Modeling and Assessing the Impacts of Sustainable Farming Practices on Food Security, Air Quality, and Public Health

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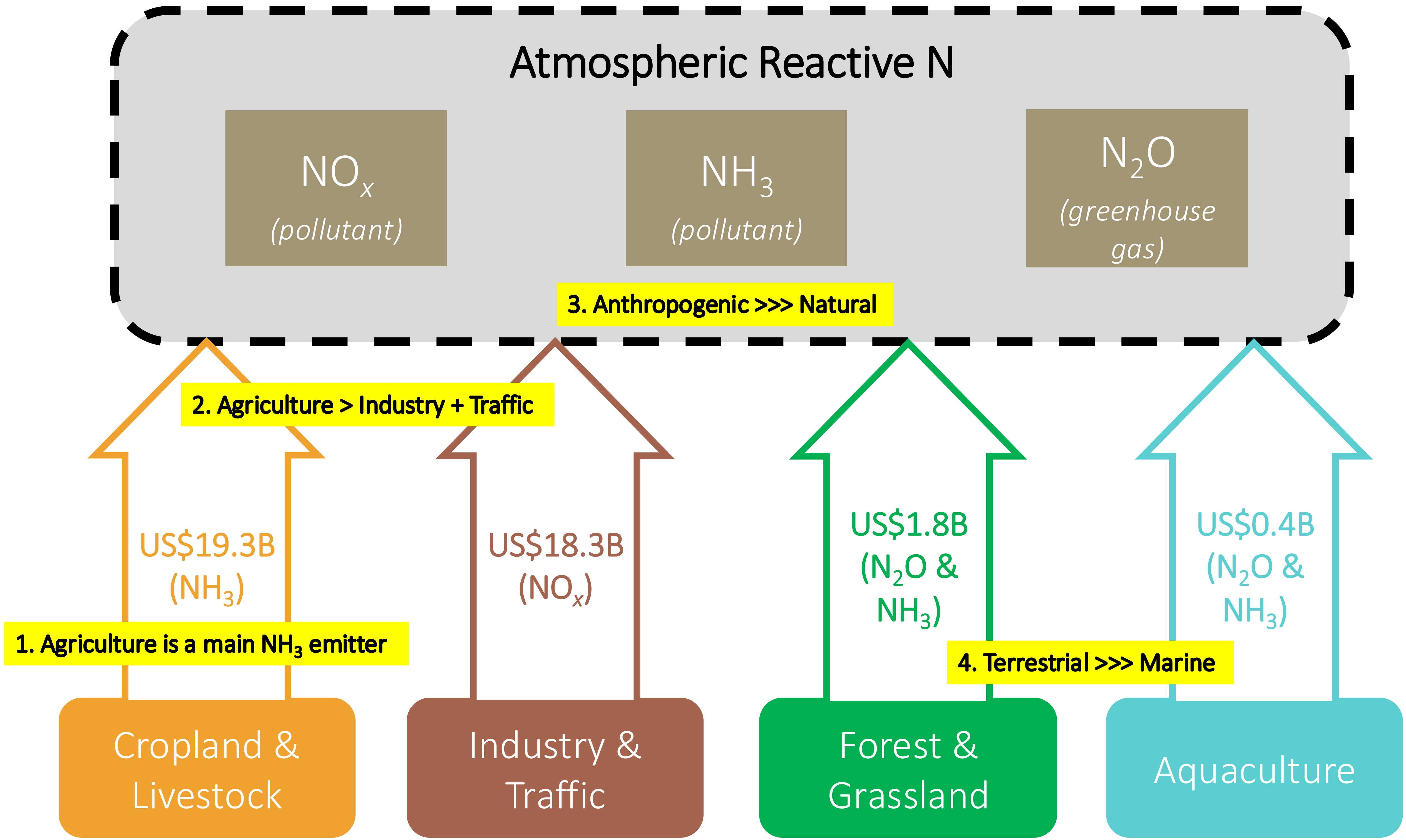
EARTH SYSTEM SCIENCE PROGRAMME

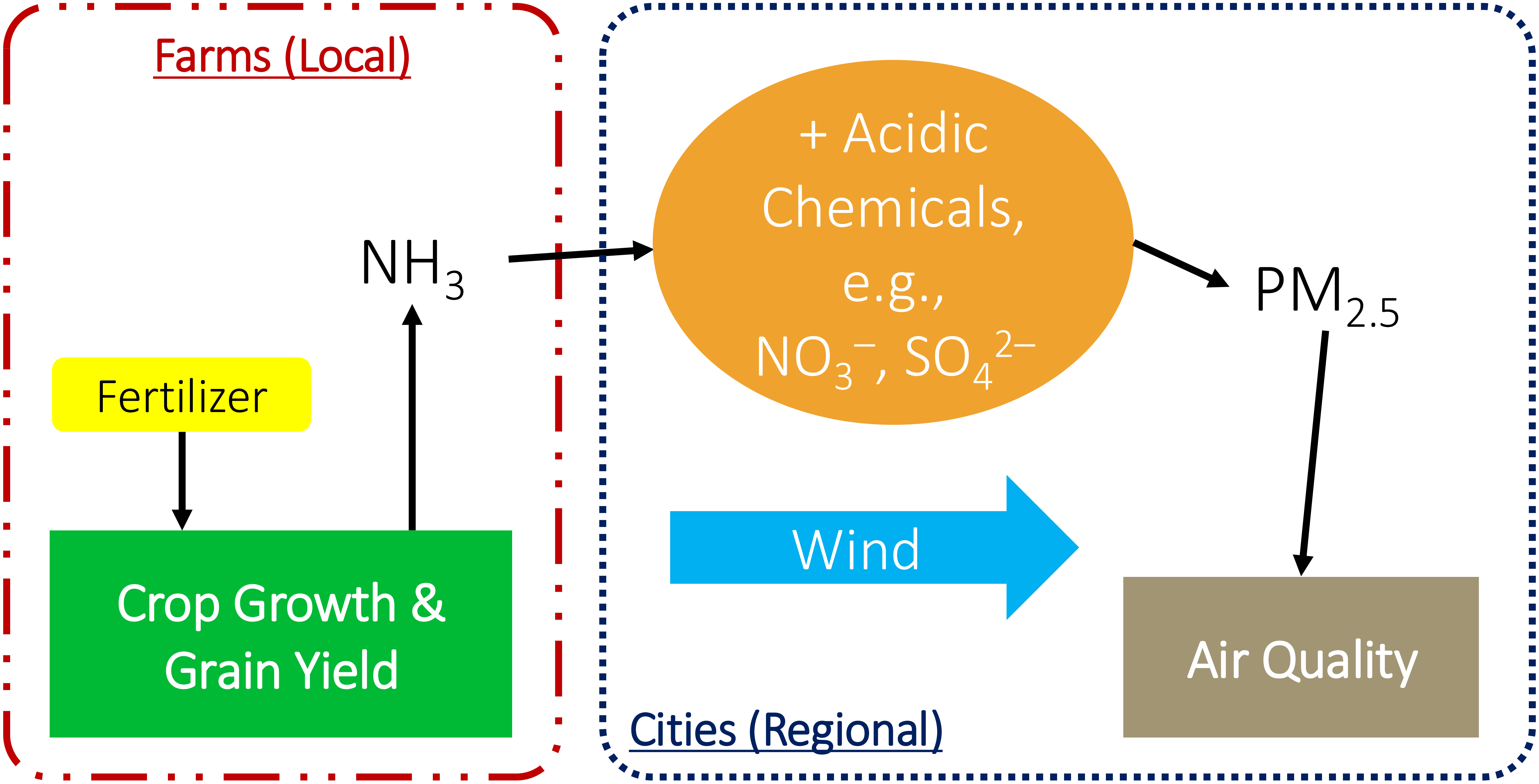
A large portion of atmospheric reactive N is emitted by terrestrial activities

Gu *et al.* (2012)

Health Damage Costs of Reactive N across China in 2008



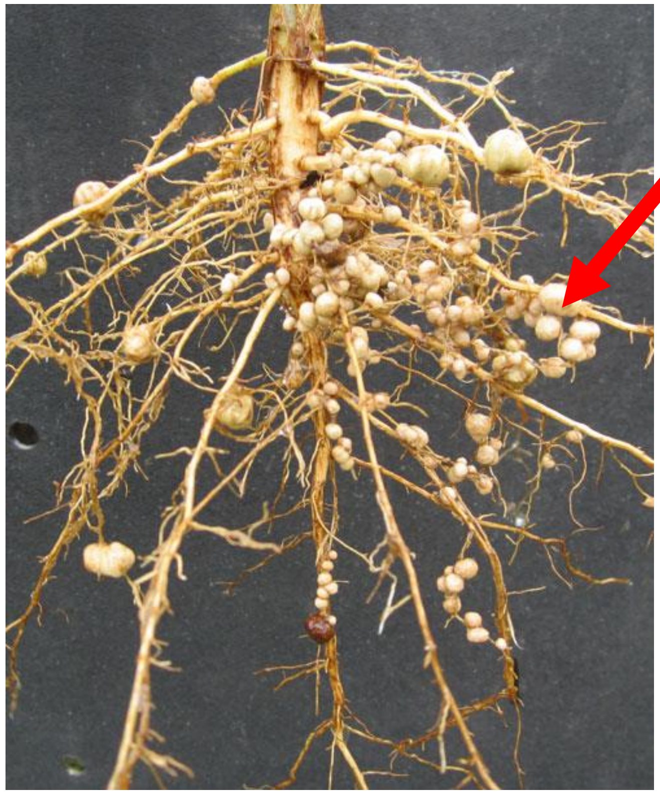
In Europe, China, and the US, 80-90% of atmospheric NH_3 is from agriculture



