Modelling and Assessing the Impacts of Intercropping, as a Sustainable Farming Practice, on Food Security, Air Quality, and Public Health

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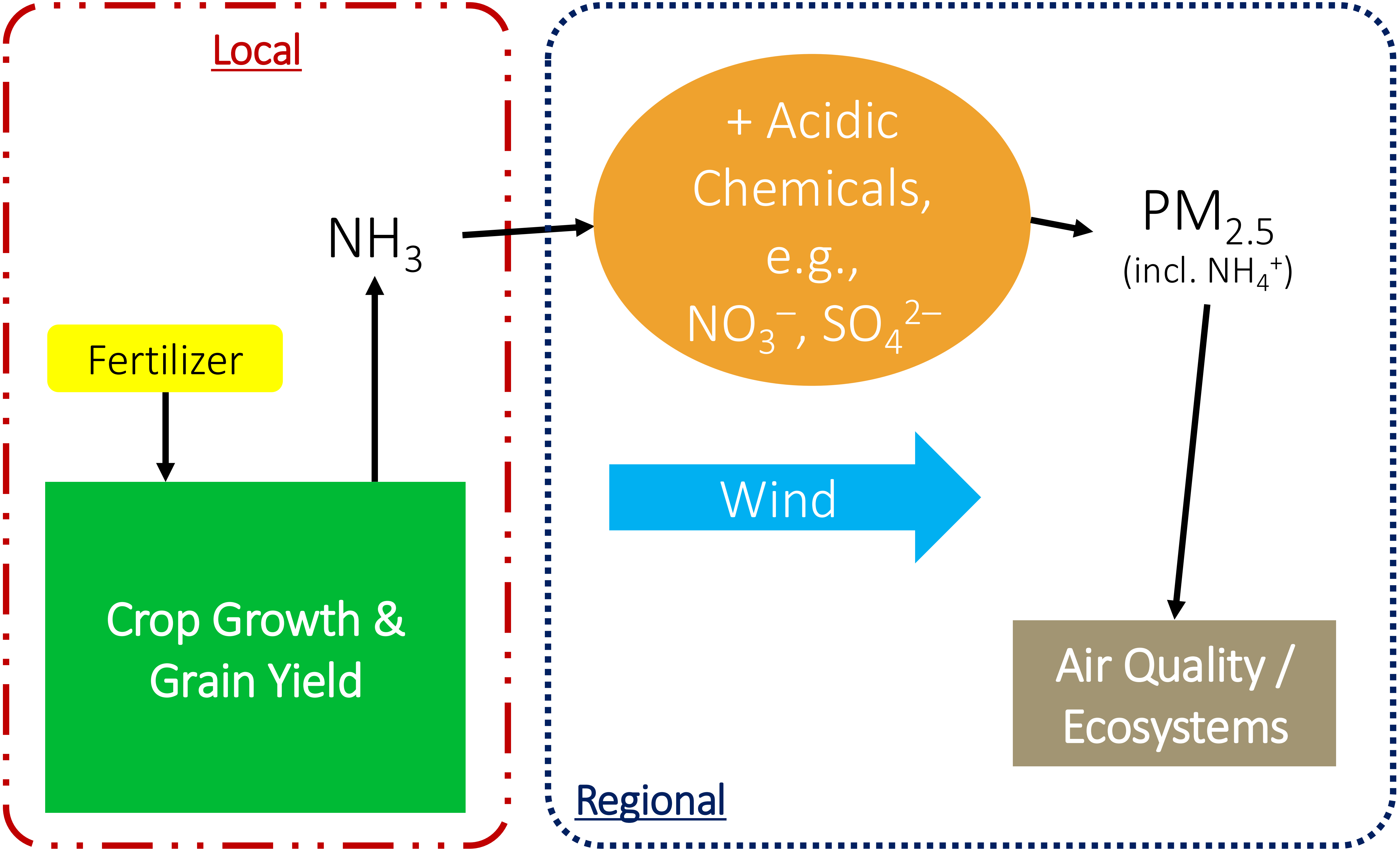
About “Ka-ming”

- From Hong Kong
  - A Pacific Rim city
  - 12-hr flight to UK
  - Before 1997 - a colony of Britain
  - After 1997 - a special administrative region of China
- Studying at CUHK
  - 4th year Ph.D. student in Earth and Atmos. Sci.
  - Defense expected in July 2019
  - A model scientist-in-training, with some experience in mechanical engineering, mathematics, and imaging radiology
- Visiting The University of Sheffield
  - Working with Dr. Maria Val Martin to model the nitrogen cycle using CESM

In Europe, China and US, 80–90% of atmospheric NH_3 emitted is agricultural, posing a threat to environmental health



Local

Fertilizer

Crop Growth & Grain Yield

NH_3

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

$PM_{2.5}$ (incl. NH_4^+)

