Integrated assessment of the biophysical and economic potential for greenhouse gas mitigation in CA agricultural soils

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Collaborators: Keith Paustian, Steve Ogle, Changsheng Li, William Salas

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US National Carbon Inventory

Mineral soils are sequestering ca. 15 million T C/yr

Slide courtesy of Ogle
Anthropogenic Sources of Methane and Nitrous Oxide Globally

**CH₄**

- Biomass burning
- Rice cultivation
- Waste treatment
- Enteric fermentation

**N₂O**

- Biomass burning
- Cattle & feedlots
- Energy
- Other combustion

Industry

Agriculture

Total Impact

- 2.0 Pg C
- 1.2 Pg C

(compare to fossil fuel CO₂ loading = 3.3 Pg C per year)

(compare to soil C sequestration of 0.3-0.5 Pg C per year)

IPCC 2001; Robertson 2004
Scoping study of Li and Salas (2004)

- Preliminary study of the potential for C sequestration and GHG mitigation in CA
- Large uncertainties in soil C dynamics due to uncertain initial conditions and crop residue management
- Recommendations
  - Improve spatial data on management practices including residue and manure management
  - Use updated SSURGO soils data base
  - Verify DNDC model for CA conditions
  - Evaluate alternative mitigation scenarios such as tillage, cover crops, optimal fertilization practices
Overall Objective

• Assess the biophysical potential and economic feasibility for soil C sequestration and reduction of trace gas emissions in CA agricultural soils

- Accomplished through integration of spatial databases on environmental factors and land use data with ecosystem simulations models and economic analyses
Specific Objectives

1. Test DAYCENT and DNDC for simulations of crop productivity, C storage, and trace gas emissions for CA agroecosystems.

2. Integrate the ecosystems models with an economic model at the field and county level.

3. Produce regional projections for the biophysical potential and economic feasibility of C sequestration and reduction in trace gas emissions.

4. Quantify uncertainties in model predictions for county scale results.

5. Perform preliminary assessment of the potential to mitigate greenhouse gas emissions for the Central Valley.
Obtain ecosystem models, determine input data required, evaluate inherent limitations

Find experiments with high detail
- Complete management details
- Yields
- SOC (and N\textsubscript{2}O if possible)

Simulate these experiments and see if yields are okay. Tune crop parameters till good fit to local genotypes.

Verify SOC and N\textsubscript{2}O against any measurements.

If it looks all-right, then we can simulate a variety of management options across a range of soil and climate, and use in a regional economic model.

Keep an eye on the big picture!
Steps in Dynamic Model-Based Approach

1. Model Selection/Development
2. Identify Model Inputs
3. Assess Uncertainties
4. Implement Model
5. Validation of Model Results (Optional)
6. Reporting/Documentation
7. Model Verification
   - Does not capture general trends from experimental data?
   - Unable to locate appropriate input data?
   - Model Results deemed unacceptable due to mismatch with validation data?
<table>
<thead>
<tr>
<th>Model</th>
<th>Origin</th>
<th>Legacy</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNDC</td>
<td>Started as an N model requiring quick dynamics.</td>
<td>Only 1 year rotations possible. Less legit for slow C dynamics</td>
</tr>
<tr>
<td>DayCent</td>
<td>Started as a C model using slow dynamics.</td>
<td>More flexibility in crop systems. Less legit for fast N dynamics</td>
</tr>
</tbody>
</table>
Major ecosystem processes to check

Crop Yield
Accurate simulated crop yield is critical because it is used in the economic model, and is the main part of the C cycle.

Soil Carbon
Accurately modeled changes in soil carbon stocks are key

$N_2O$ efflux
$N_2O$ efflux may be the major greenhouse gas component of California agricultural systems.

Fuel C
Major component of ancillary greenhouse gas mitigation
Initial test of model comparison of yield at Yolo field site

See Wolf et al. poster for comparisons at other CA sites

DNDC
No calibration
Testing against field results

DayCent and DNDC

For measurement details, see King et al. and Paw U et al. posters
Test against field results

DNDC Nitrous oxide Yolo site

![Graph showing N2O efflux rate](image)

- **Yolo site**
- **DNDC**
- **Nitrous oxide**

**N2O efflux rate (nmol m$^{-2}$ s$^{-1}$)**

**Day of year**
Test against field results

Nitrous oxide

DayCent

Yolo site
Model Sensitivity at field scale

DNDC

- Modeled 72 sample locations at Yolo field site
- Soil texture and SOC have little consistent effect on modeled N$_2$O efflux, but bulk density exerts a major control.