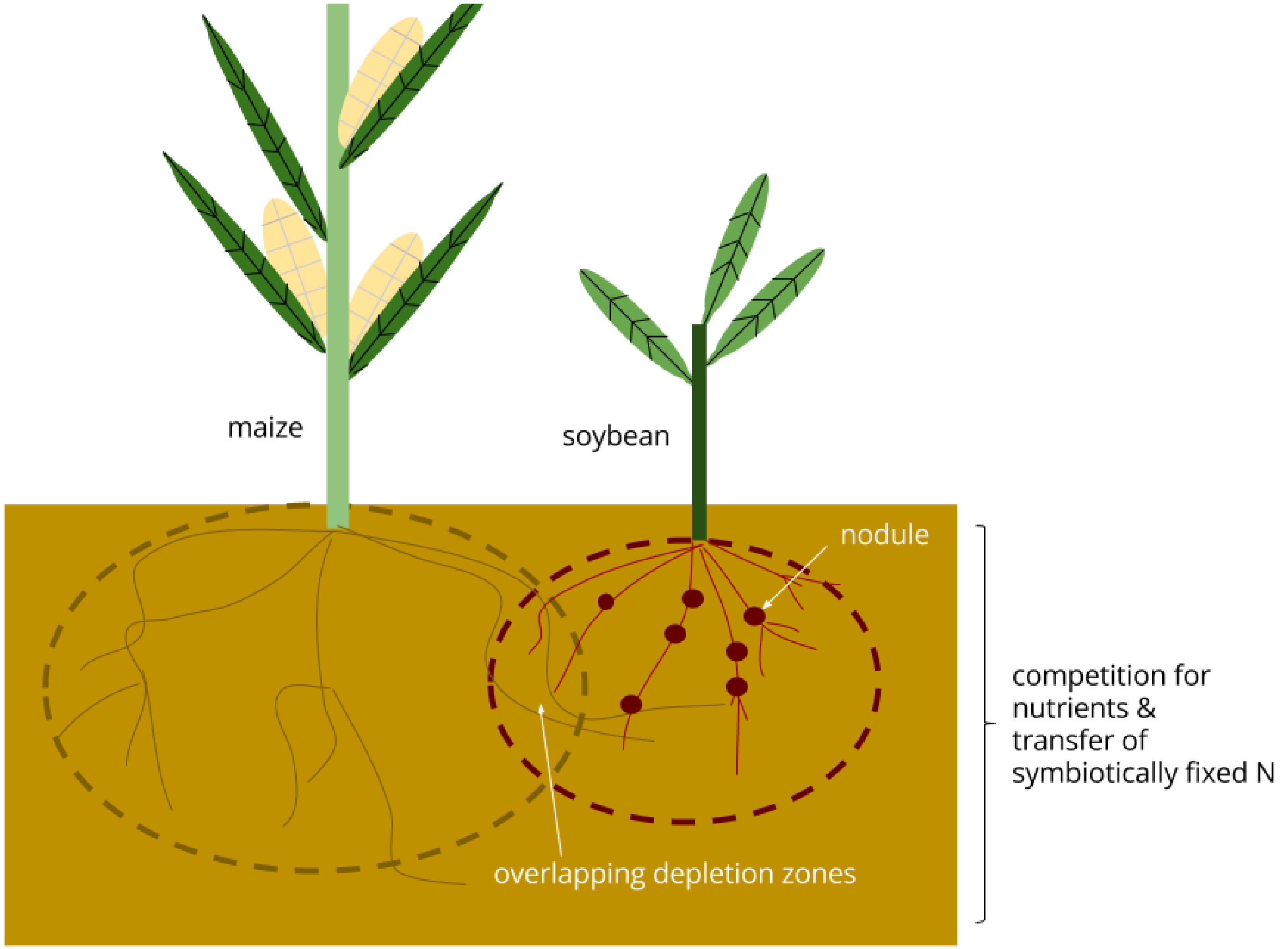
Can we secure future food supply without sacrificing the clean air?

Intercropping, a traditional wisdom, could be a way-out to this food-environment dilemma

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



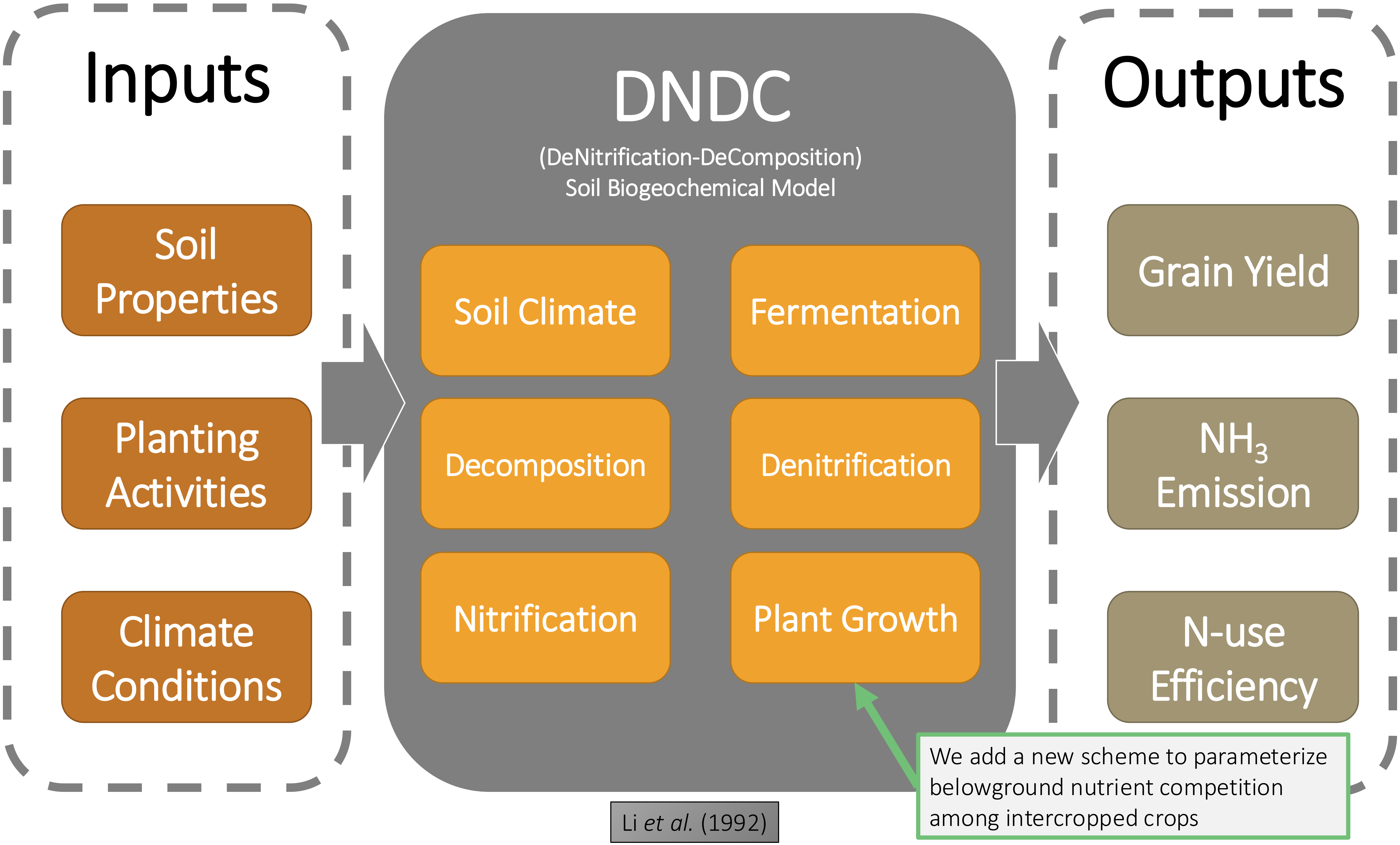
Nitrogen fixing nodules



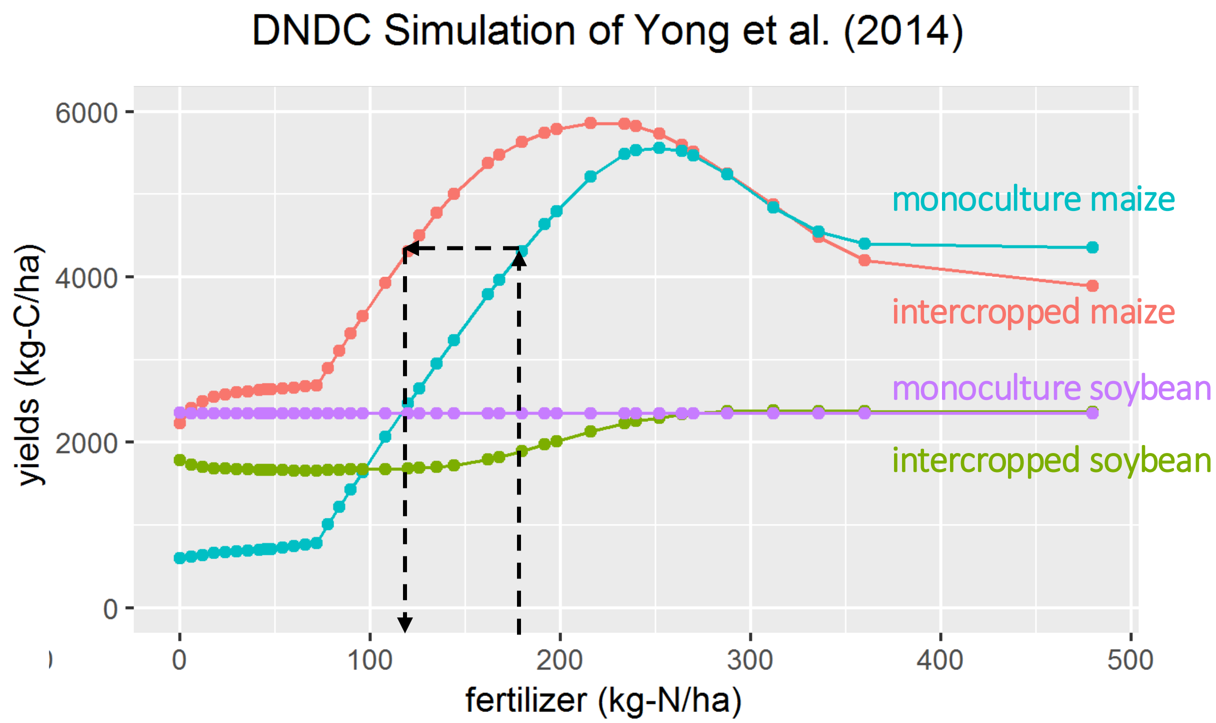
They are placed close enough to allow belowground competition

