

# Impact of UK farming on air quality, health and habitats



**U. York Seminar**

**Eloise A Marais**

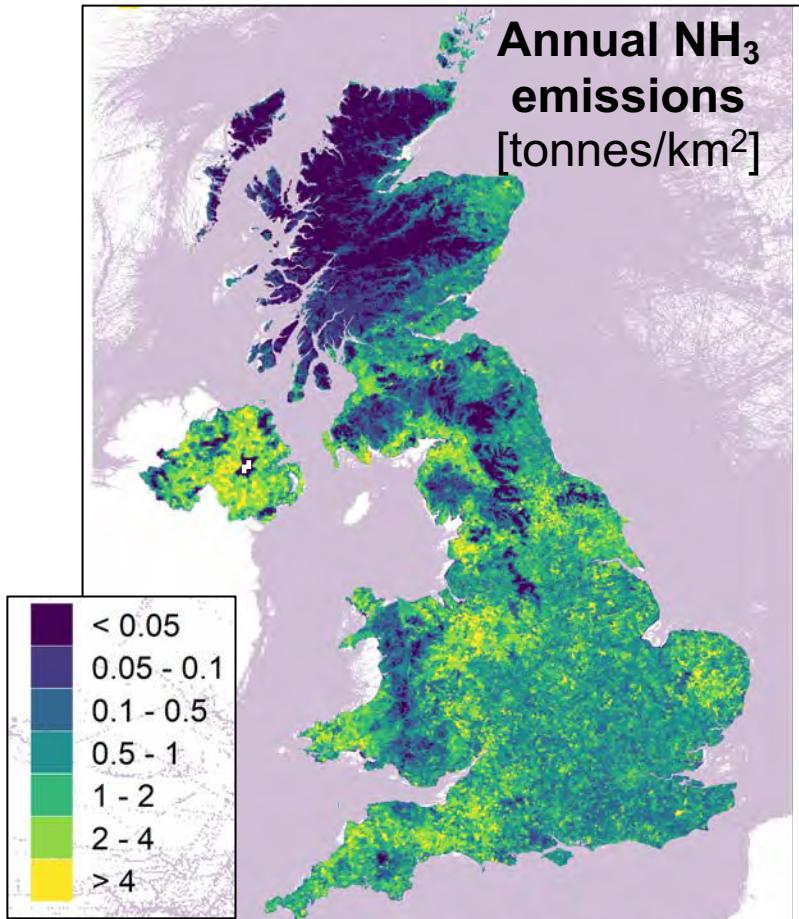
**16 November 2023**

**With ... Karn Vohra, Alok Pandey, Gongda Lu, Jamie Kelly (group members)**

**And ... collaborators at CEH, NOAA, ULB, AER, Environ. Canada, SUNY Albany, Rothamsted**

# UK NH<sub>3</sub> emissions overwhelming from farming

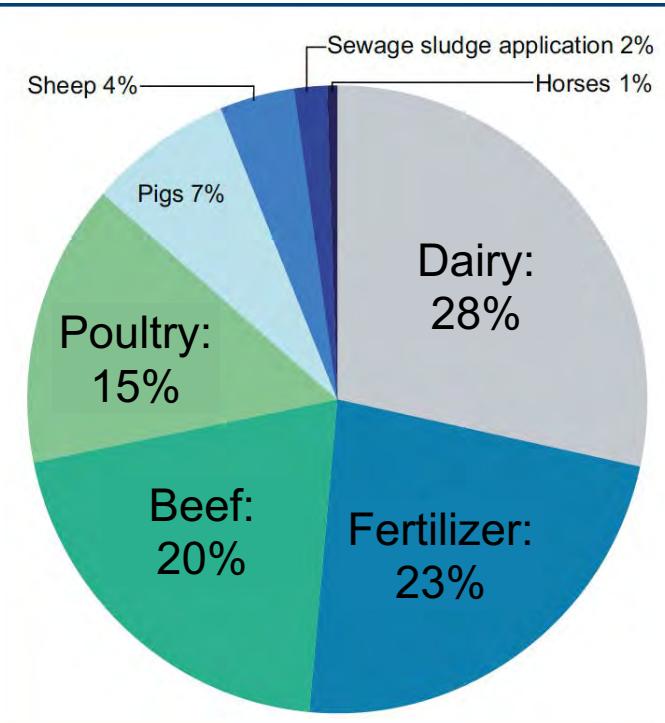
## Spatial distribution of NH<sub>3</sub> emissions



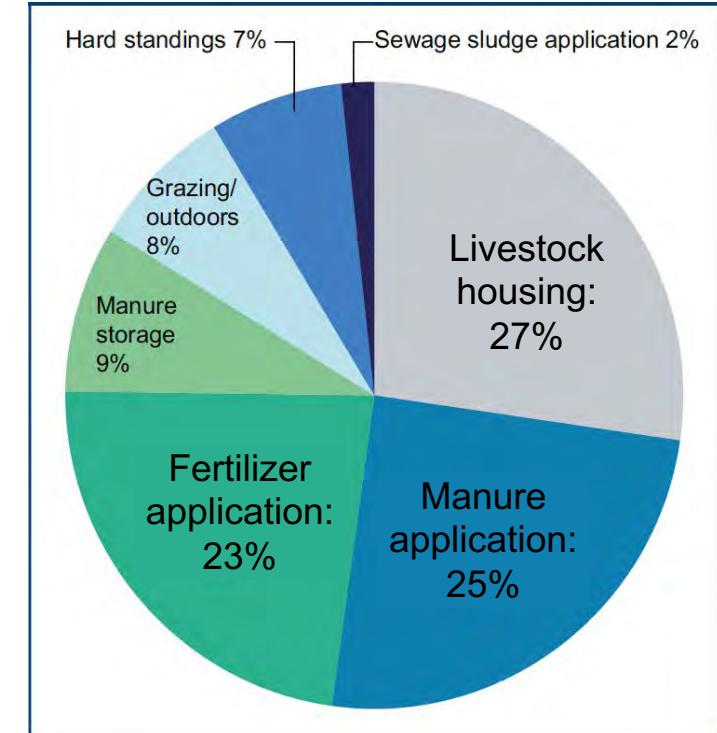
[[https://naei.beis.gov.uk/data/map-uk-das?pollutant\\_id=21](https://naei.beis.gov.uk/data/map-uk-das?pollutant_id=21)]

## UK NH<sub>3</sub> Emissions by activity and category

### by farming activity



### by management category



[UK Clean Air Strategy, 2019]

# UK NH<sub>3</sub> emissions changes compared to other precursors

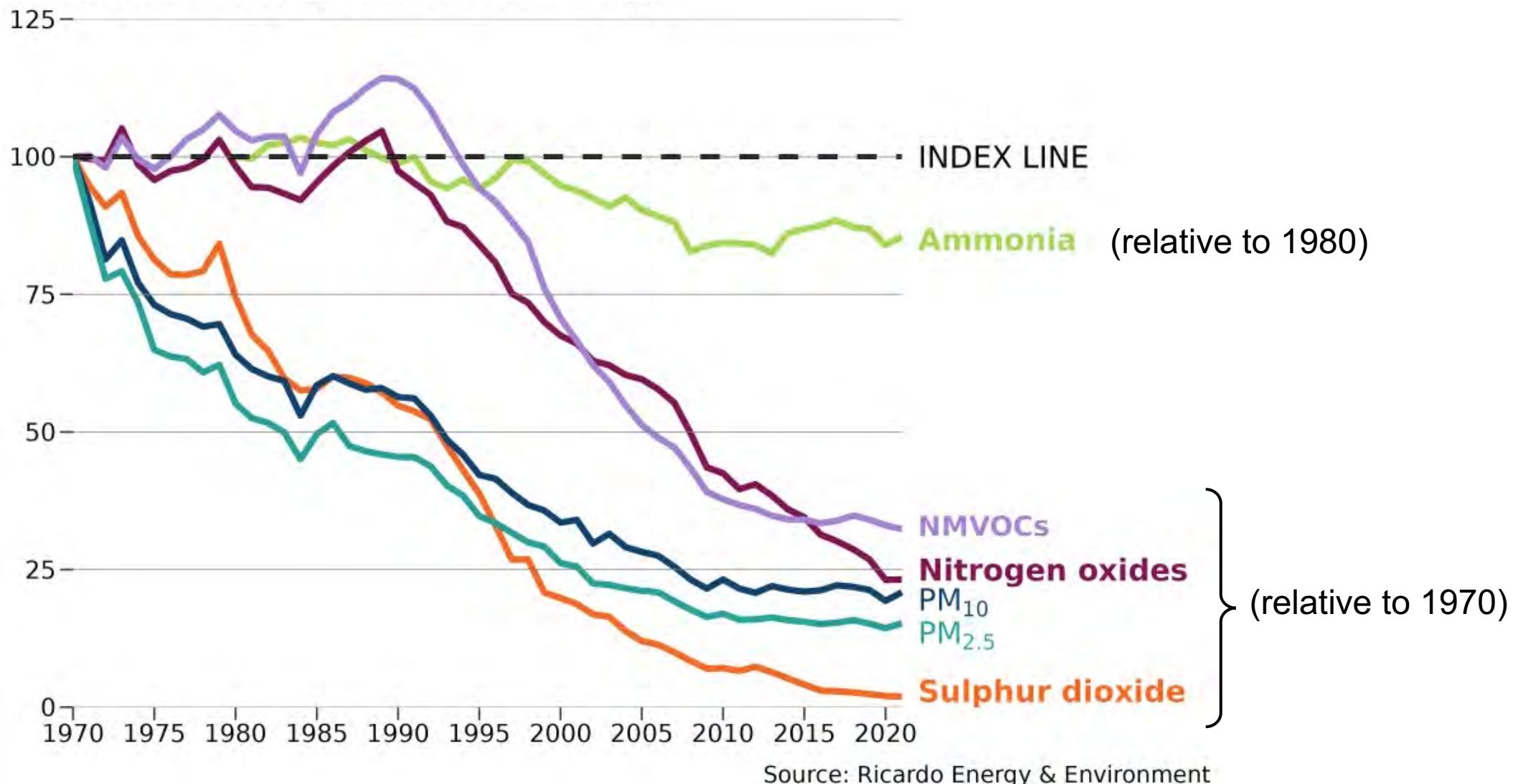


Image source: <https://www.gov.uk/government/statistics/emissions-of-air-pollutants/emissions-of-air-pollutants-in-the-uk-summary>

# UK NH<sub>3</sub> Emissions Regulations



UNECE



Alter the inventory to meet the targets

**8% decline** relative to 2005 in  
2020 to 2029

**16% decline** relative to 2005  
from 2030

Code of Good Agricultural Practice  
(COGAP) for Reducing Ammonia  
Emissions (print version)

Ref: PB14506  
PDF, 4.93 MB, 30 pages

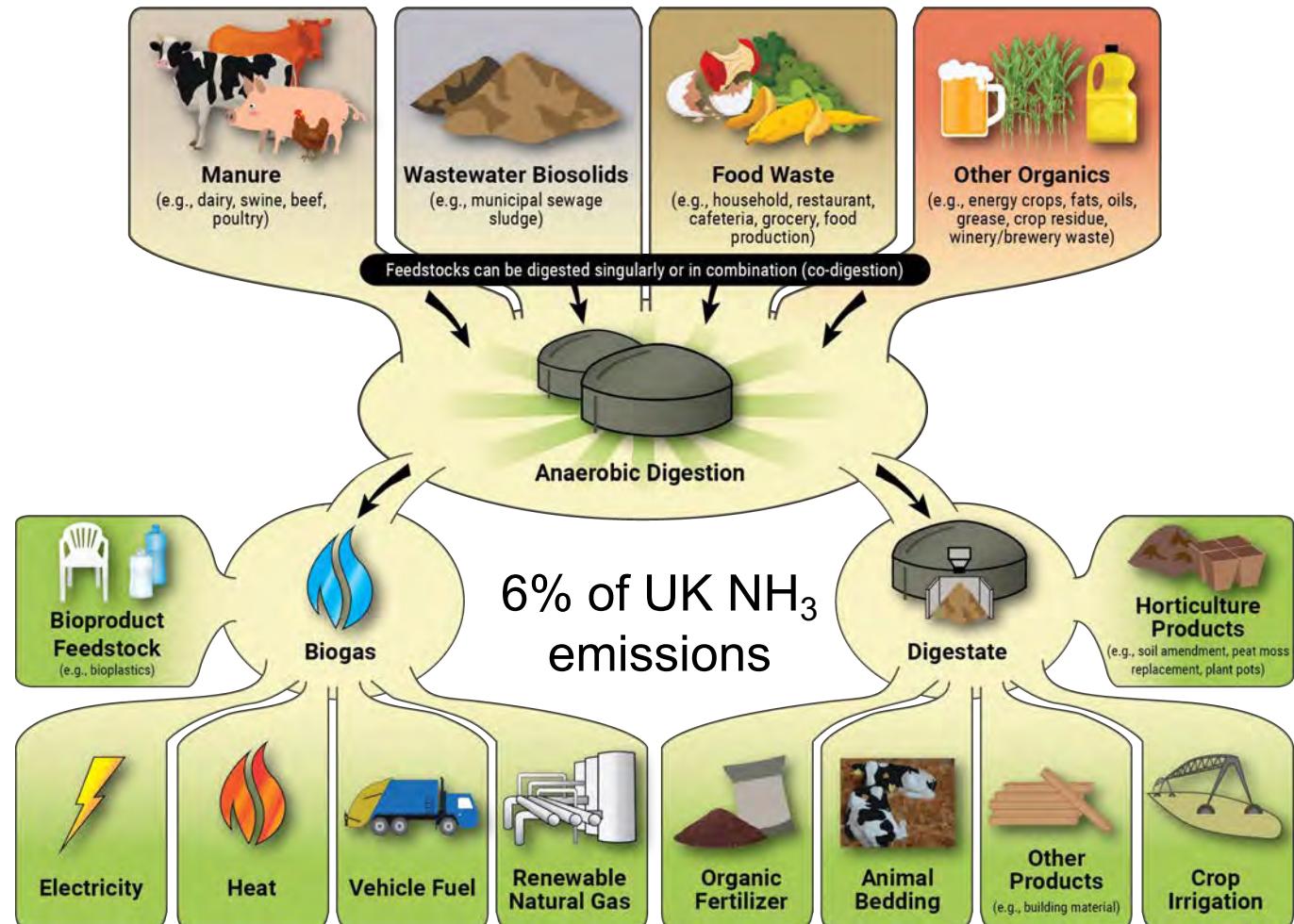


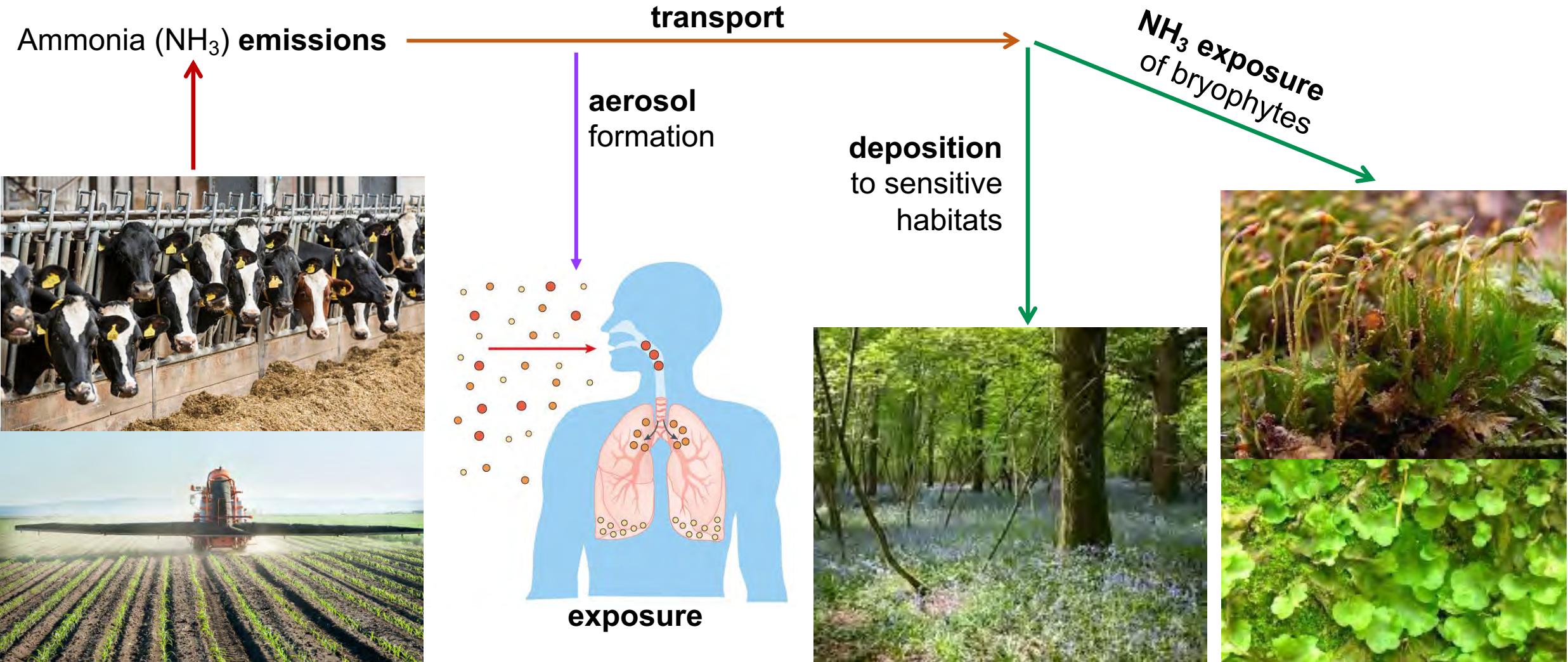
Image source: <https://www.epa.gov/agstar/how-does-anaerobic-digestion-work>

More here: <https://www.endsreport.com/article/1846831/regulatory-capture-nfu-lobbied-defra-lower-its-global-air-quality-ambitions>

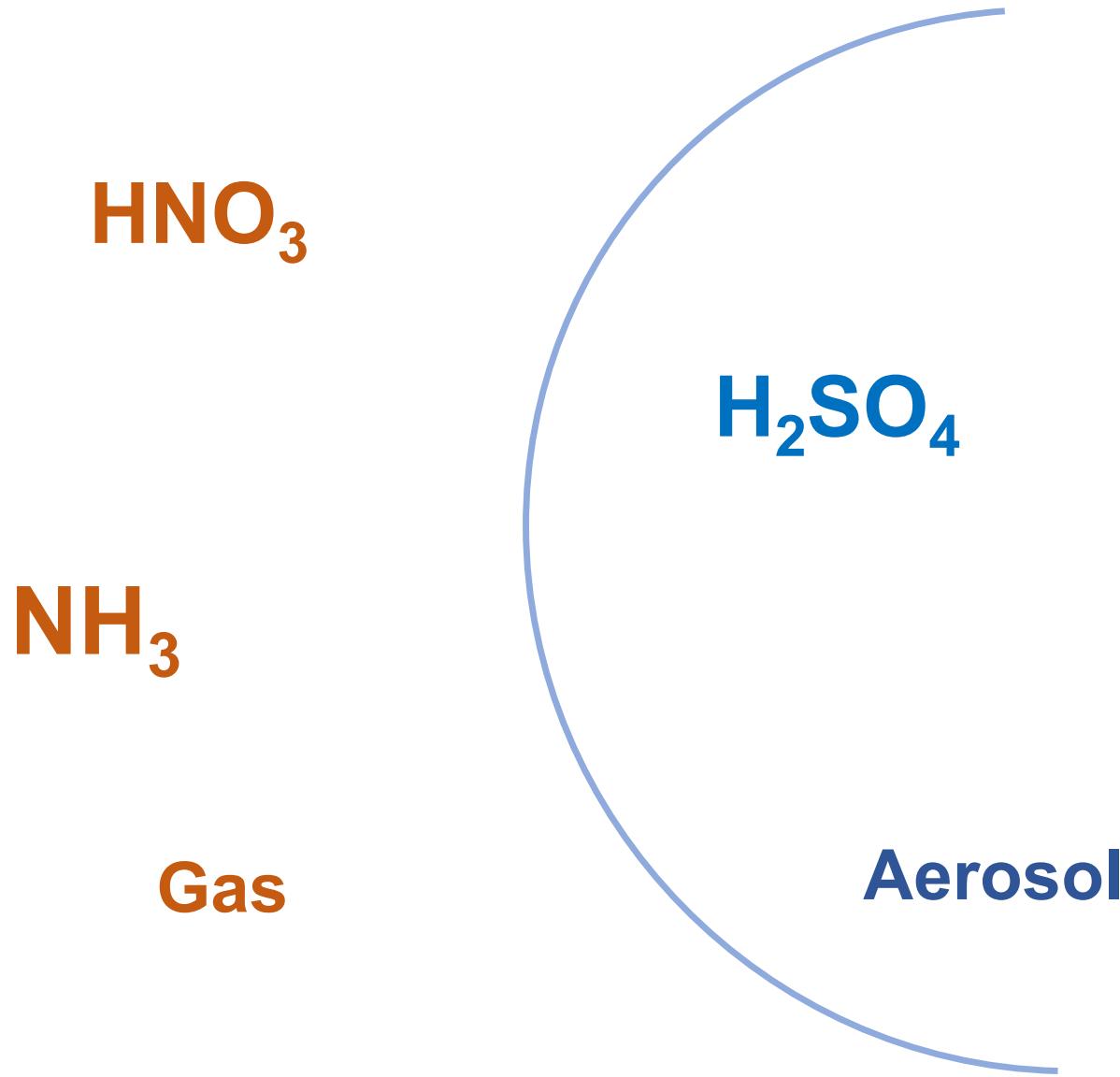
# Environmental Concerns over NH<sub>3</sub> Emissions

