basis, under the exponential and linear interpolation methods, the performances of both DNDC and DAYCENT were better than that of IPCC approach. Under the exponential interpolation method, the correlation between the measured and the DNDC-modeled annual/seasonal N_2O emissions is very significant (R^2=0.80, slope=0.97 and p=0.001); the correlation between the measured and the DAYCENT-modeled annual/seasonal N_2O emissions is not significant (R^2=0.005, slope=0.10 and p=0.74). Under the linear interpolation method, the correlation between the measured and the DNDC- or DAYCENT-modeled annual/seasonal N_2O emissions is poor (DNDC: R^2=0.21, slope=0.31; DAYCENT: R^2=0.25, slope=0.43).

Based on the model comparison, DNDC appeared capable of modeling all the cropping systems with various farming management practices with statistically acceptable results, the model was applied for estimation of N_2O inventory for CA agricultural production.

Regional simulation was conducted by linking DNDC to a GIS database which held all the input information of weather, soil, crop type and farming management practices for all the 3,806,481 hectares of cropland in 58 counties in CA. DNDC simulates not only N_2O fluxes but also the major pools and fluxes of C or N in agroecosystems, which include methane (CH_4) and carbon dioxide (CO_2) fluxes. The modeled results provided an opportunity to assess a whole span of greenhouse gas (GHG) emissions from the agricultural lands in CA. In addition, DNDC quantifies uncertainty of the modeled GHG fluxes based on the uncertainties in combination of cropping systems and soil properties at county scale. The GHG fluxes reported in this report are presented as a median with a variation range.

The modeled annual emissions of N_2O, CH_4 and CO_2 from CA were 0.0072 ± 0.0041Tg N, 0.066 ± 0.048 Tg C and -1.58 ± 2.58 Tg C, respectively (1 Tg = $1x10^{12}$ g or 1 million metric tons). The global warming potentials (GWPs) of the N_2O, CH_4 and CO_2 emissions from CA were 3.49 ± 2.02, 2.19 ± 1.59 and -5.79 ± 9.46 Tg CO_2 equivalent yr^{-1}, respectively with a sum of -0.113 ± 10.39 Tg CO_2 equivalent yr^{-1} (Table B). The modeled N_2O emission from chemical fertilizers (3.49 ± 2.02 Tg CO_2 equivalent yr^{-1}) is comparable with the 2011 N_2O emission (3.66 Tg carbon dioxide equivalent yr^{-1}) formerly reported by CA Air Resource Board (ARB).

The modeled results indicate that (1) N_2O is the leading GHG from the CA agricultural soils, (2) CH_4 emitted from CA rice production also makes non-negligible contribution to the warming effect, (3) the CA agricultural soils seem sequestering C although the magnitude is highly uncertain (± 9.46 Tg CO_2 equivalent yr^{-1}), and (4) the entire CA agriculture seems close to a neutral status regarding its contribution to global warming (-0.113 Tg CO_2 equivalent yr^{-1}) although the uncertainty is large (± 10.39 Tg CO_2 equivalent yr^{-1}). The uncertainty could be reduced if the spatial databases can be improved by refining the simulated unit from the current county to sub-county scale with better specified combinations between cropping systems and soil properties. The modeled results indicate that the major N_2O emitter crops are cotton (14%), corn 14%), rice (13%); the CH_4 emitter is solely rice; the major CO_2 emitters are cotton (37%), tomato (21%) and pasture (10%); and the major CO_2 sequestering crops are alfalfa (44%), grape (25%) and corn (15%).

Table B. DNDC-modeled annual greenhouse gas emissions from agricultural soils in California (Unit: Tg = 10^{12} g or million metric tons)

Greenhouse gas	N_2O	CH_4	CO_2*	Sum
Total emission	0.0072 ± 0.0041 Tg N	0.066 ± 0.048 Tg C	-1.58 ± 2.58 Tg C	
GWP** (Tg CO_2 equivalent yr^{-1})	3.49 ± 2.02	2.19 ± 1.59	-5.79 ± 9.46	-0.113 ± 10.39
Major contributors	Major emitter: cotton (14%), corn 14%), rice (13%)	Major emitter: rice 100%	Major emitters: cotton (37%), tomato (21%), pasture (10%); Major sequesters: alfalfa (44%), grape (25%), corn (15%)	

* Net CO_2 emission, equal to annual change in soil organic carbon (SOC) storage;

** GWP stands for global warming potential expressed as CO_2 equivalent.

Conclusions: Through the thorough comparison of DNDC with not only field observations but also other well-established models, DNDC performed well with acceptable validation results. The regional N_2O emission modeled with DNDC is also in line with results reported by other sources. The key take home messages from this study are (1) DNDC possesses a mechanism to calibrate crop parameters that enable the model to simulate the broad range of crops (annuals and perennials) and cropping systems in CA with acceptable results of yield and GHG fluxes; (2) the biogeochemical processes embedded in DNDC, which were unchanged during the validation across all the 40 dataset cases, were shown to have a sound basis in soil biogeochemistry and well suited for modeling GHG emissions from California agricultural soils; and (3) requirements for updating spatial databases for input to DNDC can be easily established to handle all the spatially differentiated input information to drive the model to fulfill regional simulations. In short, DNDC could be used to improve upon simple emission factor approaches to capture the wide range in emissions from the diverse cropping systems in California to support inventory and mitigation studies for the state.

Future Work: The extensive validation work presented in this report focused on model performance in estimating the magnitude of N_2O emissions. Additional validation work is needed to improve our understanding of model performance for simulating changes in emissions associated with a practice change. The DNDC modeling toolset can also be used to assess the impact of future scenarios of climate or management regimes on statewide crop yields and N_2O emissions and N_2O mitigation potential under current and future climate change conditions. Given the importance of the livestock sector on agricultural greenhouse gas emissions, the DNDC modeling could be expanded to include the livestock sector by using Manure-DNDC.

1. **INTRODUCTION**

With the passage of AB 32, The Global Climate Change Solution Act, quantifying N_2O emissions from California agricultural land is vital to determining GHG emission budgets. Utilization of the IPCC methodology based on default emission factors resulted in a high uncertainty. The CEC sponsored two modeling studies to assess mitigation potentials of greenhouse gas emission from California agriculture (Li et al., 2004; Six et al., 2008), both of which suffered from a lack of field data to calibrate and validate the models. This project was to help improve these earlier attempts by leveraging off several companion projects collecting N_2O data for calibrating and validating models for California specific conditions in addition to providing an independent estimate of N_2O emissions based on California crop specific fertilizer levels.

1.1 Background

The California Global Warming Solutions Act of 2006 has legislated GHG emission reductions such that 2020 emission levels are at or below 1990 levels. Mandatory GHG emission reductions are now set in law for the first time in the US. In response to this Act, a Climate Action Team (CAT) was created to identify Discrete Early Actions to reduce emissions and meet the 2020 targets. The 2006 CAT report identified the use of cover crops and conservation tillage as strategies for sequestering soil carbon in California croplands. A challenge with the development of GHG emission reduction policies, particularly market-based policies, is the need to accurately and transparently conduct full GHG accounting to quantify net emission reductions, especially given the strong linkage between soil carbon content and trace gas emissions. In addition, California is now exploring the development of various GHG emission reduction strategies including the potential use of market-based mechanisms to create incentives for producers to adopt voluntary GHG emission practices.

The 2007 California Census of Agriculture reported 3,830,135 hectares of croplands in the state, with 3,243,964 hectares irrigated and 3, 088, 978 hectares of it harvested (USDA, 2009). 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 (1 Tg = $1x10^{12}$ g or 1 million metric tons) carbon dioxide equivalent (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 chemical fertilizer and manure use for 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 using emission factor approaches as specified in IPCC guidelines, with some California specific emission factors.

The legislation passed in California creates a clear need for a system that identifies and quantifies agricultural carbon sequestration and greenhouse gas mitigation opportunities. Here, we outline our plan for the design, development, and implementation of such a system. We anticipate that this prototype system will be designed so that it can easily be updated to include new field research for model validation and future improvements in process-based models.

1.2 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 globalN_2O emissions (Scheehle and Kruger, 2005; USEPA, 2005), and thereby represent a significant opportunity for greenhouse gas (GHG) mitigation through reductions of CH_4 and N_2O emissions, as well as through soil carbon sequestration (Oenema et al., 2001). When assessing the impact of food and fiber production systems on the earth's radiation budget, the entire suite of GHGs (i.e., CO_2, CH_4 and N_2O) needs to be considered (Li, 1995; Robertson et al., 2000; Smith et al., 2001; Li et al., 2004). Since each greenhouse gas has its own radiative potential (Ramaswamy et al., 2001), a net global warming potential (GWP) of a crop production system can be estimated that accounts for all three gases. Agriculture represents a significant opportunity for greenhouse gas mitigation projects through soil carbon sequestration and reductions ofCH_4 and N_2O emissions. Recently, significant investments are being made in assessing carbon (C) sequestration projects 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 soil organic carbon (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 a number of 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 greenhouse gas emissions 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.

California rice, for example, is a unique agricultural system due to the use of flooding to meet the plant physiological demands. As a result, the per hectare GHG emissions can be quite high, primarily due to high CH_4 emissions since N_2O emissions tend to be low due to highly anaerobic soils. In developing their rice emission factor, EPA (2010) summarized field research in the US where measurements of CH_4 ranged from 22 to 1490 kg $CH_4 ha^{-1} season^{-1}$. This is equivalent to emissions of 0.6 to over 37 tons CO_2 eq.ha^{-1}. Shifts in farming management practices such as flooding regimes, rice straw amendment and fertilizer application have been shown to decrease methane emissions significantly (20-80%) (e.g., Li et al. 2005, 2006).

1.3 Coupled Carbon and Nitrogen Biogeochemical Processes

In nature, chemical elements typically act in a coupled fashion and represent one of the basic concepts of biogeochemistry. Carbon and nitrogen (N) are one of the best examples of biogeochemical coupling and are both essential elements for most life forms. Photosynthesis is the process initiating the primary production of green plants by synthesizing atmospheric C into biomass C based on the N compounds, chlorophyll. The coupled C and N in plant tissues are incorporated in the soil from litter and exudates after plants death. In the soil environment, the coupled C and N start the decoupling processes by way of soil microbes as they derive energy from the breakdown of the organic compounds. The processes result in the separation of C and N by converting the C-N compounds into dissolved organic carbon (DOC) or inorganic C (e.g., CO_2) as well as inorganic N (e.g., ammonium or nitrate). The energy is usually generated during the process by transferring electrons from the C atoms existing in the organic compounds to oxygen (O_2). If O_2 is depleted in the soil, certain groups of microbes (e.g., denitrifiers) can use other oxidants as electron acceptors. After oxygen, the most ready-reduced oxidant is nitrate. Nitrate, N_2O, and dinitrogen (N_2) are produced when the microbes transfer the electrons from organic C (Firestone 1982). The same is true for CH_4 production although the process occurs under more reductive conditions related to hydrogen production. These processes demonstrate how SOC content and N_2O are related through the coupling and decoupling of C and N in the upland plant-soil systems. In summary, increases in SOC storage, such as those expected to occur under no-till agricultural practices, elevate soil DOC and available N through decomposition, which in turn will stimulate activity of a wide scope of soil microbes including nitrifiers and denitrifiers, which are responsible for N_2O production in the soils.

1.4 Nitrous Oxide Emission and Soil Carbon Content

While nitrous oxide and methane are the major thrust of our proposed system, we contend that decision support systems for assessing GHG emissions in agro-ecosystems should be comprehensive and thus include full greenhouse gas accounting. Since N_2O is the most significant trace gas emission from upland agriculture, we also focus on the link between carbon and nitrous oxide. The correlation of N_2O production with soil C abundance has been observed in a wide scope of field measurements or laboratory experiments conducted over the past five decades. More specifically, higher N_2O fluxes have been measured from the soils with higher organic matter content. 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 SOC contents. Among the observations, organic soils consistently emitted the highest N_2O fluxes (Bremner and Shaw, 1958; Bowman and Focht, 1974; Burford and Bremner, 1975; Mosier et al.,1991; Vinther, 1992).

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 to be two dominant 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. 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. It is the complex interactions among the primary drivers, soil environmental factors, and the biogeochemical reactions that result in the observed, highly variable N_2O fluxes. For example, conversion from conventional tillage to no-till could simultaneously alter soil temperature, moisture, redox potential and soil DOC and available N content. These affected factors will simultaneously and collectively alter the direction and rates of decomposition, nitrification, denitrification, and substrate diffusion, which in turn collectively determine N_2O emission. Process-based modeling is the only 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 dynamics and N_2O emissions. 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 for 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. By tracking crop biomass production and decomposition rates, DNDC simulated long-term SOC dynamics. 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 ready to serve offset analyses between C sequestration and N_2O emissions for agro-ecosystems.

Several reports released recently discussed potentials of the alternative management practices in sequestering atmospheric C. Unfortunately, most of the research reports or proposals have not addressed non-CO_2 greenhouse gases, especially N_2O. Actually, N_2O is an important greenhouse gas due to its high radiative efficiency (298 times higher than CO_2) and relation with a series of farming practices (Li, 1995; Robertson et al., 2000; Li et al., 2002). The net offset between reductions in atmospheric CO_2 and increases in atmospheric N_2O can be significant, and in some cases can result in a net increase in atmospheric CO_2 equivalents (Robertson et al., 2000). Aulakh et al. (1984) and Robertson et al. (2000) observed emissions from cultivated soils with conventional tillage and no-till in the U.S., and found N_2O emissions were higher from the no-till cropland.

Since C sequestration and N_2O emission are both affected by many environmental factors but in different ways, shifting from one location to another will inherently alter the effects of any management alternatives on the net GWP. DNDC, with its fundamental biogeochemical processes and access to GIS data for regional assessments, can quantify the net GWP effects of alternative management practices across climatic zones, soil types, and management regimes.

Funded by the California Energy Commission assessed, a scoping study on SOC dynamics and N_2O emissions at county scale for CA was conducted in 2004 (Li et al. 2004). The recommendations of this scoping study suggested

- Establish a program to collect data on agricultural management practices, to improve the spatial representation of management practices and account for regional and cropping system differences. Critical data should also include information on residue and manure management.
- For future study, use the updated Natural Resources Conservation Service's Soil Survey Geographic (SSURGO) database. The improved spatial and thematic resolution of these data will result in improved model estimates of carbon dynamics and GHG emissions.
- Further validate the DNDC model, to better quantify the model's performance in simulating carbon dynamics, N_2O, and CH_4 over a range of California agroecosystems. This validation should consist of: (1) performing model validations using existing carbon dynamics, CH_4 and N_2O field data, and (2) developing a field measurement program to cover critical gaps in field data across a range of major crops and management systems..
- Evaluate alternative mitigation scenarios for: no-till, conservation tillage, and conventional tillage; optimized fertilizer application rates; shifts in irrigation and water management and the use of cover crops.

Since the Li et al. (2004) recommendations, there have been several field studies (ARB, CEC, Packard Foundation and CDFA N_2O projects) to collect data for a range of California cropping systems and projects to extend DNDC biogeochemical process modeling to animal agricultural systems in California.

This project built and leveraged off these efforts to work with ARB to develop a process modeling system for improving the inventory and for assessing opportunities to mitigation GHG emissions. Thus, we accomplished the following objectives:

Objective 1: develop GIS databases for statewide GHG modeling,
Objective 2: compile agricultural management databases,
Objective 3: assess model uncertainties (both structural and scaling) through model validation,
Objective 4: perform comparison of DNDC and DAYCENT models at select sites,
Objective 5: compile GHG emission estimate for California agriculture, and
Objective 6: work with ARB inventory staff on use and updates to the modeling system.

To meet the goal of project, the research team (1) collected N_2O flux data measured at the crop fields across a wide range of management conditions in California; (2) utilized the measured N_2O data to validate two models, DNDC and DAYCENT, for their applicability on quantifying agricultural N_2O emissions in California; (3) developed GIS databases including climate, soil and agricultural management practices for statewide GHG modeling; and (4) estimated N_2O emissions from California croplands. The results are presented in this report.

2. DESCRIPTION OF FIELD DATA

This task entailed compiling existing field data on nitrous oxide emissions collected by Co-PIs and collaborators. We leveraged significantly off larger effort by three research groups (Horwath at UCD, Six at UCD, Smart at UCD) measuring N_2O emissions in 9 different cropping systems located in the Sacramento Valley, San Joaquin Valley and Central Coast region. The state agencies involved in funding these efforts include Air Resources Board, California Energy Commission, and California Department of Food and Agriculture. In addition, the David and Lucile Packard Foundation is providing support. The combined efforts of these separate projects provided scientifically sound N_2O emission data that provided the basis for extensive calibration and validation of DNDC. The following summarizes methods used to collect field measurements of nitrous oxide fluxes.

2.1 Site and Cropping System Descriptions

Table 1 summarizes the cropping system where we compiled data on nitrous oxide emissions. In each of the perennial systems, gas measurements and ancillary soil properties were taken over the course of at least two years, thus representing temporal and climatic effects. Perennial systems were divided into two spatial locations: tree or vine row versus tractor row. Tomato emissions were measured under multiple management practices; conventional (standard regional practices, furrow irrigated) and integrated (reduced tillage with sub-surface drip). Emissions in the tomato systems were measured at three spatial locations, berm (top of bed, directly above drip), side (side of bed), and furrow (in between beds, subject to irrigation in conventional system at multiple sites. Wheat and alfalfa measurements were conducted at grower's fields in Sacramento Valley. For alfalfa, a field with a one-year and a field with a 5-year old stand were selected. All sites had either three or four replications as randomized block design.

Table 1: Site and cropping system description for field N_2O measurements used for validation.

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Crop	Location County	Soil Texture (SOC,Clay%, pH, BD)	Irrigation system	Fertilization rate ($kg\ N\ ha^{-1}\ yr^{-1}$)	Duration of study	PI
Wine grape	**Napa**	Loam (2.3%,25%,5.6, 1.13)	drip	17	2009-2010	D. Smart
Wine grape	**Colusa**	Loam (2.0%,19%,7.1,1.18)	drip	5-5.4	2009-2011	J. Six
Corn	**Yolo**	Loam (1.1%,19%,7.15,1.3)	furrow	241	2004	J. Six
Sunflower	**Yolo**	Loam (1.1%,19%,7.15,1.3)	furrow	90	2005	J. Six
Beans	**Yolo**	Loam (1.1%,19%,7.15,1.3)	furrow	0	2006	J. Six
Tomato	**Yolo**	Loam (1%,19%,6.5,1.35)	drip and furrow	112-162	2006	C. Kallenbach
Wheat	**Yolo**	Loam (1.1%,19%,7.15,1.3)	furrow	150	2003	J. Six
Winter Wheat	**Solano**	Silty Clay Loam (1.28%,34%,7.2,1.3)	no irrigation	0-203	2010-2011	W. Horwath
Alfalfa	**Yolo**	Silty Clay Loam (1.26%,34%,7.7,1.3)	Sprinkler	17	2010-2011	W. Horwath
Almond	Colusa	Silt Loam (1.2%,14%,7.6,1.31)	Microjet sprinkler	258-280	2010-2012	J. Six
Tomato	Yolo	Silty clay loam (1.0%,34%,6.6,1.35)	furrow	205-237	2010-2011	J. Six

2.2 Gas Sampling Protocol

Nitrous oxide emissions and soil variables were regularly measured for two years in the above cropping systems under typical management as well as with varying N fertilizer applications. Annual N_2O emissions were calculated and yields were measured to identify management practices that keep N_2O emissions as low as possible without negatively affecting yield potential.

In-situ soil-surface fluxes were measured using a closed-flux chamber method (Rochette and Bertrand, 2007). The individual chambers were made of polyvinyl chloride (PVC) and had a diameter of 20 cm and a depth of 12 cm. The caps were covered with reflective material to reduce heating within the chambers. The bottom part (i.e. collar) of the chambers were inserted to a depth of 5 cm and left in the same location for the duration of the project. At sampling time, the caps were sealed onto the bottom collars with a rubber sleeve and samples were taken through a rubber septum at regular intervals (0, 30, and 60 min. or 0,20, 40, 60 min.) using a 20 mL air-tight polypropylene syringe and pressurized into pre-evacuated 12 mL vials. The samples were then analyzed on a gas chromatograph (GC-2014 Shimdazu Gas Chromatograph) with a detection limit of 0.0114 ppm, which was calculated as twice the standard deviation of a 1 ppm N_2O standard measured 10 times. To capture event related fluxes, samples were taken for a period of 7 to 10 days following each management (fertigation, irrigation, tillage, and harvest) and precipitation event and otherwise weekly. Fluxes were calculated using the best flux method or by comparing the R^2 of linear versus least sum of squares non-linear regression. Details of the field measurement protocol can be found in final project reports by Verhoeven et al. 2013 (CEC contract PIR 08-004) and Horwath et al 2012 (California Air Resources Board, Contract No. 08-324).

2.3 Ancillary Soil Property Sampling

Soil samples were taken on alternating days within gas monitoring events and at each weekly background sampling. Using a 2 cm diameter probe to a depth of 15 cm, samples were taken from within a 1 m radius of each gas chamber. Samples were analyzed for NO_3^-, NH_4^+, and in some cases for dissolved organic carbon (DOC) and pH. A K_2SO_4 solution was used to extract NO_3^-, NH_4^+ and DOC (50 ml 0.5 M K_2SO_4:15 g soil). DOC extracts were immediately acidified to <2.0 pH and stored at 4 °C until analysis by combustion using a total organic carbon analyzer (Shimadzu TOC-V). NO_3^- and NH_4^+ extracts were frozen at -5 °C and later analyzed colorimetrically (Doane and Horwáth, 2003) on a Shimadzu UV PharmaSpec 1700 spectrophotometer. Samples were finely ground and pH was measured using a 1:1 ratio of deionized water to soil. Gravimetric water content was measured by drying soil samples at 105° for 24hrs and then converted to volumetric water content based on soil bulk density. Water filled pore space (WFPS) was then calculated by dividing the volumetric water content by porosity. Porosity was calculated assuming a particle density of 2.65 g cm^{-3} and adjusted every six months to reflect changes in bulk density.

3. MODEL VALIDATION

3.1. DNDC Validation Tests

Forty datasets of measured daily N_2O fluxes were provided by Dave Smart, Johan Six, Cynthia Kallenbach and William Horwath. The datasets covered a wide range of crop types including vineyard, almond, tomato, wheat, corn, sunflower, beans, alfalfa and cover crops, which are the ones commonly planted in California. The field data also covered routine and alternative farming management practices prevailing in CA. DNDC was applied for all the 40 field datasets using input information mostly coming with the field work reports.

As a process-based model, DNDC runs at daily time step and reports daily fluxes and pools of various C and N species for the simulated fields. The version of DNDC utilized for the project was used basically as it was. All the parameters or functions calculating the soil biogeochemistry as well as the N2O production/consumption/emission processes remained unchanged during all the 40-case simulations. During the past about two decades, DNDC has been calibrated and validated against a large number of observations on crop growth, soil climate, C dynamics and N transformations worldwide. As each calibration or validation contributed to improvements of the fundamental processes of physics, chemistry and biology, the modifications induced by the calibration/validation with each specific case have benefited not only the tested case but also all other cases. Nowadays, most of the users downloaded DNDC from the website and directly ran it for validation tests with little work on calibration with the biogeochemical processes. However, it is highly recommended that correctly simulating crop growth/yield through re-calibrating the crop physiological parameters is always the responsibility of the users. DNDC cannot provide adequate and accurate crop parameters to cover all the crop types or cultivars. As crops uptake water and N from the soil during the growing season and hence alter the soil Eh, electron donor and electron acceptor concentrations, there would be no hope to correctly simulate N_2O fluxes if the crop growth could not be correctly simulated. That was exactly what we did for the 40 cases tested in the project. We collected crop data (e.g., yield, biomass partitions, C/N ratio, TDD, water requirement etc.) from the field workers and reset the crop parameters as close as observations for each crop type/rotation. The 40-case tests showed that when the crop growth was correctly simulated the modeled N_2O fluxes were in the ball park.

The modeled daily N_2O fluxes were compared with observations. Figure 1 provides an example to show how the measured and modeled daily N_2O fluxes were compared. In the case, modeled data captured two peaks of observed N_2O fluxes in late April and late October but missed the background fluxes from observations. All the figures of daily comparisons for the tested cases are shown in Appendix A. The figures demonstrated the measured and modeled N_2O daily fluxes regarding their magnitudes and seasonal patterns. However, it is a challenge to compare the results in a quantitative manner due to the scarcity of measured data for most field campaigns where static chambers were employed for weekly or bi-weekly sampling.

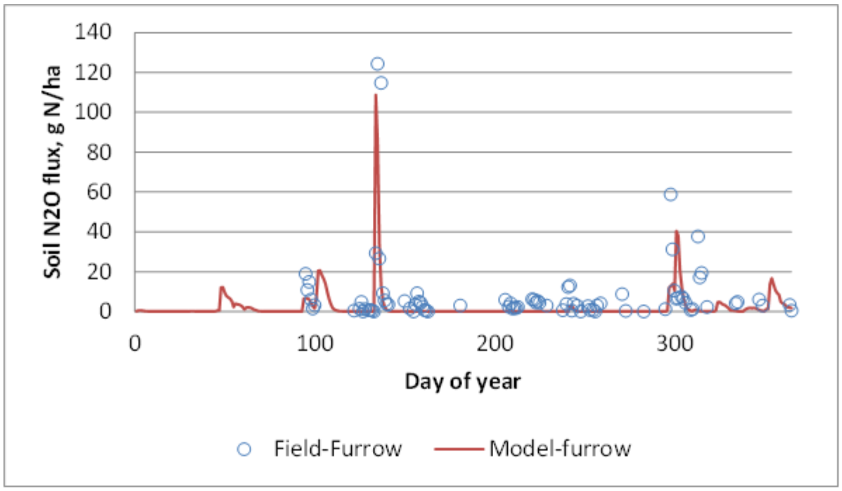

Figure 1. Comparison between measured and DNDC-modeled daily N_2O fluxes from position of furrow in a tomato field (Field 31) in Yolo, CA in 2010 (field data from Johan Six)

Annual or measuring-season total N_2O emissions are usually calculated to serve the quantitative comparison. Based on the scientific consensus that N_2O is episodically emitted from soils, an equation was adopted to interpolate the measured N_2O fluxes. In the DNDC applications, the principles set for interpolation are described as follows:

(1) Every measured N_2O flux with rate higher than 0.01 g N ha^{-1} day^{-1} will be interpolated based on

$$FLUX_{(n)} = FLUX_{(0)} * 0.8^n$$

where $FLUX_{(0)}$ is the measured N_2O flux on day 0, n is the days after the measurement, FLUX(n) is interpolated N_2O flux on day n.

(2) The interpolation will continue until meeting next measurement.

(3) The annual or seasonal N_2O flux is the sum of the interpolated daily N_2O fluxes for the time period.