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

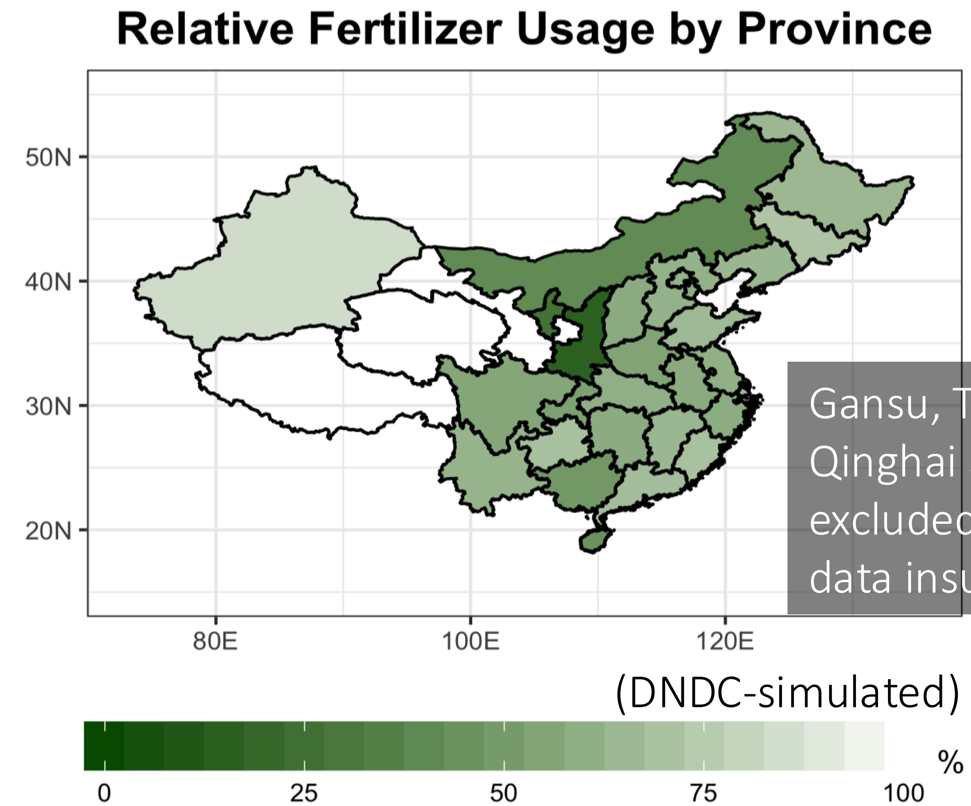
Modeling intercropping to explore the feasibility of a nationwide adoption



We validate the modified DNDC and simulate a "whole-China" conversion to intercropping



1. 33% less fertilizer to generate the same quantity of maize
2. On the same land, additional soybean can be harvested



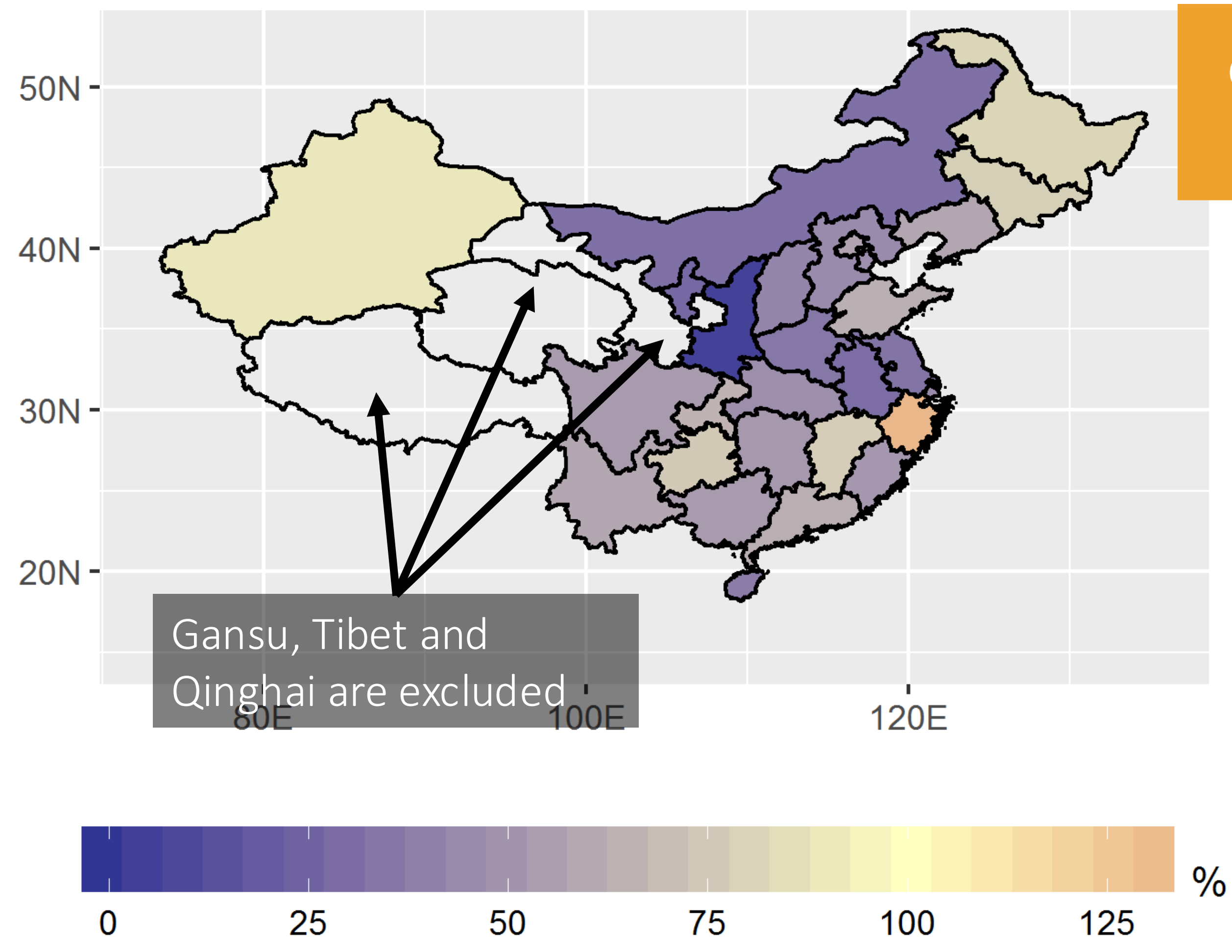
Gansu, Tibet and Qinghai are excluded due to data insufficiency

42% less fertilizer is needed to maintain maize yield if intercropping is adopted in all maize or soybean croplands

Fung *et al.* (2019)

The corresponding NH_3 emission can be reduced by 45%

Relative NH_3 Emission (Intercropping vs. Monoculture)