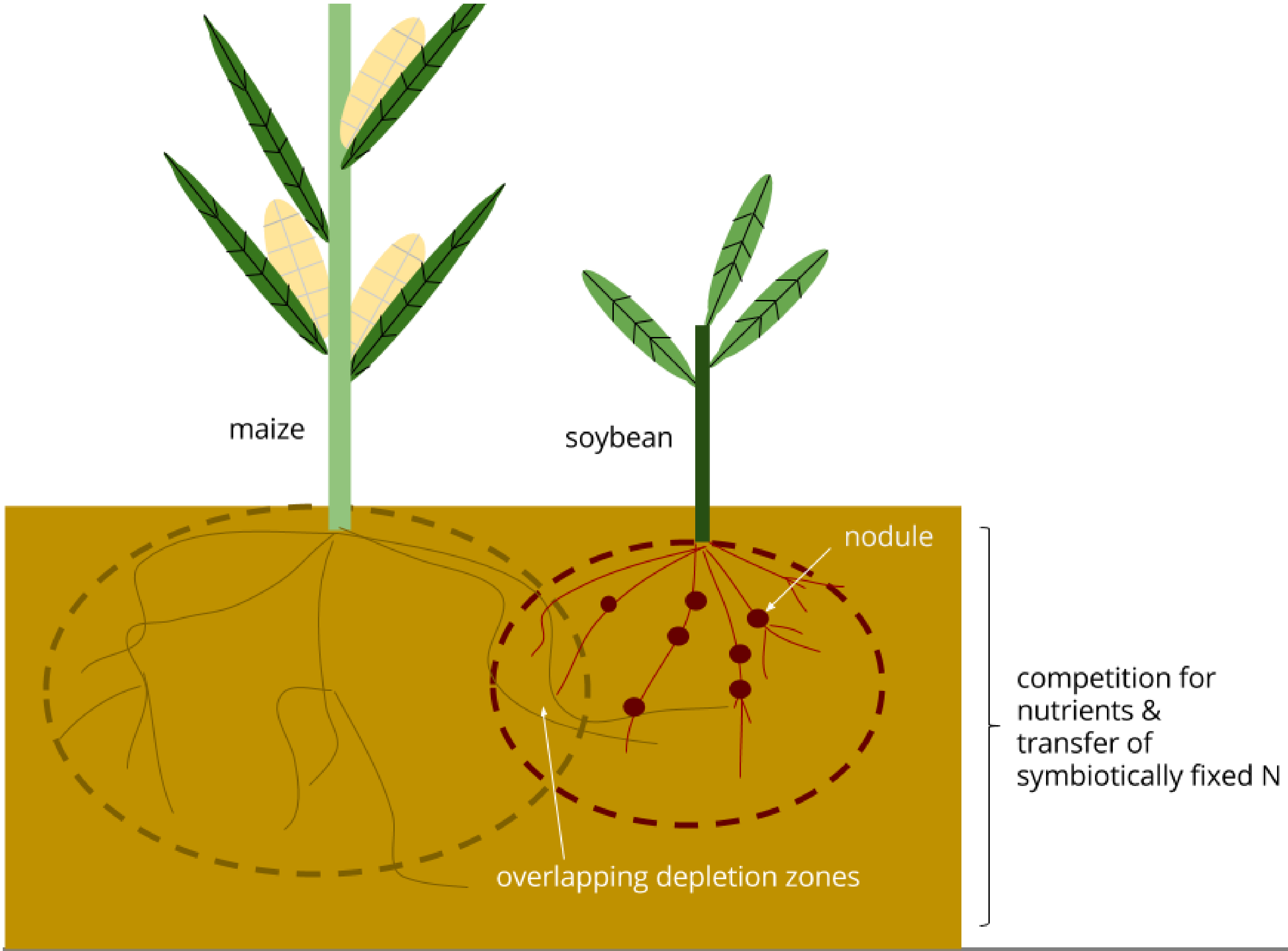
Wind

Air Quality / Ecosystems

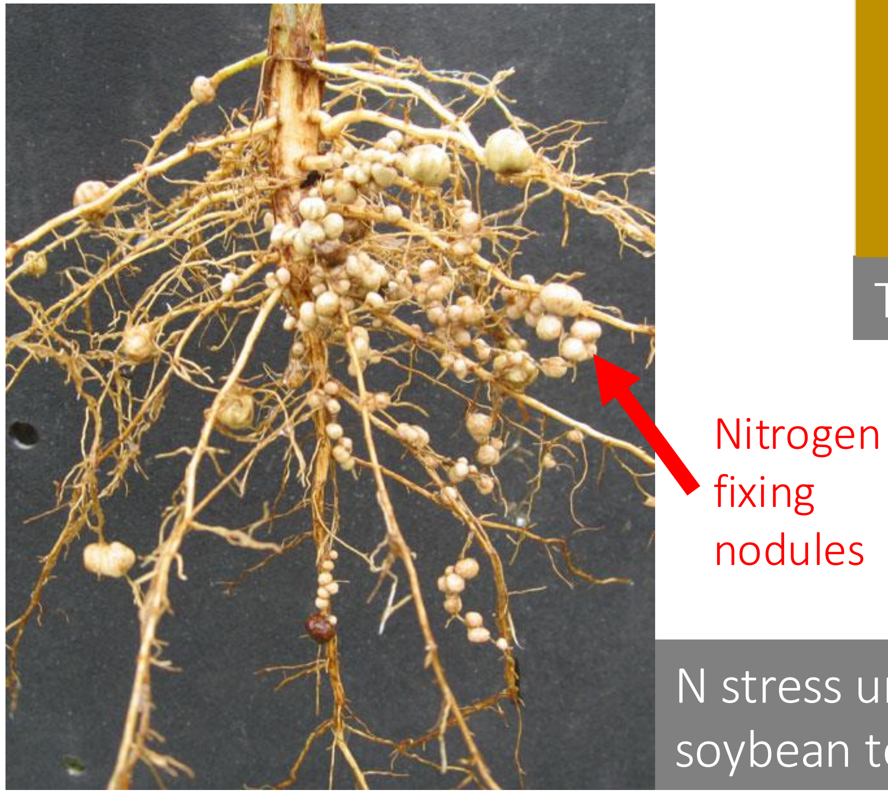
Regional

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

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



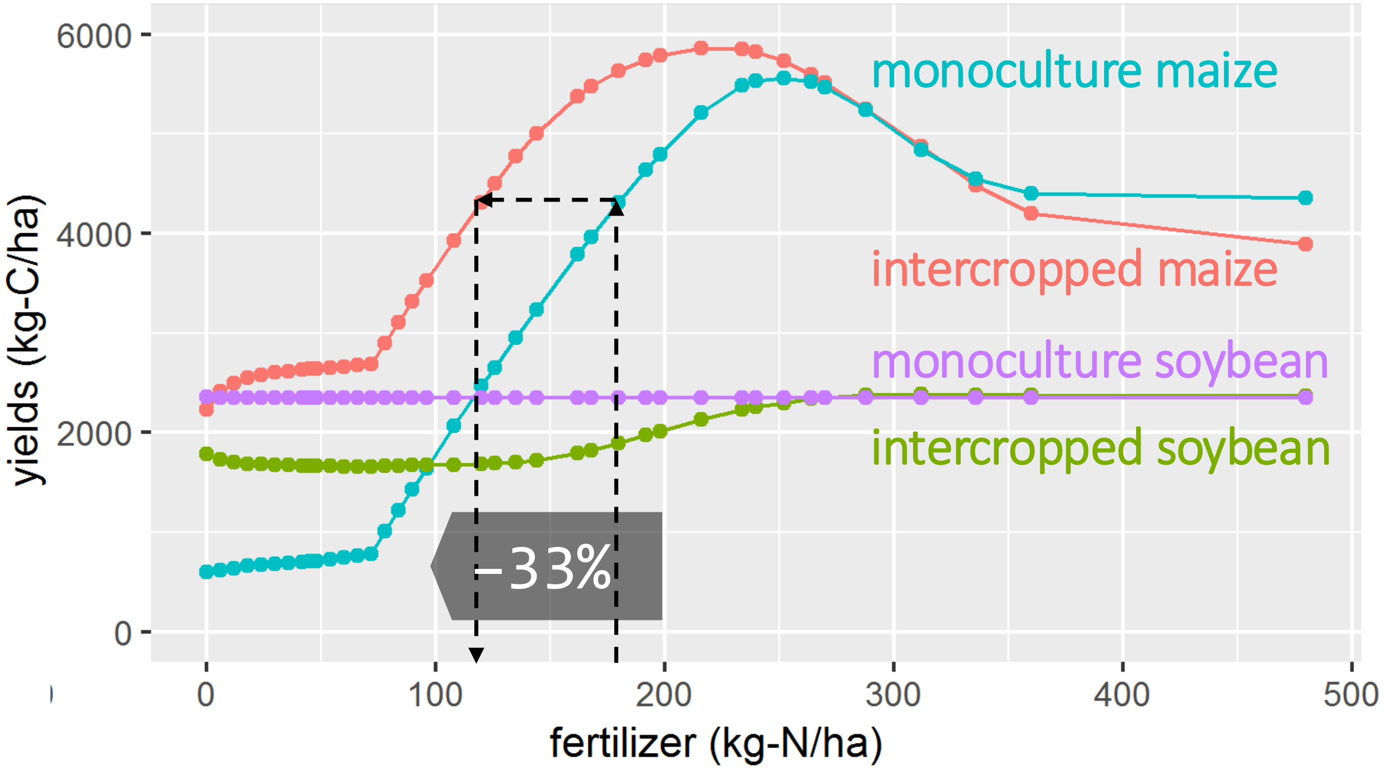
They are placed close enough to allow belowground competition



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

We reproduce results of a field experiment using DeNitrification-DeComposition (DNDC) and find that

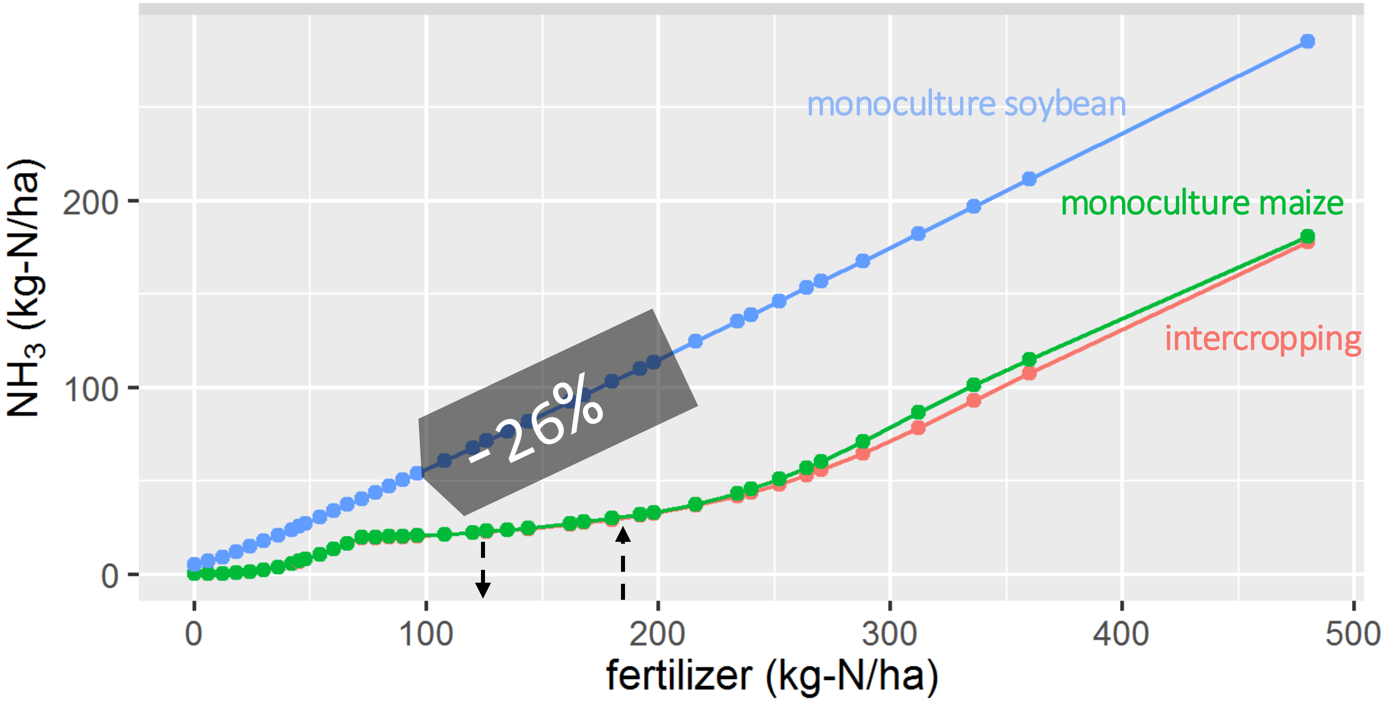
DNDC simulation of
a field experiment reported in Yong *et al.* (2015)



1. Less fertilizer (–33%) to produce the "conventional" maize yield

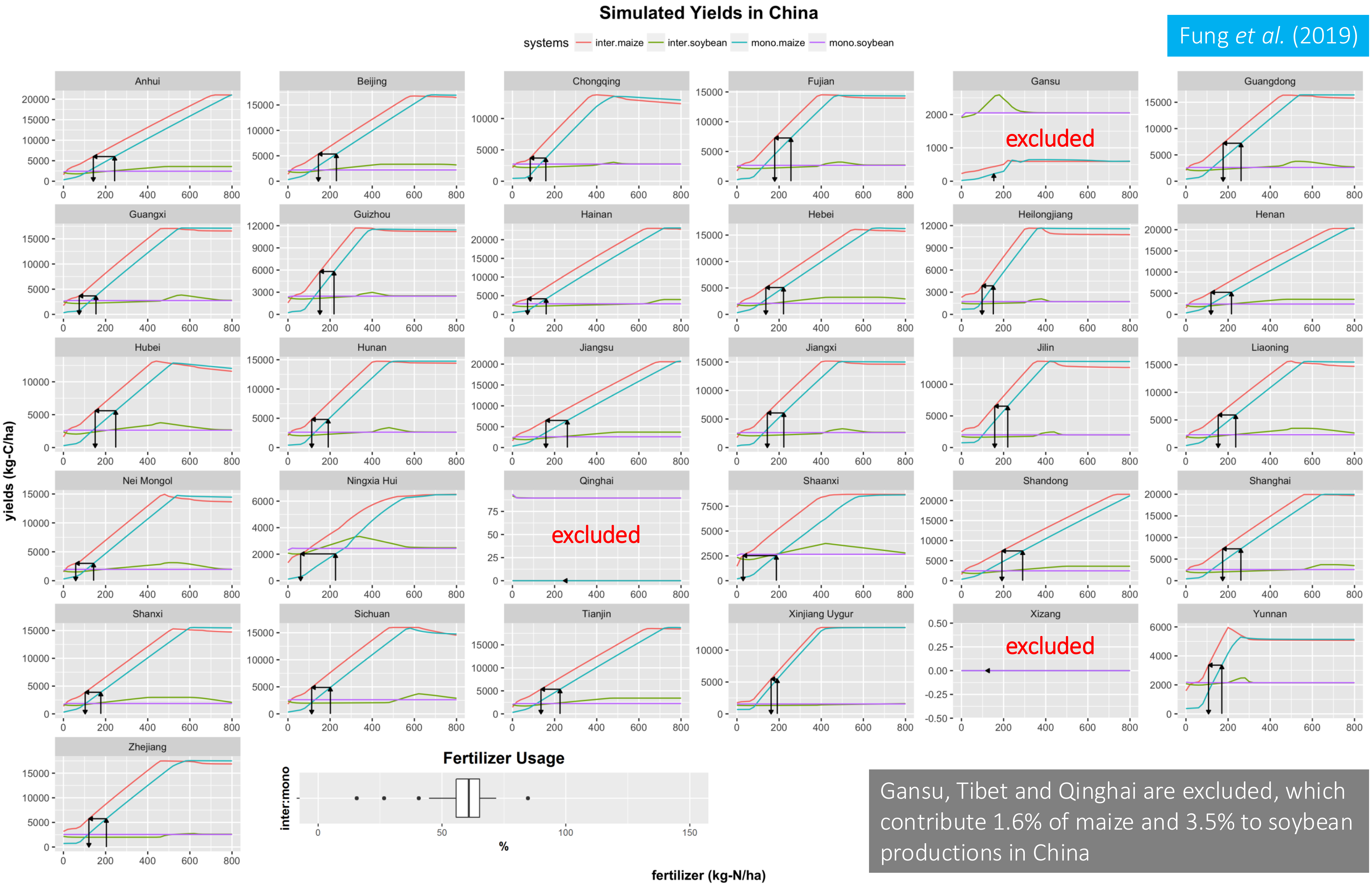
2. An additional batch of soybean can be harvested

3. Reducing NH_3 emission by 26%



Fung *et al.* (2019)

Fung *et al.* (2019)

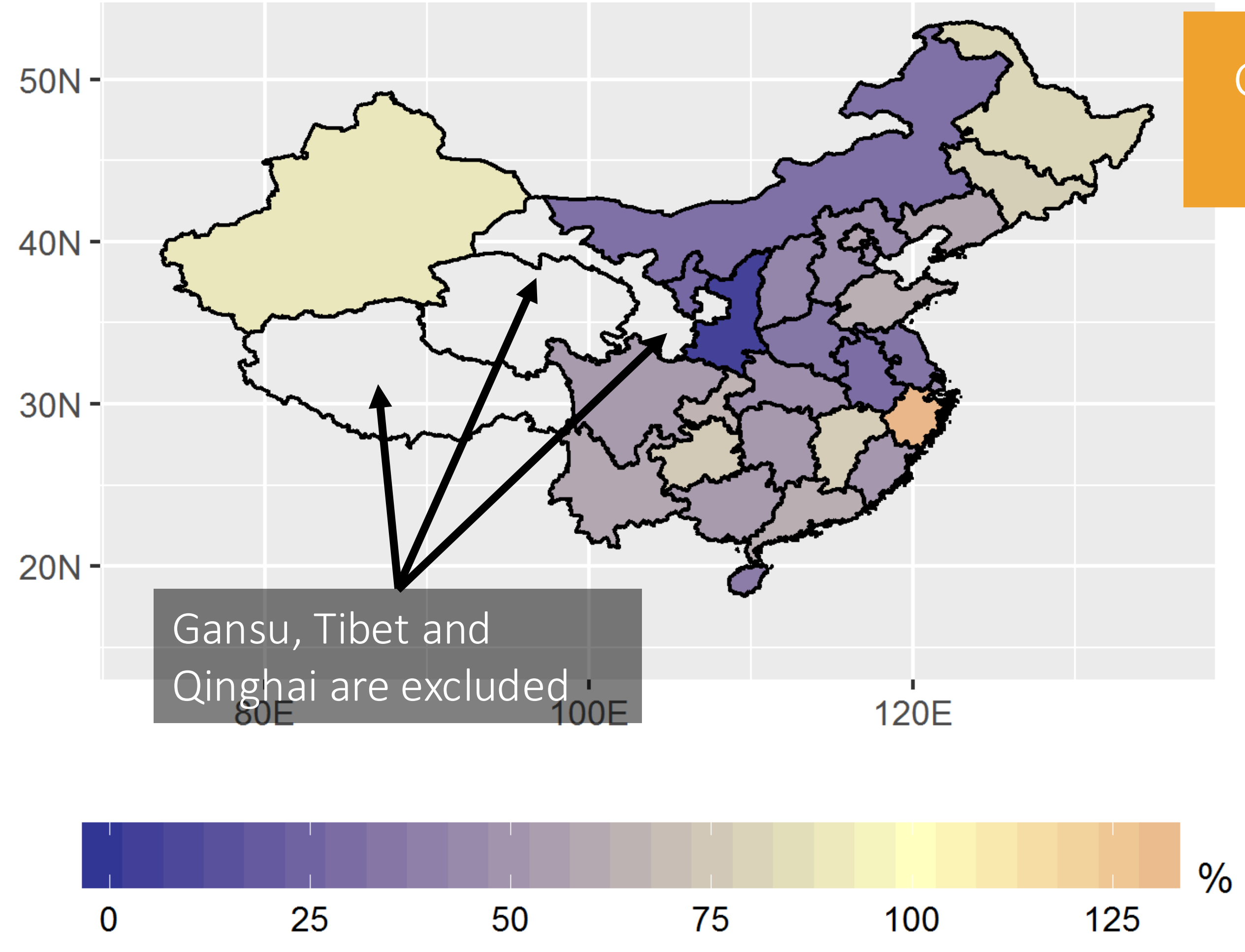


Gansu, Tibet and Qinghai are excluded, which contribute 1.6% of maize and 3.5% to soybean productions in China