Impacts health as PM<sub>2.5</sub> precursor

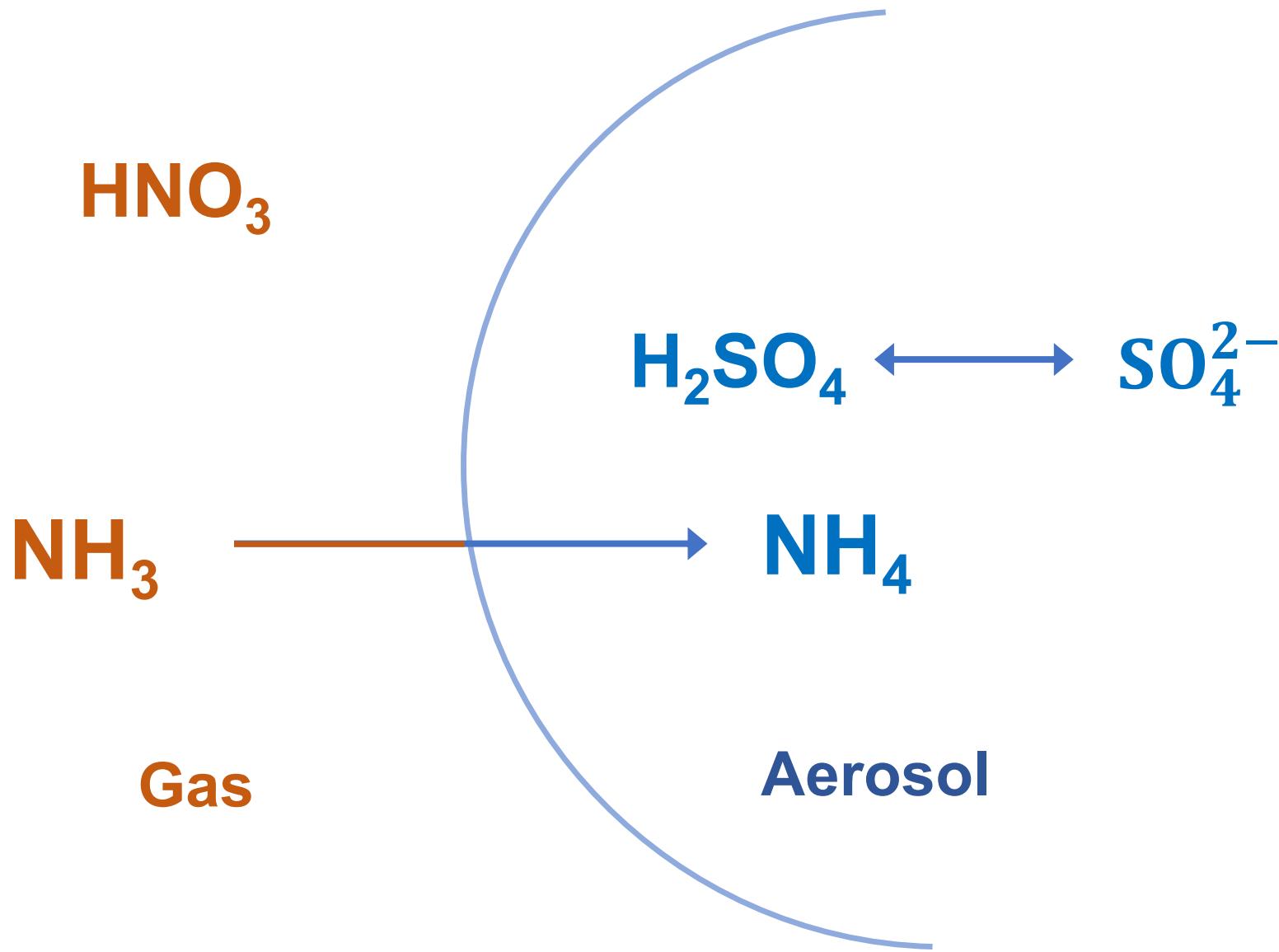
Offsets ecosystem balance via nitrogen deposition and direct exposure



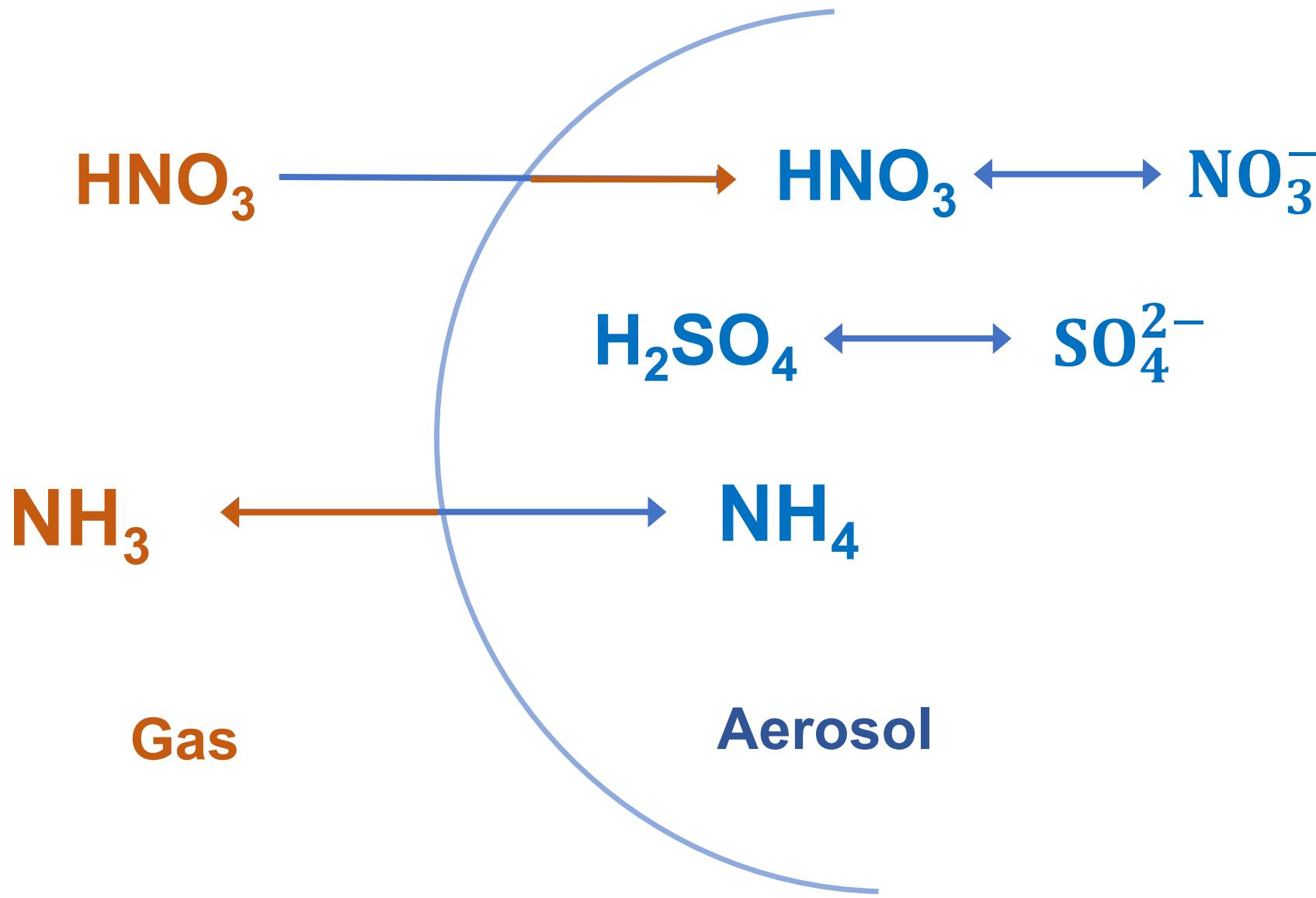
# $\text{NH}_3$ Contribution to Particulate Matter (PM) Mass



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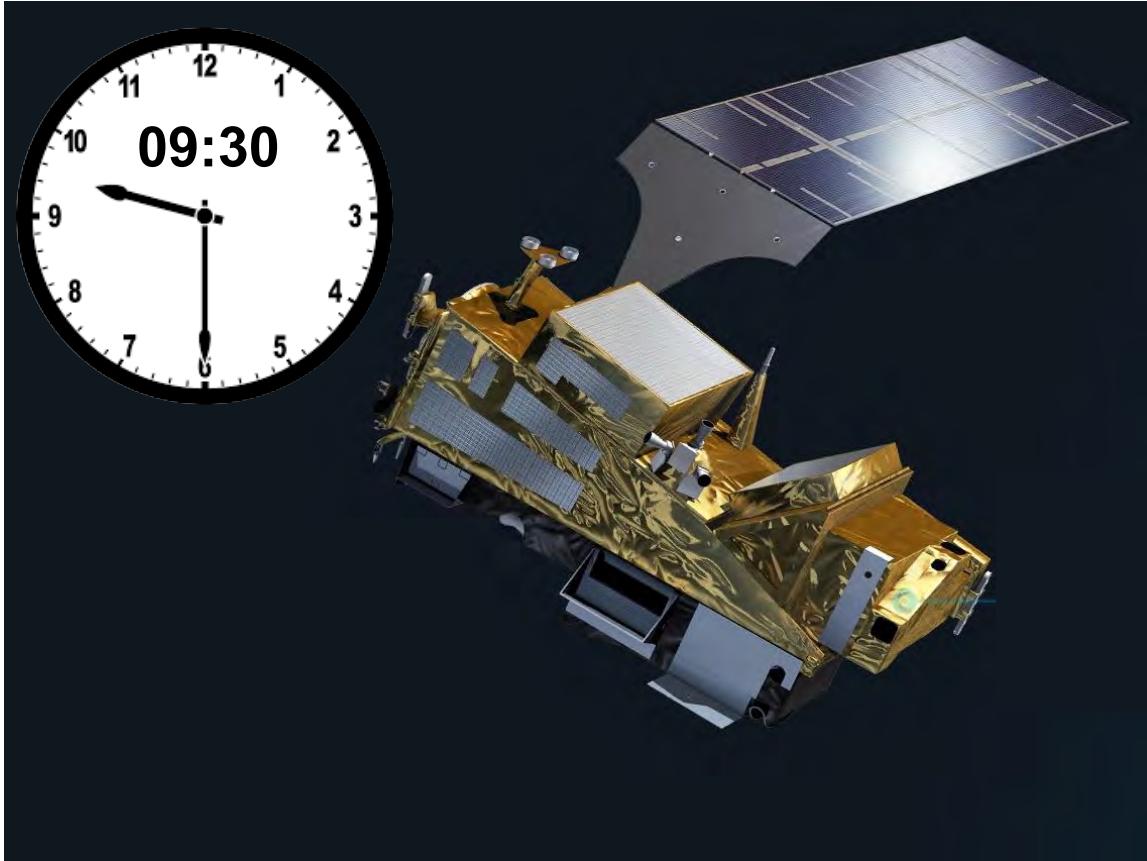


# $\text{NH}_3$ Contribution to Particulate Matter (PM) Mass



# Instruments in space measuring NH<sub>3</sub> column densities

**IASI:** Infrared Atmospheric Sounding Interferometer



Resolution: 12 km at nadir

Swath width: 2200 km

Launch date: 2006 (2012, 2018, 2024, 2031, 2038)

Years used: 2008-2018

**CrIS:** Cross-track Infrared Sounder



Resolution: 14 km at nadir

Swath width: 2200 km

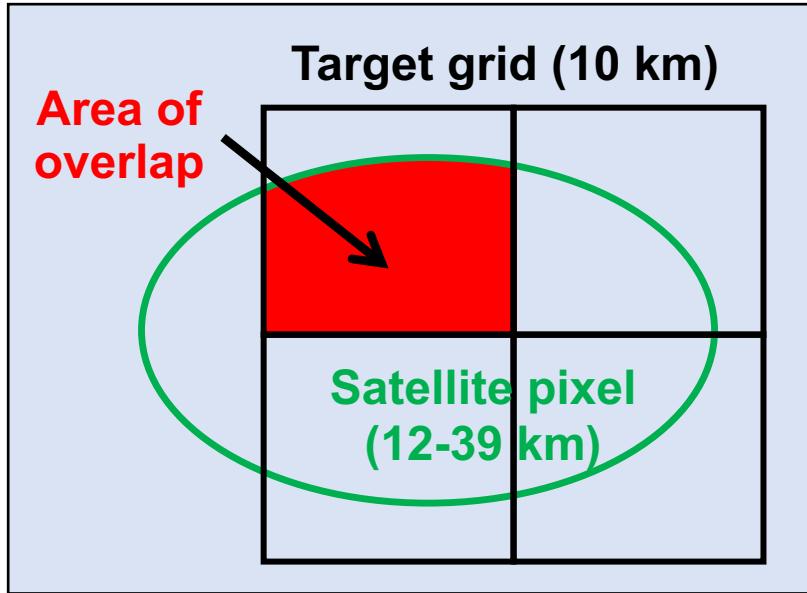
Launch date: 2011 (2017, 2022, 2027, 2032)

Years used: 2013-2018

# Fine-scale regridding of satellite observations by oversampling

Enhance the spatial resolution relative to the native resolution of the instrument by oversampling

## Oversampling Technique

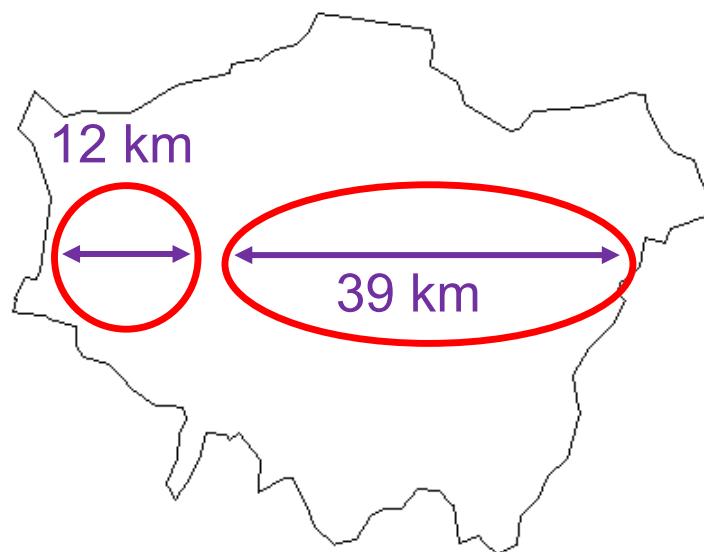


Weights each IASI NH<sub>3</sub> pixel by area of overlap and the reported uncertainty

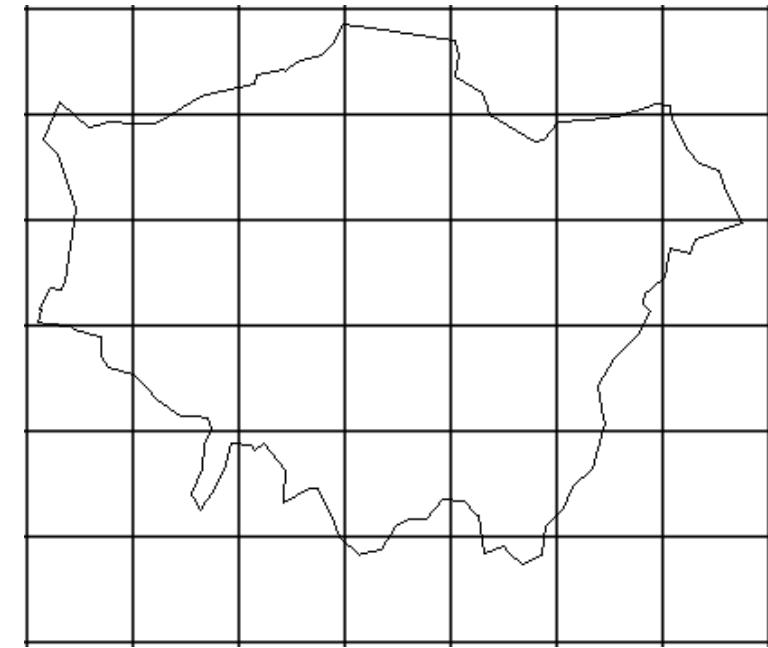
Oversampling code: L. Zhu,  
SUSTech (Zhu et al., 2017)

## Oversampling technique over London

IASI ground pixel



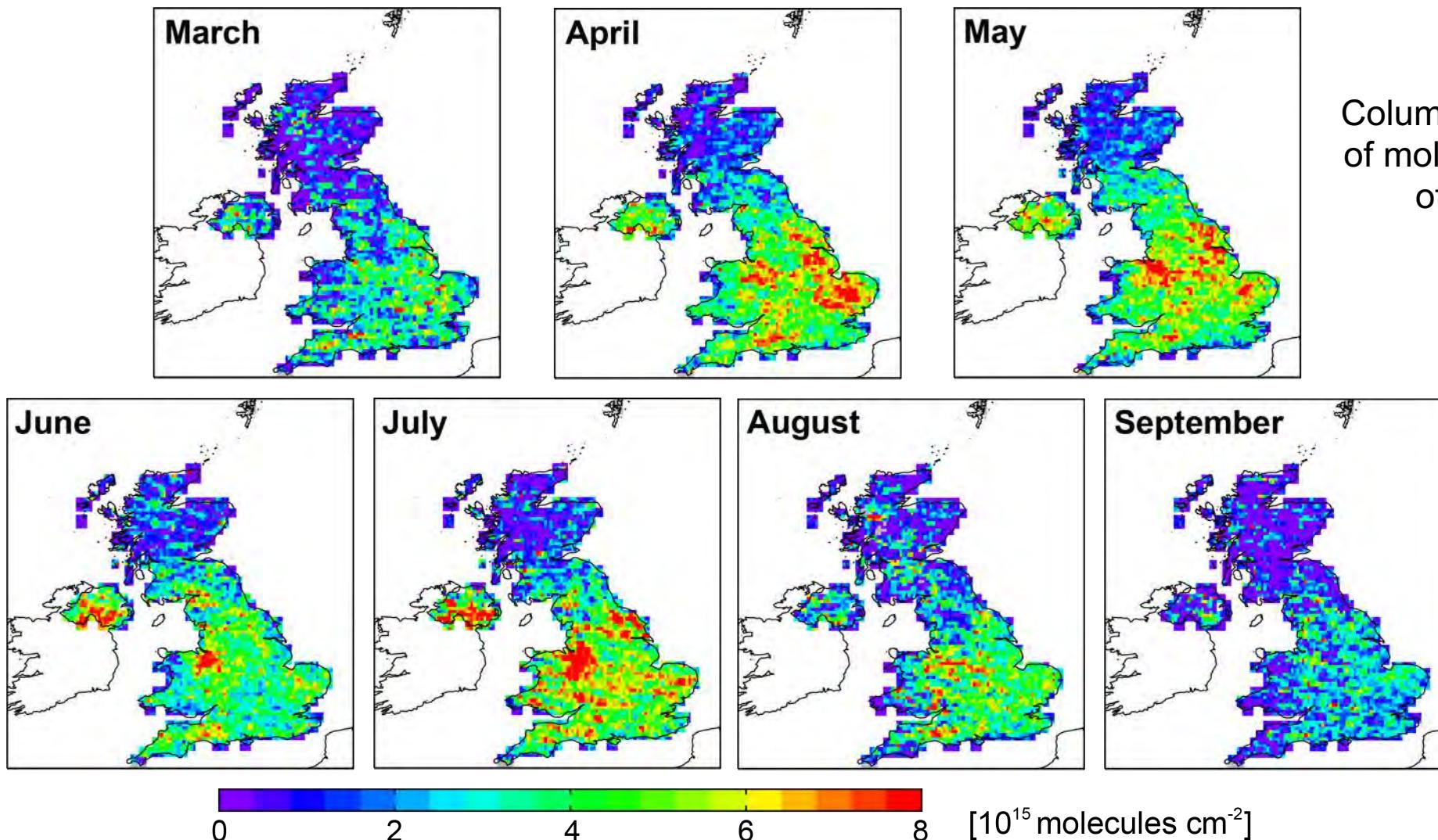
0.1° x 0.1° (~10 km) grid



Lose time (temporal) resolution; gain spatial resolution

# Multiyear means from the IASI (morning overpass) instrument

Multiyear (2008-2018) monthly means for warmer months of the year



Column densities: number  
of molecules from surface  
of Earth to top of  
atmosphere

Climatological mean to be consistent with bottom-up ammonia emissions

# Top-down estimate of ammonia emissions

Employ simple mass balance approach:

Convert atmospheric **column concentrations** to surface **emissions** by relating the two with a **model**