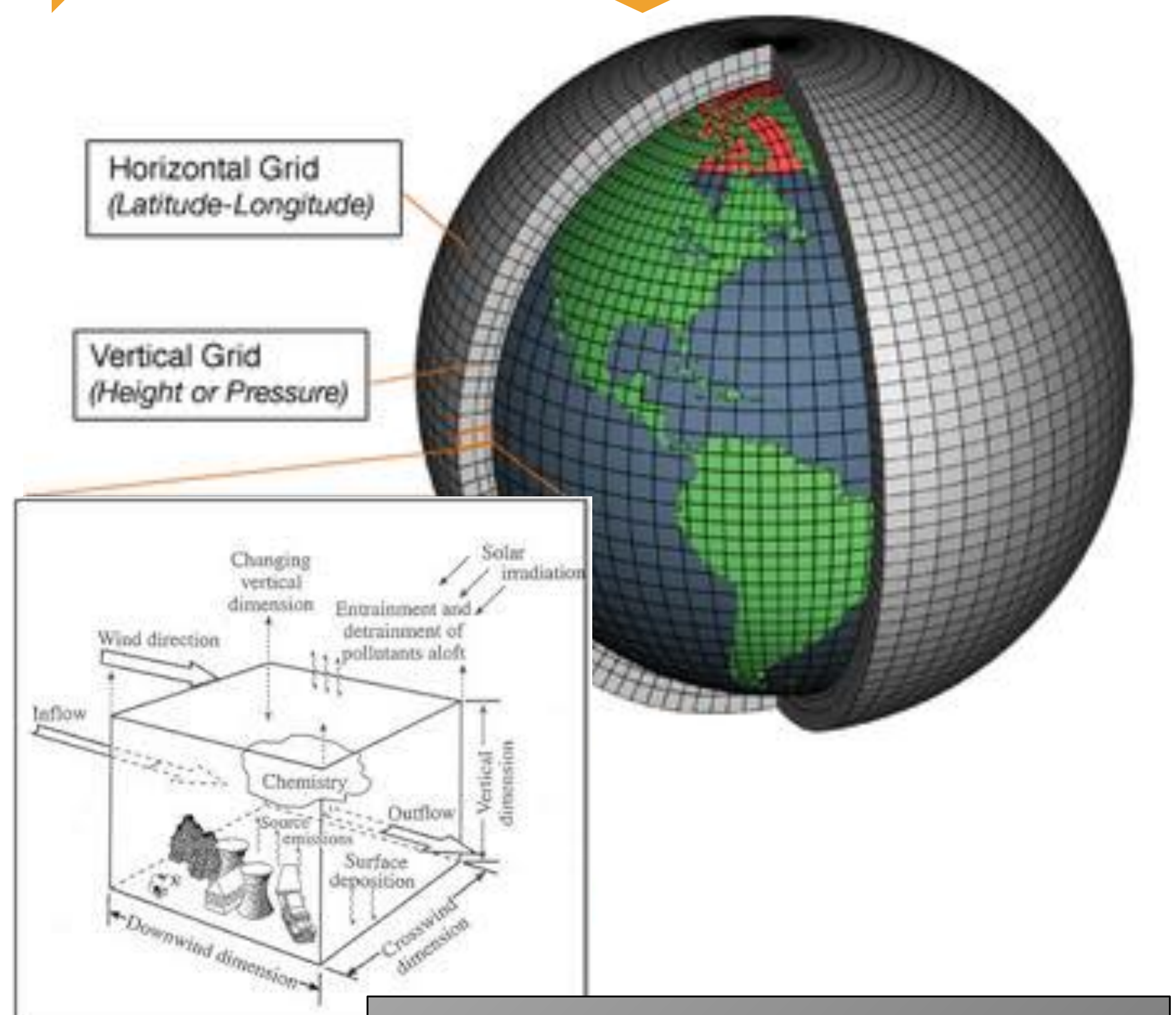


Fung *et al.* (2019)

Grid-by-grid scaling

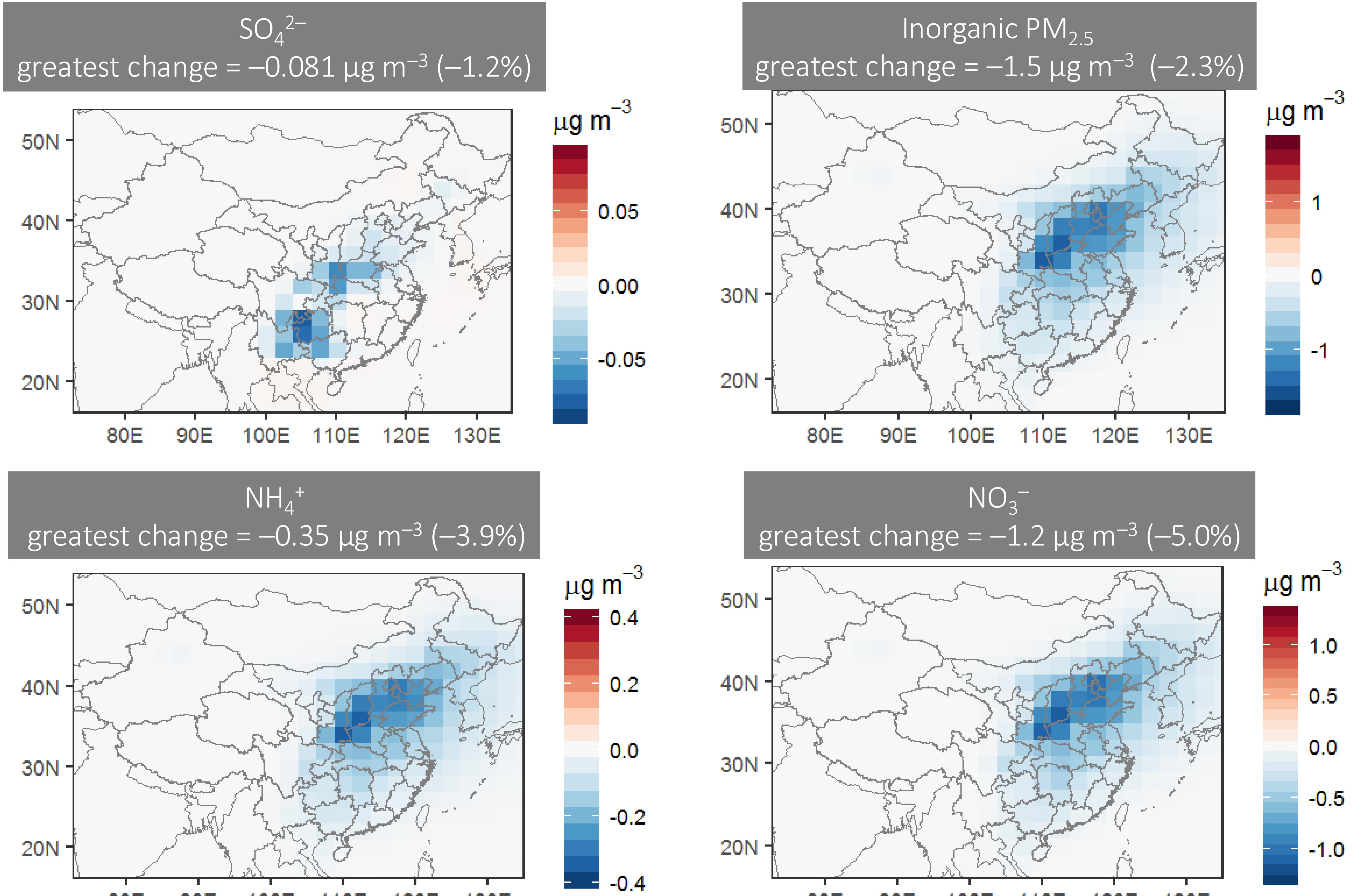
MASAGE NH_3 Emission Inventory

(Magnitude And Seasonality of Agricultural Emissions)



GEOS-Chem
3-D Global Chemical Transport Model

GEOS-Chem predicts air quality improvement if all croplands are using intercropping

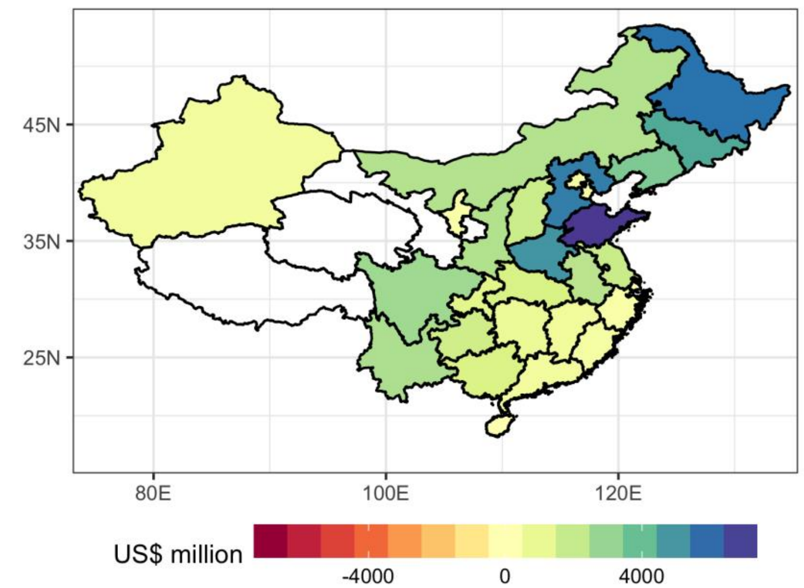


Fung *et al.* (2019)

(% to local mean without intercropping)

Intercropping could be more economic than the current practice in China

More Grain = +US$58b



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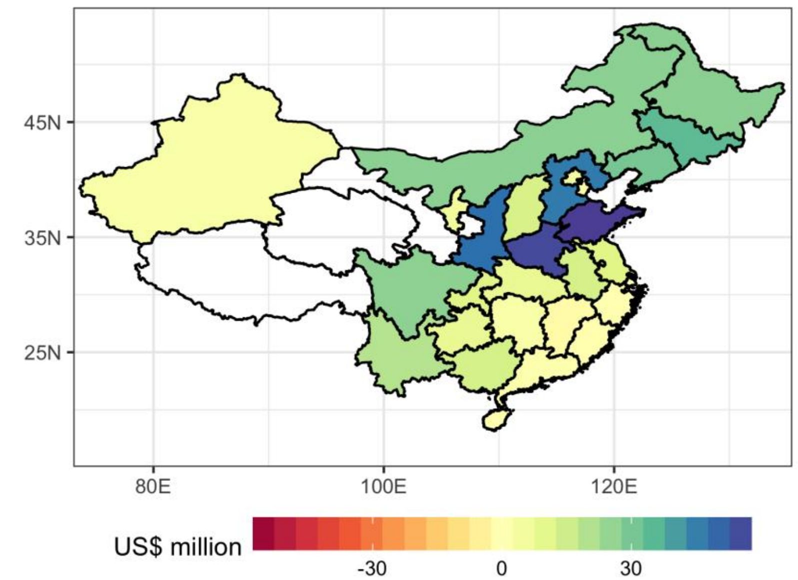
Reduced Fertilizer = +US$0.5b



