Relating atmospheric N$_2$O concentration to agricultural emissions in the US Corn Belt in a meso-scale modeling framework

Congsheng Fu & Xuhui Lee
(Yale University)
Background

- **Bottom-up method**
  total emission = N input or other activity data × emission factor for each pathway

- **Top-down method**
  total emission: determined with atmospheric N$_2$O mixing ratio observed on tall towers or aircraft.

  **Top-down estimate >> Bottom-up estimate**

  **Emission from headwater streams are severely underestimated**
Schematic of the modeling framework
1. WRF-chem modeling and inverse analysis

**Figure.** Total EDGAR42 emission and nature soil emission for the study area.
1. WRF-chem modeling and inverse analysis

**Fig. 1.** Locations of the $\text{N}_2\text{O}$ monitoring towers, scope of the Corn Belt, modeling domains, and the default $\text{N}_2\text{O}$ emissions. Emission unit is $\text{nmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. KCMP – Minnesota; NWR – Niwot Ridge, Colorado.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Items</th>
<th>Emission (nmol m(^{-2}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A1_1A2</td>
<td>Energy manufacturing transformation</td>
<td>0.00698</td>
</tr>
<tr>
<td>1A3a_c_d_e</td>
<td>Non-road transportation</td>
<td>0.00248</td>
</tr>
<tr>
<td>1A3b</td>
<td>Road transportation</td>
<td>0.01552</td>
</tr>
<tr>
<td>1A4</td>
<td>Residential</td>
<td>0.00227</td>
</tr>
<tr>
<td>1B2a_c</td>
<td>Oil production and refineries</td>
<td>0.00002</td>
</tr>
<tr>
<td>2_3</td>
<td>Inudstrial process and product use</td>
<td>0.01388</td>
</tr>
<tr>
<td>4B</td>
<td>Manure management</td>
<td>0.00217</td>
</tr>
<tr>
<td>4C_4D</td>
<td>Agricultural soil</td>
<td>0.12813</td>
</tr>
<tr>
<td>4D3</td>
<td>Indirect emission from agriculture</td>
<td>0.02215</td>
</tr>
<tr>
<td>4F</td>
<td>Agricultural waster burn</td>
<td>0.00028</td>
</tr>
<tr>
<td>7A</td>
<td>Fossil fuel fires</td>
<td>0</td>
</tr>
<tr>
<td>7B_7C</td>
<td>Indirect emission from NOx and NH3</td>
<td>0.01010</td>
</tr>
<tr>
<td>WASTER</td>
<td>Waste solid and wastewater</td>
<td>0.00388</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>0.208</td>
</tr>
</tbody>
</table>

**Table.** EDGAR42 N\(_2\)O emissions and EDGAR2 nature soil emission within the Corn Belt. Note: 4B + 4C_4D + 4D3 + 4F = 0.153 nmol/m\(^2\)/s.
1. WRF-chem modeling and inverse analysis

Table 1. Model set-up used in WRF.

<table>
<thead>
<tr>
<th>Basic equation</th>
<th>Non-hydro mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time-integration scheme option</td>
<td>Runge-Kutta 3rd order</td>
</tr>
<tr>
<td>Time step for integration</td>
<td>120 s</td>
</tr>
<tr>
<td>Microphysics option</td>
<td>WRF Single-Moment (WSM) 5-class scheme</td>
</tr>
<tr>
<td>Longwave radiation option</td>
<td>Rapid Radiative Transfer Model (RRTM)</td>
</tr>
<tr>
<td>Shortwave radiation option</td>
<td>Goddard Shortwave scheme</td>
</tr>
<tr>
<td>Cumulus option</td>
<td>Grell-Devenyi ensemble scheme</td>
</tr>
<tr>
<td>Boundary-layer option</td>
<td>Yonsei University Scheme (YSU) scheme</td>
</tr>
<tr>
<td>Surface-layer option</td>
<td>Monin-Obukhov Similarity scheme</td>
</tr>
<tr>
<td>Land-surface option</td>
<td>Community Land Model Version 4 (CLM4)</td>
</tr>
</tbody>
</table>