ABUNDANCES

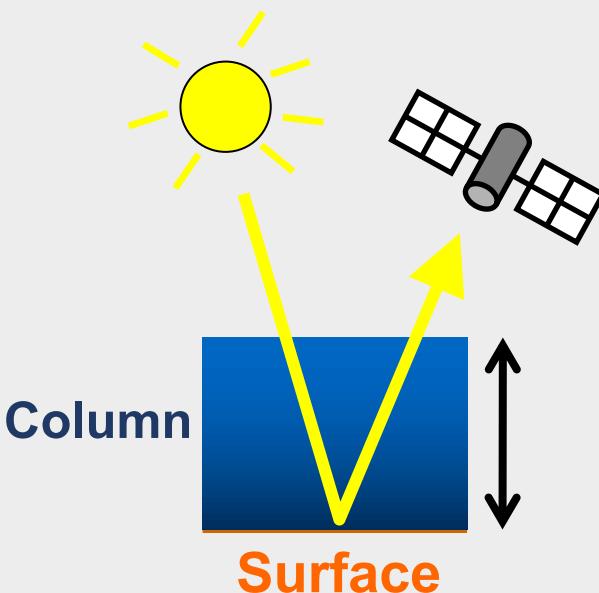


Conversion Factor

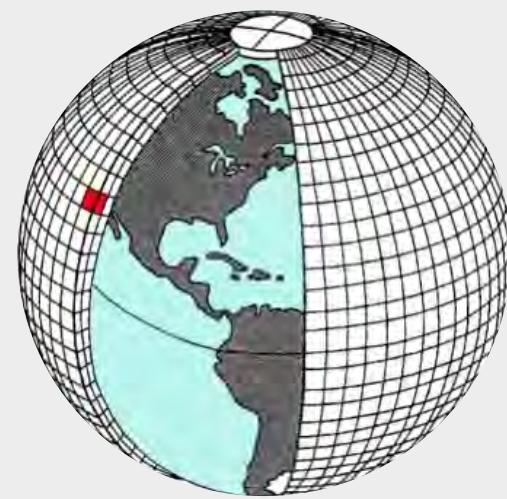


EMISSIONS

Satellite column densities



Model Concentration-to-Emission Ratio



Satellite-derived Surface Emissions

Emission



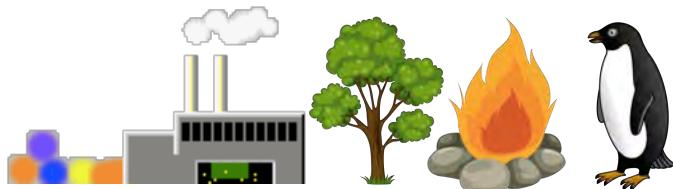
This approach possible as  $\text{NH}_3$  has a relatively short lifetime (2-15 hours) at or near sources

# Modelled concentration-to-emissions-ratio from GEOS-Chem

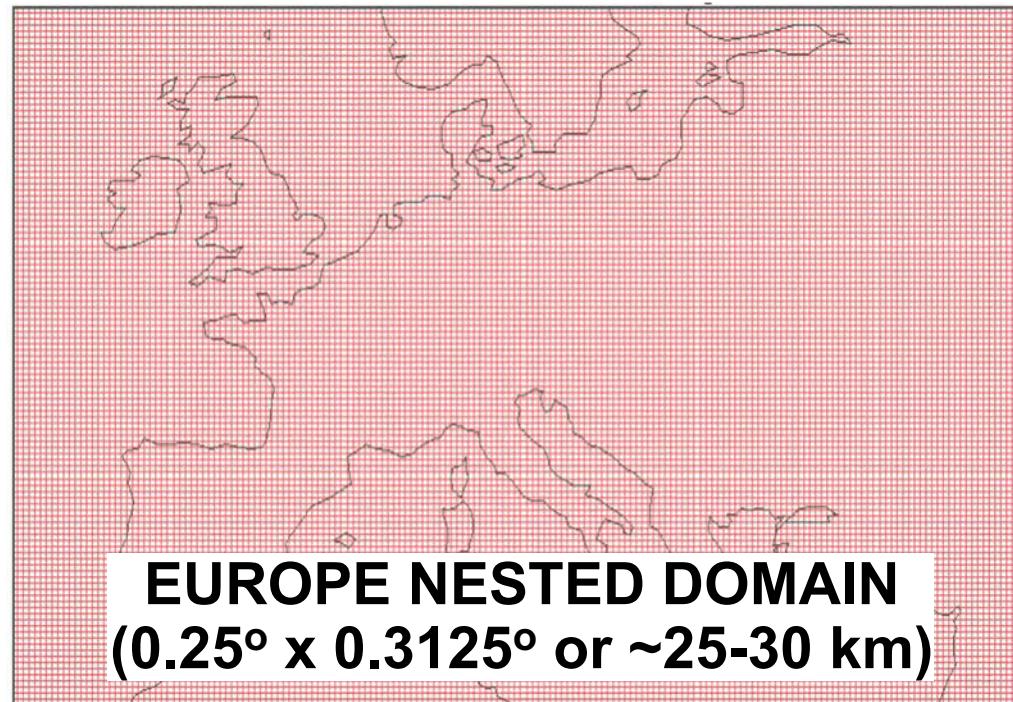


3D Atmospheric Chemistry Transport Model

Emissions  
(natural/human)



UK NAEI emissions  
(with temporal information)



Offline assimilated  
meteorology



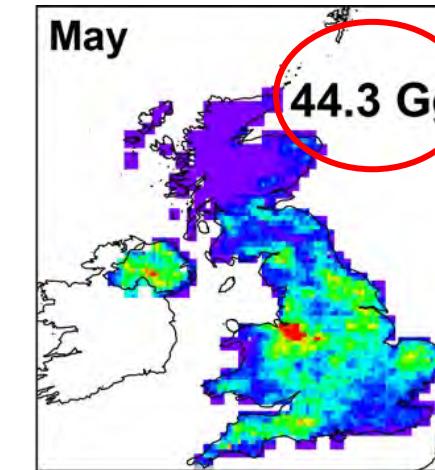
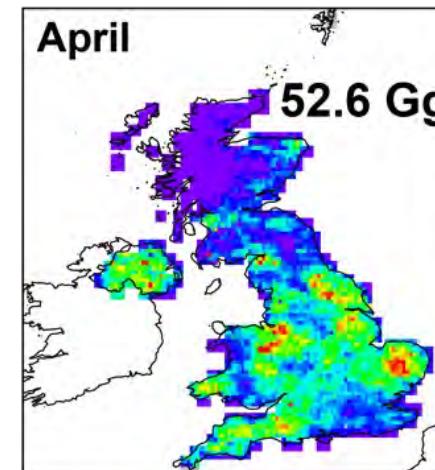
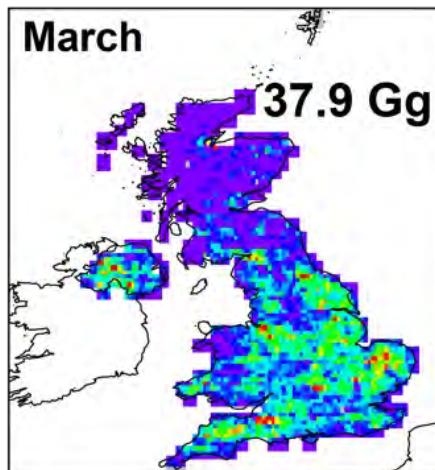
NASA GEOS-FP for 2016

Gas phase and heterogeneous chemistry  
Transport  
Dry/wet deposition

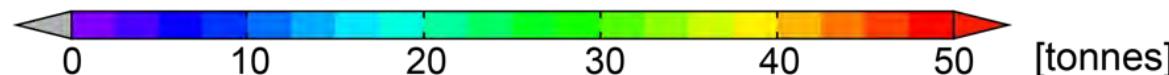
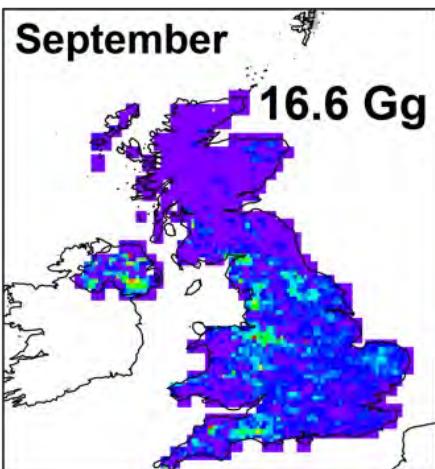
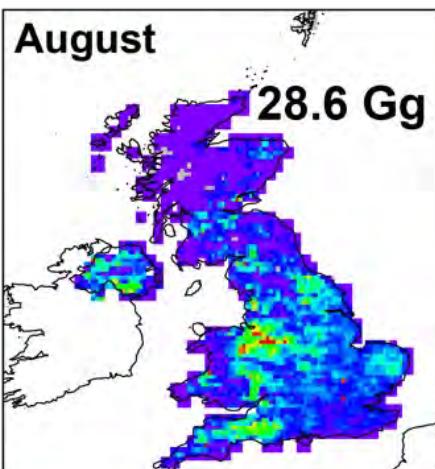
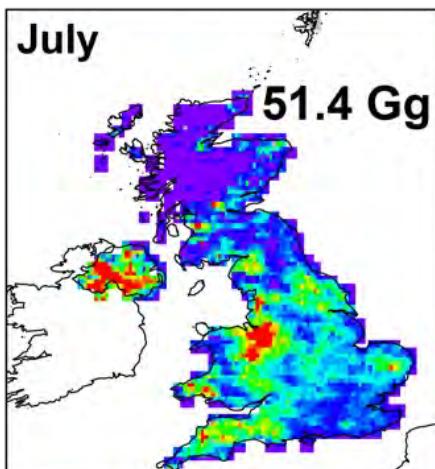
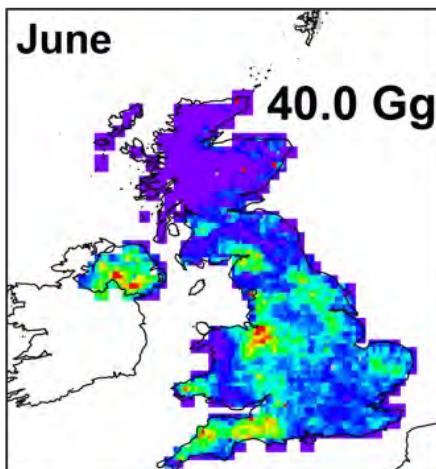
# IASI-derived multiyear (2008-2018) monthly mean $\text{NH}_3$ emissions

Focus on **Mar-Sep** when warm temperatures and clearer conditions increase sensitivity to surface  $\text{NH}_3$

IASI: morning overpass



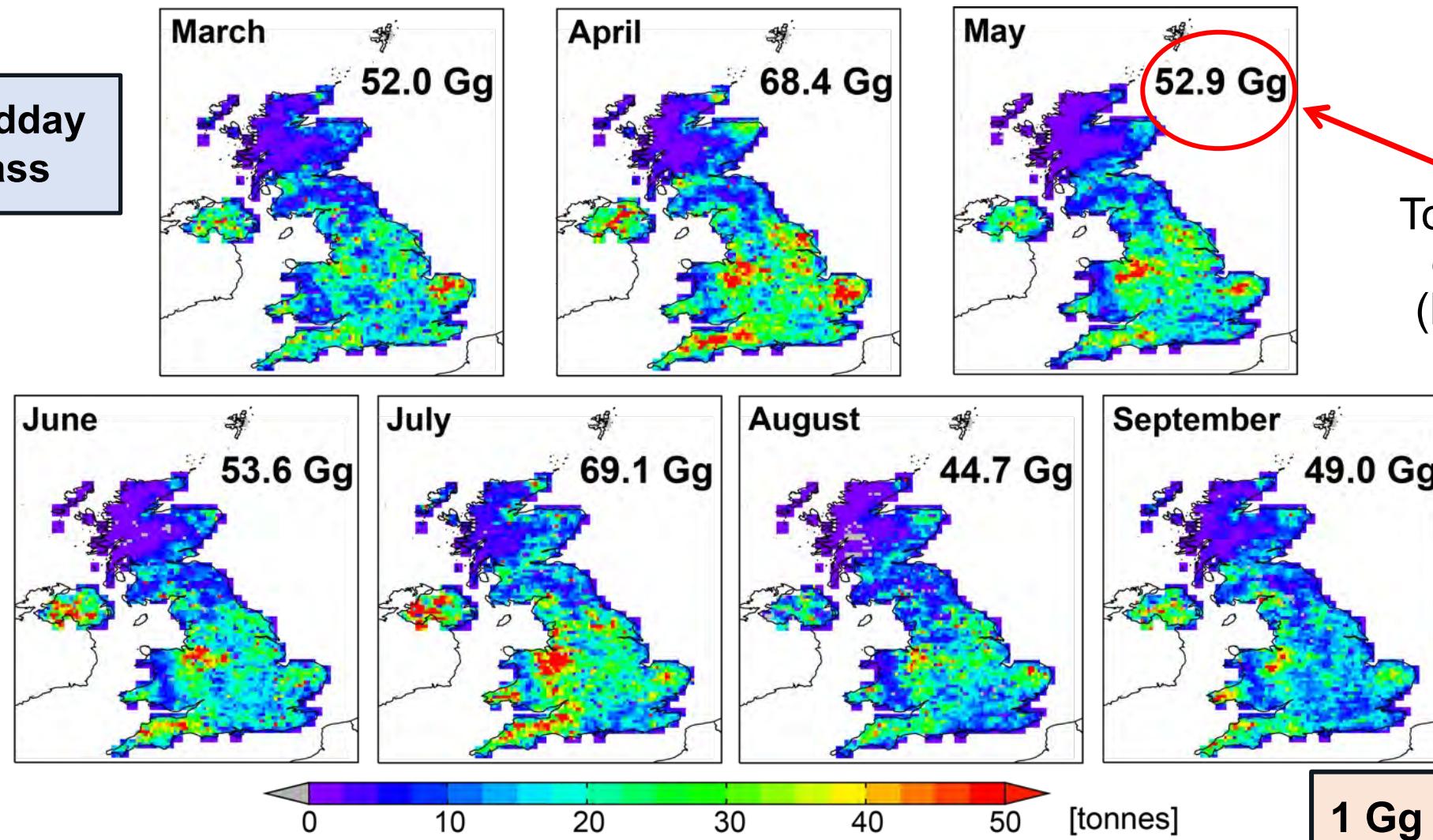
1 Gg = 1 kilotonne



Monthly emissions for March-September from IASI-derived estimates sum to **271.5 Gg**

# CrlS-derived multiyear (2008-2018) monthly mean NH<sub>3</sub> emissions

CrlS: midday  
overpass

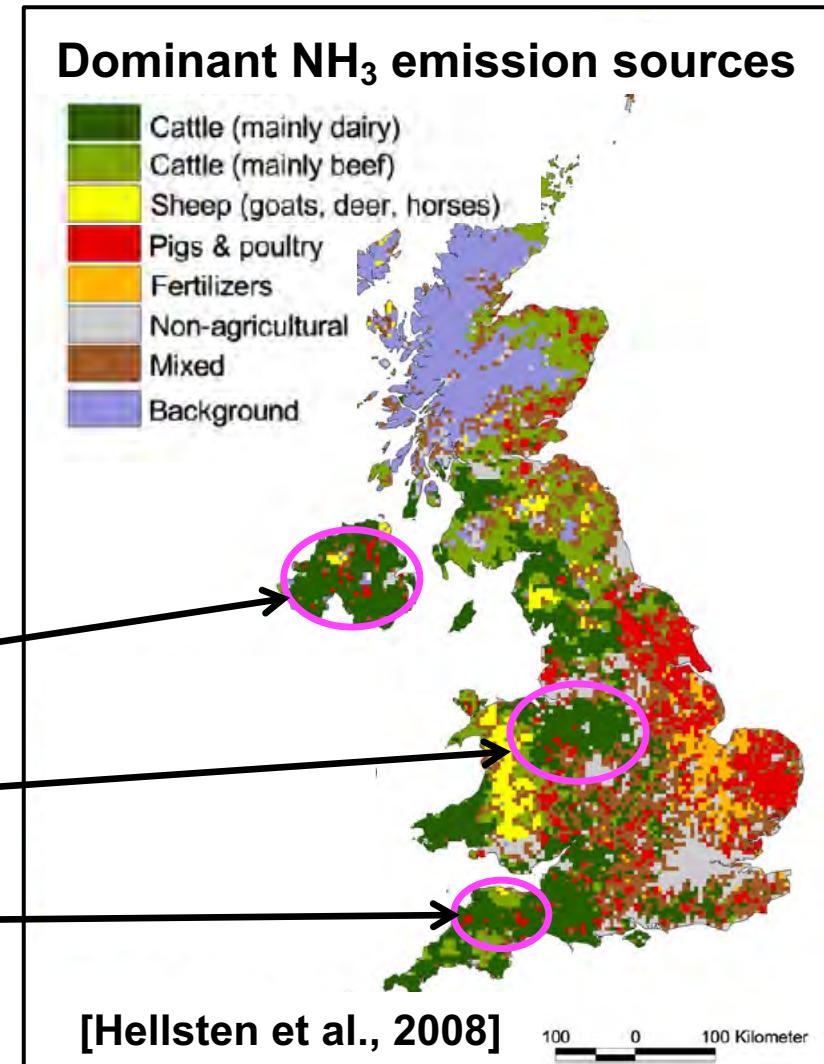
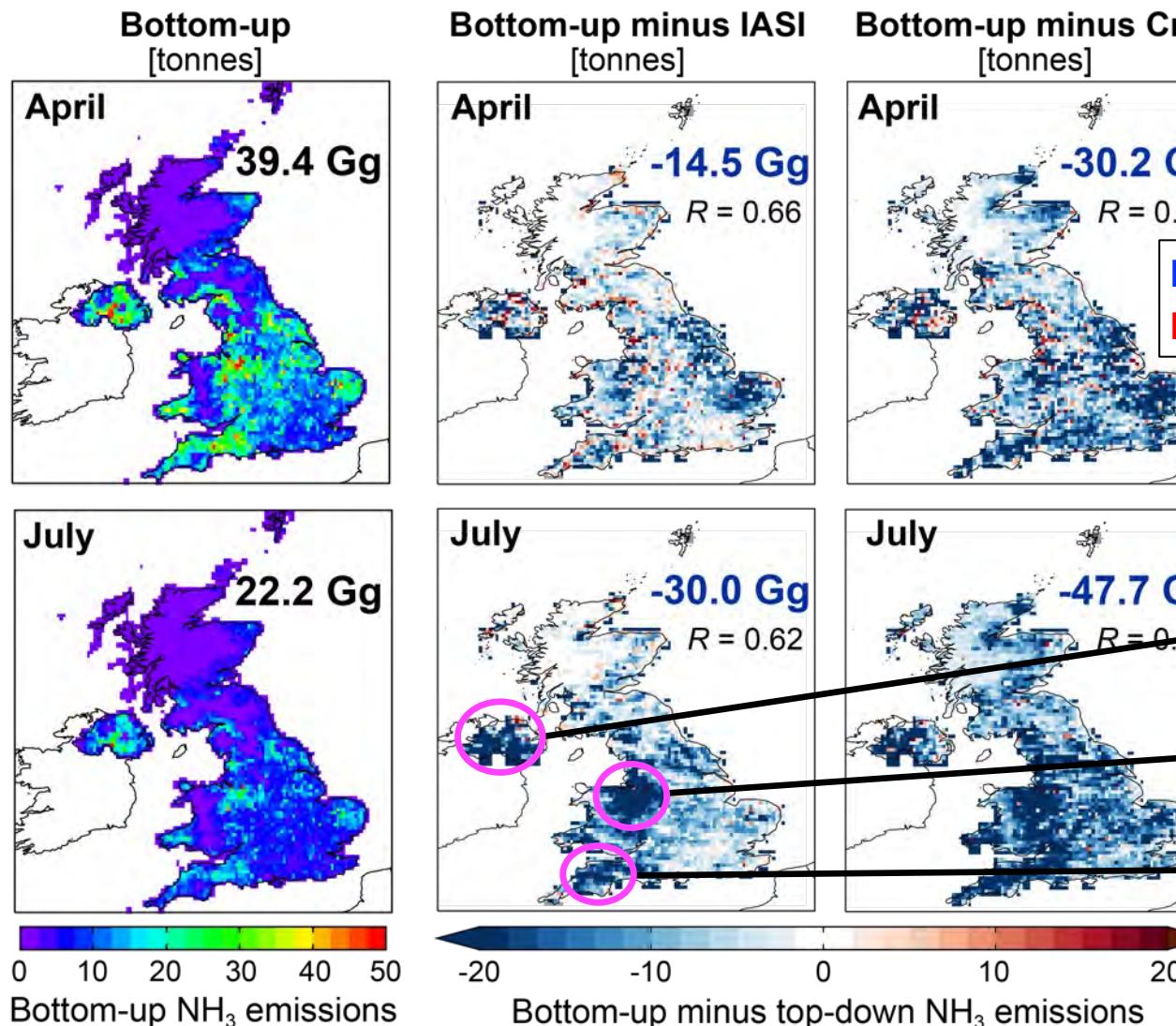


Monthly emissions for March-September from CrlS-derived estimates sum to **389.6 Gg**

CrlS is 43% more than IASI. Largest difference of >a factor of 2 in September.