<table>
<thead>
<tr>
<th>Bulk density (g cm$^{-3}$)</th>
<th>Annual N$_2$O efflux (kg N ha$^{-1}$ year$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>3.5</td>
</tr>
<tr>
<td>0.9</td>
<td>4.0</td>
</tr>
<tr>
<td>1.0</td>
<td>4.5</td>
</tr>
<tr>
<td>1.1</td>
<td>5.0</td>
</tr>
<tr>
<td>1.2</td>
<td>5.5</td>
</tr>
<tr>
<td>1.3</td>
<td>6.0</td>
</tr>
<tr>
<td>1.4</td>
<td>6.5</td>
</tr>
</tbody>
</table>

- Clay %
- SOC %
Specific Objectives

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Integrated modeling approach

Field experiments

Land use and management identification

Spatial Information

Ecosystem model

Plant Growth

Residues

Active SOM

Slow SOM

Passive SOM

Dynamic economics

Decision support

With uncertainty estimates

Integration approach

Yellow is trees

Light green is small grain & field crops

Red is mostly tomatoes

Dark green is pasture

Beige is native vegetation

Black is urban

DWR Land use survey

Yolo county 1997

Land use and
management
identification

Field experiments
The environmental benefit from a change in management

The financial impact of a change in yields and a change in costs

$/tCO_2e = \frac{\Delta \$ \text{ (alternate – baseline)}}{\Delta tCO_2e \text{ (alternate – baseline)}}$

For greenhouse gas emissions in agriculture, this tradeoff changes:

- For different soils (e.g., sand versus clay)
- For different farming systems (e.g., wine grapes vs wheat)
- For different climatic/economic regions (e.g., Chico vs Coachella)
- For different management changes (e.g., reduced tillage or cover crops)
Coupling ecosystem and economic models

- Ecosystem models give predictions of yield and global warming potential as input into economic model
- Economic model predicts how growers may adapt their practices to maximize profit
- Change in practices from economic model then input back into ecosystem models
To a first approximation this exercise requires:

- Identifying all cultivated lands in a county
- Summarizing the variability in soil properties for each map unit
- Identifying standard “baseline” land management practices
- Identifying management changes to reduce greenhouse gases
- Running the model for every combination of soil characteristics and land management over a range of historical weather conditions just to get the environmental part of the equation.

For 100 map units, a range of clay in each map unit, and only 4 management scenarios, over 5 years of weather conditions:

100 * 2 * 4 * 5 = 4000 model runs!

At a typical computation speed of 1 year s⁻¹, this equals 13 hours . . . .

When we start talking about many management scenarios, with changes in variable input usage (i.e. fertilizer) it all grows exponentially . . .
Grower adaptation and coupled modeling

• When farmers face a constraint or incentive, they can shift crop mix

• Some crops and soils will be preferentially suited to reduce greenhouse gas emission, based on their biophysical potential, and the opportunity costs embodied with their place in the crop mix

  example: when faced with a water shortage, farmers do not cut back on irrigation, but switch to crops which demand less water

• This requires true interaction between biophysical & economic models at county and state levels to predict agriculture’s aggregate response to efforts to curb greenhouse gas emissions
Greenhouse gas budget

- \( \text{N}_2\text{O} \) is the MAJOR component of the GHG budget
- Fuel C emissions exceeds soil emissions
- Cover crops can substantially mitigate GHG emission

### Davis, Yolo County

#### Conventional

<table>
<thead>
<tr>
<th></th>
<th>Tomato</th>
<th>Saff</th>
<th>Corn</th>
<th>Bean</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \text{Soil C} )</td>
<td>-658</td>
<td>878</td>
<td>656</td>
<td>-1295</td>
<td>-105</td>
</tr>
<tr>
<td>( \text{N}_2\text{O} )</td>
<td>2.8</td>
<td>2.5</td>
<td>4.1</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Fuel-C</td>
<td>449</td>
<td>173</td>
<td>213</td>
<td>276</td>
<td>278</td>
</tr>
</tbody>
</table>

#### with Cover Crops

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \text{Soil C} )</td>
<td>-62</td>
<td>1578</td>
<td>1356</td>
<td>-1171</td>
<td>425</td>
</tr>
<tr>
<td>( \text{N}_2\text{O} )</td>
<td>2.2</td>
<td>1.8</td>
<td>2.8</td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Fuel-C</td>
<td>446</td>
<td>172</td>
<td>216</td>
<td>200</td>
<td>258</td>
</tr>
</tbody>
</table>

#### tCO2e

<table>
<thead>
<tr>
<th></th>
<th>Tomato</th>
<th>Saff</th>
<th>Corn</th>
<th>Bean</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil C</td>
<td>2.4</td>
<td>-3.2</td>
<td>-2.4</td>
<td>4.7</td>
<td>0.4</td>
</tr>
<tr>
<td>( \text{N}_2\text{O} )</td>
<td>2.6</td>
<td>2.3</td>
<td>3.8</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>Fuel-C</td>
<td>1.6</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>Corn</th>
<th>Bean</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil C</td>
<td>0.2</td>
<td>-5.8</td>
<td>-5.0</td>
<td>4.3</td>
<td>-1.6</td>
</tr>
<tr>
<td>( \text{N}_2\text{O} )</td>
<td>2.0</td>
<td>1.6</td>
<td>2.6</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Fuel-C</td>
<td>1.6</td>
<td>0.6</td>
<td>0.8</td>
<td>0.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>

\( \text{N}_2\text{O} \) and soil C are simulated

Source: SAFS
Greenhouse gas budget

- Reduced tillage can cut fuel-CO₂ emissions by half
- Integration of reduced tillage with cover cropping!