The exponential index 0.8 has been determined based on numerous field datasets of N_2O emissions observed worldwide. These observations indicated that daily N_2O flux rate rapidly decreased after the formation of a high peak emission following the events of rainfall, irrigation, fertilization, manure amendment, or soil freezing/thawing. 0.8 was empirically adopted to best fit all observations. Slightly changing the index by about 20% would alter the pattern of the episodes but not change the annual/seasonal emissions very much. The methodology has been utilized for DNDC validation tests for years and proved applicable across a wide range of ecosystems worldwide. The same method was used in this study to serve comparison between measured and DNDC-modeled N_2O fluxes for the 40 datasets observed in CA.

By means of the interpolation method, annual or seasonal total N_2O emissions were calculated for all the measured dataset in the study in CA. The total N_2O emissions for the 40 field measurements are shown in Table 2.

Table 2. Comparison of DNDC-modeled annual/seasonal N_2O fluxes (g N ha^{-1}) with measured N_2O fluxes (g N ha^{-1}) for 40 site-year datasets from agricultural fields in California (Field data from Dave Smart, Johan Six, Cynthia Kallenbach and William Horwath)

Data source	Land-use	Year	Location/treatment	Modeled N_2O flux	Measured N_2O flux (mean)	Measured N_2O flux (STD)
Dave Smart	Vineyard	2009	Drip area	115	145	44
		2010	Drip area	243	199	116
		2009	Alley area	85	113	21
		2010	Alley area	368	101	13
Johan Six	Almond	2010	Tree row	271	297	40
		2010	Tractor row	89	116	35
Johan Six	Tomato (Field-10)	2010	Berm	183	240	20
		2010	Furrow	296	309	146
Johan Six	Tomato (Field-31)	2010	Berm	183	371	162
		2010	Furrow	734	940	280
Johan Six	Wheat (Field 74)	2003	Standard till	98	148	57
	Corn	2004	Standard till	920	1056	525
	Sunflower	2005	Standard till	324	305	235
	Beans	2006	Standard till	279	181	106
	Wheat	2003	Reduced till	105	214	112
	Corn	2004	Reduced till	1054	1496	928
	Sunflower	2005	Reduced till	413	351	254
	Beans	2006	Reduced till	487	412	180
Johan Six	Vineyrad	2009	Vine	113	140	13
		2010	Vine	222	203	150
		2009	Row	1294	1150	323
		2010	Row	435	594	377
Synthia Kallenbach	Tomato/cover crop	2006	DI-NCC	295	359	217
		2006	DI-WLCC	1461	1298	670
		2006	FI-NCC	1310	1714	1381
		2006	FI-WLCC	1216	665	512
William Horwath	Alfalfa	2010	5-year old	2760	253	63
		2011	5-year old	5490	5304	1374
		2010	1-year old	567	429	113
		2011	1-year old	1579	1437	293
William Horwath	Winter wheat	2010	0 kg N/ha (fertilizer rate)	1	27	
		2011	0 kg N/ha (fertilizer rate)	100	189	31
		2010	91 kg N/ha	44	17	
		2011	91 kg N/ha	348	347	72
		2010	151 kg N/ha	76	28	
		2011	151 kg N/ha	528	426	95
		2010	203 kg N/ha	98	175	
		2011	203 kg N/ha	705	881	265
		2010	254 kg N/ha	1677	1876	
		2011	254 kg N/ha	1282	724	

There were totally 40 cases provided by the field researchers and all the cases were utilized to test DNDC for its applicability for quantifying N_2O emissions from the various agricultural fields in California. Table 2 and Figure 2 show the results from the validation tests. Based on the validation tests against the 40 field datasets, the correlation between the measured and DNDC-modeled annual/seasonal N_2O fluxes is very significant $p<0.01$ with R^2=0.80, slope=0.97 and p=0.001 (Figure 2). In the field cases, there were two outliers (253 and 5,304 g N_2O-N ha^{-1} for a 5-years-old alfalfa field in 2010 and 2011, respectively). Without any exclusion, we simulated all the 40 field datasets respecting their authenticity. If the two outliers were excluded from the statistical analysis, the R^2 value would increase from 0.80 to 0.85.

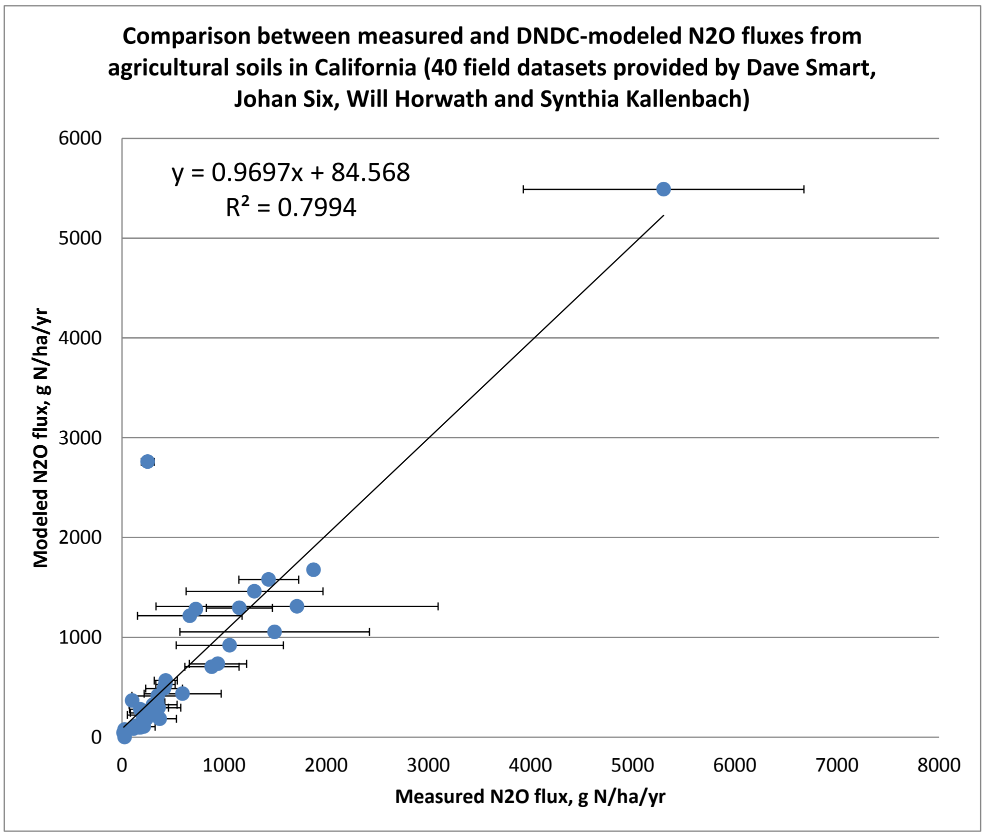

Figure 2. Comparison between DNDC-modeled and measured annual or seasonal N_2O fluxes with exponential interpolation for 40 site-year datasets from agricultural fields in California (R^2=0.80, slope=0.97, p=0.001)

3.2. DAYCENT Validation Tests

Among the 40 datasets provided by the field researchers, DAYCENT was applied for only 25 datasets due to the limited capacity of the model for simulating (1) perennial tree crops such as vineyard or almond, (2) some alternative management practices such as drip irrigation, and (3) different functional locations within a field. The DAYCENT-modeled daily N_2O fluxes were compared with observations as shown in the figures in Appendix B.

To compare DAYCENT-modeled results against observations, the DAYCENT group calculated annual or seasonal total N_2O fluxes based on measured data with the method of linear interpolation. This method assumes that the daily N_2O fluxes between two measured fluxes are linearly related to the initial flux and the end flux. With this method, the calculated observation N_2O emissions are compared with the DAYCENT-modeled results (Table 3).

Table 3. Comparison of DAYCENT-modeled annual/seasonal N_2O fluxes with measured N_2O fluxes (generated with linear interpolation) for 25 datasets from agricultural fields in California (Field data from Johan Six, Cynthia Kallenbach and William Horwath)

Working group	Field site	Year	Treatment	Annual/seasonal N_2O flux, g N/ha	
				Field (linear)	Daycent
Johan Six	Field 31	2010	Tomato	2010	5763
Johan Six	Field 74	2003	Standard till	1050	829
Johan Six	Field 74	2004	Standard till	4100	4316
Johan Six	Field 74	2005	Standard till	2816	4109
Johan Six	Field 74	2006	Standard till	1149	664
Johan Six	Field 74	2003	Reduced till		571
Johan Six	Field 74	2004	Reduced till	7496	4231
Johan Six	Field 74	2005	Reduced till	3789	3827
Johan Six	Field 74	2006	Reduced till	2967	444
William Horwath	Alfalfa	2010	5-year old alfalfa	521	742
William Horwath	Alfalfa	2011	5-year old alfalfa	5200	899
William Horwath	Alfalfa	2010	1-year old alfalfa	1026	3530
William Horwath	Alfalfa	2011	1-year old alfalfa	2300	1018
William Horwath	Winter wheat	2010	0 kg N/ha	240	993
William Horwath	Winter wheat	2011	0 kg N/ha	720	1326
William Horwath	Winter wheat	2010	91 kg N/ha	310	993
William Horwath	Winter wheat	2011	91 kg N/ha	880	1490
William Horwath	Winter wheat	2010	151 kg N/ha	570	995
William Horwath	Winter wheat	2011	151 kg N/ha	1420	1495
William Horwath	Winter wheat	2010	203 kg N/ha	1300	993
William Horwath	Winter wheat	2011	203 kg N/ha	2050	1492
William Horwath	Winter wheat	2010	254 kg N/ha	500	996
William Horwath	Winter wheat	2011	254 kg N/ha	2150	1498
Synthia Kallenbach	Tomato	2006	With cover crop	95696	4728
Synthia Kallenbach	Tomato	2006	No cover crop	38137	4952

Statistical results: R^2=0.23, slope=0.04

Figure 3 shows the correlation between measured and DAYCENT-modeled annual or seasonal N_2O fluxes for 25 datasets. The correlation between the measured and DAYCENT-modeled N_2O fluxes is significant with $p<0.05$ ($p=0.018$, $R^2 = 0.2279$, slope=0.0402) (Figure 3).

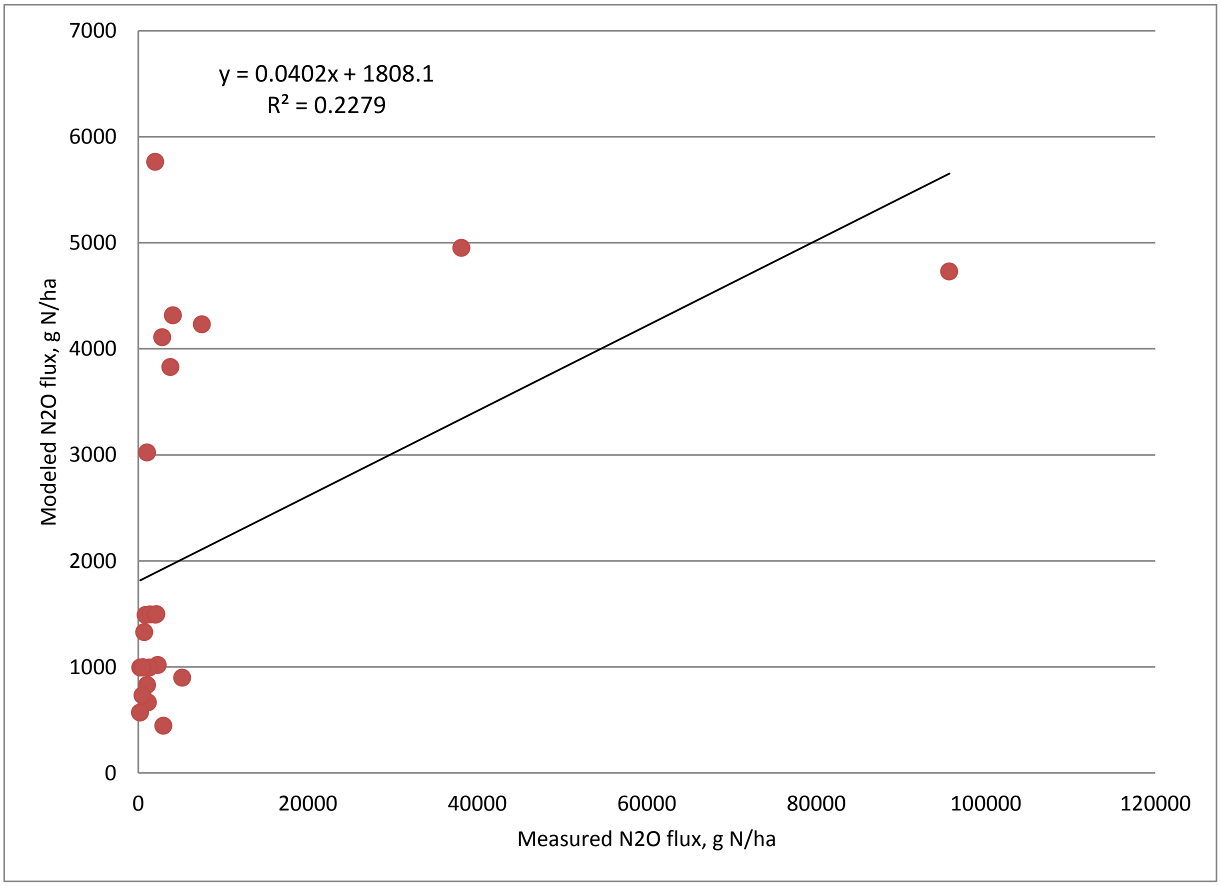

Figure 3. Comparison between DAYCENT-modeled and measured annual or seasonal N_2O fluxes with linear interpolation for 25 site-year datasets from agricultural fields in California (R^2=0.23, slope=0.04)

3.3. DNDC-DAYCENT Comparison

We conducted comparisons on N_2O fluxes modeled with DNDC and DAYCENT in two ways: i.e., at daily basis and at annual/seasonal basis.

3.3.1. Model comparison on daily basis:

DNDC- and DAYCENT-modeled daily N_2O fluxes were compared against measured N_2O fluxes for 25 site-year datasets which DNDC and DAYCENT were both capable of simulating. The results of the daily comparisons are provided in a group of figures in Appendix C. Due to the scarcity of the field data as well as the time lag on the peak emissions between measured and modeled daily N_2O fluxes, neither linear nor non-linear regression method could produce meaningful results to show the correlation between the measured and modeled daily N_2O fluxes. The lack of proper statistical tools for this kind of comparison at daily basis has hindered the comparison between the DNDC- and DAYCENT-modeled daily N_2O fluxes. However, the figures attached in Appendix C should be able to provide the intuitive comparisons for the readers who are interested in the daily results from the two models.

3.3.2. Model comparison on annual basis:

To conduct the model comparison against observations on annual/seasonal basis, we had to first calculate the field annual/seasonal N_2O fluxes based on measured daily N_2O fluxes for each case. All the measurements conducted for the project were carried out with static chambers with sampling intervals of 2-10 days. Interpolation must be employed to convert the sparsely measured flux data into annual or seasonal total flux. There are two methods for interpolation of gas emissions. The first method is linear interpolation which is suitable for the gases continuously and smoothly emitted from soils, such as CO_2 or CH_4. The second method is exponential interpolation which is suitable for the gases episodically emitted from soils such as N_2O. When the field sampling time interval is approaching to 1-2 days, the discrepancy generated from the two methods will be diminishing. If the field sampling time interval increases, the discrepancy generated from the two methods will becoming significant. Usually, the results generated with the linear method are higher than that with the exponential method mainly due to overestimation for the prior-episode fluxes (see Figure 4). The sparser the measured data the larger the discrepancy between the two methods. It has been reported that the annual CH_4 emission generated with the linear method was usually 22% higher than that measured with automated chamber method (Zheng et al., 1998; Wood et al., 2013). Given the high daily fluctuation of N_2O fluxes, the discrepancy on annual/seasonal N_2O emissions calculated with the linear and exponential methods should be expected to be high. Figure 4 demonstrates the difference between the linear and exponential interpolation methods for an actual case of N_2O fluxes measured at a tomato field in California by Cynthia Kallenbach in 2006. The annual N_2O emissions are 13.9 vs. 1.9 kg N/ha based on the linear and exponential interpolation methods, respectively. The linear method overestimated the annual N2O emission due to the apparent overestimations of areas A and B. As there is no consensus for the interpolating methods, we applied the two methods to serve the model comparison in the project. The calculated annual/seasonal total N_2O fluxes for the CA datasets with the two methods are summarized in Table 4.

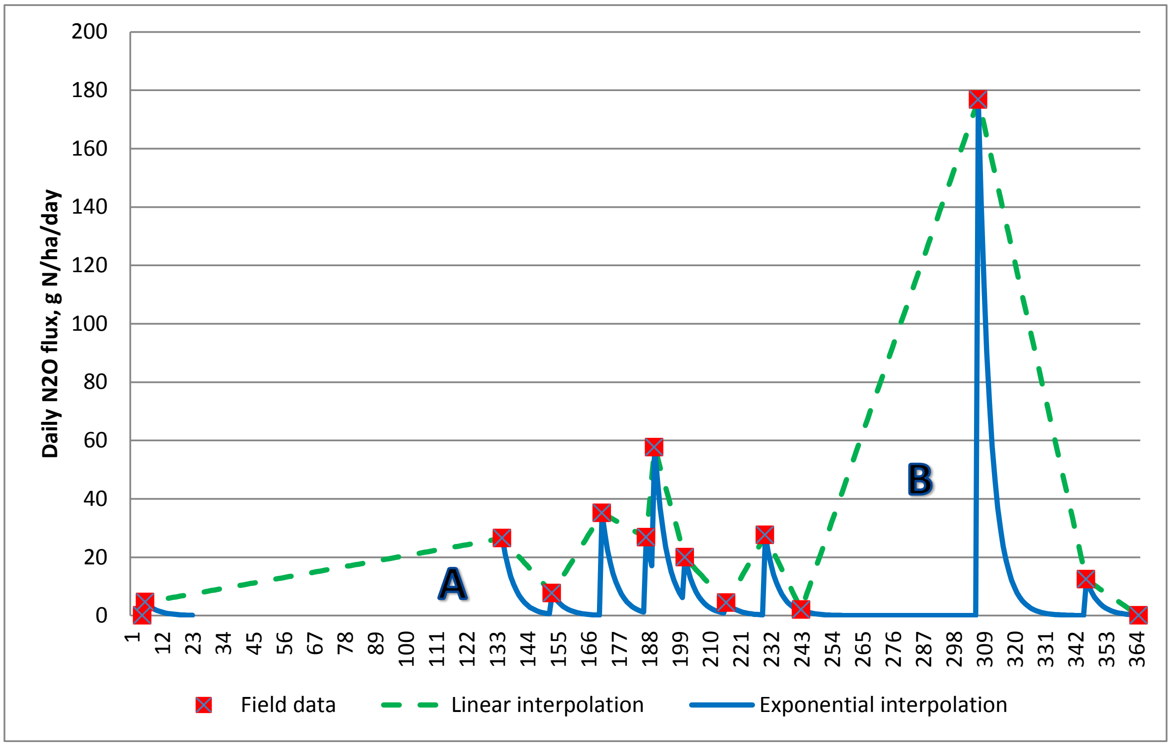

Figure 4. Comparison between exponential and linear interpolation methods for calculating annual total N_2O emission based on discontinuously measured daily N_2O fluxes at a tomato field in California in 2006 (field data from Kallenbach). The calculated annual N_2O emissions are 1.89 kg N ha^{-1} and 13.86 kg N ha^{-1} using the exponential and linear methods, respectively. The linear method overestimated the annual N2O emission due to the apparent overestimations of areas A and B.

Given the observed annual/seasonal N_2O emissions calculated with both the exponential and linear interpolation methods, we conducted comparison of DNDC with two well-documented and widely applied models, the DAYCENT model and IPCC Approach.

The current ARB inventory for direct emissions of N_2O from agricultural soils uses the IPCC emission factor approach. Direct N_2O emissions are calculated with the following equation (Source ARB GHG Inventory Technical Support Document):

$$E_{direct} = \begin{Bmatrix} [N_{SF} + N_{OF} + N_{MM} + N_{CR}] \bullet EF_1 \\ + N_{UM,CPP} \bullet EF_{2,CPP} + N_{UM,SGH} \bullet EF_{2,SGH} \\ + A_{OS} \bullet EF_3 \end{Bmatrix} \bullet 1.5711$$

Where,

E_{direct}	= Direct N_2O emissions from managed soils (kg N_2O)
N_{SF}	= Amount of N from synthetic fertilizers applied to soils (kg N)
N_OF	= Amount of N from organic fertilizers applied to soils (kg N)
N_{MM}	= Amount of N from managed manure spread on soils (kg N)
N_{CR}	= Amount of N in crop residues that is returned to soils (kg N)
$N_{UM, CPP}$	= Amount of N from un-managed manure from grazing cattle, poultry and pigs (kg N)
$N_{UM, SGH}$	= Amount of N from the un-managed manure from grazing sheep, goats and horses (kg N)
A_{OS}	= Area of drained organic soil (histosols) (ha)
EF_1	= Emission factor: proportion of N applied to agricultural soils that is emitted as N_2O
$EF_{2, CPP}$	= Emission factor: proportion of N from cattle, poultry and pigs un-managed manure that is emitted as N_2O
$EF_{2, SGH}$	= Emission factor: proportion of N from sheep, goats and horses un-managed manure that is emitted as N_2O
EF_3	= Emission factor: N emitted as N_2O per unit area of cultivated of organic soils (kg N per ha)
1.5711	= Molecular weight ratio of N_2O to N_2

We applied this emission factor approach to the field validation data (see Table 4) that were used to compare DNDC and DAYCENT to assess if the use of the mechanistic models would improve the California inventory. N_{CR} was estimated based on DNDC modeled crop biomass and the fraction of residues applied following harvest. We compared the IPCC, DNDC and DAYCENT estimates against both approaches for interpolating daily field measurements (exponential and linear). As for two of the field data sets (Cynthia Kallenbach) using the linear approach for interpolation lead to unrealistically high annual N_2O fluxes of over 38 and 95 kg N- N_2O from tomato receiving 162 kg N (effective emissions factors of over 23% and 58%, respectively), the two datasets were considered to be outliers and not included in the comparison. Table 4, Figures

5 and 6 show the comparison of annual emissions interpolated with exponential and linear interpolation, respectively, with IPCC, DNDC and DAYCENT estimates for the 23 field datasets. It is clear that both DNDC and DAYCENT performed significantly better than IPCC approach in estimating annual N_2O fluxes for these field sites. Under the exponential interpolation comparison, the correlation between measured and DNDC-modeled annual/seasonal N_2O emissions was very significant with $p<0.01$ (Table 5). Under the linear interpolation comparison, the correlation between measured and both DNDC- and DAYCENT-modeled annual/seasonal N_2O emissions was significant with $p<0.05$ (Table 5). The results from IPCC method were not significantly related to the measured results calculated with either exponential or linear interpolation approach (Table 5).

Table 4. Measured and IPCC-, DNDC- and DAYCENT-modeled annual/seasonal N_2O fluxes for 23 datasets for California

Data source	Field site	Year	Treatment	Annual/seasonal N2O flux, g N/ha				
				Field (exponential)	Field (linear)	DNDC	Daycent	IPCC
Johan Six	Field 31	2010	Tomato	940	2010	734	5763	5527
Johan Six	Field 74	2003	Standard till	148	1050	98	829	2081
Johan Six	Field 74	2004	Standard till	1056	4100	920	4316	2715
Johan Six	Field 74	2005	Standard till	305	2816	324	4109	1382
Johan Six	Field 74	2006	Standard till	181	1149	279	664	29
Johan Six	Field 74	2003	Reduced till	214	214	105	571	2081
Johan Six	Field 74	2004	Reduced till	1496	7496	1054	4231	2716
Johan Six	Field 74	2005	Reduced till	351	3789	413	3827	1112
Johan Six	Field 74	2006	Reduced till	412	2967	487	444	141
William Horv	Alfalfa	2010	5-yr alfalfa	253	521	2760	742	763
William Horv	Alfalfa	2011	5-yr alfalfa	5304	5200	5490	899	798
William Horv	Alfalfa	2010	1-yr alfalfa	429	1026	567	3530	389
William Horv	Alfalfa	2011	1-yr alfalfa	1437	2300	1579	1018	827
William Horv	Winter whea	2010	0 kg N/ha	27	240	1	993	32
William Horv	Winter whea	2011	0 kg N/ha	189	720	100	1326	12
William Horv	Winter whea	2010	91 kg N/ha	17	310	44	993	942
William Horv	Winter whea	2011	91 kg N/ha	347	880	348	1490	1020
William Horv	Winter whea	2010	151 kg N/ha	28	570	76	995	1542
William Horv	Winter whea	2011	151 kg N/ha	426	1420	528	1495	1663
William Horv	Winter whea	2010	203 kg N/ha	175	1300	98	993	2062
William Horv	Winter whea	2011	203 kg N/ha	881	2050	705	1492	2183
William Horv	Winter whea	2010	254 kg N/ha	38	500	130	996	2572
William Horv	Winter whea	2011	254 kg N/ha	421	2150	821	1498	2693

Figures 5 and 6 show the comparisons of IPCC-, DNDC- and DAYCENT-modeled annual/seasonal total N_2O emissions against measurement-induced annual/seasonal total N_2O emissions with linear and exponential interpolation methods, respectively. If using the exponential method, only DNDC results are significantly correlated with observations. If using the linear method, both DNDC and DAYCENT results are significantly correlated with observations.

