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Assessing the potential for greenhouse gas mitigation in intensively managed annual cropping systems at the regional scale

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ABSTRACT

We predicted changes in yields and direct net soil greenhouse gas (GHG) fluxes from converting conventional to alternative management practices across one of the world's most productive agricultural regions, the Central Valley of California, using the DAYCENT model. Alternative practices included conservation tillage, winter cover cropping, manure application, a 25% reduction in N fertilizer input and combinations of these. Alternative practices were evaluated for all unique combinations of crop rotation, climate, and soil types for the period 1997–2006. The crops included were alfalfa, corn, cotton, melon, safflower, sunflower, tomato, and wheat. Our predictions indicate that, adopting alternative management practices would decrease yields up to 5%. Changes in modeled SOC and net soil GHG fluxes corresponded to values reported in the literature. Average potential reductions of net soil GHG fluxes with alternative practices ranged from −0.7 to −3.3 Mg CO_2-eq ha^{-1} yr^{-1} in the Sacramento Valley and −0.5 to −2.5 Mg CO_2-eq ha^{-1} yr^{-1} for the San Joaquin Valley. While adopting a single alternative practice led to modest net soil GHG flux reductions (on average −1 Mg CO_2-eq ha^{-1} yr^{-1}), combining two or more of these practices led to greater decreases in net soil GHG fluxes of up to −3 Mg CO_2-eq ha^{-1} yr^{-1}. At the regional scale, the combination of winter cover cropping with manure application was particularly efficient in reducing GHG emissions. However, GHG mitigation potentials were mostly non-permanent because 60–80% of the decreases in net soil GHG fluxes were attributed to increases in SOC, except for the reduced fertilizer input practice, where reductions were mainly attributed to decreased N_2O emissions. In conclusion, there are long-term GHG mitigation potentials within agriculture, but spatial and temporal aggregation will be necessary to reduce uncertainties around GHG emission reductions and the delivery risk of the associated C credits.

1. Introduction

Conventional agricultural practices, characterized by intense soil disturbance and large NPK fertilizer inputs, have caused a significant decrease in soil organic carbon (SOC) and large fluxes of CO_2 and other greenhouse gases (GHG) to the atmosphere (IPCC, 2007). These agricultural practices have been developed over several decades with the primary goal to maximize yields. In contrast, a number of alternative agricultural management practices have attempted to maintain yields while mitigating anthropogenic GHG emissions or delivering other environmental co-benefits, and therefore serve multiple goals. Pacala and Socolow (2004) suggested that a wide-scale adoption of such alternative agricultural practices should be an essential part of the effort to decrease anthropogenic GHG emissions. Wide-scale adoption of improved agricultural management practices may occur through the participation of farmers in a cap-and-trade system of GHG offsets; farmers would be compensated for the extra costs and potentially reduced revenues related to the adoption of alternative management practices.

Various initiatives aimed at establishing a legally binding cap-and-trade system recognize the benefits of including agricultural C credits as well as the need for more fundamental research to understand potentials, risks, and limitations. For example, the American Clean Energy and Security Act, H.R.2454, approved by the House of Representatives in late 2009 but failed to move on to the Senate, proposed to allow emission allowances for agricultural projects that reduce GHG emissions administered by the United States Department of Agriculture (USDA). However, exactly how agricultural C credits should be quantified and what the potential is for GHG mitigation is subject to significant debate. Likewise, the state

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Fig. 1. Position of the 10 counties that were included in this study.

of California committed to a reduction in GHG emissions to 1990 levels by 2020 with the approval of the California Global Warming Solutions Act of 2006 (Assembly Bill 32, Nuñez, Chapter 488, Statutes of 2006). Even though the California Air Resources Board (ARB), charged with conducting the rulemaking process for AB 32, has not yet officially endorsed the inclusion of agricultural C credits from cropland management and agricultural nutrient management, ARB is actively assessing the potential to include such credits as offsets. Finally, the Climate Action Reserve (CAR), an independent US voluntary offsets program, has created workgroups to develop protocols for agricultural C credits in the US. While CAR generates purely voluntary C credits, ARB is poised to adopt existing CAR protocols with minor modifications.

The hesitation in adopting agricultural C credits is, in part, due to a number of critical issues such as permanence (reversibility), uncertainty, and verifiability that have been reviewed extensively elsewhere (Smith et al., 2007). As a consequence, a detailed analysis of the potentials, risks, and uncertainties related to measuring and monitoring agricultural C credits is pertinent, especially for the Central Valley of California, in which 13% of the total US value of agricultural commodities is produced, and very little research has been devoted to potential GHG mitigation options.

Previously, De Gryze et al. (2010) calibrated the DAYCENT ecosystem model for the main field crops grown under California conditions using data from several long-term field experiments. In this study, we used the calibrated model to evaluate the potential for GHG mitigation in the Central Valley of California, encompassing thousands of combinations of soil types and climatic conditions. The alternative practices considered include conservation tillage, winter cover cropping, manure application and/or reduced N fertilizer input. This modeling study focuses on biogenic changes in direct GHG emissions and disregards effects of alternative practices on fuel use or changes in GHG emissions beyond the farmer's field. Unlike most previous modeling studies, which have looked at individual years or monocultures over multiple years, this study set out to model crop rotations as they typically occur in the region. In California, crops are almost always grown in complex rotations to improve soil fertility and minimize pest problems. Furthermore, it has been reported that yield declines or changes in N_2O emissions following adoption of alternative practices may become apparent only after several years (Six et al., 2004). Therefore, model results are reported for a period of 10 years after 1997 for a sound analysis of the long-term potential mitigation of various strategies.

