Large-scale adoption of intercropping for securing global food supply and air quality – a model study using CLM 4.5

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Damages done by agricultural emissions are comparable to those caused by industrial sectors.
Rising food production driven by fast population growth could be a bigger threat to air quality.

Farms (Local)

Crop Growth & Grain Yield

NH$_3$

Fertilizer

Wind

Urban Air Quality

Cities (Regional)

+ Acidic Chemicals, e.g., NO$_3^-$, SO$_4^{2-}$

PM$_{2.5}$
Maize-soybean intercropping is capable of generating the same amount of crop production with 30% less fertilizer, and 26% less NH$_3$

Maize is first planted in the field. After a month, soybean is seeded in between maize strips.

Such competition triggers and enhances soybean to fix more atmospheric N to the soil.
Nation-wide adoption of intercropping could bring China both environmental and economic benefits

On average, maize production could be maintained with 42% less fertilizers

NH$_3$ emission could be lowered by 45%

Net profit could increase US$45b (+85%) nationwide, including US$1.5b saved health cost

Downwind PM$_{2.5}$ could be reduced by up to 2.1% (1.5 µg m$^{-3}$)

Fung et al. (in prep.)
Crop growth is highly coupled with climate and the environment.

We are adding “NH$_3$ volatilization” and “intercropping” to CLM4.5.
A missing pathway in the nitrogen cycle of CLM

- Atmospheric N's
- deposition
- Fertilizer N
- fertilization
- Microbes N
- N fixation
  - (soybean only)
- Litter N
- decomposition
- N fixation
- NH_4^+
- immobilization
- NH_3
- volatilization
- Leached NO_3^-
- denitrification
- uptake
- NO_3^-
- leaching
- N_2O
- Food N
- harvesting
- nitrification
- deposition
- senescence
- uptake
- nitrification
- leaching
We borrow the multi-stage NH$_3$ volatilization scheme for CLM from DNDC (Li et al., 2012)

$NH_4^+$(soil) $\rightarrow$ $NH_4^+$(non-ads) $\rightarrow$ NH$_3$(aq) $\rightarrow$ NH$_3$(g)

DNDCv9.5 uses an empirical equation for adsorption of NH$_4^+$:

$$f_{ads} = 0.99(7.2733f_{clay}^3 - 11.22f_{clay}^2 + 5.7198f_{clay} + 0.0263)$$

The non-adsorbed [NH$_4^+$] is given by:

$$[NH_4^+_{(non-ads)}] = [NH_4^+_{(soil)}](1 - f_{ads})$$

Equilibrium between [NH$_4^+_{(non-ads)}$] and [NH$_3$(aq)]:

$$K_w = 10^{0.08946 + (0.03605)T_{soil} \times 10^{-15}} \text{ (mol}^2 \text{ L}^{-2})$$

$$K_a = (1.416 + (0.01357)T_{soil}) \times 10^{-5} \text{ (mol L}^{-1})$$

$$[H^+] = 10^{-pH}$$

$$[OH^-] = K_w/[H^+]$$

$$[NH_3(aq)] = [NH_4^+_{(non-ads)}][OH^-]/K_a$$

Volatilization rate of [NH$_3$(aq)] from a soil layer in one time-step is found by:

$$\frac{d[NH_3(g)]}{dt} = [NH_3(aq)] \left( \frac{1.5s}{1 + s} \right) \left( \frac{T_{soil}}{50 + T_{soil}} \right) \left( \frac{q_{max} - q}{q_{max}} \right) \frac{1}{\Delta t}$$

where:

- $f_{clay}$ is the clay fraction
- $T_{soil}$ is soil temperature (°C)
- $K_w$ is the equilibrium constant for the dissociation of water
- $K_a$ is the acid dissociation constant for NH$_4^+$
- $[H^+]$ is the hydronium ion concentration
- $[OH^-]$ is the hydroxide ion concentration
- $[NH_3(aq)]$ is the concentration of ammonia in solution
- $[NH_4^+_{(soil)}]$ is the concentration of ammonium in the soil
- $[NH_4^+_{(non-ads)}]$ is the non-adsorbed ammonium concentration
- $f_{ads}$ is the adsorption fraction
- $q_{max}$ is the maximum emission rate
- $q$ is the actual emission rate
- $\Delta t$ is the time-step size (s)
- $s$ is the soil layer index
- $T_{soil}$ is the soil temperature (°C)
- $V$ is the wind speed (m s$^{-1}$)
CLM-simulated monthly-averaged NH₃ emission agrees well with MASAGE over most high emission regions.

CLM-simulated NH₃ emissions from crops lands compared with MASAGE agricultural NH₃ emission inventory grid-by-grid

Fung et al. (in prep.)
To allow intercropped crops to compete for nutrients, soil N deployed for plant growth is now transferrable among intercropped soil columns.
A new variable added to quantify belowground crop-crop competition under intercropping

1. Assuming surface area of a crop’s root is proportional to its mass, a crop’s competition factor (CF) is then defined as:

\[
CF_{\text{crop}} = \frac{\text{total root surface area a crop}}{\text{total root surface area of both crops}}
\]

\[
\approx \frac{\text{mass}_{\text{root,crop}} \cdot \text{weighting}_{\text{crop}}}{\sum_{\text{system}} \text{mass}_{\text{root,crop}} \cdot \text{weighting}_{\text{crop}}}
\]

2. The amount of soil N a crop can take up is co-limited by its demand and accessible soil N:

\[
N_{\text{uptake,crop}} = \min \left( N_{\text{demand,crop}}, CF_{\text{crop}} \cdot \sum_{\text{system}} N_{\text{deployed,crop}} \right)
\]

Fung et al. (in prep.)
Assuming all croplands cultivating both maize and soybean are now converted to intercropping (Fung et al. (in prep.))

- **Monoculture maize**
  - Total = 197 Tg
- **Monoculture soybean**
  - Total = 49.7 Tg
- **Intercropped maize**
  - Total = 244 Tg
- **Intercropped soybean**
  - Total = 1.24 Tg
- **Difference in maize**
  - Total = 47 Tg (+23%)
- **Difference in soybean**
  - Total = -48.4 Tg (-97%)
The same amount of fertilizer is applied; NH$_3$ emissions is reduced by >40%

Fung et al. (in prep.)
Our preliminary results show that intercropping can secure global food production and reduce air pollution.

- **Future work:**
  - Revising soybean fixation algorithm
  - Adding spatial variability on fertilizer use
  - Examining other intercropping pairs
  - Adding $N_2O$ & $NO_x$ emissions and $NO_3$ leaching
  - Coupling $NH_3$, $N_2O$ & $NO_x$ emissions with CAM
  - Investigating interrelationship between intercropping, the environment, and climate

Thank You!

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