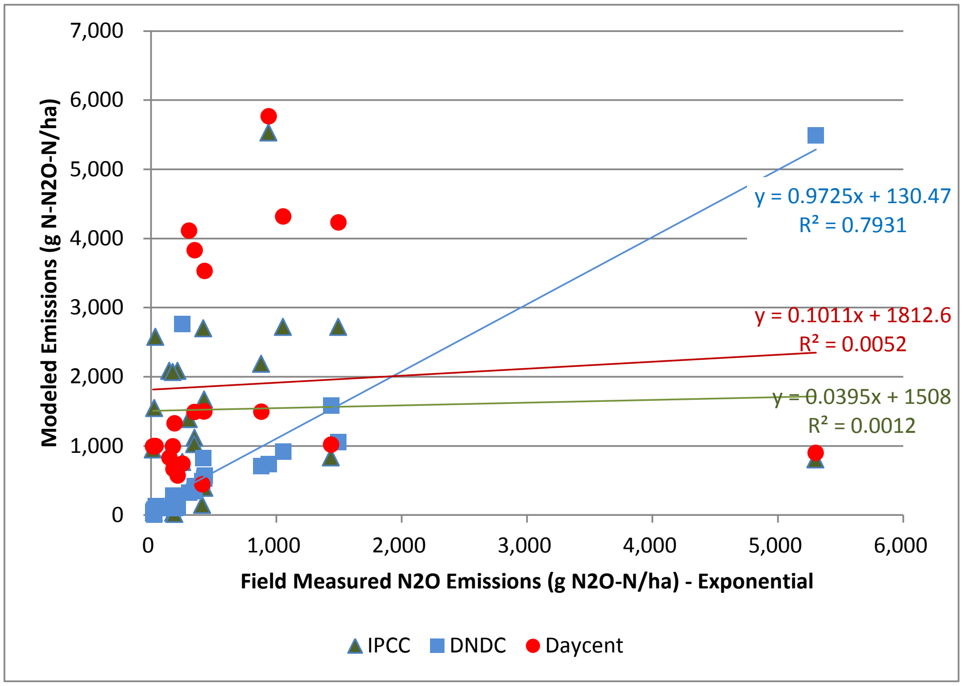

Figure 5. Comparison of IPCC-, DNDC- and DAYCENT-modeled annual or seasonal N_2O fluxes with measured N_2O fluxes (with exponential interpolation) for all the tested 23 datasets in California (IPCC: R^2=0.00, slope=0.04, p=0.876; DNDC: R^2=0.79, slope=0.97, p=0.001; Daycent: R^2=0.01, slope=0.10, p=0.743)

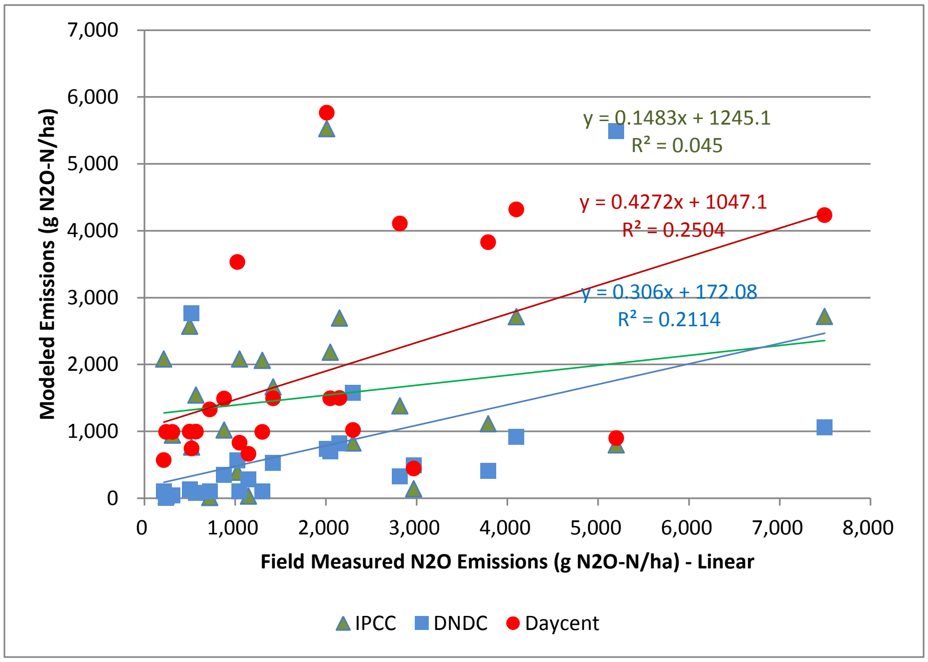

Figure 6. Comparison of IPCC, DNDC- and DAYCENT -modeled annual or seasonal N_2O fluxes with measured N_2O fluxes (with linear interpolation) for all the tested 23 datasets in California (IPCC: R^2=0.00, slope=0.15, p=0.331; DNDC: R^2=0.21, slope=0.31, p=0.027; Daycent: R^2=0.25, slope=0.43, p=0.015)

Table 5. Comparison of measured annual/seasonal N_2O fluxes with IPCC, DNDC and DAYCENT-modeled annual/seasonal N_2O fluxes for 23 datasets for California

Interpolation method for field data	Exponential interpolation			Linear interpolation		
Model	IPCC	DNDC	DAYCENT	IPCC	DNDC	DAYCENT
R^2	0.0012	0.7931	0.0052	0.0045	0.2116	0.2504
Slope	0.0395	0.9725	0.1011	0.1483	0.306	0.4272
p	0.876	0.001	0.743	0.331	0.027	0.015
Significance	Not significant	Very significant	Not significant	Not significant	Not significant	Not significant

4. Inventory of N_2O Emissions from Agricultural Lands in California

4.1. Regional database

To implement the simulations of N_2O emissions from California croplands, we established a database that would contain all the input information required by the DNDC model. The basic unit chosen for the modeling database was county, which has been frequently chosen for regional simulations of greenhouse gases emissions (e.g., Del Grosso et al., 2006; Li et al., 2005). In each county (totally 58 counties in California, Table 6), input information, including daily meteorological data of 2010 and 2011, atmospheric N deposition, areas of different cropping systems (totally 48 cropping systems in California), soil properties, and farming management practices, was collected and organized into a geospatial database to support the regional simulations.

In this project, daily meteorological data (maximum and minimum temperatures in ºC, precipitations in cm, and solar radiation in MJ/m2/day) were derived from weather data produced by the Daymet model (Thornton et al., 2012). Atmospheric N deposition data were extracted from the National Atmospheric Deposition Program (NADP) National Trends Network (NTN) stations (NADP, 2007). We estimated total N deposition as the sum of nitrate and ammonium (in annual average N concentration in rainfall). For any given county centroid in this simulation, we assumed that the data from the nearest station were representative for the county.

For area of croplands, field boundaries of different cropping systems were determined by using a combination of two datasets: for available survey areas, we used the California Department of Water Resources (DWR) Land Use Survey data; for areas where DWR data were not available, we used the USGS National Land Cover Dataset (NLCD).The area of each cropping system in any given county was then calculated based on the field boundaries of cropping systems. In California, approximately 3.81 million ha croplands have been included in the database and were simulated by the DNDC model for N_2O inventory.

Soil data, including bulk density, clay content, soil organic carbon (SOC) content, and pH, were determined based on the USDA Natural Resource Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (NRCS, 2012). We calculated the area-weighted soil attributes in each polygon of croplands. The maximum and minimum values of bulk density, clay content, fraction of SOC, and pH (Figure 7) in each county were then estimated by combining information of croplands distribution and soil attributes in each polygon of croplands. As shown in Figure 7, heterogeneities of soil properties appeared in each county, which may result in uncertainties in regional N_2O simulations (Li et al., 2005). To quantify the potential uncertainties during the simulations, the maximum and minimum values of soil attributes has been used to support the ‘‘most sensitive factor’’ method for regional simulations (Li et al., 2005) in this project.

Detailed information on farming management practices was determined by referring a range of studies about California agriculture, including cost and return studies for crop commodities produced in California provided by the University of California, Davis Agricultural and Resource Economics Department (http://coststudies.ucdavis.edu/), 2007 census of agriculture: California state and county data (USDA, 2009), and California's 2000-2009 greenhouse gas emissions inventory: technical support document (California Air Resources Board, 2011). The information on planting/harvest dates, tillage, fertilization, irrigation, flooding, manure amendment, and residue management has been included in the database. In addition, in order to better represent spatial variations in farming management practices within vineyard and almond orchard, we determined farming management practices of different parts (alley and row) in the California vineyard (Cooper et al., 2012; McGourty et al., 2008a, b; Smith et al., 2010; Verdegaal et al., 2012) and almond orchard (Connell et al., 2012; Duncan et al., 2011a, b; Freeman et al., 2008) based on information in the Cost and Return Studies (see http://coststudies.ucdavis.edu/current.php).

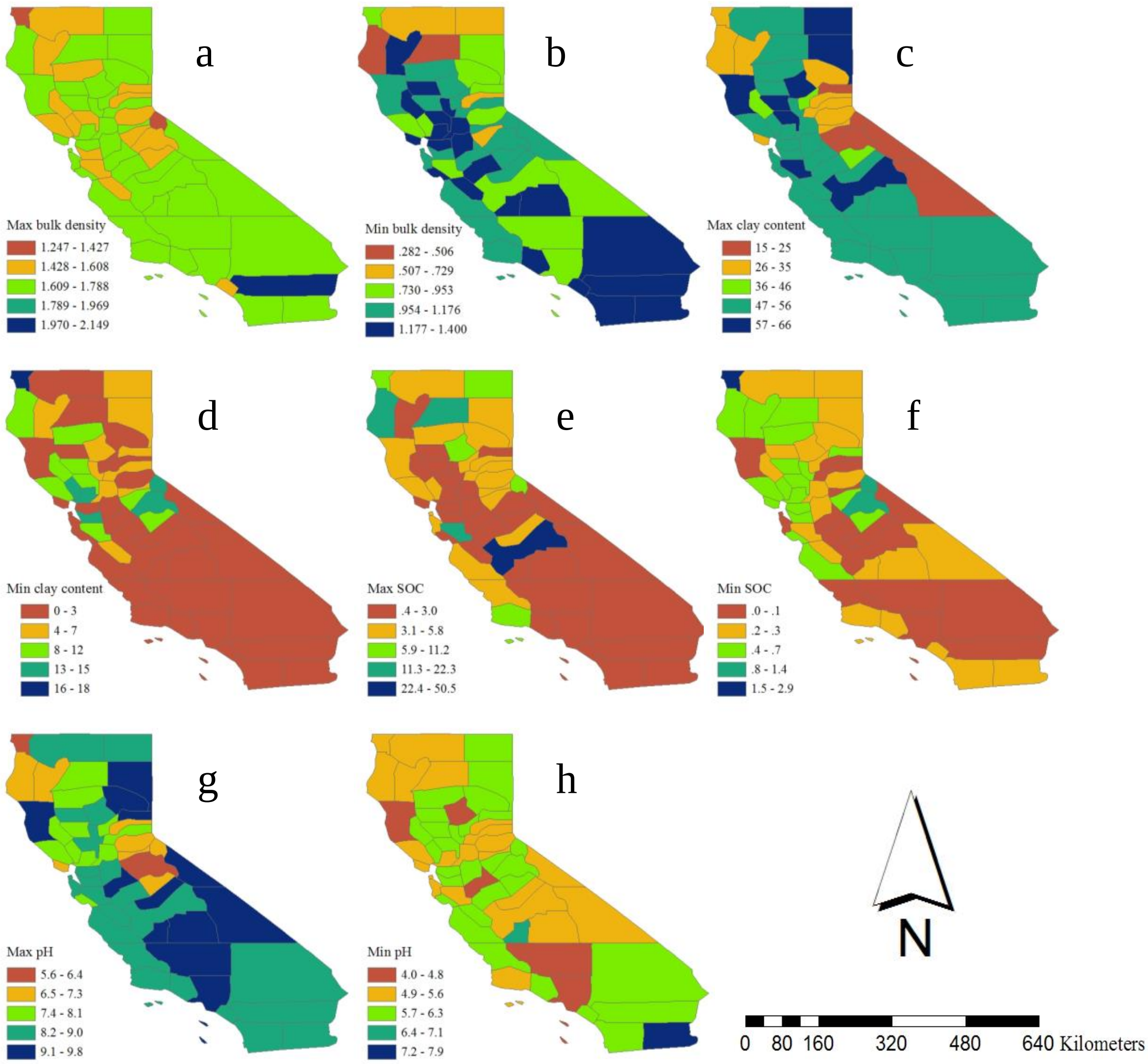

Figure 7. Maps of maximum and minimum (a and b) bulk density (g cm-3), (c and d) clay content (%), (e and f) soil organic carbon content (%), and (g and h) pH in California.

4.2. Regional Simulation

Regional simulation was conducted by linking DNDC to a GIS database which held all the input information of weather, soil, crop type and farming management practices for all the 3,806,481 hectares of cropland in 58 counties in CA. Driven by the input database, the DNDC was run for 2010 and 2011 across the state of California. The simulations in 2010 were used for model initiation and the modeled results in 2011 were summarized for analysis. Uncertainty due to soil inputs was addressed by applying the ‘‘most sensitive factor’’ method (Li et al., 2005). To do this, we ran DNDC for each cropping system in each county twice, once with low SOC, low pH, and high clay content, and once with high SOC, high pH, and low clay content, to produce a range in N_2O emissions wide enough to represent likely variations in actual fluxes caused by the heterogeneous of soil properties. The modeled gas fluxes are presented as a median with a variation range.

4.3.Baseline Inventory of N_2O Emissions in California

The simulations of total N_2O emission from California croplands in 2011 is 0.0072 $\pm$0.0041 Tg N yr^{-1} (or 3.49 $\pm$2.02 Tg CO_2 equivalent yr^{-1} by using the IPCC Second Assessment Report 100-year global warming potential of 310 kg CO_2-equivalents kg^{-1} for N_2O). Based on the simulations, 0.44% to 1.6% of the N in synthetic fertilizers, organic fertilizers and crop residues applied for cropland in CA was emitted as N_2O in 2011. We compared the DNDC modeled results with ARB reported emissions for IPCC category Nitrous Oxide from Agricultural Soil Management (California Air Resources Board, 2013). The appropriate categories for direct comparison include nitrogen applications in synthetic fertilizers and nitrogen in crop residues. The sum of these two source categories in the ARB inventory was 3.66 Tg CO_2 equivalent in 201.This value locates between the ranges of N_2O emissions (3.49 $\pm$2.02 Tg CO_2 equivalent) simulated by DNDC. It is a bit surprising that the DNDC estimates are close to the ARB estimate given that the two approaches had significant difference in total synthetic fertilizer use. Based on the nitrogen fertilizer application rates reported in the UCCE Cost and Return Studies, the total amount of N fertilizers applied for CA croplands was 0.555 Tg N. The ARB inventory used 0.773 Tg synthetic N fertilizers to calculate N_2O emissions (California Air Resources Board, 2011). Therefore, the fertilizer data used by ARB are approximately 40% higher than that used for the DNDC simulations. However, further comparison between the IPCC and DNDC methodologies can be conducted if the IPCC method can provide quantified uncertainties for its results and a consensus on the fertilizer amount can be reached.

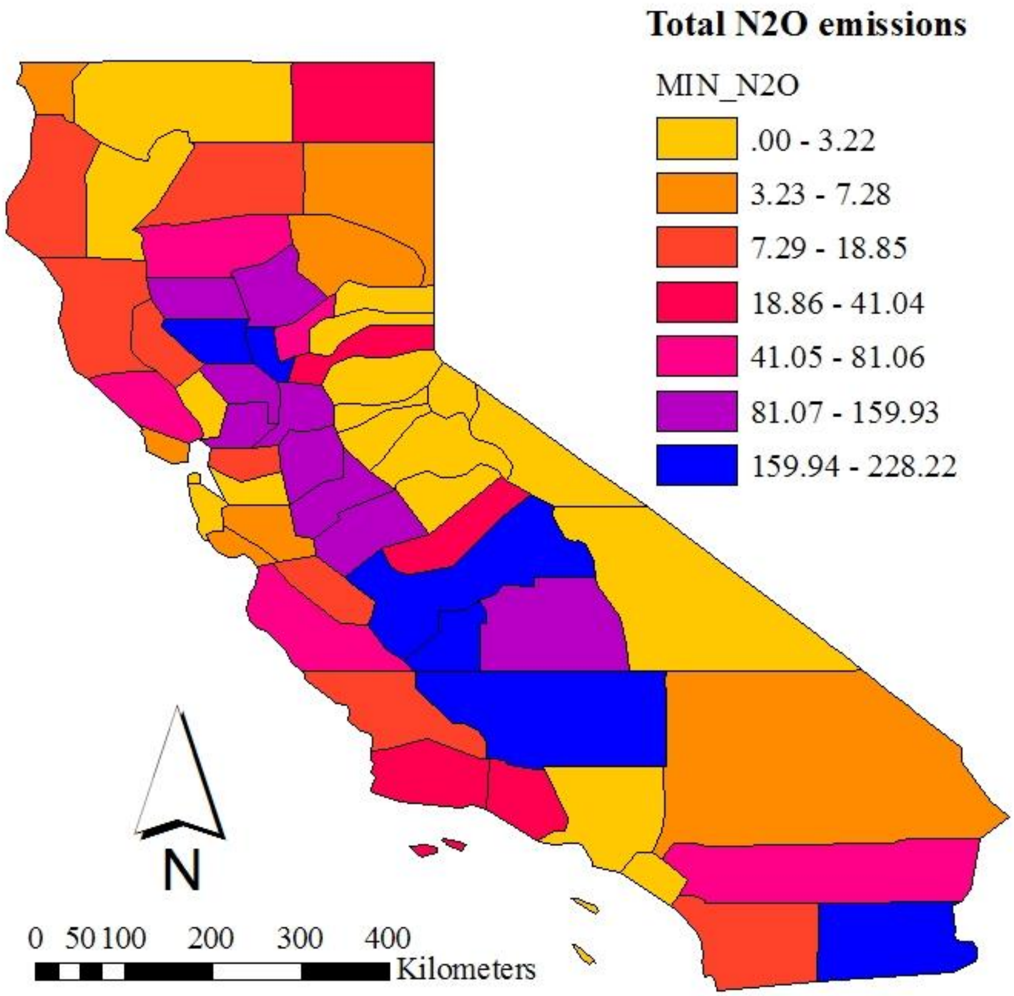

Figure 8. DNDC-simulated county-scale minimum N_2O emissions (Tg N yr^{-1}) from agricultural lands in California.

As shown in Figures 8-9 and Table 6, the simulations of total N_2O emissions from croplands were highly variable across different counties in California. The counties with significant N_2O emissions are usually located in the Central Valley of California. Therefore, this area may substantially contribute to the N_2O emissions in California. The variation in total N_2O emissions was apparently resulted from the difference in croplands area. However, other factors also obviously contributed to the variations of annual total N_2O emissions, which can be testified by the different N_2O emission rates (in kg N ha^{-1} yr^{-1}) across different counties (Table 6). The model results indicate that the N_2O emission rates were jointly affected by climate, soil properties, as well as farming management practices. DNDC usually predicted relative high rate of N_2O emission in those counties (e.g., Del Norte, Fresno, Santa Barbara, Shasta) with high temperature, SOC content, and/or dominated by cropping systems with high N application rate. Therefore, these factors should be considered when quantifying and mitigating N_2O emissions from California croplands. It should be noted that there is substantial uncertainty in our simulated N_2O emissions, especially in those counties where great heterogeneities of soil properties appeared. Studies on decreasing uncertainty of soil properties in input database are necessary to make the model predictions more accurate.

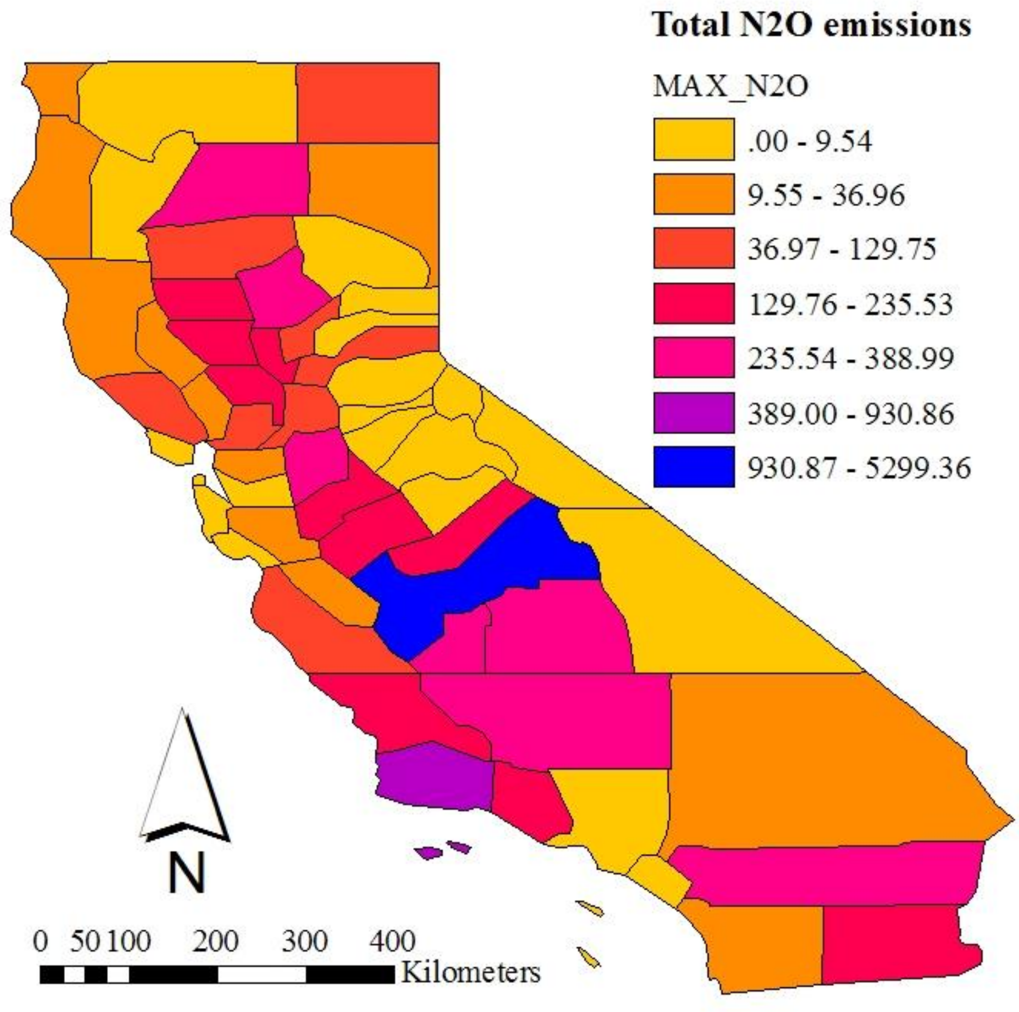

Figure 9. DNDC-simulated county-scale maximum N_2O emissions (Tg N yr^{-1}) from agricultural lands in California.

Table 6. Area of croplands, total N_2O emissions and N_2O emission rate at county and state scales in California

	Cropland areas (ha)	Total N_2O emissions (metric tons N yr-1)		N_2O emission rate (kg N ha-1 yr-1)	
		Min	Max	Min	Max
Alameda	4117	3.22	4.05	0.78	0.98
Alpine	1724	1.04	2.78	0.60	1.61
Amador	3682	2.51	6.85	0.68	1.86
Butte	94589	150.64	306.98	1.59	3.25
Calaveras	1340	1.54	1.55	1.15	1.15
Colusa	114345	201.12	235.53	1.76	2.06
Contra Costa	16148	16.26	19.99	1.01	1.24
Del Norte	3951	4.23	19.71	1.07	4.99
El Dorado	250	0.29	0.88	1.18	3.53
Fresno	478525	215.68	5299.36	0.45	11.07
Glenn	98497	121.13	149.39	1.23	1.52
Humboldt	19920	10.48	15.04	0.53	0.76
Imperial	212884	195.89	233.05	0.92	1.09
Inyo	1588	0.15	0.85	0.10	0.54
Kern	326417	175.29	388.99	0.54	1.19
Kings	199771	228.22	299.40	1.14	1.50
Lake	13682	10.56	12.73	0.77	0.93
Lassen	54855	7.02	12.75	0.13	0.23
Los Angeles	6001	0.74	1.83	0.12	0.31
Madera	138529	35.92	182.95	0.26	1.32

Marin	1402	3.91	6.21	2.79	4.43
Mariposa	1467	1.05	1.92	0.71	1.31
Mendocino	22358	18.80	36.96	0.84	1.65
Merced	216102	116.66	187.99	0.54	0.87
Modoc	75320	29.77	89.31	0.40	1.19
Mono	13206	0.78	4.17	0.06	0.32
Monterey	120091	81.06	119.26	0.67	0.99
Napa	20279	3.09	13.30	0.15	0.66
Nevada	650	0.44	1.64	0.68	2.53
Orange	80	0.03	0.08	0.42	0.95
Placer	23340	41.04	67.07	1.76	2.87
Plumas	16883	7.28	8.32	0.43	0.49
Riverside	98943	60.28	264.43	0.61	2.67
Sacramento	65037	111.70	129.75	1.72	2.00
San Benito	17770	10.84	16.66	0.61	0.94
San Bernardino	12403	3.92	14.09	0.32	1.14
San Diego	28940	12.57	21.04	0.43	0.73
San-Francisco	0	0.00	0.00		
San Joaquin	215349	159.93	295.96	0.74	1.37
San Luis Obispo	39621	10.42	169.49	0.26	4.28
San Mateo	204	0.30	0.30	1.49	1.45
Santa Barbara	47226	24.30	930.86	0.51	19.71
Santa Clara	6596	7.22	33.80	1.09	5.12

Santa Cruz	8417	6.02	7.01	0.71	0.83
Shasta	29692	18.85	270.32	0.63	9.10
Sierra	7697	2.39	4.02	0.31	0.52
Siskiyou	72557	2.95	9.54	0.04	0.13
Solano	64518	103.87	118.86	1.61	1.84
Sonoma	35522	49.75	63.04	1.40	1.77
Stanislaus	146456	123.59	209.29	0.84	1.43
Sutter	114093	181.65	190.47	1.59	1.67
Tehama	41558	49.71	60.84	1.20	1.46
Trinity	1407	1.18	1.19	0.84	0.84
Tulare	260516	132.00	354.15	0.51	1.36
Tuolumne	638	0.78	1.03	1.22	1.62
Ventura	39801	31.93	212.21	0.80	5.33
Yolo	112214	133.91	168.19	1.19	1.50
Yuba	37311	64.54	87.34	1.73	2.34
California state	3806481	2990.44	11364.78	0.79	2.99

4.4. Crop type-sorted N_2O, CH_4 and CO_2 Emissions in California

DNDC simulates not only N_2O fluxes but also the major pools and fluxes of C or N in agroecosystems, which include methane (CH_4) and carbon dioxide (CO_2) fluxes. The modeled results provided an opportunity to assess a whole span of greenhouse gas (GHG) emissions from the agricultural lands in CA. In addition, DNDC quantifies uncertainty of the modeled GHG fluxes based on the uncertainty in combination of cropping systems and soil properties at county scale. The uncertainty is presented in the report as a variation range attached to a median.

The modeled annual emissions of N_2O, CH_4 and CO_2 from CA were 0.0072 ± 0.0041Tg N, 0.066 ± 0.048 Tg C and -1.58 ± 2.58 Tg C, respectively (1 Tg = 1×10^{12} g or 1 million metric tons). The GWP values of the N_2O, CH_4 and CO_2 emissions from CA were 3.49 ± 2.02, 2.19 ± 1.59 and -5.79 ± 9.46 Tg CO_2 equivalent yr^{-1}, respectively with a sum of -0.113 ± 10.39 Tg CO_2 equivalent yr^{-1}. The modeled N_2O emission (3.49 ± 2.02 Tg CO_2 equivalent yr^{-1}) is comparable with the 2011 N_2O emission (3.66 Tg carbon dioxide equivalent yr^{-1}) formerly reported by CA Air Resource Board (ARB).

Table 7 shows crop type-sorted emissions of N_2O, CH_4 and CO_2 from CA. The major N_2O emitter crops are cotton (14%), corn 14%) and rice (13%). Rice is the sole CH_4 emitter which emitted 0.100 ±0.013 Tg CH_4-C in 2011. All the upland crops consumed the atmospheric CH_4 but with negligible magnitudes. The major CO_2 emitters are cotton (37%), tomato (21%) and pasture (10%); and the major CO_2 sequestering crops are alfalfa (44%), grape (25%) and corn (15%). Alfalfa showed high rate in C sequestration due to its high production of root biomass.