2. Materials and methods

2.1. Model description

DAYCENT (Parton et al., 1998; Del Grosso et al., 2000) is a daily version of the well-known CENTURY ecosystem model (Parton et al., 1987). The model simulates all major processes that affect soil C and N dynamics, including plant production, water flow, heat transport, SOC decomposition, N mineralization and immobilization, nitrification, denitrification, and methane oxidation. Methanogenesis is not included in the current version of the model. In addition, the DAYCENT model only simulates direct GHG emissions within the agricultural fields; no indirect N_2O emissions are quantified. The plant sub-model simulates crop phenology, N uptake and distribution in plant tissue compartments, C allocation between roots and shoots, and growth responses to light and temperature. A variety of agricultural management variables can be specified including crop type, tillage intensity, fertilization rate, organic matter and manure addition rates, residue removal during harvest, drainage extent, irrigation intensity, burning frequency, and grazing intensity. Additional inputs to the model are soil data, crop rotation data, and daily weather data.

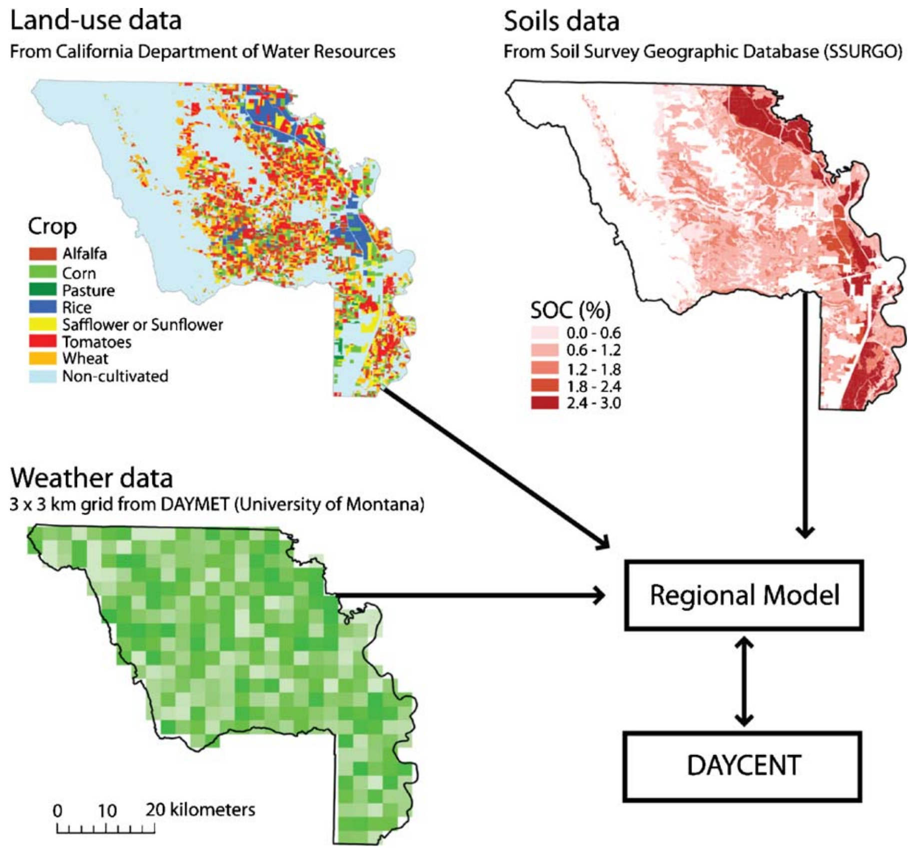

Fig. 2. Input data sources for the modeling strategy.

2.2. Regional extent

The Central Valley of California is divided into the northern Sacramento Valley and the southern San Joaquin Valley. The simulations included eight counties from the Sacramento Valley: Butte, Colusa, Glenn, Sacramento, Solano, Sutter, Yolo, and Yuba. Two counties were included from the San Joaquin Valley: Kings and Fresno (see Fig. 1). These counties were chosen based on the county-level economic importance of field crop agriculture. The cropping systems modeled included alfalfa, cotton, tomatoes, (winter) wheat, corn, other vegetables, safflower, and barley (USDA, 2002). No perennial systems, such as fruit and nut orchards or vineyards, were considered in this study due to insufficient development, calibration, and validation of the DAYCENT model for these systems. Similarly, no rice systems were included since DAYCENT does not simulate methanogenesis.

2.3. Input data

2.3.1. Soil data

Soil data was extracted from the Soil Survey Geographic Database (SSURGO) of the Natural Resources Conservation Service (NRCS). The SSURGO database is the digital form of the most detailed level of soil mapping done by the NRCS in the National Cooperative Soil Survey program. Soil parameters were estimated from the geographic information system (GIS) version of the county soil survey maps, available within the SSURGO database. More specifically, soil texture class, bulk density, hydraulic properties (such as field capacity, wilting point, minimum volumetric soil–water content, and saturated hydraulic conductivity), potential rooting depth, and pH to the depth of 1.5 m were obtained from SSURGO and used for the simulations (Fig. 2).

2.3.2. Crop types and rotations

The crops modeled were limited to hay crops (which mainly consisted of alfalfa), cotton, small grains (wheat, oats and barley), tomatoes, and corn/sorghum. To be consistent with typical crop rotations carried out in the Sacramento Valley, sunflower, and melons (such as honeydew, cantaloupe, and watermelon) were also included. Corn for grain was simulated in the counties of the Sacramento Valley and for silage in the San Joaquin Valley (USDA, 2002). By limiting the simulations to these crops, 50% of the land under crop production in the counties studied was included in the study (1.5 million ha out of a total of about 2.9 million ha).

