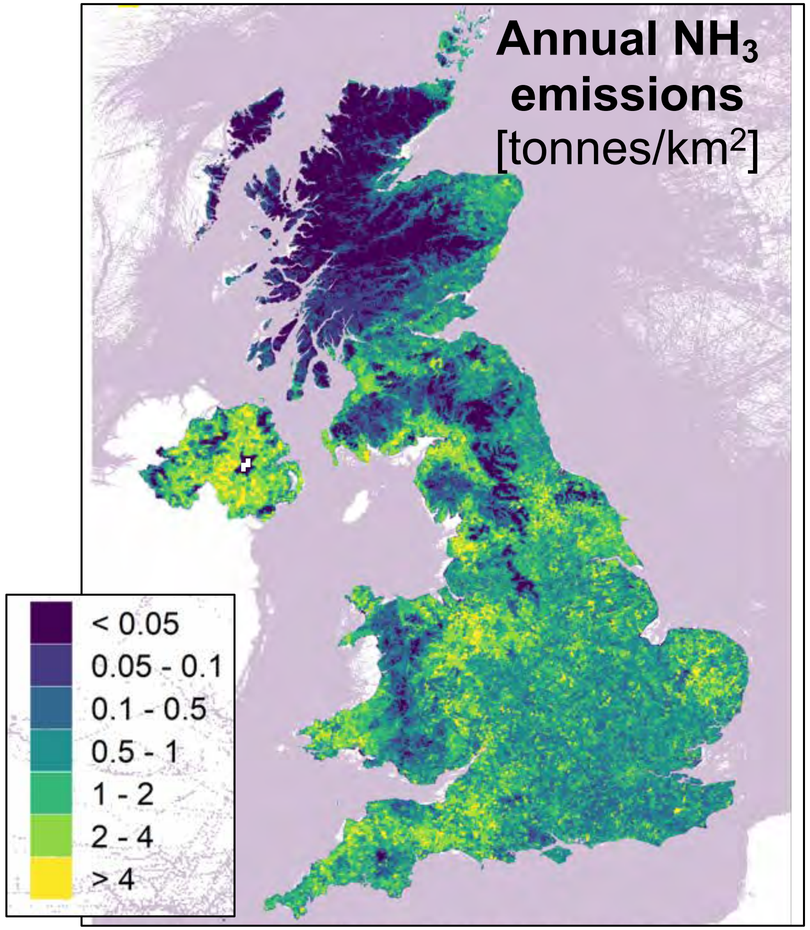
Impact of UK farming on air quality, health and habitats

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_3 emissions overwhelming from farming

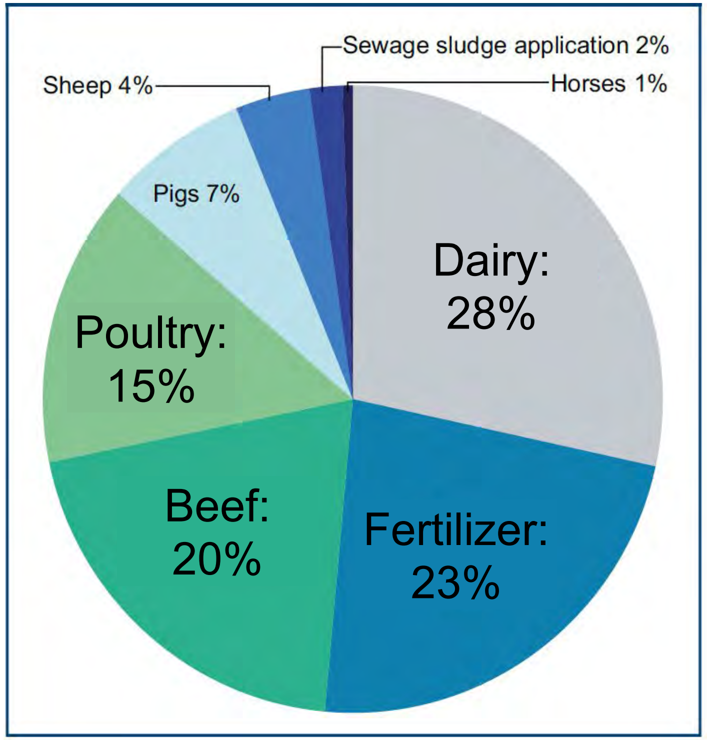
Spatial distribution of NH_3 emissions



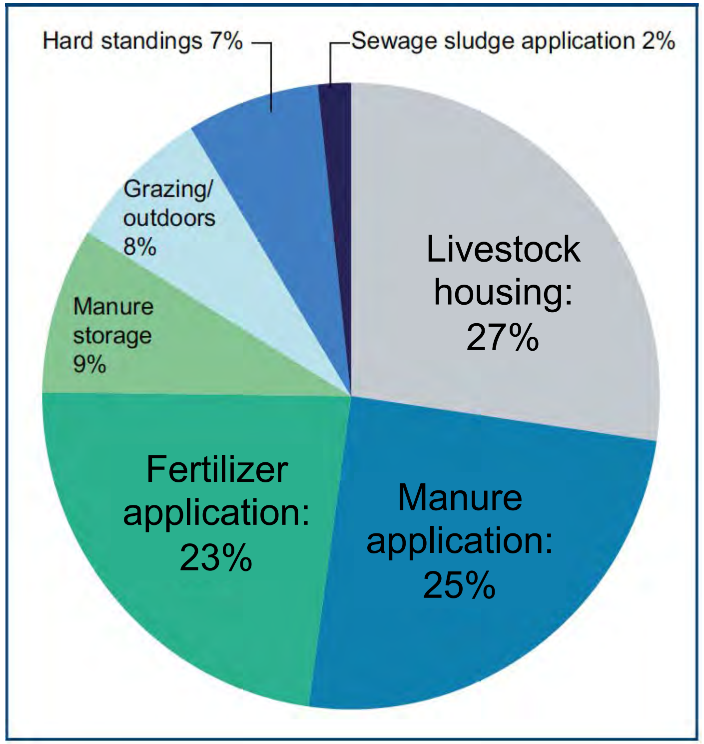
[https://naei.beis.gov.uk/data/map-uk-das?pollutant_id=21]

UK NH_3 Emissions by activity and category

by farming activity

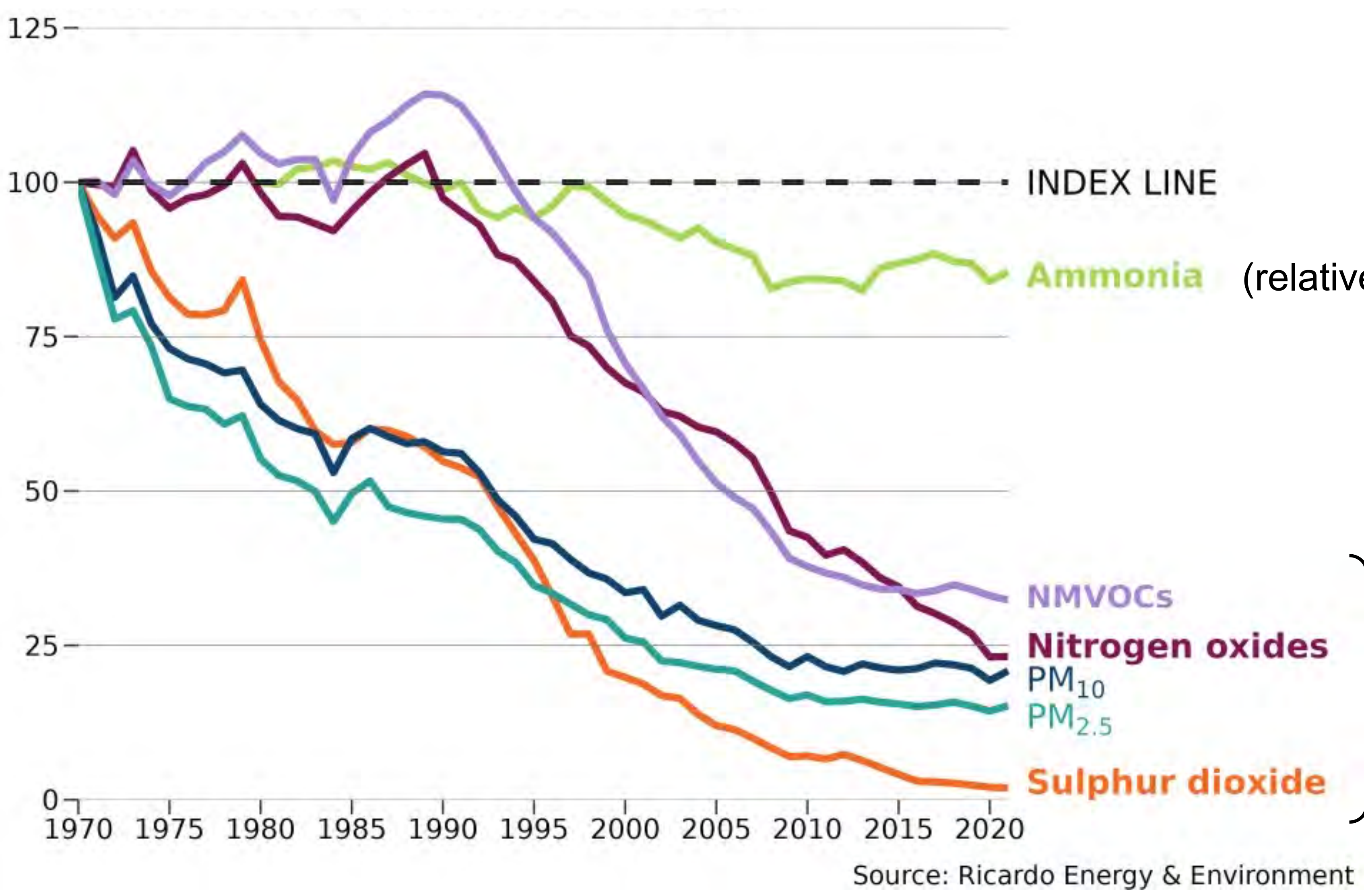


by management category



[UK Clean Air Strategy, 2019]

UK NH_3 emissions changes compared to other precursors



(relative to 1980)

(relative to 1970)