We converted the gas fluxes into GWP values so that comparison could be conducted across the crop types and gases. The results shown in Table 8 indicate that (1) N_2O is the leading GHG from the CA agricultural soils, (2) CH_4 emitted from CA rice production also makes non-negligible contribution to the warming effect, (3) the CA agricultural soils seem sequestering C (-5.11 Tg CO_2 equivalent yr^{-1}) although the magnitude is highly uncertain (± 9.46 Tg CO_2 equivalent yr^{-1}), and (4) the entire CA agriculture seems close to a neutral status regarding its contribution to global warming (-0.11 Tg CO_2 equivalent yr^{-1}) although the uncertainty is large (± 10.39 Tg CO_2 equivalent yr^{-1}) (Table 9). The uncertainty in the modeled results could be reduced if the spatial databases can be improved by refining the simulated unit from the current county to sub-county scale with better specified combinations between cropping systems and soil properties.

Table 7. DNDC-modeled crop type-sorted N_2O, CH_4 and CO_2 emissions from agricultural soils in California

Crop type	N_2O (Tg N)			CH_4 (Tg C)			CO_2 (Tg C)		
Cotton	0.00124	±	0.00097	-0.004	±	0.004	0.453	±	0.501
Corn	0.00089	±	0.00041	-0.002	±	0.002	-0.442	±	0.150
Rice	0.00065	±	0.00009	0.100	±	0.013	0.008	±	0.124
Grape_alley	0.00063	±	0.00062	-0.003	±	0.003	-0.688	±	0.130
Pasture	0.00048	±	0.00023	-0.003	±	0.002	0.116	±	0.199
Tomattos	0.00042	±	0.00021	-0.002	±	0.002	0.257	±	0.340
Small_grain_hay	0.00032	±	0.00003	-0.001	±	0.001	-0.119	±	0.030
Winwheat	0.00029	±	0.00014	-0.001	±	0.001	-0.113	±	0.066
Lettuce	0.00021	±	0.00009	-0.001	±	0.001	-0.010	±	0.091
Alfalfa	0.00021	±	0.00019	-0.004	±	0.004	-1.236	±	0.146
Onions	0.00019	±	0.00017	0.000	±	0.000	0.065	±	0.072
Other_hay	0.00018	±	0.00005	0.000	±	0.000	0.041	±	0.062
Orange	0.00013	±	0.00009	-0.001	±	0.001	-0.026	±	0.060
Brocollis	0.00012	±	0.00011	-0.001	±	0.001	0.060	±	0.055
Almonds_row	0.00012	±	0.00010	-0.002	±	0.002	-0.004	±	0.080
Dry_Beans	0.00010	±	0.00005	0.000	±	0.000	-0.007	±	0.025
Walnut	0.00009	±	0.00001	-0.001	±	0.001	-0.001	±	0.039
Melons	0.00008	±	0.00006	-0.001	±	0.001	0.042	±	0.045
Peppers	0.00006	±	0.00003	0.000	±	0.000	0.010	±	0.009
Avocados	0.00006	±	0.00005	0.000	±	0.000	-0.009	±	0.021
Lemons	0.00006	±	0.00004	0.000	±	0.000	-0.003	±	0.012
Sugarbeets	0.00005	±	0.00003	0.000	±	0.000	0.012	±	0.015
Cauliflower	0.00005	±	0.00004	0.000	±	0.000	0.021	±	0.019
Strawberries	0.00004	±	0.00004	0.000	±	0.000	0.015	±	0.022
Prunes	0.00004	±	0.00001	0.000	±	0.000	-0.010	±	0.014
Safflowers	0.00004	±	0.00001	0.000	±	0.000	-0.015	±	0.010
Almonds_alley	0.00004	±	0.00004	-0.001	±	0.001	-0.041	±	0.016
Grape_row	0.00004	±	0.00002	0.000	±	0.000	-0.011	±	0.023
Potatos	0.00003	±	0.00000	0.000	±	0.000	0.002	±	0.009
Peach	0.00003	±	0.00003	-0.001	±	0.001	-0.003	±	0.030
Olives	0.00003	±	0.00001	0.000	±	0.000	-0.006	±	0.008
Pistachios	0.00003	±	0.00003	-0.001	±	0.001	0.005	±	0.032
Beans_green	0.00003	±	0.00003	0.000	±	0.000	0.016	±	0.010
Barley	0.00003	±	0.00002	0.000	±	0.000	-0.002	±	0.009
Carrots	0.00002	±	0.00002	0.000	±	0.000	0.013	±	0.012
Fallow	0.00002	±	0.00002	-0.001	±	0.001	0.051	±	0.048
Plums	0.00002	±	0.00001	0.000	±	0.000	-0.003	±	0.015
Cabbage	0.00002	±	0.00001	0.000	±	0.000	0.009	±	0.006
Oats	0.00001	±	0.00001	0.000	±	0.000	-0.017	±	0.001
Sorghum	0.00001	±	0.00000	0.000	±	0.000	-0.005	±	0.001
Artichokes	0.00001	±	0.00001	0.000	±	0.000	0.004	±	0.004
Sweet_Potatos	0.00001	±	0.00000	0.000	±	0.000	-0.001	±	0.001
Sunflowers	0.00001	±	0.00000	0.000	±	0.000	0.000	±	0.002
Asparagus	0.00001	±	0.00000	0.000	±	0.000	0.006	±	0.006
Dates	0.00001	±	0.00000	0.000	±	0.000	-0.003	±	0.002
Apples	0.00000	±	0.00000	0.000	±	0.000	0.000	±	0.004
Figs	0.00000	±	0.00000	0.000	±	0.000	-0.003	±	0.003
Cherries	0.00000	±	0.00000	0.000	±	0.000	-0.004	±	0.003
Apricots	0.00000	±	0.00000	0.000	±	0.000	-0.003	±	0.001
Pears	0.00000	±	0.00000	0.000	±	0.000	-0.001	±	0.001
Sum	0.00716	±	0.00414	0.066	±	0.048	-1.578	±	2.580

Table 8. Crop-sorted N_2O, CH_4 and CO_2 emissions in GWP from agricultural soils in California

Crop type	N2O			CH4			CO2			GWP		
	Tg CO2e			Tg CO2e			Tg CO2e			Tg CO2e		
Rice	0.316	±	0.045	3.345	±	0.442	0.031	±	0.456	3.693	±	0.942
Cotton	0.603	±	0.473	-0.121	±	0.121	1.660	±	1.839	2.142	±	2.190
Tomattos	0.206	±	0.103	-0.056	±	0.056	0.943	±	1.246	1.093	±	1.294
Pasture	0.232	±	0.112	-0.084	±	0.079	0.424	±	0.729	0.571	±	0.762
Onions	0.091	±	0.081	-0.012	±	0.012	0.238	±	0.264	0.316	±	0.332
Brocollis	0.058	±	0.052	-0.020	±	0.020	0.222	±	0.201	0.260	±	0.233
Other_hay	0.090	±	0.023	-0.016	±	0.014	0.152	±	0.226	0.226	±	0.234
Melons	0.041	±	0.028	-0.020	±	0.020	0.155	±	0.166	0.177	±	0.174
Fallow	0.010	±	0.009	-0.043	±	0.041	0.188	±	0.178	0.154	±	0.146
Cauliflower	0.023	±	0.019	-0.005	±	0.005	0.078	±	0.069	0.095	±	0.082
Strawberries	0.021	±	0.018	-0.005	±	0.005	0.056	±	0.081	0.073	±	0.095
Beans_green	0.015	±	0.012	-0.003	±	0.003	0.059	±	0.037	0.071	±	0.046
Sugarbeets	0.026	±	0.017	-0.004	±	0.004	0.042	±	0.056	0.064	±	0.069
Peppers	0.030	±	0.016	-0.005	±	0.005	0.038	±	0.035	0.064	±	0.046
Carrots	0.011	±	0.008	-0.006	±	0.006	0.047	±	0.042	0.051	±	0.044
Cabbage	0.008	±	0.006	-0.002	±	0.002	0.033	±	0.020	0.039	±	0.024
Lettuce	0.104	±	0.043	-0.034	±	0.034	-0.036	±	0.334	0.034	±	0.343
Potatos	0.017	±	-0.001	-0.003	±	0.003	0.009	±	0.034	0.023	±	0.030
Asparagus	0.003	±	0.002	-0.005	±	0.005	0.023	±	0.024	0.020	±	0.020
Artichokes	0.005	±	0.003	-0.002	±	0.002	0.015	±	0.014	0.018	±	0.015
Dry_Beans	0.047	±	0.024	-0.010	±	0.010	-0.027	±	0.090	0.010	±	0.104
Pistachios	0.016	±	0.015	-0.027	±	0.027	0.019	±	0.116	0.008	±	0.104
Lemons	0.027	±	0.020	-0.009	±	0.009	-0.012	±	0.045	0.006	±	0.057
Sunflowers	0.004	±	0.000	-0.003	±	0.003	0.001	±	0.006	0.001	±	0.003
Barley	0.014	±	0.011	-0.007	±	0.006	-0.007	±	0.032	0.001	±	0.036
Walnut	0.042	±	0.004	-0.040	±	0.040	-0.002	±	0.144	0.000	±	0.108
Sweet_Potatos	0.004	±	0.001	-0.001	±	0.001	-0.004	±	0.003	-0.001	±	0.003
Apples	0.002	±	0.002	-0.005	±	0.005	0.001	±	0.014	-0.001	±	0.012
Pears	0.001	±	0.000	-0.002	±	0.002	-0.005	±	0.002	-0.006	±	0.001
Dates	0.003	±	0.002	-0.002	±	0.002	-0.009	±	0.006	-0.008	±	0.007
Plums	0.010	±	0.007	-0.008	±	0.008	-0.011	±	0.055	-0.010	±	0.054
Olives	0.016	±	0.004	-0.006	±	0.006	-0.020	±	0.029	-0.010	±	0.027
Figs	0.002	±	0.001	-0.002	±	0.002	-0.010	±	0.010	-0.011	±	0.009
Apricots	0.001	±	0.000	-0.002	±	0.002	-0.011	±	0.005	-0.012	±	0.003
Sorghum	0.005	±	0.002	-0.001	±	0.001	-0.018	±	0.003	-0.015	±	0.004
Peach	0.016	±	0.014	-0.020	±	0.020	-0.012	±	0.109	-0.015	±	0.103
Cherries	0.001	±	0.001	-0.003	±	0.003	-0.013	±	0.009	-0.016	±	0.007
Avocados	0.028	±	0.023	-0.011	±	0.011	-0.035	±	0.076	-0.018	±	0.088
Prunes	0.021	±	0.003	-0.011	±	0.011	-0.038	±	0.052	-0.028	±	0.043
Almonds_row	0.058	±	0.049	-0.074	±	0.074	-0.016	±	0.292	-0.033	±	0.267
Grape_row	0.017	±	0.008	-0.015	±	0.015	-0.041	±	0.084	-0.040	±	0.077
Safflowers	0.020	±	0.005	-0.009	±	0.009	-0.055	±	0.036	-0.044	±	0.032
Oats	0.006	±	0.004	-0.003	±	0.003	-0.064	±	0.003	-0.061	±	0.004
Orange	0.065	±	0.045	-0.046	±	0.046	-0.094	±	0.220	-0.075	±	0.219
Almonds_alley	0.020	±	0.020	-0.041	±	0.041	-0.149	±	0.059	-0.170	±	0.038
Small_grain_hay	0.155	±	0.015	-0.026	±	0.026	-0.436	±	0.109	-0.308	±	0.099
Winwheat	0.140	±	0.070	-0.041	±	0.040	-0.414	±	0.240	-0.315	±	0.270
Corn	0.432	±	0.201	-0.061	±	0.061	-1.622	±	0.549	-1.252	±	0.689
Grape_alley	0.306	±	0.302	-0.109	±	0.109	-2.523	±	0.478	-2.327	±	0.286
Alfalfa	0.103	±	0.093	-0.119	±	0.118	-4.533	±	0.535	-4.549	±	0.511
Sum	3.489	±	2.018	2.185	±	1.591	-5.787	±	9.461	-0.113	±	10.386

Table 9. DNDC-modeled annual greenhouse gas emissions from agricultural soils in California (Unit: Tg = 10^{12} g or million metric tons)

Greenhouse gas	N_2O	CH_4	CO_2*	Sum
Total emission	0.0072 ± 0.0041 Tg N	0.066 ± 0.048 Tg C	-1.58 ± 2.58 Tg C	
GWP** (Tg CO_2 equivalent yr^{-1})	3.49 ± 2.02	2.19 ± 1.59	-5.79 ± 9.46	-0.11 ± 10.39
Major contributors	Major emitter: cotton (14%), corn 14%), rice (13%)	Major emitter: rice 100%	Major emitters: cotton (37%), tomato (21%), pasture (10%); Major sequesters: alfalfa (44%), grape (25%), corn (15%)	

* Net CO_2 emission, equal to annual change in soil organic carbon (SOC) storage;

** GWP stands for global warming potential expressed as CO_2 equivalent.

5. Technology Transfer of Modeling System to ARB

The project held a series of discussions with ARB staff regarding how to transfer the DNDC modeling system to ARB staff in a way that would make it relatively easy to make routine updates to the DNDC input data to facilitate statewide simulations. There are two approaches for regional modeling with DNDC. The first and easiest approach is to use DNDC in regional mode where spatially explicit information on DNDC inputs are provided in tab-delimited text input files. The second approach is to run DNDC using batch mode with individual site inputs. Using the batch mode has more flexibility as it allows users to define detailed cropping and management systems using the site mode interface. The downside of using batch mode is that it requires customized scripting to efficiently process a large number of site input files and post process model output. These pros and cons were discussed with ARB staff. It was decided that 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.

Inputs processing

The DNDC regional database format includes the following 10 tab-delimited text 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.

We have created a spreadsheet with a set of tables based on the input text files. 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, and how to simulate greenhouse gas emission flux (either methane, nitrous oxide, dSOC) and irrigation (either with or without irrigation).

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. These files can then be used to start a simulation via the DNDC GUI.

Retrieving weather data

The initial California crops regional simulations used DAYMET weather data – DAYMET is free and readily available, covers the entirety of the continental US, and is designed to facilitate ecological and other modeling. We have created a tool that builds on DAYMET's freely available multiple coordinates downloader tool. The Python script-based tool does the following things:

- Retrieves county centroids (latitude and longitude)

- Calls the DAYMET multiple coordinates downloader and downloads DAYMET format weather data
- Converts DAYMET format files to DNDC format climate files
- Installs the DNDC climate files in the proper location so that simulations can be initiated without any other climate file management

Outputs processing

DNDC regional mode returns output files with annual per acre results in native units (e.g. nitrous oxide emissions are returned in units of kg N/ac/y). Also, some winegrape and almond systems are built to be post-processed to return "whole field" results (in the existing database, alley and row management were split into two systems because of contrasting management and crops on vineyard/orchard alleys and rows).

For each county and each crop, the Python script-based tool calculates:

- Area-weighted whole field results for split crop systems
- Indirect nitrous oxide emissions
- Greenhouse gas emissions in units of kgCO2e/ha/y
- Combined global warming potential
- Totals for all results based on county / crop area

Post-processed results are returned in .CSV format to facilitate import into Microsoft Excel or other spreadsheet processing software for additional analyses.

6. Summary and Conclusions

The project has provided an opportunity to establish close communications between field workers and modelers by sharing a same focus on N_2O emissions from agricultural production in California. Through the collaboration, DNDC has been extensively validated for the first time across a wide range of cropping systems including specialty crops such as vine and tree crops under the CA climate, soil and management conditions. The validation results indicated that DNDC when calibrated for crop yields can provide a reasonable estimate of N_2O emissions for the varied crops and cropping systems found in California.

The modeling practice has demonstrated DNDC's flexibility for modeling the broad range of crops and cropping management systems that drive California agriculture. Based on the regional modeling results, it appears that the current ARB inventory estimate of direct nitrous oxide emissions from nitrogen fertilizers and crop residues is low.

7. **Recommendations**

Continued validation of DNDC with new field data from additional studies will enhance our understanding of model uncertainty and identify areas for model improvement. Potential further improvements in the modeling system would include (1) modeling spatially differentiated N_2O fluxes from different locations within a same field by obtaining precise data of the spatial physical and chemical conditions in the field, (2) improving crop parameters especially for the tree crops and (3) improvements in extrapolating field measurements to seasonal and annual emissions.

The DNDC modeling system has built off significant investment in field data collection to improve statewide estimates of N_2O emissions. Hence, at its current status, the DNDC modeling system can be still used to augment the statewide inventory for California. However, there are signification opportunities to improve the modeling system to enhance the inventory. Potential improvements include:

- ✓ Improving the fidelity of the spatial databases to reduce the uncertainty due to cropping system and soil drivers. Uncertainty in soil drivers led to a large uncertainty in modeled N_2O emissions (1.46 to 5.54 million MT CO_2eq).
- ✓ Improved estimates of actual fertilizer use by crops to harmonize assumptions on fertilizer use between existing ARB inventory and DNDC databases.
- ✓ Include manure use in the DNDC simulations. Based on the ARB activity approximately 0.4 MMT N in managed and unmanaged manure in California. CEC, National Milk Producers, National Pork Board and USDA have invested in the development of ManureDNDC for ammonia and greenhouse gas emissions modeling. ARB and others have supported the collection of GHG emission data from land application of manure in California. These data could be used to validate DNDC.

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Appendix A: Daily DNDC Model Validation Results

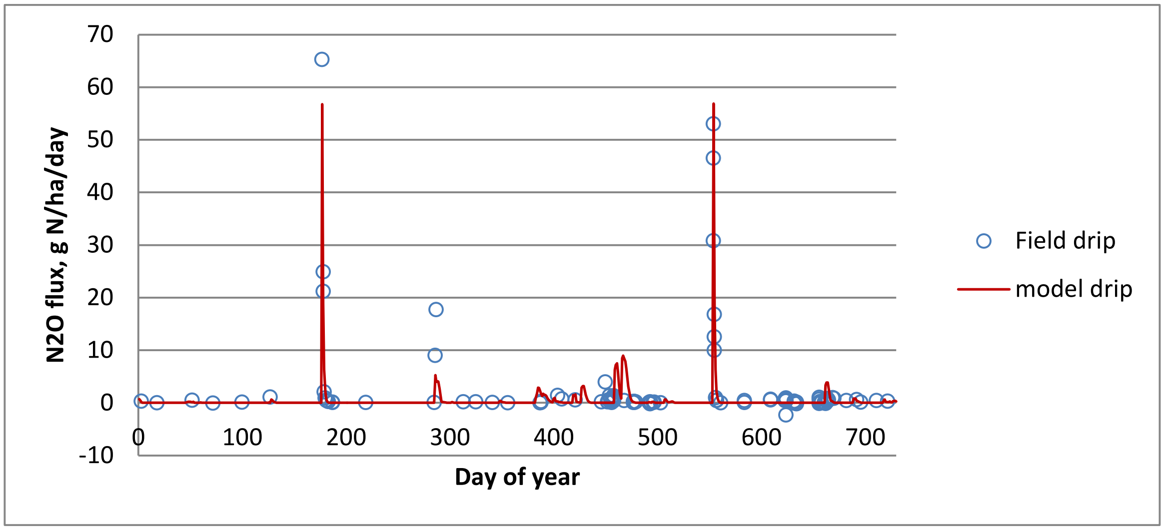

Figure A-1a. Comparison between measured and DNDC-modeled daily N_2O fluxes from drip position in a vineyard field in Oakville, CA in 2009-2010 (field data from Dave Smart)

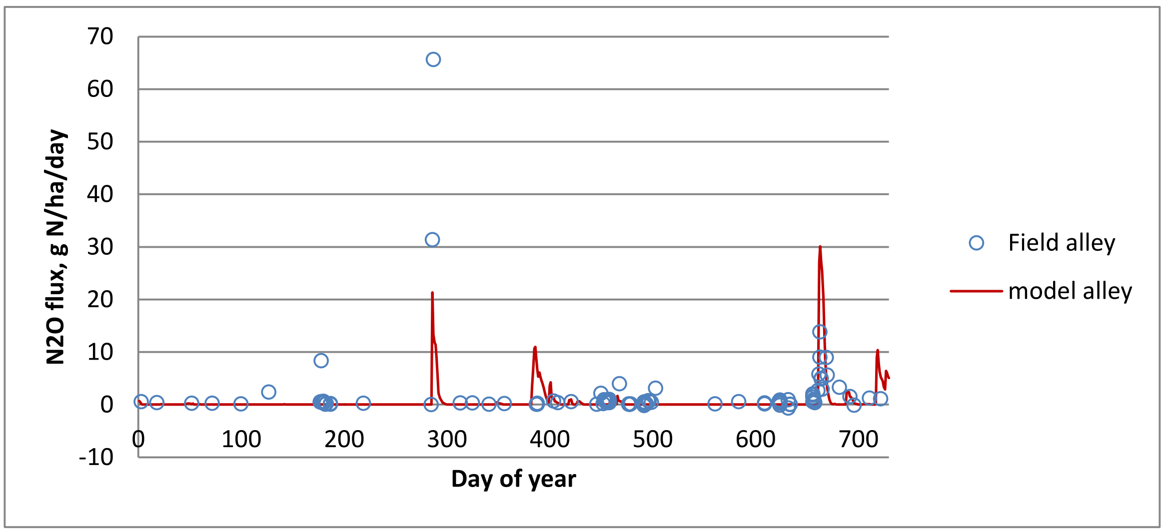

Figure A-1b. Comparison between measured and DNDC-modeled daily N_2O fluxes from alley position in a vineyard field in Oakville, CA in 2009-2010 (field data from Dave Smart)

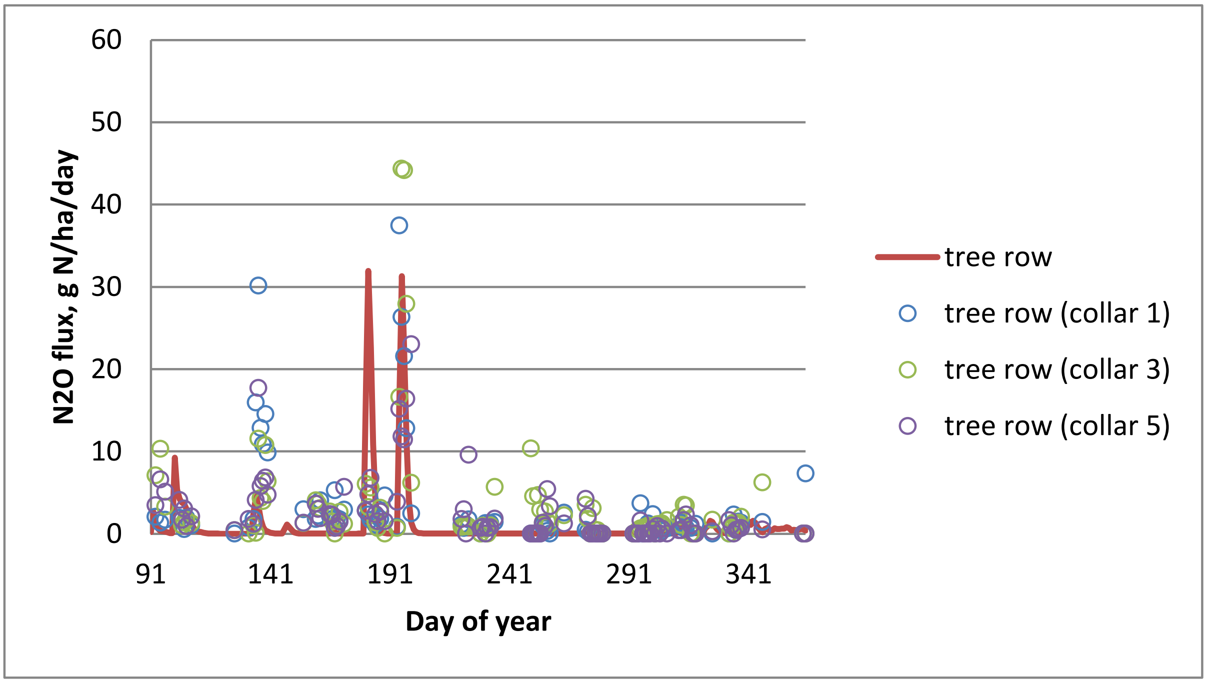

Figure A-2a. Comparison between measured and DNDC-modeled daily N_2O fluxes from position of tree in an almond field in Davis, CA in 2010 (field data from Johan Six)

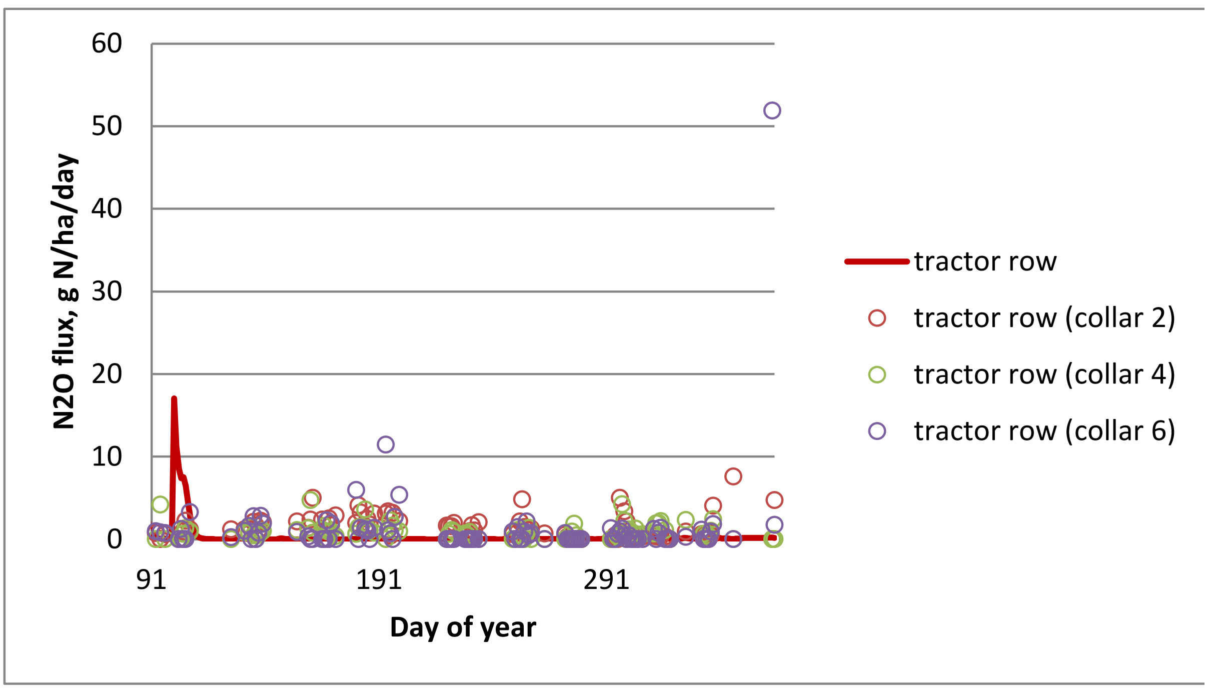

Figure A-2b. Comparison between measured and DNDC-modeled daily N_2O fluxes from position of tractor in an almond field in Davis, CA in 2010 (field data from Johan Six)