In California, most crops are grown in complex rotations. The California Department of Water Resources (DWR) land-use GIS survey was used to determine the spatial distribution of crops coupled with a probability approach to generate crop rotations through time. The DWR GIS product contains detailed maps of field locations and cultivated crops derived from analyses of aerial photos and field surveys. Solano and Placer Counties were surveyed in 1994; Yuba in 1995; Yolo in 1997; Colusa, Glenn, and Sutter in 1998; Butte in 1999; Fresno and Sacramento in 2000; and Kings in 2003. In addition, more than 1000 empirical 5-year sequences of crops were also gathered from farmer surveys (Howitt et al., 2009) and pesticide use reports obtained by agricultural commissioners. The data suggest that, a farmer's decision on which crop to plant in the current year is dependent on which crops were grown in the previous years. A probabilistic model was used to simulate realistic crop rotations. This probabilistic model was calibrated by calculating the following (conditional) probabilities:

$$Pr\ (Cr_t = A) \quad (1)$$

$$Pr\ (Cr_t = A|Cr_{t-1}) \quad (2)$$

$$Pr\ (Cr_t = A|Cr_{t-1}, Cr_{t-2}) \quad (3)$$

where $Cr_t = A$ is the probability to have crop A in the current year (time t), $\Pr(Cr_t = A|Cr_{t-1})$ is the probability to have crop A in the current year contingent on previous-year's crop Cr_{t-1}; and $\Pr(Cr_t = A|Cr_{t-1}, Cr_{t-2})$ is the probability to have crop A in the current year contingent on previous-year's crop Cr_{t-1}, and the crop from 2 years before Cr_{t-2}. The data indicated that a farmer's decision to plant a crop was only dependent on the crops that were planted 2 years before, except for alfalfa–hay, which was grown in 4- or 5-year rotations. These conditional probabilities were applied as following. For each individual field in each of the 10 counties, the crop grown in 1997, the first year of the simulations, was selected based on the DWR data. The crop grown in the following year, 1998, was selected based on the probabilities from Eq. (2) and conditioned by the crop grown in 1997 for that individual field. In all subsequent years until 2006, the crop planted was selected randomly based on the probabilities from Eq. (3), and conditioned on the crops grown over 2 years before, except for rotations containing alfalfa–hay.

2.3.3. Agricultural management practices

Details on conventional management practices in the region (e.g., planting, fertilization, irrigation, weed control, and harvesting) were obtained from the Agronomy Research and Information Center (AgRIC; http://agric.ucdavis.edu/) and the cost and return studies through the University of California Cooperative Extension (UCCE, 2007). The AgRIC is an outreach service that provides research-based, comprehensive, reliable information on current California agronomic cropping practices for alfalfa, corn, safflower, and small grains such as wheat. The cost and return studies contain details on agricultural inputs, planting and harvesting dates, and other operations for each crop considered in this study. The cost and return studies are updated on a regular basis.

Next to conventional farming, all possible combinations of conservation tillage, manure application, reduced N fertilizer input, and/or winter cover cropping were considered as possible alternative management options, except for winter cover cropping under winter wheat and alfalfa, and conservation tillage and manure application under alfalfa, as the latter is grown continuously for four growing seasons. The N application rate when manure was applied remained equivalent to the N application rate when mineral N fertilizer was applied. A mixture of pea (*Pisum sativum* L.) and 76% common vetch (*Vicia sativa* L.) was used as a leguminous crop for winter cover cropping (De Gryze et al., 2010). Information on these alternative management practices was obtained from farm advisors and the Long-Term Research on Agricultural Systems (LTRAS) at Russell Ranch of the University of California, Davis.

2.3.4. Climate data

Spatially explicit daily weather data for 1980 until 2003 were obtained from the DAYMET model developed at the Numerical Terradynamic Simulation Group of the University of Montana. This model uses a digital elevation model and daily observations from ground-based meteorological stations to produce a daily data set of temperature, precipitation, humidity, and radiation. The data were obtained for each 1×1 km grid cell representing the counties included in this study and were aggregated into 3×3 km grid cells for use within the DAYCENT model due to computational constraints. Spatially explicit daily weather data for 2004–2006 were obtained from the different weather stations of CIMIS (http://www.cimis.water.ca.gov) and aggregated into individual grid cells.

2.4. Modeling approach

2.4.1. Individual modeling units

A large database of individual modeling units was created by intersecting field boundaries from DWR with soil types from SSURGO and the 3×3 km weather grid cells within a GIS. The 25% smallest modeling units, comprising less than 1% of the area, were omitted from this database to reduce computational time with minimal effects on the model outcome. In total, about 10,000 modeling units were retained. The smallest modeling unit was about 1 ha in size.

2.4.2. Historical runs

The CENTURY model, on which the DAYCENT model is based, divides the total SOM into three homogeneous soil pools, i.e., active, slow, and passive, with a specific turnover time associated with each pool, and two plant residue pools, termed metabolic and structural, that are differentiated on the basis of plant litter quality. To initialize the relative size of these compartments, historical runs were executed. The historical runs represent the average long-term history of land use and management in the Central Valley. More specifically, before 1870, the model simulated a native grassland system and was run until equilibrium was attained. Between 1870 and 1996, an agricultural system was simulated in which fertilization and irrigation were gradually introduced and increased in intensity, and in which crop diversity increased until the end of the 20th century (De Gryze et al., 2010). Such historical runs were performed on all individual modeling units according to the procedures from De Gryze et al. (2010).

2.4.3. Current simulation and calculations

After the historical runs, crop yields and GHG fluxes were simulated for each individual modeling unit for the 10 years from 1997 to 2006. Annual crop yields, CO_2 flux, N_2O flux, and the net soil GHG flux were computed for each modeling unit under the baseline (conventional practice) scenario and an alternative management practice scenario. Within each modeling unit, changes in yield and GHG fluxes were calculated by subtracting values for the alternative management practice scenario from the baseline (conventional practice) scenario. Averages of yield and GHG flux changes were taken for each crop over the simulation period by management practice, crop, and region weighed by the size of each of the modeling units.