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

UK NH_3 Emissions Regulations

UNECE LRTAP Long-range Transboundary Air Pollution

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

Alter the inventory to meet the targets

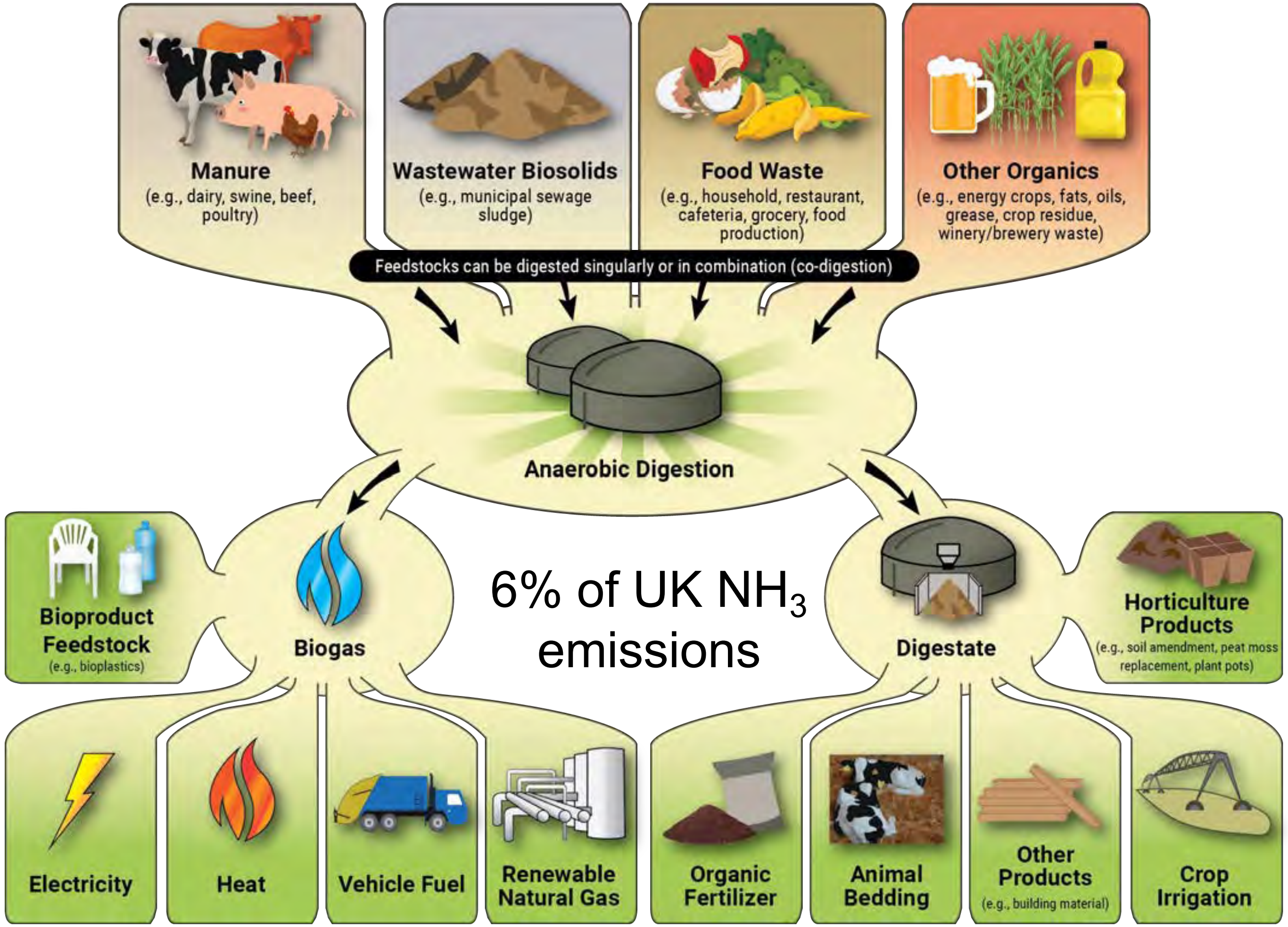


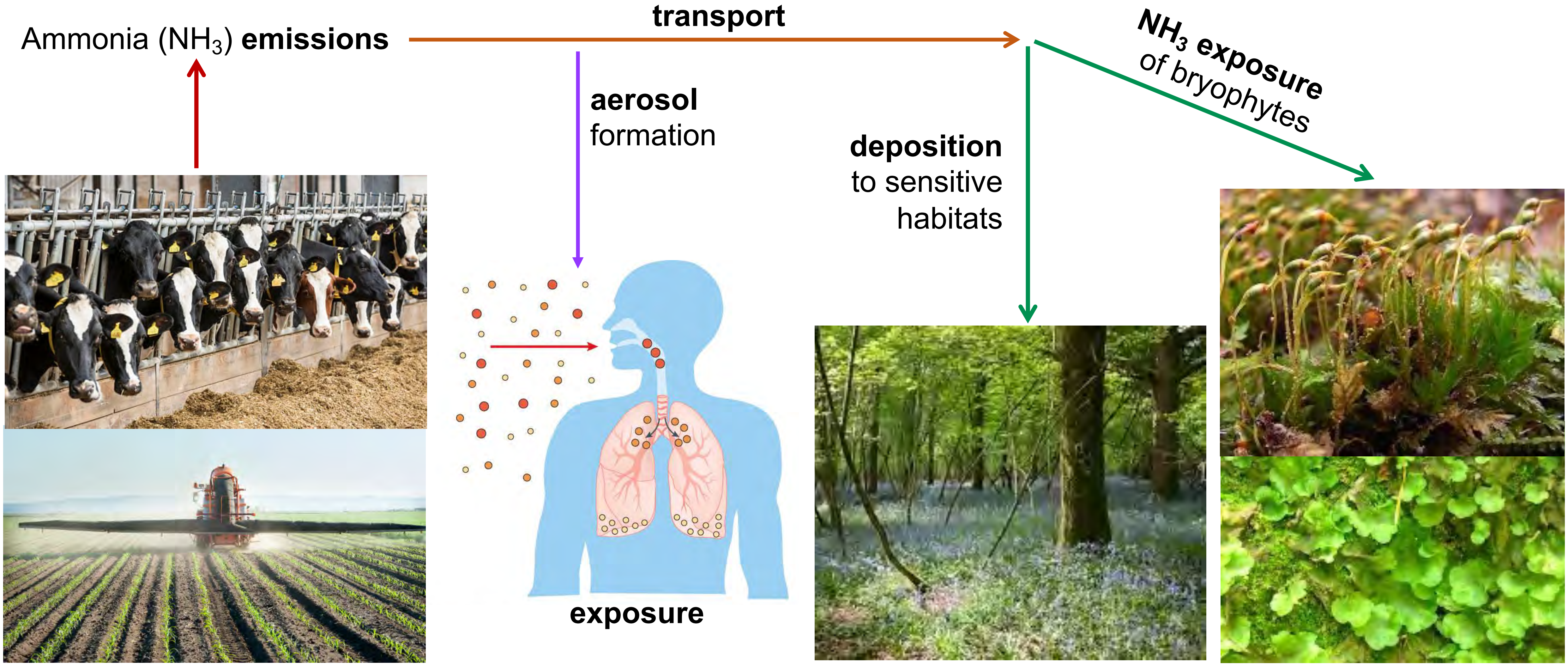
Image source: https://www.epa.gov/agstar/how-does-anaerobic-digestion-work

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

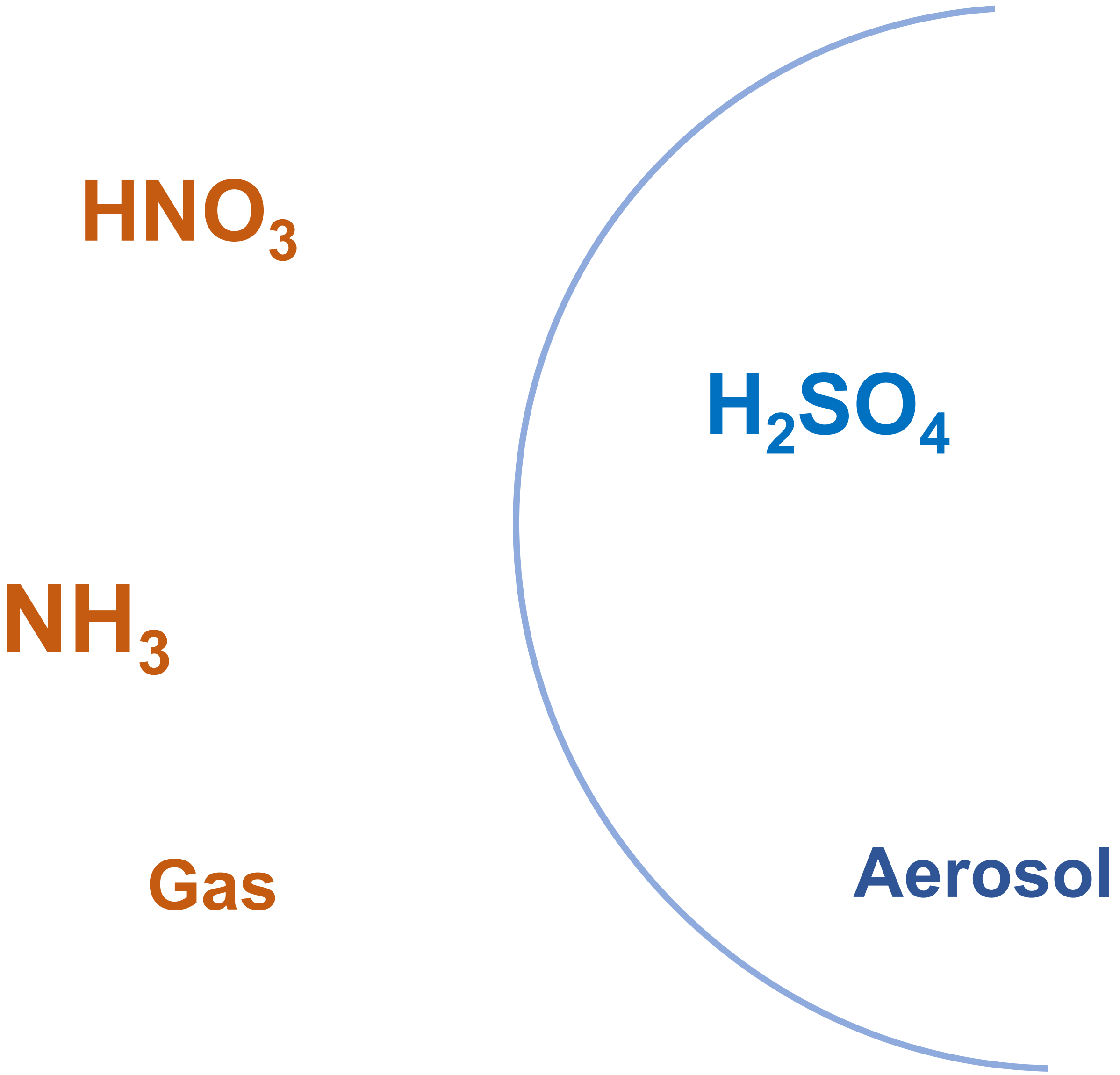
Environmental Concerns over NH_3 Emissions