# Satellite vs inventory NH<sub>3</sub> emissions: spatial distribution

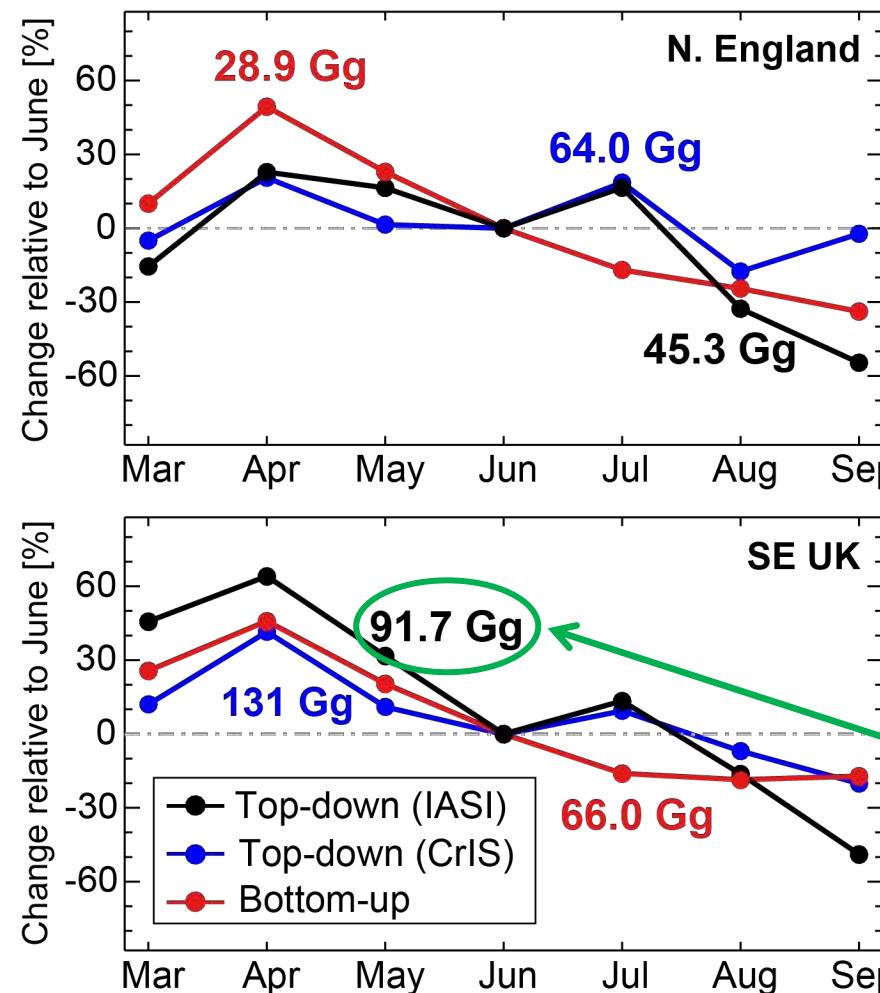
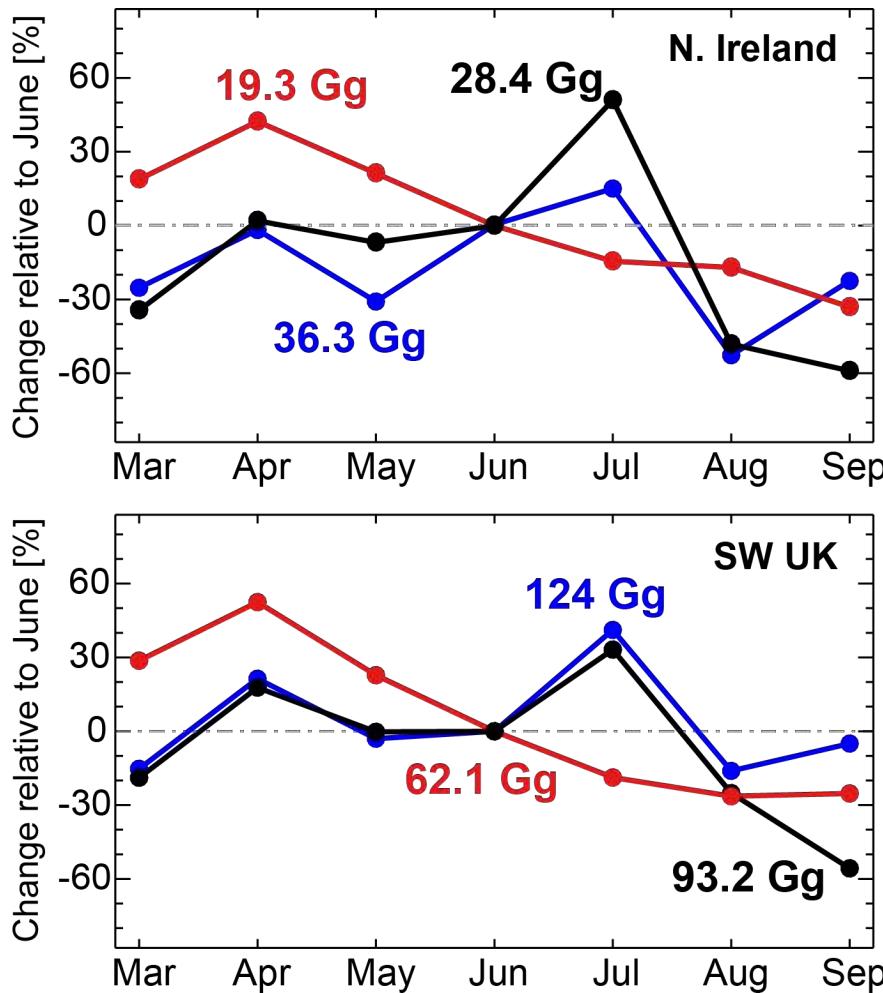
Comparison of months with peak emissions according to IASI and CrIS (April and July)



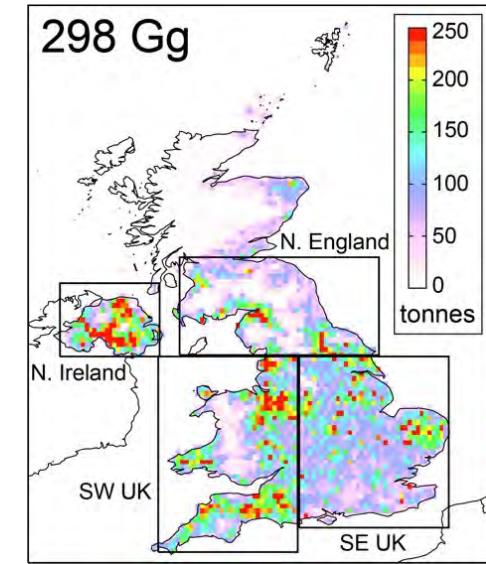
Large July difference over locations dominated by dairy cattle. Inventory is 27-49% less than the satellite values.

# Satellite vs inventory NH<sub>3</sub> emissions: seasonality

Seasonality shown as emissions in each month relative to June



Regions and annual inventory emissions



Mar-Sep emission totals in each region

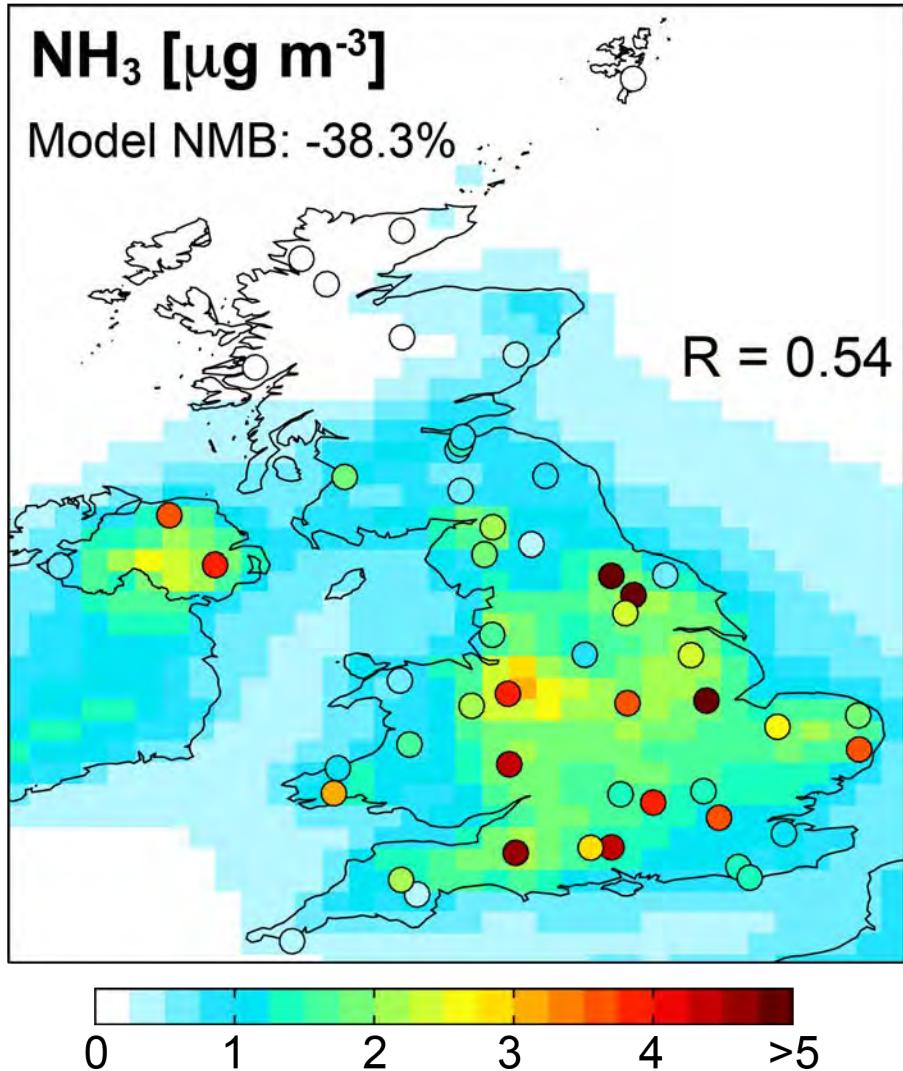
1 Gg = 1 kilotonne

All reproduce spring April peak (fertilizer & manure use). Only the satellites show summer July peak (dairy cattle?).

The increase in emissions in September in CrIS is spurious.

# Surface network observations corroborate top-down results

Network (points) and model (background)  
surface NH<sub>3</sub> in Mar-Sep



Points are for DELTA  
instruments (blue circles)

DELTA instruments support  
model underestimate  
(NMB = -38%)

So do passive low-cost ALPHA  
instruments (yellow triangles)  
(NMB = -41.5%)

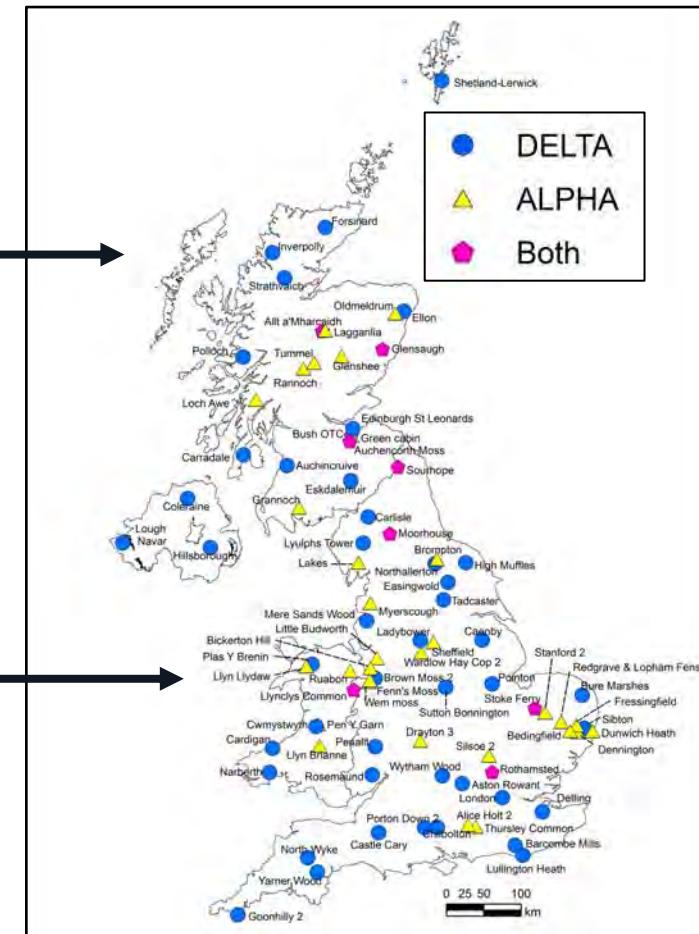


Image source:  
[http://www.pollutantdeposition.ceh.ac.uk  
/content/ammonia-network](http://www.pollutantdeposition.ceh.ac.uk/content/ammonia-network)

GEOS-Chem underestimate in surface NH<sub>3</sub> driven with the NAEI corroborates results from IASI

# Takehome Messages So Far

- Spring and Summer peak in NH<sub>3</sub> emissions
- Inventories may underestimate NH<sub>3</sub> emissions, as missing summer peak

**What's the contribution of agricultural NH<sub>3</sub> to urban PM<sub>2.5</sub>?**

# Test Contribution of Potentially Influential Sources

## Local



**City**



**County**

## National



**Nearby large cities**

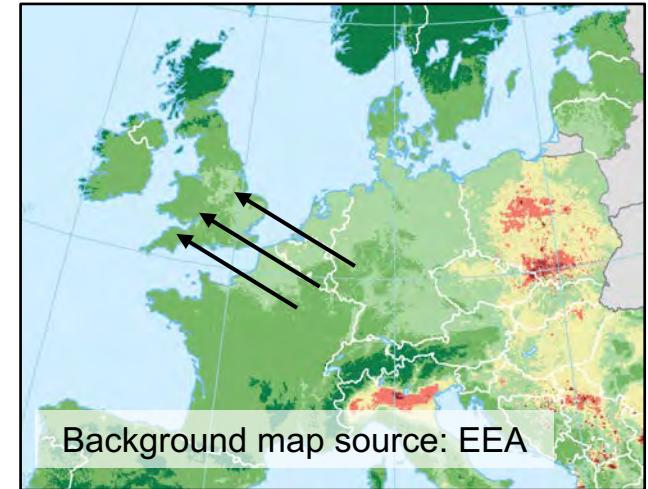


**Transport**



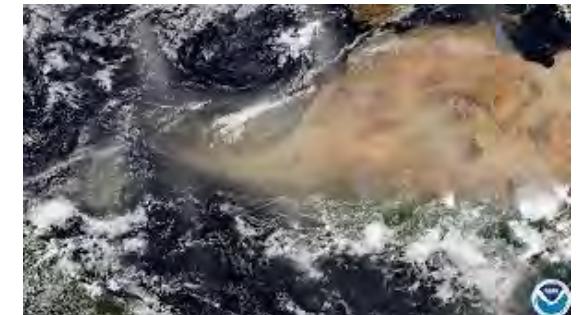
**Agriculture**

## Regional



**Mainland Europe**

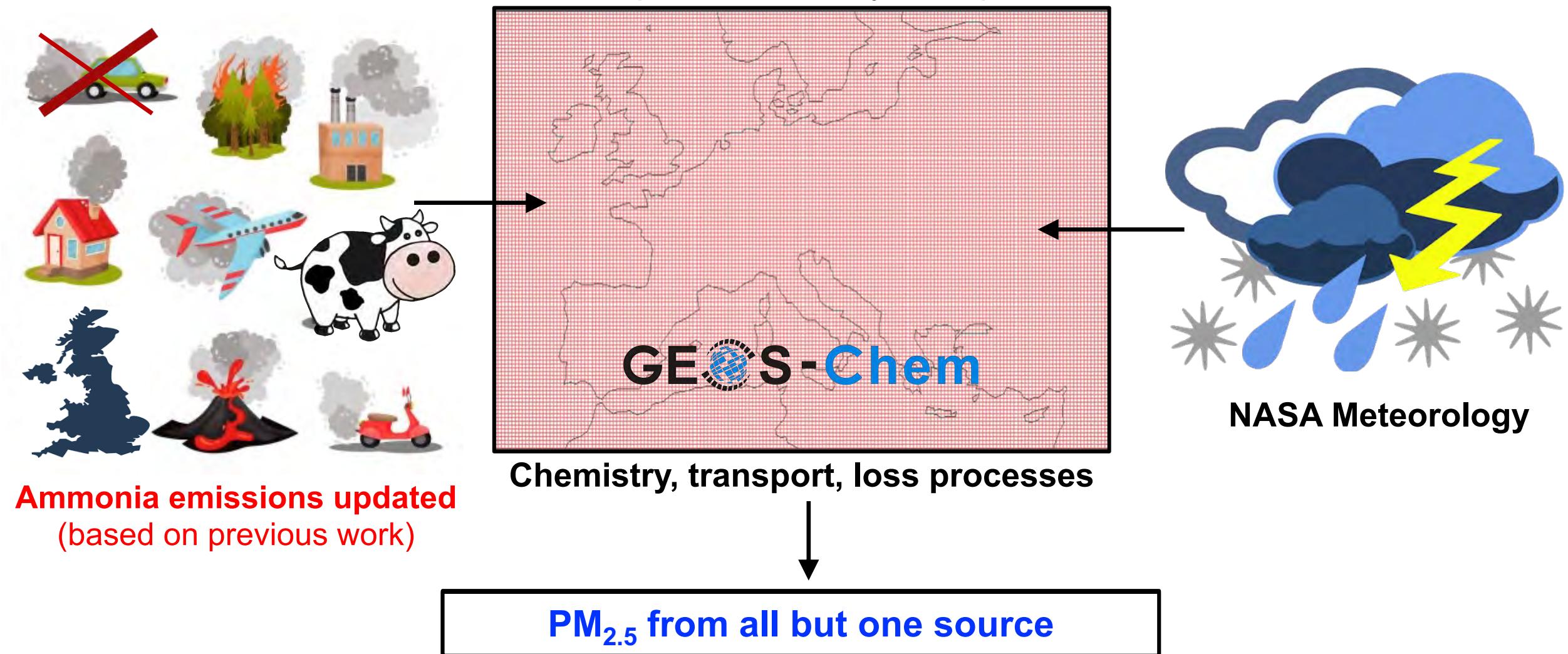
## Global



**Desert Dust**

# Simulate PM<sub>2.5</sub> with GEOS-Chem

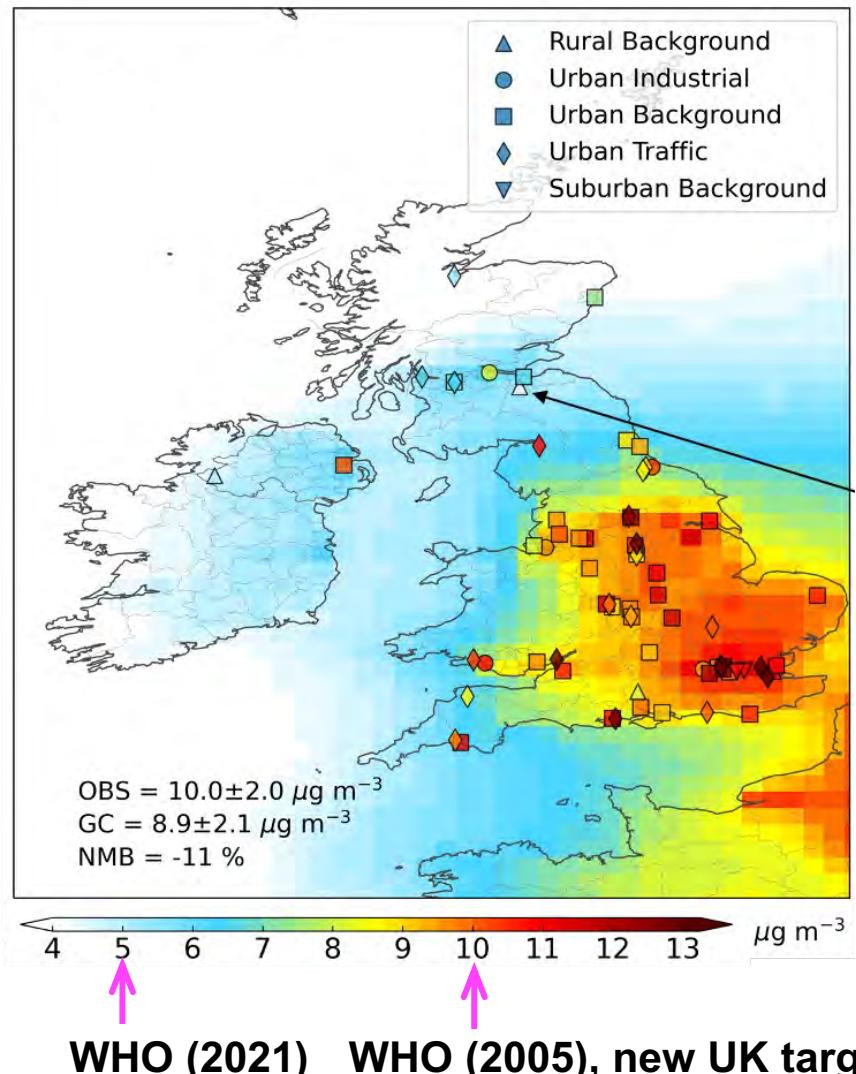
3D Atmospheric Chemistry Transport Model