Within each modeling unit, the net change in net soil GHG flux with alternative management was calculated as follows:

$$\mathrm{GHG} = \frac{44}{12}\,\Delta\mathrm{SOC} + 296\,[\mathrm{N_2O}] + 23\,[\mathrm{CH_4}] \qquad (4)$$

where GHG is the net soil GHG flux in Mg CO_2-equivalents (CO_2-eq) $ha^{-1}\,yr^{-1}$; ΔSOC is the change in SOC in Mg C $ha^{-1}\,yr^{-1}$, [N_2O] is the flux of N_2O in Mg N_2O $ha^{-1}\,yr^{-1}$, and [CH_4] is the flux of CH_4 in Mg CH_4 $ha^{-1}\,yr^{-1}$. Note that these fluxes only represent direct emissions within the field's boundaries. Indirect N_2O emissions were not included in the reported GHG fluxes, due to great uncertainties associated with those emissions and insufficient calibration and validation data. The DAYCENT model is currently not designed to simulate continuously flooded soils and therefore does not simulate CH_4 production. The DAYCENT model does, however, include CH_4 oxidation. As a consequence, CH_4 fluxes are generally negative. The radiative forcing constants from IPCC (2001) were used to calculate 100-year net soil GHG fluxes.

2.5. Statistical analysis

Ten-year averages and standard deviations of net soil GHG fluxes were calculated using an ANOVA model in which crop, region (Sacramento Valley or San Joaquin Valley), tillage treatment, and implementation of winter cover cropping, manure application, reduced fertilizer input and their interactions were considered as fixed effects. The reported variability in SOC changes, N_2O and net soil GHG fluxes represents differences in soil parameters and

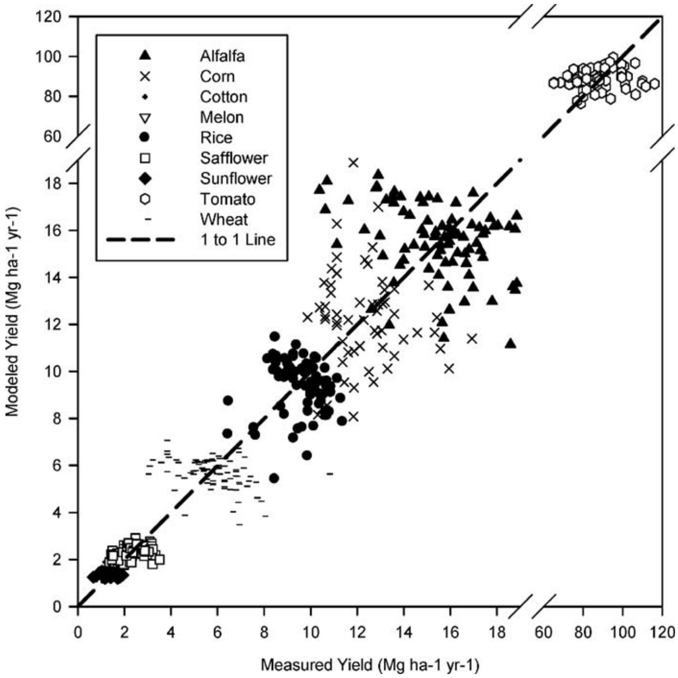

Fig. 3. Measured versus modeled county-wide yields. Values are county-wide annual averages for 10 years (1997–2006) and 10 counties.

climate data across the landscape. Due to computational limits, it was not feasible to consider uncertainty from other model inputs than soil parameters and climate data or model structure in this analysis.

3. Results

3.1. Yields

While, within one crop, there was less correspondence between the modeled county-wide average yields under conventional management and the yields reported by the USDA's National Agricultural Statistics Service (NASS), the model was still able to satisfactorily predict major differences in crop yields among crops (Fig. 3). For tomato, sunflower, and safflower, the modeled variability of county-wide averages was smaller than the variability of the averages reported by the NASS. For alfalfa, corn and wheat, modeled and observed variability of yields were similar.

For most crops, alternative management practices decreased yields by less than 5% compared to conventional practices (Table 1). In both the Sacramento and San Joaquin Valleys, the largest decrease, averaged over all crops and weighted by cropping area, was noted for manure application with winter cover cropping and conservation tillage. This decrease was −2.4% in the Sacramento Valley and −3.5% in the San Joaquin Valley. Reducing mineral N fertilizer input by about 25% led to decreased yields of about −2.9% in the Sacramento Valley and −2.3% in the San Joaquin Valley averaged over all the crops.

Of all the crops considered, tomatoes showed the highest yield decrease averaged over all alternative management practices (−2.5% and −3.1% in the Sacramento and San Joaquin Valleys), followed by cotton (−2.9%, only present in the San Joaquin Valley). None of the alternative practices were implemented when alfalfa was grown. Therefore, changes in alfalfa yields remained minimal. The greatest yield decrease for a single management practice in the Sacramento Valley was −12.9% for safflower under reduced N fertilizer input (MNRL 75%), and −6.5% in the San Joaquin Valley for melon under reduced N fertilizer input.

3.2. Average changes in GHG emissions

Average decreases in GHG emissions for each of the alternative management practices ranged from −0.70 to −3.23 Mg CO_2-eq ha^{-1} yr^{-1} in the Sacramento Valley, and from −0.50 to −2.0 Mg CO_2-eq ha^{-1} yr^{-1} in the San Joaquin Valley (Fig. 4). In general, reduced N fertilizer input and conservation tillage treatments had the least potential to reduce GHG emissions. Reduced fertilizer input led to decreased emissions of −0.89 and −0.61 Mg CO_2-eq ha^{-1} yr^{-1} in the Sacramento and San Joaquin Valleys, respectively, while conservation tillage decreased emissions by −0.68 and −0.57 Mg CO_2-eq ha^{-1} yr^{-1}. Manure application led to a greater GHG reduction in the Sacramento Valley (−1.16 Mg CO_2-eq ha^{-1} yr^{-1}), compared to the San Joaquin Valley (−0.5 Mg CO_2-eq ha^{-1} yr^{-1}). Overall, winter cover cropping decreased GHG emissions by −1.36 and −1.35 Mg CO_2-eq ha^{-1} yr^{-1}.

Combining the alternative management practices led to even greater reductions in GHG emissions that were characterized by both negative and positive interactive effects. For example, conservation tillage did not lead to an additional reduction in GHG emissions when combined with winter cover cropping compared

Table 1
Average relative changes in yield (%) by alternative practices compared to conventional practices for main field crops in the Sacramento Valley and San Joaquin Valley. Values are averaged over individual fields and for the period 1997–2006. Values represent biophysical potentials only, not practical limitations of combining these alternative practices.

