Modeling and assessing effectiveness of intercropping as a sustainable agricultural practice for food security and air pollution mitigation

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FAO: to feed the fast growing population, we need to double our food supply by 2050

But, is the Earth ready for more agricultural activities?

- **Cropland Expansion**
- **Intensified Farming**

> Agriculture is the cause of 80% of deforestation worldwide

> 70% of fresh water is used for crops and livestock

> Over-fertilization makes NH₃ emission an air pollution problem

Foley et al. (2011)
>90% of NH₃ in Europe & China are agricultural emissions and attributable to downwind PM₂.₅

Gu et al. (2012)

Acidic Chemicals
NO₃⁻, SO₄²⁻

Wind

NH₃

Farmlands (fertilizers)

PM₂.₅

Urban (public health)
Intercropping could be a way-out to this food-environment dilemma

Two or more crops are planted in alternate strips with a time-delay

They are placed close enough to allow belowground competition

Such competition triggers and enhances soybean to convert more atmospheric N to soil nutrients.
To investigate its beneficial effects, we simulate a large-scale intercropping in China.

Adding intercropping into DeNitrification-DeComposition (DNDC) biogeochemical model.

Simulating a nationwide conversion of the maize and soybean monoculture farmlands to intercropping in China.

Predicting downwind PM$_{2.5}$ using GEOS-Chem 3-D global chemical transport model.

Performing a cost-and-benefit analysis of such conversion of farmlands.
We enable intercropping in DNDC by adding a new nutrient allocation algorithm.

### DeNitrification-DeComposition (DNDC) Biogeochemical Model

**Inputs:** Climate, Crop Parameters, Farming Practices

- Soil Physics and Chemistry
- Microbial Activities
- Plant Growth
- Grain Yields
- NH$_3$ emissions
- Fertilizer Use Efficiency

1. **Fraction of non-nodulated roots:**
   \[
   f_{\text{uptake}} = \frac{N_{\text{uptake}}}{N_{\text{demand}}} = \frac{1}{\frac{N_{\text{demand}}}{N_{\text{uptake}}}} = \frac{1}{1 + \frac{N_{\text{fix}}}{N_{\text{uptake}}}}
   \]
   \[= \frac{1}{N \text{ Fixation Index}}\]

2. **Assuming size of depletion zone is proportional to root mass, competition factor is defined as:**
   \[
   CF_{\text{crop}} = \frac{\text{space occupied by crop}}{\text{space occupied by system}}
   \]
   \[\approx \frac{\text{mass}_{\text{root,crop}} \cdot f_{\text{uptake,crop}}}{\sum_{\text{crop}} \text{mass}_{\text{root,crop}} \cdot f_{\text{uptake,crop}}}\]

3. **In each iteration, the amount of N a crop could get from a soil layer:**
   \[
   N_{\text{uptake,crop}} = \min(N_{\text{accessible,crop}}, N_{\text{demand,crop}})
   \]
   \[= \min(CF_{\text{crop}} \cdot N_{\text{soil}}, N_{\text{demand,crop}})\]
Using input data of a field experiment, our simulation shows that

1. Less fertilizer (-33%) to maintain maize yield
2. Extra batch of soybean produced
3. \( \text{NH}_3 \) emission is reduced by 26\%
On average, converting monoculture to intercropping in China could save 42% of fertilizer use while maintaining the maize production.

Gansu, Tibet and Qinghai are excluded, which contribute 1.6% of maize and 3.5% to soybean productions in China.
Correspondingly, NH$_3$ emission could be reduced by 45%.
GEOS-Chem predicts improvements in air quality after converting farmlands to intercropping

SO$_4^{2-}$ greatest change = -0.081 µg m$^{-3}$ (-1.2%)

Inorganic PM$_{2.5}$ greatest change = -1.5 µg m$^{-3}$ (-2.1%)

NH$_4^+$ greatest change = -0.30 µg m$^{-3}$ (-3.3%)

NO$_3^-$ greatest change = -1.0 µg m$^{-3}$ (-4.9%)

(% to local mean without intercropping)
Costs and benefits of converting monoculture to intercropping

Paulot & Jacob (2013)

- Revenue from Grain Yields (Sum = US$ 51.021 million)
- Saved Costs on Fertilizers (Sum = US$ 610 million)
- Saved Health Costs (Sum = US$ 1.545 million)
- Net Gain with Intercropping (Maize-Soybean) (Sum = US$ 44.689 million)

<table>
<thead>
<tr>
<th>Item</th>
<th>Per Unit (US$)</th>
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<tbody>
<tr>
<td>Maize</td>
<td>0.410/kg</td>
</tr>
<tr>
<td>Soybean</td>
<td>0.798/kg</td>
</tr>
<tr>
<td>Urea</td>
<td>0.309/kg</td>
</tr>
<tr>
<td>NH₃</td>
<td>3.300/kg</td>
</tr>
<tr>
<td>Labor &amp; Machinery</td>
<td>263.14/ha</td>
</tr>
</tbody>
</table>

+85%
Summary

**Land Use Efficiency**
Multiple crops are produced on the same land over a single planting period.

**N Use Efficiency**
Yield of maize is maintained and an extra crop of soybean is produced while saving 42% of fertilizer.

**Intercropping in China**

**Environmental Sustainability**
NH$_3$ emissions are reduced by 45% and PM$_{2.5}$ concentration is dropped by up to 2.1%.

**Profitability**
Net economic benefits can be up to US$45b including US$1.5b health costs saved.

Next: Intercropping and NH$_3$ emissions in the Community Land Model (CLM)