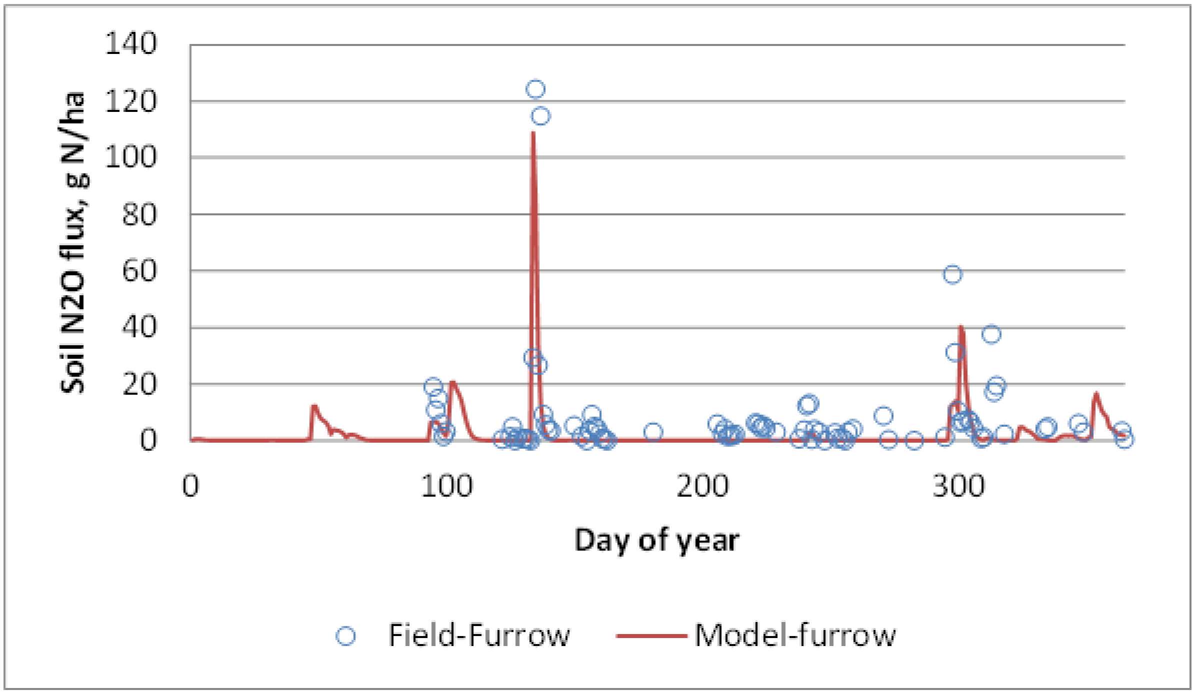

Figure A-3a. Comparison between measured and DNDC-modeled daily N_2O fluxes from position of furrow in a tomato field (Field 31) in Yolo, CA in 2010 (field data from Johan Six)

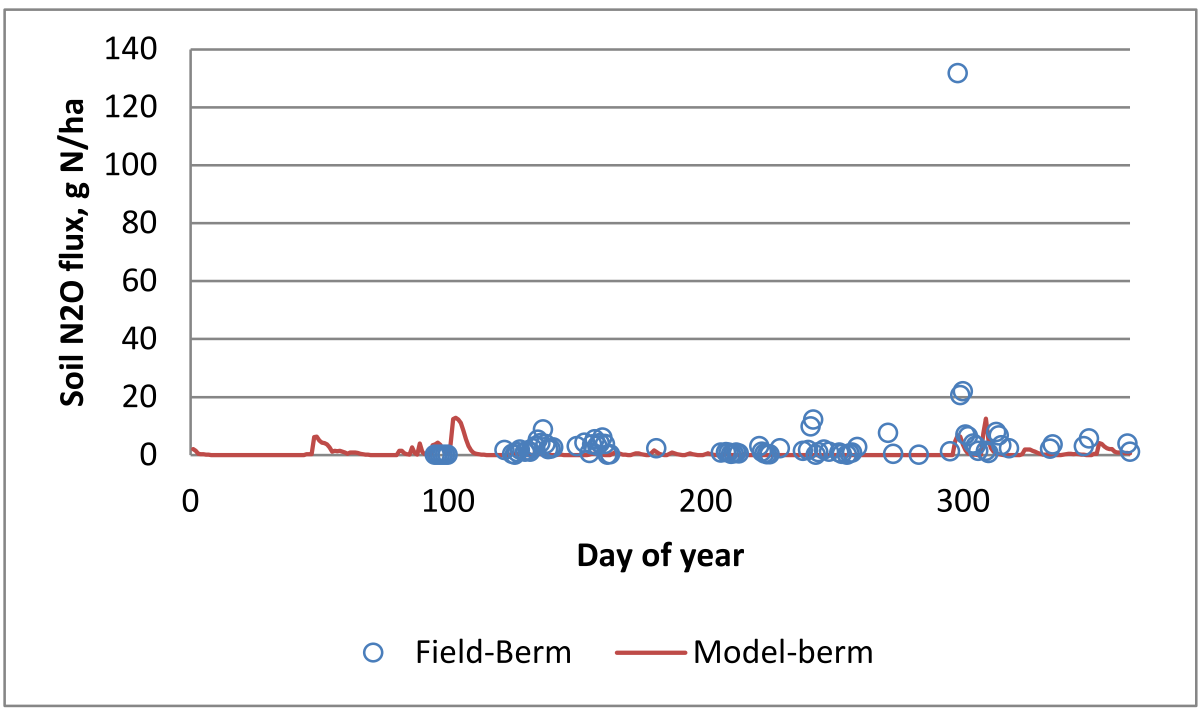

Figure A-3b. Comparison between measured and DNDC-modeled daily N_2O fluxes from position of berm in a tomato field (Field 31) in Yolo, CA in 2010 (field data from Johan Six)

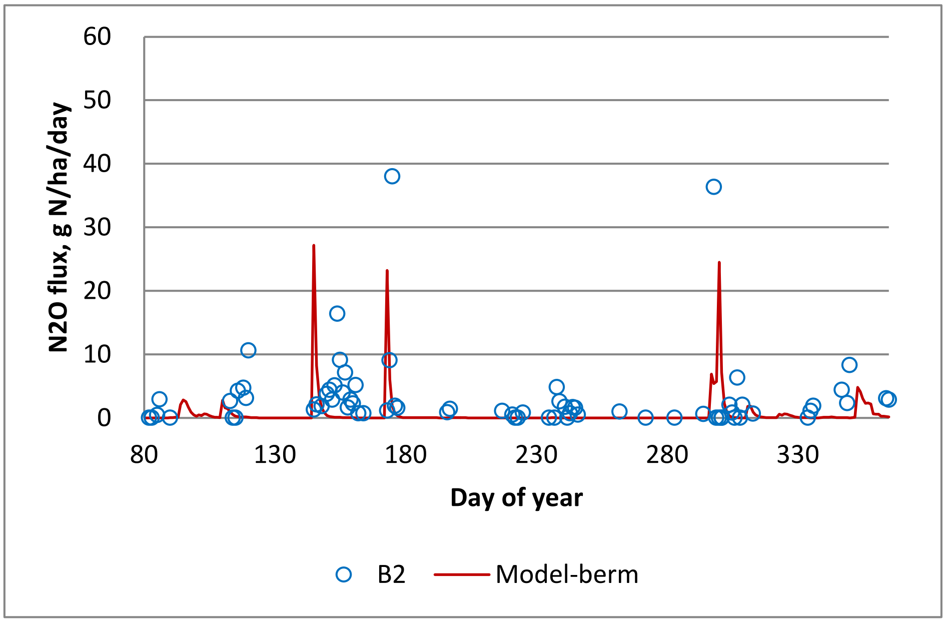

Figure A-4a. Comparison between measured and DNDC-modeled daily N_2O fluxes from position of berm in a tomato field (Field 10) in Davis, CA in 2010 (field data from Johan Six)

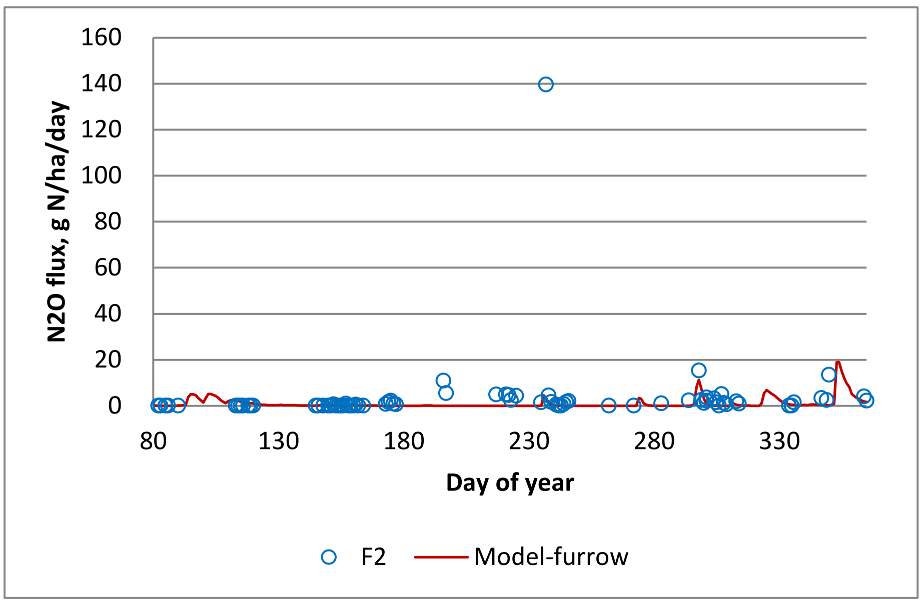

Figure A-4b. Comparison between measured and DNDC-modeled daily N_2O fluxes from position of furrow in a tomato field (Field 10) in Davis, CA in 2010 (field data from Johan Six)

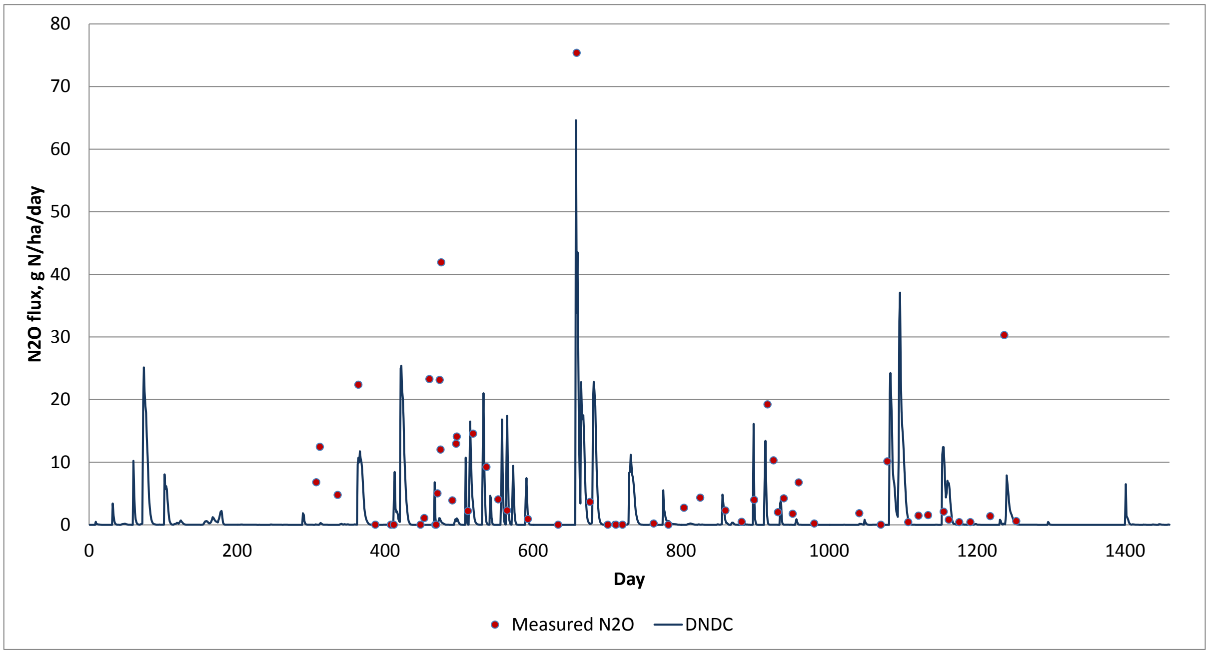

Figure A-5. Comparison between measured and DNDC-modeled daily N_2O fluxes from a field rotated with winter wheat-corn-sunflower-beans with standard tillage in Davis, CA in 2003-2006 (field data from Johan Six)

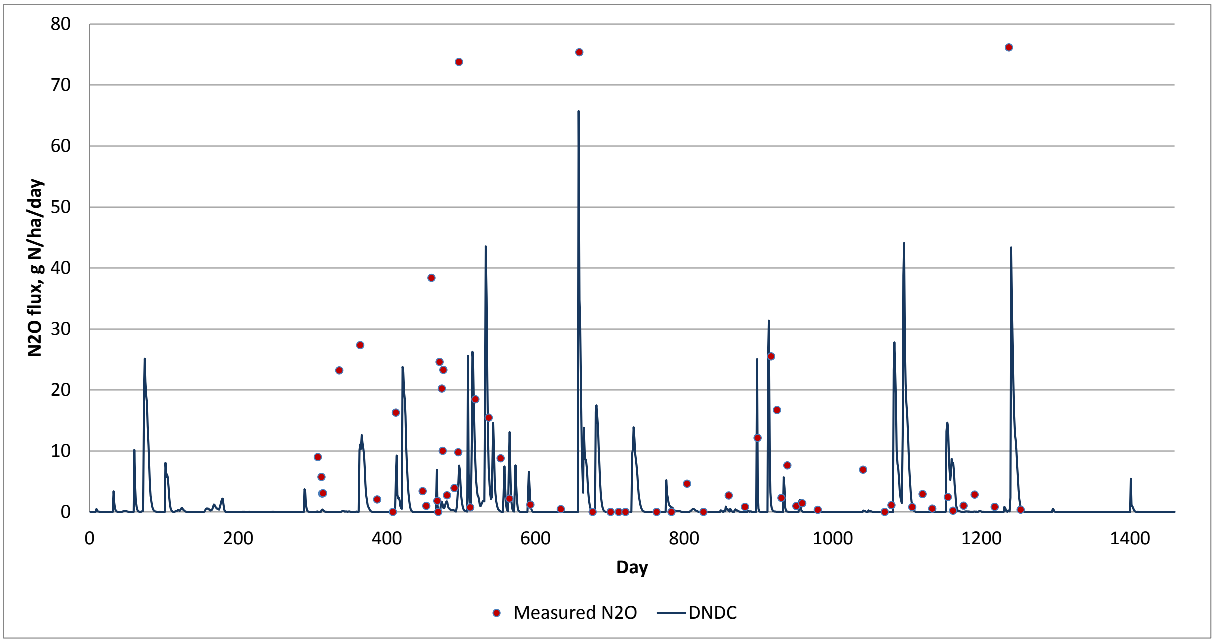

Figure A-6. Comparison between measured and DNDC-modeled daily N_2O fluxes from a field rotated with winter wheat-corn-sunflower-beans with reduced tillage in Davis, CA in 2003-2006 (field data from Johan Six)

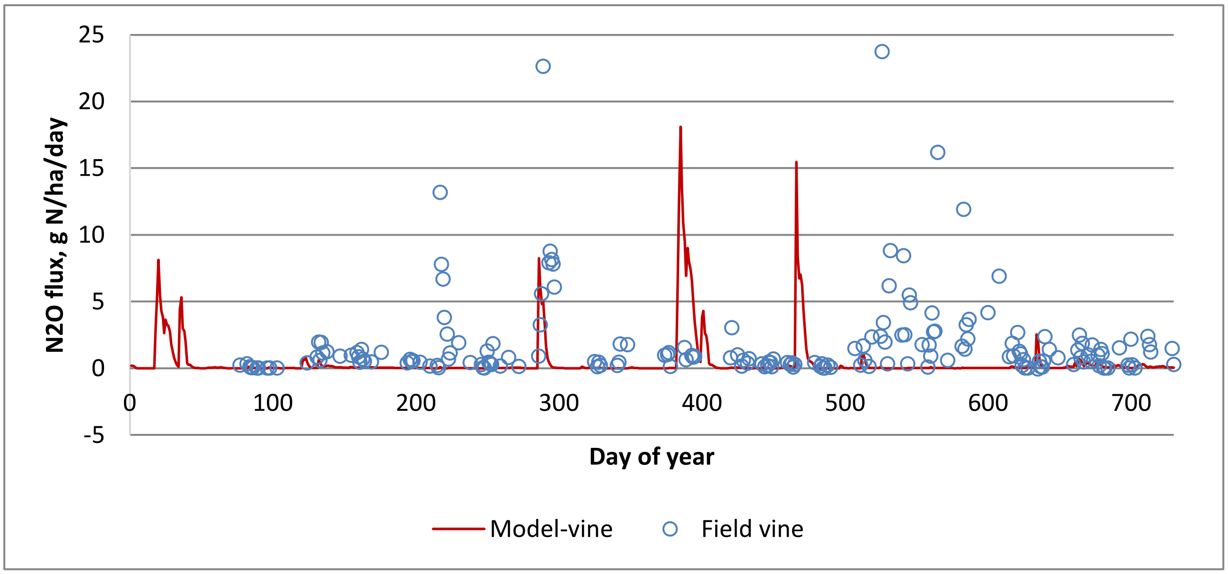

Figure A-7a. Comparison between measured and DNDC-modeled daily N_2O fluxes from location of vine in a vineyard field in Robuckle, CA in 2009-2010 (field data from Johan Six)

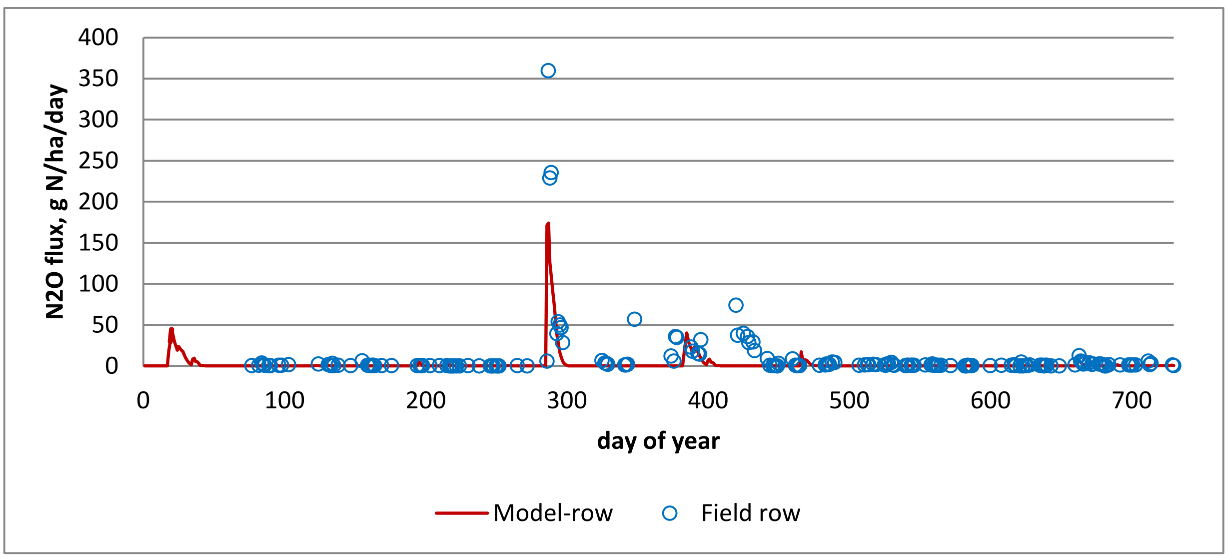

Figure A-7b. Comparison between measured and DNDC-modeled daily N_2O fluxes from location of row in a vineyard field in Robuckle, CA in 2009-2010 (field data from Johan Six)

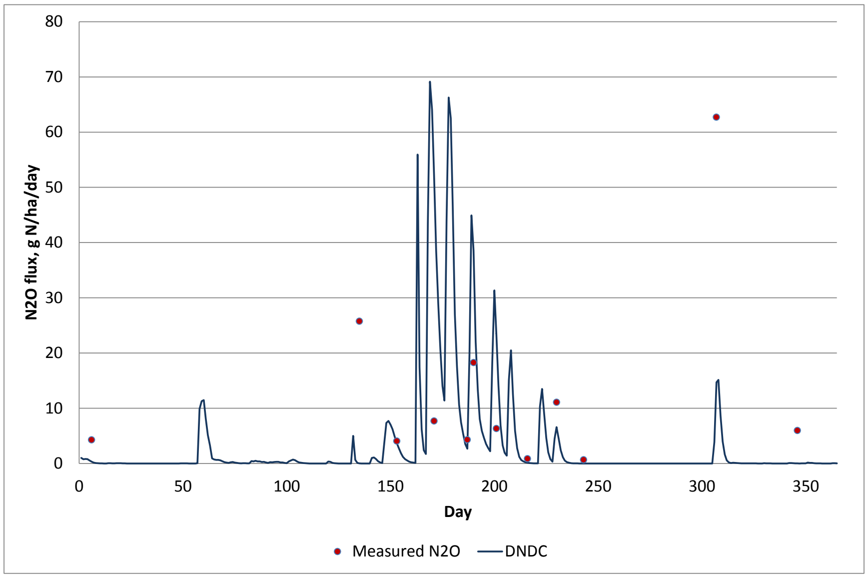

Figure A-8a. Comparison between measured and DNDC-modeled daily N_2O fluxes from a tomato field with drip irrigation and without cover crop in Davis, CA in 2006 (field data from Cynthia Kallenbach)

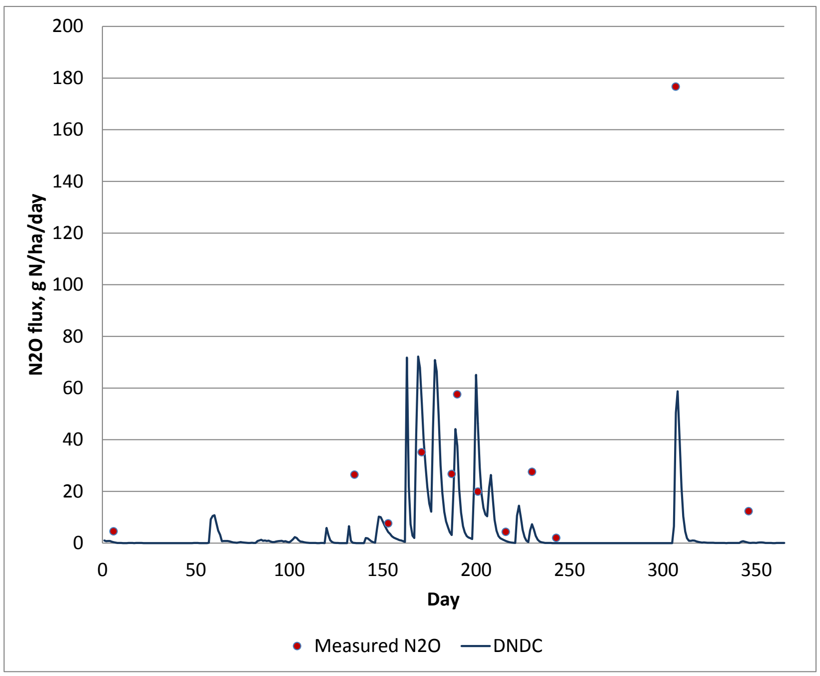

Figure A-8b. Comparison between measured and DNDC-modeled daily N_2O fluxes from a tomato field with drip irrigation and with cover crop in Davis, CA in 2006 (field data from Cynthia Kallenbach)

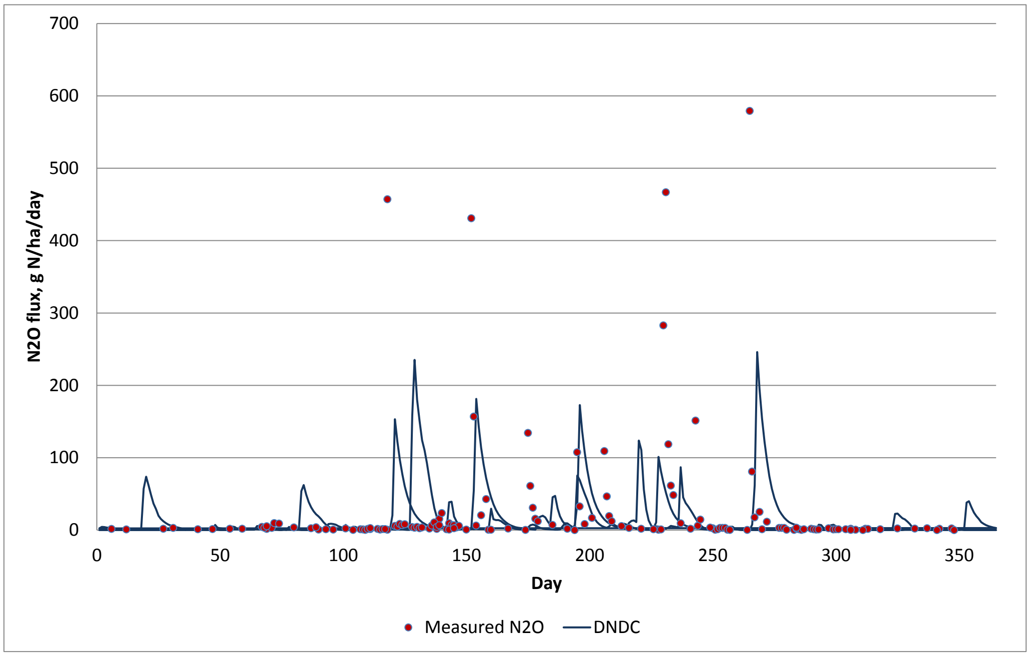

Figure A-9a. Comparison between measured and DNDC-modeled daily N_2O fluxes from two alfalfa field with 5-years old alfalfa in Davis, CA in 2011 (field data from William Horwath)