Tillage: Fertilizer: Cover crop:	CONV MNRL, 75% No	CONS MNRL No	CONV MNRL Yes	CONS MNRL Yes	CONV ORG No	CONS ORG No	CONV ORG Yes	CONS ORG Yes
Sacramento Valley								
Alfalfa	0.4	0.0	0.3	0.3	0.3	0.3	0.3	0.4
Corn	−0.2	3.1	−0.5	−0.6	−1.9	−3.0	−2.5	−3.3
Safflower	−12.9	0.1	4.5	4.3	−3.6	−0.6	1.6	−6.3
Sunflower	0.0	0.2	−0.9	−1.0	−0.1	−1.3	−1.0	0.0
Tomato	−4.0	−0.8	−1.3	−1.3	−1.7	−4.4	−3.6	−2.6
Wheat	−0.1	0.1	0.1	0.1	−4.1	−2.6	−2.4	−1.9
San Joaquin Valley								
Alfalfa	2.0	0.4	3.4	3.5	0.0	0.3	3.8	3.9
Corn	0.0	1.6	0.5	0.6	0.1	0.1	0.7	0.7
Cotton	−2.1	−0.3	−3.6	−3.6	−0.5	−1.1	−5.2	−6.5
Melon	−6.5	1.4	−0.8	−0.8	−1.1	1.1	−3.1	−3.6
Tomato	−5.2	−1.0	−4.2	−4.2	−0.3	−0.8	−4.2	−5.2
Wheat	0.1	−0.2	−0.1	−0.2	−3.5	−3.7	−3.4	−3.9

CONV, conventional; CONS, conservation; MNRL 75%, mineral N application 75% of common practice; MNRL, mineral; ORG, organic.

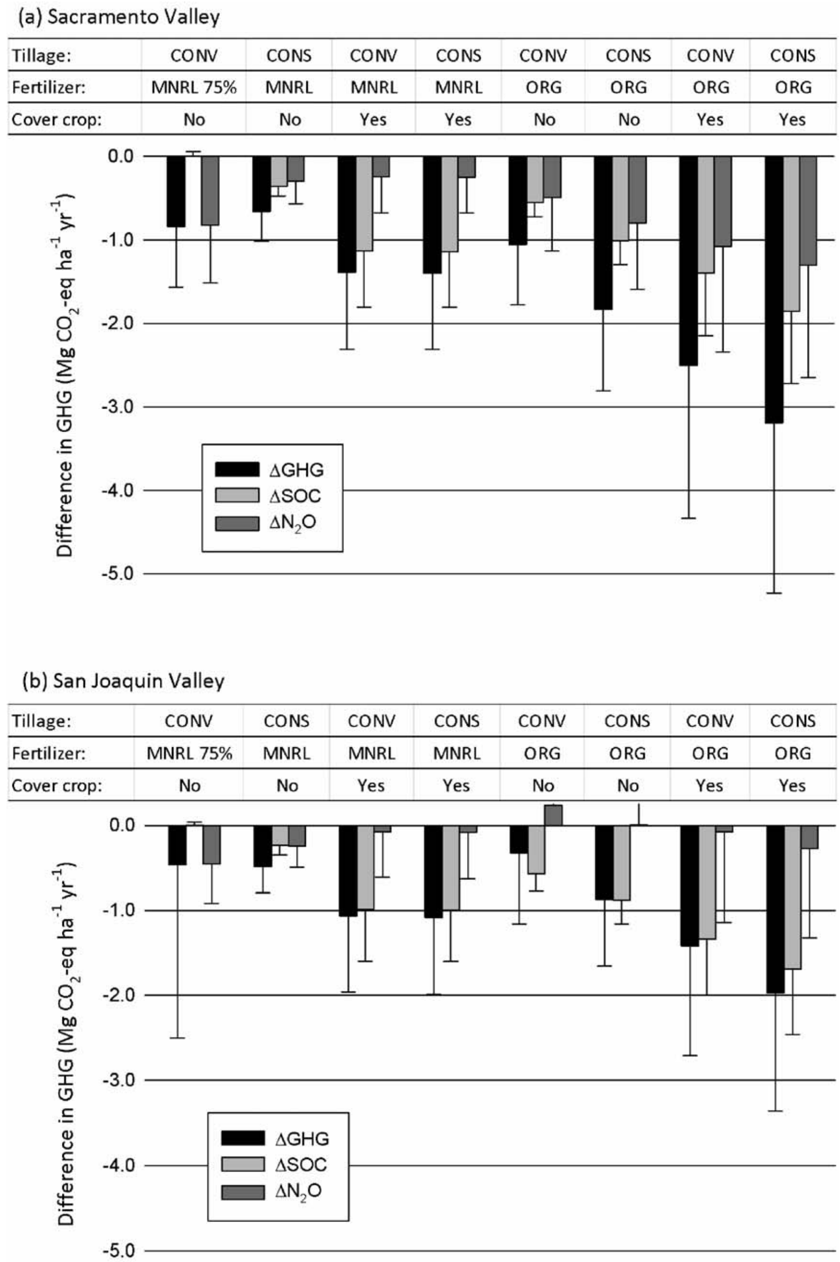

Fig. 4. Average changes in net soil GHG flux (GHG), soil organic C (SOC), and N_2O flux. Averages are taken per crop over 10 years (1997–2006) across all individual fields and crop rotations separately for the Sacramento and San Joaquin Valleys. Error bars indicate standard deviations representing the uncertainty around net soil GHG fluxes for one single field if this field was under the specific management for 10 years.

to the reduction observed by winter cover cropping alone. In contrast, there was an additional effect of conservation tillage when combined with manure application. The greatest GHG mitigation potentials were reached by combining all three options: conservation tillage, manure application, and winter cover cropping. This combination reduced GHG emissions by −3.29 and −2.45 Mg CO_2-eq ha^{-1} yr^{-1}, for the Sacramento and San Joaquin Valley, respectively. Potentials in the San Joaquin Valley were on average 25% smaller than the potentials in the Sacramento Valley, except for winter cover cropping with mineral fertilization. Increases in SOC were responsible for more than half of the reductions in GHG emissions for all the alternative practices, except for reduced N fertilizer input, for which reductions in N_2O emissions were driving the GHG mitigation. In the San Joaquin Valley, manure application increased N_2O emissions.