Impacts health as $PM_{2.5}$ precursor

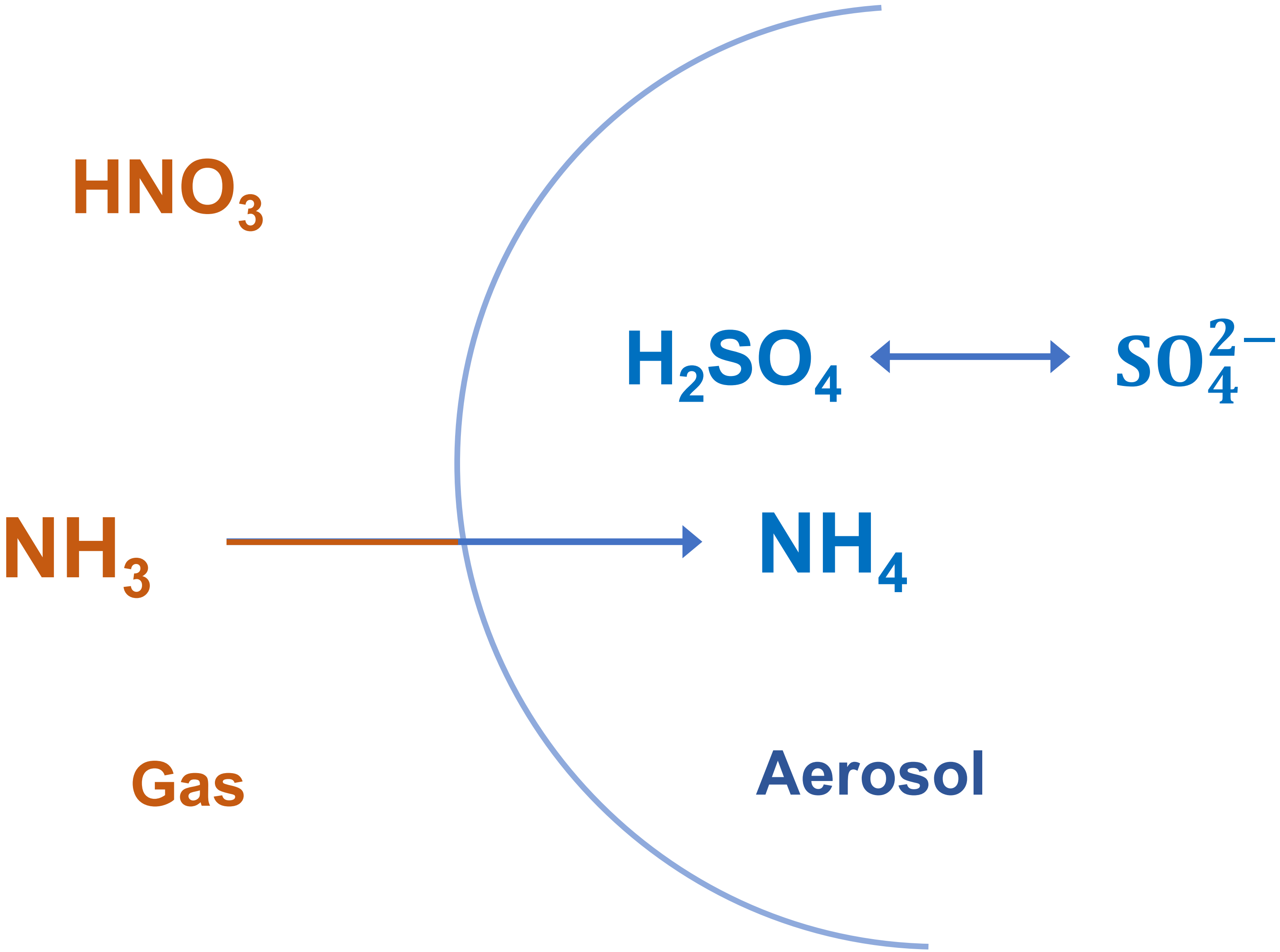
Offsets ecosystem balance via nitrogen deposition and direct exposure



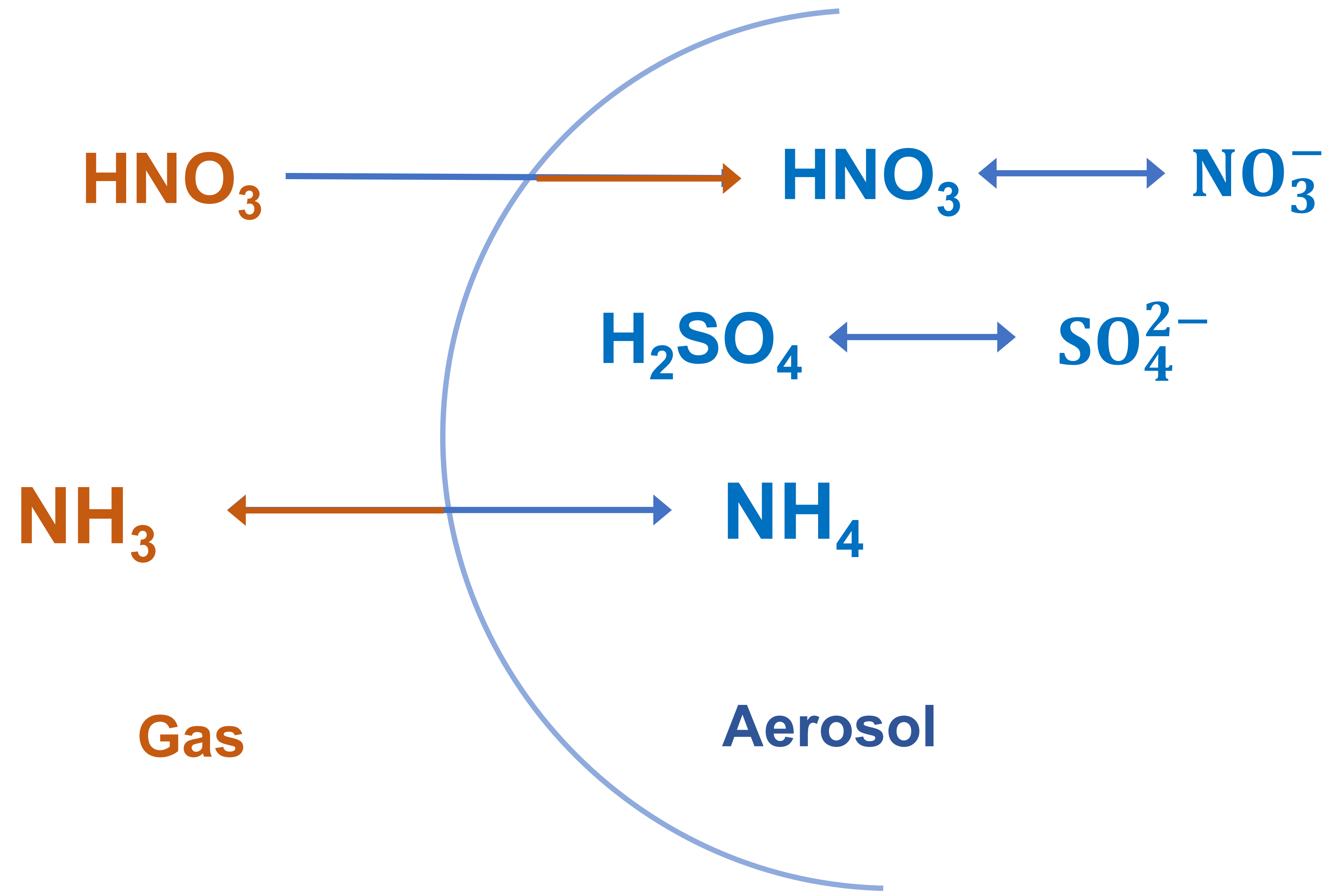
NH_3 Contribution to Particulate Matter (PM) Mass



NH_3 Contribution to Particulate Matter (PM) Mass

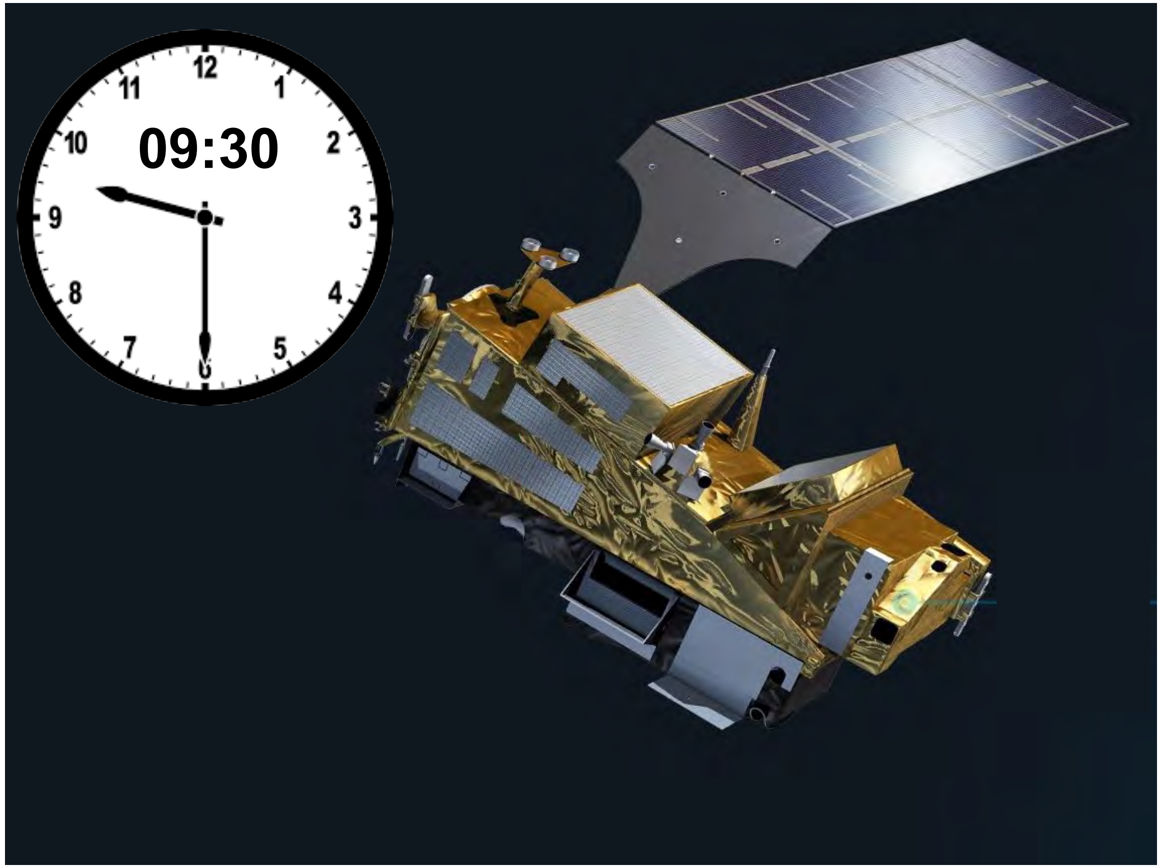


NH_3 Contribution to Particulate Matter (PM) Mass



Instruments in space measuring NH_3 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