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 Emission (Intercropping vs. Monoculture)



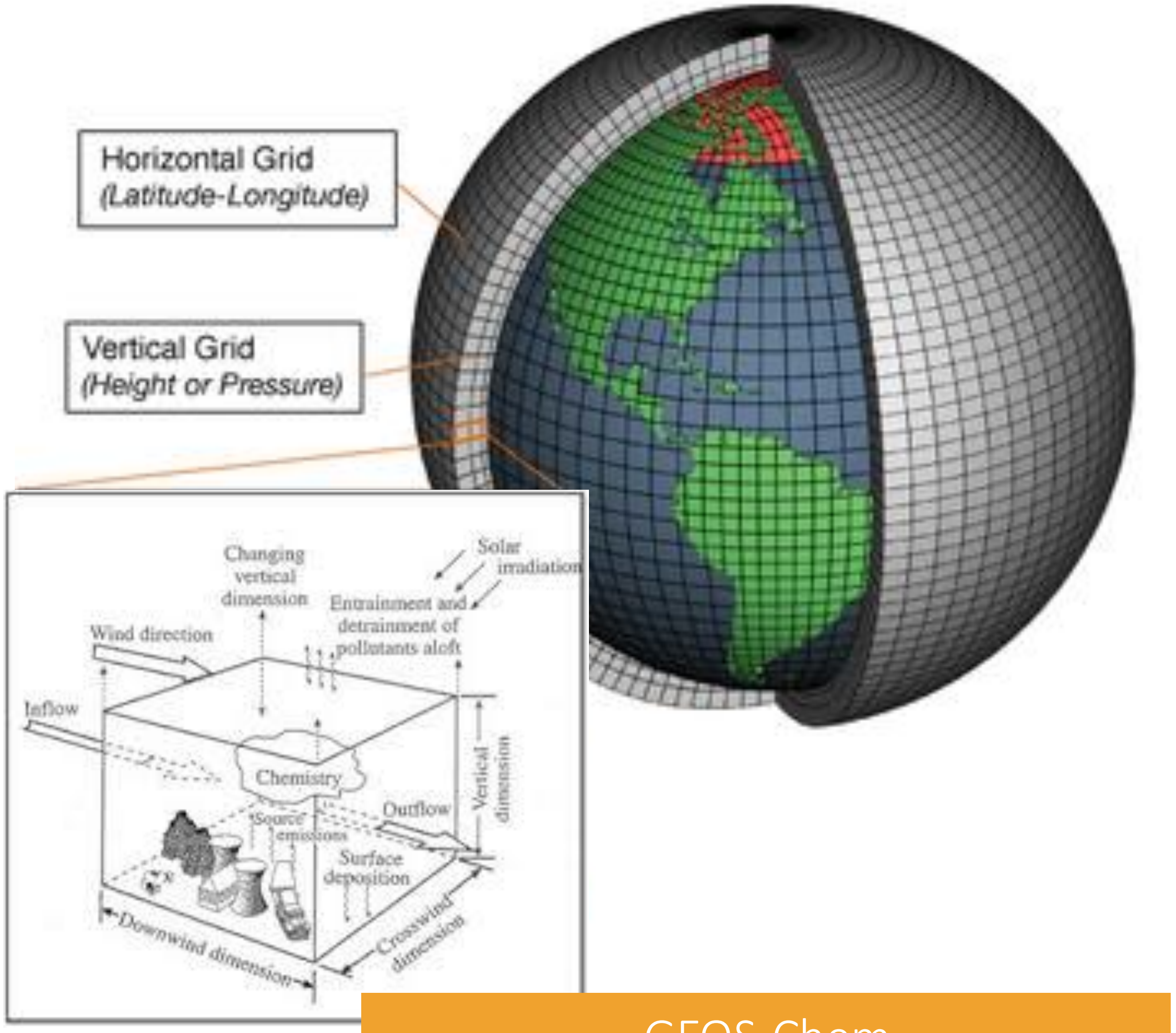
Gansu, Tibet and Qinghai are excluded

Fung *et al.* (2019)

Grid-by-grid scaling

NH_3 Emission Inventory

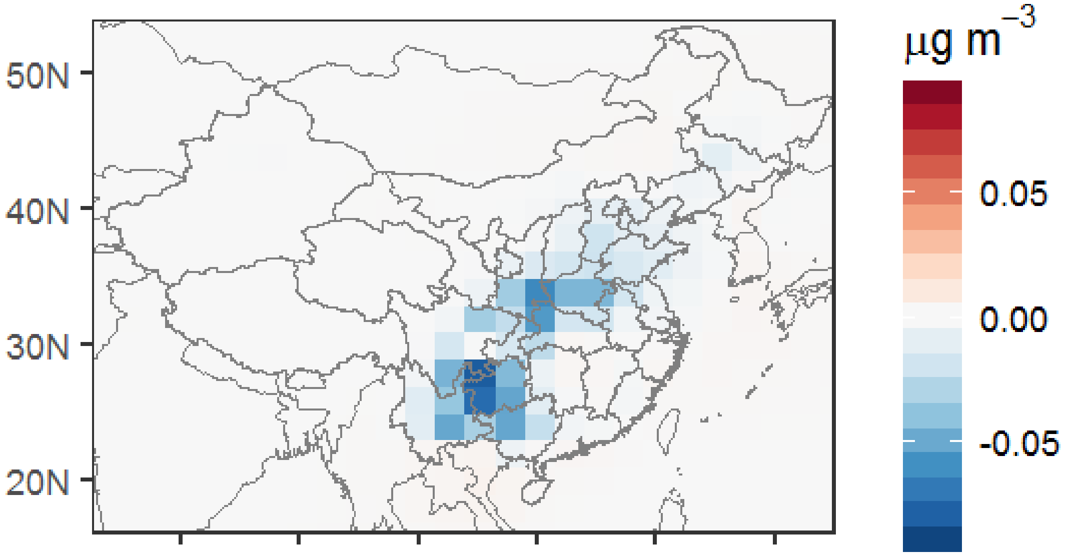
(Magnitude And Seasonality of Agricultural Emissions; MASAGE)



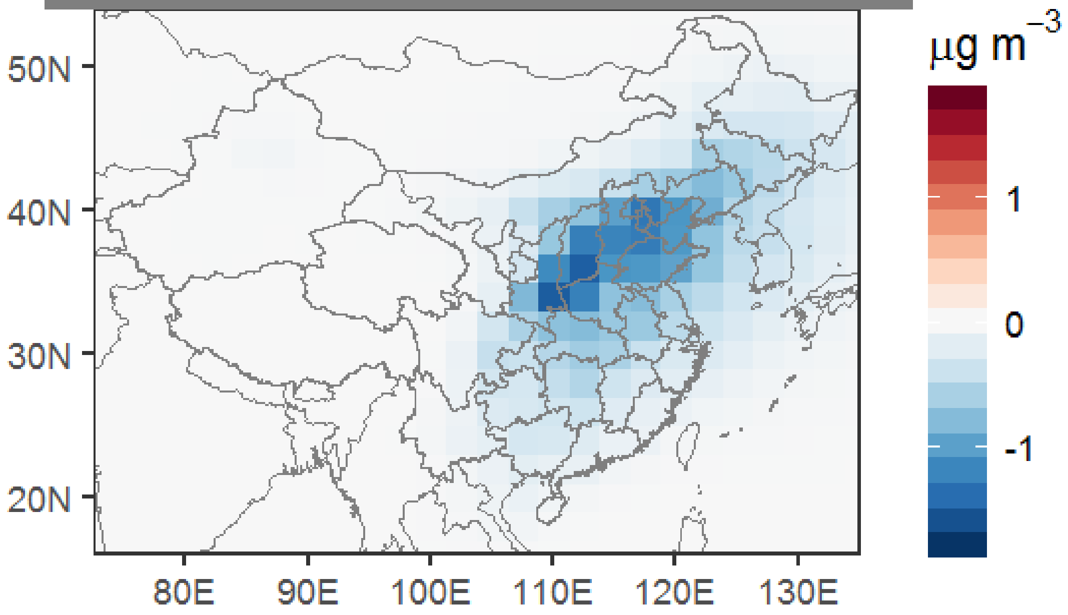
GEOS-Chem
3-D Global Chemical Transport Model

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

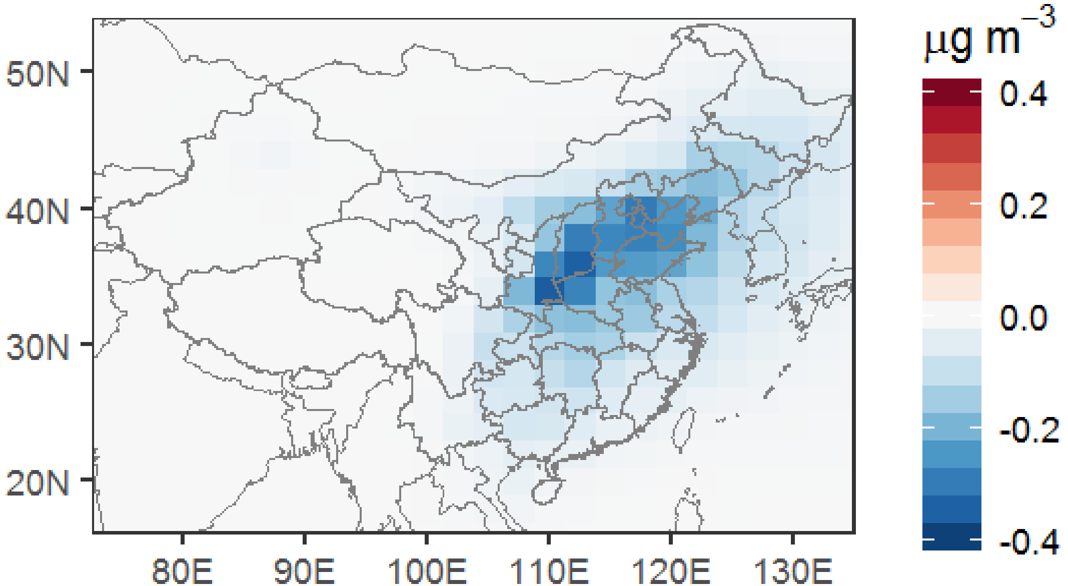
SO_4^{2-}
greatest change = –0.081 µg m^{-3} (–1.2%)