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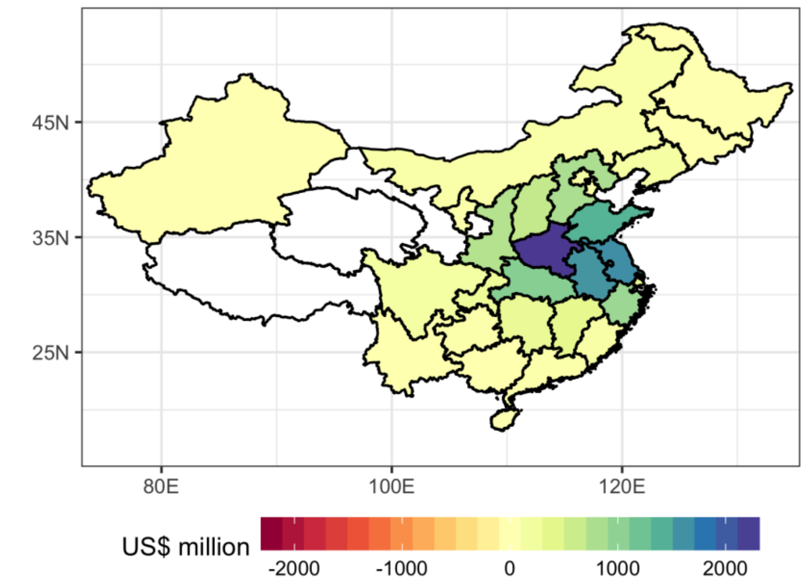
Avoided Health Costs = +US$13b



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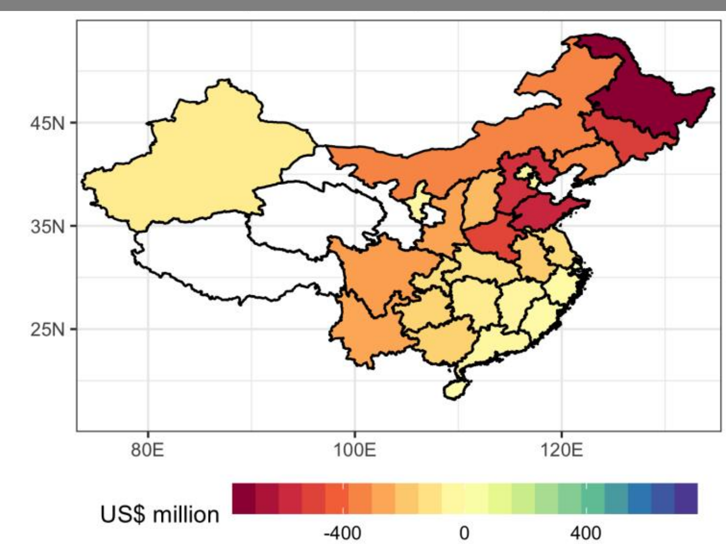
Additional Machinery & Labor = –US$6.0b



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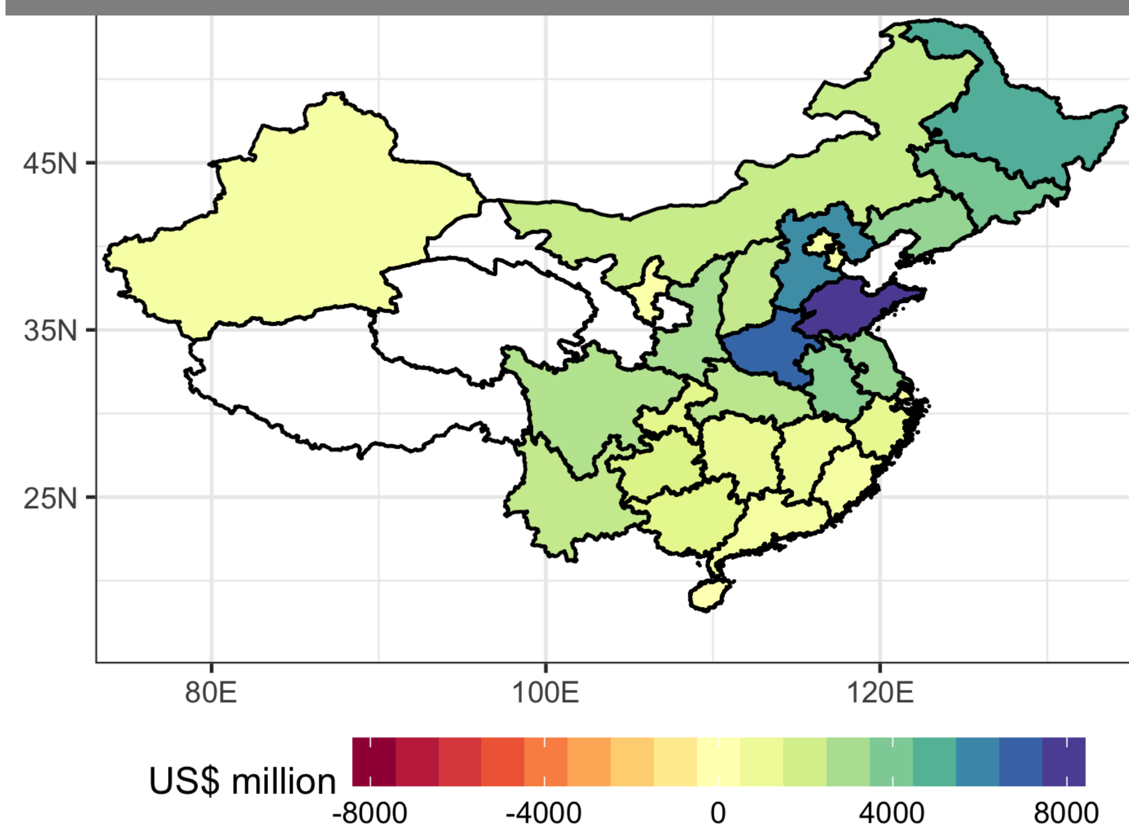
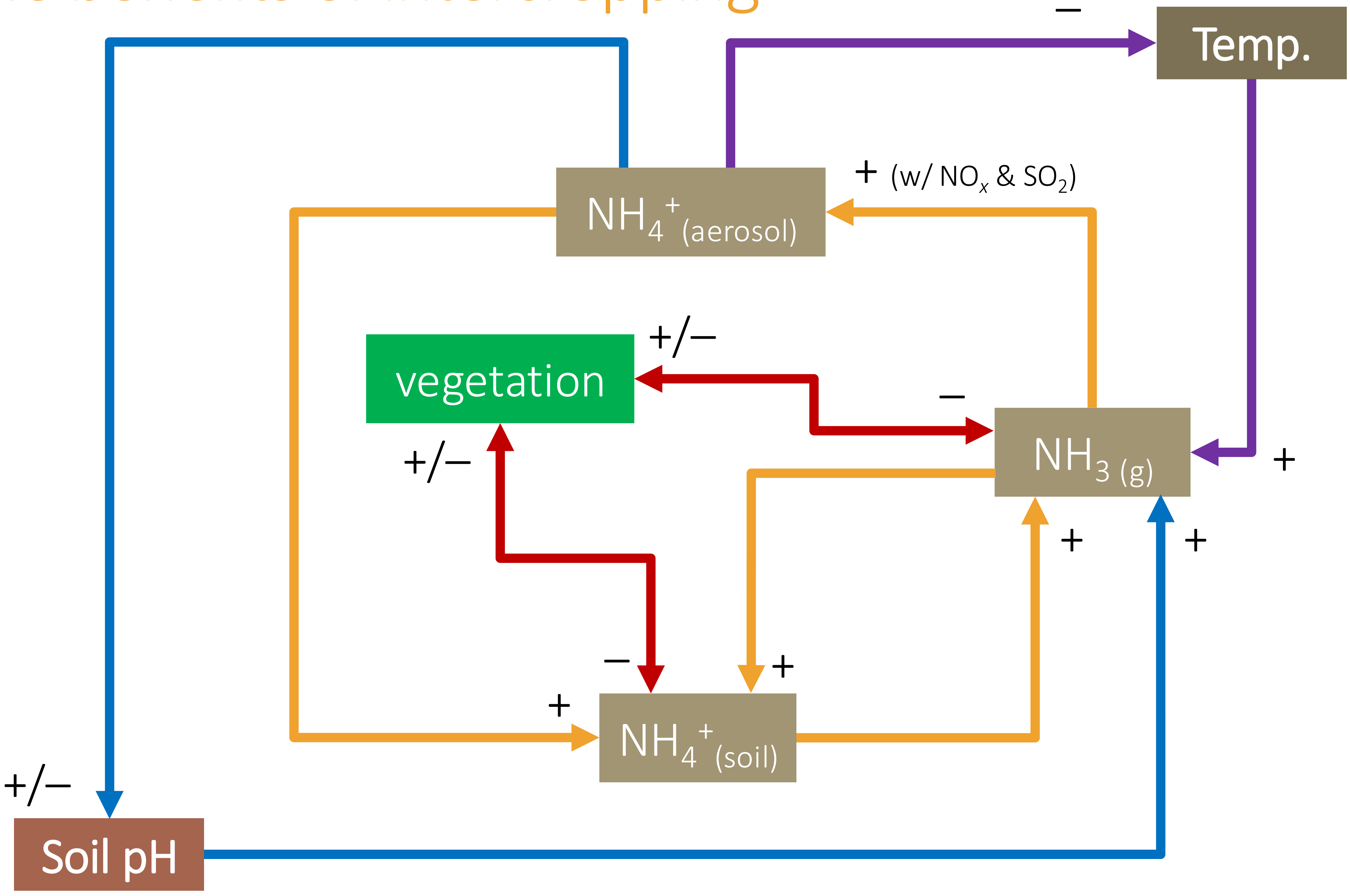
Net profit = +US$67b
(+93% relative to the current practice)



