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# Modeling large-scale adoption of intercropping as a sustainable agricultural practice for food security and air pollution mitigation around the globe

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| | |
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地球系統科學課程
EARTH SYSTEM SCIENCE PROGRAMME

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

But, is our Earth ready for more agricultural activities?

Foley et al. (2011)

**Cropland Expansion**

**Intensified Farming**

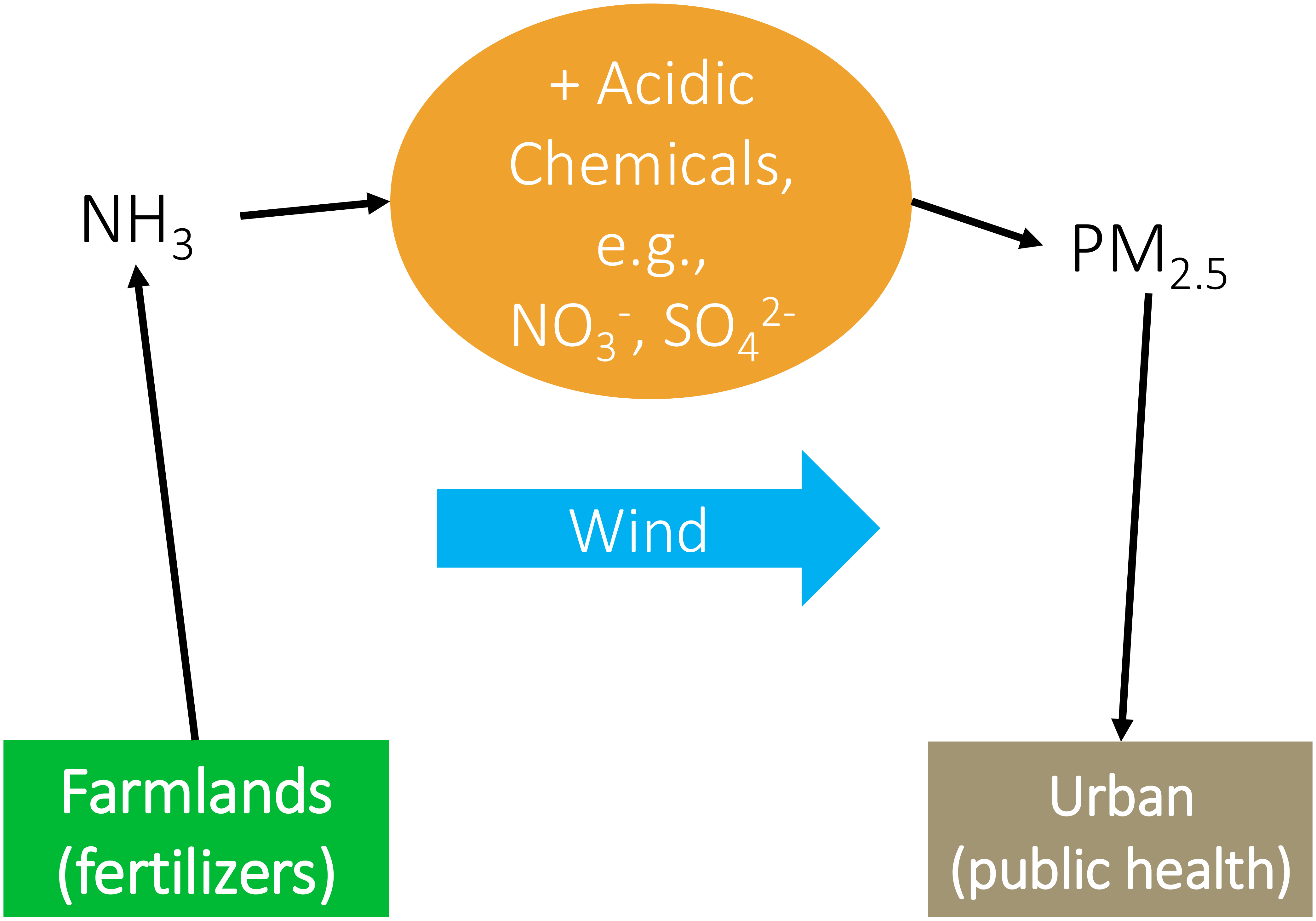
80% of deforestation worldwide are for agriculture

70% of fresh water is used for crops and livestock

Over-fertilization makes $NH_3$ emission an air pollution problem

# >90% of $NH_3$ in Europe & China are agricultural emissions and attributable to downwind $PM_{2.5}$

Gu et al. (2012)



$NH_3$

+ Acidic Chemicals, e.g., $NO_3^-$, $SO_4^{2-}$

$PM_{2.5}$

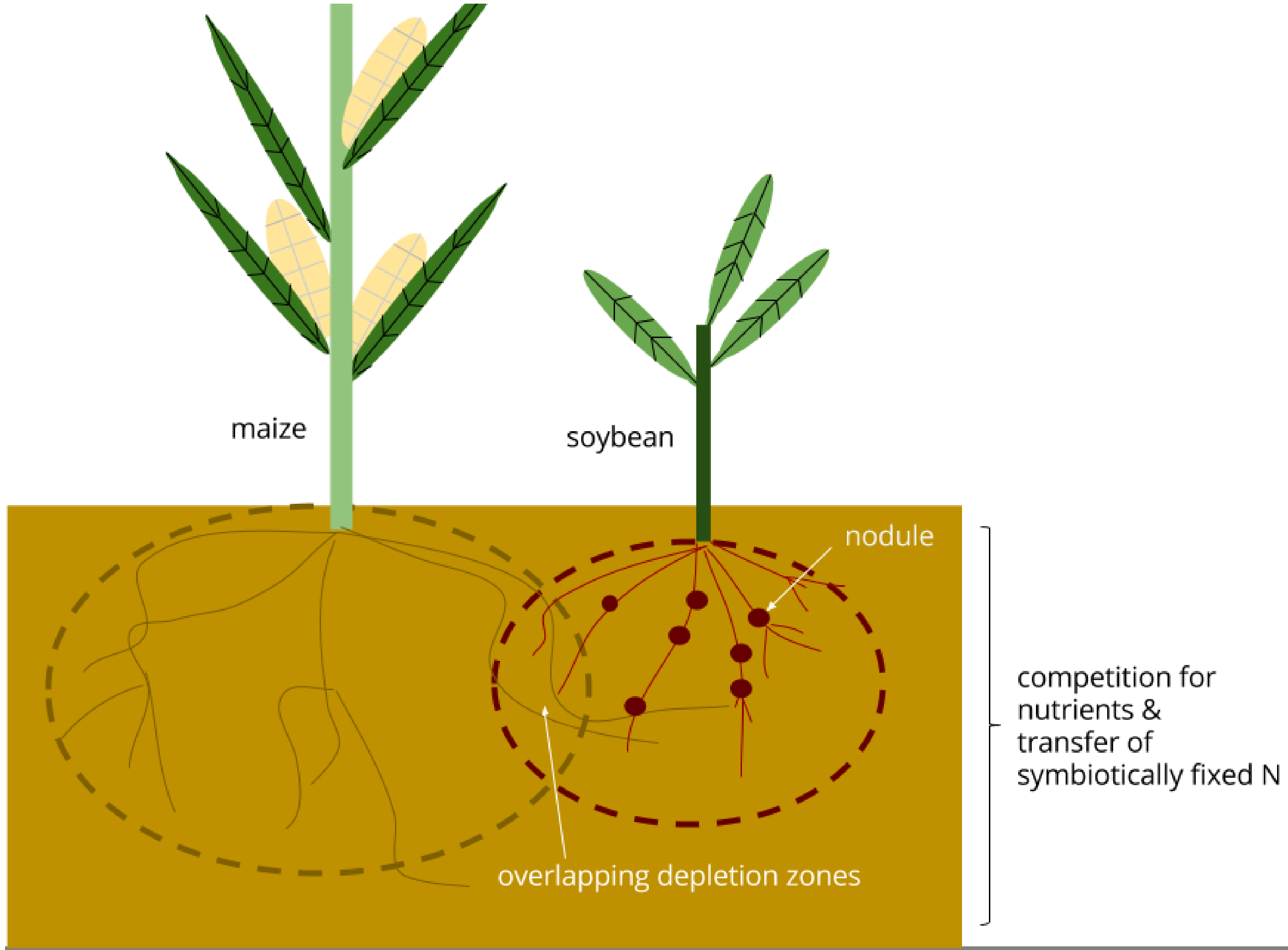
Wind

Farmlands (fertilizers)

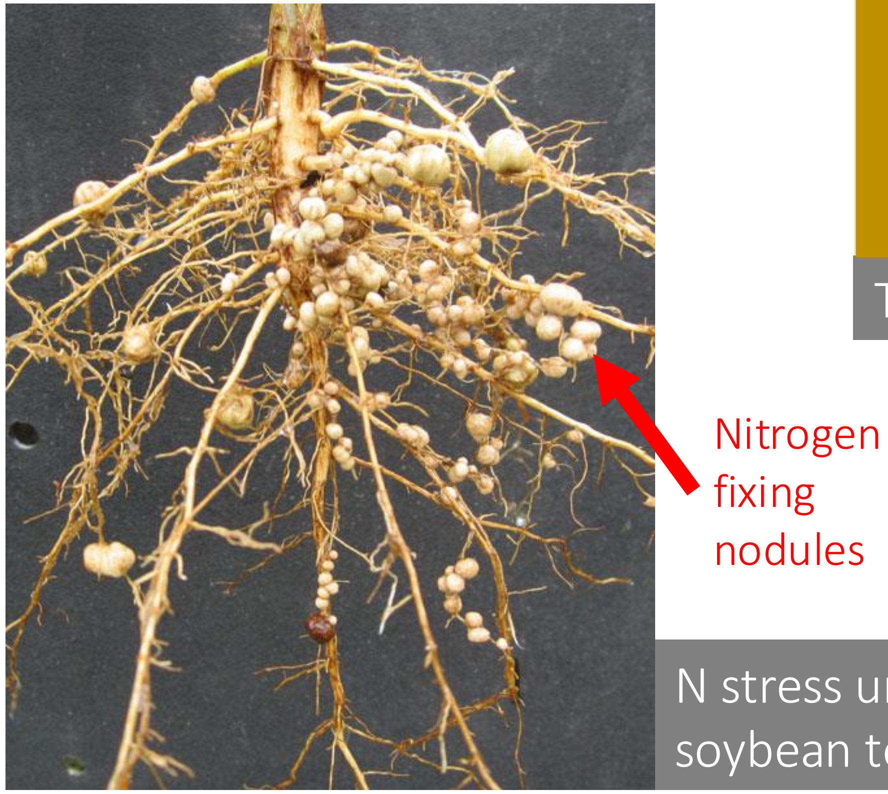
Urban (public health)