Initial and boundary conditions:
weather forecast model Global Forecast System
Model for Ozone and Related Chemical Tracers (MOZART) version 4

Experimental design
• background simulation:
nature soil emission + EDGAR42 non-agricultural emissions for both domains
• default simulation
nature soil emission + total EDGAR42 emission (agricultural and non-agricultural) in both domains
• scaled simulation
inner domain: sum of nature soil emission, EDGAR42 non-agricultural emissions, and a multiple of EDGAR42 agricultural emissions
outer domain: nature soil emission + total EDGAR42 emission
1. WRF-chem modeling and inverse analysis

Table 2. Experimental and calibrated multipliers of EDGAR42 agricultural \( \text{N}_2\text{O} \) emissions in the study. Values in brackets are the constrained agricultural emission in unit of nmol·m\(^{-2}\)·s\(^{-1}\).

<table>
<thead>
<tr>
<th>Time</th>
<th>June 1 – 20</th>
<th>August 1 – 20</th>
<th>October 1 – 20</th>
<th>December 1 – 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental multipliers</td>
<td>0, 1, 25</td>
<td>0, 1, 12</td>
<td>0, 1, 3</td>
<td>0, 1, 6</td>
</tr>
<tr>
<td>Calibrated multiples using</td>
<td>19.0 (2.91)</td>
<td>9.3 (1.43)</td>
<td>3.4 (0.52)</td>
<td>3.0 (0.47)</td>
</tr>
<tr>
<td>observation at 32 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibrated multiples using</td>
<td>22.5 (3.44)</td>
<td>11.6 (1.77)</td>
<td>3.83 (0.59)</td>
<td>3.6 (0.55)</td>
</tr>
<tr>
<td>observation at 100 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibrated multiples using</td>
<td>28.1 (4.29)</td>
<td>13.0 (1.99)</td>
<td>4.7 (0.72)</td>
<td>4.3 (0.66)</td>
</tr>
<tr>
<td>observation at 185 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. WRF-chem modeling and inverse analysis

**Fig. 2.** Correlations between experimental multiples, wind direction, and modeled N$_2$O mixing ratio increases from ‘default’ and ‘scaled’ simulations at height of 185 m at the KCMP tower site. Degrees of 0°, 90°, 180°, and 270° represent north, east, south, and west winds, respectively. The regression slope in sub-figures (d) – (f) refers to the slopes as those shown in sub-figures (a) – (c).
Results at 100 m
Results at 32 m
Fig. 3. Observed (grey lines), modeled (red lines), and the scaled (blue and navy blue lines) N$_2$O mixing ratio increases at the KCMP tower site. The modeled increases (red lines) are the values from ‘default simulation’ subtracted by values from ‘background simulation’. Results in this figure are for the height of 185 m.
Results in this figure are for the height of 100 m.
Results in this figure are for the height of 32 m.
1. WRF-chem modeling and inverse analysis

Fig. 4. Correlations between the observed and scaled daily N$_2$O mixing ratio increases at the KCMP tower site. Results in this figure are for the height of 185 m.
1. WRF-chem modeling and inverse analysis

**Fig.** Correlations between the observed and scaled daily N2O mixing ratio increases at the KCMP tower site.
**Figure.** Correlations between simulated air temperature, wind direction, and N\textsubscript{2}O mixing ratio at height of 100 m at KCMP tower site.

**Figure.** Scatter plot between simulated air temperature and N\textsubscript{2}O mixing ratio at the KCMP tower site.
Figure. Correlations between simulated air temperature, wind direction, and N$_2$O mixing ratio at height of 32 m at the KCMP tower site in October.
**Fig. 5.** Spatial characteristics of the mean values of the modeled N$_2$O mixing ratio increases during June 1$^{st}$ – 20$^{th}$. In sub-figure (a), the averages of the entire modeling period; (b) the modeling results are for hours 19 and 20 (UTC), the observations – illustrated using colors in the filled squares, are for hour 19 and / or 20 (UTC). BAO is the background site for WBI, LEF, SCT, AMT, and WKT.
Figure. Simulated mixing heights for different periods.
Fig. 6. Simulated mixing height at the KCMP tower site in the present study (blue lines) and in Kim et al. (2013) (grey, black, and green lines). “EDAS” and “NARR” represent the mixing heights calculated by the STILT model using the meteorological data sets of “Eta Data Assimilation System” and “North American Regional Reanalysis”, respectively, and “GEOS-5” is the mixing height used to drive the GEOS-Chem model in Kim et al. (2013).
Key findings:

- The simple inverse analysis method based on the WRF-Chem modeling in the present study could be used to do the inverse analysis for N$_2$O emission within the Corn Belt.