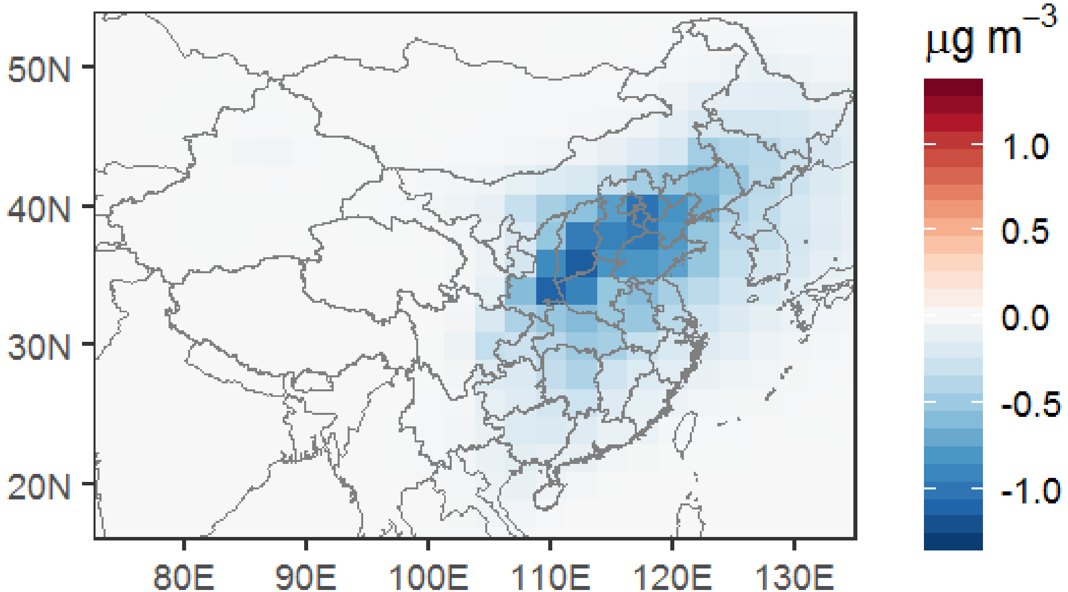
Inorganic $PM_{2.5}$
greatest change = –1.5 µg m^{-3} (–2.3%)



NH_4^+
greatest change = –0.35 µg m^{-3} (–3.9%)



NO_3^-
greatest change = –1.2 µg m^{-3} (–5.0%)



Fung *et al.* (2019)

(% to local mean without intercropping)

Estimating the health costs associated with $PM_{2.5}$

- Increase in mortality rate:

Empirical health impact factor of $PM_{2.5}$, $\beta = 0.0058\ \mathrm{m^3 \mu g^{-1}}$ (Krewski *et al.*, 2009)

$$\Delta M = P_{>30} M_0 \left(1 - \mathrm{e}^{-\beta \Delta C}\right)$$

Change in $PM_{2.5}$ concentration

Provincial population > 30 yo

Annual mortality rate

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

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

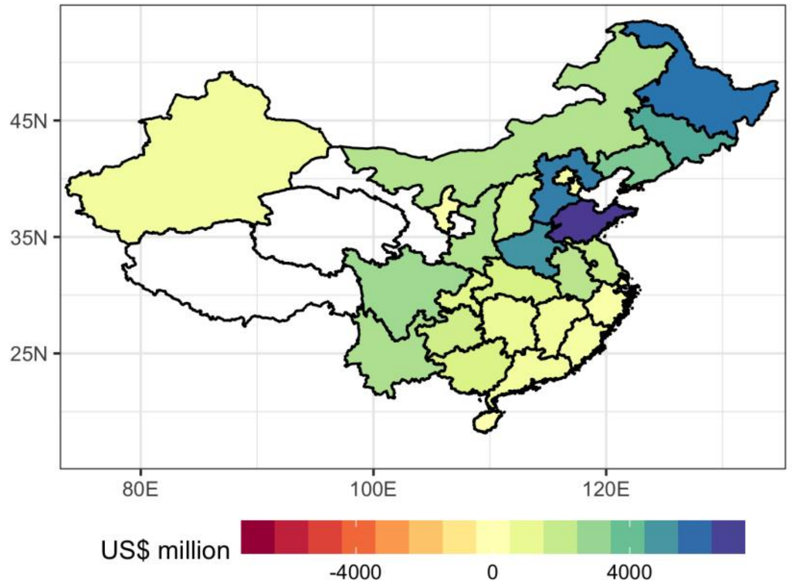
- Assuming premature mortality lags change in $PM_{2.5}$ by 20 years and the risk-free interest rate (e.g., 20-year US government issued bond) is 3%, the health costs associated with $PM_{2.5}$ is given by:

$$\mathrm{Cost} = \Delta M \times \mathrm{VSL} \times \underbrace{\mathrm{e}^{(-0.03)(20)}}_{\text{Continuously-compounded discount}}$$

Paulot & Jacob (2014)

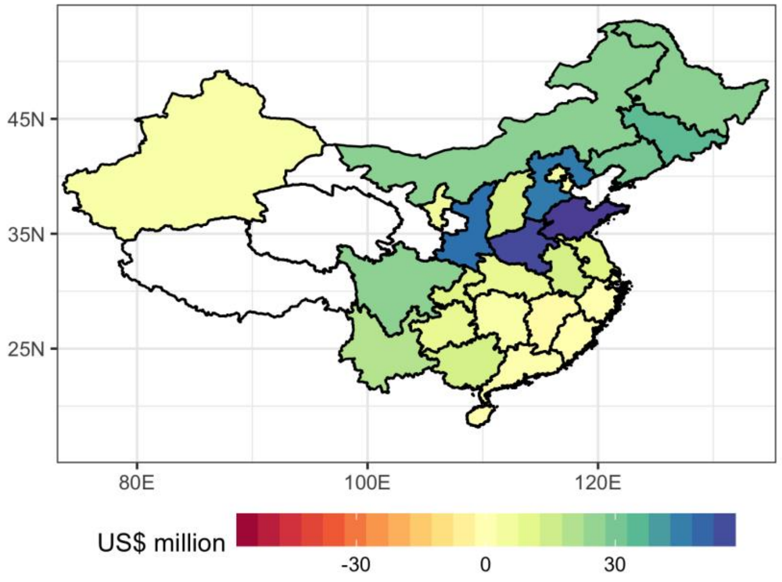
Intercropping could be more economical than Chinese current practice

More Grain = +US$58b



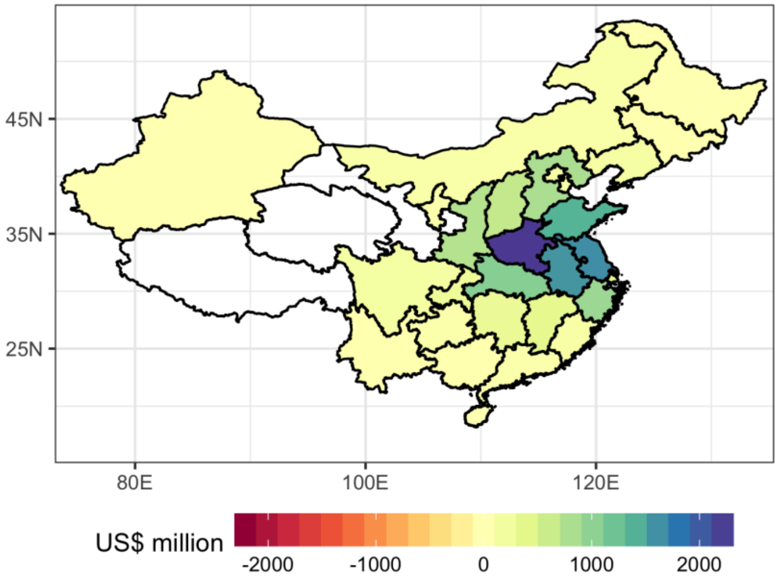
+

Reduced Fertilizer = +US$0.5b



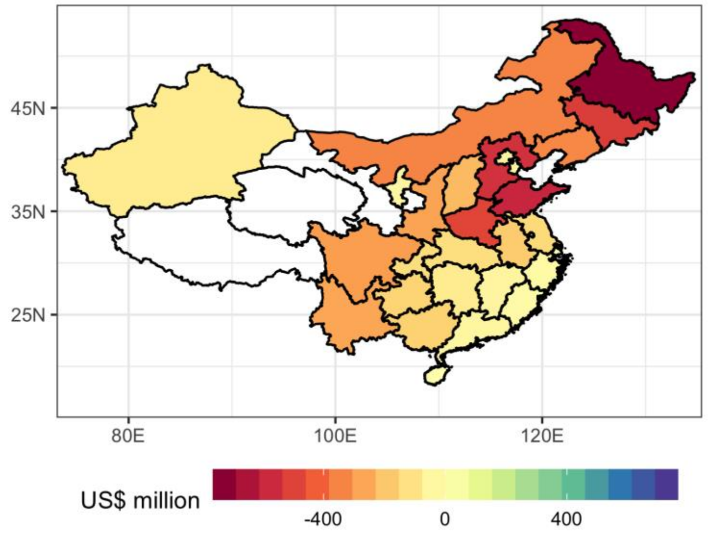
+

Avoided Health Costs = +US$13b



Additional Machinery & Labor Costs = –US$6.0b

+



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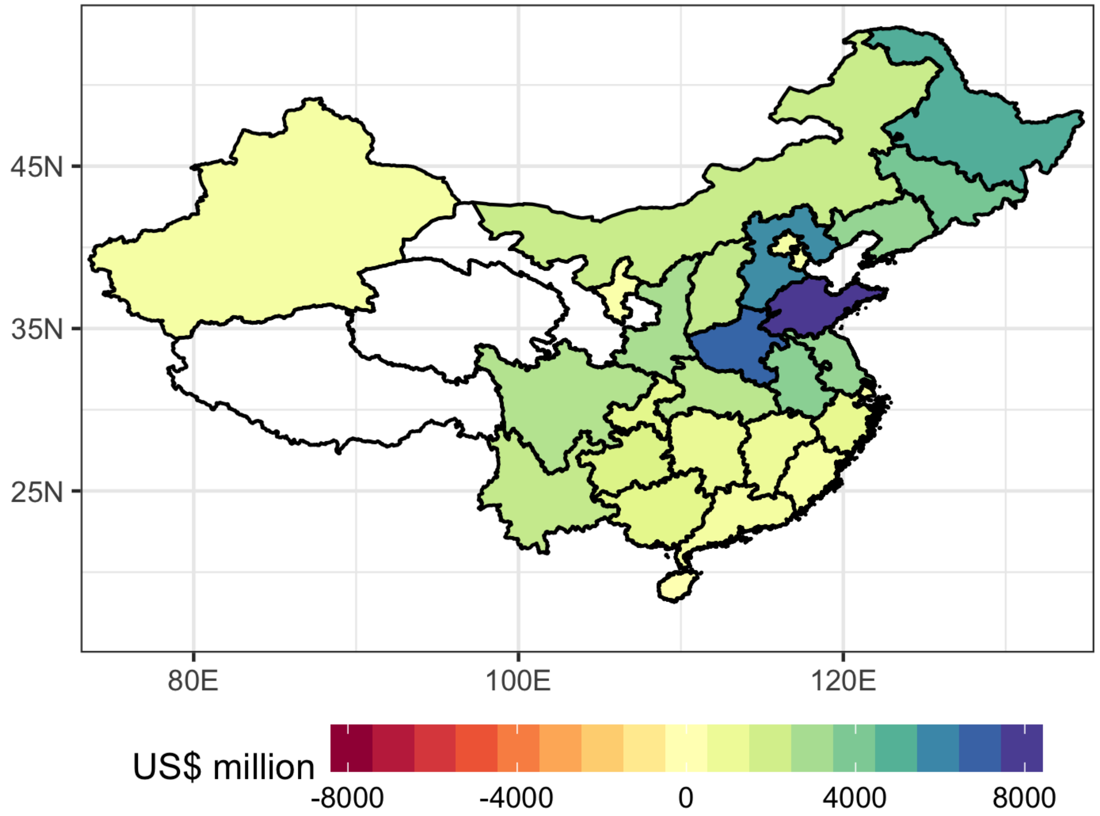
Net profit = +US$67b
(+93% relative to the current practice)



Item	US$ (2006) Per Unit
Maize	0.25/kg
Soybean	0.41/kg
Urea	0.27/kg
Statistical Life	170k
Labor	186.50/ha
Machinery	40.00/ha

Fung *et al.* (2019)

Take-home messages from this study

Large-scale Intercropping in China

Efficient in Land-use

~200% relative yield, maize and soybean combined, on the same area of cropland and over a single planting season

Efficient in Nitrogen-use

Less fertilizer use (–42%)