# A way-out to this food-environment dilemma could be intercropping

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

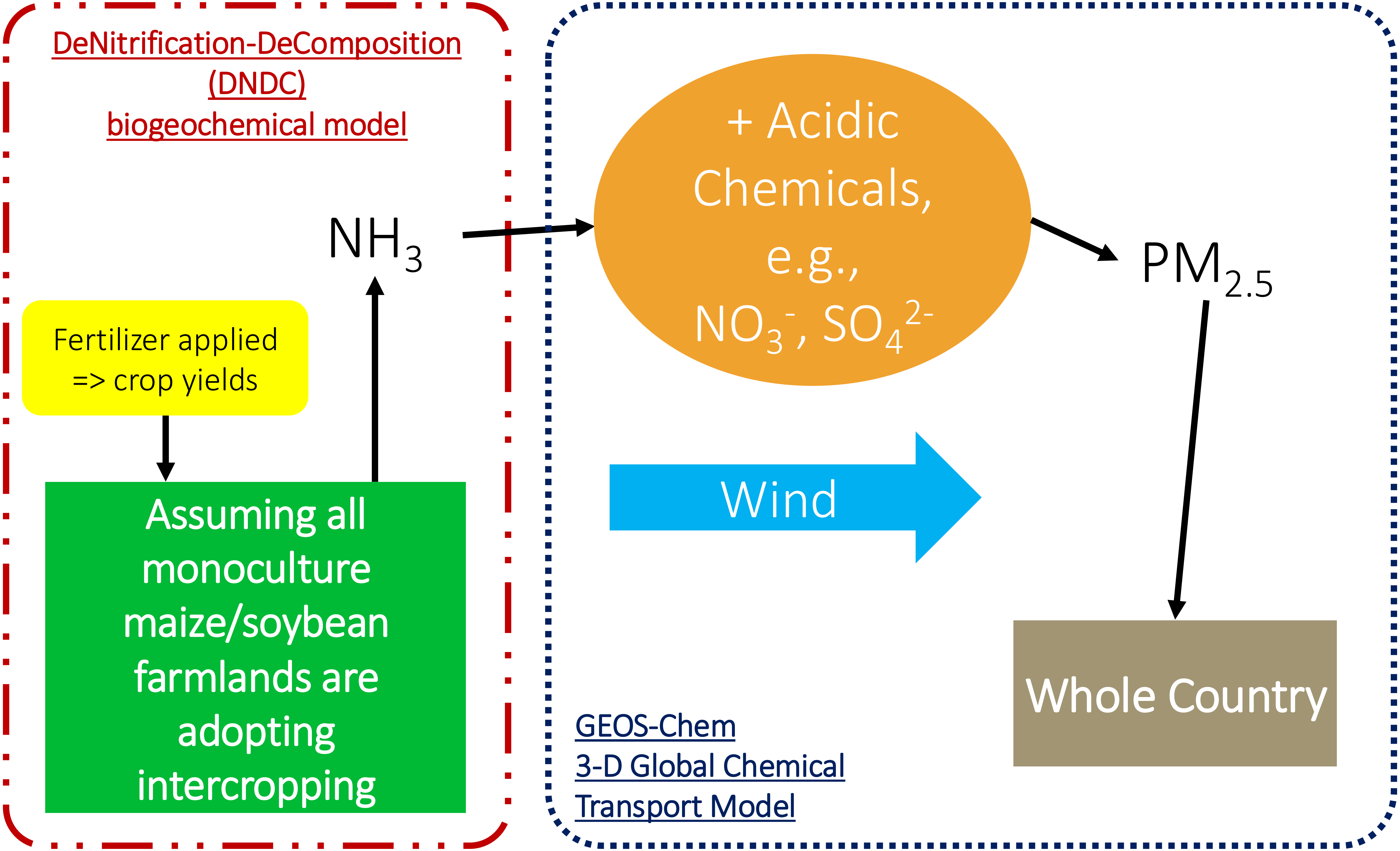


They are placed close enough to allow belowground competition



N stress under such competition stimulates soybean to fix more atmospheric N

# We examine its beneficial effects by simulating a large-scale intercropping scheme in China



DeNitrification-DeComposition (DNDC) biogeochemical model

Fertilizer applied => crop yields

Assuming all monoculture maize/soybean farmlands are adopting intercropping

$NH_3$

+ Acidic Chemicals, e.g., $NO_3^-$, $SO_4^{2-}$

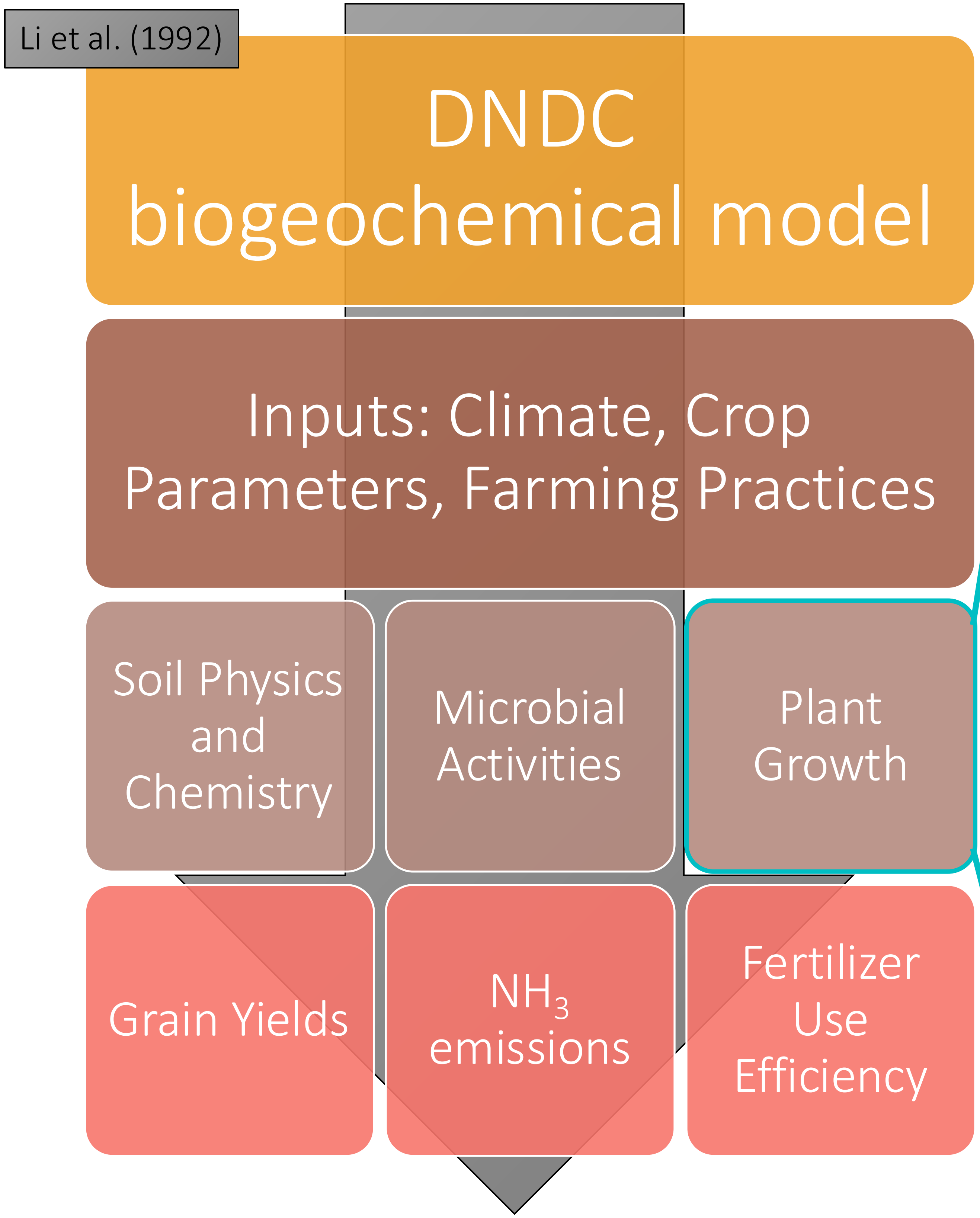
$PM_{2.5}$

Wind

Whole Country

GEOS-Chem 3-D Global Chemical Transport Model

# We enable intercropping in DNDC by adding a new N allocation algorithm



Li et al. (1992)

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. Assuming a crop's competitiveness for acquiring soil N is proportional to its root mass, a competition factor is hence defined as:

$$CF_{\text{crop}} = \frac{\text{space occupied by crop}}{\text{space occupied by system}}$$

$$\approx \frac{mass_{\text{root,crop}} \cdot f_{\text{uptake,crop}}}{\sum_{crop} mass_{\text{root,crop}} \cdot f_{\text{uptake,crop}}}$$

2. Fraction of non-nodulated roots:

$$f_{\text{uptake}} = \frac{N_{\text{uptake}}}{N_{\text{demand}}} = \frac{1}{\frac{N_{\text{demand}}}{N_{\text{uptake}}}} = \frac{1}{\frac{N_{\text{uptake}} + N_{\text{fix}}}{N_{\text{uptake}}}}$$

$$= \frac{1}{\text{N Fixation Index defined in DNDC}}$$

3. In each iteration, the amount of N a crop could get from a soil layer:

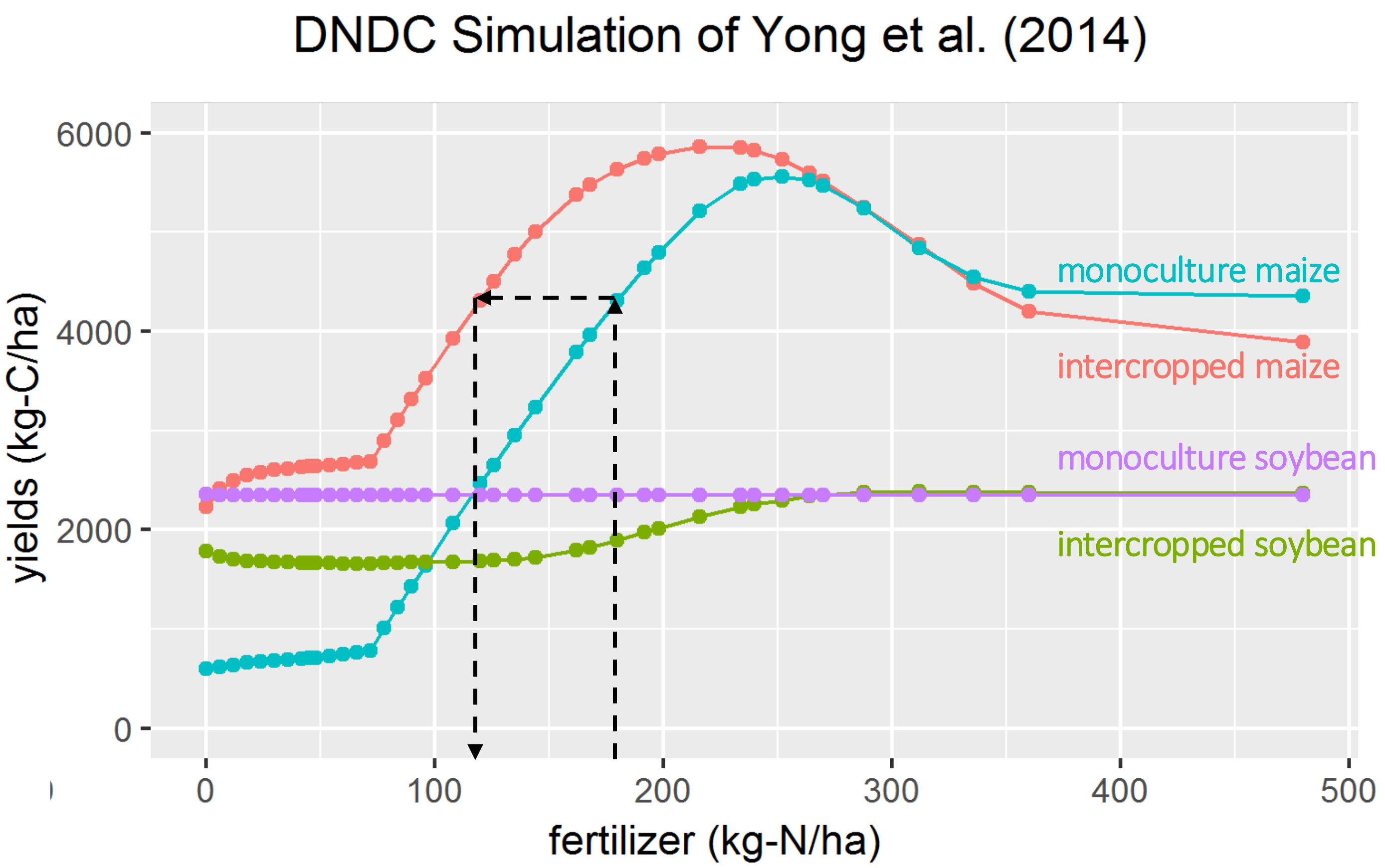
$$N_{\text{uptake,crop}} = \min\left(N_{\text{accessible,crop}}, N_{\text{demand,crop}}\right)$$

$$= \min(CF_{\text{crop}} \cdot N_{\text{soil}}\,, N_{\text{demand,crop}})$$

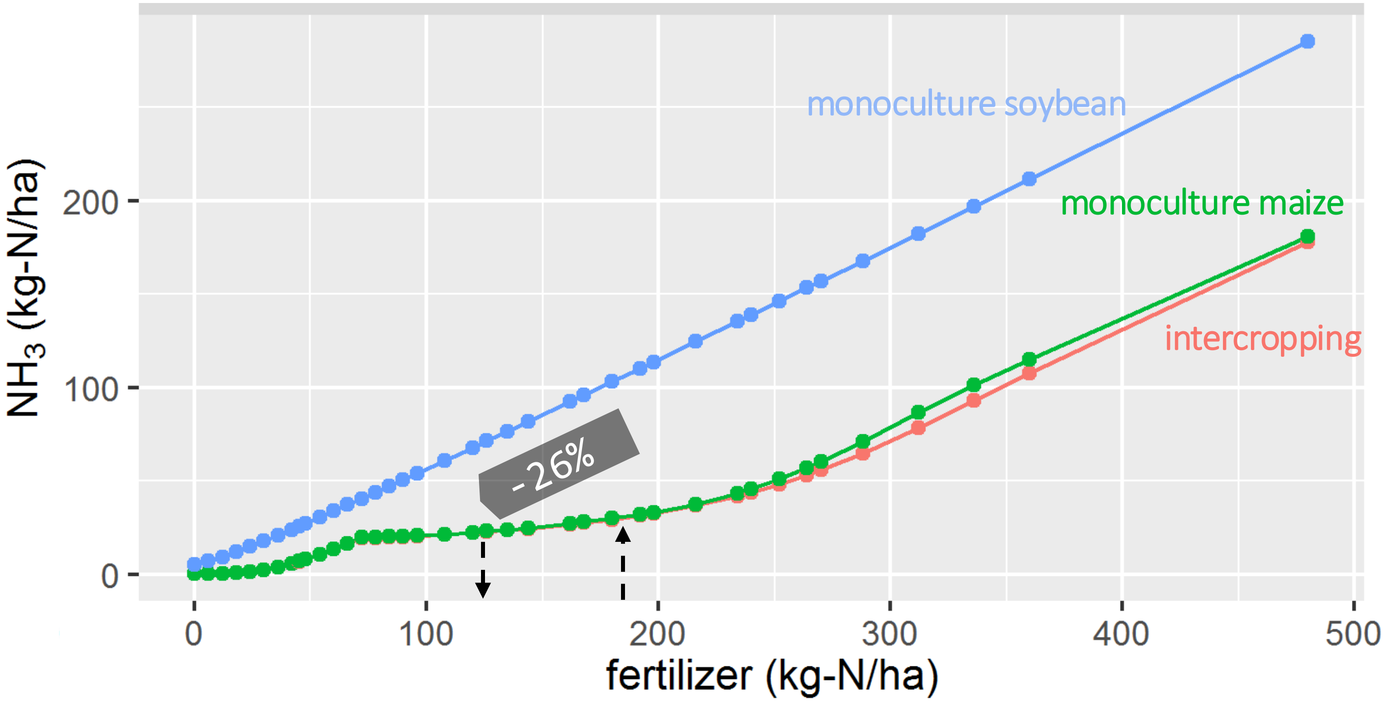
Fung et al. (in prep)

# Using data of a field experiment, our simulation shows that

DNDC Simulation of Yong et al. (2014)

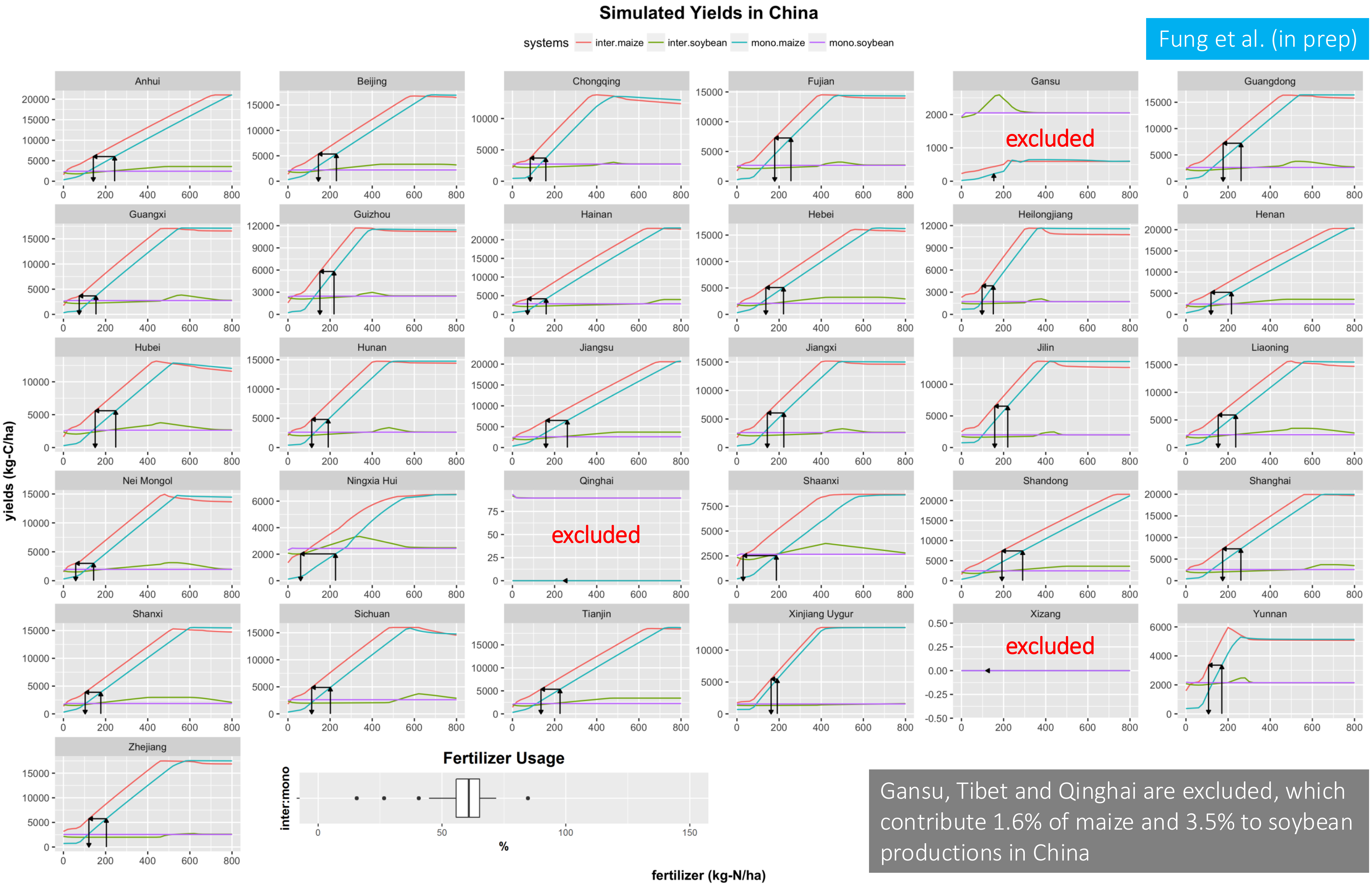


1. Less fertilizer (-33%) to maintain maize yield
2. Extra batch of soybean can be harvested
3. $NH_3$ emission is reduced by 26%



Fung et al. (in prep)