- The agricultural N$_2$O emissions within the Corn Belt was clearly underestimated in the EDGAR42 database for all four periods from June to December, which is needed to be scaled up to at least 19 folds during the emission peak month – June, 2010.

- The dynamics of the monitored high-resolution N$_2$O mixing ratio at the KCMP tower site, which were influenced by diffusivity and wind direction, could be captured and reproduced by the WRF-Chem. The diffusivity affected the N$_2$O mixing ratio dynamics more in June and August than that in October and December, while wind direction influenced the dynamics more in October and December than that in June and August.

- The spatial patterns of the influences of the Corn Belt on the atmospheric N$_2$O mixing ratios during the emission peak month – June, 2010 could be perfectly captured by WRF-Chem model, and the Corn Belt-induced N$_2$O mixing ratio increase at height of 300 m is larger than 1 ppb during June 2010 within a scope that is larger than the Corn Belt itself.
2. CLM single-point mode modeling

Table. Land cover for the simulated grid (~5km × 5km).

<table>
<thead>
<tr>
<th>PFT number in CLM4.5</th>
<th>PFT name</th>
<th>Percentage of PFT in the modeling grid (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Bare Ground</td>
<td>1.9</td>
</tr>
<tr>
<td>1</td>
<td>Needleleaf evergreen tree – temperate</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Broadleaf deciduous tree – temperate</td>
<td>8</td>
</tr>
<tr>
<td>13</td>
<td>Unmanaged crop</td>
<td>45</td>
</tr>
<tr>
<td>15</td>
<td>C\textsubscript{3} Unmanaged Irrigated Crop</td>
<td>3</td>
</tr>
<tr>
<td>17</td>
<td>Rainfed Corn</td>
<td>16</td>
</tr>
<tr>
<td>18</td>
<td>Irrigated Corn</td>
<td>3</td>
</tr>
<tr>
<td>19</td>
<td>Rainfed Temperate Cereals</td>
<td>7</td>
</tr>
<tr>
<td>23</td>
<td>Rainfed Soybean</td>
<td>11</td>
</tr>
<tr>
<td>24</td>
<td>Irrigated Soybean</td>
<td>1</td>
</tr>
<tr>
<td>-</td>
<td>Urban area</td>
<td>2.1</td>
</tr>
</tbody>
</table>
2. CLM single-point mode modeling

Figure. Modeled HR flux, as represented by the amount of soil moisture given or received per day, for the rainfed Corn column. Results shown here are the averaged values for Julian days over the entire simulation period (2005-2012). Hydraulic descent – plant root transfers soil water from shallower to deeper soil layers, could be found during Julian days 60-120; Hydraulic lift - plant root lifts soil water from deeper to shallower soil layers, could be found during Julian days 150-210.
2. CLM single-point mode modeling

Figure. Observed and modeled hourly latent heat flux (evapotranspiration).
2. CLM single-point mode modeling

Figure. Observed and modeled daily latent heat flux (evapotranspiration).
2. CLM single-point mode modeling

Figure. Observed and modeled N\textsubscript{2}O emission.
3. SWAT modeling

Figure. Watershed delineation. DEM data (background figure) are taken from the National Elevation Dataset at a resolution of 30 meters.
3. SWAT modeling

Figure. Land cover data for the model come from the 2001 National Land Classification Dataset (NLCD), 2011 Edition, amended 2014.

Figure. Soils data are from the STATSGO state soils coverage (USDA, 1991) distributed with ArcSWAT.
3. SWAT modeling

Figure. Results for all years for Reach #11 in the first figure.
3. SWAT modeling

Figure. Results for year 2010 for Reach #11 in the first figure.
谢谢大家！