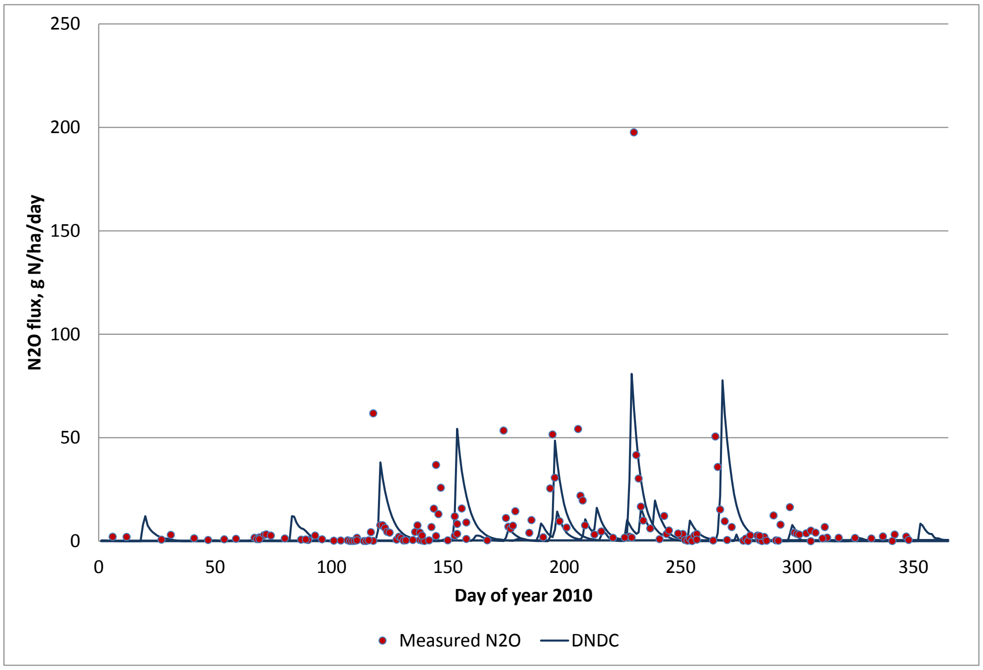

Figure A-9b. Comparison between measured and DNDC-modeled daily N_2O fluxes from a alfalfa field with 1-year old alfalfa in Davis, CA in 2011 (field data from William Horwath)

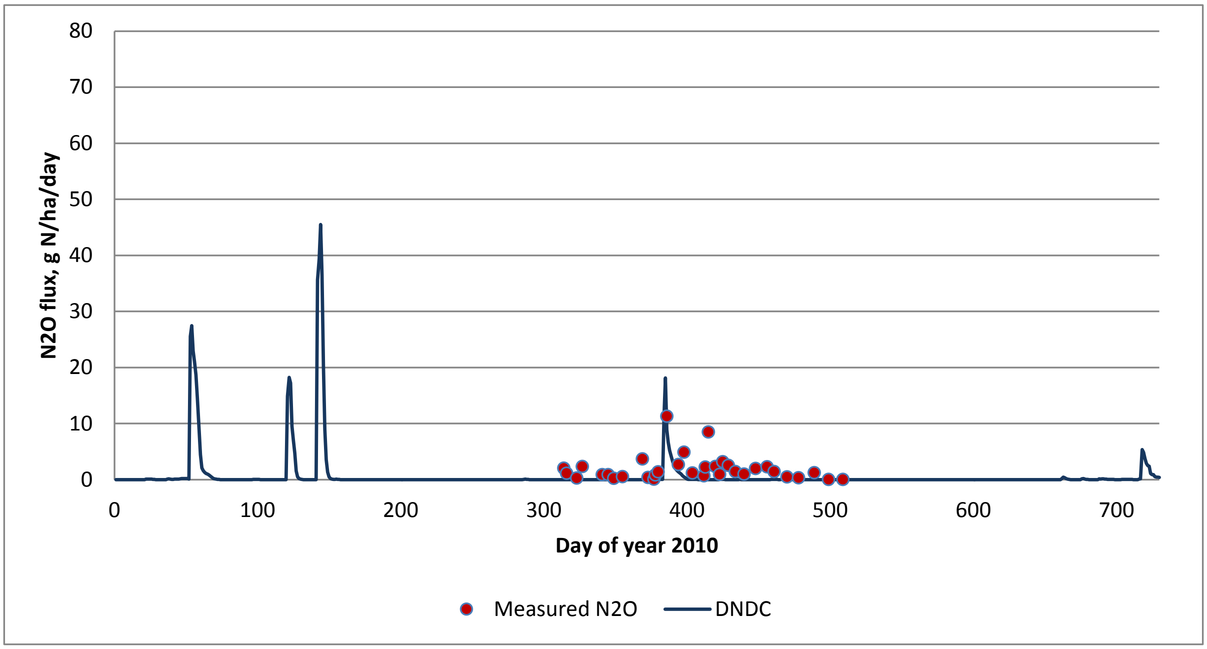

Figure A-10a. Comparison between measured and DNDC-modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 0 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

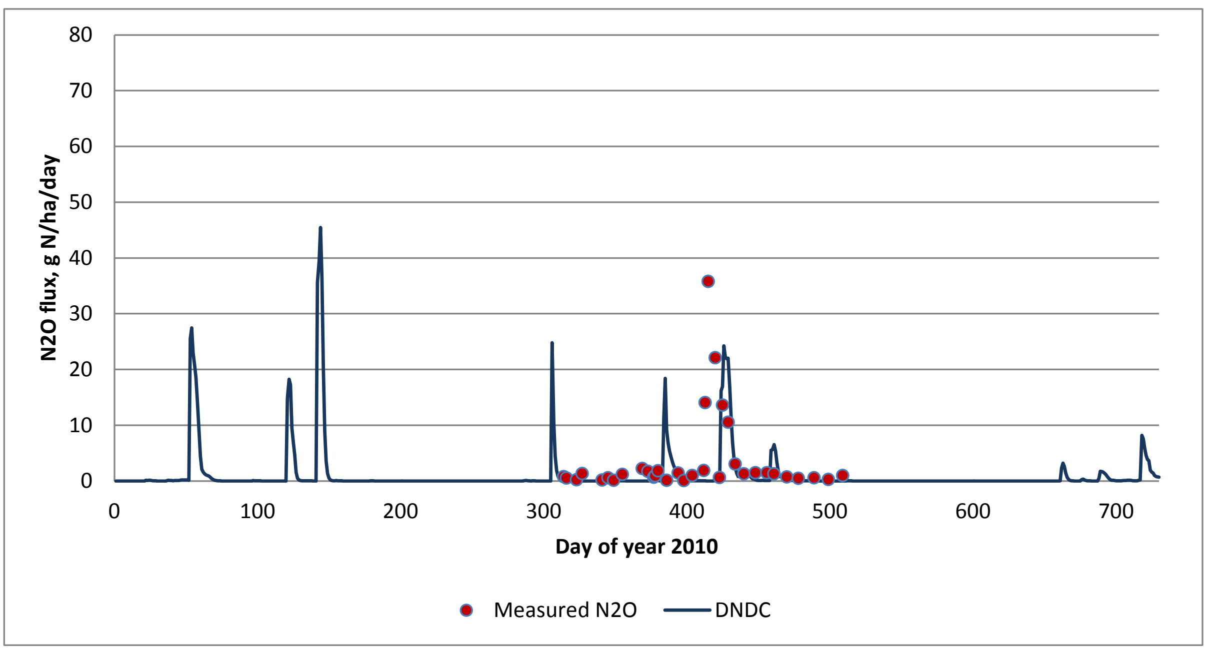

Figure A-10b. Comparison between measured and DNDC-modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 91 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

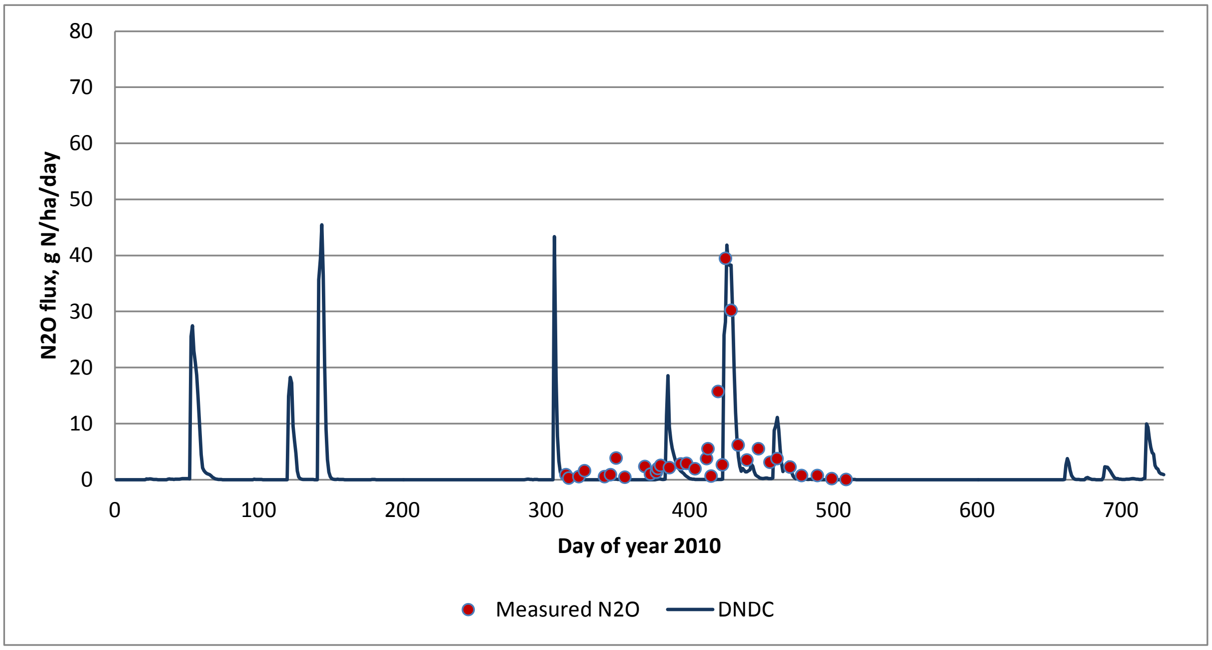

Figure A-10c. Comparison between measured and DNDC-modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 151 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

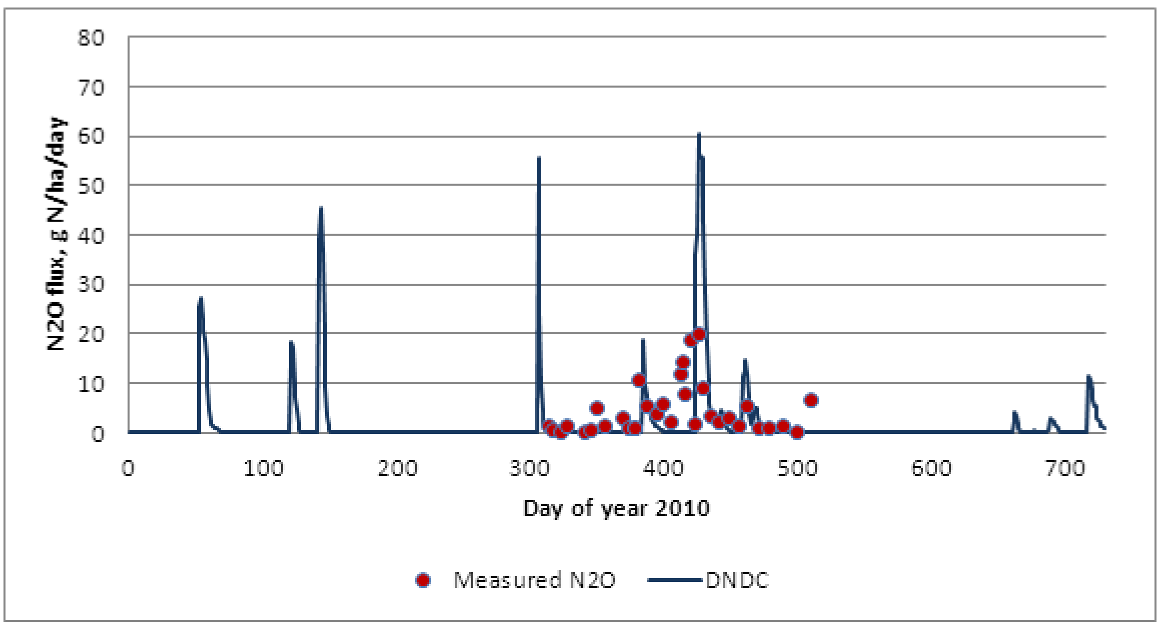

Figure A-10d. Comparison between measured and DNDC-modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 203 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

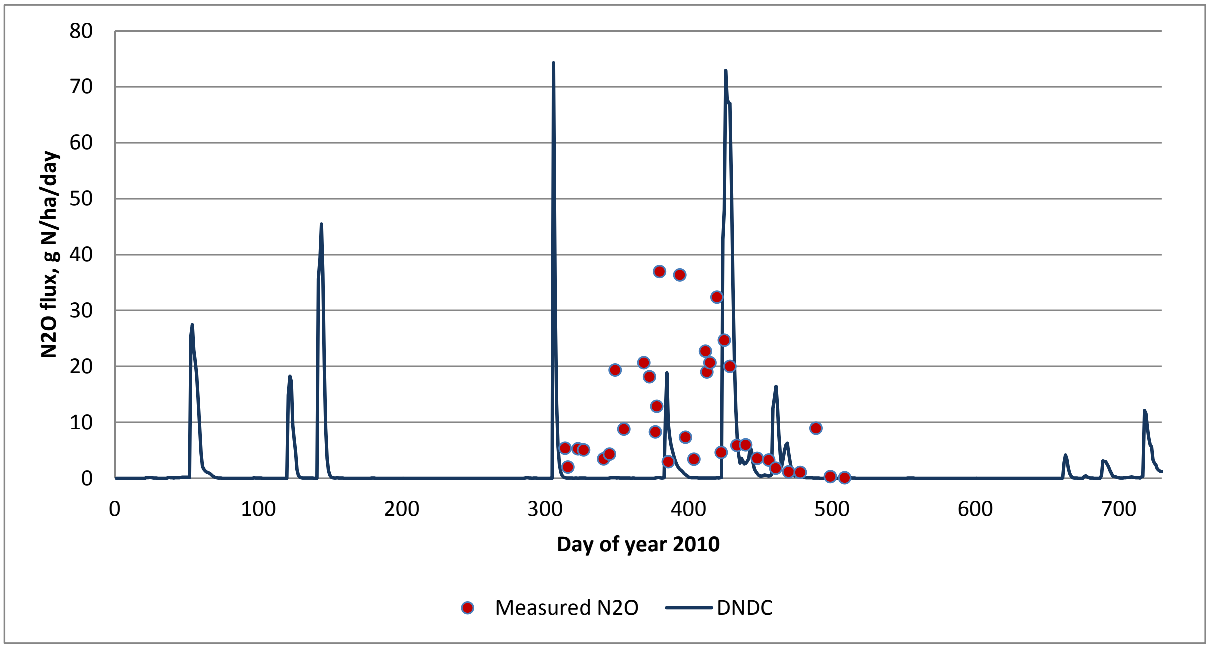

Figure A-10e. Comparison between measured and DNDC-modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 254 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

Appendix B: Daily DAYCENT Model Validation Results

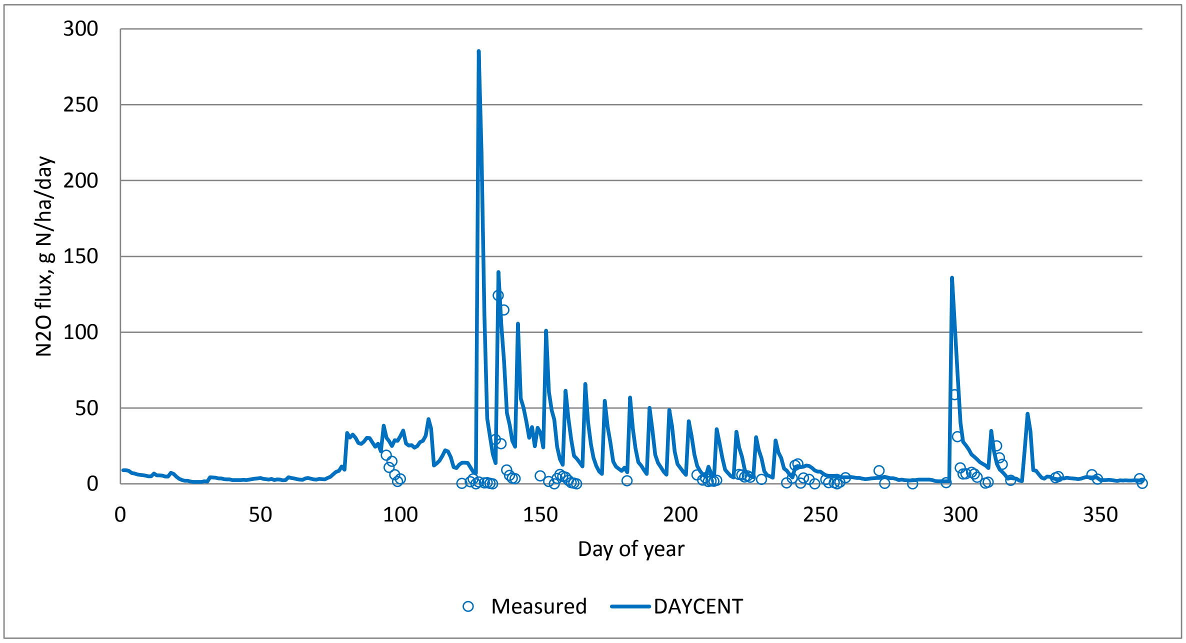

Figure B-1. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a tomato field (furrow) in Davis, CA in 2010 (field data from Johan Six)

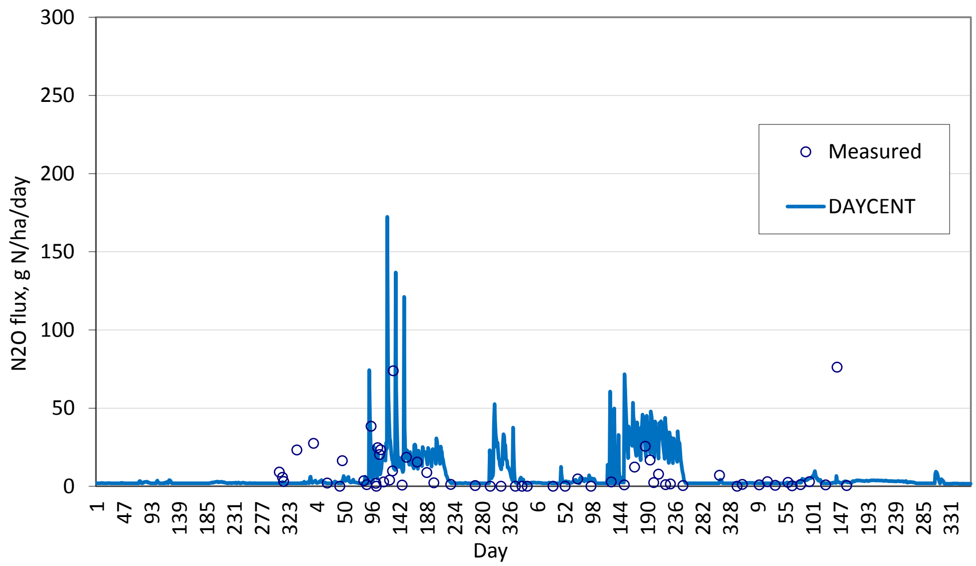

Figure B-2. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a field rotated with winter wheat-corn-sunflower-beans with reduced tillage in Davis, CA in 2003-2006 (field data from Johan Six)

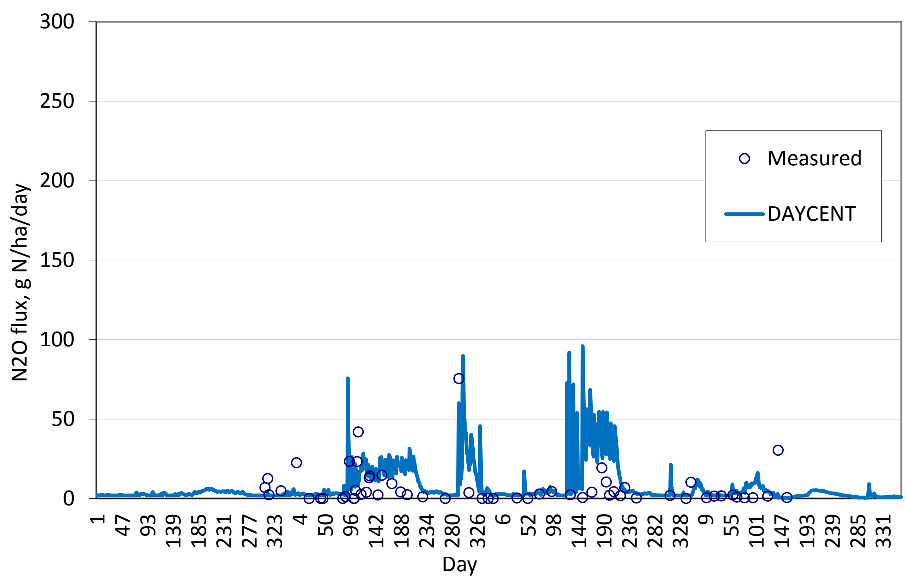

Figure B-3. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a field rotated with winter wheat-corn-sunflower-beans with standard tillage in Davis, CA in 2003-2006 (field data from Johan Six)

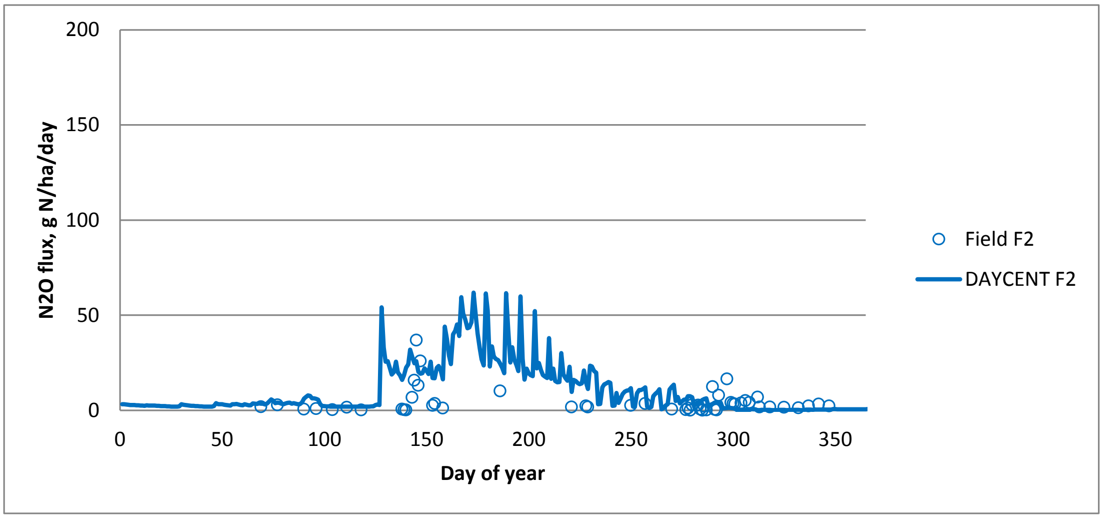

Figure B-4a. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a alfalfa field of 5-years old in Davis, CA in 2012 (field data from William Horwath)

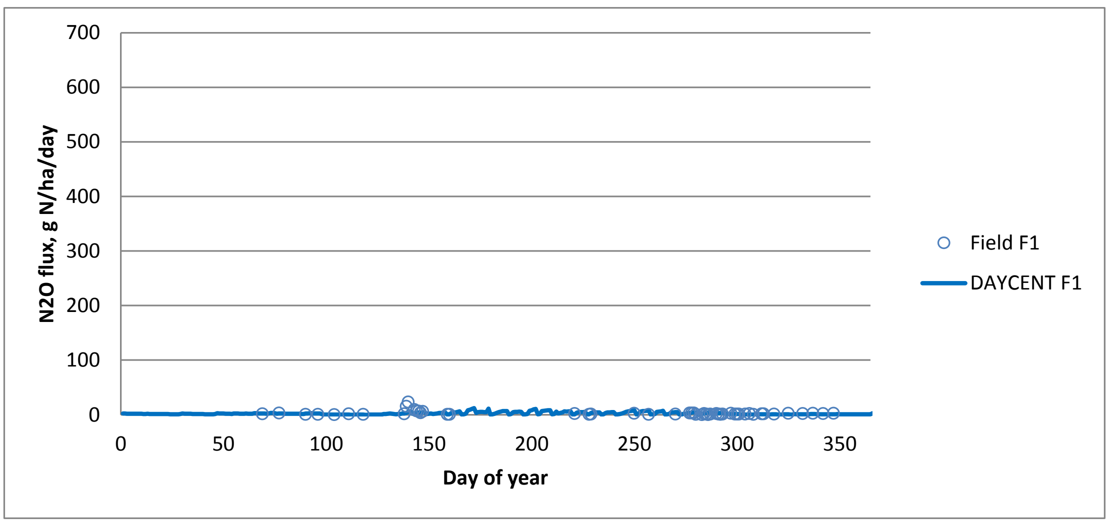

Figure B-4b. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a alfalfa field of 1-year old in Davis, CA in 2012 (field data from William Horwath)

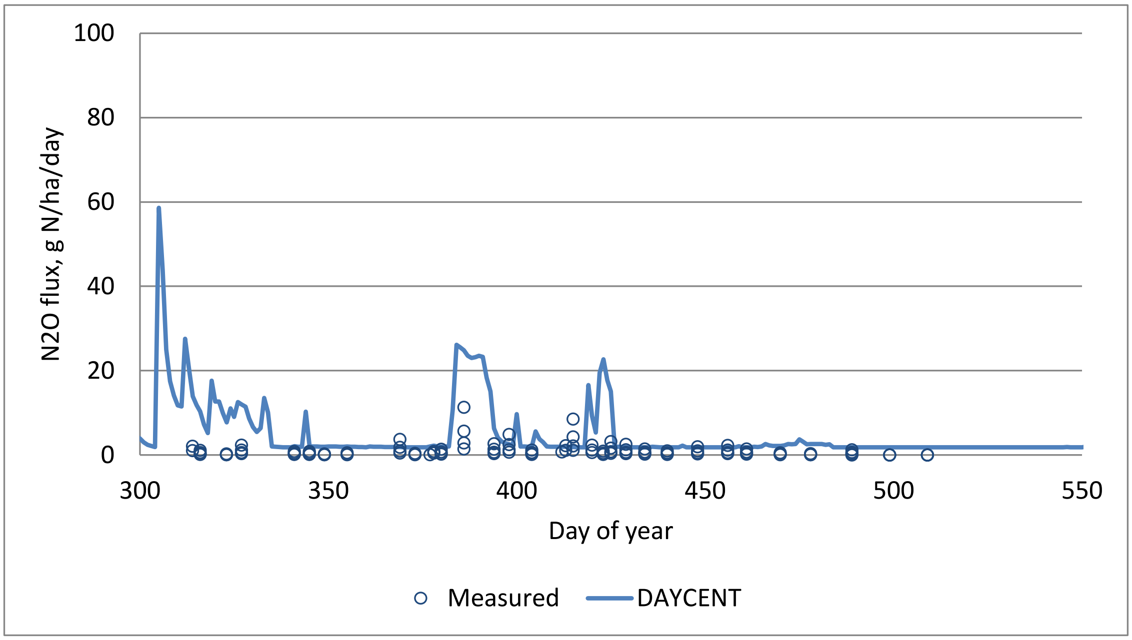

Figure B-5a. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of o kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