GEOS-Chem manual: <http://acmg.seas.harvard.edu/geos/>

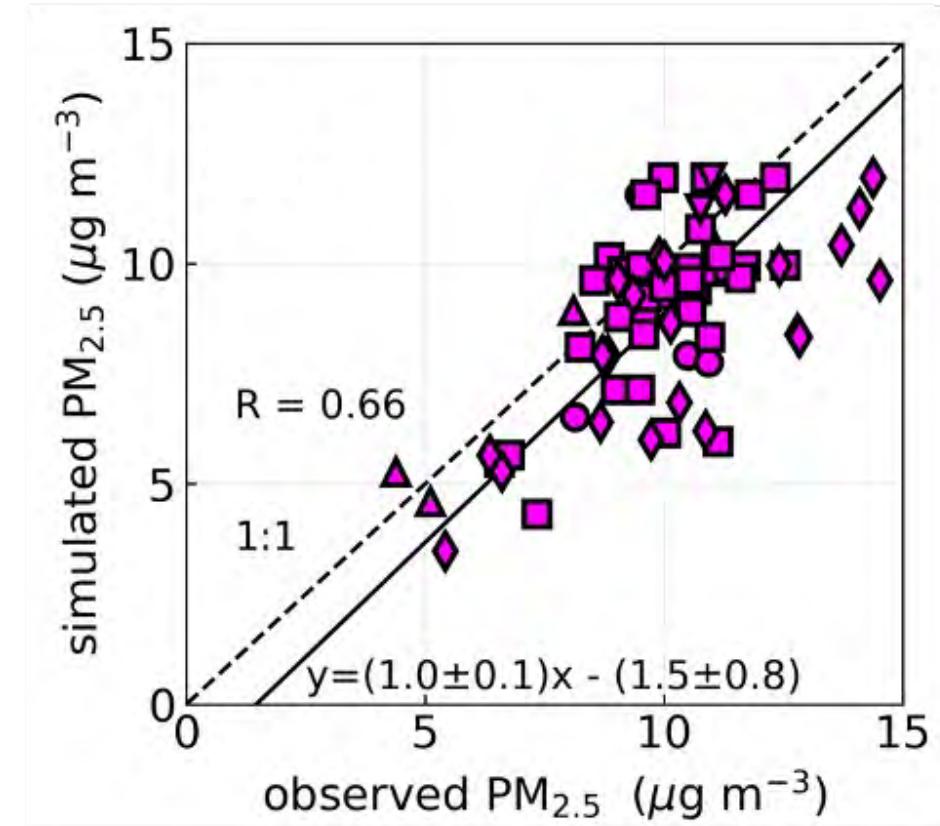
# Assess Validity of Model using Permanent Networks

Use total PM<sub>2.5</sub> observations from the Automatic Urban and Rural Network (AURN) to assess model



79% of UK exceeds updated WHO guideline

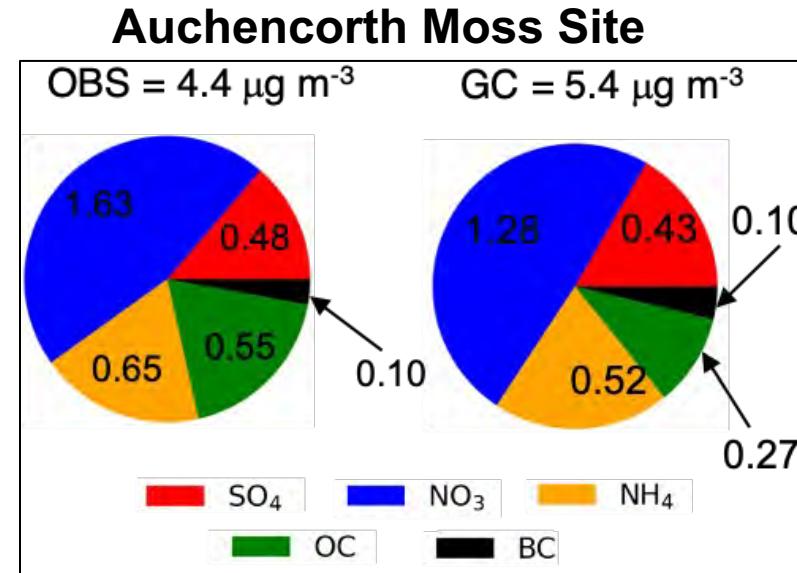
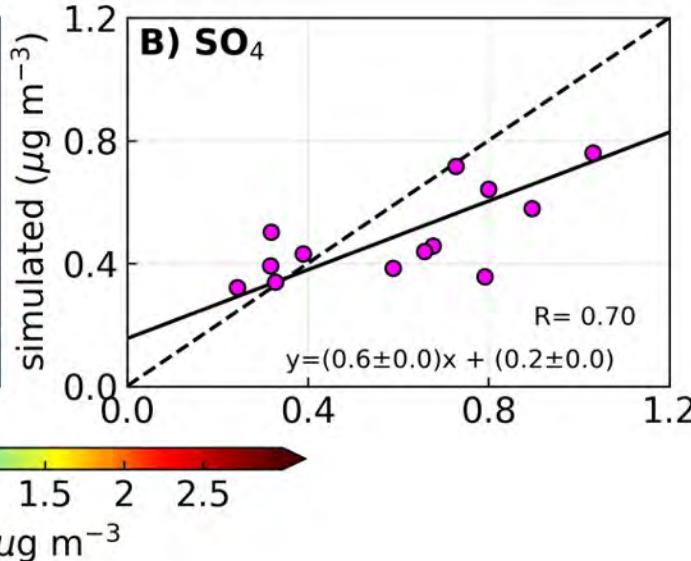
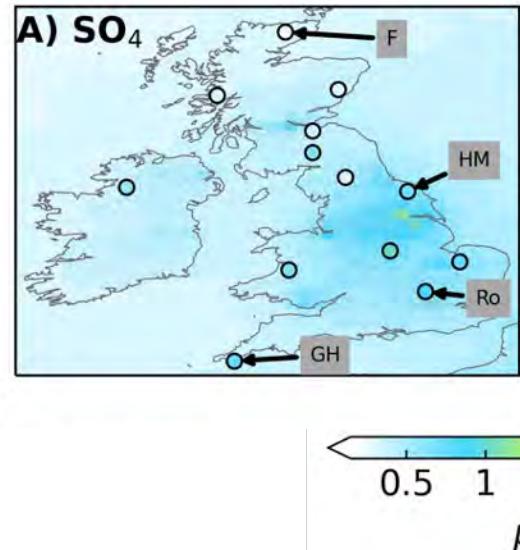
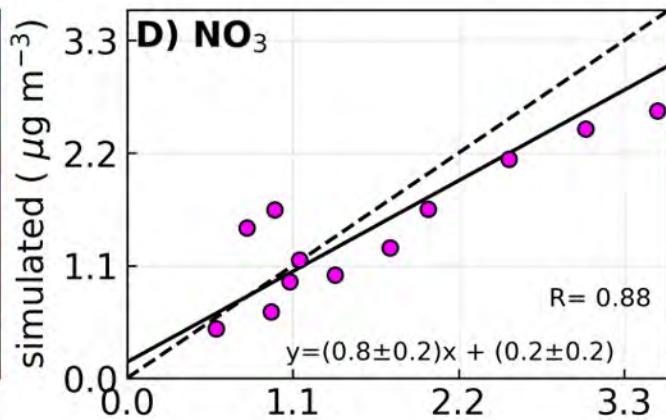
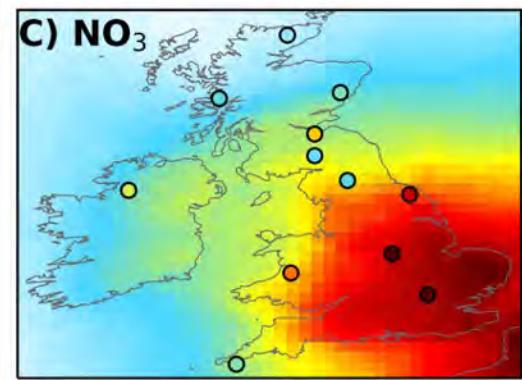
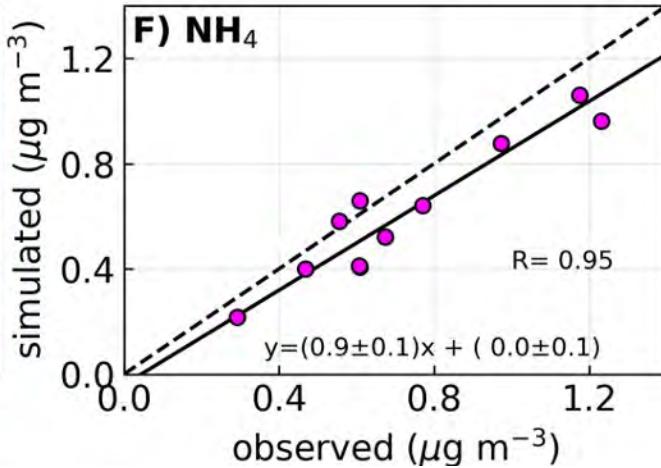
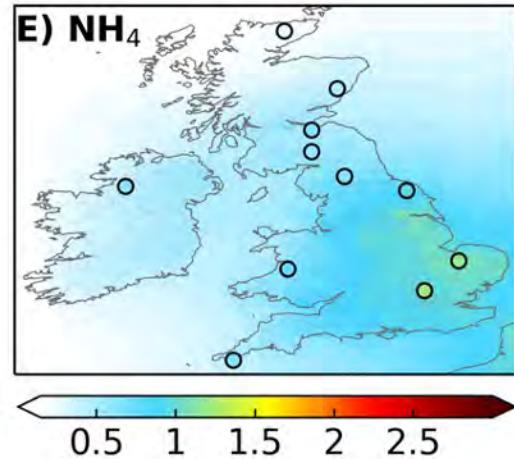
Compare annual mean surface concentrations of PM<sub>2.5</sub> for 2019



Consistent spatial pattern ( $R = 0.66$ ) and variance (slope = 1.0). Model 11% less than observations

# Assess Validity of Model using Permanent Networks

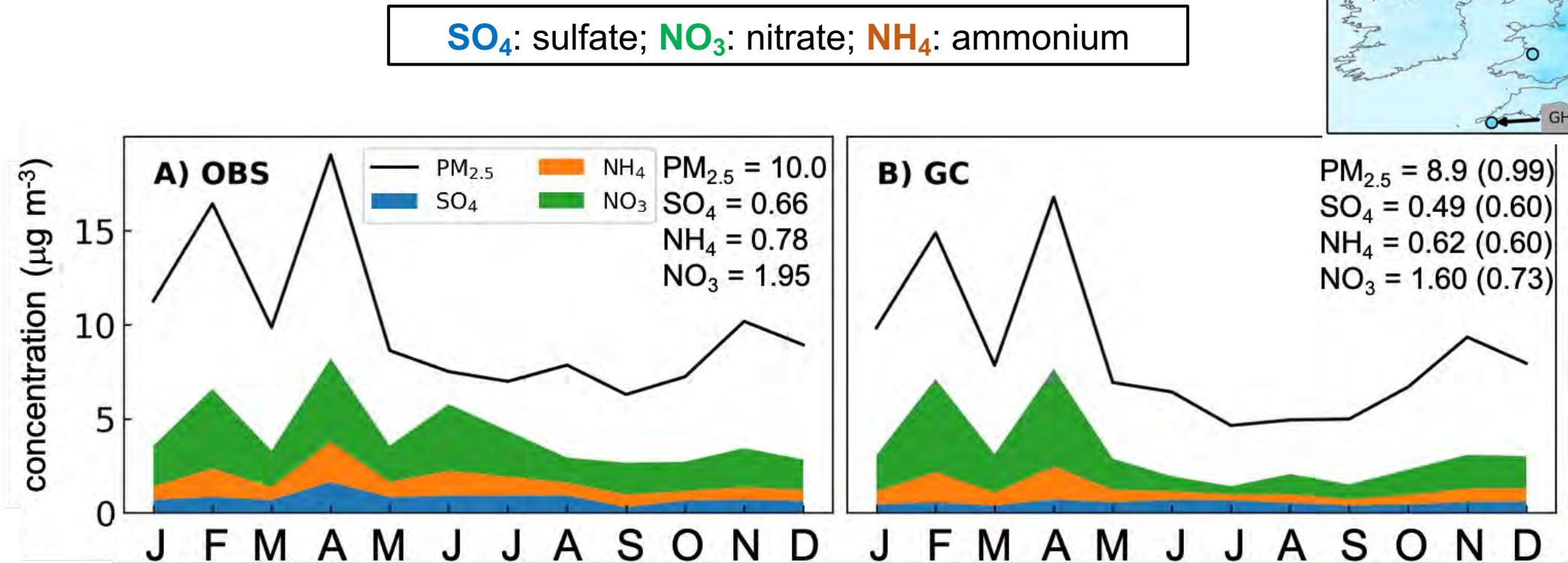
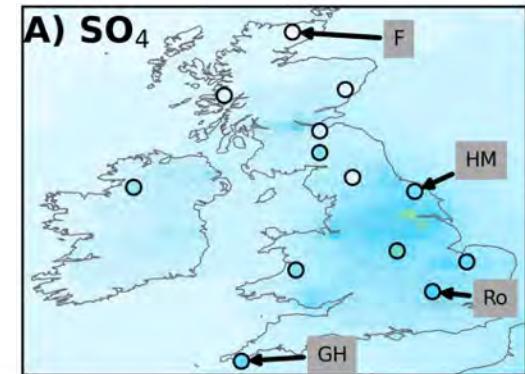
Use PM<sub>2.5</sub> composition measurements from UKEAP and EMEP sites to assess model



Model underpredicts observed (sulfate, nitrate, ammonium) and possibly overpredicts unobserved (dust) components. Model captures variance of components from NO<sub>x</sub> (nitrate) and ammonia (ammonium)

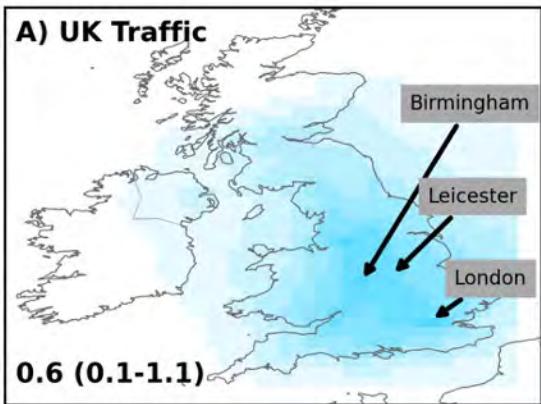
# Assess Validity of Model using Reference Monitors

Also evaluate model skill at reproducing observed seasonality in PM<sub>2.5</sub>

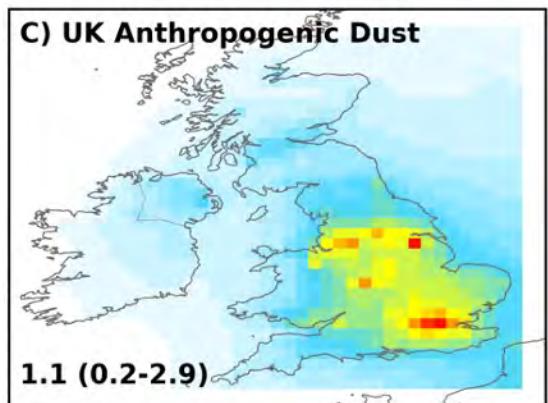
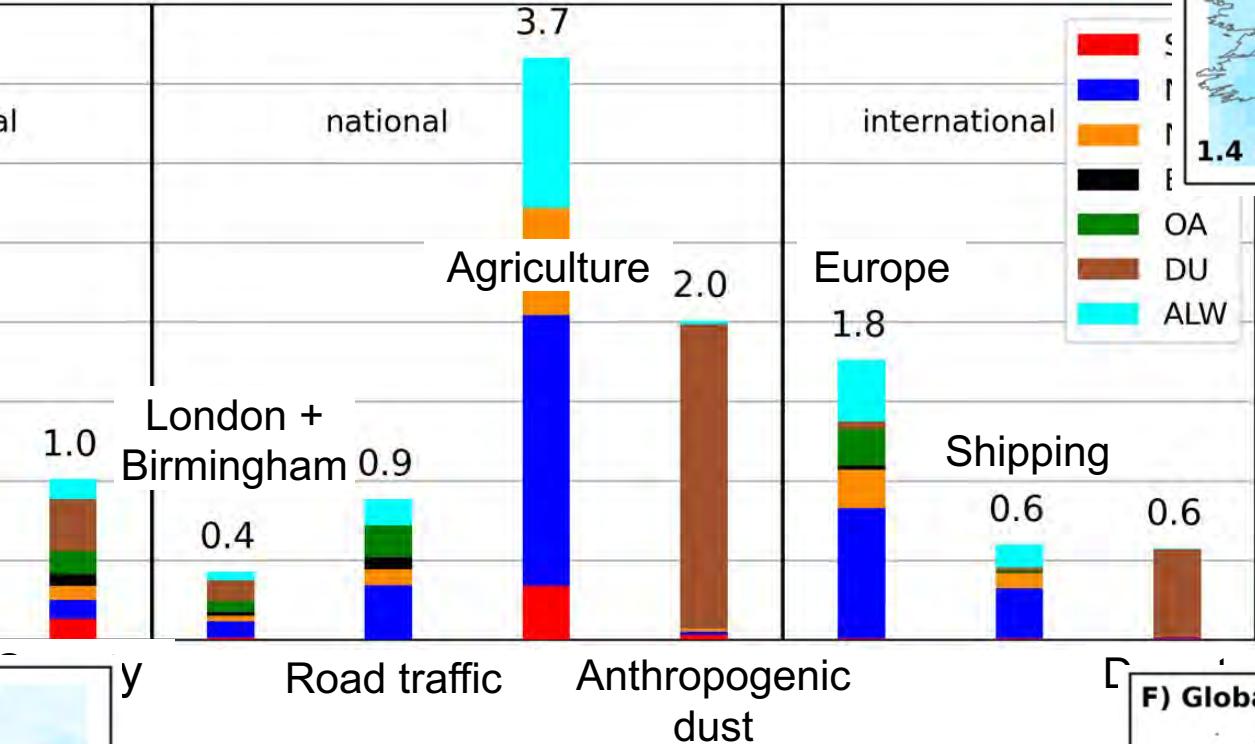
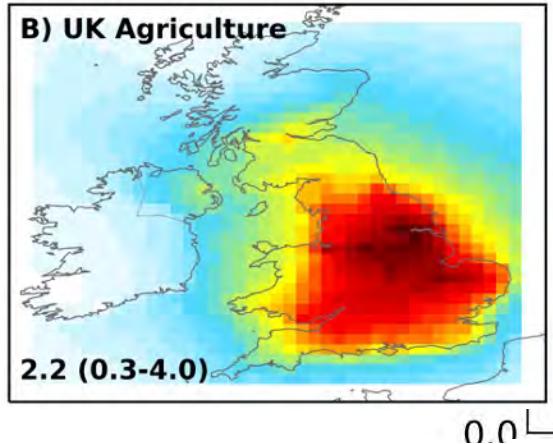
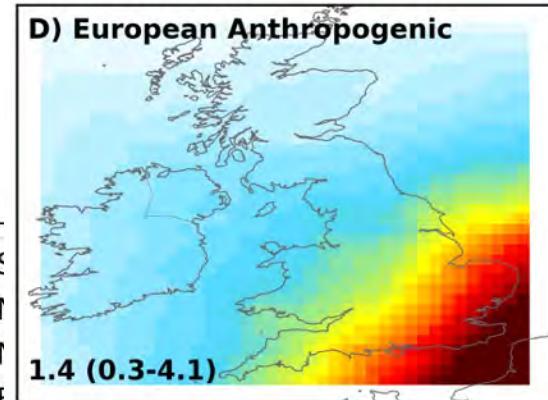


Enhancements in cold months and when ammonia emissions from agriculture peak due to application of synthetic fertilizer in March-April

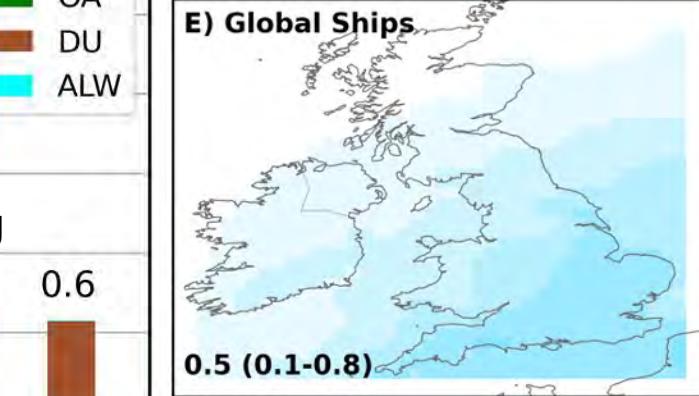
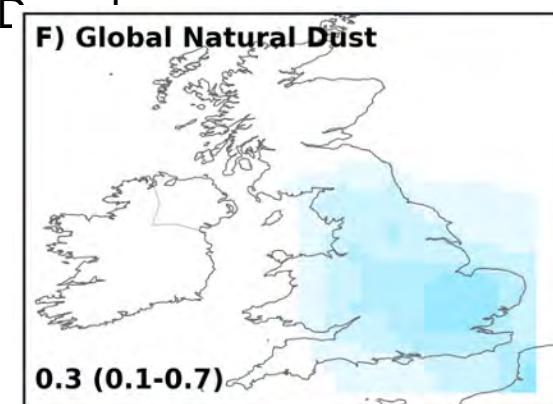
# Contribution of Sources to annual PM<sub>2.5</sub> in Leicester