Sustainable

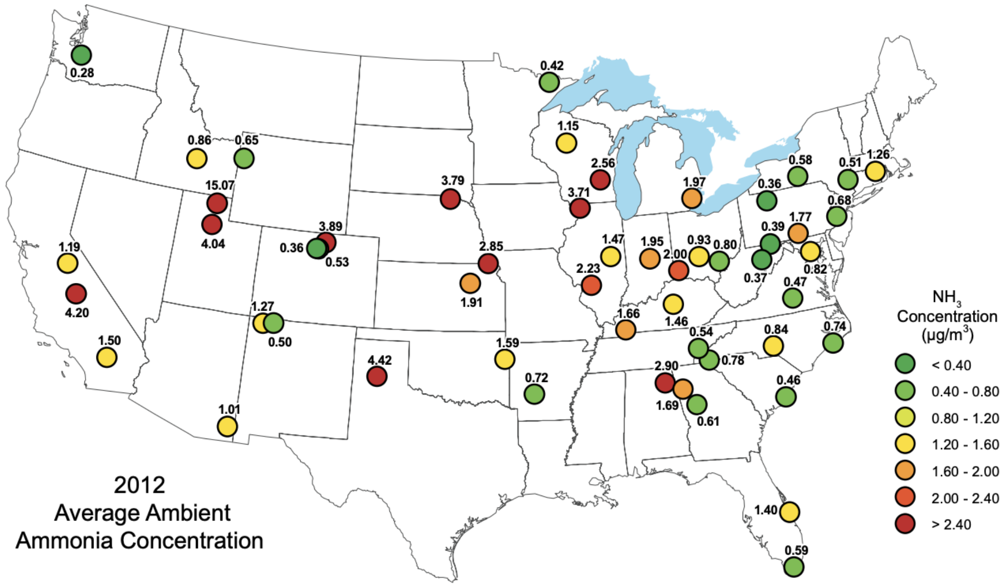
Reduced NH_3 emissions (–45%) and $PM_{2.5}$ concentration (up to –2.3%)

Profitable

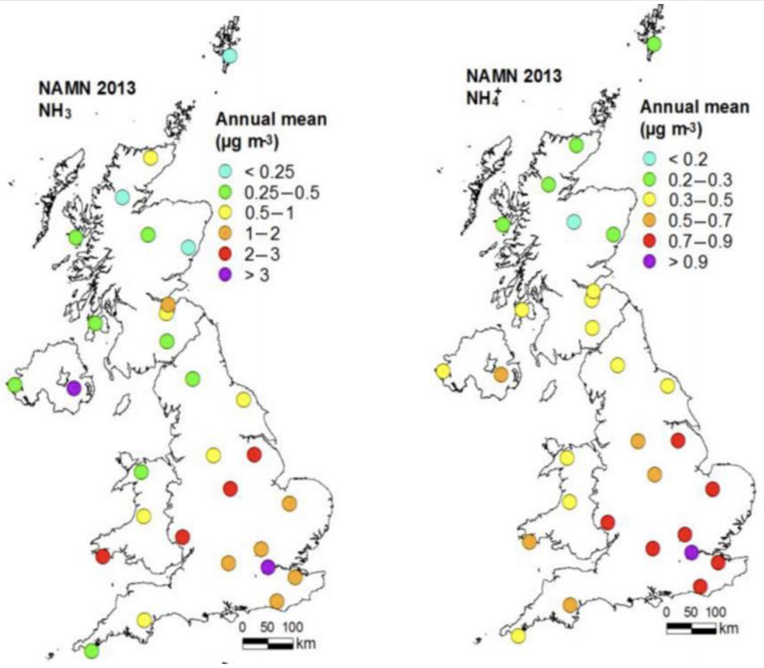
US$67b net economic benefits including US$13b from avoided health costs

Observations and emission inventories aid monitoring of NH_3/NH_4^+

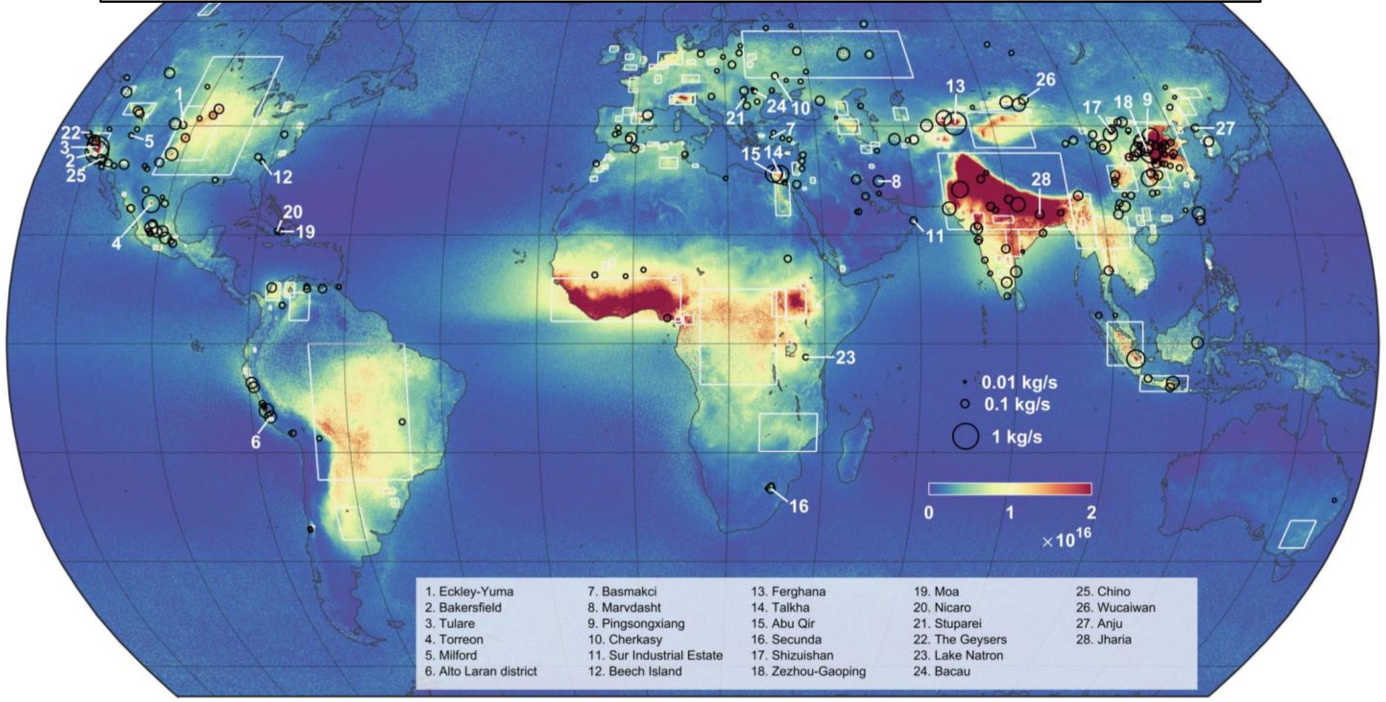
Ammonia Monitoring Network (US EPA, 2014)



UK National Ammonia Monitoring Network (Tang *et al.*, 2018)

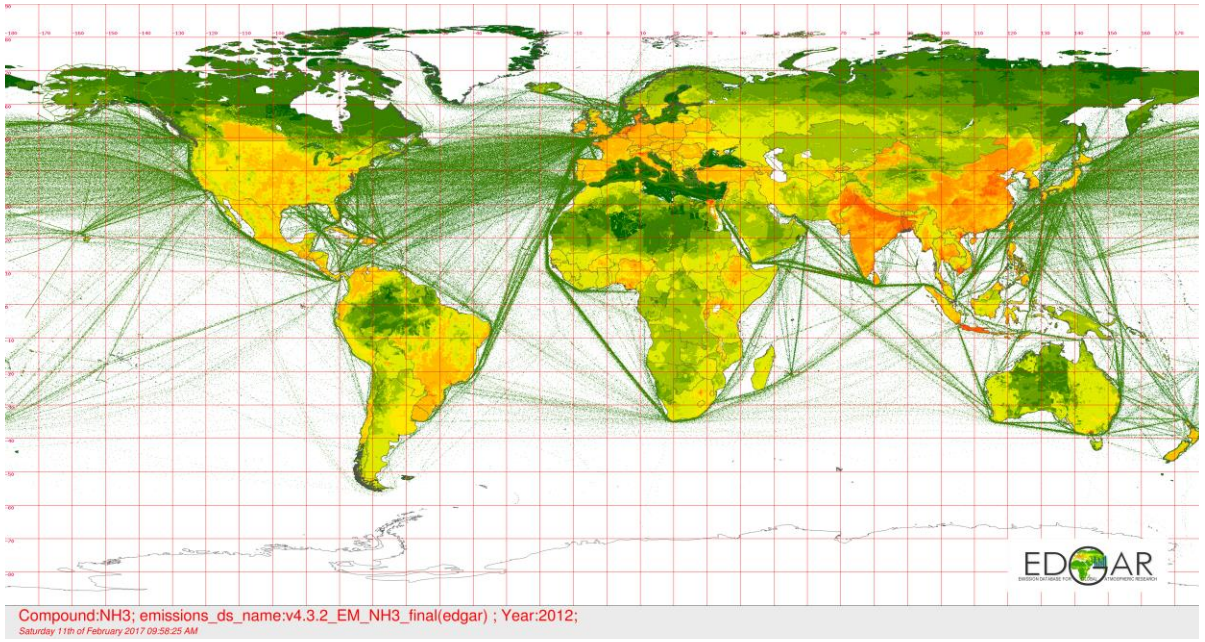


IASI Satellite at 0.01º x 0.01º (Van Damme *et al.*, 2018)



Extended Data Fig. 1 | Source areas and hotspot locations. Global nine-year NH_3 average (in molecules per square centimetre) with identified hotspots, their associated flux estimates (black circles), and source areas (white rectangles). In total 248 hotspots and 178 source areas are indicated (see Supplementary Information for details). The locations and names of the hotspots discussed in the main text are also provided. The largest average NH_3 column is found over the Indus Valley (Pakistan) with a value of 1.1×10^{17} molecules cm^{-2}.

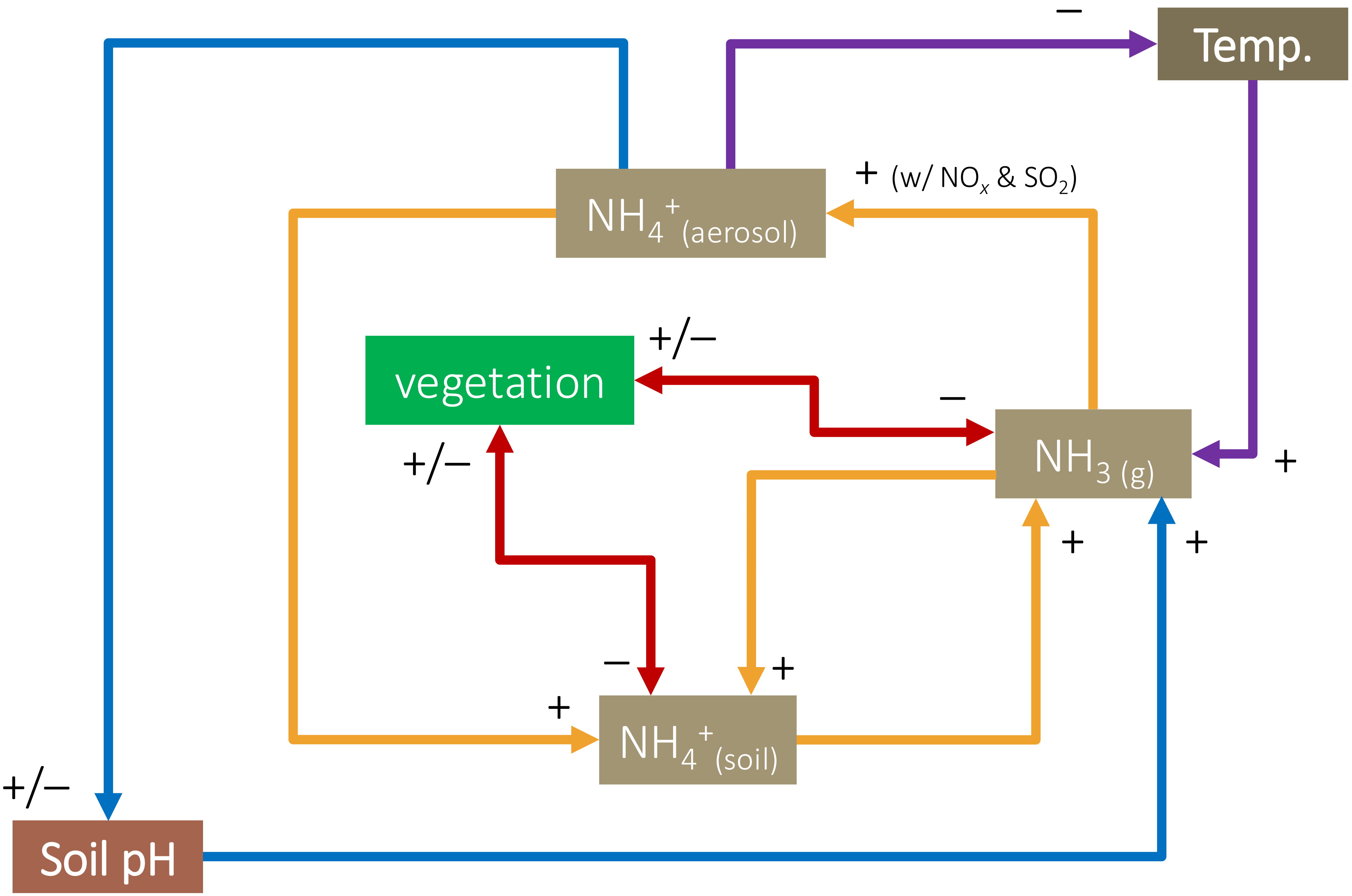
EDGAR Anthropogenic Emission Inventory at 0.1º x 0.1º (Crippa *et al.*, 2018)



Compound:NH3; emissions_ds_name:v4.3.2_EM_NH3_final(edgar) ; Year:2012;

Saturday 11th of February 2017 09:58:25 AM

But, there are potential feedbacks in the land-atmosphere NH_3/NH_4^+ cycle



Fung *et al.* (in prep.)