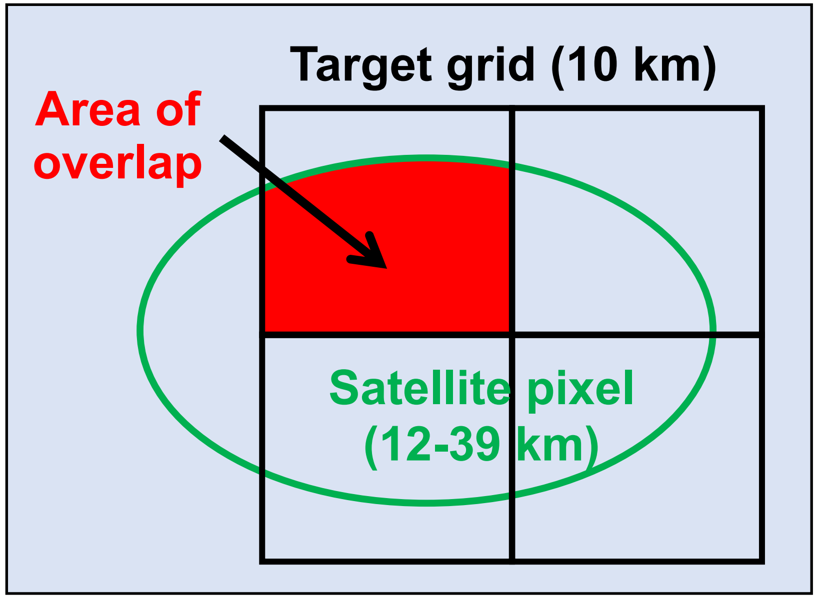
Launch date: 2011 (2017, 2022, 2027, 2032)

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

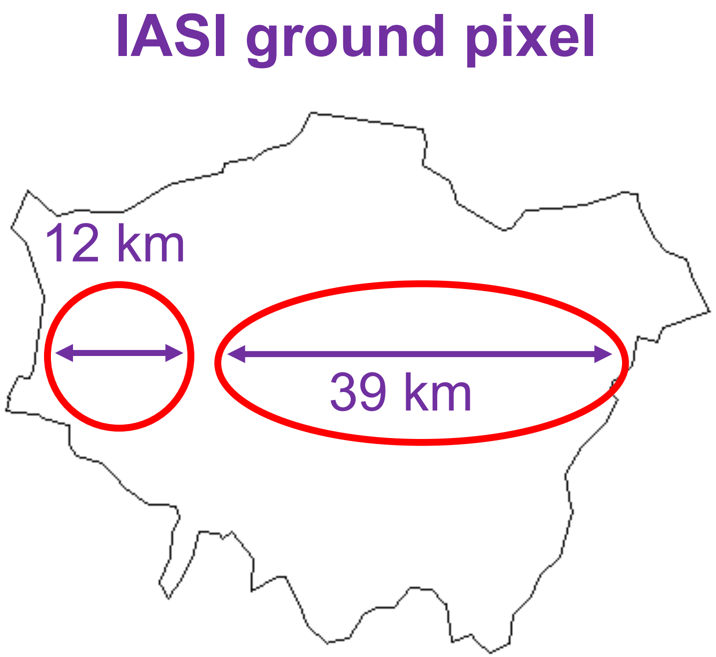
Oversampling Technique

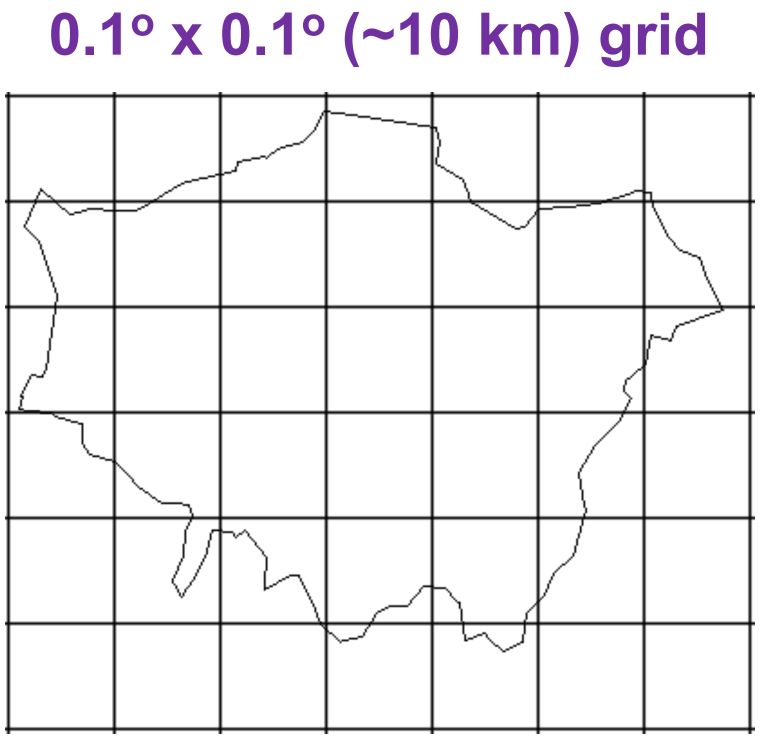


Weights each IASI NH_3 pixel by area of overlap and the reported uncertainty

<u>Oversampling code</u>: L. Zhu, SUSTech (Zhu et al., 2017)

Oversampling technique over London

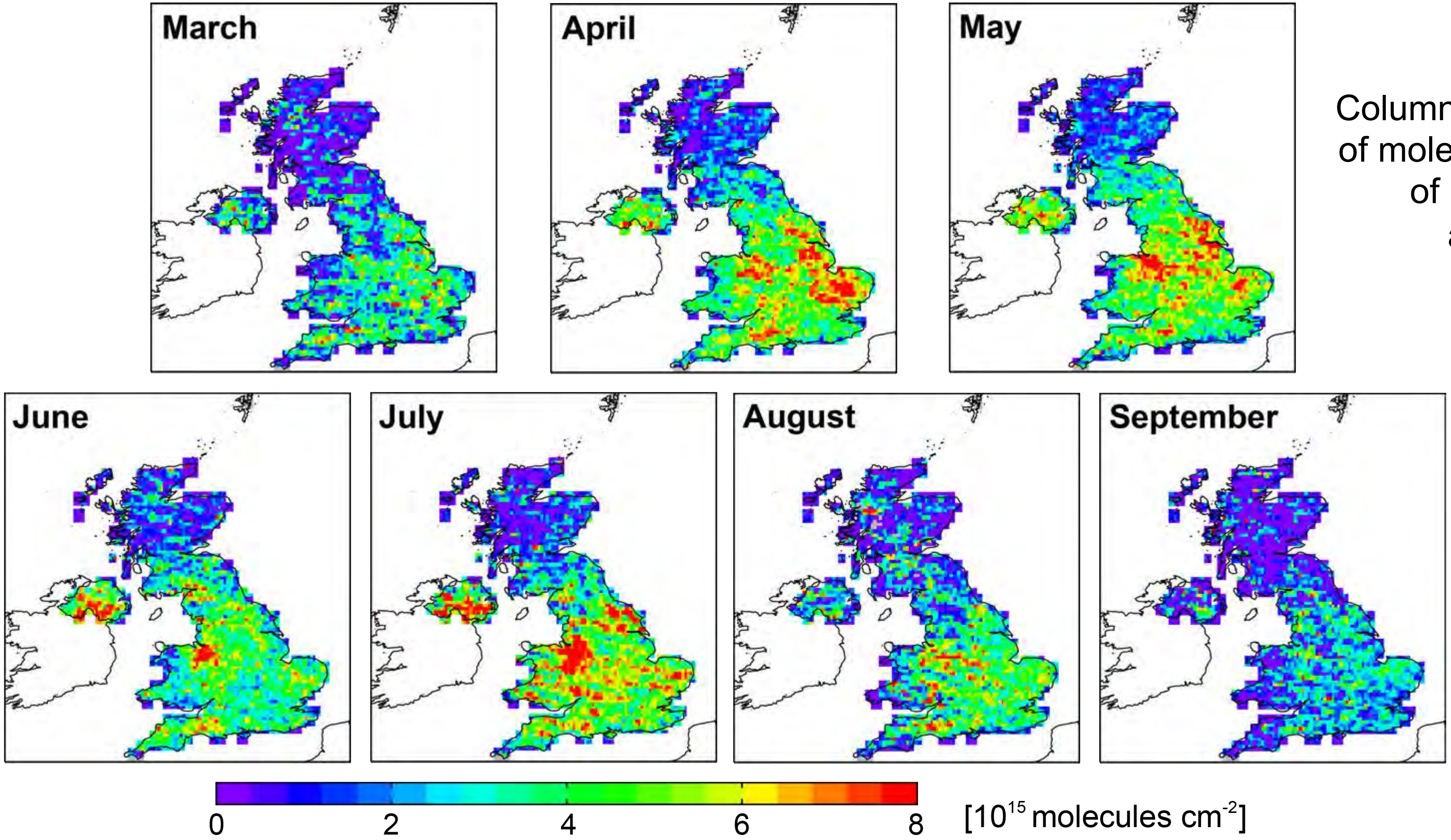




Lose time (temporal) resolution; gain spatial resolution

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

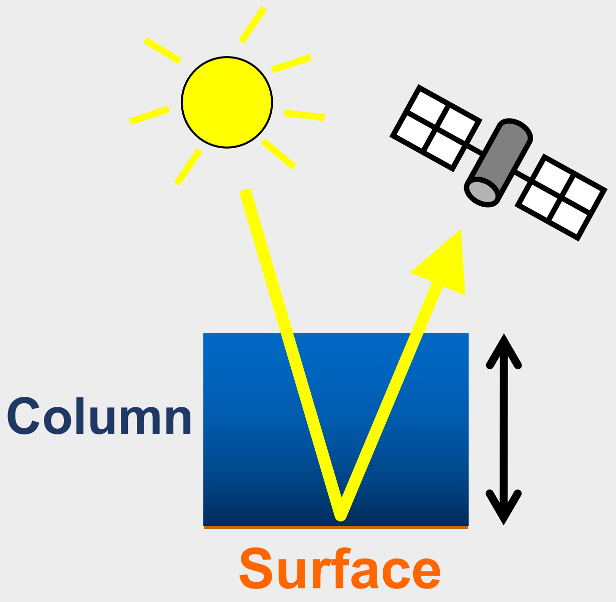
Climatological mean to be consistent with bottom-up ammonia emissions

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**

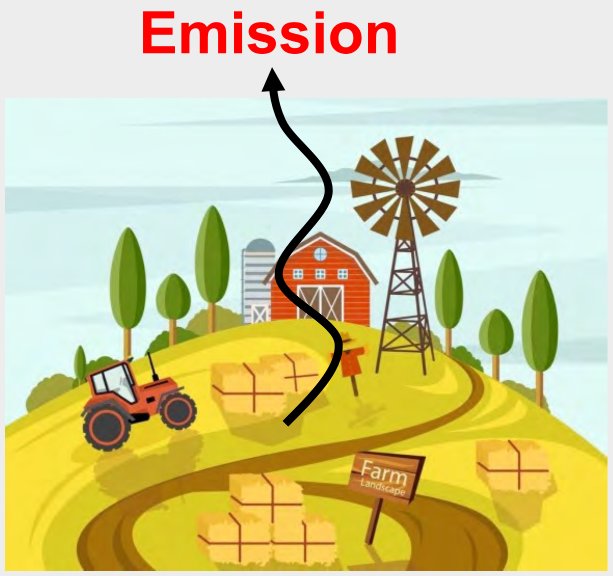
ABUNDANCES → **Conversion Factor** → **EMISSIONS**