3.3. Changes in GHG emissions per crop

Emission reductions reported per crop represent averages over a large number of crop rotation patterns calibrated based on empirically observed crop rotations. Therefore, the reported emission reductions are only valid within the context of the current common practice of crop rotation patterns. Averaged over all the alternative management practices, the highest emission reductions were achieved during seasons in which corn, or tomato were grown (about −2.4 to −1.9 Mg CO_2-eq ha^{-1} yr^{-1}) in the Sacramento Valley and corn or cotton in the San Joaquin Valley (−3.9 to −1.6 Mg CO_2-eq ha^{-1} yr^{-1}). Emission reductions associated with a specific alternative management practice were to a large extent dependent on the crop grown during the simulation season. In the Sacramento Valley (Table 2), for example, conservation tillage

Table 2
Changes in the net soil GHG flux (GHG), soil organic C (SOC), and N_2O flux for the Sacramento Valley. Averages were taken for each crop over 10 years (1997–2006), across individual fields and crop rotations. Values represent biophysical potentials only, not practical limitations of combining these alternative practices.

Tillage: Fertilizer: Cover crop:	CONV MNRL, 75% No	CONS MNRL No	CONV MNRL Yes	CONS MNRL Yes	CONV ORG No	CONS ORG No	CONV ORG Yes	CONS ORG Yes
ΔGHG, Mg ha^{-1} yr^{-1}								
Alfalfa	−0.04	−0.01	0.02	0.02	0.03	0.01	0.08	0.06
Corn	−0.70	−0.42	−0.93	−0.95	−2.91	−3.17	−4.97	−4.95
Safflower	−0.02	−0.08	−0.44	−0.48	−0.71	−1.46	−0.29	−1.10
Sunflower	−0.62	−1.44	−2.36	−2.47	−0.54	−2.20	−1.44	−3.03
Tomato	−0.79	−1.13	−1.79	−1.8	−1.27	−2.70	−2.16	−3.43
Wheat	−0.16	0.09	0.19	0.16	−0.75	−0.80	−0.66	−0.59
ΔSOC, kg C ha^{-1} yr^{-1}								
Alfalfa	4.23	2.72	−4.01	−4.17	−10.1	−5.59	−21.0	−17.2
Corn	16.1	56.0	193	196	600	623	1171	1132
Safflower	−105	56.8	144	157	108	267	53.7	230
Sunflower	19.0	316	557	585	144	491	361	705
Tomato	−4	213	410	413	227	514	411	675
Wheat	−6.90	−28.0	−49.0	−41.0	86.0	108	79.0	50.0
ΔN_2O, kg N ha^{-1} yr^{-1}								
Alfalfa	−0.06	0.00	0.01	0.01	−0.02	−0.03	0.00	0.00
Corn	−1.37	−0.46	−0.48	−0.49	−1.51	−1.89	−1.44	−1.70
Safflower	−0.88	0.27	0.20	0.21	−0.68	−1.02	−0.19	−0.54
Sunflower	−1.18	−0.60	−0.67	−0.69	−0.03	−0.84	−0.26	−0.96
Tomato	−1.71	−0.74	−0.61	−0.61	−0.94	−1.74	−1.40	−2.04
Wheat	−0.40	−0.02	0.02	0.02	−0.92	−0.86	−0.79	−0.86

CONV, conventional; CONS, conservation; MNRL 75%, mineral N application 75% of common practice; MNRL, mineral; ORG, organic.

alone slightly increased GHG emissions for wheat by 0.09 Mg CO_2-eq ha^{-1} yr^{-1}, while it significantly decreased GHG emissions for tomatoes by −0.79 Mg CO_2-eq ha^{-1} yr^{-1}. Winter cover cropping reduced emissions for all crops, but especially for sunflower (−2.36 Mg CO_2-eq ha^{-1} yr^{-1}). However, during the winter seasons when wheat was grown and no winter cover crop could be planted, emissions increased with 0.16 Mg CO_2-eq ha^{-1} yr^{-1}. Regardless of the region, the additional effect of cover cropping was strongly dependent on the crop when combined with manure application. There were additional decreases in GHG emissions for tomatoes (Tables 2 and 3), but an increase in GHG emissions for safflower when combined with manure application (Table 2). The alternative management practices led to no decrease in net soil GHG flux for alfalfa (Tables 2 and 3).

Cropping systems in which manure was applied increased the net soil GHG fluxes slightly during seasons when alfalfa was grown by 0.03–0.04 Mg CO_2-eq ha^{-1} yr^{-1}, and decreased emissions most notably for corn, by −2.91 Mg CO_2-eq ha^{-1} yr^{-1} in the Sacramento Valley and by −1.42 Mg CO_2-eq ha^{-1} yr^{-1} in the San Joaquin Valley.

Averaged over all alternative management systems, for all crops, increases in SOC accounted for at least 70% of the potential reductions in net soil GHG flux. However, the increases in SOC accounted for only 29% of the reduction in net soil GHG flux for wheat in the Sacramento Valley, and 51% for wheat in the San Joaquin Valley.

Table 3
Changes in the net soil GHG flux (GHG), soil organic C (SOC), and N_2O flux for the San Joaquin Valley. Averages were taken for each crop over 10 years (1997–2006), across all individual fields and crop rotations. Values represent biophysical potentials only, not practical limitations of combining these alternative practices.