Item	US$ Per Unit
Maize	0.25/kg
Soybean	0.41/kg
Urea	0.27/kg
Statistical Life	160k
Labor	186.50/ha
Machinery	40.00/ha

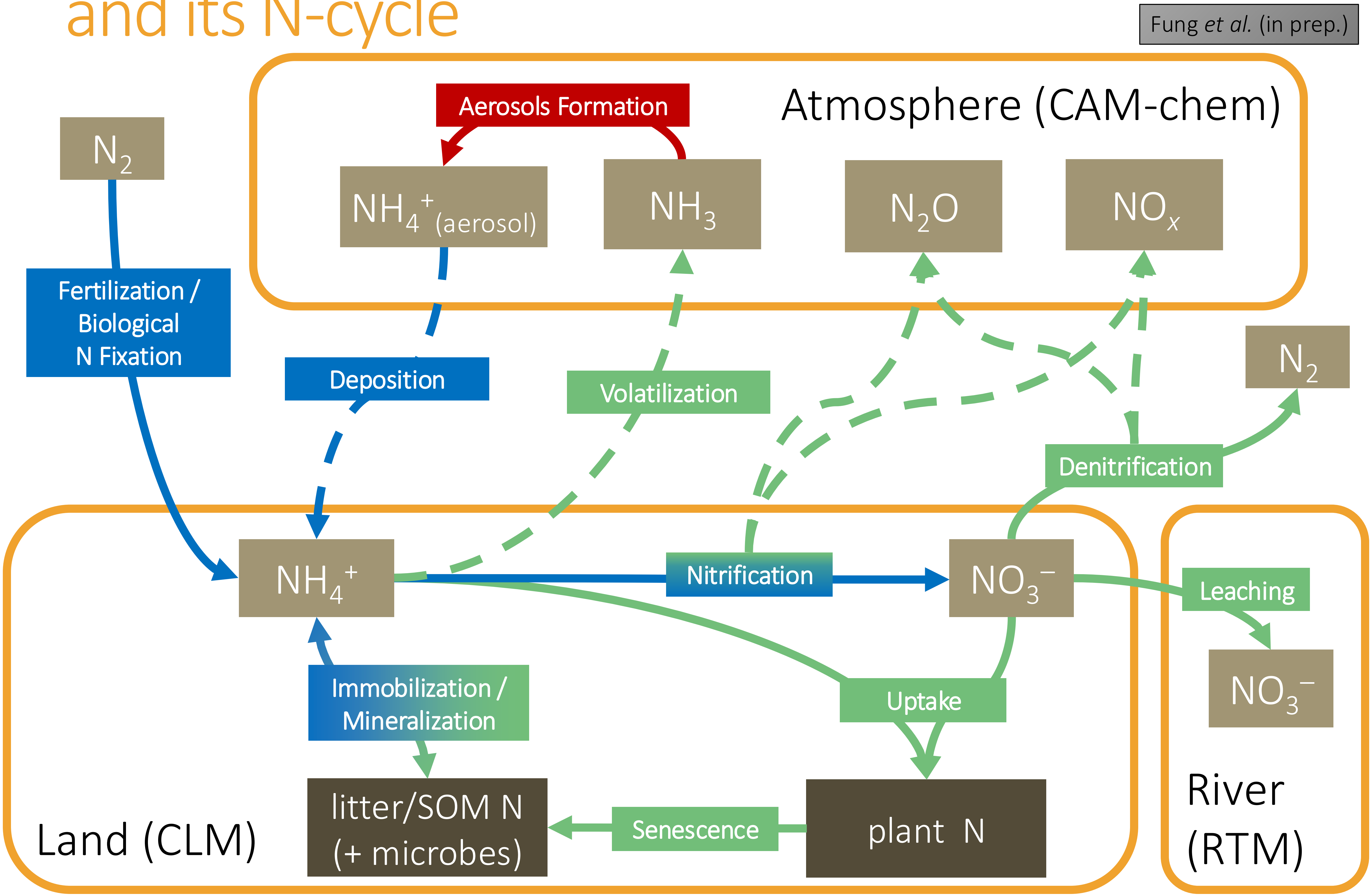
Fung *et al.* (2019)

Potential feedbacks complicate the land-atmospheric NH_3/NH_4^+ cycle, which may offset the benefits of intercropping



Fung *et al.* (in prep.)

Community Earth System Model (CESM) and its N-cycle

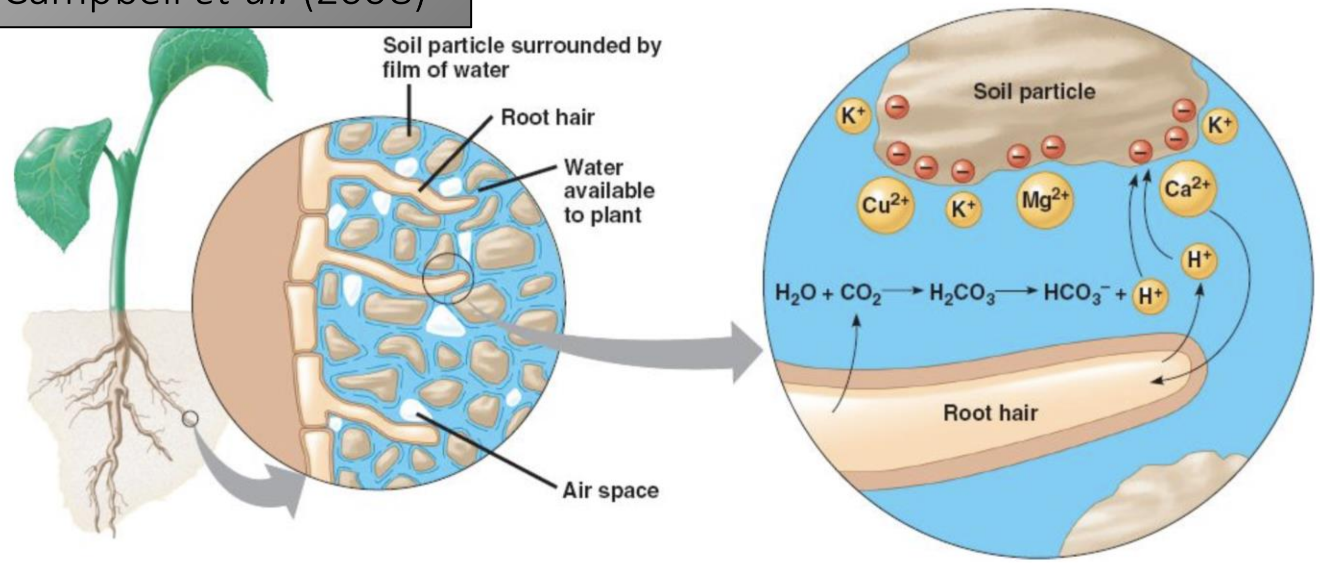


We implement into CLM the “multi-step” NH_3 emission scheme from DNDC (Li *et al.*, 2012)

$$\left(\frac{\mathrm{d}[NH_{3\,(g)}]}{\mathrm{d}t}\right)_{\text{from soil}} \approx [NH^{+}_{4\,(soil)}](1 - f_{ads})f_{dis}f_{vol}\left(\frac{1}{\Delta t}\right)$$

$NH_4^+{}_{(soil)}$ → $NH_4^+{}_{(aq)}$ → $NH_{3\,(aq)}$ → $NH_{3\,(g)}$

Campbell *et al.* (2008)



Fraction of dissociated non-adsorbed NH_4^+:

$$NH_4^+{}_{(non\text{-}ads)} + OH^-{}_{(aq)} \rightleftharpoons NH_{3\,(aq)} + H_2O_{(l)}$$

$$f_{dis} = \frac{K_w}{[H^+]K_a}$$

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

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

$$[H^+] = 10^{-pH}\ (\text{mol L}^{-1})$$

$$pH = 6.8$$

rate constant of dissociation (K_a)

soil temperature (°C) (T_{soil})

rate constant of hydrolysis (K_w)

Fraction of NH_4^+ adsorbed to soil matrix is determined by an empirical equation:

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

clay fraction (f_{clay})

Fraction of volatilized $NH_{3\,(aq)}$:

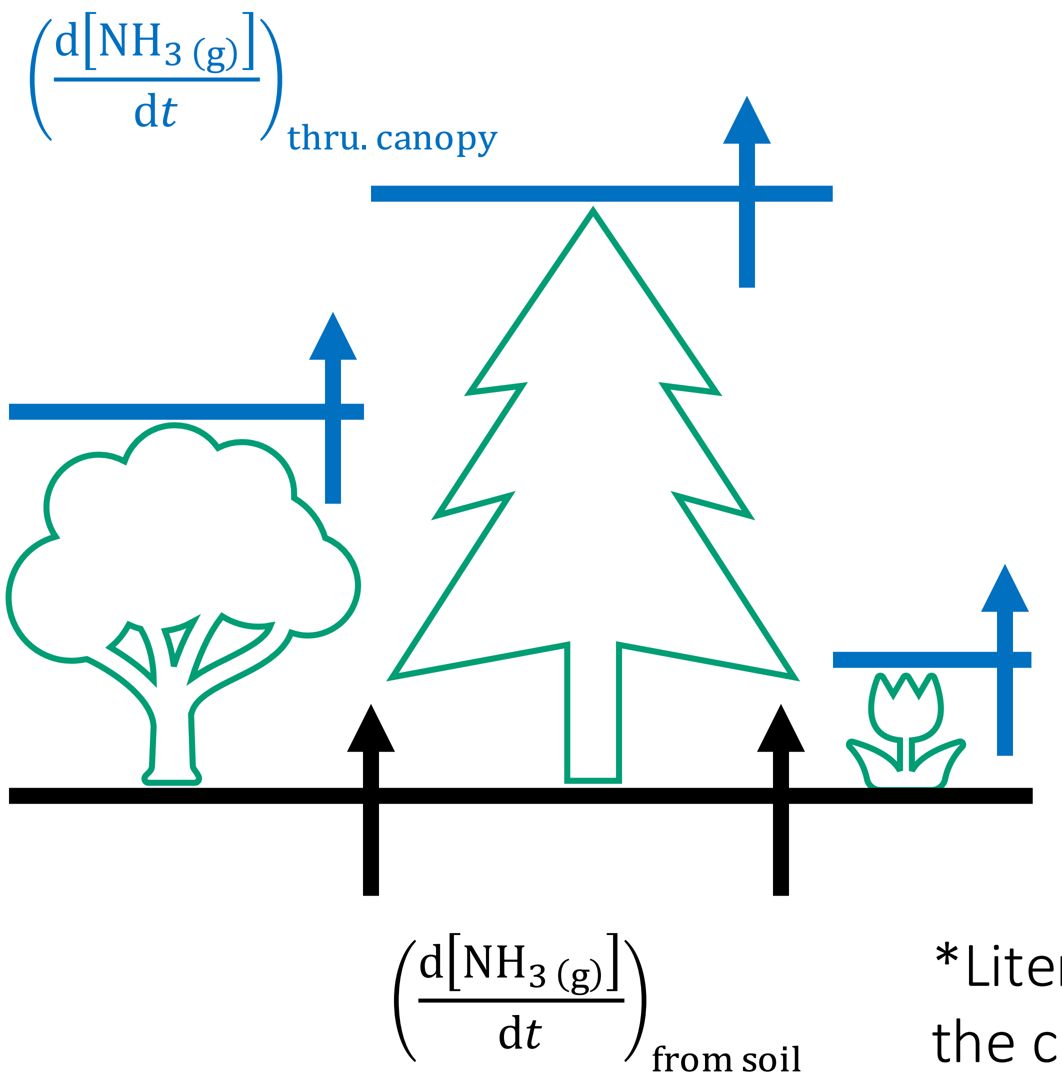
$$f_{vol} = \left(\frac{1.5s}{1+s}\right)\left(\frac{T_{soil}}{50 + T_{soil}}\right)\left(\frac{l_{max} - l}{l_{max}}\right)$$

soil layer depth (m) (l)

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

We further propose to calculate a prognostic canopy capture fraction

$$\left(\frac{d[NH_{3\,(g)}]}{dt}\right)_{\text{thru. canopy}} = \left(\frac{d[NH_{3\,(g)}]}{dt}\right)_{\text{from soil}} (1 - f_{cap})$$



Derived from DNDC (Li *et al.*, 2012) and CMAQ (Pleim *et al.*, 2013), fraction of NH_3 captured by canopy is estimated as:

$$f_{cap} = 14(h_{top} - h_{bot}) \times \text{TLAI} \times \frac{1}{v_{fric}} \times \text{RH}_{canopy} \times v_{NH_3}$$

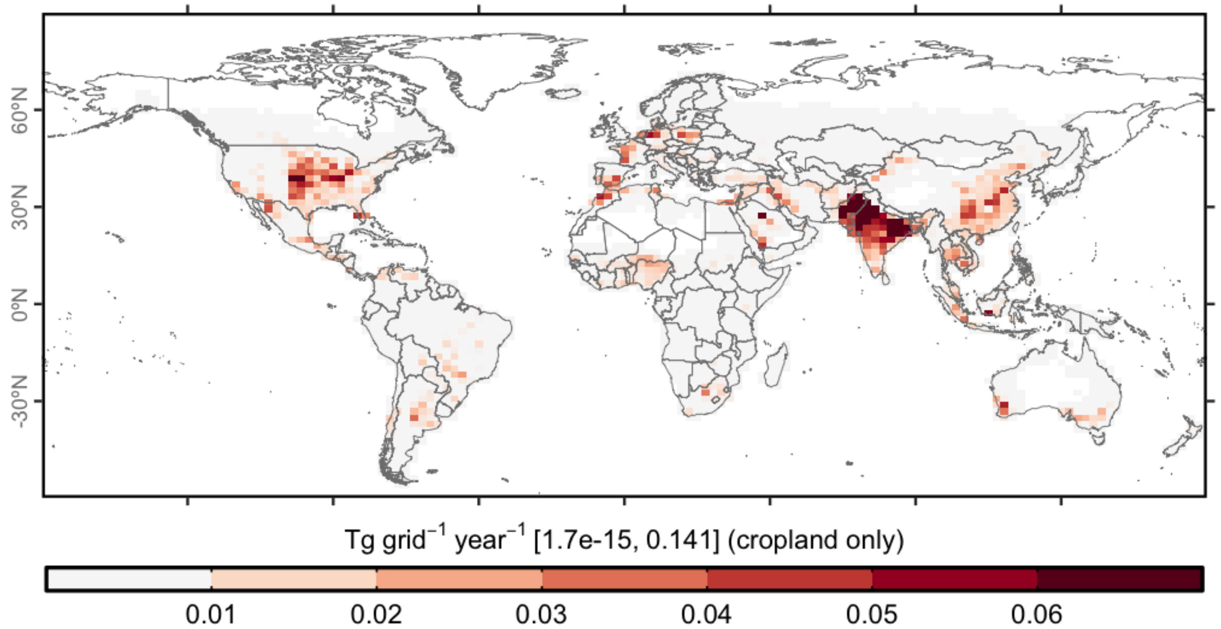
- $14(h_{top} - h_{bot})$: Account for effect of canopy height
- TLAI: Snow-free one-sided leaf area index (LAI)
- v_{fric}: frictional velocity (m s^{-1})
- RH_{canopy}: Relative humidity within canopy
- v_{NH_3}: Deposition velocity of NH_3 on leaf (0.05 m s^{-1} here)

*Literature suggests that the captured NH_3 can be
1) metabolized
2) retained on leaves
3) returned to the soil

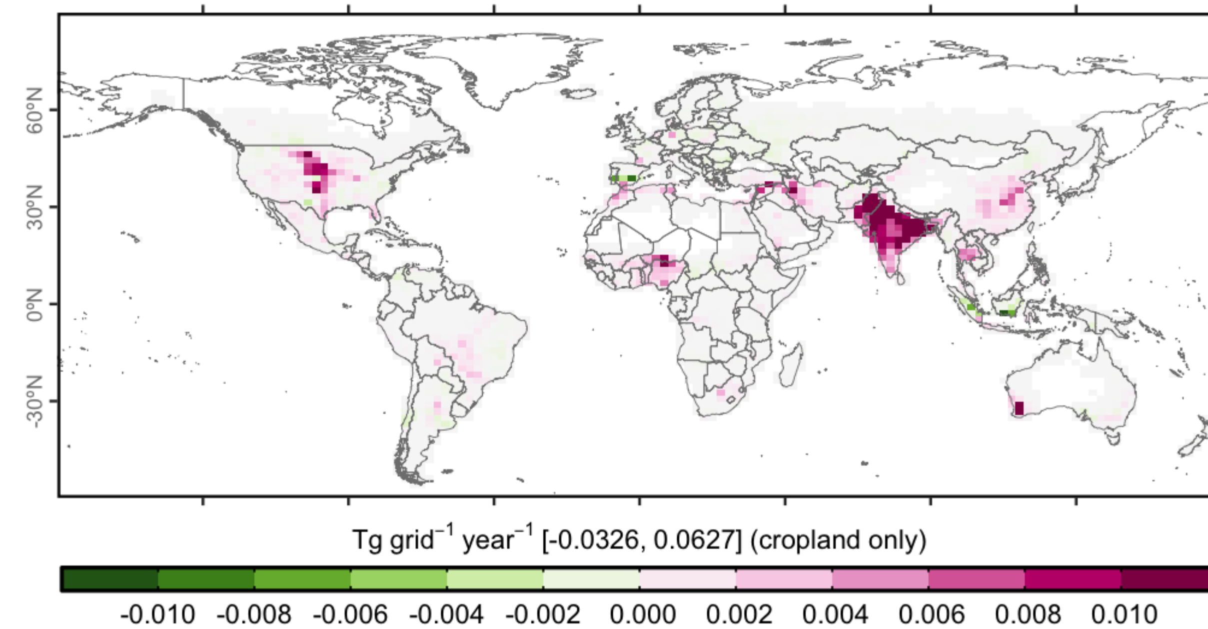
Fung *et al.* (in prep.)