Satellite column densities



Model Concentration-to-Emission Ratio

Satellite-derived Surface Emissions



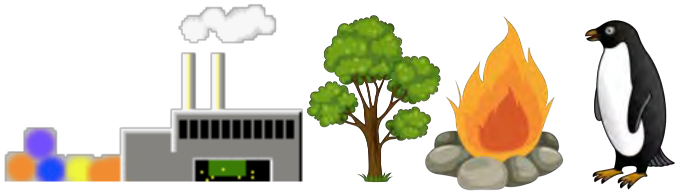
This approach possible as NH_3 has a relatively short lifetime (2-15 hours) at or near sources

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

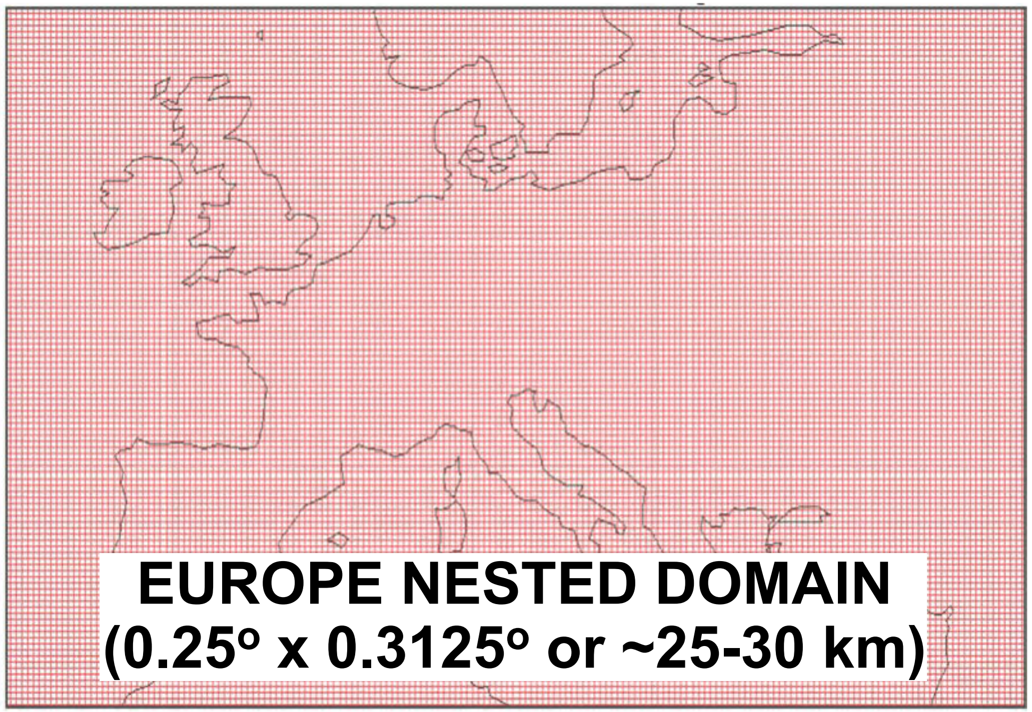
GEOS-Chem

3D Atmospheric Chemistry Transport Model

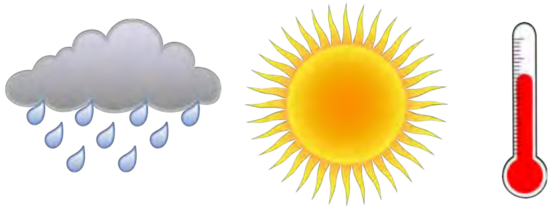
Emissions (natural/human)



UK NAEI emissions
(with temporal information)



Offline assimilated meteorology



NASA GEOS-FP for 2016

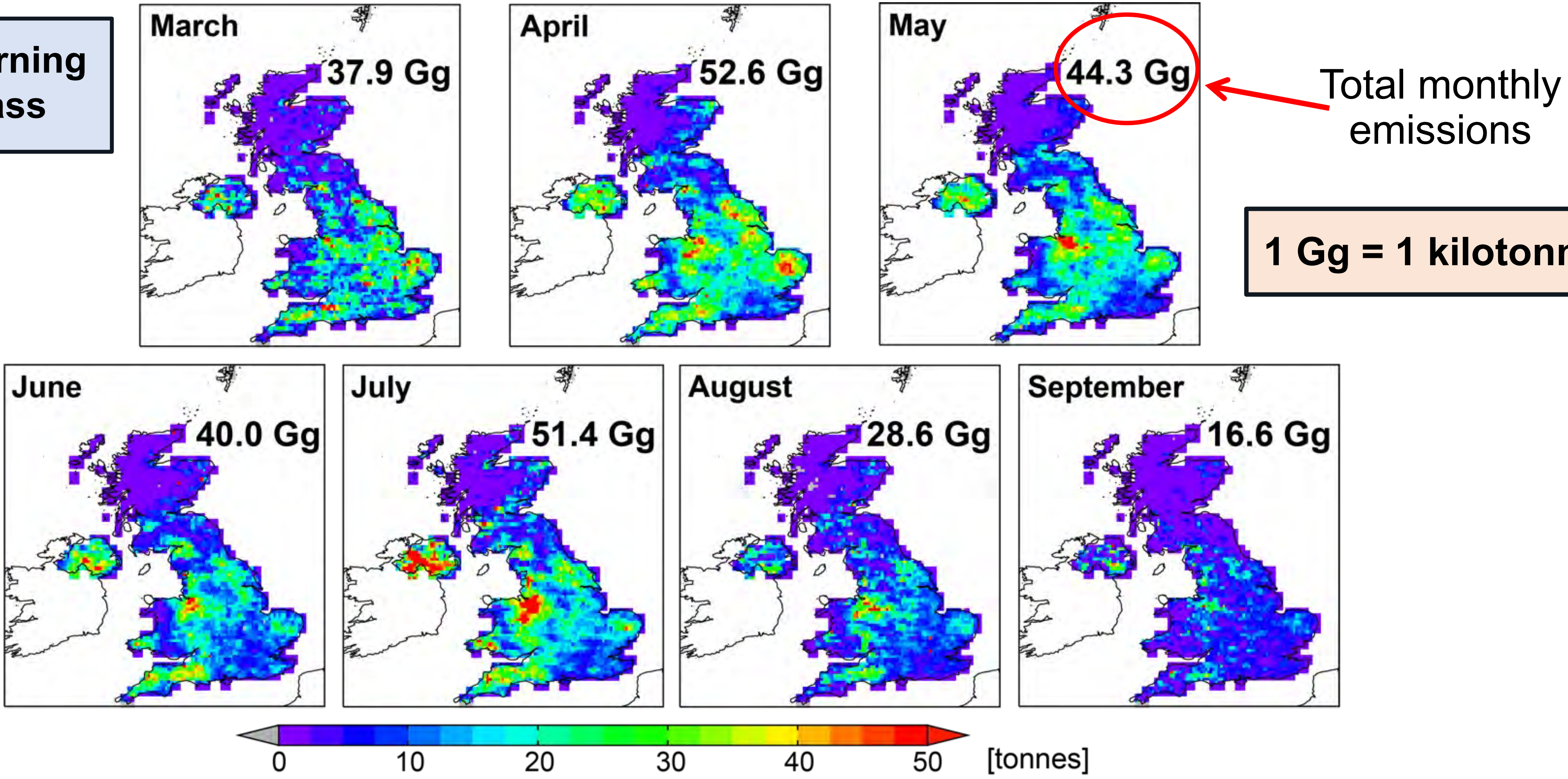
Gas phase and heterogeneous chemistry
Transport
Dry/wet deposition

GEOS-Chem **version 12.1.0** (doi:10.5281/zenodo.1553349)

IASI-derived multiyear (2008-2018) monthly mean NH_3 emissions

Focus on **Mar-Sep** when warm temperatures and clearer conditions increase sensitivity to surface NH_3

IASI: morning overpass

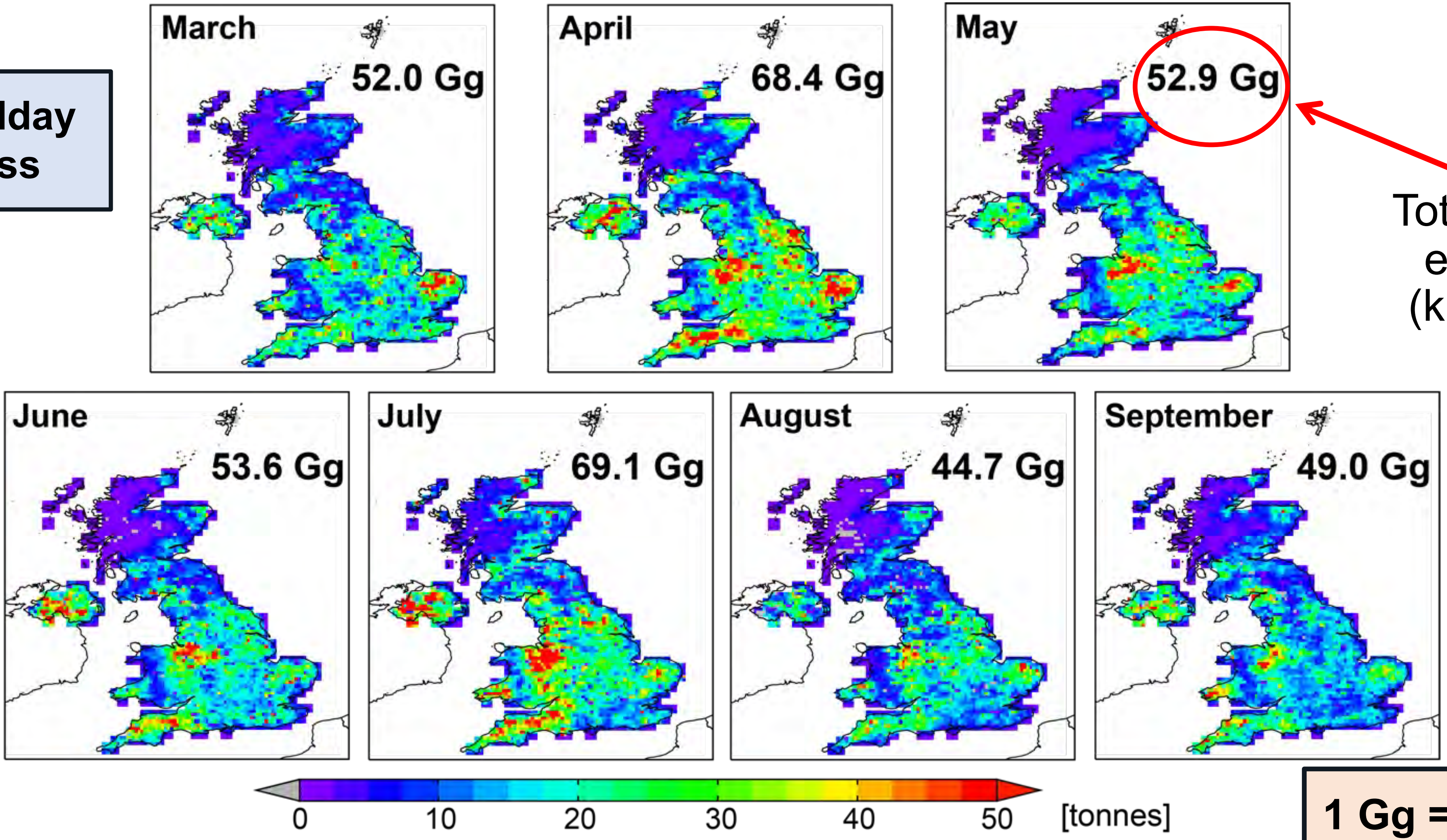


1 Gg = 1 kilotonne

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

CrIS-derived multiyear (2008-2018) monthly mean NH_3 emissions

CrIS: midday overpass



Total monthly emissions (kilotonnes)