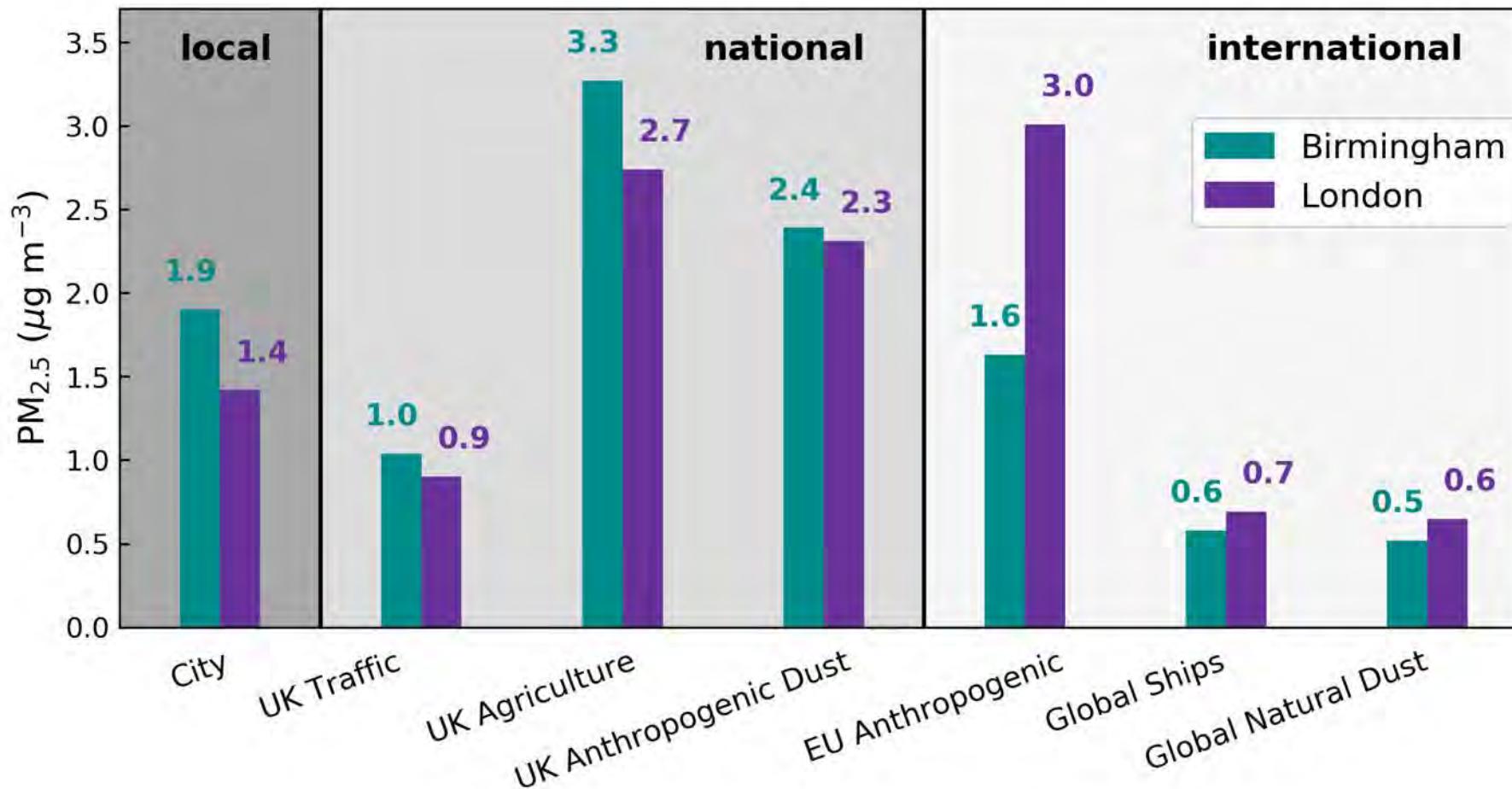
**SO<sub>4</sub>**: sulfate; **NO<sub>3</sub>**: nitrate; **NH<sub>4</sub>**: ammonium  
**BC**: black carbon; **OC**: organic carbon; **DU**: dust



Colour scale for maps of PM<sub>2.5</sub> in  $\mu\text{g m}^{-3}$



# Results for Large Cities like London and Birmingham



London: 1,600 km<sup>2</sup>  
Birmingham: 270 km<sup>2</sup>  
Leicester: 70 km<sup>2</sup>

Lower local than rural agricultural ammonia contribution even for large UK cities

# Takehome Messages So Far

- Spring and Summer peak in NH<sub>3</sub> emissions
- Inventories may underestimate NH<sub>3</sub> emissions, as missing summer peak
- Rural NH<sub>3</sub> large or dominant contributor to PM<sub>2.5</sub> in UK cities.
- Local controls have limited efficacy at addressing PM<sub>2.5</sub> pollution

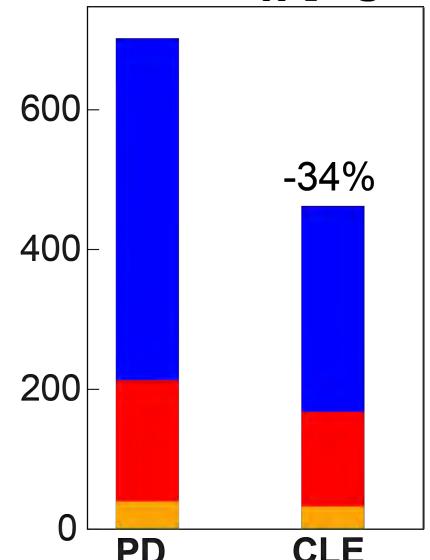
**How effective are current measures at decreasing PM<sub>2.5</sub>?**

# Emission Control Options for the UK (and EU)

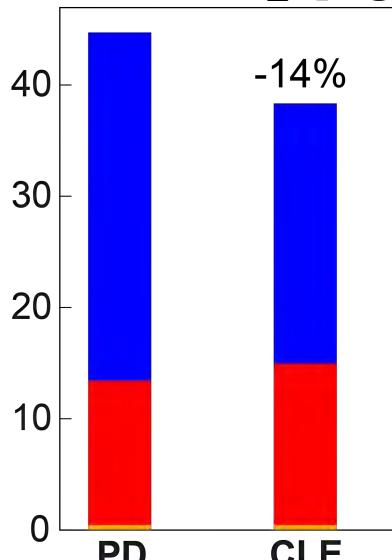
Legislated emissions targets (CLE)

Emissions for present-day or PD (2019) and future (2030) for legislation (CLE)

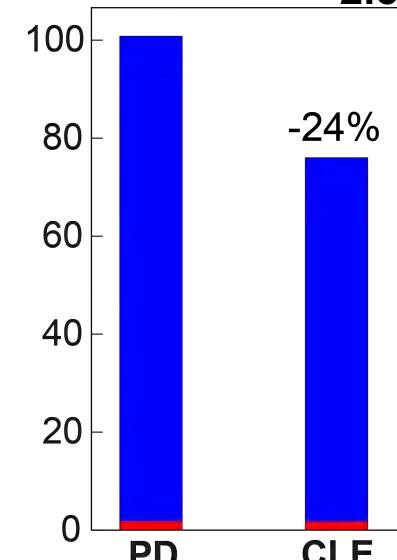
$\text{NO}_x$  [Gg NO]



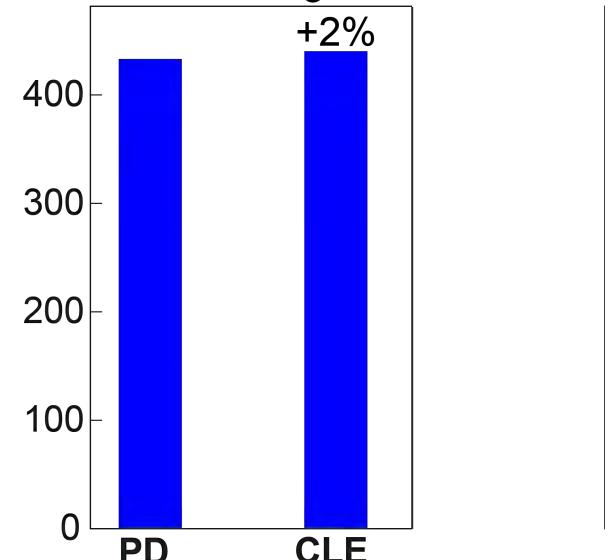
$\text{SO}_2$  [Gg S]



$\text{PM}_{2.5}$  [Gg]



$\text{NH}_3$  [Gg]



- Terrestrial Anthropogenic
- Shipping
- Aviation

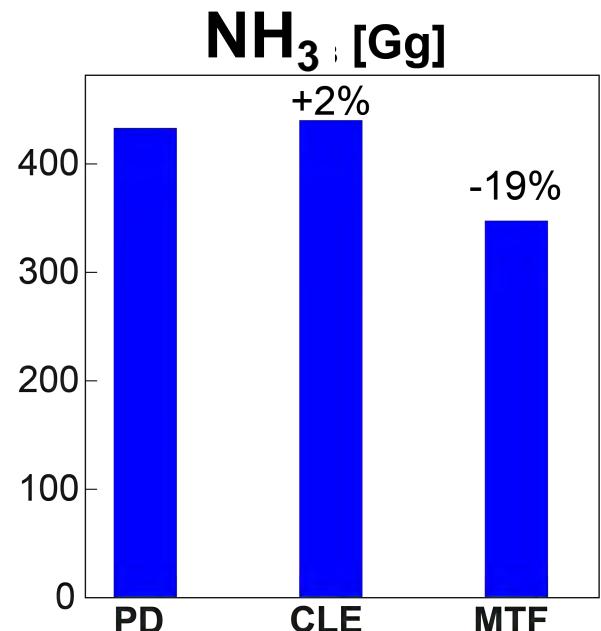
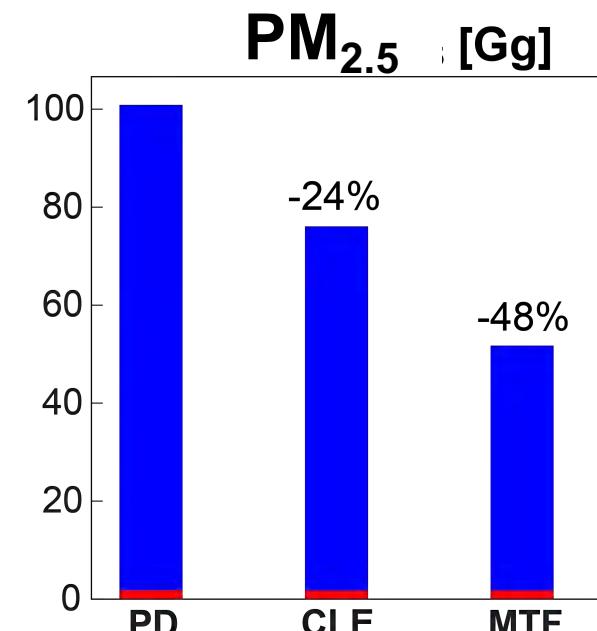
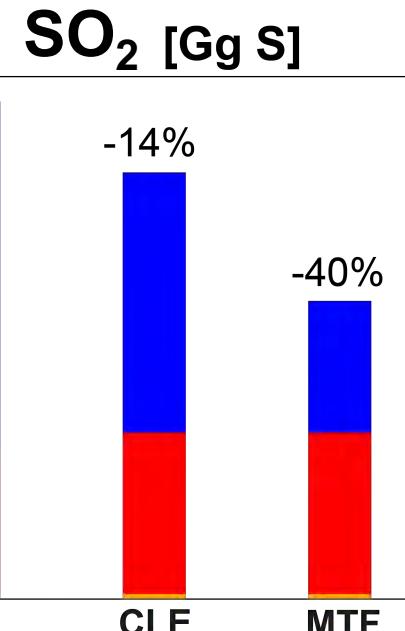
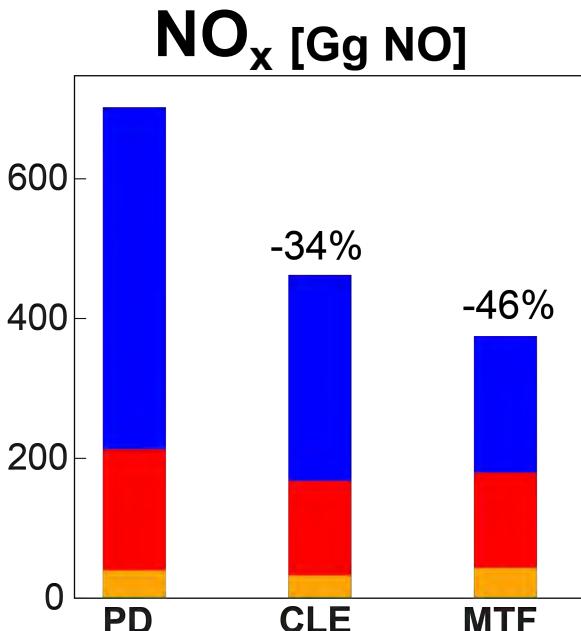
Projections from **ECLIPSE v6b** for all but aviation (from **IPCC**)

NH<sub>3</sub> emissions increase, as controls insufficient to curtail increases from growth in demand

# Emission Control Options for the UK (and EU)

Adoption of best best, readily available technology (**MTF**)

Emissions for present-day (2019) and future (2030) for legislation (**CLE**) vs best-available technology (**MTF**)



- Terrestrial Anthropogenic
- Shipping
- Aviation

Projections from **ECLIPSE v6b** for all but aviation (from **IPCC**)

Best technology decreases all precursors except ammonia (NH<sub>3</sub>) by 40-48%

NH<sub>3</sub> controls limited to suggested rather than enforced measures

# Influence of emissions controls on PM<sub>2.5</sub>, NH<sub>3</sub>, and N deposition

## Emissions

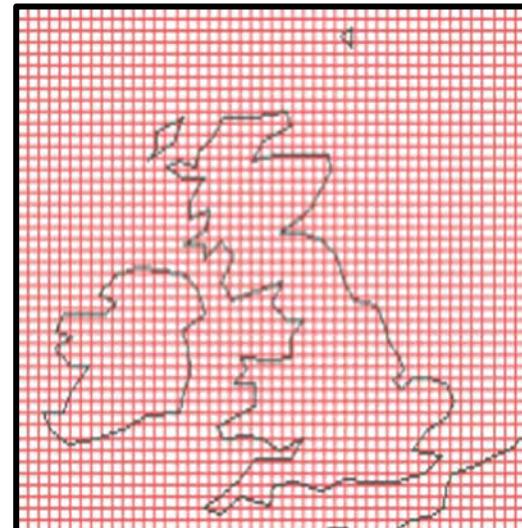


**Present-day:** UK National Atmospheric Emission Inventory (NAEI)

**Future:** scale NAEI with projections

## GEOS-Chem

FlexGrid nested over the UK at 0.25° x 0.3125°



Gas- and aerosol-phase chemistry,  
transport, wet+dry deposition

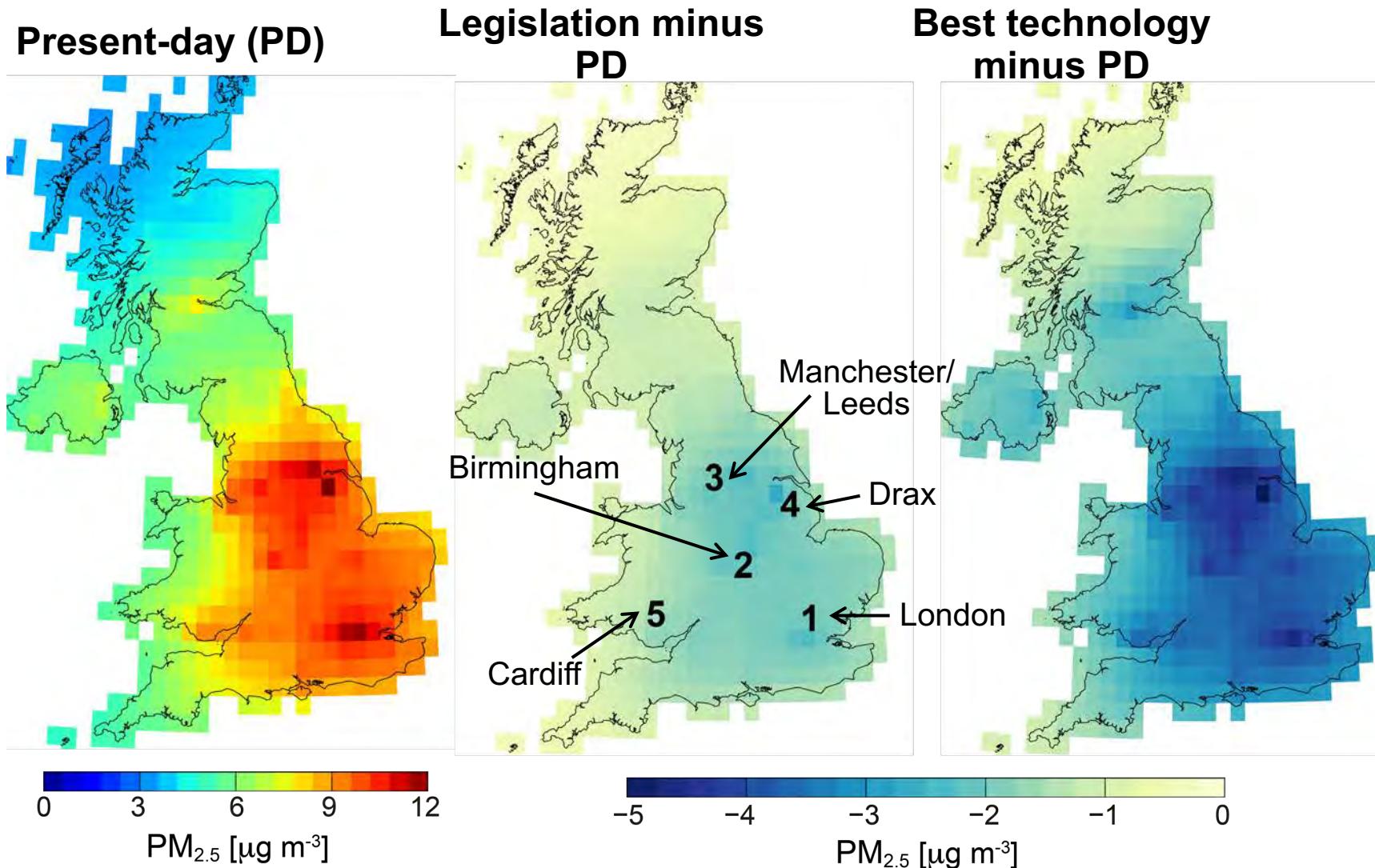


**NASA GEOS-FP  
Meteorology**

2019  
throughout

**Surface NH<sub>3</sub> and PM<sub>2.5</sub> components  
Nitrogen wet and dry deposition**

# Influence of emission controls on PM<sub>2.5</sub>

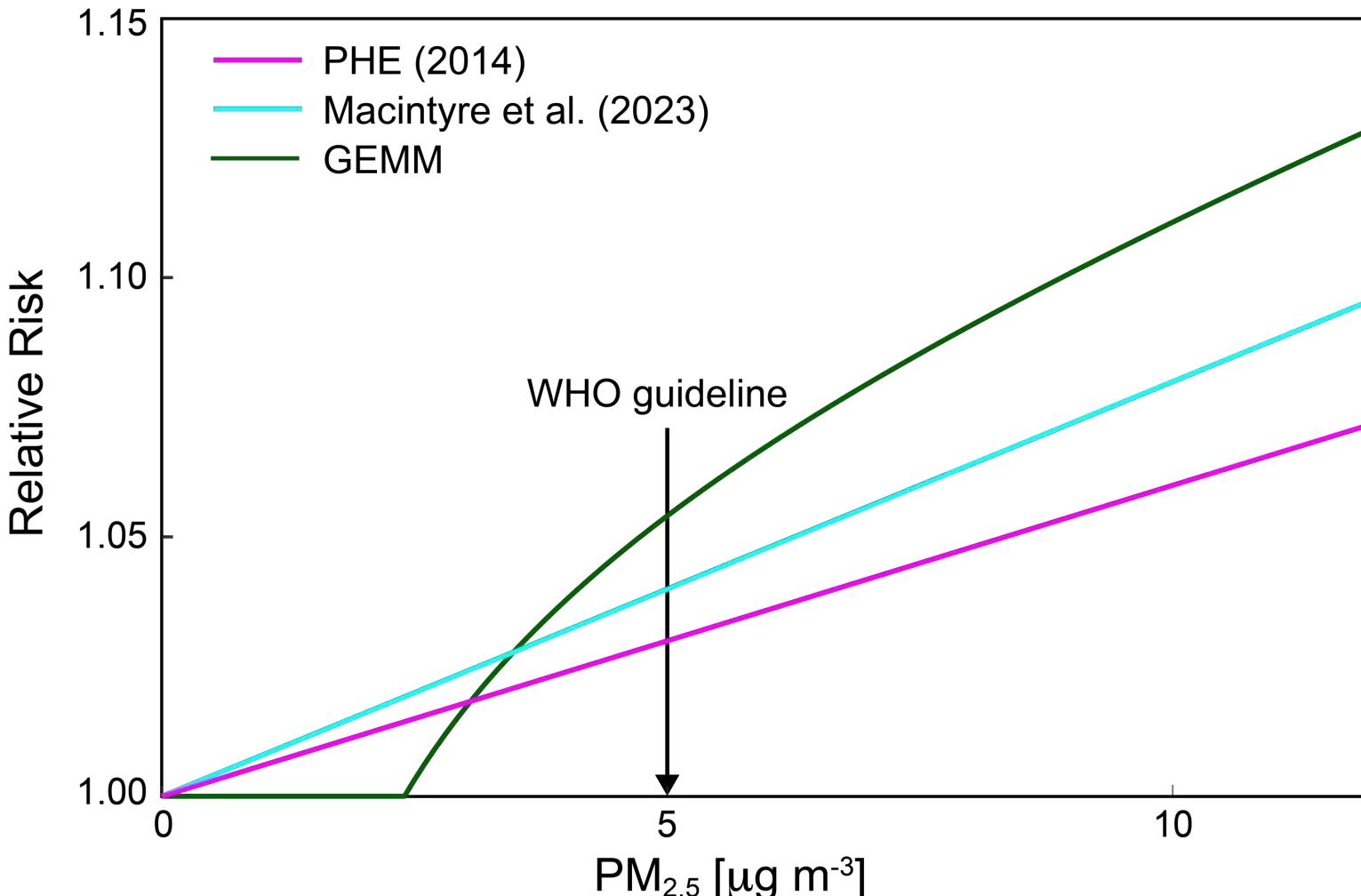


Current legislation controls cause PM<sub>2.5</sub> decline of at most **2  $\mu\text{g m}^{-3}$**  compared to **5  $\mu\text{g m}^{-3}$**  for best technology  
UK grids > 5  $\mu\text{g m}^{-3}$ : 79% in the PD, 58% with legislated controls, and 36% with best technology