Changes in cropland NH_3 emission driven by N deposition & aerosol-climate interactions

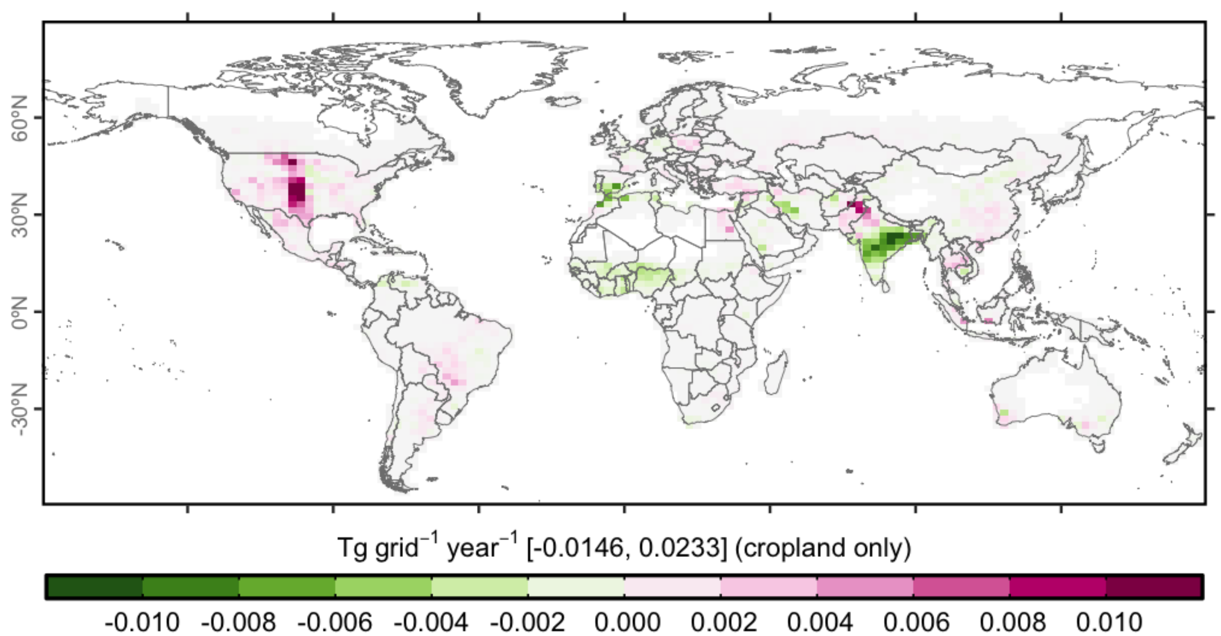
Baseline
(Global Total = 15.2 Tg-N year^{-1})



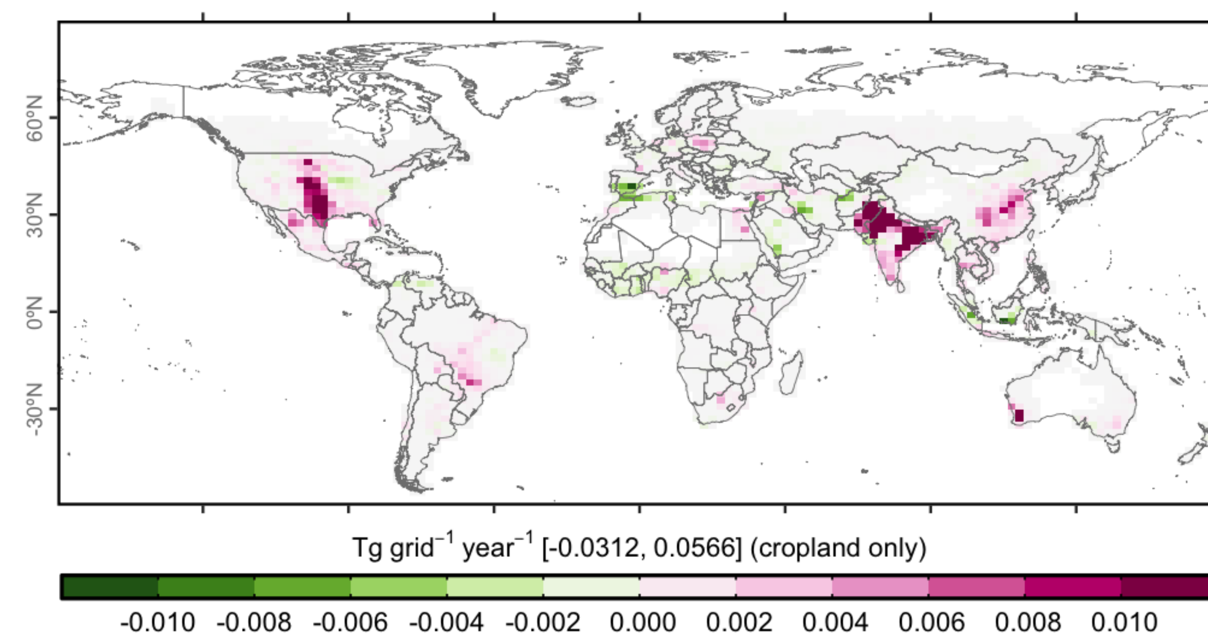
Δ(deposition)
(Global Total = +1.7 Tg-N year^{-1})



Δ(aerosol-climate interactions)
(Global Total = +0.1 Tg-N year^{-1})



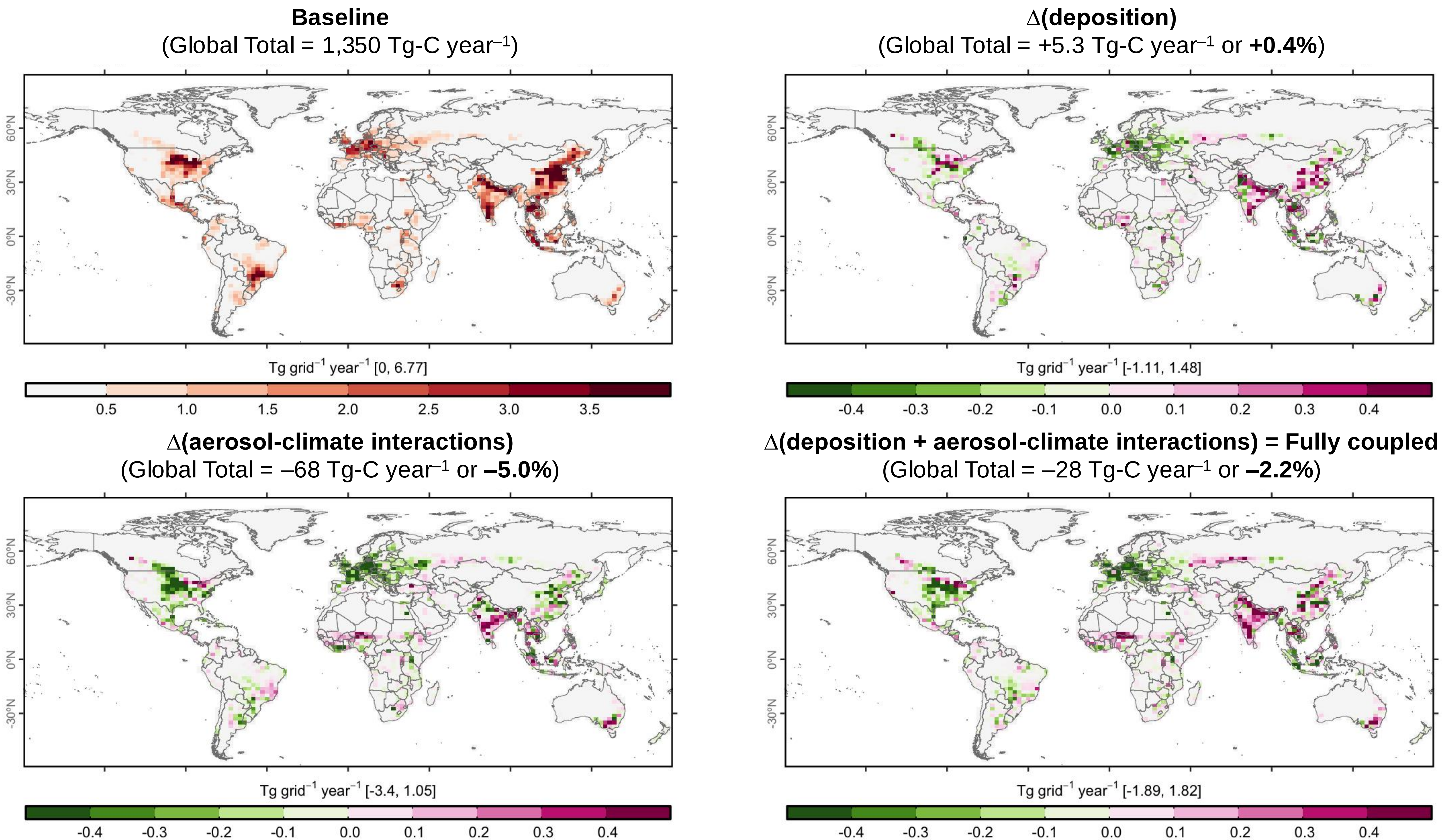
Δ(deposition + aerosol-climate interactions) = Fully coupled
(Global Total = +1.3 Tg-N year^{-1})



Please note that the colormaps are saturated at respective values.

Fung *et al.* (in prep.)

Impacts of the feedbacks on total food production



Please note that the colormaps are saturated at respective values.

Fung *et al.* (in prep.)

Conclusions & Implications

Thank you!

For more, please visit

kamingfung.wordpress.com

- Large-scale Intercropping in China [Fung *et al.* 2019]
  - **Land-use Efficiency:** 200% relative yield, maize and soybean combined, on the same size of cropland and over a single planting season
  - **Nitrogen-use Efficiency:** Less fertilizer use (–42%)
  - **Environmental Sustainability:** Reduced NH_3 emissions (–45%) and $PM_{2.5}$ concentration (up to –2.3%)
  - **Profitability:** US$67B net economic benefits including US$13B from avoided health costs
- Fully coupled land-atmospheric NH_3/NH_4^+ modeling with CESM2.0
  - **Quantifying impacts of N deposition and aerosol-climate interactions** on NH_3 emission and food production
- Science-based evidence to **aid policymakers in formulating sustainable agricultural plans** that safeguard food security, air quality, and environmental health