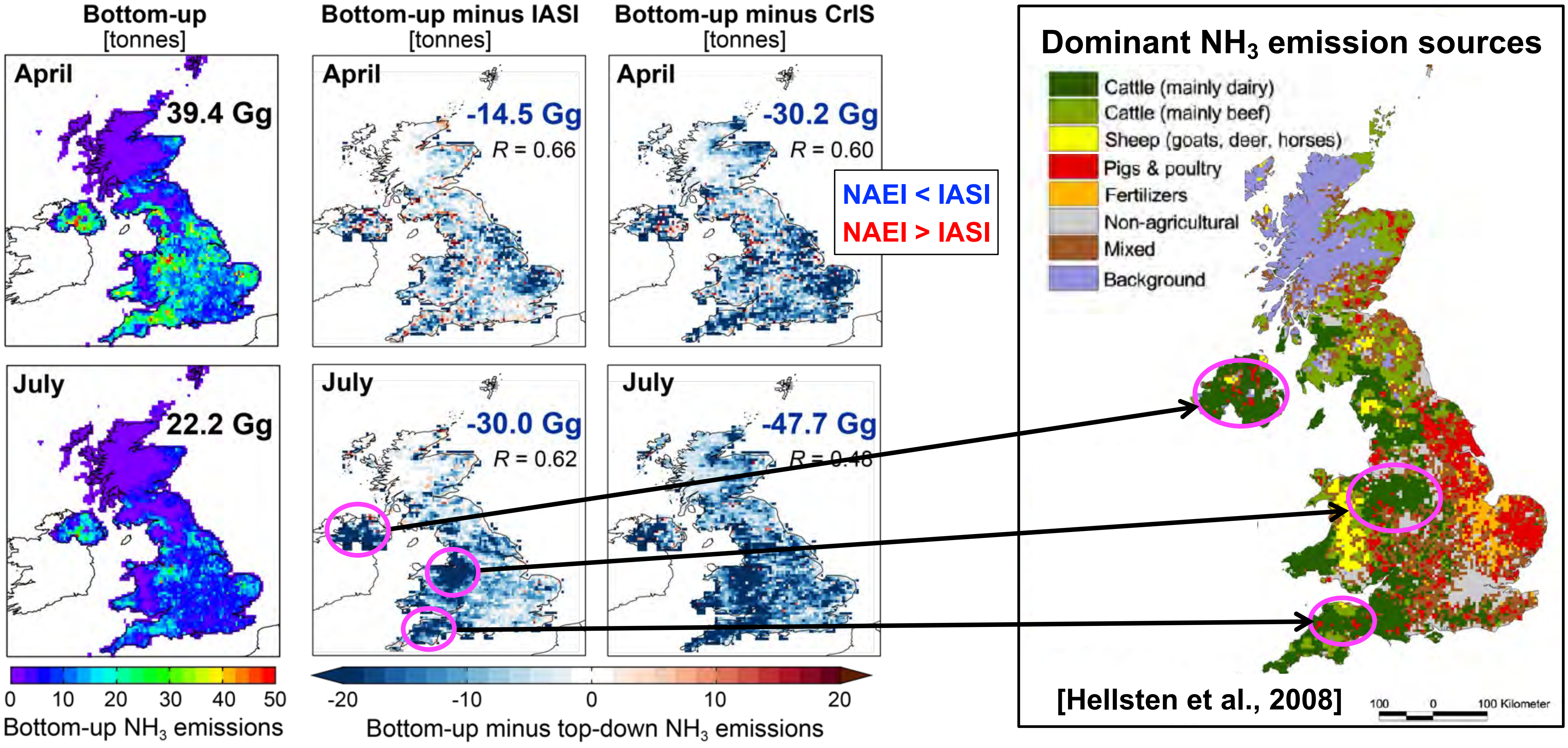
1 Gg = 1 kilotonne

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

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

Satellite vs inventory NH_3 emissions: spatial distribution

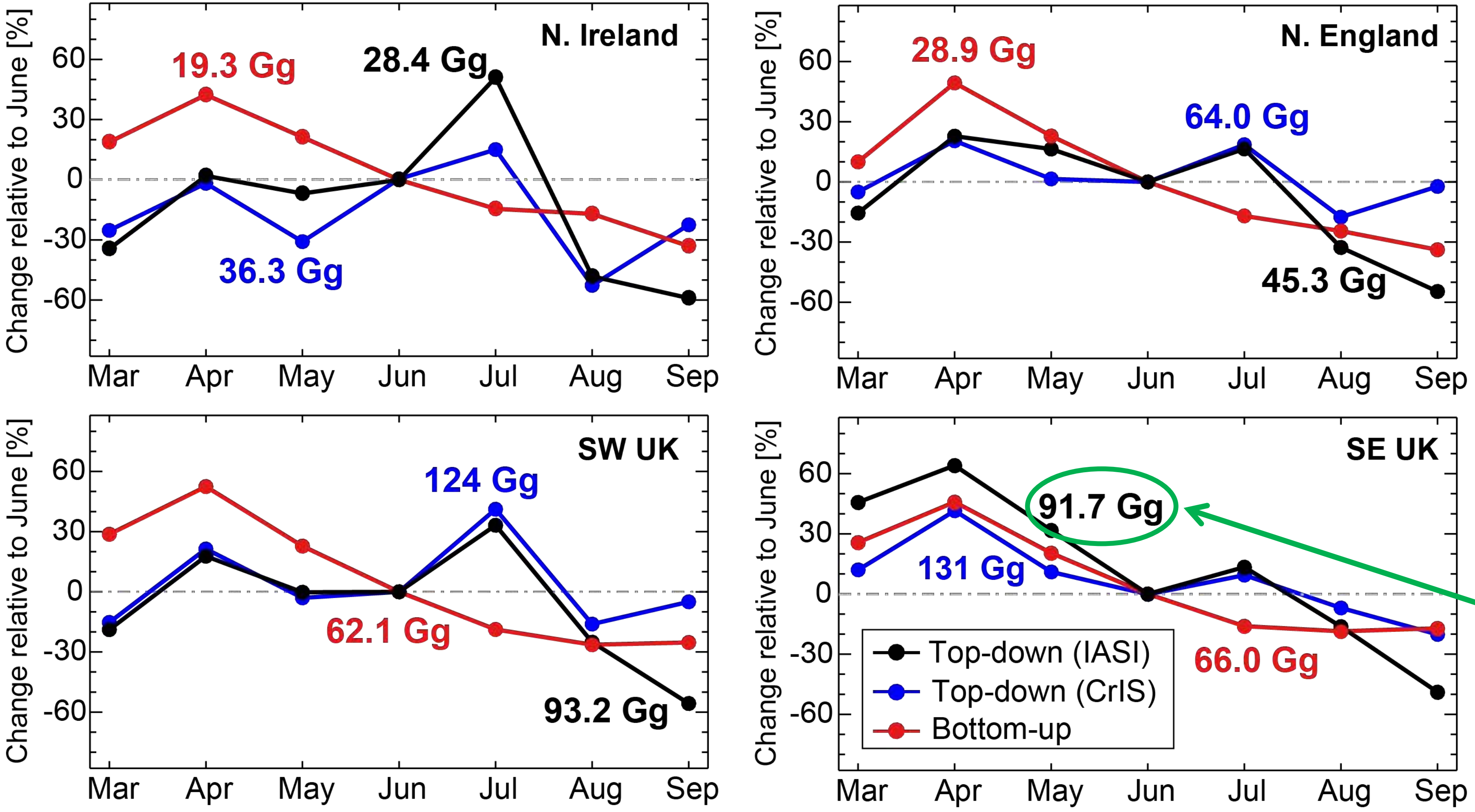
Comparison of months with peak emissions according to IASI and CrIS (April and July)



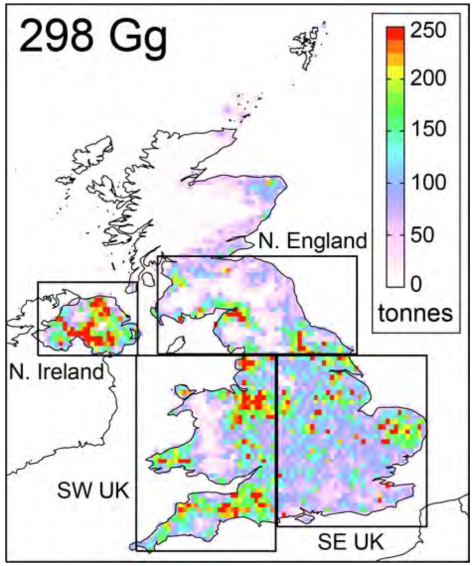
Large July difference over locations dominated by dairy cattle. Inventory is 27-49% less than the satellite values.