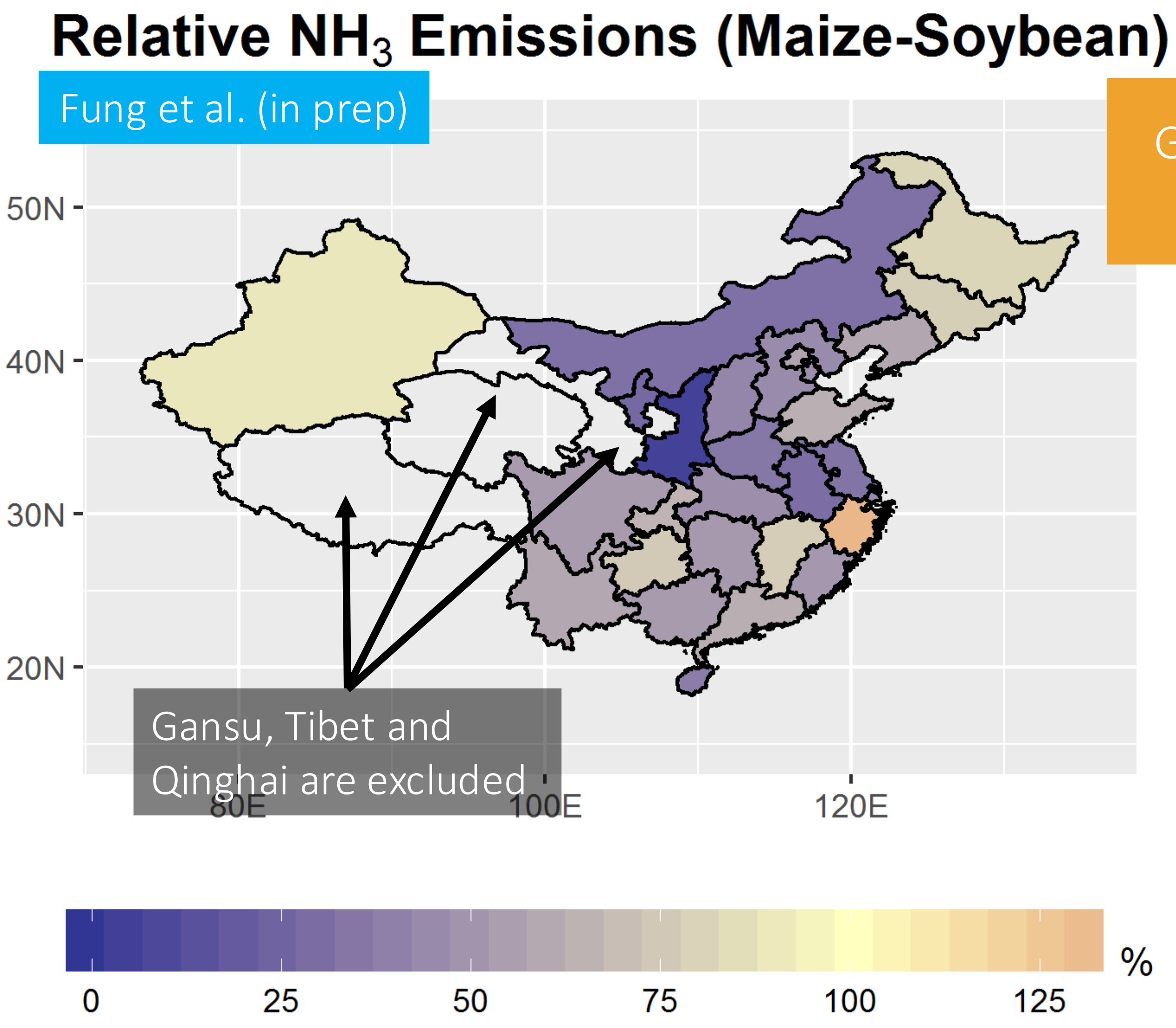
Fung et al. (in prep)



Gansu, Tibet and Qinghai are excluded, which contribute 1.6% of maize and 3.5% to soybean productions in China

# On average, intercropping can maintain the same maize production while cutting down fertilizer required by 42%

# Correspondingly, $NH_3$ emission can be reduced by 45%


**Relative $NH_3$ Emissions (Maize-Soybean)**

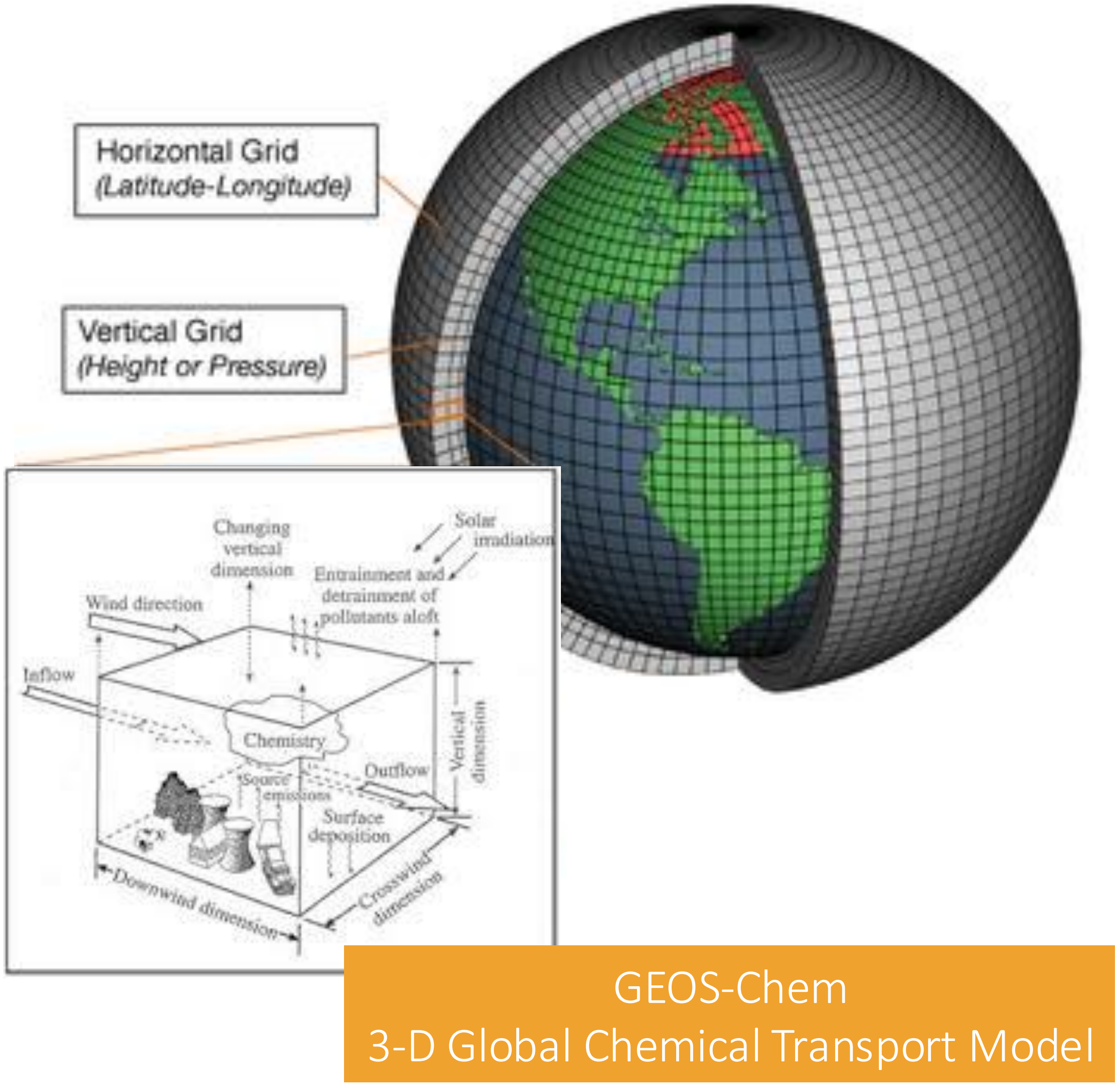
Fung et al. (in prep)

Gansu, Tibet and Qinghai are excluded

Grid-by-grid scaling

## $NH_3$ Emission Inventory

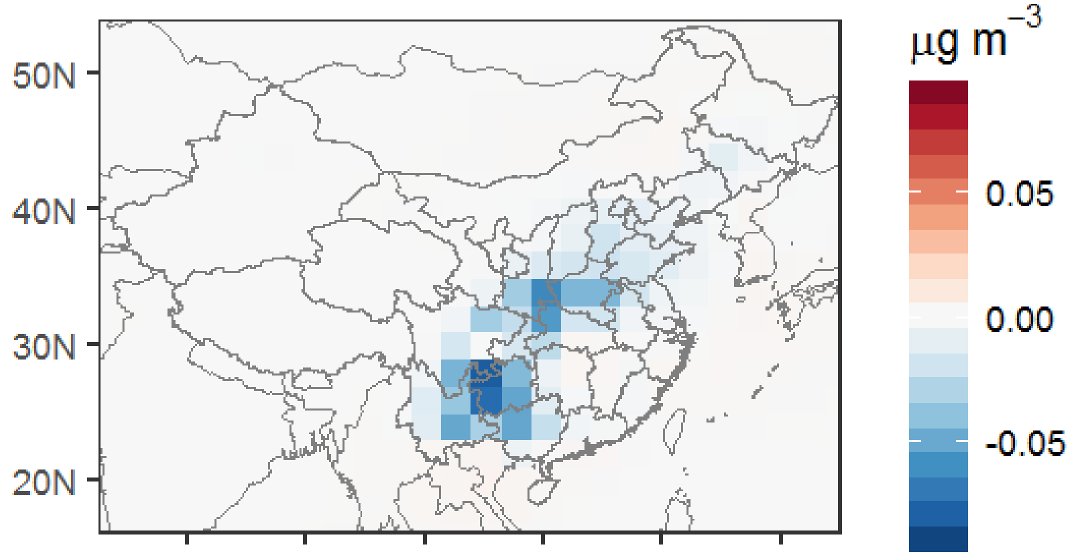
(Magnitude And Seasonality of Agricultural Emissions; MASAGE)



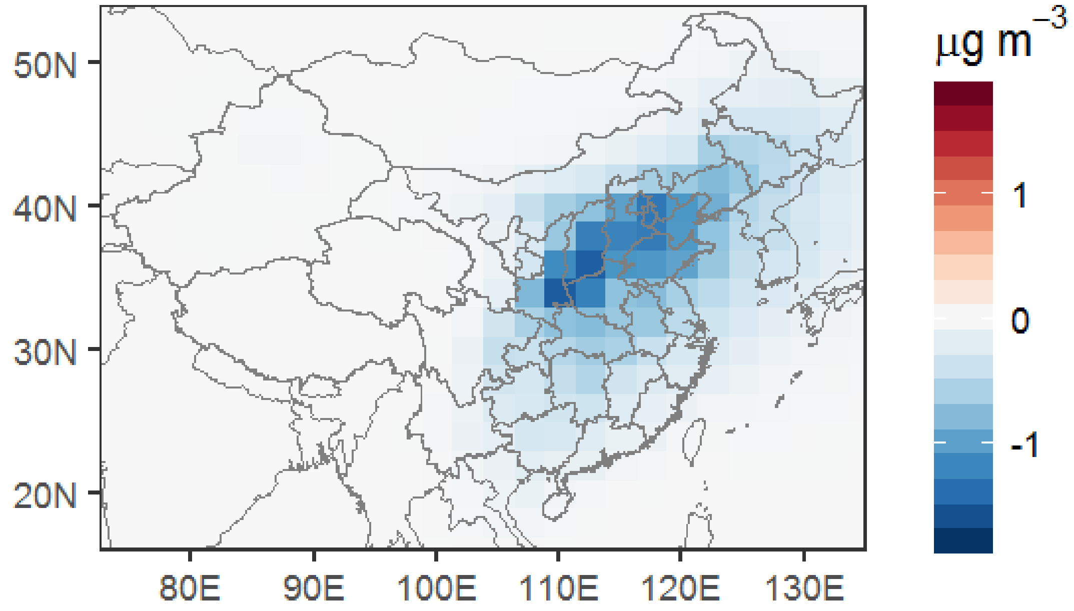
GEOS-Chem
3-D Global Chemical Transport Model

# GEOS-Chem predicts improvement in air quality after converting farmlands into intercropping

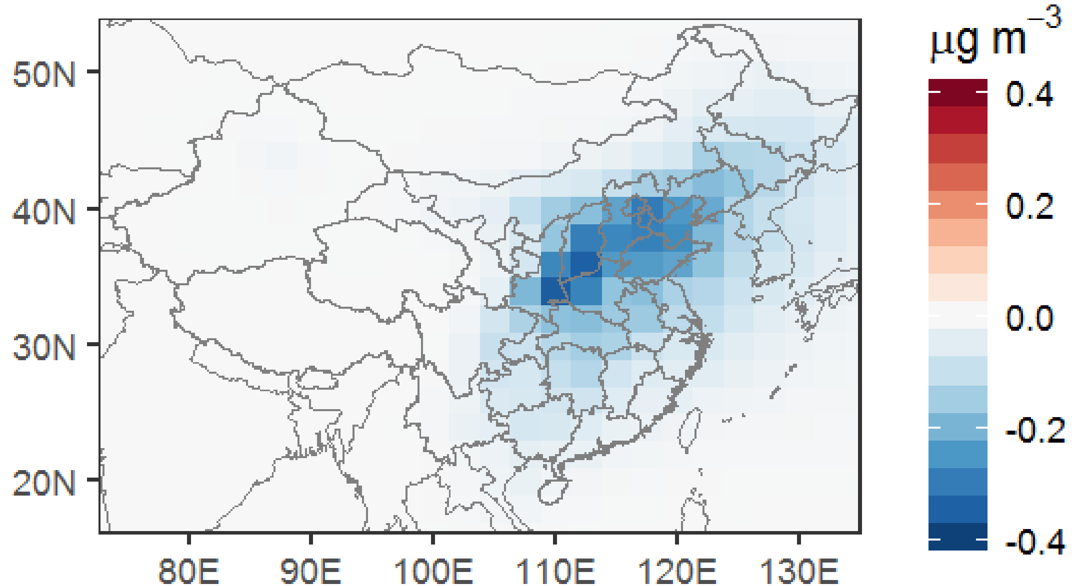
$O_4^{2-}$ greatest change = -0.081 μg m$^{-3}$ (-1.2%



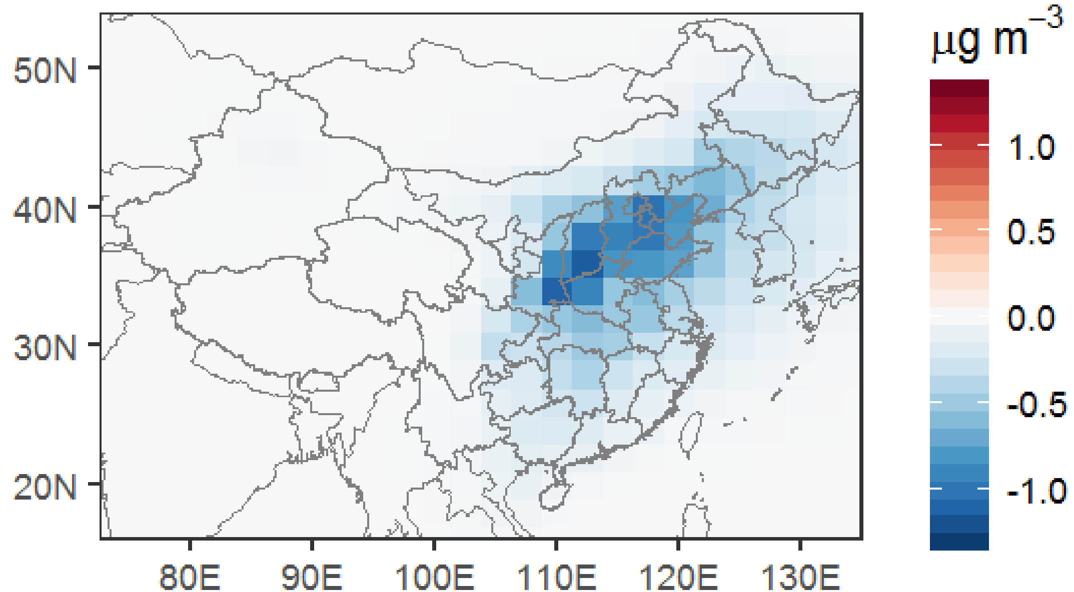
norganic $PM_{2.5}$ greatest change = -1.5 μg m$^{-3}$ (-2.1%