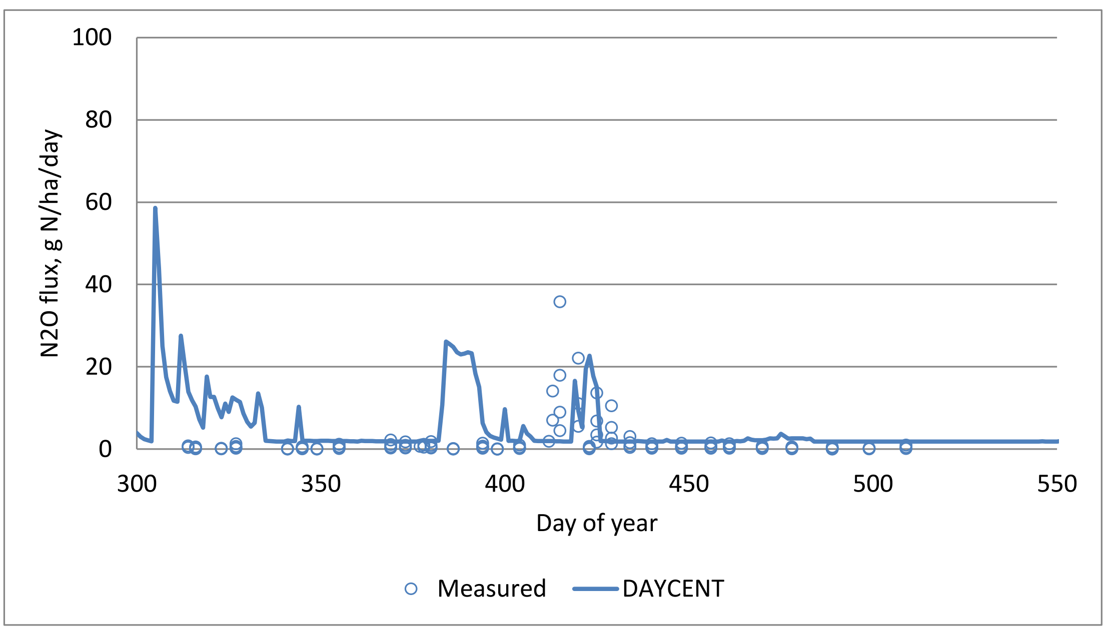

Figure B-5b. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 91 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

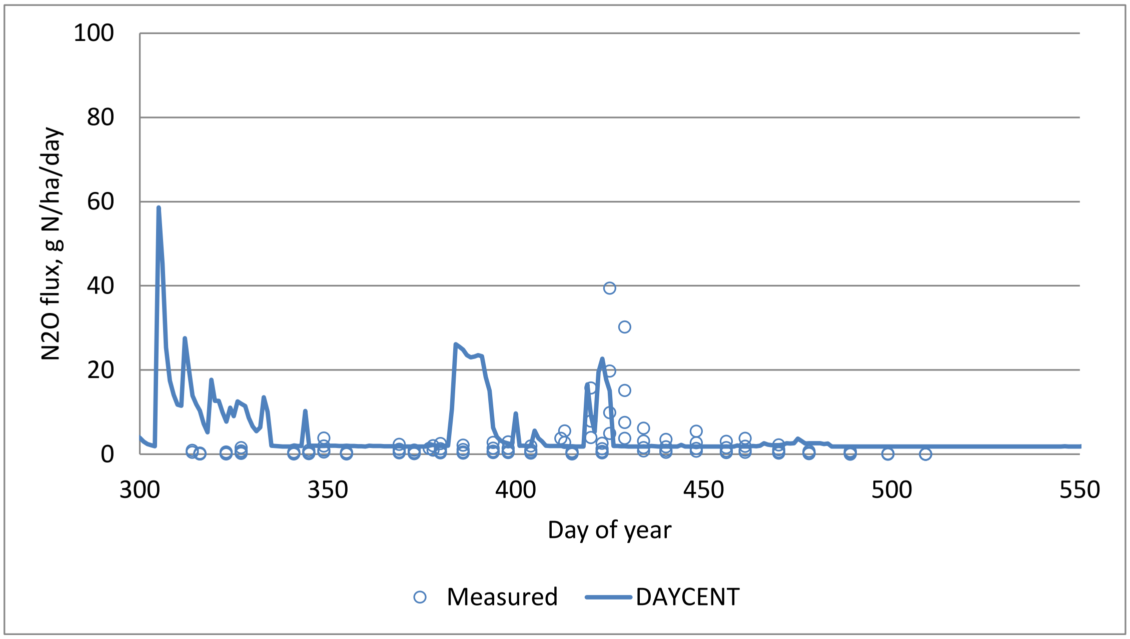

Figure B-5c. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 151 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

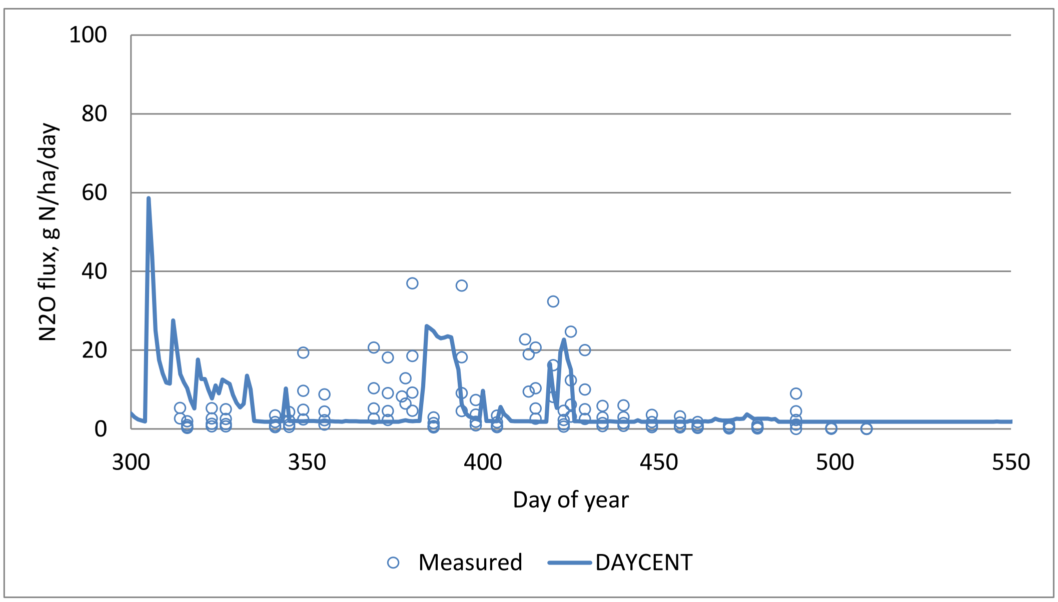

Figure B-5d. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 203 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

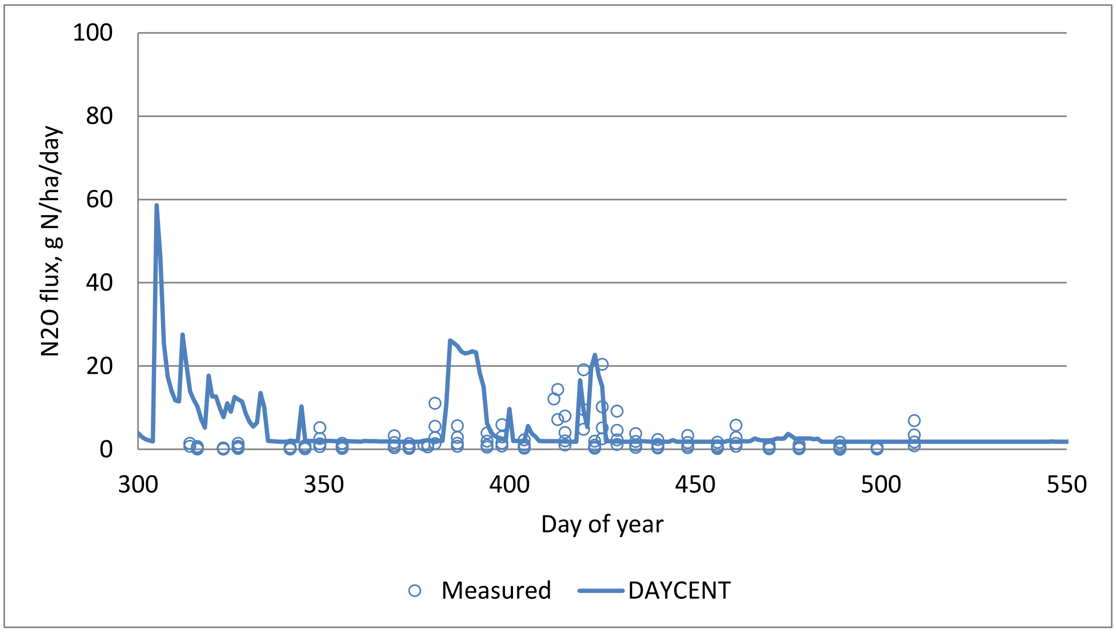

Figure B-5e. Comparison between measured and DAYCENT -modeled daily N_2O fluxes from a winter wheat field with fertilizer application rate of 254 kg N ha^{-1} in Davis, CA in 2009-2010 (field data from William Horwath)

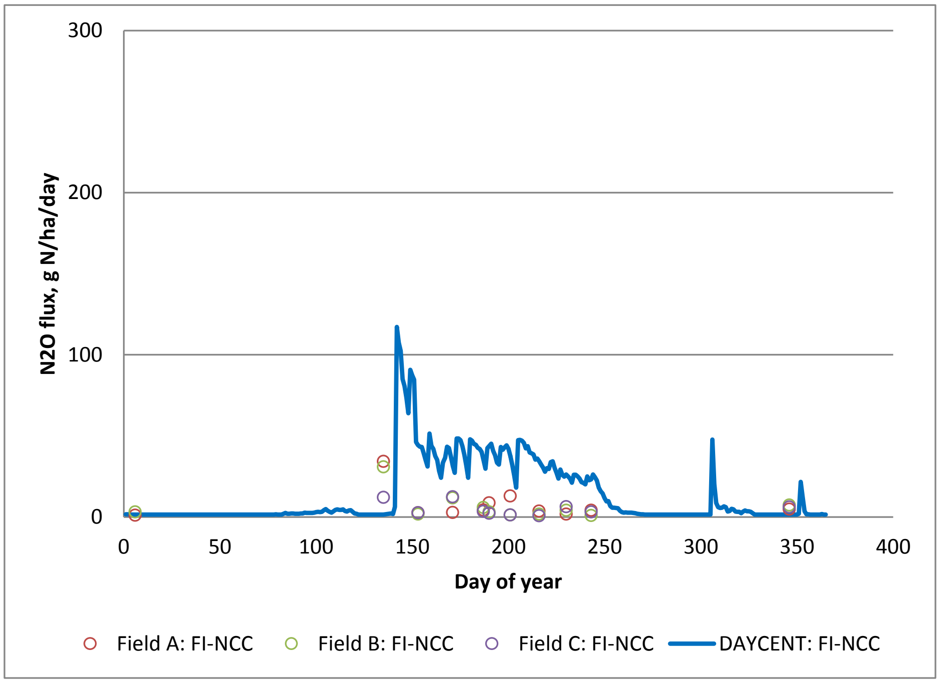

Figure B-6a. Comparison between measured and DAYCENT-modeled daily N_2O fluxes from a tomato field without winter cover crop in Davis, CA in 2006 (field data from Cynthsia Kallenbach)

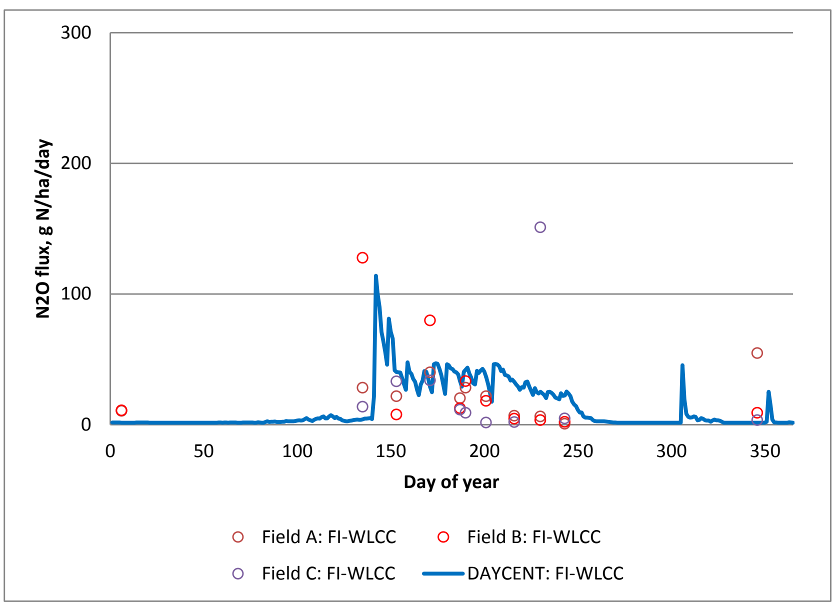

Figure B-6b. Comparison between measured and DAYCENT-modeled daily N_2O fluxes from a tomato field with winter cover crop in Davis, CA in 2006 (field data from Cynthsia Kallenbach)

Appendix C: Comparison of Models with Measurements on Daily Basis

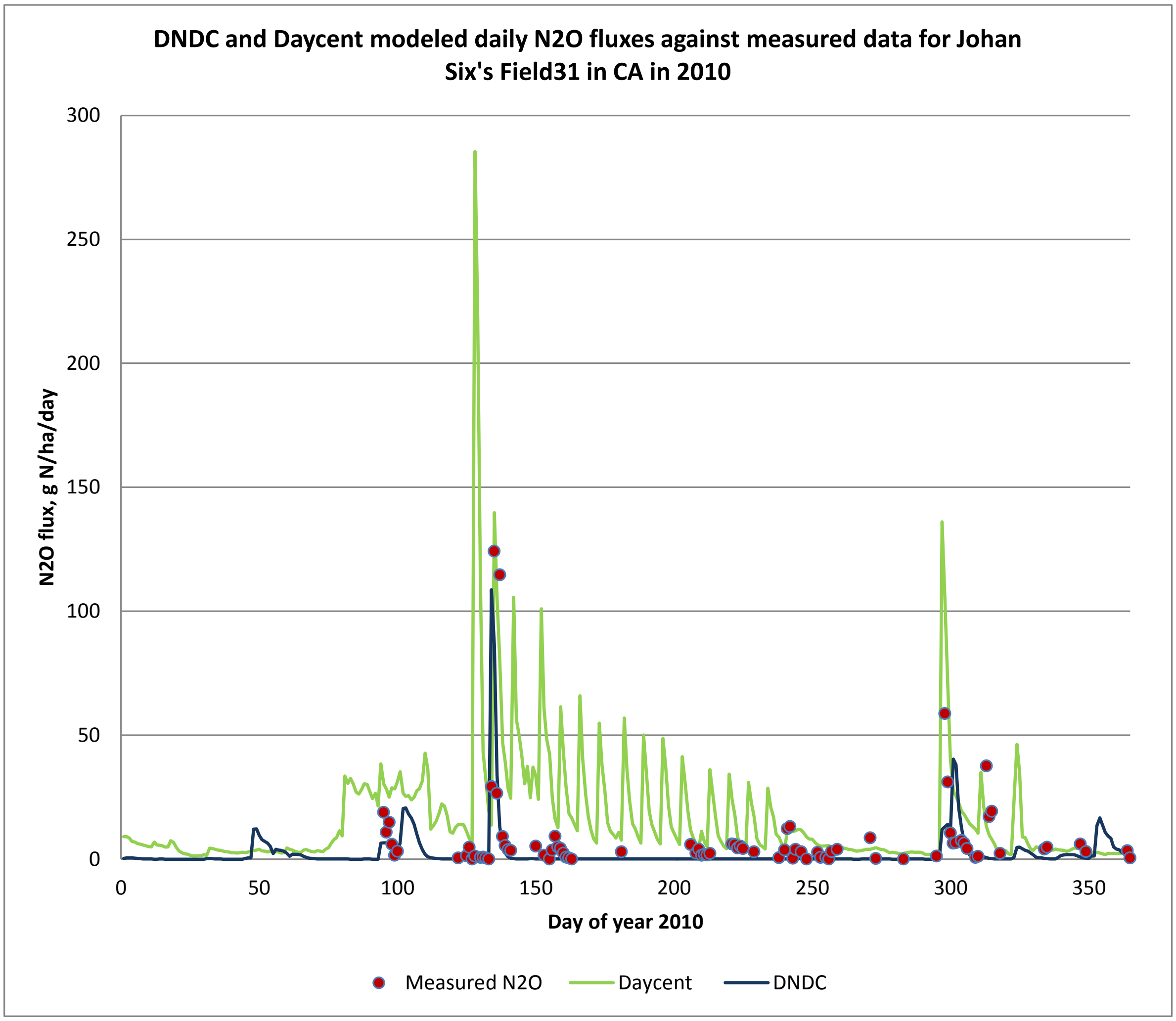

Figure C-1. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a tomato field in California in 2010 (Field data from Johan Six)

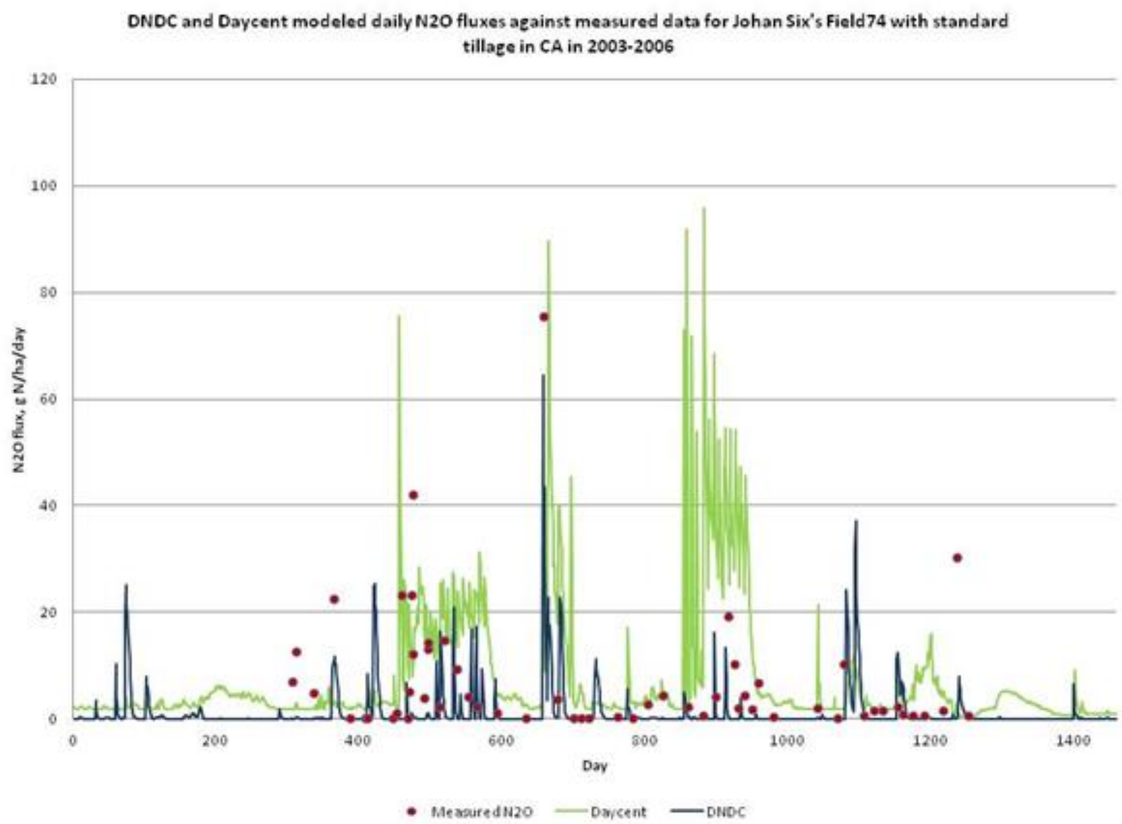

Figure C-2. Comparison of DNDC- and DAYCENT t-modeled daily N_2O fluxes with measured N_2O fluxes for a wheat/corn/sunflower/beans field (Field 74) with standard tillage in California in 2003-2006 (Field data from Johan Six)

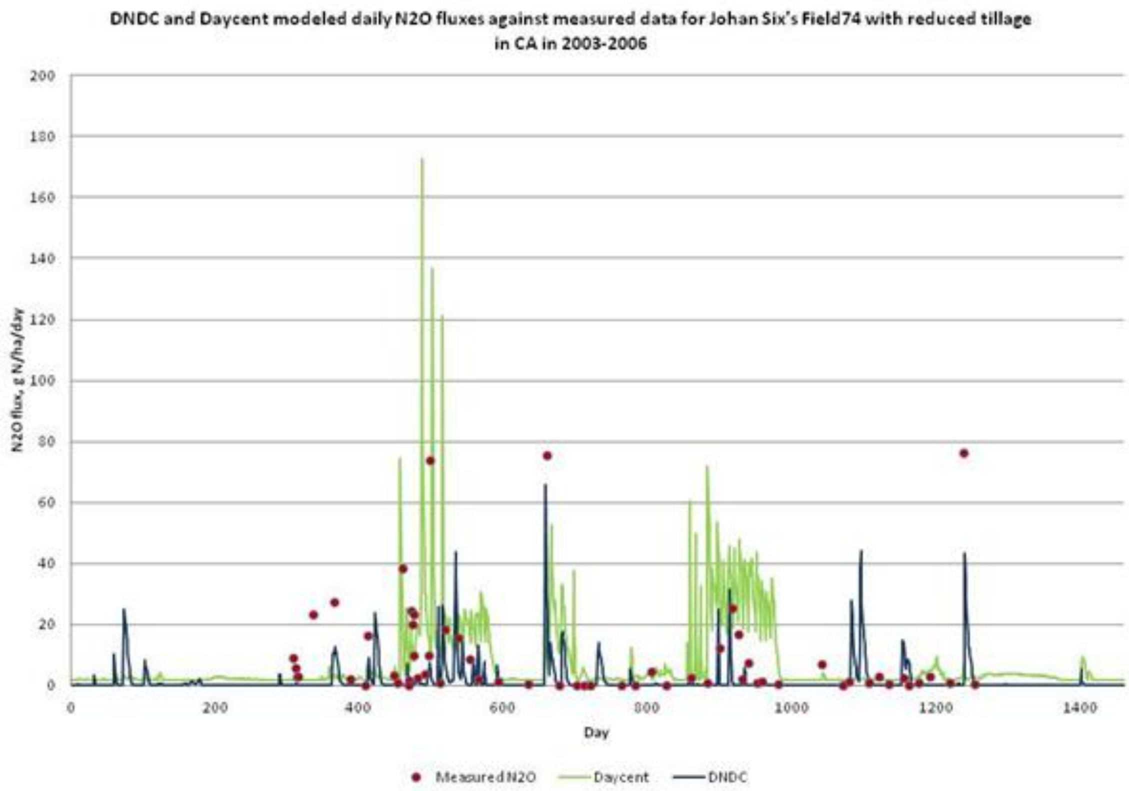

Figure C-3. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a wheat/corn/sunflower/beans field (Field 74) with reduced tillage in California in 2003-2006 (Field data from Johan Six)

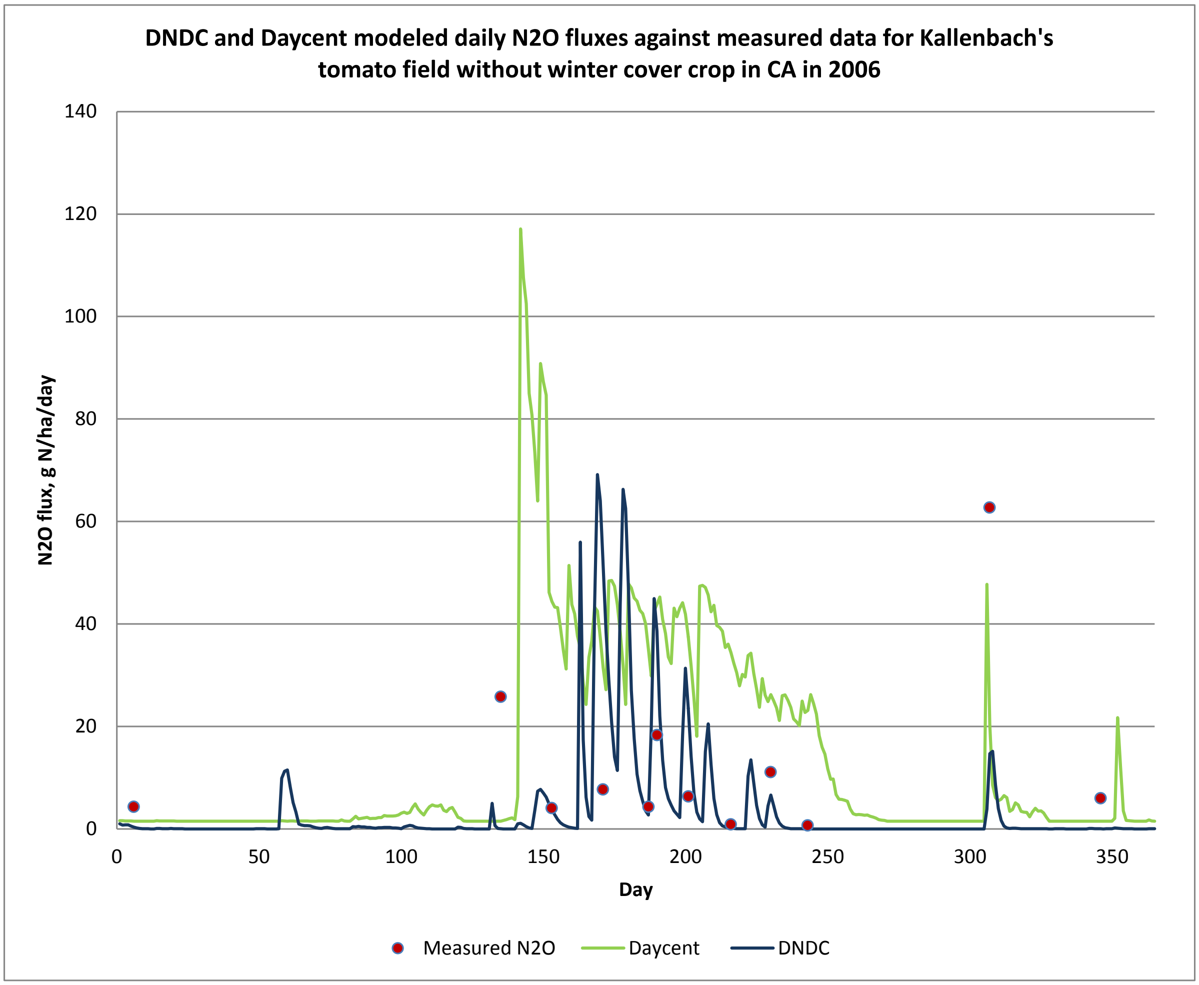

Figure C-4. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a tomato field without cover crop in California in 2006 (Field data from Cynthia Kallenbach)