Satellite vs inventory NH_3 emissions: seasonality

Seasonality shown as emissions in each month relative to June



Regions and annual inventory emissions



Mar-Sep emission totals in each region

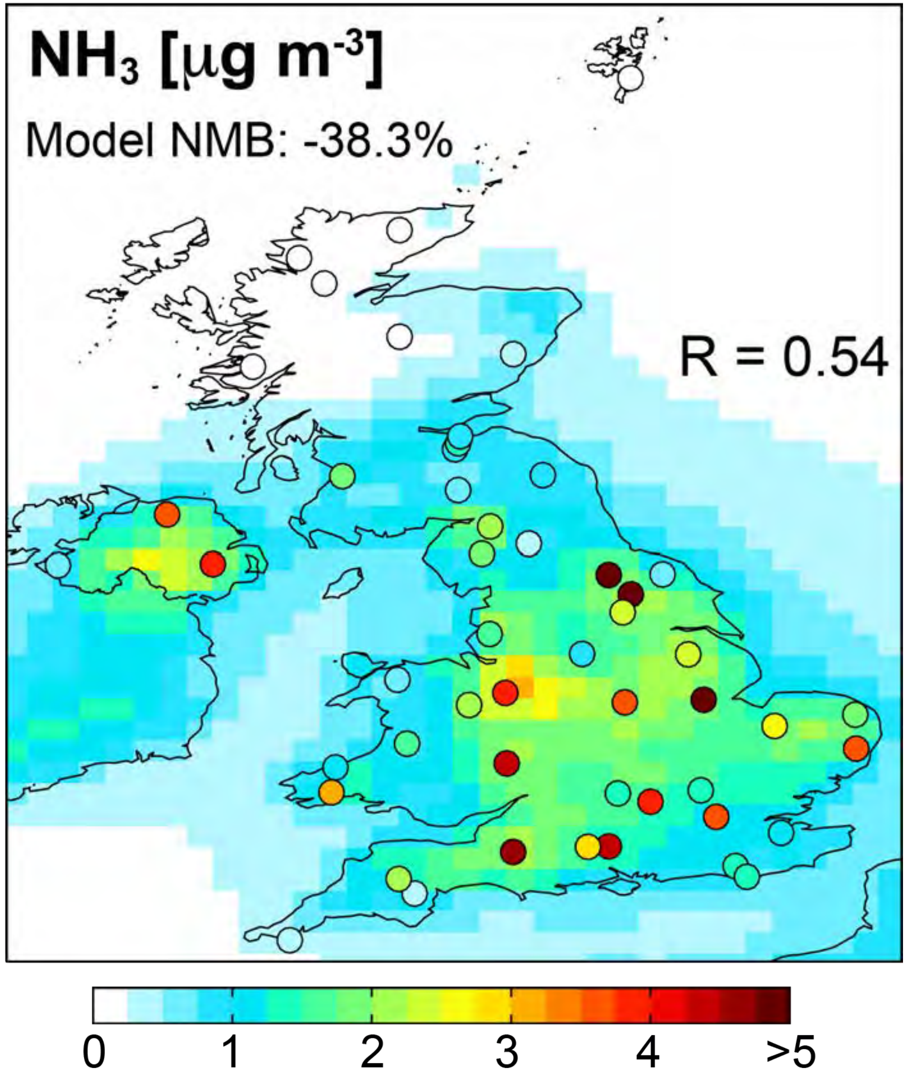
1 Gg = 1 kilotonne

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_3 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%**)

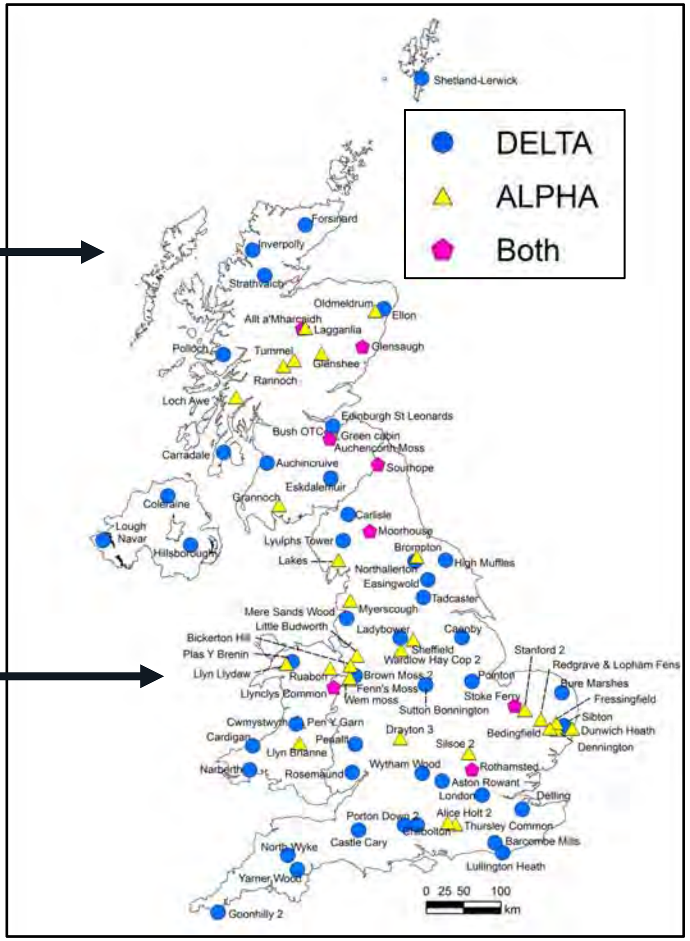


Image source: http://www.pollutantdeposition.ceh.ac.uk/content/ammonia-network

GEOS-Chem underestimate in surface NH_3 driven with the NAEI corroborates results from IASI

Takehome Messages So Far

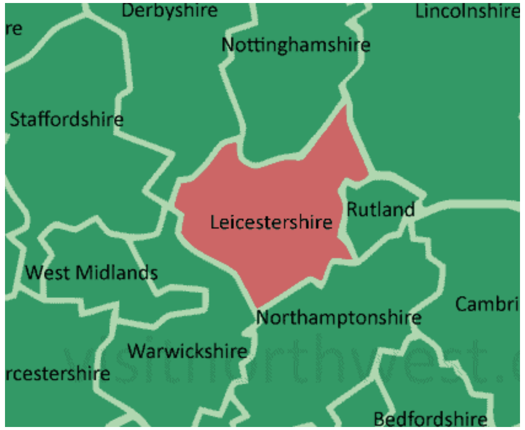
- Spring and Summer peak in NH_3 emissions
- Inventories may underestimate NH_3 emissions, as missing summer peak

What's the contribution of agricultural NH_3 to urban $PM_{2.5}$?

Test Contribution of Potentially Influential Sources

Local

City



County

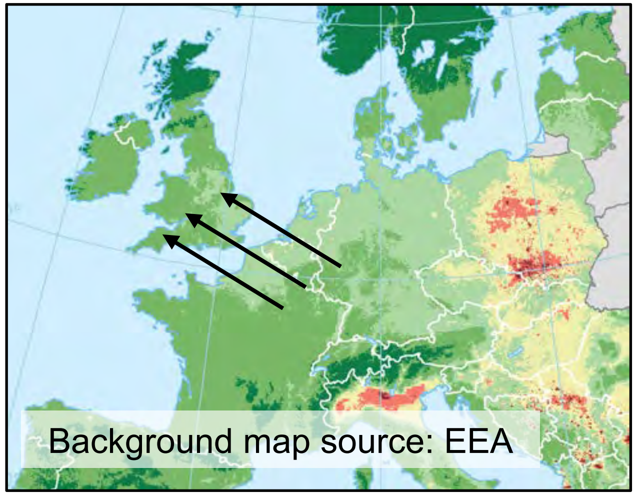
National

Nearby large cities

Transport

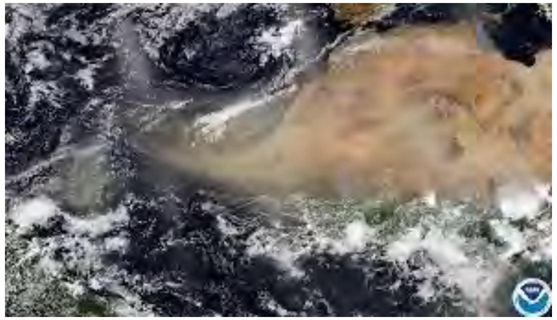
Agriculture

Regional



Mainland Europe

Global

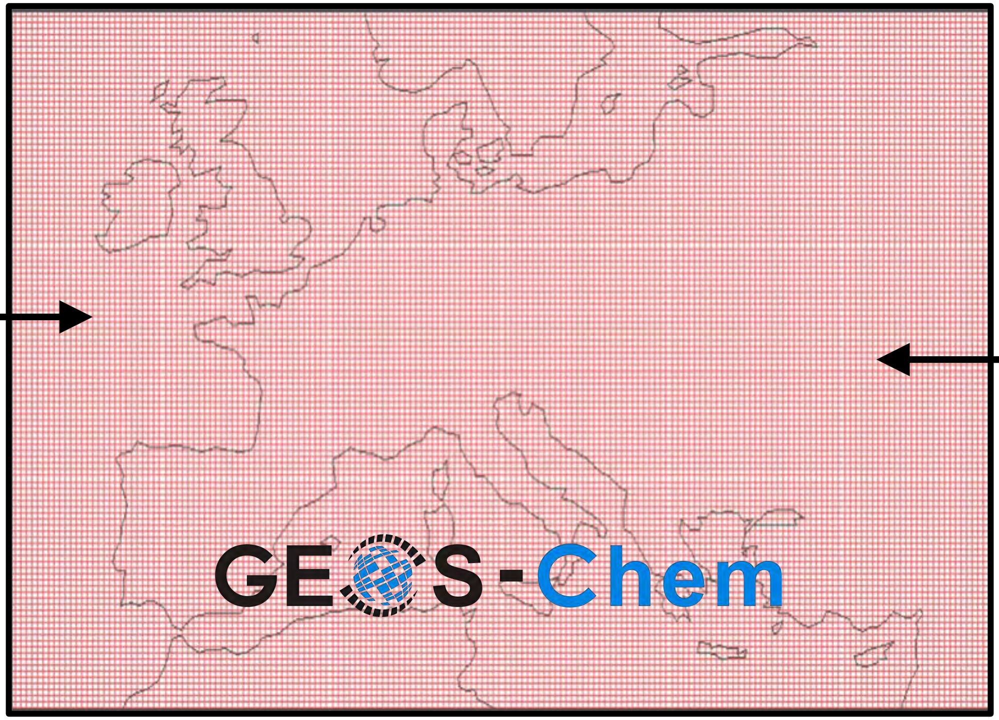


Desert Dust

Simulate $PM_{2.5}$ with GEOS-Chem

Ammonia emissions updated
(based on previous work)