Tillage: Fertilizer: Cover crop:	CONV MNRL, 75% No	CONS MNRL No	CONV MNRL Yes	CONS MNRL Yes	CONV ORG No	CONS ORG No	CONV ORG Yes	CONS ORG Yes
ΔGHG, Mg ha^{-1} yr^{-1}								
Alfalfa	−0.23	−0.04	0.05	0.05	0.04	−0.02	0.26	0.20
Corn	−0.63	−0.92	−0.98	−1.02	−1.42	−2.38	−3.42	−4.00
Cotton	−0.64	−0.65	−2.08	−2.10	−0.55	−1.26	−2.36	−3.10
Melon	−0.32	−0.29	−0.25	−0.25	−0.90	−1.12	−1.17	−1.41
Rice	−2.34	−1.10	−3.79	−3.79	−2.38	−3.56	−6.38	−7.55
Tomato	−0.61	−0.60	−1.24	−1.24	−0.20	−0.94	−1.37	−2.24
Wheat	−0.13	−0.14	−0.08	−0.11	−0.91	−1.36	−0.87	−1.02
ΔSOC, kg C ha^{-1} yr^{-1}								
Alfalfa	5.21	7.64	−7.50	−7.10	−18.8	−5.00	−45.9	−33.7
Corn	2.43	176	264	276	344	548	884	1017
Cotton	−0.17	108	428	433	151	267	462	609
Melon	−18.9	44.8	95.1	95.1	240	269	302	346
Rice	6.13	136	678	678	158	313	719	914
Tomato	−8.20	89.6	330	329	154	286	392	538
Wheat	0.65	29.2	13.8	22	112	219	105	132
ΔN_2O, kg N ha^{-1} yr^{-1}								
Alfalfa	−0.45	−0.03	0.05	0.06	−0.05	−0.09	0.19	0.16
Corn	−1.33	−0.58	−0.02	−0.01	−0.34	−0.78	−0.38	−0.59
Cotton	−1.38	−0.54	−1.07	−1.07	0.02	−0.60	−1.41	−1.84
Melon	−0.83	−0.27	0.20	0.20	−0.04	−0.28	−0.12	−0.31
Rice	−4.96	−1.28	−2.79	−2.79	−3.85	−5.14	−7.99	−8.96
Tomato	−1.38	−0.59	−0.07	−0.07	0.78	0.23	0.14	−0.57
Wheat	−0.27	−0.06	−0.06	−0.06	−1.06	−1.19	−1.03	−1.14

CONV, conventional; CONS, conservation; MNRL 75%, mineral N application 75% of common practice; MNRL, mineral; ORG, organic.

4. Discussion

4.1. Simulated changes in yield under alternative management

The model simulated that yields generally decreased less than 5% when alternative management practices were adopted. This magnitude in yield decreases corresponds with what has been reported in the literature. For example, Miguez and Bollero (2005) found that when organic fertilizer was amended to corn-winter cover cropping systems, there was no difference in corn yield. Similarly, substituting mineral fertilizer by manure application did not lead to consistent changes in wheat yields in a study in a Mediterranean climate (Deria et al., 2003). A similar observation was made for tomato cropping systems in California (Drinkwater et al., 1995). For winter cover cropping systems, the relatively small observed reductions in modeled crop yields can be attributed in part to some competition for N supply between the cover crop and the main crop.

Even though average cropping yields were modeled accurately, the variability of modeled yields was smaller than empirically measured variability. No biogeochemical model can take all factors that regulate crop growth into account. For example, DAYCENT does not simulate potential changes in crop disease and pest incidence under alternative cropping practices (Karungi et al., 2006). DAYCENT also does not account for the potential decrease in seedling growth when a new crop is sown under conservation tillage. Finally, only C and N fluxes were simulated in this study; potential deficiencies in other macronutrients, such as phosphorus and sulfur, or micronutrients, such as zinc and molybdenum were not represented. The decreases in modeled yield by these alternative practices mainly represent N and moisture limitations. As a consequence, the magnitude of response of simulated yields to alternative practices may be smaller than empirically measured responses to alternative practices.

4.2. Comparison of changes in soil C and trace gas fluxes with literature data

The range in average simulated differences in SOC corresponded with what has been reported in the literature. With conservation tillage alone, modeled SOC increased by about 125 $kg\,C\,ha^{-1}\,yr^{-1}$ on average. This increase was somewhat smaller than average values of SOC increase reported in the literature for various conservation tillage systems. For a 10-year-old no-tillage system in a humid climate, Franzluebbers (2005) reported a value of around 250 $kg\,C\,ha^{-1}\,yr^{-1}$, and Six et al. (2004) a value of about 200 $kg\,C\,ha^{-1}\,yr^{-1}$. These literature values represent no-tillage systems that were mainly located in the Midwest and the Great Plains regions. The reduction in tillage intensity in our simulated conservation tillage system, calibrated based on common practices and long-term field studies in California, is smaller than the reduction in tillage intensity in the Midwest and the Great Plains regions (De Gryze et al., 2010), explaining the smaller increase in SOC due to conservation tillage. The increases in modeled SOC for the conservation tillage and winter cover cropping system (300 $kg\,C\,ha^{-1}\,yr^{-1}$) is larger than the average SOC increase for no-tillage winter cover cropping systems reported by Franzluebbers (2005) (160 $kg\,C\,ha^{-1}\,yr^{-1}$). The magnitude of simulated increases in SOC content after manure application was close to values in the literature; the model simulated an average manure-C-to-SOC conversion rate of 13%, which is very close to the empirical conversion rate of 17% reported by Franzluebbers (2005). For no-tillage systems, Six et al. (2004) reported changes in N_2O emissions between -1.2 and 0.2 $kg\,N\,ha^{-1}\,yr^{-1}$, depending on the duration of the experiment. The modeled averages, -0.41 ± 0.23 and -0.38 ± 0.35 $kg\,N\,ha^{-1}\,yr^{-1}$ for the Sacramento and San Joaquin Valleys, respectively, was in the middle of this range.