Earth system models enable us to better understand those convoluted relations

Land
CLM 5.0

Atmosphere
CAM-chem 6.0

River

CESM2.0
(coupler)

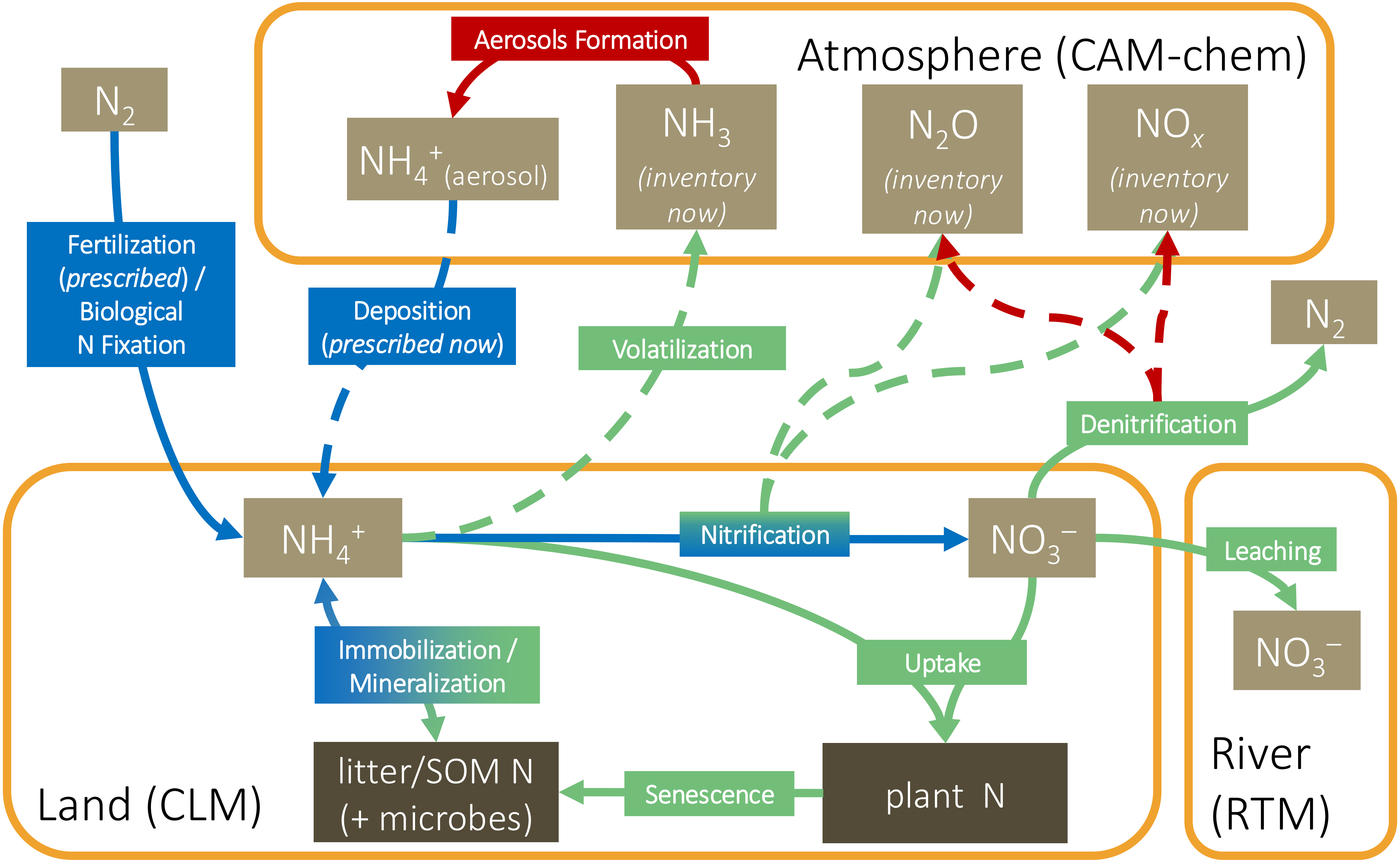
Wave

Sea Ice

Land
Ice

N cycle as part of the CESM terrestrial-atmosphere-climate system

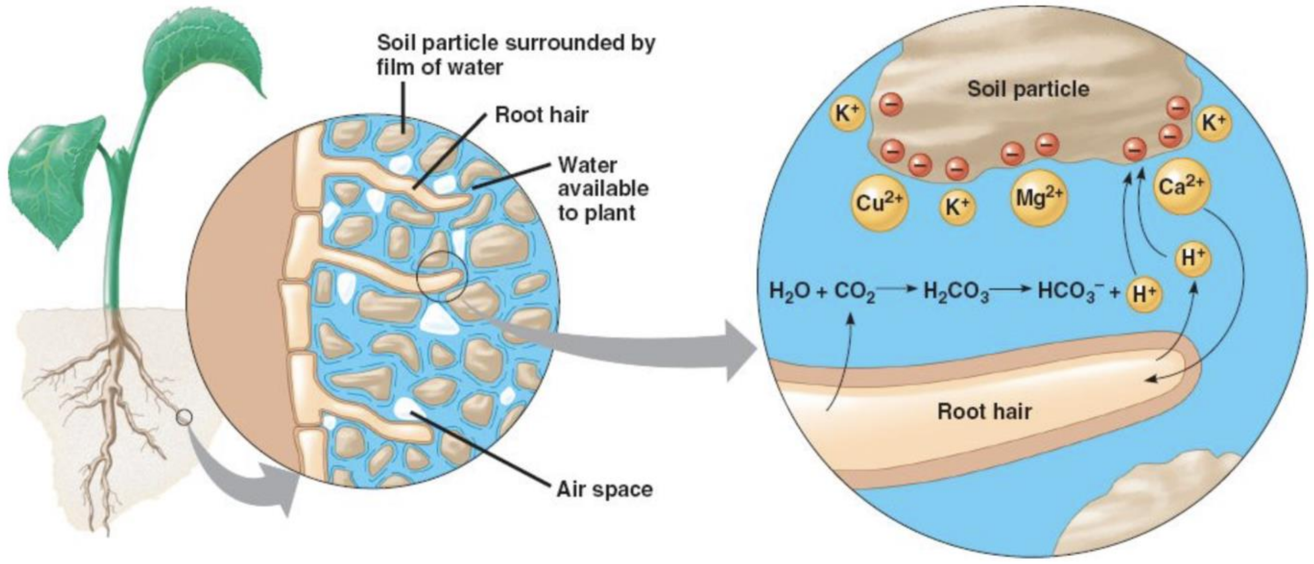
Fung *et al.* (in prep.)



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

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

Campbell et al. (2008)



Fraction of soil NH_4^+ adsorbed is determined by an empirical equation for adsorption:

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

clay fraction

Fraction of dissociated non-adsorbed NH_4^+:

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

rate constant of dissociation

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

soil temperature (°C)

$$\begin{cases} K_a = (1.416 + (0.01357)T_{\text{soil}}) \times 10^{-5}\ (\text{mol. L}^{-1}) \\ K_w = 10^{0.08946+(0.03605)T_{\text{soil}}} \times 10^{-15}\ (\text{mol.}^2\ \text{L}^{-2}) \\ [H^+] = 10^{-\text{pH}}\ (\text{mol. L}^{-1}) \\ \text{pH as prescribed} \end{cases}$$

rate constant of hydrolysis

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

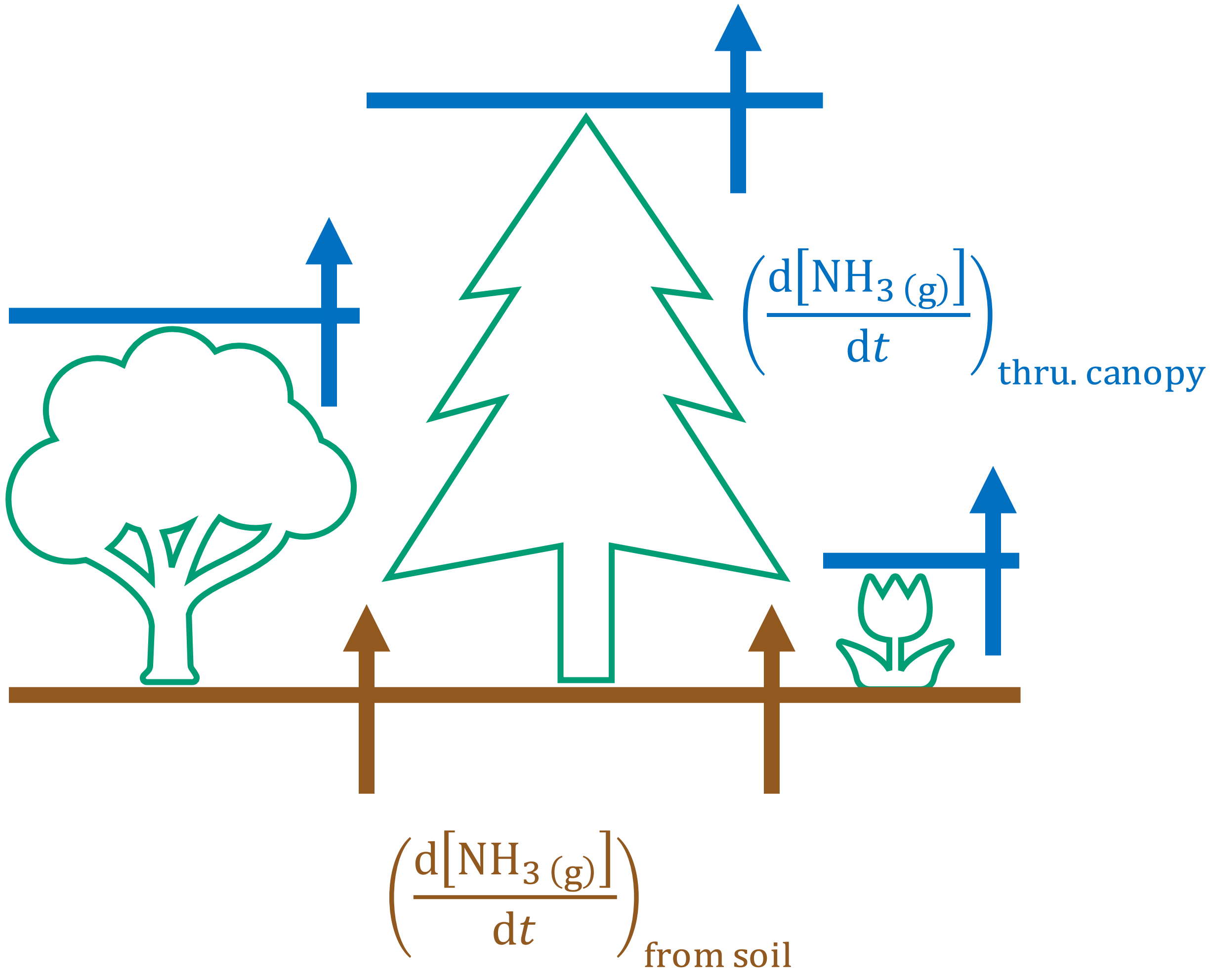
soil layer depth (m)