$IH_4^+$ greatest change = -0.30 μg m$^{-3}$ (-3.3%



$NO_3^-$ greatest change = -1.0 μg m$^{-3}$ (-4.9%

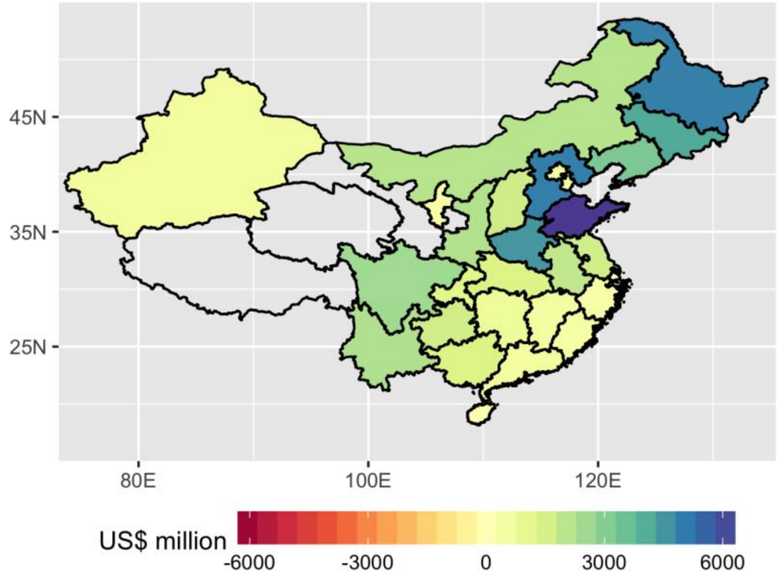


Fung et al. (in prep)

(% to local mean without intercropping)

# Costs and benefits of adopting intercropping nationwide

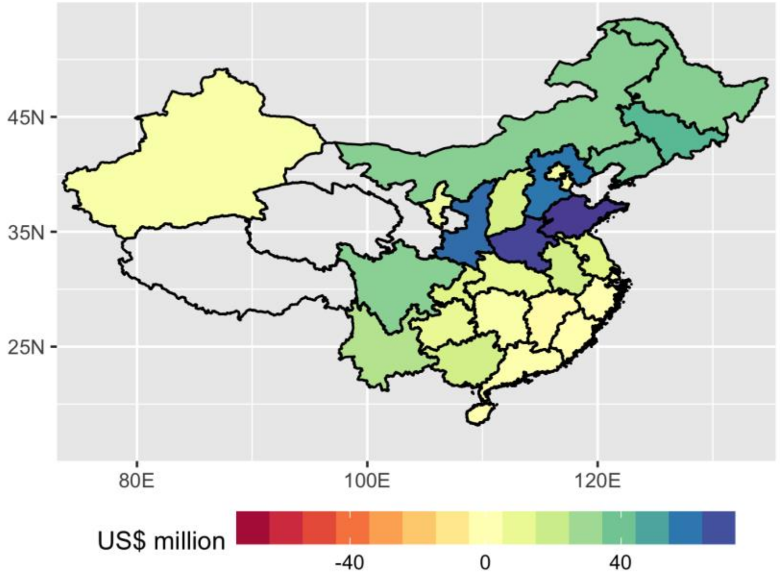
Paulot & Jacob (2013)



**Revenue from Grain Yields**

(Sum = US$ 51,021 million)

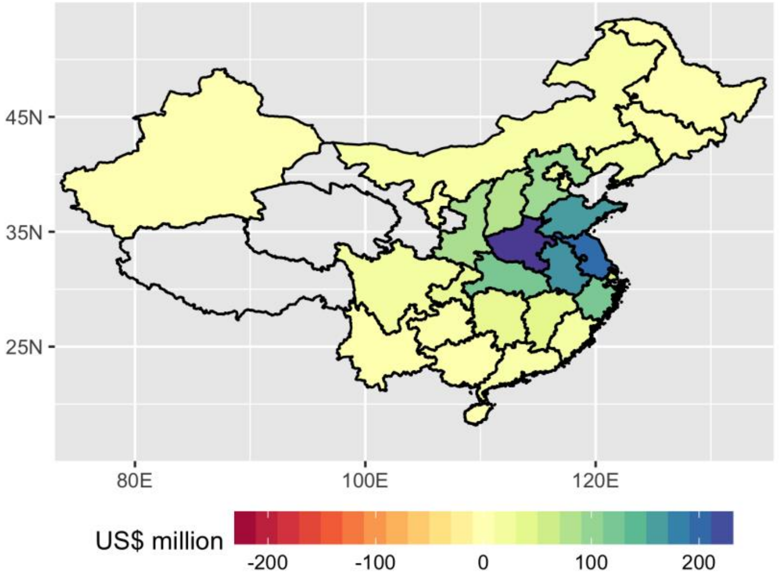
+



**Saved Costs on Fertilizers**

(Sum = US$ 610 million)

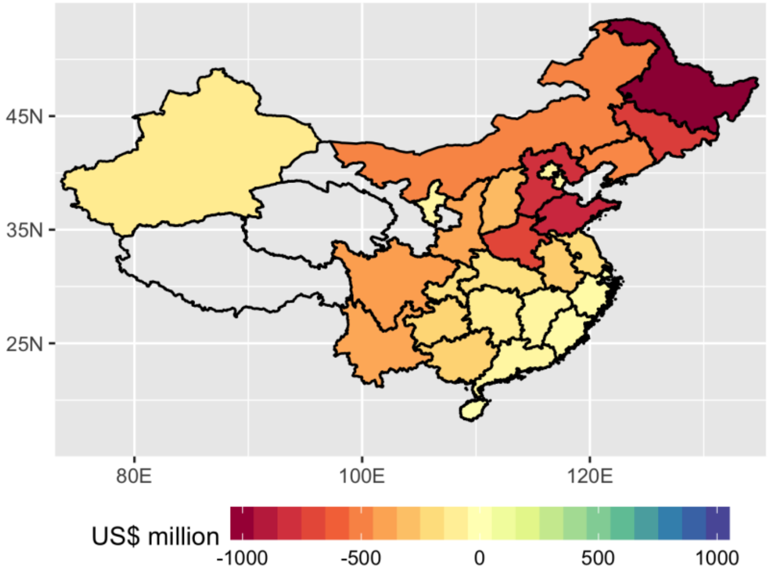
+



**Saved Health Costs**

(Sum = US$ 1,545 million)

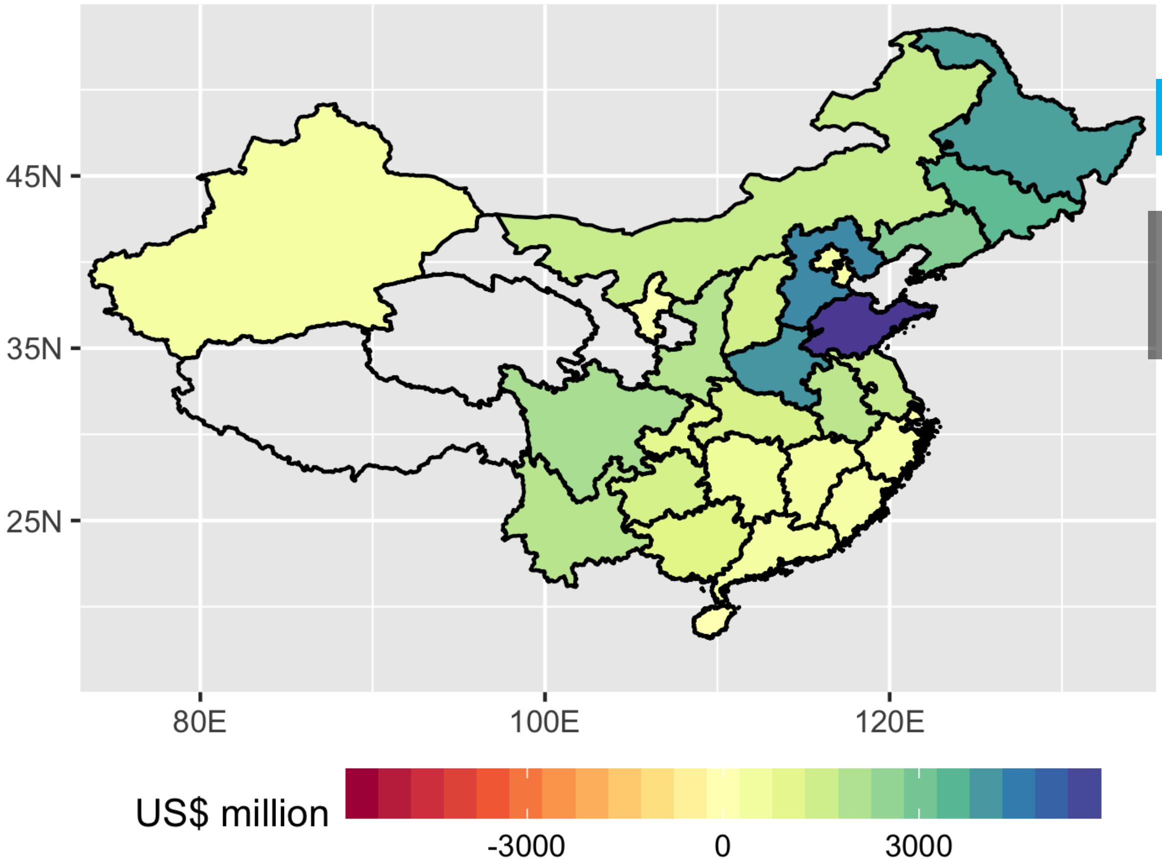
\+



**Saved Production Costs (Machinery & Labour)**

(Sum = US$ -8,487 million)

=



**Net Gain with Intercropping (Maize-Soybean)**

(Sum = US$ 44,689 million)

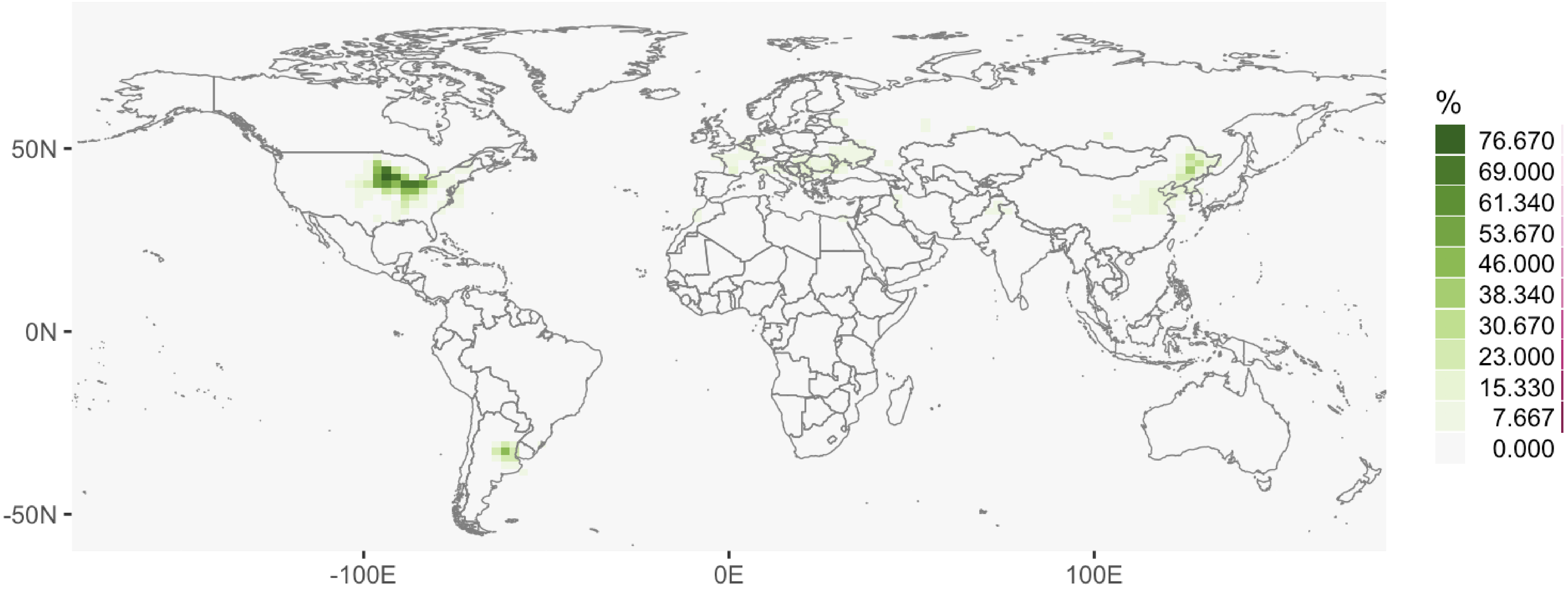
Fung et al. (in prep)

+85%

| Item | Per Unit (US$) |
|---|---|
| Maize | 0.410/kg |
| Soybean | 0.798/kg |
| Urea | 0.309/kg |
| $NH_3$ | 3.300/kg |
| Labor & Machinery | 263.14/ha |

# Looking into a bigger picture: a globe intercropping scenario

- Based on Community Land Model (CLM4.5) surface data, we identify croplands cultivating both maize and soybean



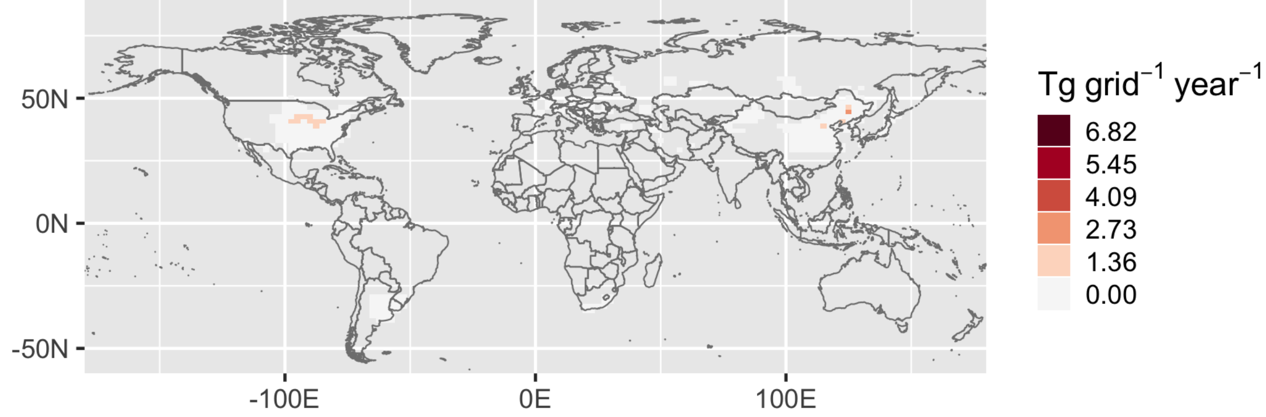
- Then, we convert those croplands into maize/soybean

# Our preliminary results with revised-CLM show that intercropping raises maize production without sacrificing soybean's

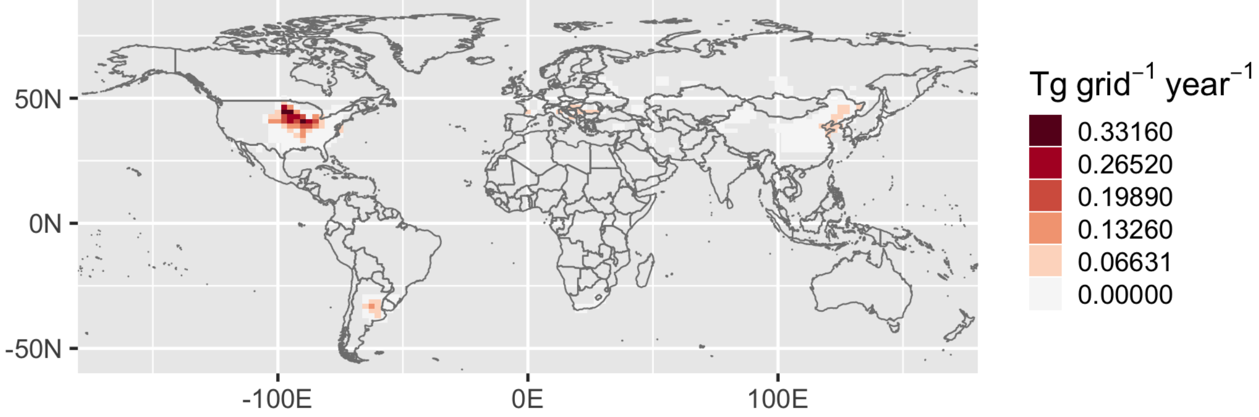
Fung et al. (in prep)