4.3. Evaluation of the GHG mitigation potentials

The reported reductions in modeled GHG emissions represent changes in direct emissions within the boundaries of the agricultural field. Emissions outside of the agricultural field were not included in the reported emission reductions. Potential reductions in modeled GHG emissions were on the order of -0.7 to -3.3 $Mg\,CO_2\text{-eq}\,ha^{-1}\,yr^{-1}$ for the Sacramento Valley and -0.5 to -2.5 $Mg\,CO_2\text{-eq}\,ha^{-1}\,yr^{-1}$ for the San Joaquin Valley. These values were averages per crop as grown within a range of crop rotations and weighed by the areas of the individual cropping fields. Note that the values presented in this study do not include the GHG benefits from a potential reduction in fuel use or a potential reduction in GHGs associated with mineral fertilizer production when the alternative practice uses less mineral fertilizer. The emission reductions by the three single C-sequestering management practices separately, conservation tillage, winter cover cropping, and manure application, were modest. However, our results suggest that, by combining these single options, larger GHG mitigation potentials can be attained. Most markedly, combining manure application with winter cover cropping seems to be a very efficient option to reduce GHG emissions. The combination of all three C-sequestering options has the greatest potential for GHG mitigation, even though it does not seem practically and economically feasible from a farmer's operational standpoint (Howitt et al., 2009). In addition, this study does not consider any limits to the availability of the manure, nor any potential GHG reductions related to alternative use of manure.

The simulated decreases in GHG emissions were for a large part due to gains in SOC (e.g., 90% for winter cover cropping, 70–80% for manure application). However, the capacity of a soil to store C is limited (VandenBygaart et al., 2002; Six et al., 2004), and if the proper soil management is not maintained, all sequestered C will be released again to the atmosphere in a matter of years. Therefore, alternative management options that rely almost solely on increases in soil C, such as winter cover cropping, seem only a viable option to curb GHG emissions over a few decades until a new SOC equilibrium is reached.

Even though the 25% N fertilizer reduction system had a modest overall potential to decrease GHG, the majority of this decrease was due to a decrease in N_2O emissions, which does not have the issue of permanence. Likewise, in the Sacramento Valley, a consistent decrease in N_2O emissions of about 0.5 $Mg\,CO_2\text{-eq}\,ha^{-1}\,yr^{-1}$ was simulated when applying manure instead of mineral N fertilizer. Management practices that reduce N_2O emissions, such as N fertilizer reduction or manure application, are more permanent GHG mitigation options than management practices that rely mostly on increases in SOC.

Both the substantial decreases in N_2O emissions as well as the limited effect on yields to a 25% reduced N fertilizer system indicate there is a potential surplus of mineral N in the soil according to the simulations, which is being denitrified and converted to N_2O (McSwiney and Robertson, 2005). Some over-fertilization is a common practice in the region due to the low price of N fertilizer and the minimization of the risk for yield loss due to N limitation (Cassman et al., 2002). The 25% reduced N fertilizer system seems to be an efficient way to permanently mitigate N_2O emissions and net soil GHG fluxes, regardless of the duration of the practice, if farmers can be compensated for the increased risk of decreases in yield. Similarly, a reduced number and duration of tillage operations is straightforward to implement, and leads to a direct reduction in costs and an additional and permanent reduction in fuel-related GHG emissions beyond the GHG mitigation potentials reported in Tables 2 and 3 (Howitt et al., 2009).

In general, GHG mitigation potentials were greater in the Sacramento Valley than in the San Joaquin Valley. We hypothesize that the higher temperatures in the San Joaquin Valley increase the decomposition of SOC compared to the Sacramento Valley, and decrease the GHG mitigation potentials significantly, which are largely driven by C sequestration.

4.4. Model uncertainties

The standard deviations of the GHG mitigation potentials of single cropping fields were large, and in the same order of magnitude as the average GHG mitigation itself (Fig. 4). However, these standard deviations represent the distribution of GHG mitigation potentials when a single and randomly selected cropping field would be converted into alternative management for a period of 10 years. The standard deviation of GHG mitigation potentials would decrease significantly if individual fields would be aggregated and the GHG mitigation potential of a larger region would be calculated. Consequently, C credit contracts over a larger area, encompassing a variety of crops in every cropping season, and soils will be necessary to reduce the uncertainty around potential sequestration rates.

Standard deviations of N_2O emissions were larger than standard deviations of SOC changes. Likewise, Winiwarter and Rypdal (2001) report standard deviations of agricultural N_2O emissions in the order of 60%, while this was only 3% for SOC changes. Del Grosso et al. (2010) estimated uncertainty in N_2O emissions from US agricultural soils from −34% to 51%. The variability of N_2O emissions originates partially from the dependence of nitrification and denitrification on moisture levels in the soil, which are highly variable over time and partially from the lack of empirical data for annual N_2O fluxes of various cropping systems under cropping conditions similar to California's Central Valley. A concerted research effort will be necessary to decrease the variability of N_2O flux predictions by biogeochemical models.

In conclusion, model simulations indicated that the adoption of alternative management practices such as conservation tillage, manure application, or winter cover cropping, affected cropping yields only very minimally. While the reductions in GHG emissions of individual practices were modest, combining these alternative practices led to larger reductions, albeit smaller than the sum of the reductions of the separate alternative practices. The GHG mitigation potentials were greater in the more northern Sacramento Valley than in the southern San Joaquin Valley. Emission reductions were mostly non-permanent since emission reductions were to a large extent due to increases in SOC. In contrast, emission reductions from reducing N fertilizer were mostly permanent since nearly all of the emission reductions were due to a permanent decrease in N_2O emissions. Similarly, the reduction of fuel use associated with conservation tillage practices is a permanent reduction in GHG emissions. The main source of variability of GHG reductions originated from the uncertainty around N_2O fluxes. Only a concerted research effort can advance the general understanding of the processes involved and decrease the uncertainty around these model estimates. To reduce the uncertainty around emission reductions, and minimize the risk for under-delivery of emission reductions, GHG mitigation projects will have to be implemented over large areas, encompassing a variety of crops and soils, and longer time periods.

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