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

wind speed (m s^{-1})

In stead of using a global constant scales, we propose to quantify canopy capture as

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



Modified from DNDC (Li *et al.*, 2012),
we parameterize canopy capture factor as:

$$f_{\text{canopy}} = \overbrace{\log_{10}\left(1 + 2\left(h_{\text{top}} - h_{\text{bot}}\right)\right)}^{\text{Account for effect of canopy height}} \times \mathrm{TLAI} \times \frac{1}{s_{10}} \times \mathrm{RH}_{\text{canopy}} \times v_{\mathrm{NH}_3}$$

Snow-free one-sided leaf area index (LAI)

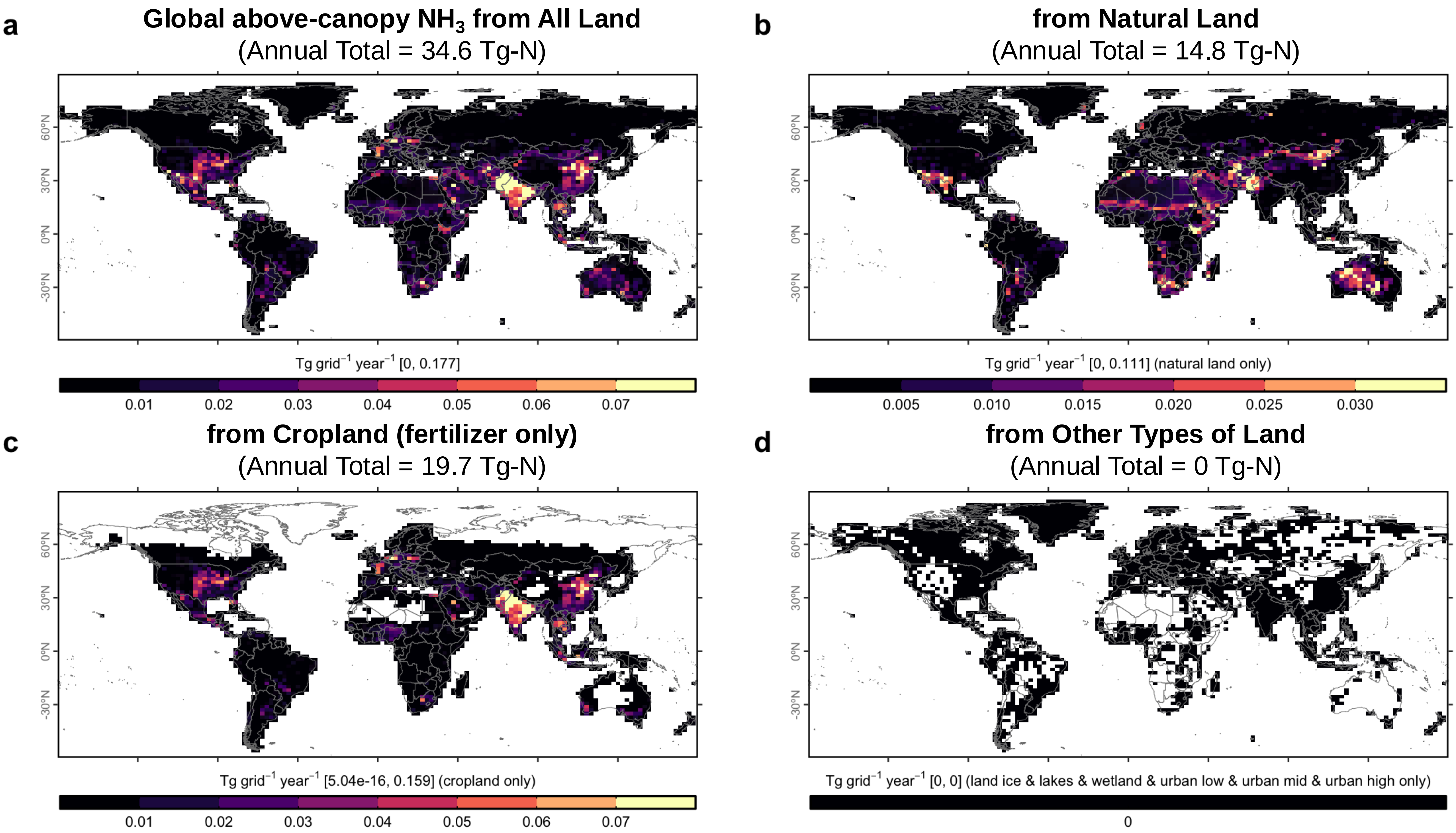
wind speed (m s^{-1}) at 10-m height

Relative humidity within canopy

Deposition velocity of NH_3 on leaf (0.05 m s^{-1} here)

Fung *et al.* (in prep.)

Preliminary CLM simulation results for soil NH_3 emission



a **Global above-canopy NH_3 from All Land**
(Annual Total = 34.6 Tg-N)

b **from Natural Land**
(Annual Total = 14.8 Tg-N)

c **from Cropland (fertilizer only)**
(Annual Total = 19.7 Tg-N)

d **from Other Types of Land**
(Annual Total = 0 Tg-N)

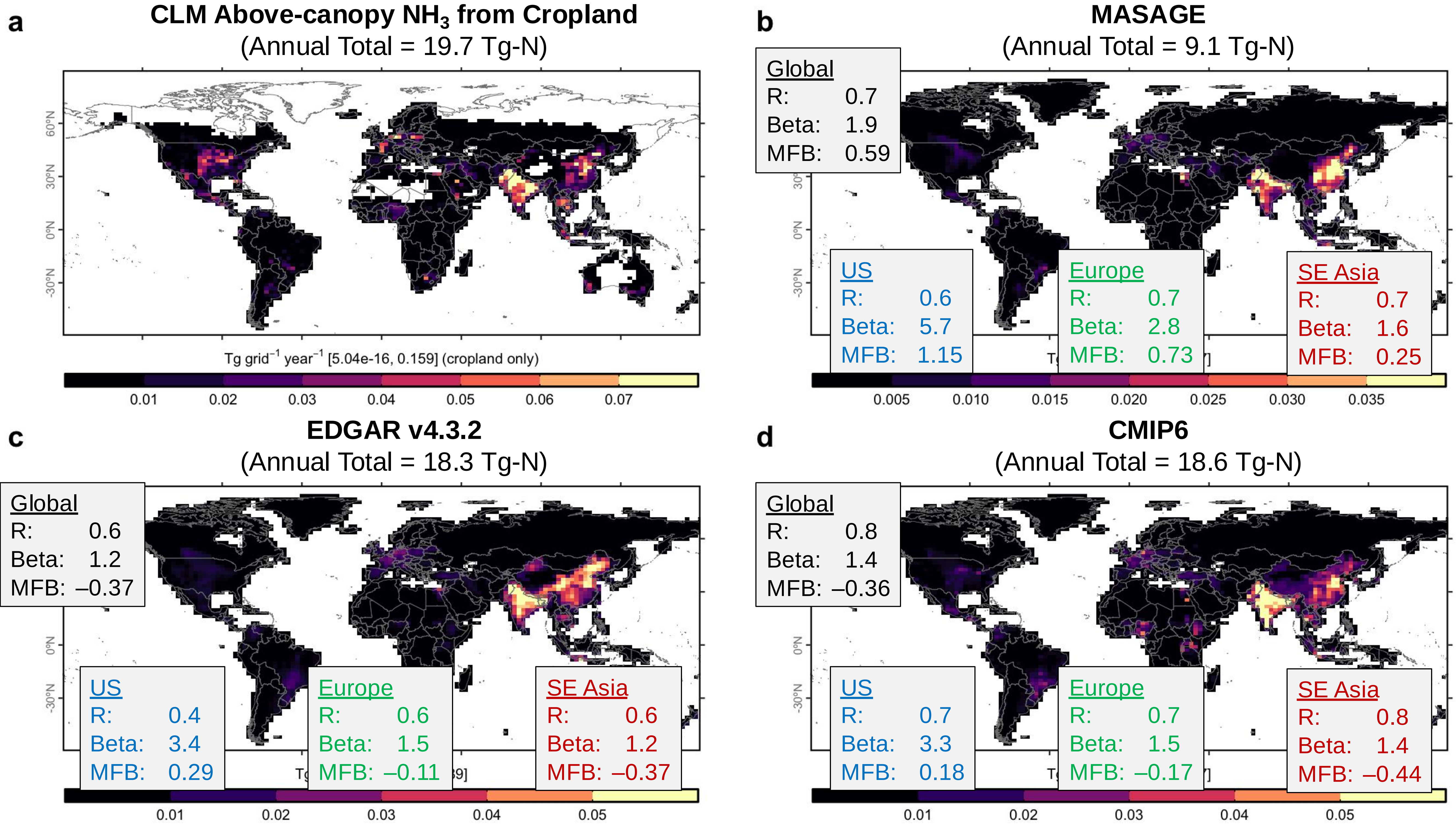
Please note that the colorbar scales are different.

Fung *et al.* (in prep.)

CLM5.0 vs. Emission Inventories: Spatial comparison of annual rates

Fung *et al.* (in prep.)

Paulot *et al.* (2014)



a **CLM Above-canopy NH_3 from Cropland**
(Annual Total = 19.7 Tg-N)

b **MASAGE**
(Annual Total = 9.1 Tg-N)

Global
R: 0.7
Beta: 1.9
MFB: 0.59

US
R: 0.6
Beta: 5.7
MFB: 1.15

Europe
R: 0.7
Beta: 2.8
MFB: 0.73

SE Asia
R: 0.7
Beta: 1.6
MFB: 0.25

c **EDGAR v4.3.2**
(Annual Total = 18.3 Tg-N)

Global
R: 0.6
Beta: 1.2
MFB: –0.37

US
R: 0.4
Beta: 3.4
MFB: 0.29

Europe
R: 0.6
Beta: 1.5
MFB: –0.11

SE Asia
R: 0.6
Beta: 1.2
MFB: –0.37

d **CMIP6**
(Annual Total = 18.6 Tg-N)