Only intercropping croplands are shown on the maps

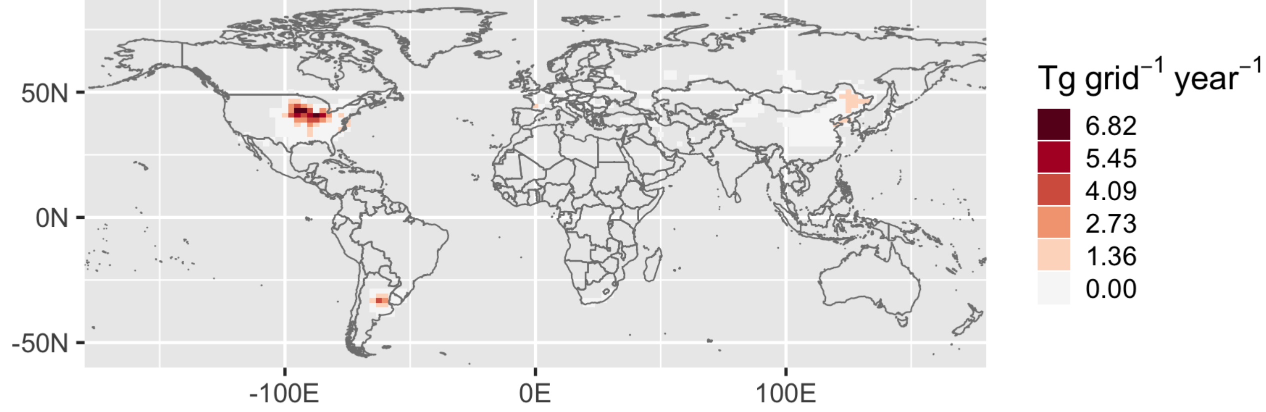
Monoculture Maize (Total = 46 Tg year $^{-1}$)



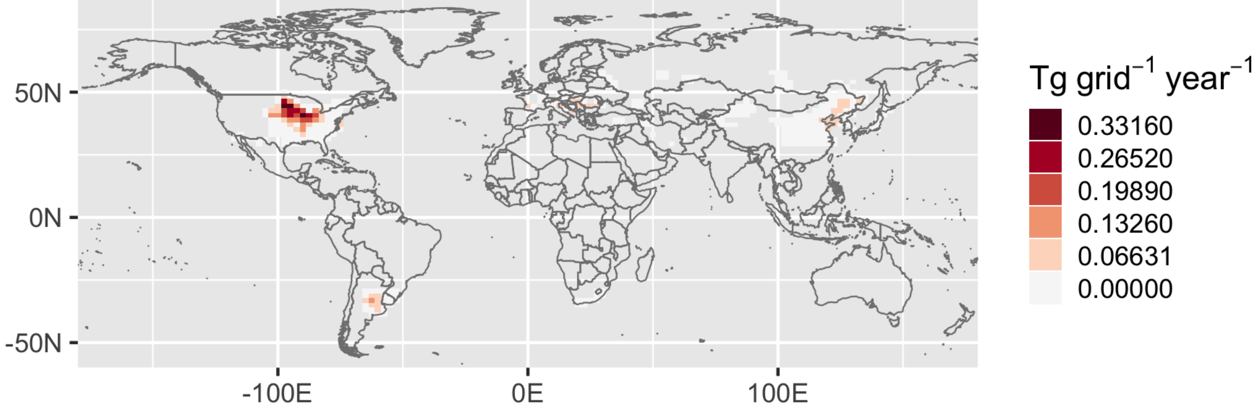
Monoculture Soybean (Total = 10 Tg year $^{-1}$)



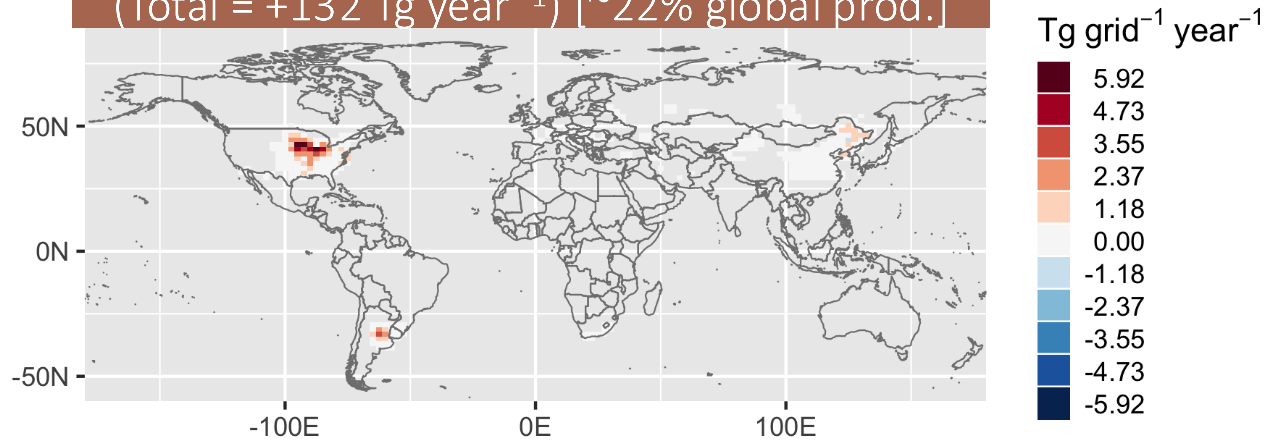
Intercropped Maize (Total = 179 Tg year $^{-1}$)



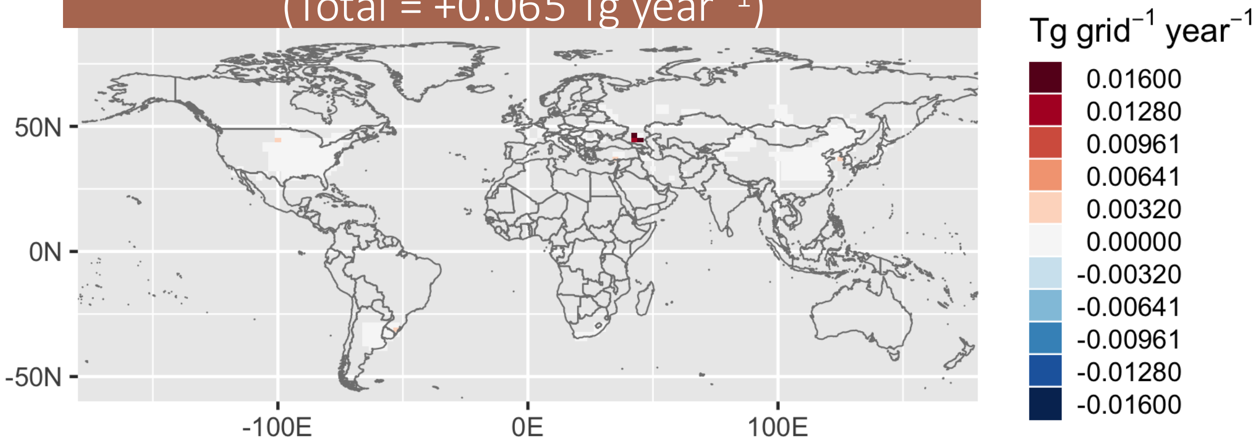
Intercropped Soybean (Total = 10 Tg year $^{-1}$)



Intercropped – monoculture
(Total = +132 Tg year $^{-1}$) [~22% global prod.]



Intercropped – monoculture
(Total = +0.065 Tg year $^{-1}$)

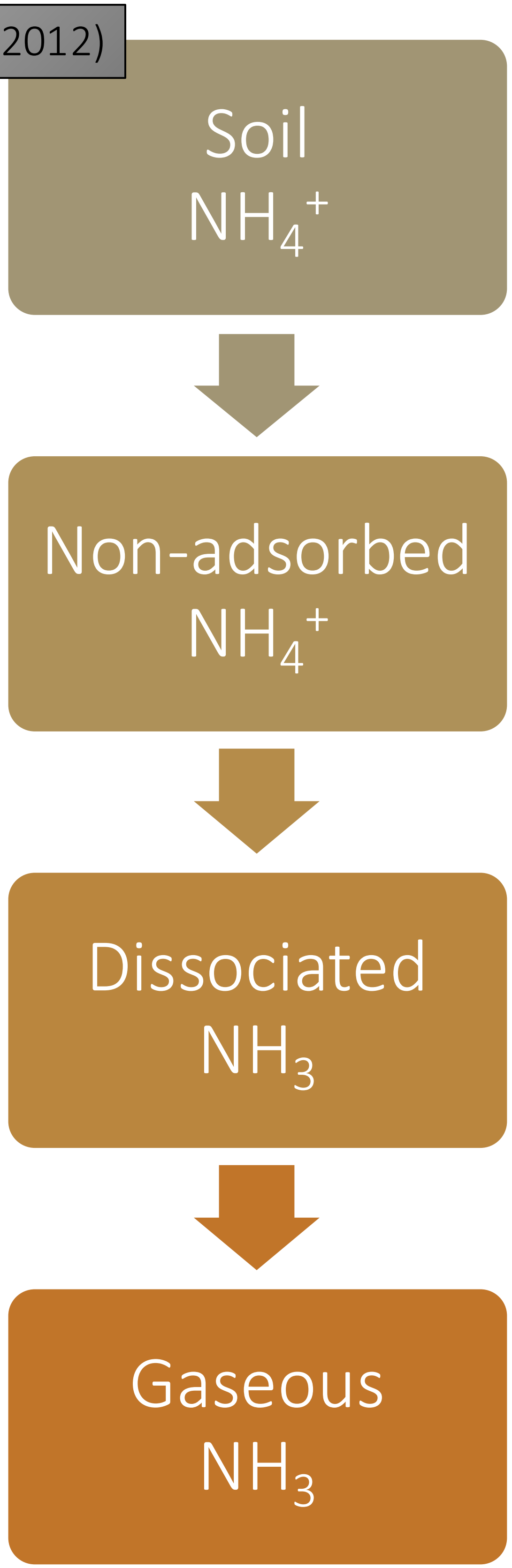


# Adding a new scheme in CLM, we can also estimate reduction in $NH_3$

Fung et al. (in prep)

Only intercropping croplands are shown on the maps

Li et al. (2012)



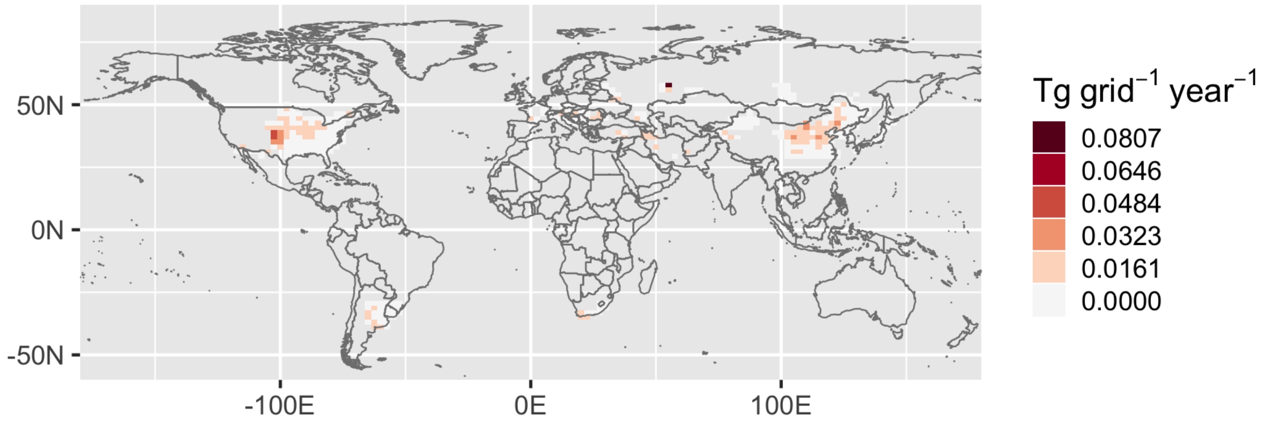
Soil $NH_4^+$

Non-adsorbed $NH_4^+$

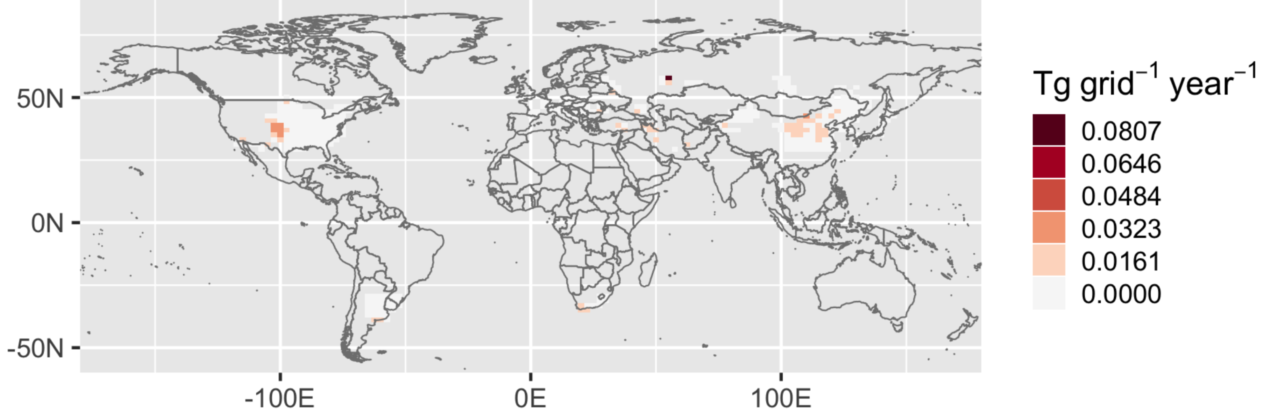
Dissociated $NH_3$

Gaseous $NH_3$

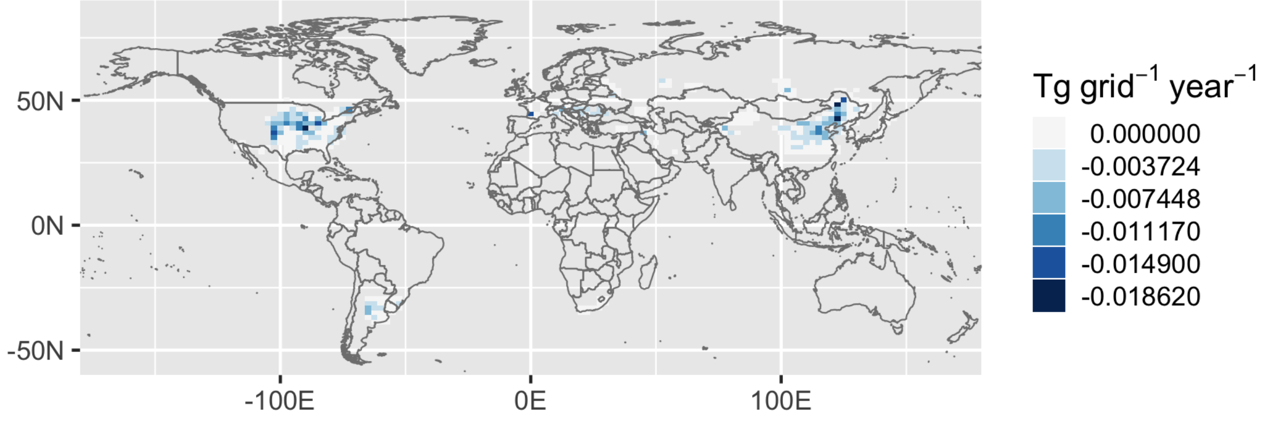
Monoculture (Total = 2.39 Tg year $^{-1}$)