# Relating long-term exposure to PM<sub>2.5</sub> to adverse health outcomes

Available curves relating PM<sub>2.5</sub> to premature mortality unconstrained at PM<sub>2.5</sub> < 5 µg m<sup>-3</sup>

UK PM<sub>2.5</sub> range is 2.5-12 µg m<sup>-3</sup>



**PHE (2014):**  
Public Health England report

**MacIntyre et al. (2023):**  
doi:10.1016/j.envint.2023.107862

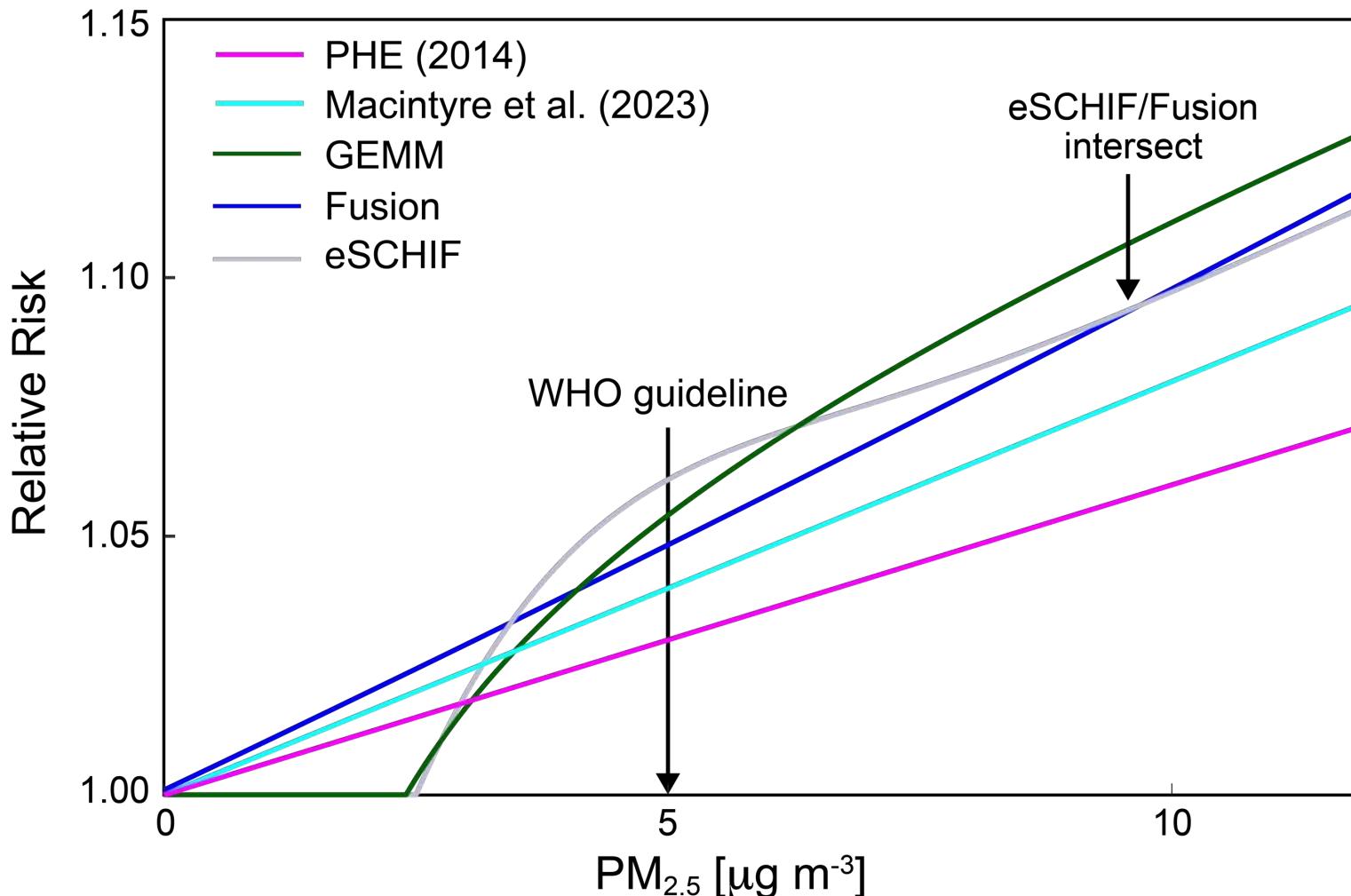
**GEMM:**  
Global Exposure Mortality Model

All curves relate adult (mostly 25+ years old) premature mortality and annual mean PM<sub>2.5</sub>

# Relating long-term exposure to PM<sub>2.5</sub> to adverse health outcomes

Recent curves combine best of 3 well-established curves (Fusion)

Recent epidemiological study in Canada (CanCHEC) provides low-concentration constraints (eSCHIF curve)



## Fusion:

Burnett et al. (2022), doi:  
10.1016/j.envres.2021.112245

## eSCHIF:

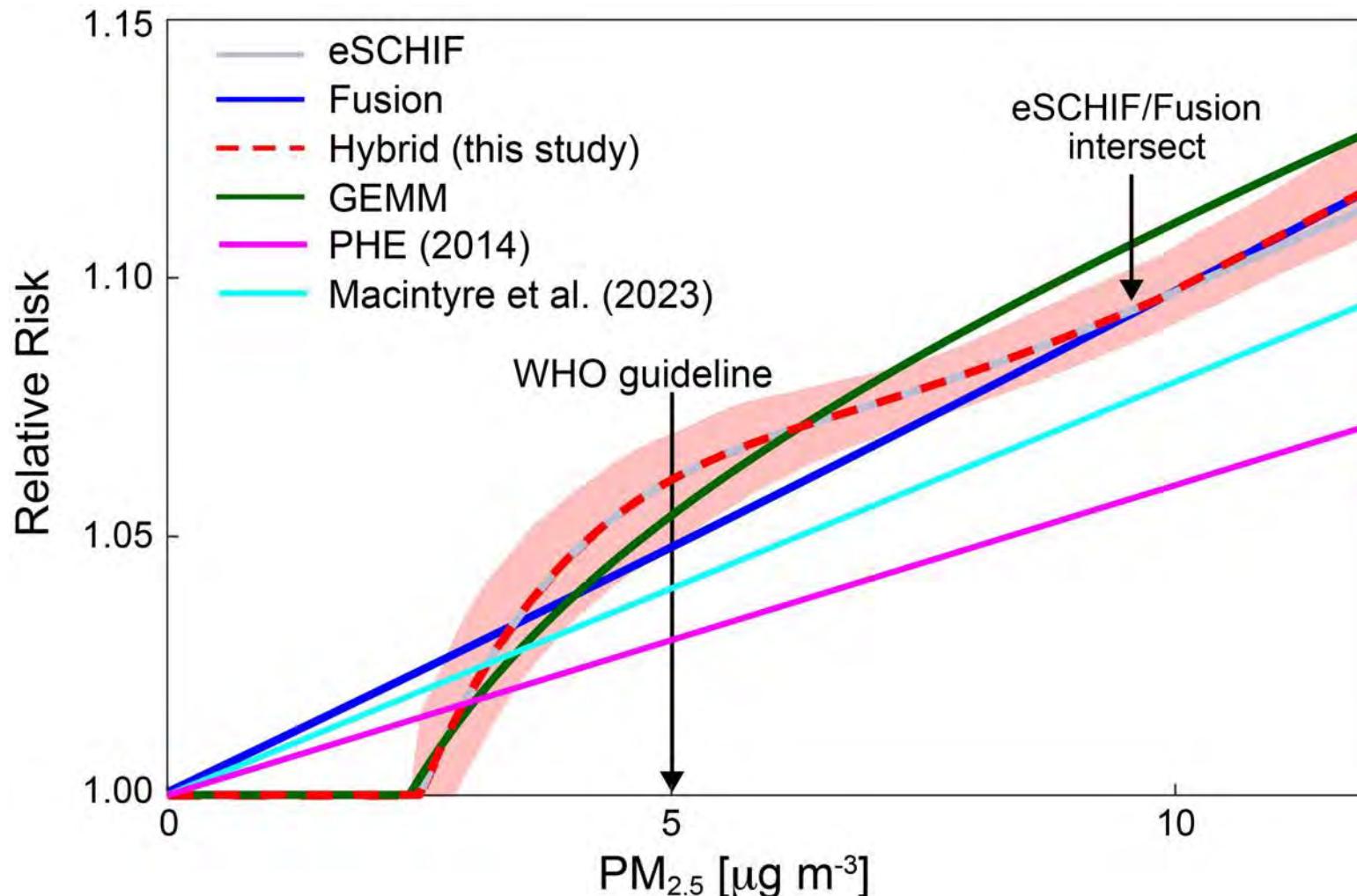
extended Shape Constrained  
Health Impact Function (Brauer et  
al., 2022 US HEI report)

Fusion addresses deficiencies in  
individual curves

# Relating long-term exposure to PM<sub>2.5</sub> to adverse health outcomes

Hybrid curve combines Fusion and CanCHEC

Approach motivated by Weichenthal et al. (2022)



## Hybrid:

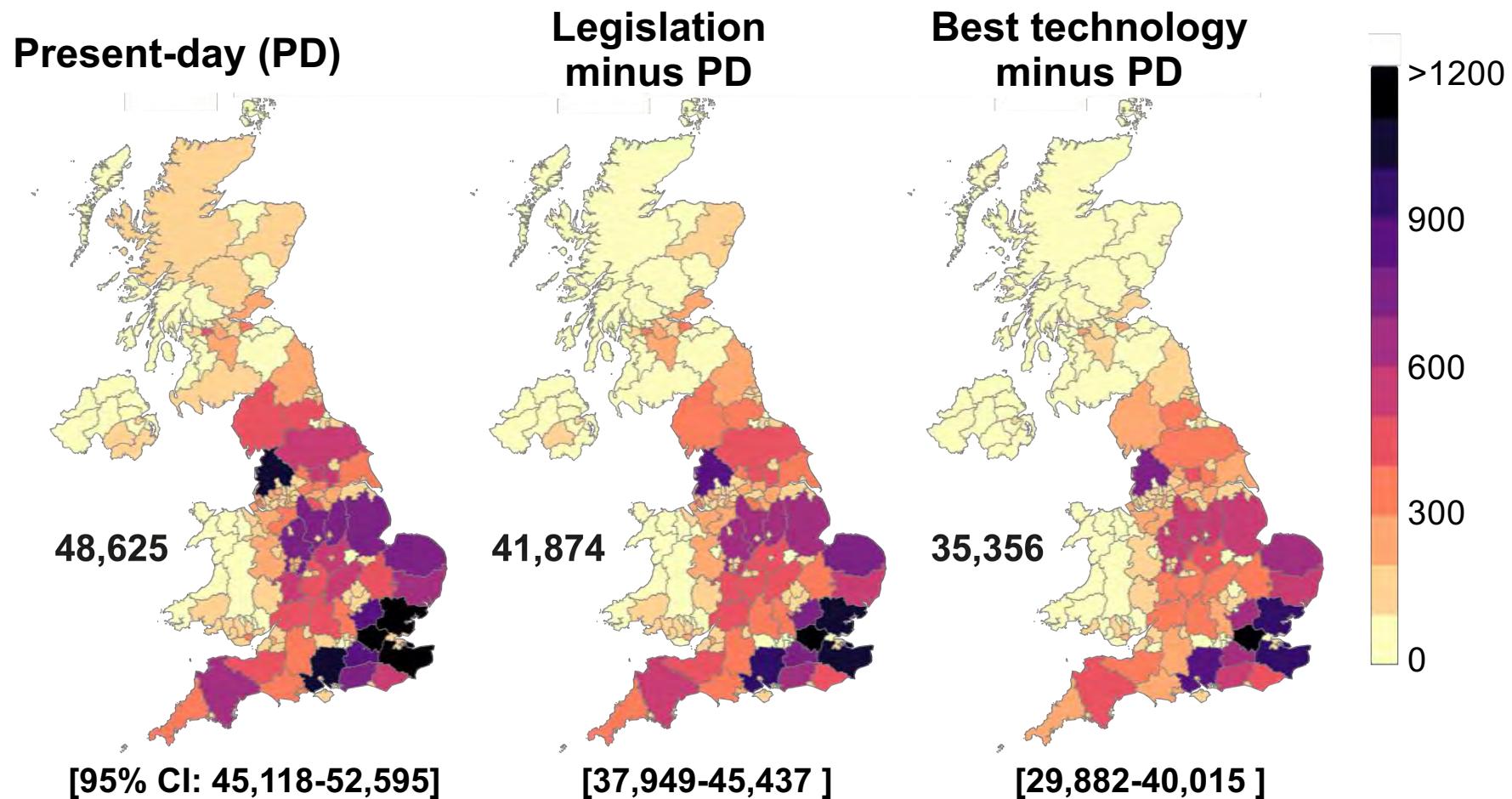
eSCHIF at 2.5-9.8  $\mu\text{g m}^{-3}$  and  
Fusion beyond 9.8  $\mu\text{g m}^{-3}$

Weichenthal et al. (2022) transition  
between curves at 5  $\mu\text{g m}^{-3}$   
requiring an artificial increase in  
Fusion Relative Risks

85% of UK grids use eSCHIF in the present day; 100% in future for both scenarios. None are < 2.5  $\mu\text{g m}^{-3}$

# Adult premature mortality from long-term exposure to PM<sub>2.5</sub>

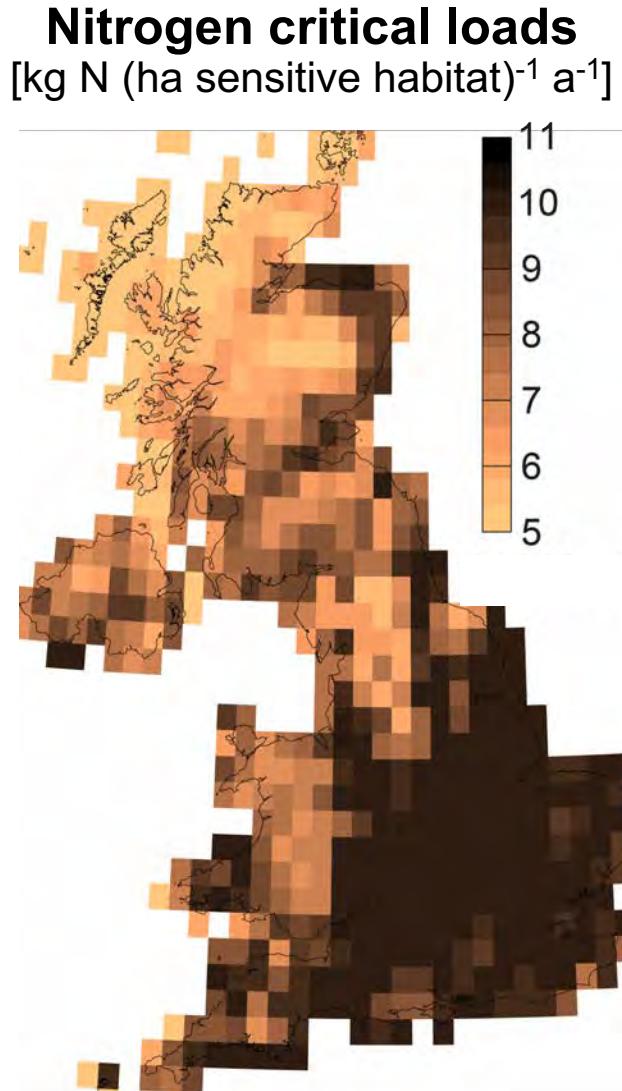
Values for all 184 administrative areas in the UK (115 in England, 32 in Scotland, 22 in Wales, 11 in N. Ireland)



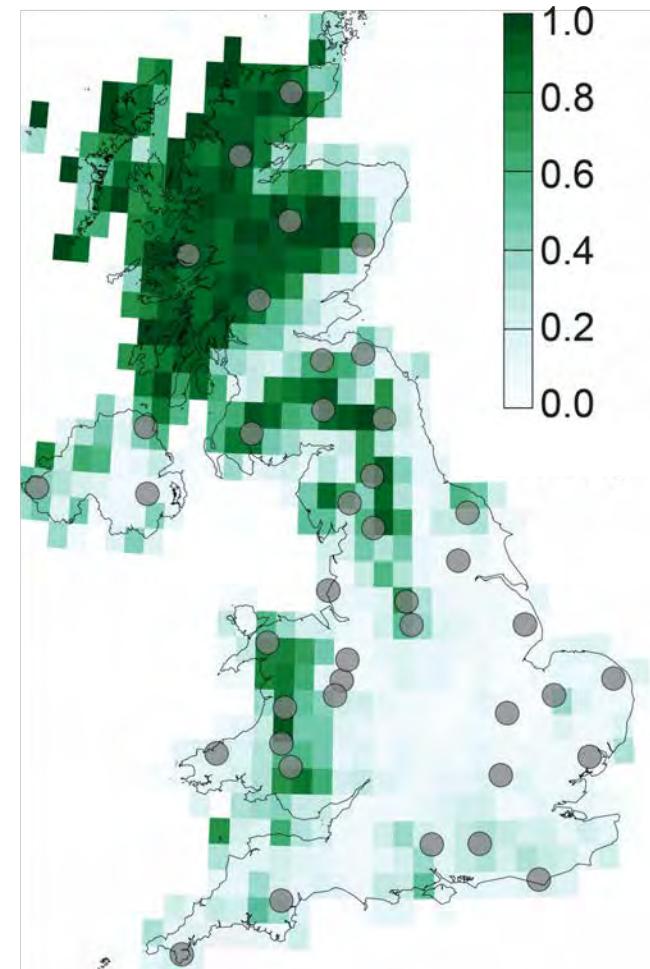
6,751 avoided early deaths with legislated controls, double that (3,269) with best available technology

Burden of disease estimates greater than past UK-focused studies and similar to those obtained with GEMM curve

# Assessing Adverse Effects on Ecosystem Health



**Sensitive habitat cover**  
[fraction]



- 13 sensitive habitats cover 38% of UK. ~60% in Scotland.
- Use very recently revised critical loads

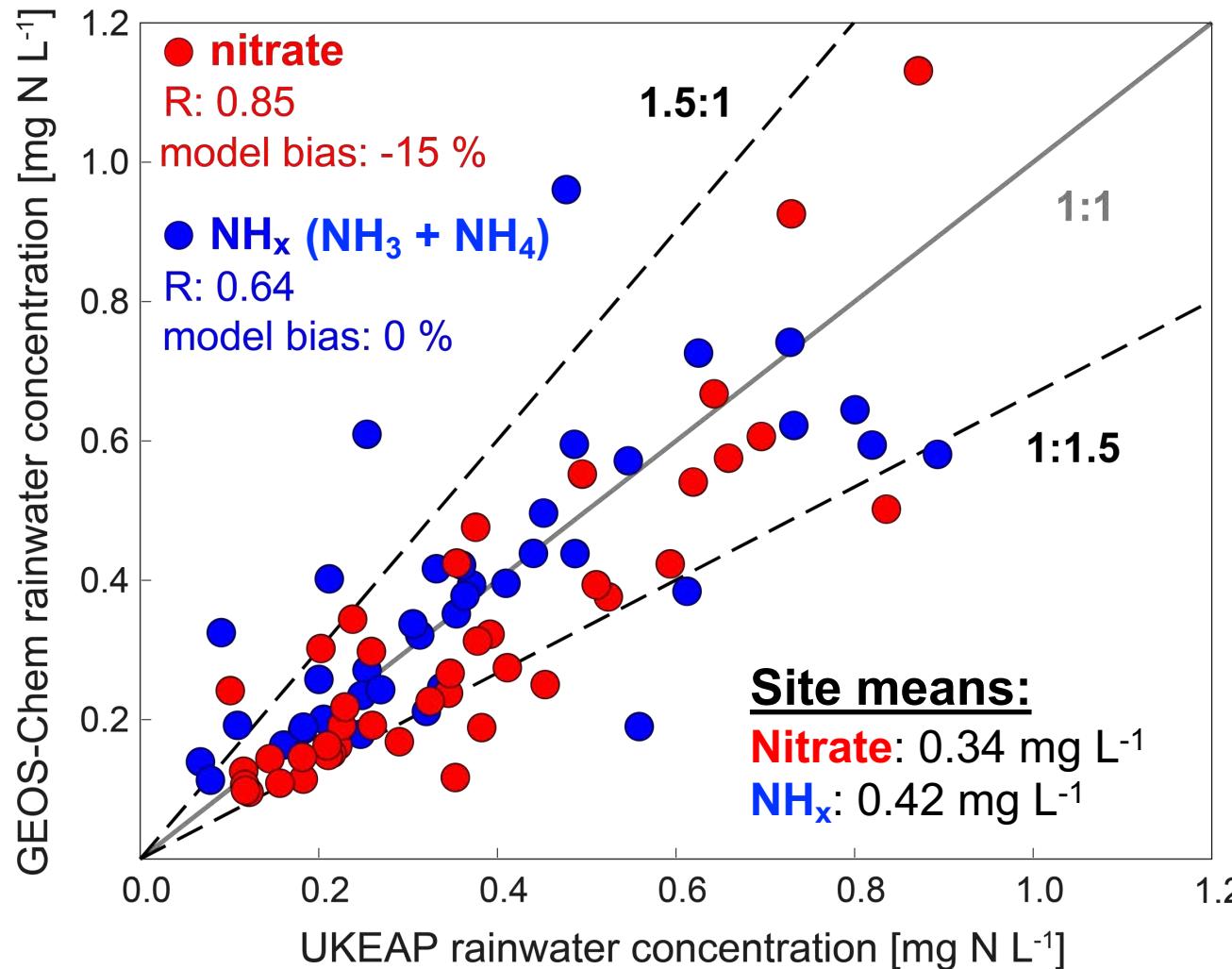
Critical load and sensitive habitat maps from Ed C. Rowe & N. Hina at the UK Centre for Ecology & Hydrology (UKCEH)