Global
R: 0.8
Beta: 1.4
MFB: –0.36

US
R: 0.7
Beta: 3.3
MFB: 0.18

Europe
R: 0.7
Beta: 1.5
MFB: –0.17

SE Asia
R: 0.8
Beta: 1.4
MFB: –0.44

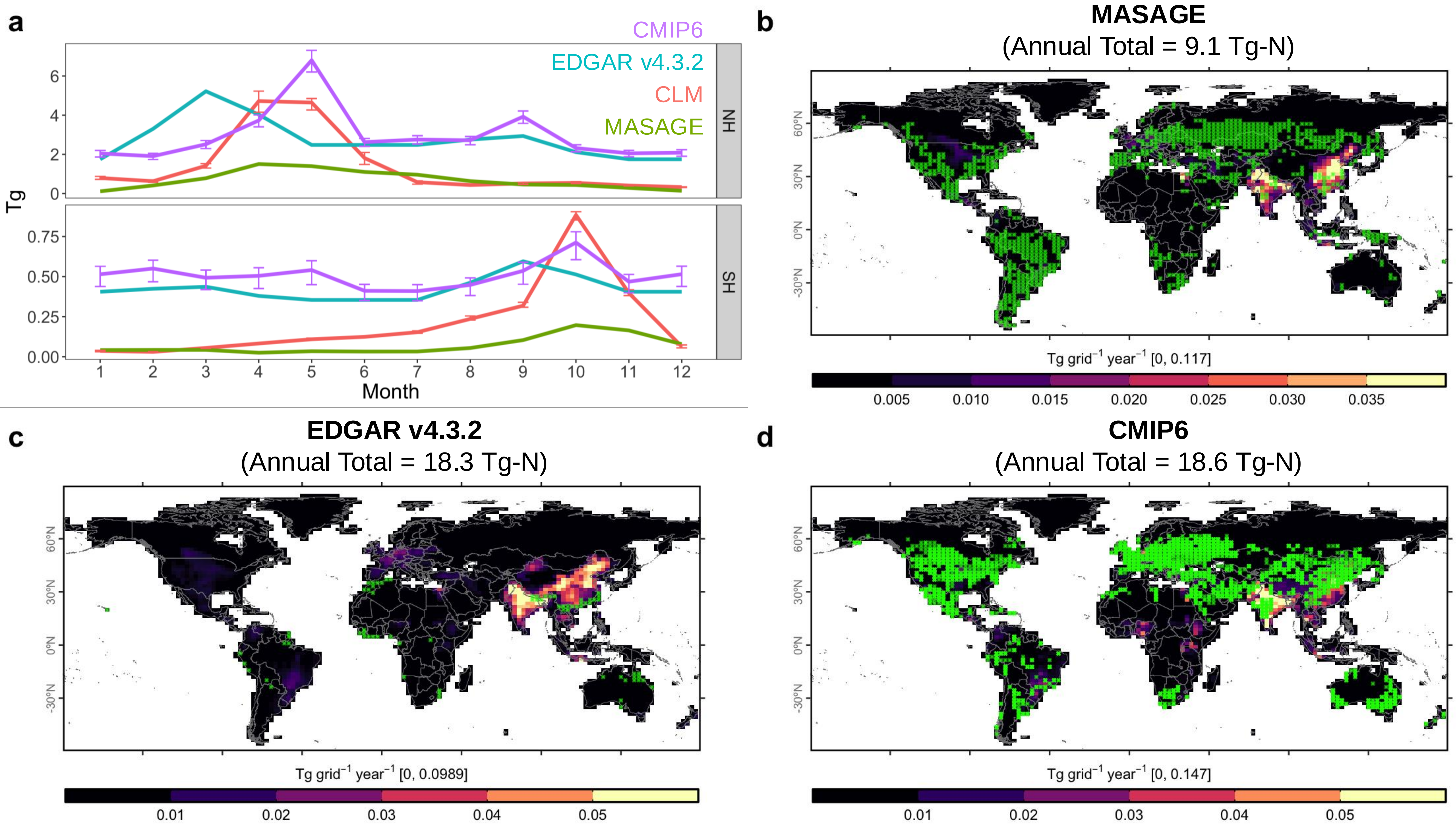
Crippa *et al.* (2018)

Please note that the colorbar scales are different.

Hoesly *et al.* (2018)

CLM5.0 vs Emission Inventories: Spatiotemporal comparison of monthly rates

Green dots indicate R^2>50% and $p<0.05$

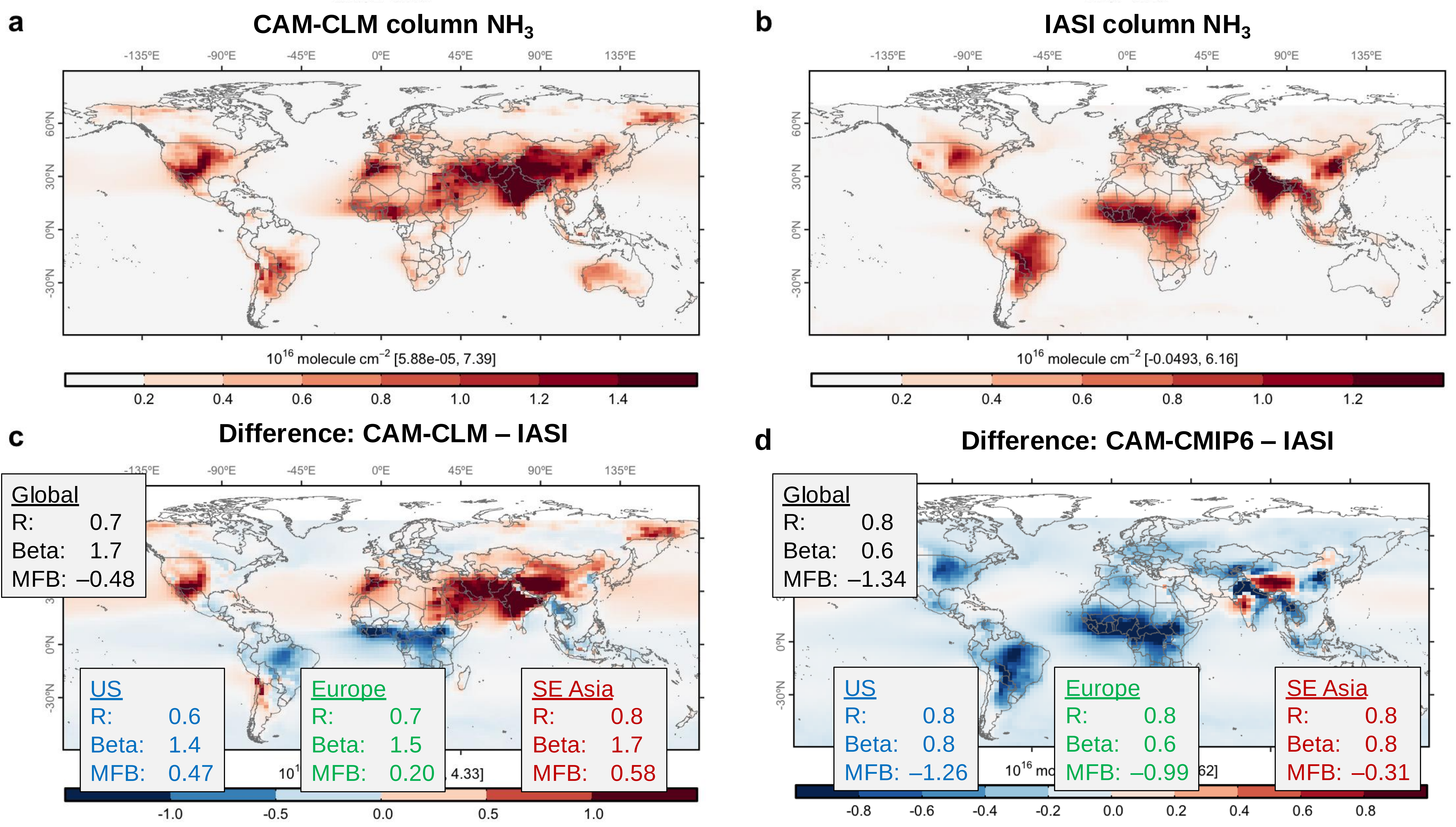


Please note that the colorbar scales are different.

Fung *et al.* (in prep.)

CAM-CLM vs IASI Observations:
Spatial comparison of annual average

Vam Damme *et al.* (2018)



Difference: CAM-CLM – IASI

Global	
R:	0.7
Beta:	1.7
MFB:	–0.48

US	
R:	0.6
Beta:	1.4
MFB:	0.47

Europe	
R:	0.7
Beta:	1.5
MFB:	0.20

SE Asia	
R:	0.8
Beta:	1.7
MFB:	0.58

Difference: CAM-CMIP6 – IASI

Global	
R:	0.8
Beta:	0.6
MFB:	–1.34

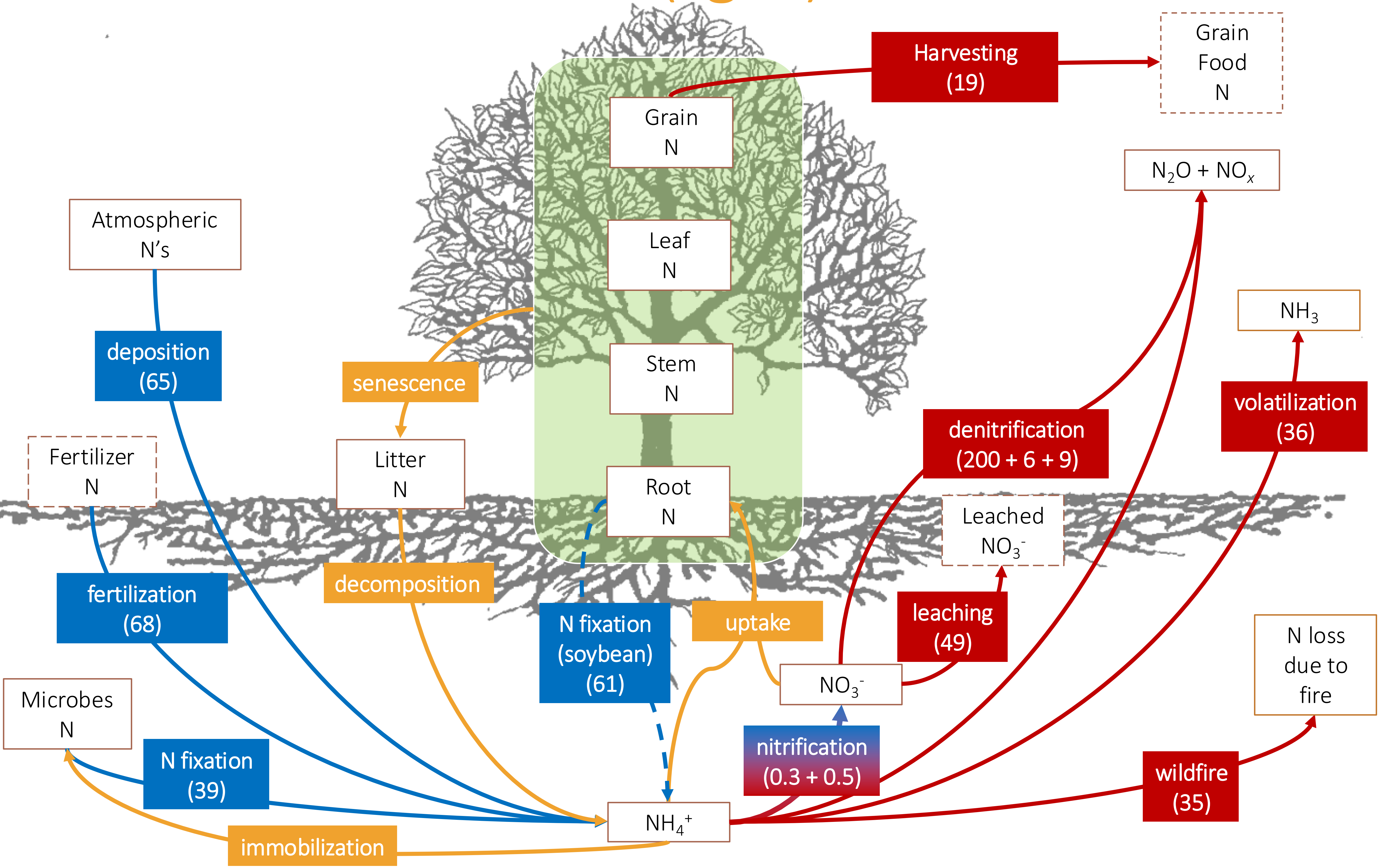
US	
R:	0.8
Beta:	0.8
MFB:	–1.26

Europe	
R:	0.8
Beta:	0.6
MFB:	–0.99

SE Asia	
R:	0.8
Beta:	0.8
MFB:	–0.31

Please note that the colorbar scales are different.

N-budget in CLM
In vs. Out = 230 : 350 (Tg-N)



Grain N

Harvesting (19)

Grain Food N

Leaf N

$N_2O + NO_x$

Atmospheric N's

NH_3

deposition (65)

senescence

Stem N

volatilization (36)

denitrification (200 + 6 + 9)

Fertilizer N

Litter N

Root N

Leached NO_3^-

fertilization (68)

decomposition

N fixation (soybean) (61)

uptake

leaching (49)

N loss due to fire

NO_3^-

Microbes N

N fixation (39)

nitrification (0.3 + 0.5)

wildfire (35)

NH_4^+

immobilization

In summary

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

- NH_3/NH_4^+ cycle modeling with CESM2.0 [on-going]
  - Using CLM5.0 to estimate NH_3 emissions associated with cropland and natural soil
  - Fairly agreeing with CMIP6 and MASAGE inventories, and IASI observation over high-emission regions
  - Ammonia-aerosol-climate feedbacks to be investigated