Intercropped (Total = 1.53 Tg year $^{-1}$)



Intercropped – monoculture
(Total = -0.86 Tg year $^{-1}$ [-36%])



# Summary & Future work

Large-scale Intercropping in China

**Land Use Efficiency**

Two batches of crops are produced on the same land over less than two planting periods

**N Use Efficiency**

Yield of maize is maintained and an extra crop of soybean is produced while cutting fertilizer use down by 42%

**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

If all maize or soybean farmlands are adopting intercropping, our preliminary simulation results using revised-CLM show:

- Increase in maize production without sacrificing soybean yields
- Reduction in $NH_3$ emission under the same fertilizer input

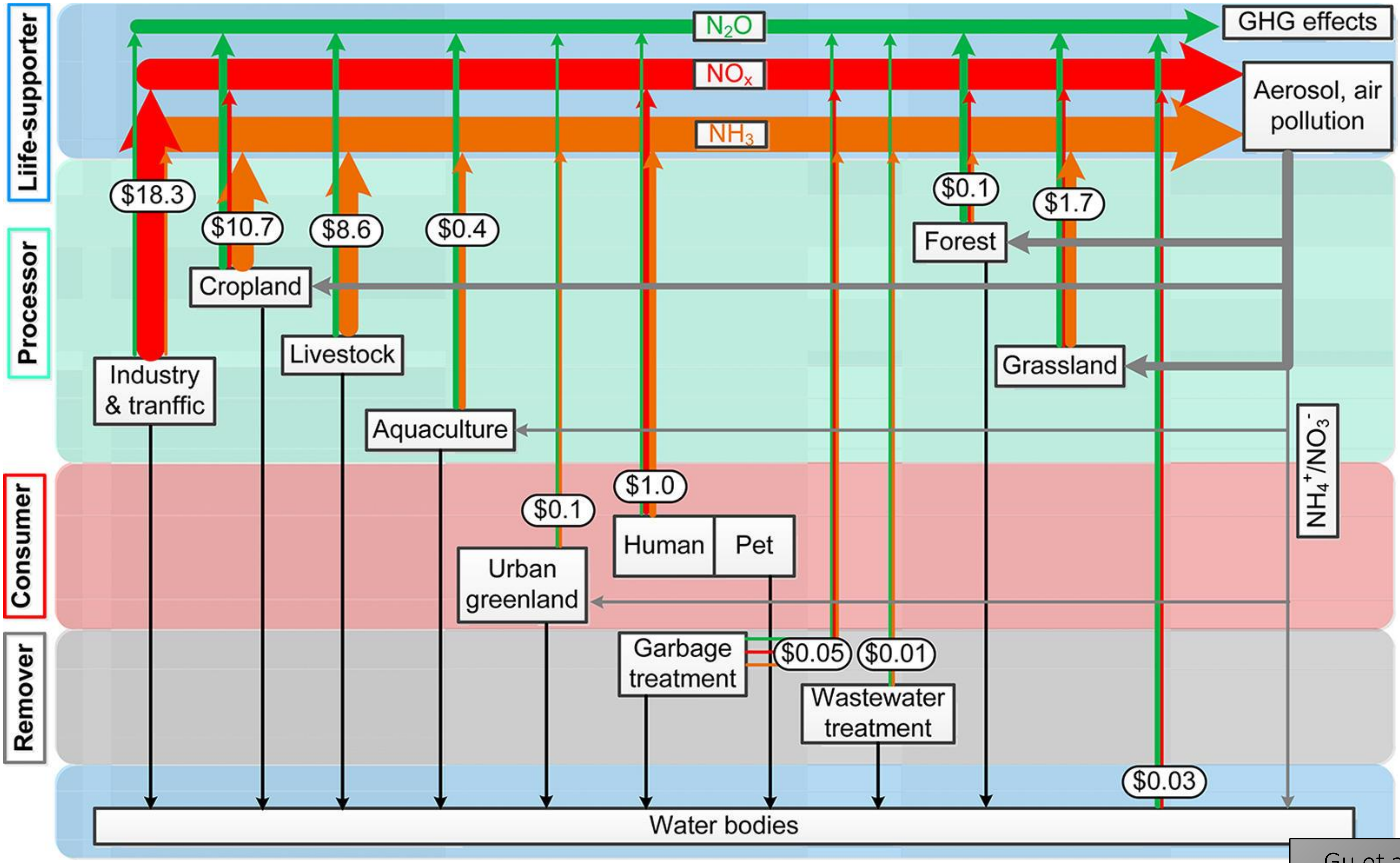
Future work:

- Finishing $NH_3$ volatilization model and validation
- Adding $N_2O$ and $NO_x$ emissions
- Modeling other sustainable farming practices, e.g. rotation, zero-tillage

# Thank you!

Please don’t hesitate to send me any question at kamingfung@link.cuhk.edu.hk

Health Damage Costs of China in 2008 (US billion dollars)

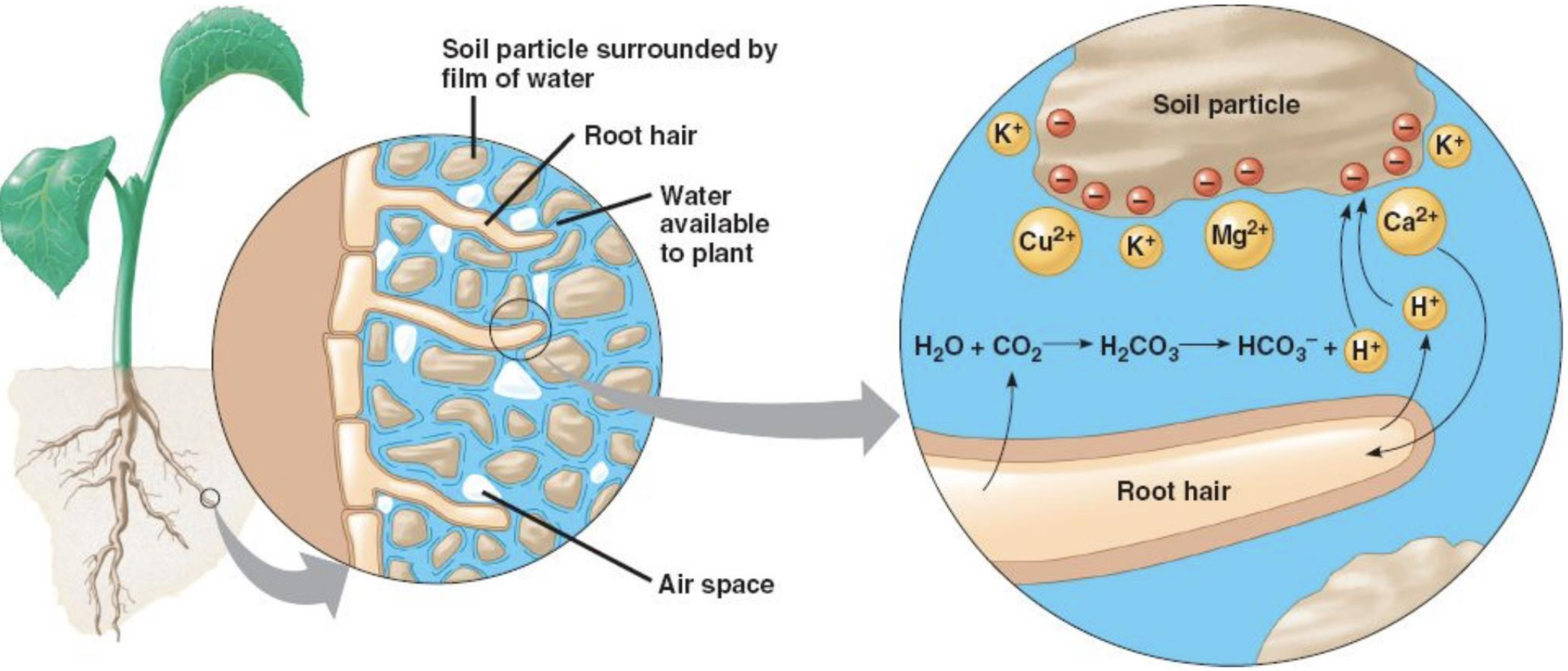


Gu et al. (2012)

# Atmospheric $NH_3$ is mainly from soil and vegetation

# Preliminary work of Phase II on a proposed CLM4.5 multi-stage $NH_3$ volatilization scheme

Soil $NH_4^+$ → Non-adsorbed $NH_4^+$ → Dissociated $NH_3$ → Gaseous $NH_3$



Campbell (2008)

DNDCv9.5 uses an empirical equation for adsorption of $NH_4^+$:

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

clay fraction

The non-adsorbed [$NH_4^+$] is given by:

$$\left[NH_4^+{}_{(\mathrm{non-adsorbed})}\right] = \left[NH_4^+{}_{(\mathrm{soil})}\right](1 - f_{\mathrm{adsoption}})$$

# $NH_3$ volatilization rate relies on free $NH_4^+$, dissociation and climate

Soil $NH_4^+$ → Non-adsorbed $NH_4^+$ → Dissociated $NH_3$ → Gaseous $NH_3$

Equilibrium between $[NH_4^+{}_{(non\text{-}absorbed)}]$ and $[NH_{3\,(aq)}]$:

soil temperature (°C)

$$\begin{cases} K_w = 1.945e^{0.0645T_{soil}} \times 10^{-15}\ (\mathrm{mol^2\,L^{-2}}); K_a = (1.416 + 0.01357T_{soil}) \times 10^{-5}\ (\mathrm{mol\,L^{-1}}) \\ [\mathrm{H^+}] = 10^{-\mathrm{pH}}; [\mathrm{OH^-}] = K_w/[\mathrm{H^+}] \\ \left[\mathrm{NH}_{3\,(aq)}\right] = \left[\mathrm{NH}_4^+{}_{(non-adsorbed)}\right][\mathrm{OH^-}]/\mathrm{K_a} \end{cases}$$

rate constants of hydrolysis

rate constants of dissociation

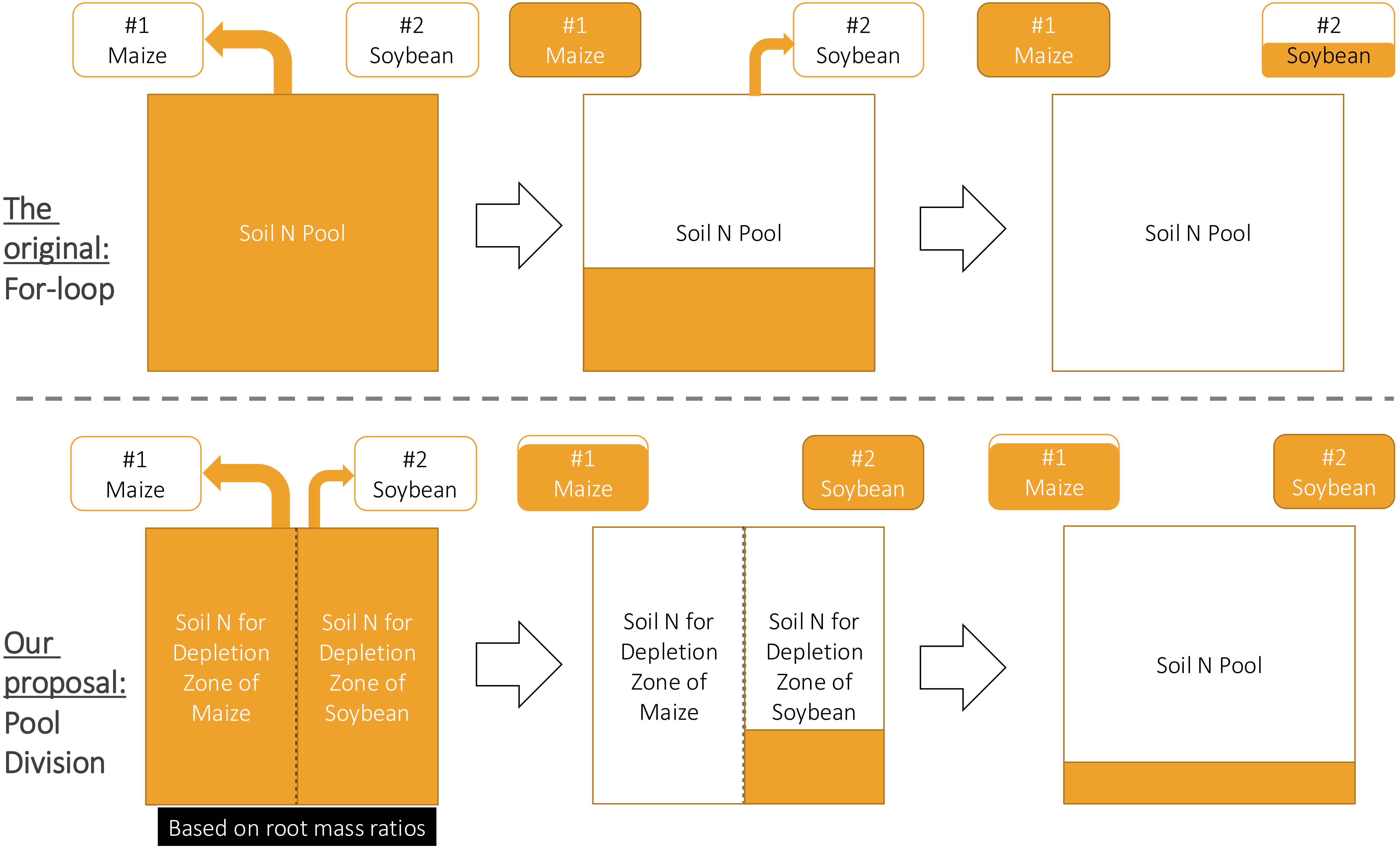
Volatilization of $[NH_{3\,(aq)}]$ from a soil layer in one time-step is found by:

soil layer index

$$\left[\mathrm{NH}_{3\,(g)}\right] = \left[\mathrm{NH}_{3\,(aq)}\right]\left(\frac{1.5s}{1+s}\right)\left(\frac{T_{\mathrm{soil}}}{50+T_{\mathrm{soil}}}\right)\left(\frac{q_{\max}-q}{q_{\max}}\right)$$

wind speed (m $s^{-1}$)

# DNDC nitrogen uptake scheme is revised to capture below-ground competitions



**The original:** For-loop

#1 Maize

#2 Soybean

Soil N Pool

#1 Maize

#2 Soybean

Soil N Pool

#1 Maize

#2 Soybean

Soil N Pool

**Our proposal:** Pool Division

#1 Maize

#2 Soybean

Soil N for Depletion Zone of Maize

Soil N for Depletion Zone of Soybean

Based on root mass ratios

#1 Maize

#2 Soybean

Soil N for Depletion Zone of Maize

Soil N for Depletion Zone of Soybean

#1 Maize

#2 Soybean

Soil N Pool

# Estimation of health costs associated with PM$_{2.5}$

- Increase in mortality rate:

Empirical health impact factor of PM$_{2.5}$, $\beta = 0.0058\, m^3 \mu g^{-1}$ (Krewski et al)

$$\Delta M = P M_0 \left(1 - \mathrm{e}^{-\beta \Delta C}\right)$$

Provincial population > 30yo

Annual mortality rate

- Value of statistical life in China from Gu et al. (2012)

$$VSL = US\$\, 170{,}000$$

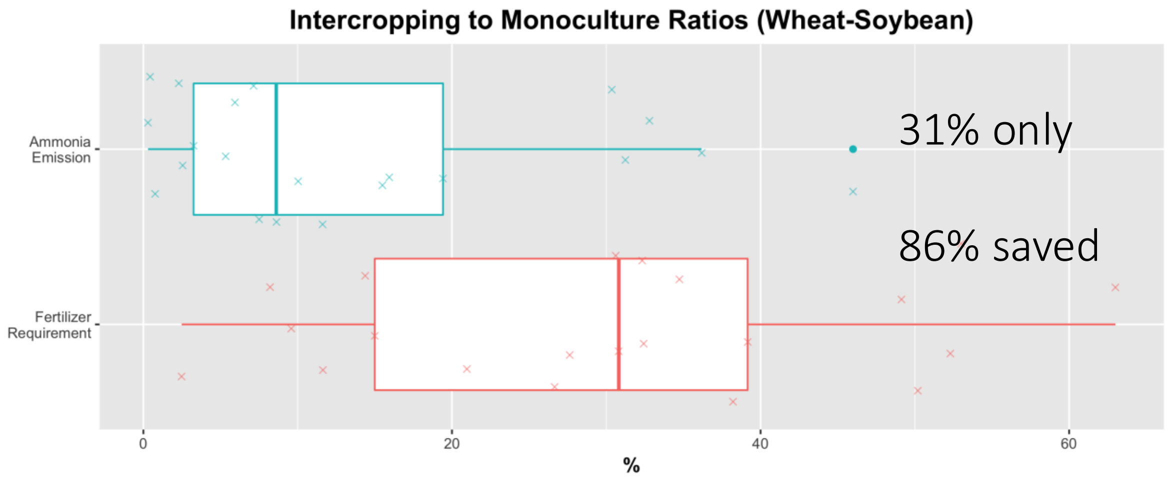
- Assuming premature mortality lags PM$_{2.5}$ by 20 years and the risk-free interest rate (e.g. 20-year US government issued bond) is 3%, then the health costs associated with PM$_{2.5}$ is given by:

Continuously-compounded discount

$$Cost_{PM_{25}} = \Delta M \times VSL \times \mathrm{e}^{(-0.03)(20)}$$

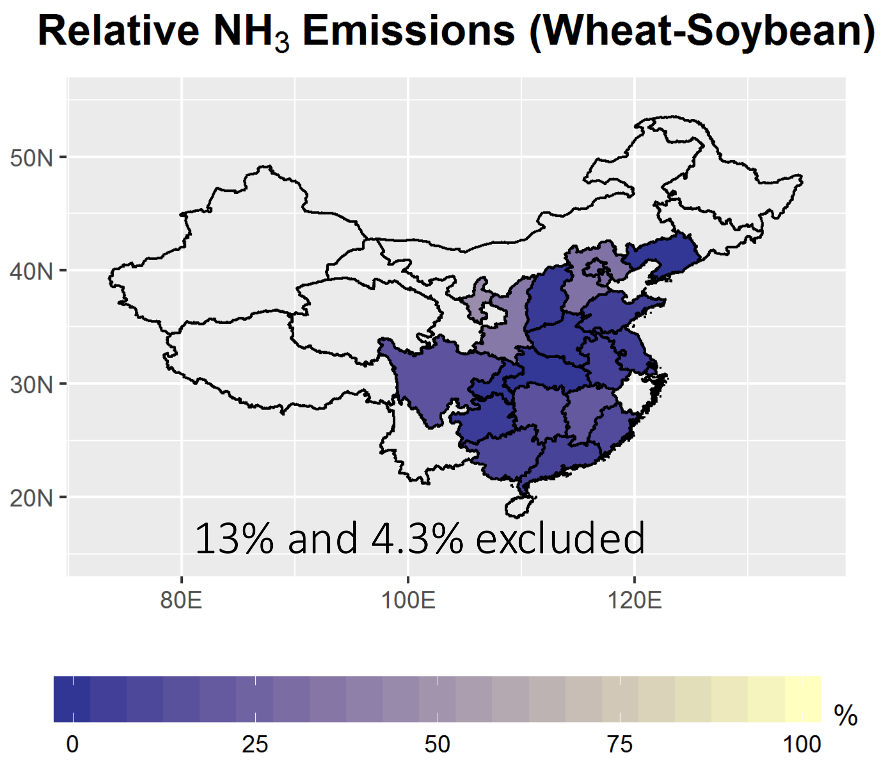
(Paulot & Jacob 2013)

# Supplementary: Intercropping of Wheat and soybean

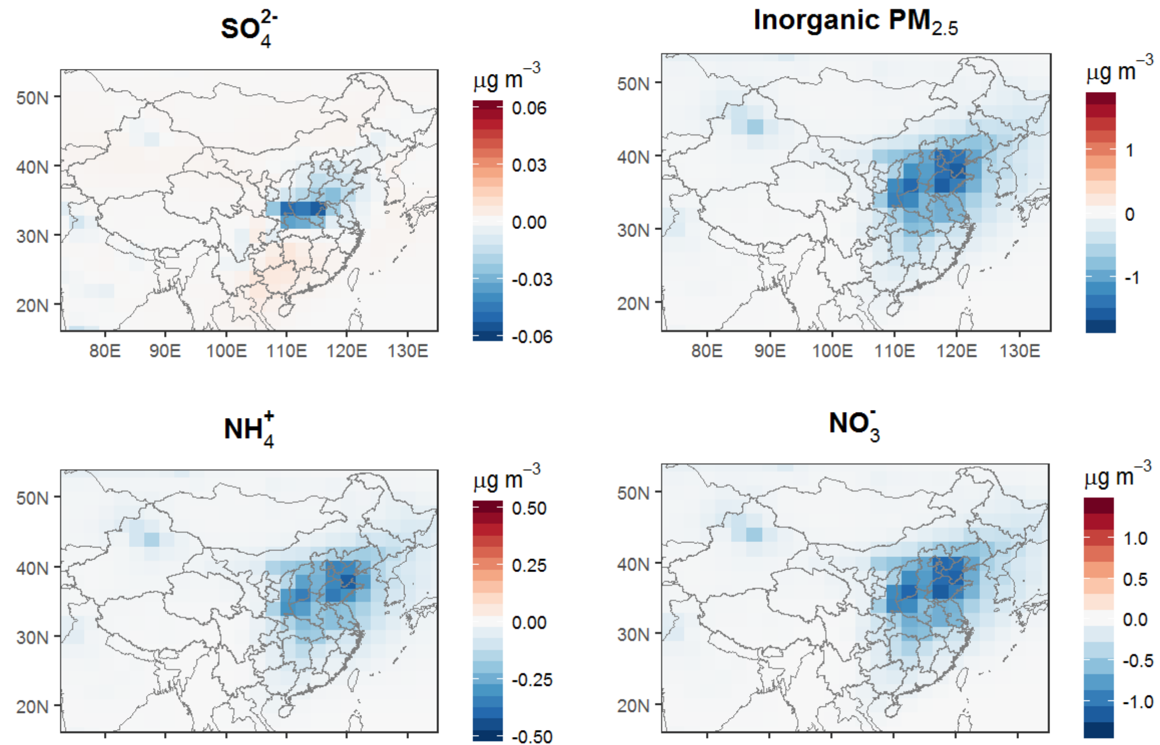

**Intercropping to Monoculture Ratios (Wheat-Soybean)**

31% only

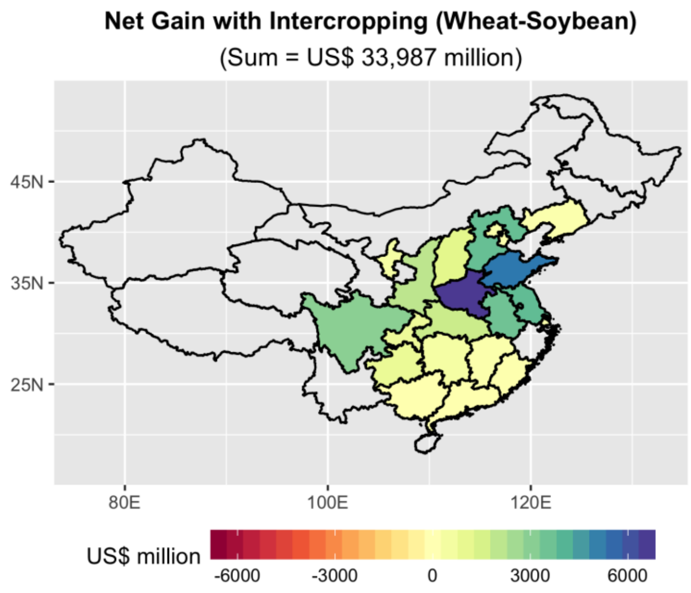
86% saved


**Relative $NH_3$ Emissions (Wheat-Soybean)**

13% and 4.3% excluded

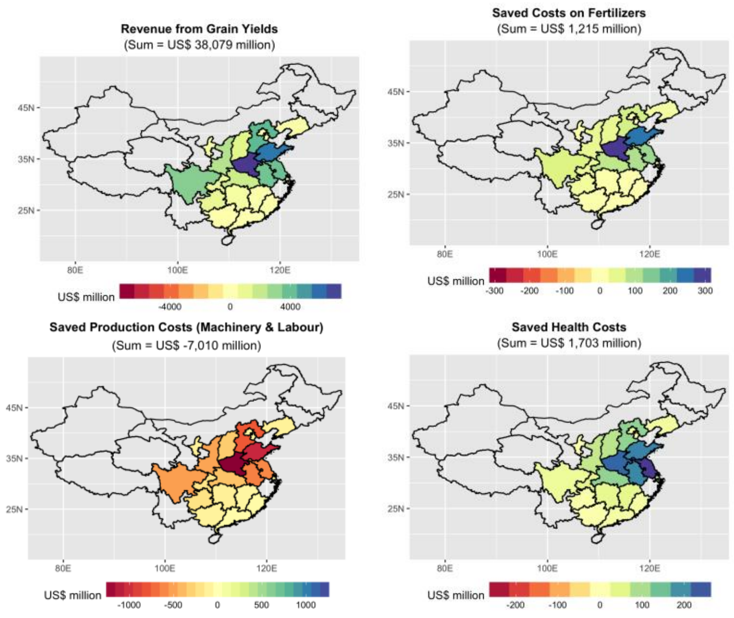


Over the whole China, inorganic PM$_{2.5}$, NH$_4^+$ and NO$_3^-$ are decreased up to 1.5 μg m$^{-3}$ (2.1%), 0.36 μg m$^{-3}$ (4.0%) and 1.1 μg m$^{-3}$ (7.0%), respectively.


**Net Gain with Intercropping (Wheat-Soybean)**

(Sum = US$ 33,987 million)

276% more than monoculture

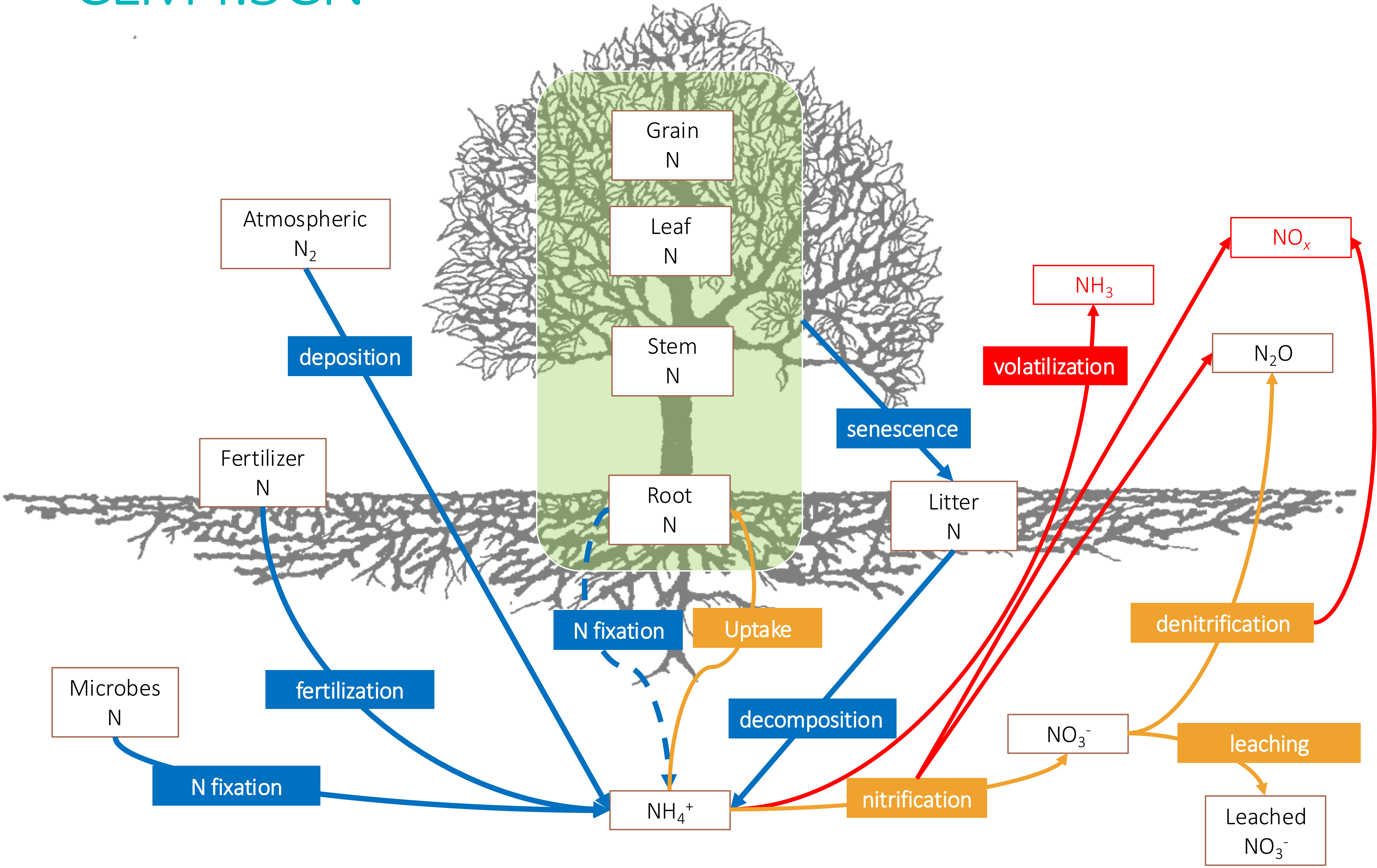

**Revenue from Grain Yields**
(Sum = US$ 38,079 million)

**Saved Costs on Fertilizers**
(Sum = US$ 1,215 million)

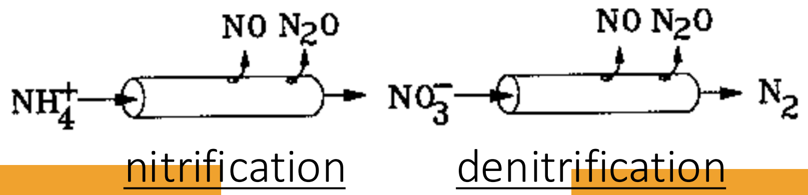
**Saved Production Costs (Machinery & Labour)**
(Sum = US$ -7,010 million)