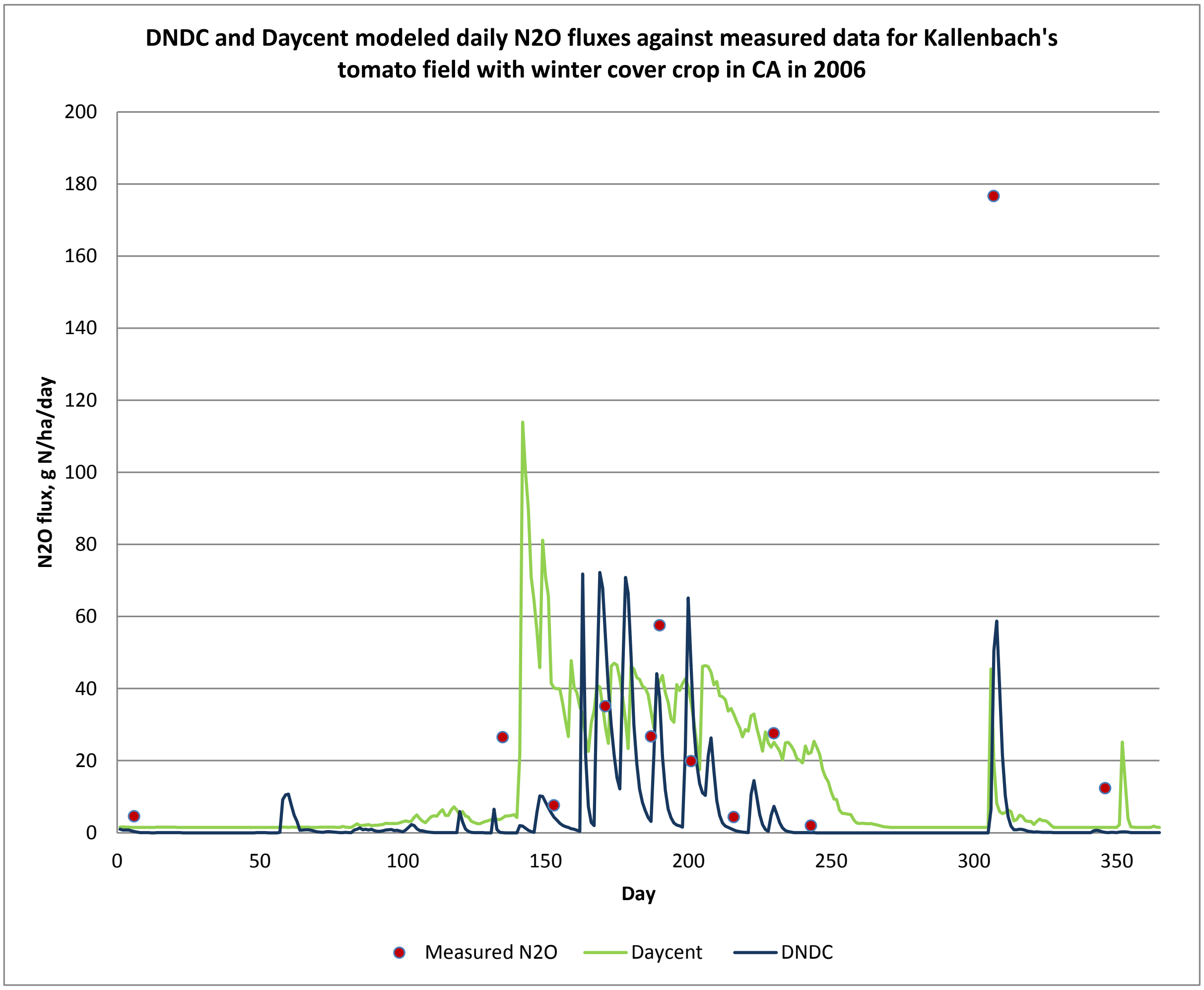

Figure C-5. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a tomato field with winter cover crop in California in 2006 (Field data from Cynthia Kallenbach)

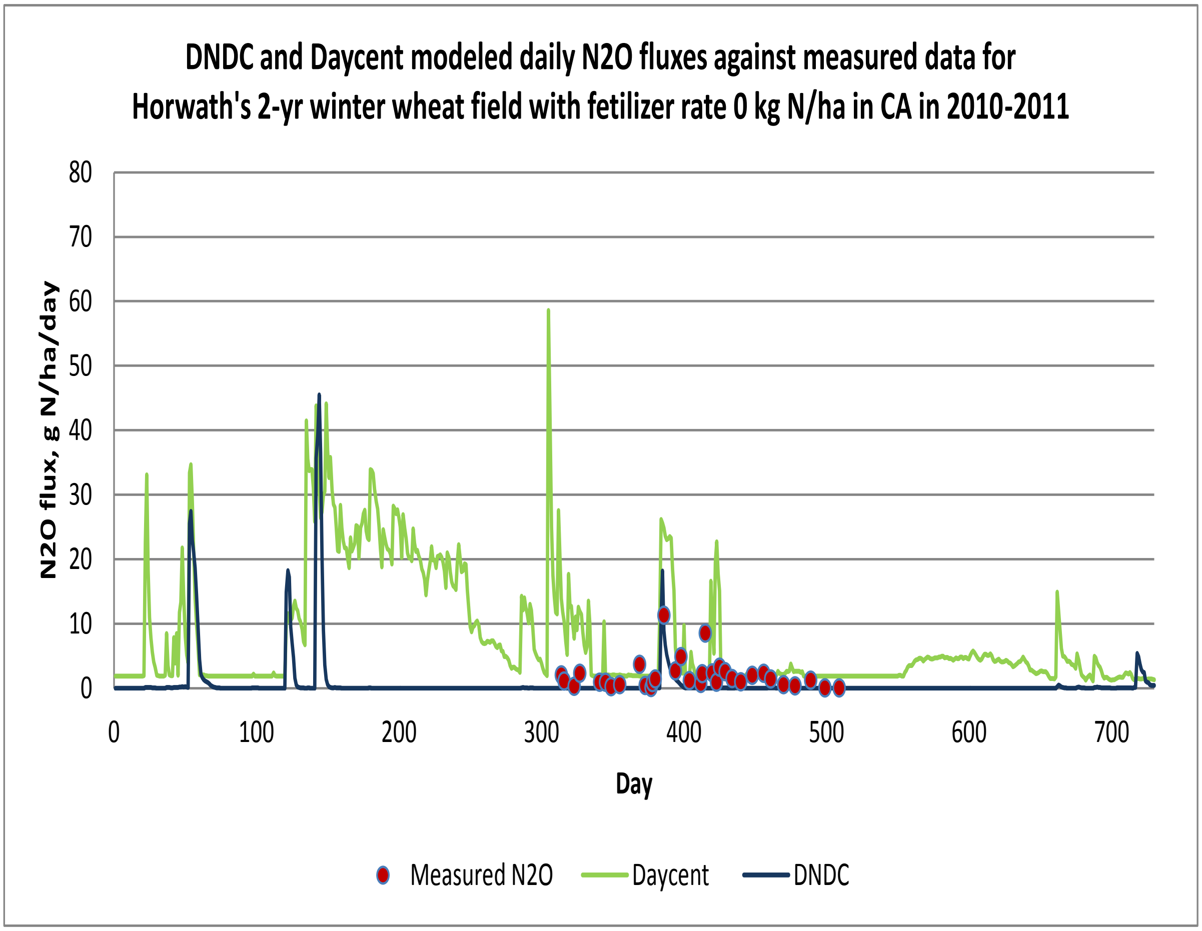

Figure C-6. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a winter wheat field with fertilizer application rate of 0 kg N/ha in California in 2010-2011 (Field data from William Horwath)

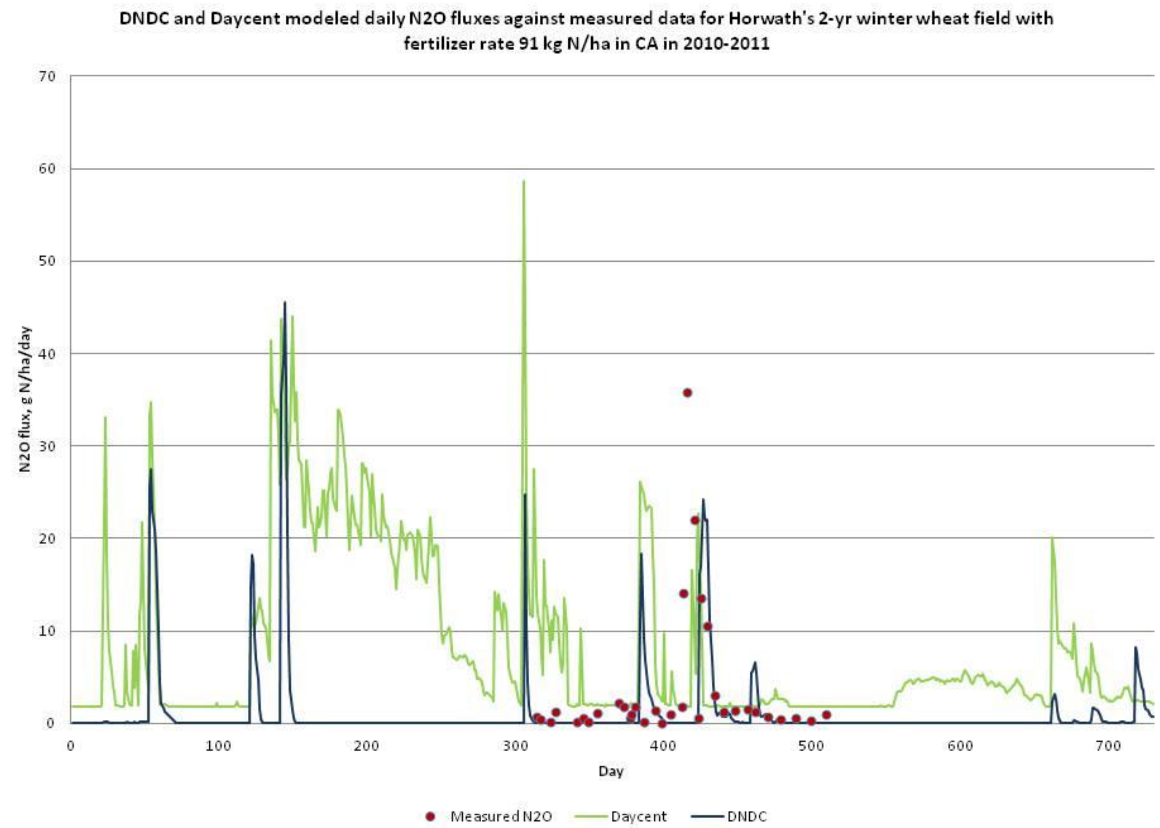

Figure C-7. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a winter wheat field with fertilizer application rate of 91 kg N/ha in California in 2010-2011 (Field data from William Horwath)

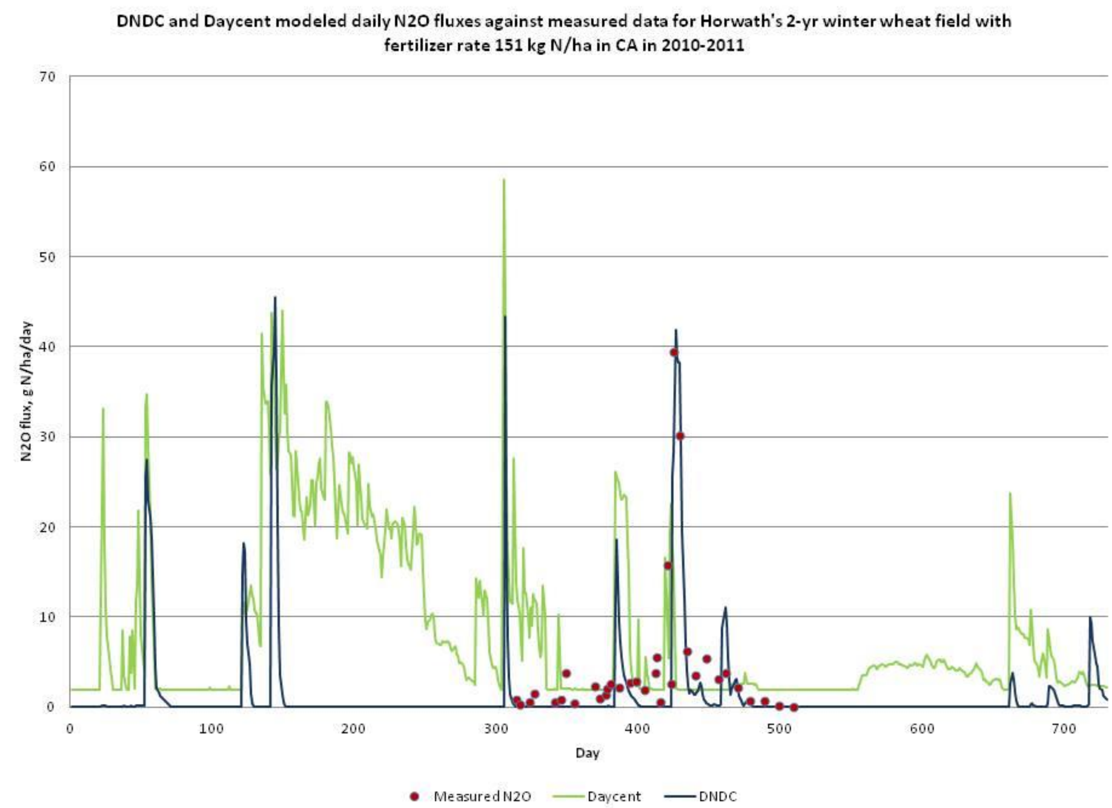

Figure C-8. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a winter wheat field with fertilizer application rate of 151 kg N/ha in California in 2010-2011 (Field data from William Horwath)

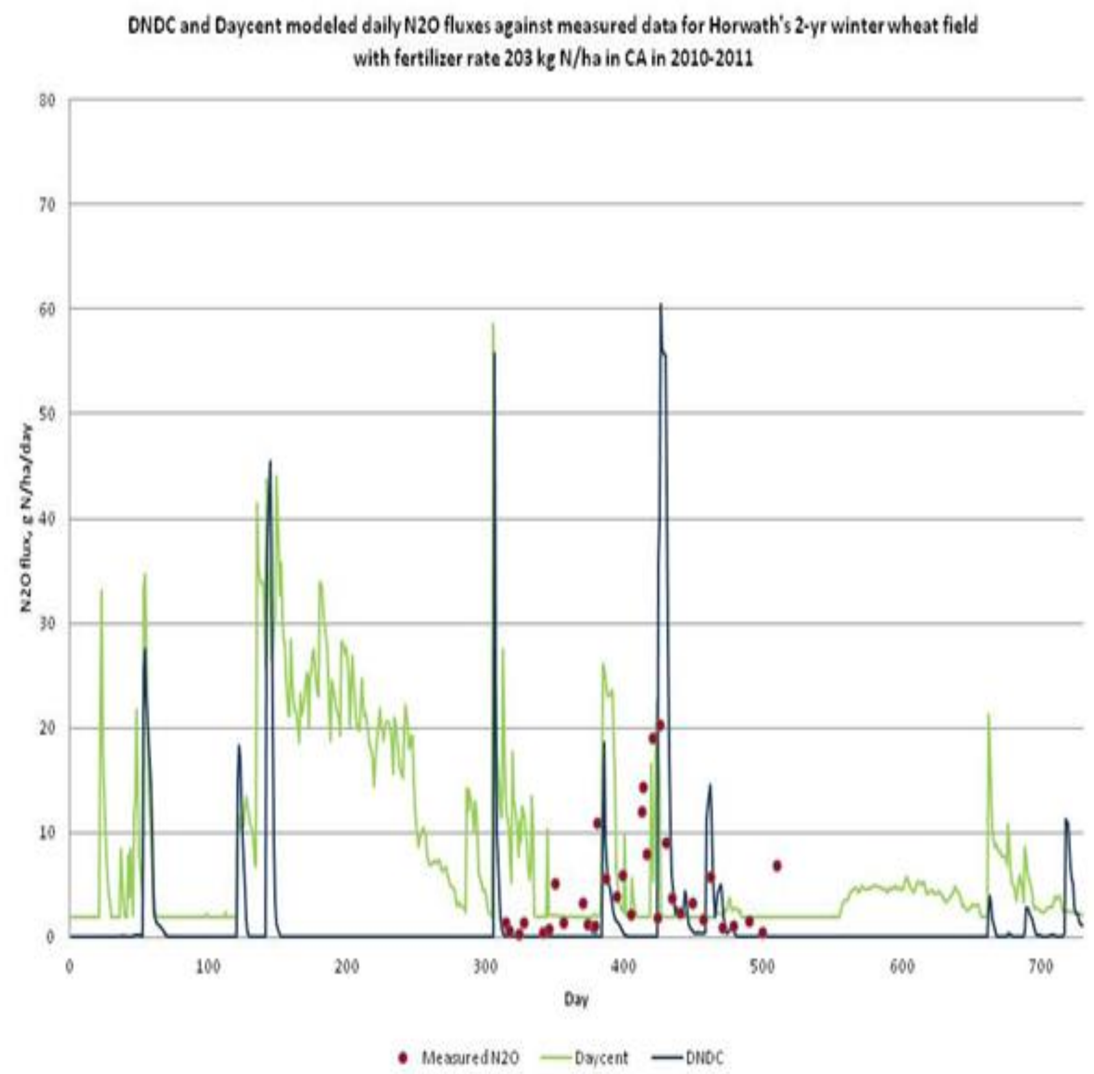

Figure C-9. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a winter wheat field with fertilizer application rate of 203 kg N/ha in California in 2010-2011 (Field data from William Horwath)

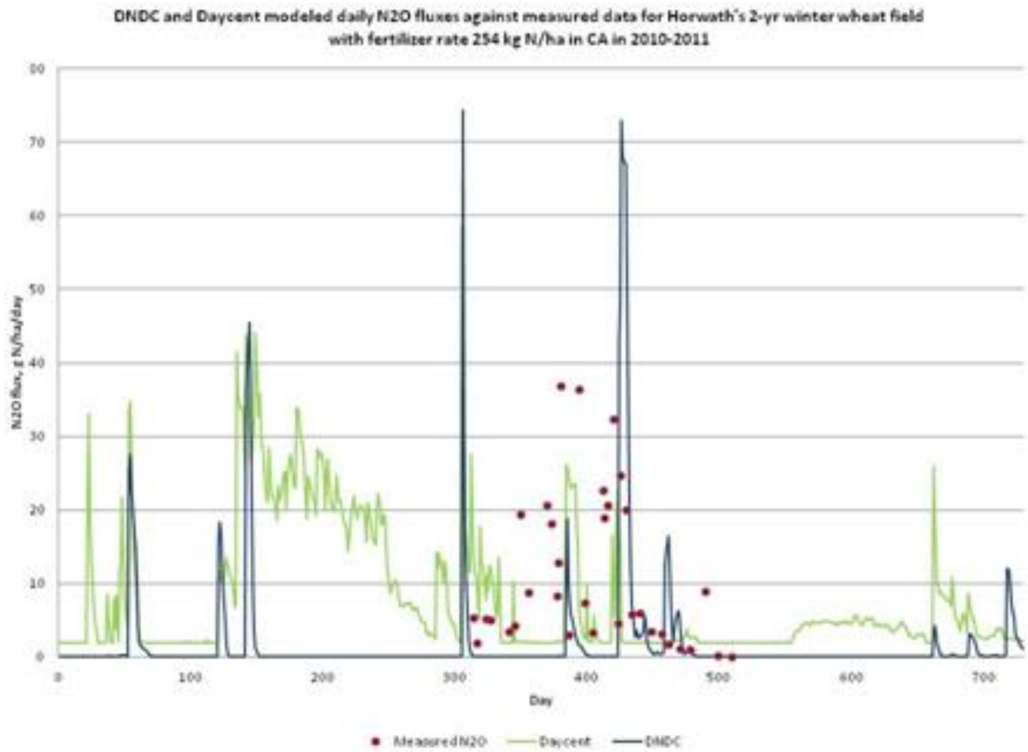

Figure C-10. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a winter wheat field with fertilizer application rate of 254 kg N/ha in California in 2010-2011 (Field data from William Horwath)

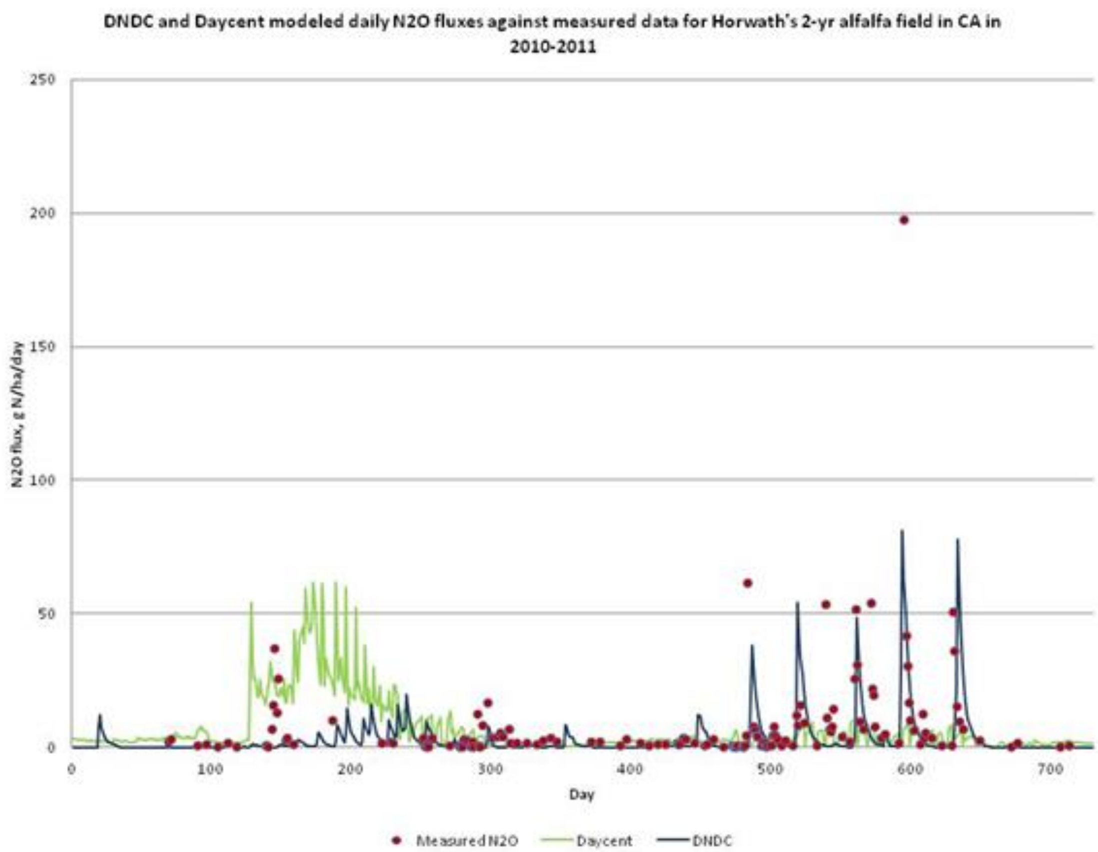

Figure C-11. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a 1-year old alfalfa field in California in 2010-2011 (Field data from William Horwath)

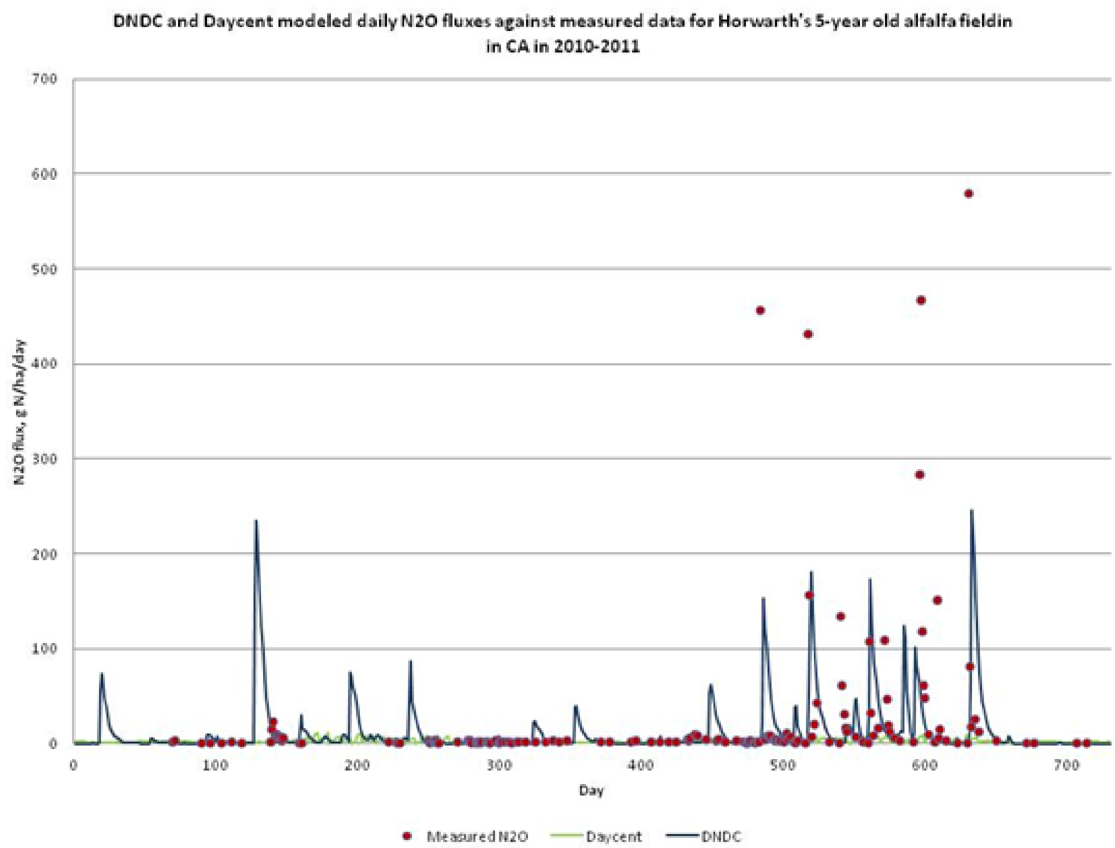

Figure C-12. Comparison of DNDC- and DAYCENT -modeled daily N_2O fluxes with measured N_2O fluxes for a 5-year old alfalfa field in California in 2010-2011 (Field data from William Horwath)