Quantify annual total nitrogen wet and dry deposition in excess of critical loads

Also assess impact of ambient NH<sub>3</sub> on bryophytes (NH<sub>3</sub> > 1 µg m<sup>-3</sup>)

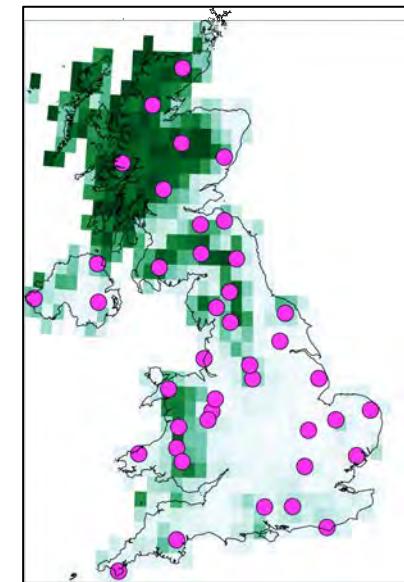
# Evaluate GEOS-Chem nitrogen wet deposition

Modelled vs observed rainwater concentrations of oxidized and reduced nitrogen



Dashed lines  
bound 50%  
difference

Precip-Net sites



Requires correction to monthly total  
GEOS-FP precipitation  
Ranges from 40-50% increase to 23-  
26% decrease.  
GEOS-FP annual total increases by 4%

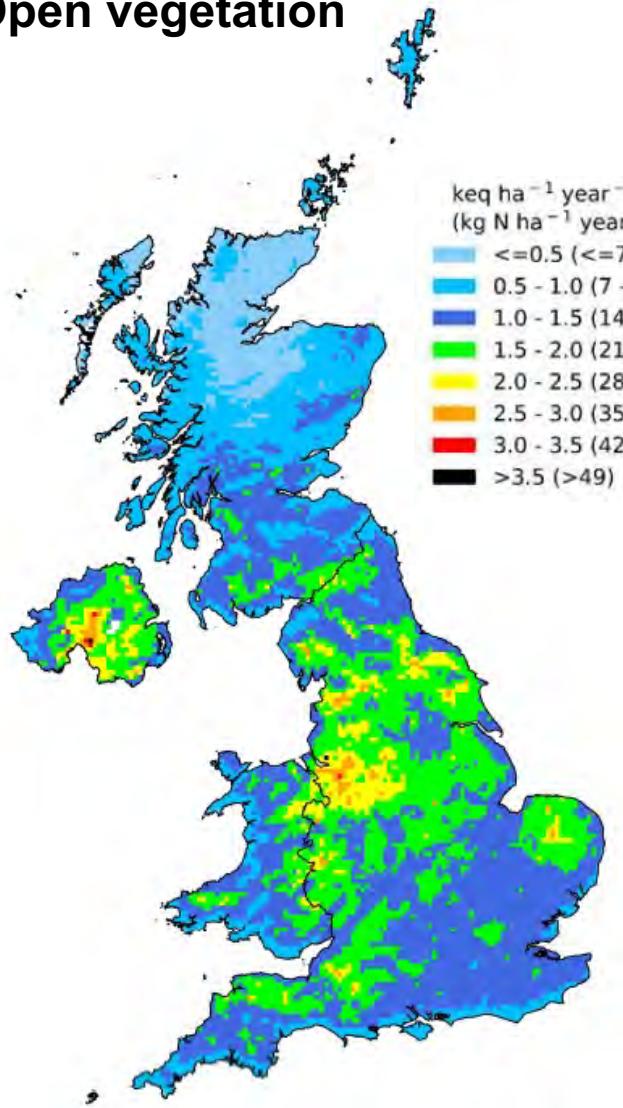
Model 15% underestimate in nitrate may be due to low bias in  $\text{NO}_x$  emissions

Wet deposition ~60% of total deposition. Unvalidated ~40% dry deposition mostly (64%)  $\text{NH}_3$ .

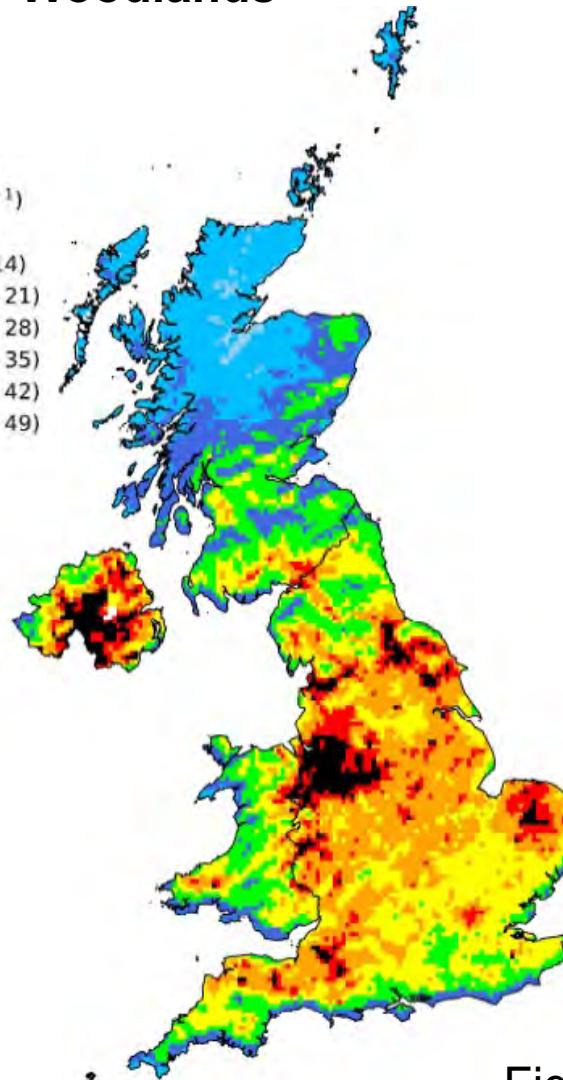
# High Resolution Total Nitrogen Wet + Dry Deposition

UKCEH Concentration Based Estimated Deposition at high (5 km) spatial resolution

Open vegetation



Woodlands



GEOS-Chem too coarse to resolve deposition over sensitive habitats

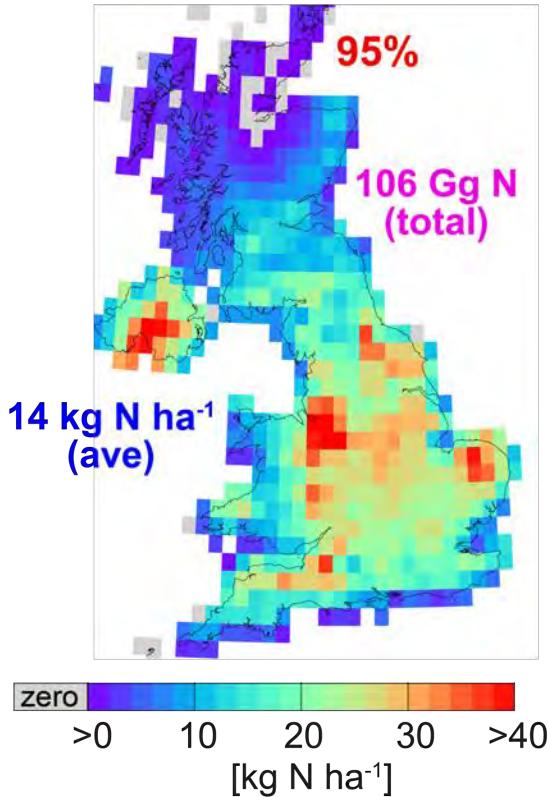
GEOS-Chem also doesn't account for enhanced washout over upland areas or deposition of cloud droplets to vegetation.

GEOS-Chem total N deposition 57 Gg N less than CBED

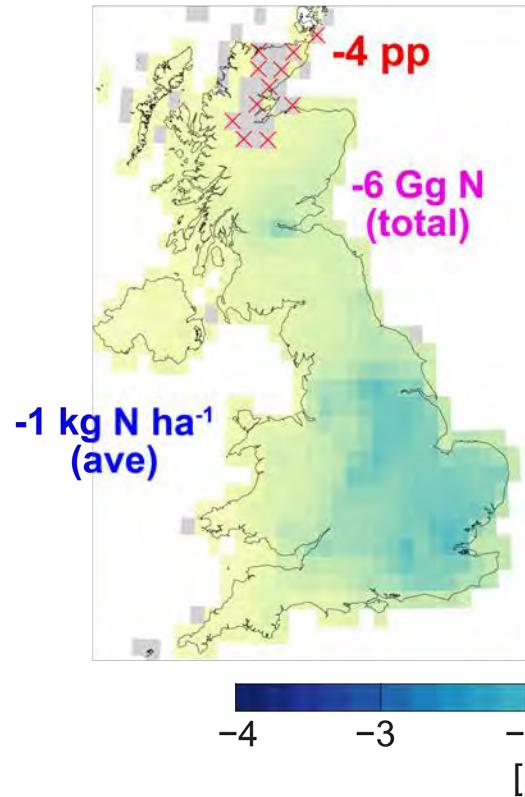
Use CBED for present day and GEOS-Chem for response to emissions controls

# Ecosystem health benefits of emission controls

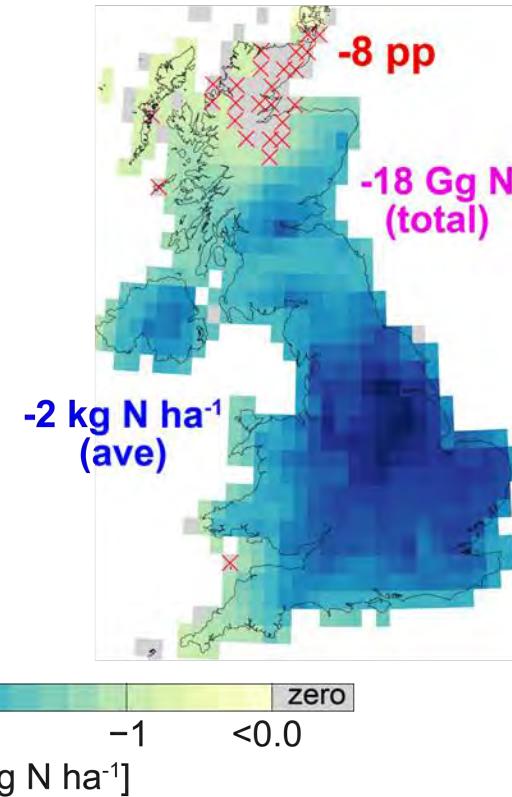
Present-day (PD)



Legislation minus PD



Best technology minus PD



Values are **total**, **mean**, and **coverage** of exceedances

Crosses show grids that fall below critical loads relative to present day

According to GEOS-Chem, more than half (60%) emitted nitrogen transported offshore

Decline in N deposition with emission controls only one-third of emissions reductions

Decline below critical loads modest. Similarly modest decrease due to past controls (2010-2019)

Exposure to harmful levels of NH<sub>3</sub>: 73% today, 75% with legislated controls, 69% with best technology

# Takehome Messages

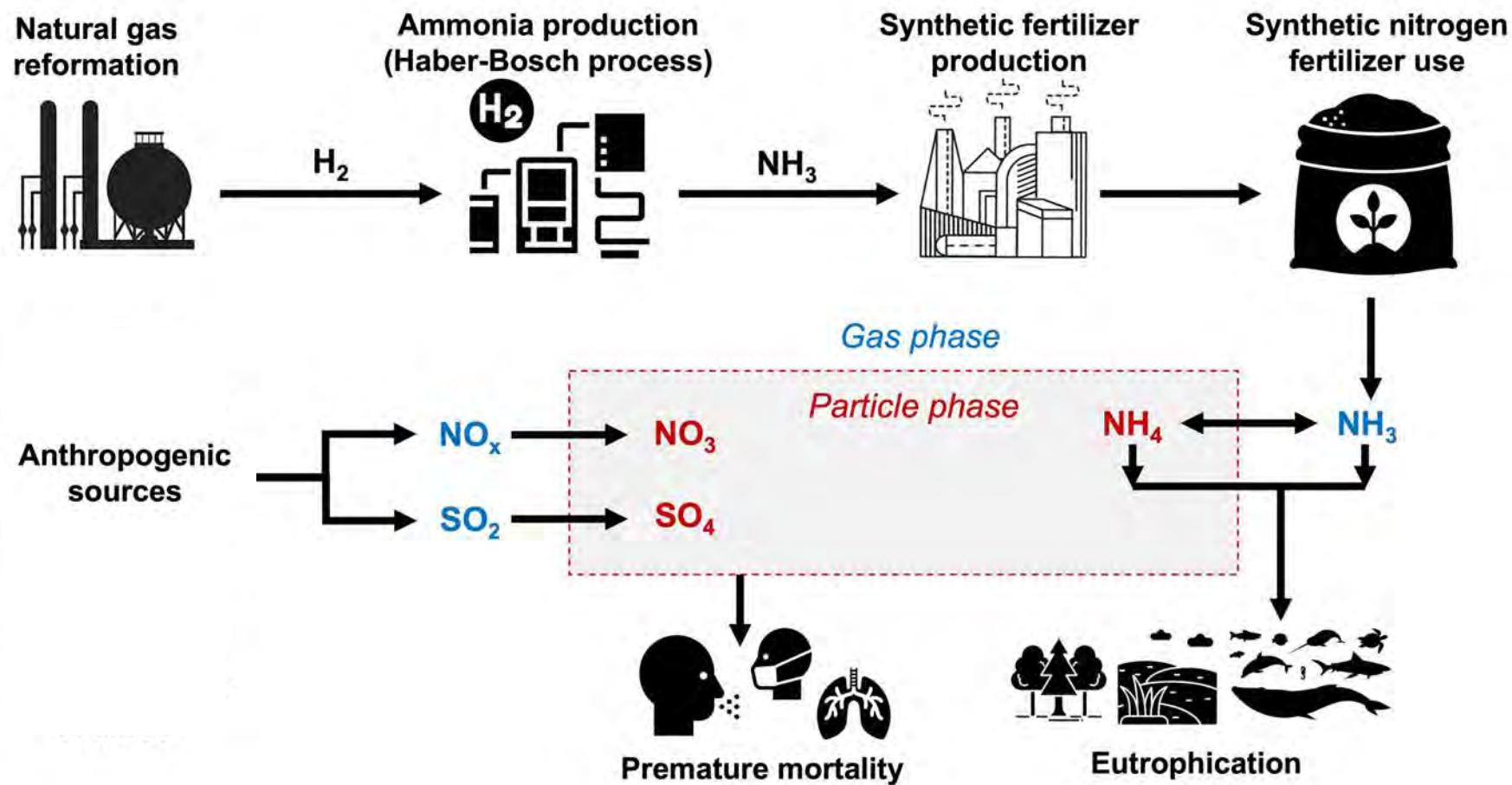
- Spring and Summer peak in NH<sub>3</sub> emissions
- Inventories may underestimate NH<sub>3</sub> emissions, as missing summer peak
- Rural NH<sub>3</sub> large or dominant contributor to PM<sub>2.5</sub> in UK cities.
- Local controls have limited efficacy at addressing PM<sub>2.5</sub> pollution
- Substantial improvements to public health with emission controls, especially adoption of best available measures
- Decline in harm to sensitive habitats negligible to modest

**Satellite derived emissions:** JGR: Atmospheres, 2021 (doi:10.1029/2021JD035237)

**Urban PM<sub>2.5</sub>:** City & Environment Interactions, 2023 (doi:10.1016/j.cacint.2023.100100)

**Emission controls:** GeoHealth, 2023 (doi:10.1029/2023GH000910)

# Health burden of fossil-fuel derived synthetic nitrogen fertilizer

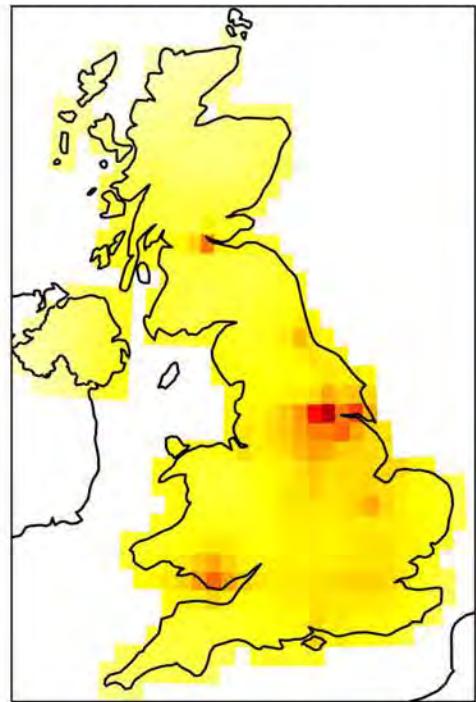


Overwhelming majority of synthetic nitrogen fertilizer from natural gas

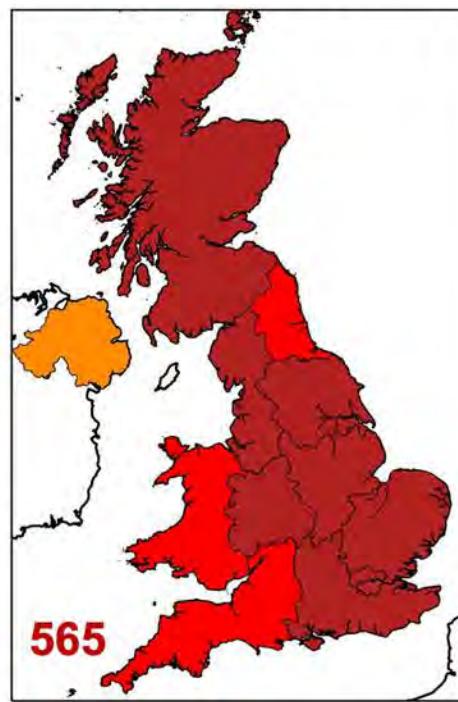
[Vohra et al., in progress]

# Health burden of fossil-fuel derived synthetic nitrogen fertilizer

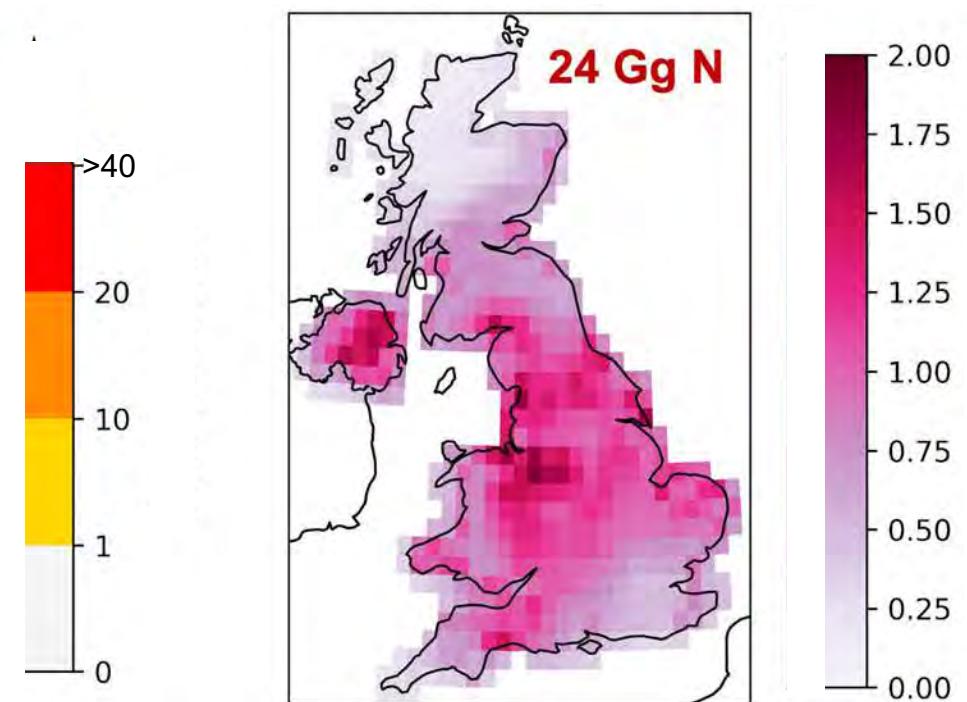
Annual mean  $\text{PM}_{2.5}$  [ $\mu\text{g m}^{-3}$ ]



$\text{PM}_{2.5}$ -attributable early deaths



Nitrogen deposition [ $\text{kg ha}^{-1} \text{a}^{-1}$ ]



Total attributable to  $\text{PM}_{2.5}$  is 48,625. Total attributable to all oil and gas end use activities is 3,671, so synthetic nitrogen fertilizer is ~15% of all O&G end use activities