**Saved Health Costs**
(Sum = US$ 1,703 million)

# Missing pathways in the nitrogen cycle of CLM4.5CN

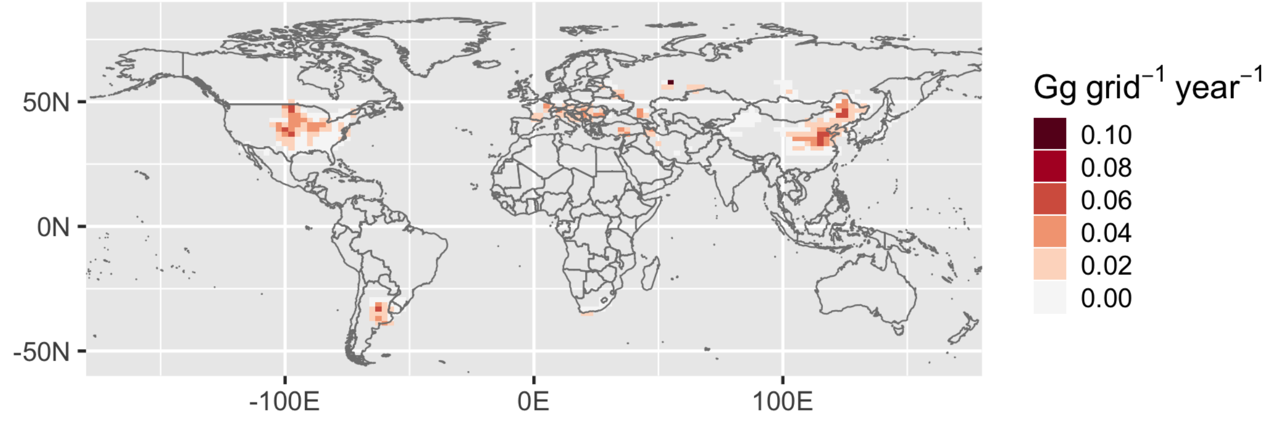


# Intercropping also reduce $N_2O$ emissions

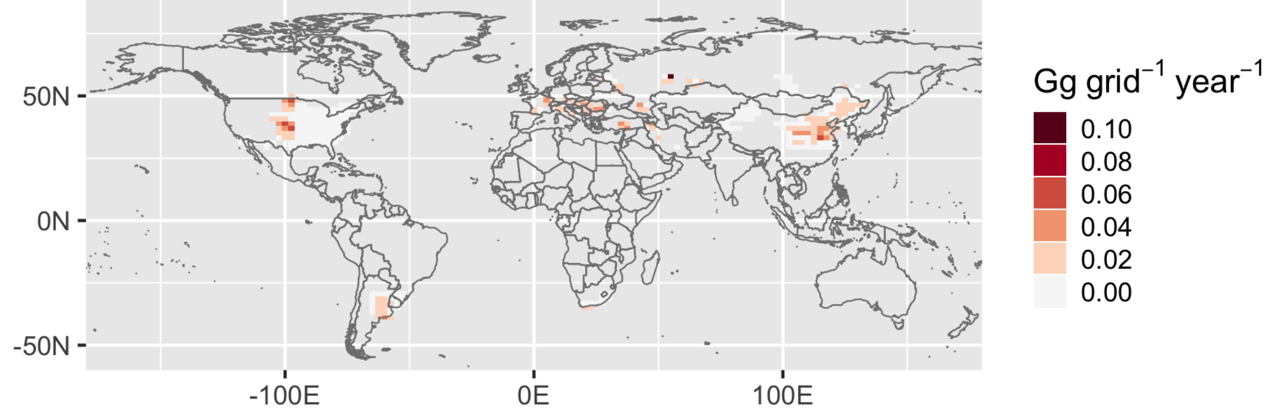


Firestone (1989)

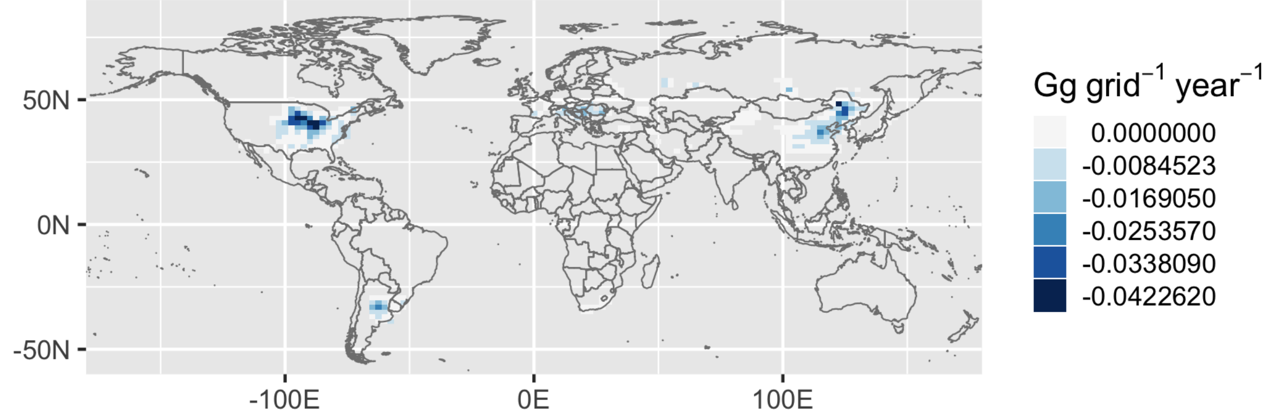
Monoculture (Total = 5.89 Gg year $^{-1}$)



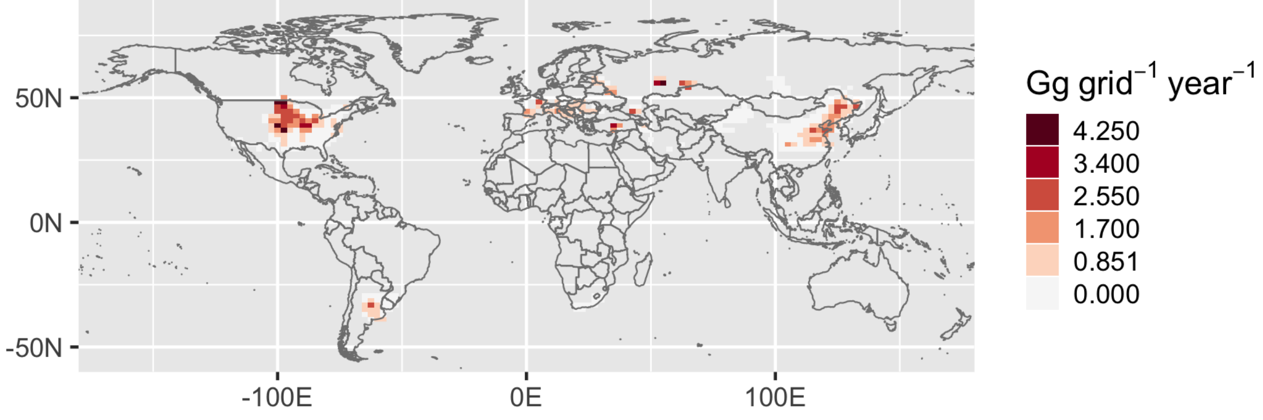
Intercropped (Total = 3.78 Gg year $^{-1}$)



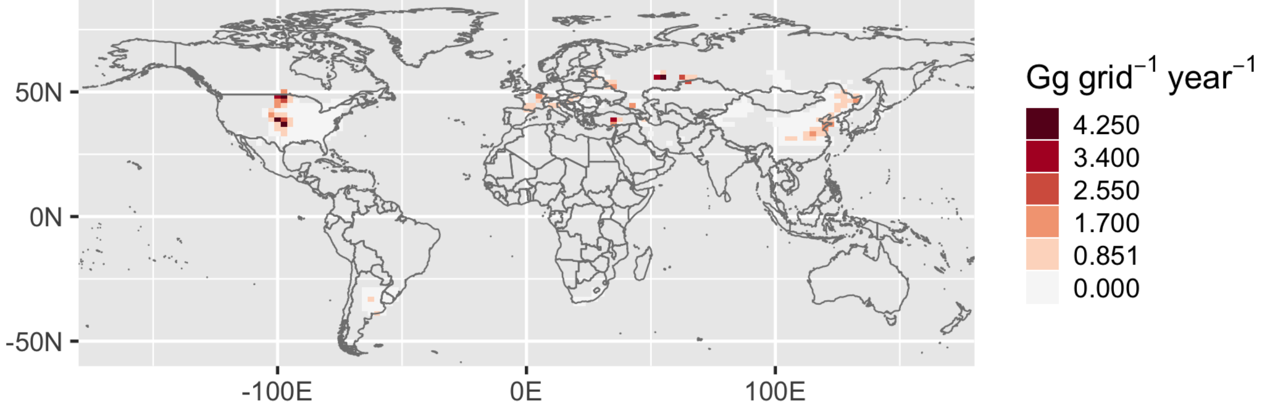
Intercropped – monoculture
(Total = -2.11 Gg year $^{-1}$ [-36%])



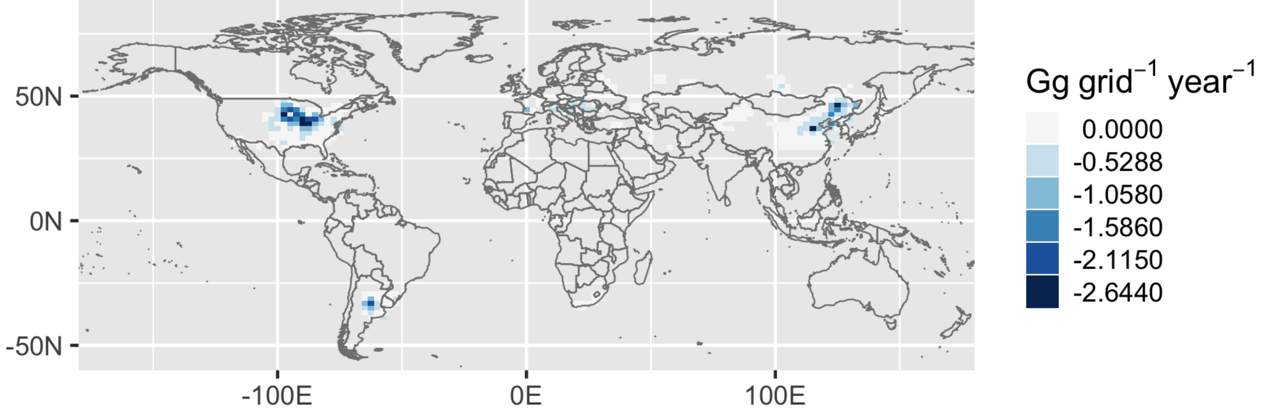
Monoculture (Total = 244 Gg year $^{-1}$)



Intercropped (Total = 130 Gg year $^{-1}$)



Intercropped – monoculture
(Total = -114 Gg year $^{-1}$ [-47%])



# Nitrification under Century-based Formulation

CLM4.5 Tech Notes Ch16

- Rate of nitrification of $NH_4^+$ to $NO_3^-$ is

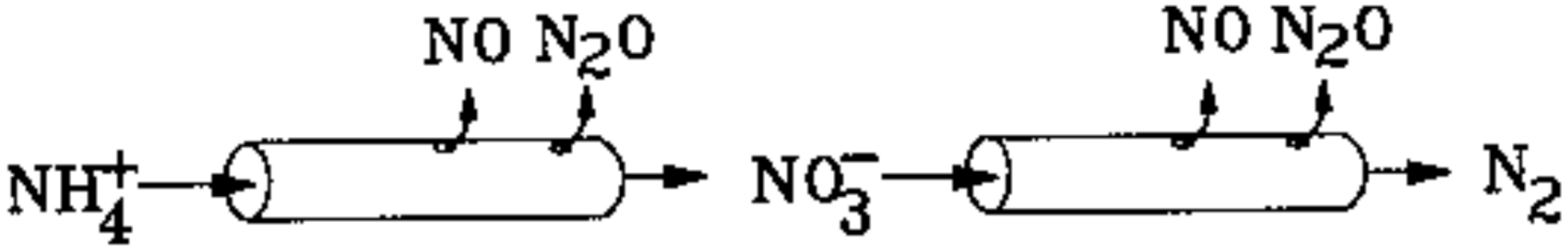
$$f_{nitr,p} = [NH_4] k_{nitr} f(T) f(H_2O) f(pH)$$

Potential nitrification rate

max. nitrification rate (~10%)

Rate modifiers according to temp., water and pH (fixed at 6.5)

- A constant fraction of nitrification flux ($6 \times 10^{-4}$) is assumed to be $N_2O$ (“holes in a pipe” approach)

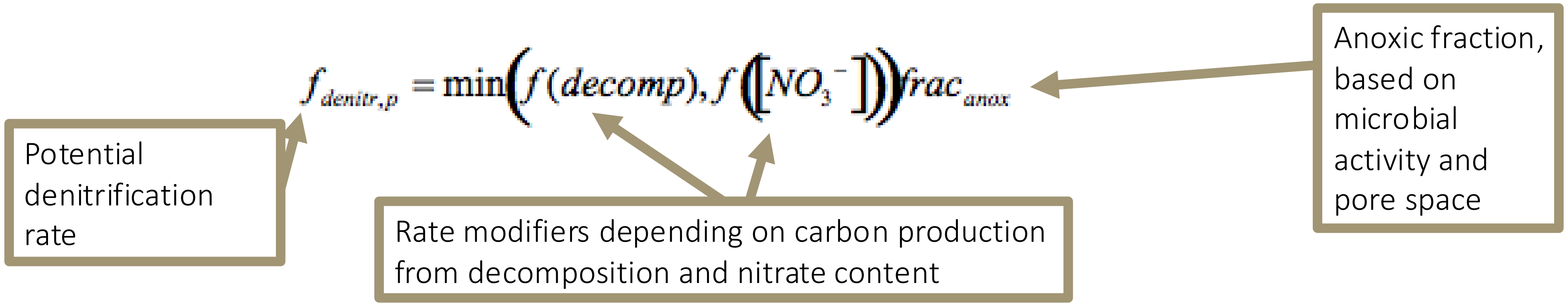


Firestone (1989)

# Denitrification under Century-based formulation

CLM4.5 Tech Notes Ch16

- Potential rate is co-limited by [$NO_3^-$], consumption rates and only in anoxic soil (with dissolved oxygen depleted):



$$f_{denitr,p} = \min\left(f(decomp), f\left(\left[NO_3^-\right]\right)\right) frac_{anox}$$

Potential denitrification rate

Rate modifiers depending on carbon production from decomposition and nitrate content

Anoxic fraction, based on microbial activity and pore space

- Fraction of $N_2$:$N_2O$ produced is given by

$$P_{N_2:N_2O} = \max\left(0.16k_1, k_1 \exp\left(-0.8P_{NO_3:CO_2}\right)\right) f_{WFPS} \qquad (16.14)$$

where $P_{NO3:CO2}$ is the ratio of $CO_2$ production in a given soil layer to the $NO_3^-$ concentration, $k_1$ is a function of $d_g$, the gas diffusivity through the soil matrix:

$$k_1 = \max\left(1.7, 38.4 - 350 * d_g\right) \qquad (16.15)$$

and $f_{WFPS}$ is a function of the water filled pore space $WFPS$:

$$f_{WFPS} = \max\left(0.1, 0.015 \times WFPS - 0.32\right) \qquad (16.16)$$

# Denitrification under CLN-CN: $NS_{sminn}$ -> $N_{atmos}$ (single pool)

CLM4.5 Tech Notes Ch16

- For calculating fluxes of denitrification,

$$NF_{denit,SOM3\rightarrow SOM4} = \begin{cases} 0 & \text{for } NF_{pot\_min,SOM3\rightarrow SOM4} > 0 \\ -NF_{pot\_min,SOM3\rightarrow SOM4}\, f_{denit} & \text{for } NF_{pot\_min,SOM3\rightarrow SOM4} \le 0 \end{cases}$$

$$f_{denit} = 0.01$$

$$NF_{denit,SOM4} = -NF_{pot\_min,SOM4}$$

- If mineral nitrogen is in excess,50% of the exceeded will be denitrified and discharged to the atmosphere as one species at each time step,

$$NF_{sminn,denit} = \begin{cases} \left(\dfrac{NS_{sminn}}{\Delta t}\right) - NF_{total\_demand}\, f_{dnx} & \text{for } NF_{total\_demand}\Delta t < NS_{sminn} \\ 0 & \text{for } NF_{total\_demand}\Delta t \ge NS_{sminn} \end{cases}$$

$$f_{dnx} = 0.5\frac{\Delta t}{86400}$$