### Five Points, Fresno County

<table>
<thead>
<tr>
<th></th>
<th>Standard Tillage</th>
<th>Reduced Tillage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td>with Cover Crop</td>
</tr>
<tr>
<td></td>
<td>Tomato</td>
<td>Cotton</td>
</tr>
<tr>
<td>Δ Soil C (kg [-]/ha)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td>5.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Fuel-C</td>
<td>171</td>
<td>138</td>
</tr>
<tr>
<td>tCO₂e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil C</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>N₂O</td>
<td>4.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Fuel-C</td>
<td>0.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Soil C measured, N₂O simulated

See Wolf et al. poster
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4. **Quantify uncertainties in model predictions for county scale results.**

5. Perform preliminary assessment of the potential to mitigate greenhouse gas emissions for the Central Valley.
Major sources of variation

• Inherent errors in model predictions
• Large differences in properties between and within soil types
• Differences in current and historic cropping affects soil C now, and land use history is generally unknown
• Uncertainties in weather and climate
Uncertainty in model predictions

• Most Sensitive Factor Method (Li et al., 2004) (Sensitivity of input variables)
  – Run models for minimum and maximum values of each input variable

• Monte Carlo approach (Structural uncertainties of model)
  – Randomly selecting values from PDFs and running the models to produce an ensemble of results
  – Data intensive
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Mitigation potential – Central Valley

• Repeat ecosystem and economic modeling process for rest of the counties
• Assess multiple management scenarios in order to determine mitigation potential for policy analysis
Summary and Conclusions

• Testing DNDC and DAYCENT with data from CA field experiments
  – Accurate predictions of field-scale yield is mixed
  – DNDC better predicts N\textsubscript{2}O emissions than DAYCENT
  – Models seem comparable for CO\textsubscript{2}
  – Cover cropping and/or reduced tillage seem to offer some mitigation potential in CA
  – Fuel C and N\textsubscript{2}O will be major player in greenhouse gas budgets in CA

• Currently assembling county-wide data sets for Yolo, Fresno, and Kings and beginning to make model runs for input to economic model
Thanks for your attention
N$_2$O Flux x N-fertilizer Level

![Graph showing the relationship between N$_2$O flux and N-fertilizer level (kg N/ha)].
## 20 Year Cumulative GWP (NT - CT)

### Humid Climate

<table>
<thead>
<tr>
<th>Gas</th>
<th>Estimate (s.e.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>-16296 (88)</td>
</tr>
<tr>
<td>N₂O</td>
<td>5027 (3706)</td>
</tr>
<tr>
<td>CH₄</td>
<td>-258 (46)</td>
</tr>
</tbody>
</table>

**Soil-derived GWP**: -11526 (3707)

**Ancillary GHG changes**: -2273

**Total GWP**: -13799

### Dry Climate

<table>
<thead>
<tr>
<th>Gas</th>
<th>Estimate (s.e.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂₁</td>
<td>-7128 (115)</td>
</tr>
<tr>
<td>N₂O</td>
<td>5105 (5814)</td>
</tr>
<tr>
<td>CH₄</td>
<td>-258 (46)</td>
</tr>
</tbody>
</table>

**Soil-derived GWP**: -2281 (5815)

**Ancillary GHG changes**: -2273

**Total GWP**: -4554

---

¹ GWP = in CO₂ equivalents
² s.e. = standard error

Six et al., 2003
<table>
<thead>
<tr>
<th></th>
<th>1990-92 (Tg C yr(^{-1}))</th>
<th>1993-97 (Tg C yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mineral Soils</strong></td>
<td>9.76 (3.8 to 16.0)</td>
<td>9.65 (5.7 to 13.7)</td>
</tr>
<tr>
<td><strong>Organic Soils</strong></td>
<td>-9.36 (-6.3 to -13.2)</td>
<td>-9.47 (-6.4 to -13.4)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.41 (-6.6 to 7.4)</td>
<td>0.18 (-5.3 to 5.3)</td>
</tr>
</tbody>
</table>
Slide courtesy Paustian

McCarl and Schneider 2001
Minimum payment needed to cover expenses

- Yolo: $-100
- Fresno (STCC): $0
- Fresno (CTNO): $-200
- Fresno (CTCC): $-250

$ per ton CO2 equivalent