3D Atmospheric Chemistry Transport Model



Chemistry, transport, loss processes

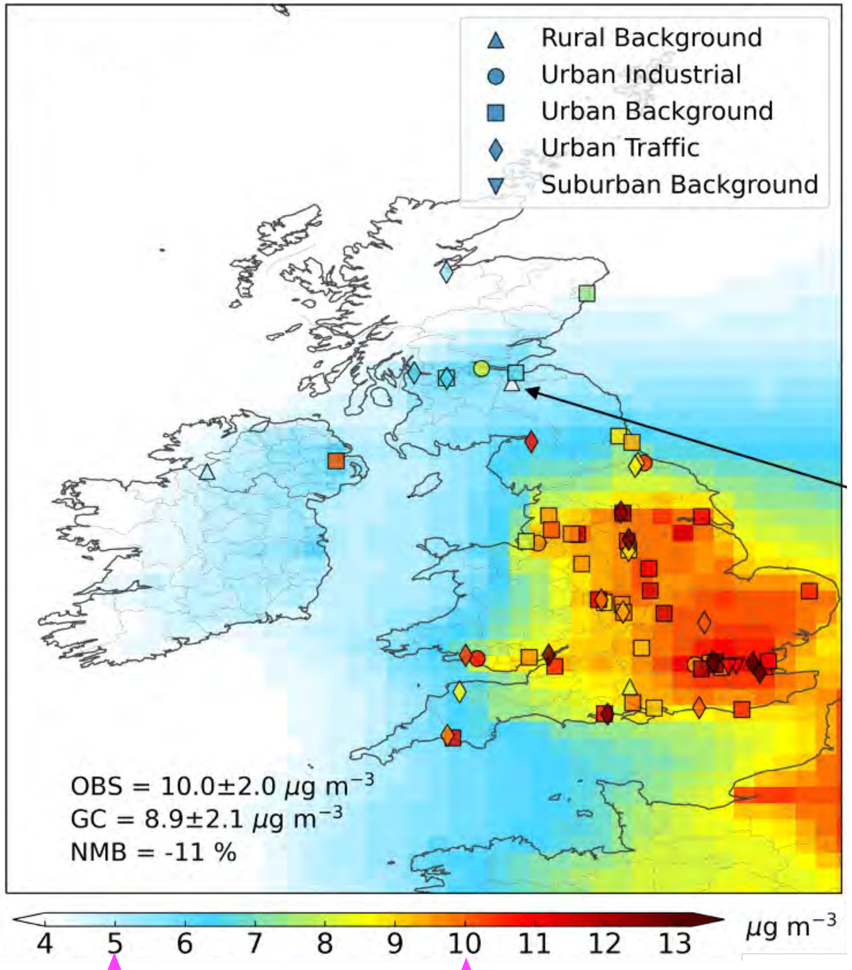
NASA Meteorology

$PM_{2.5}$ from all but one source

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

Assess Validity of Model using Permanent Networks

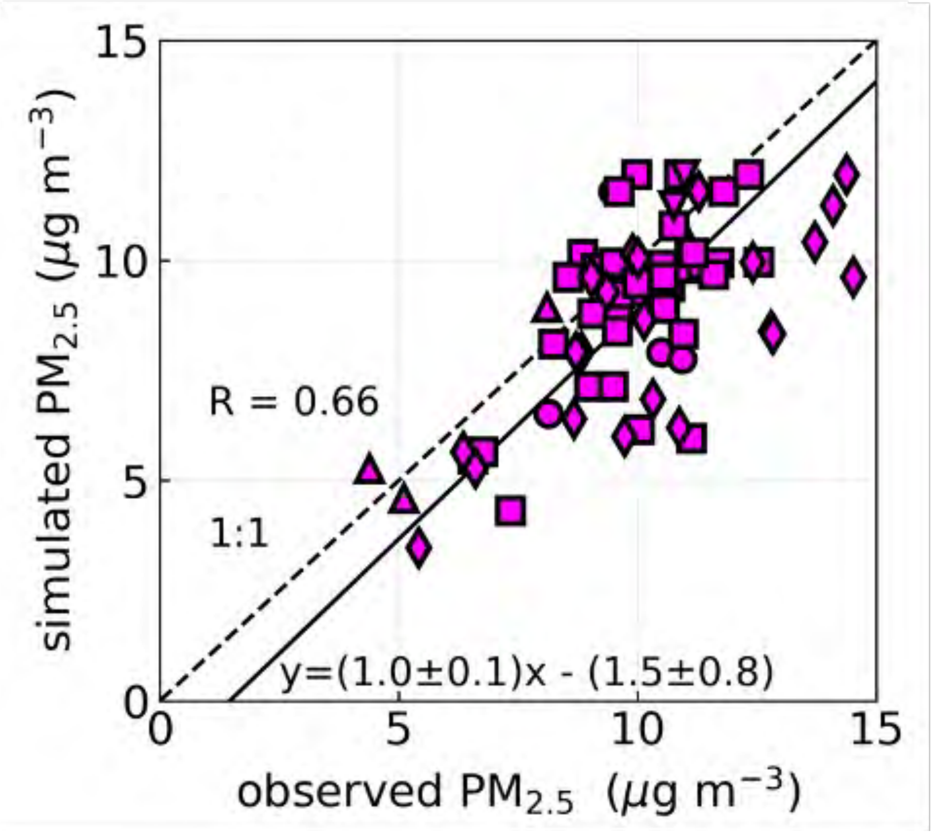
Use total $PM_{2.5}$ observations from the Automatic Urban and Rural Network (AURN) to assess model



WHO (2021) **WHO (2005), new UK target**

79% of UK exceeds updated WHO guideline

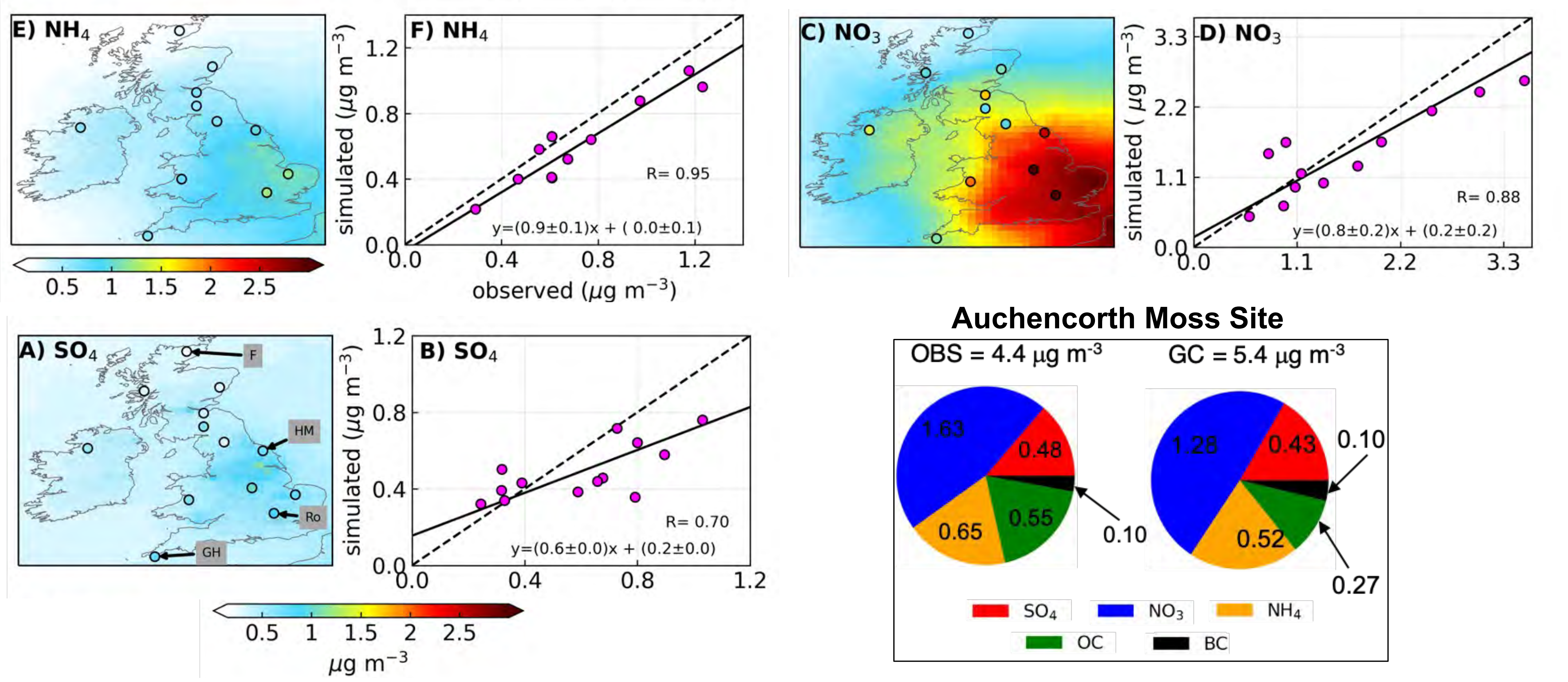
Compare annual mean surface concentrations of $PM_{2.5}$ for 2019



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

Assess Validity of Model using Permanent Networks

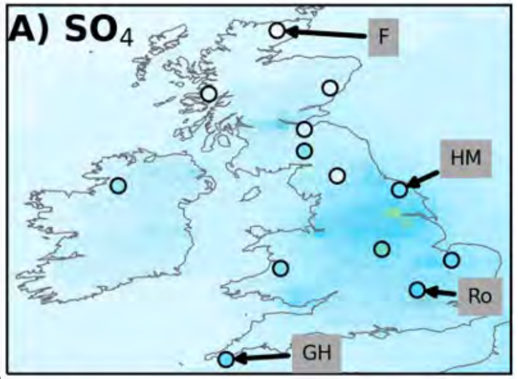
Use $PM_{2.5}$ composition measurements from UKEAP and EMEP sites to assess model



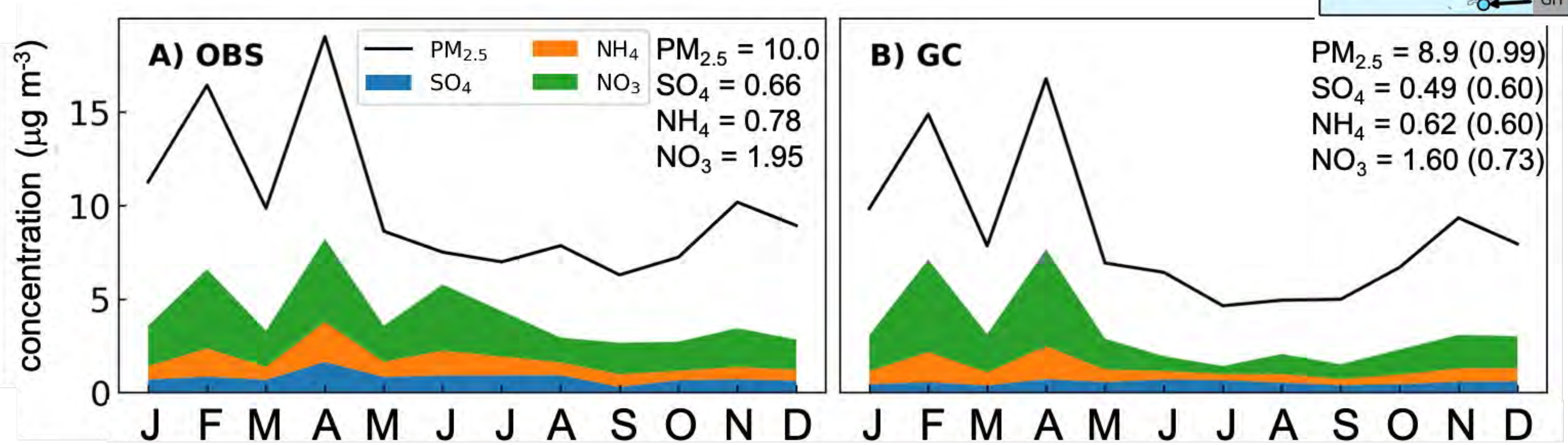
Model underpredicts observed (sulfate, nitrate, ammonium) and possibly overpredicts unobserved (dust) components. Model captures variance of components from NO_x (nitrate) and ammonia (ammonium)

Assess Validity of Model using Reference Monitors

Also evaluate model skill at reproducing observed seasonality in $PM_{2.5}$



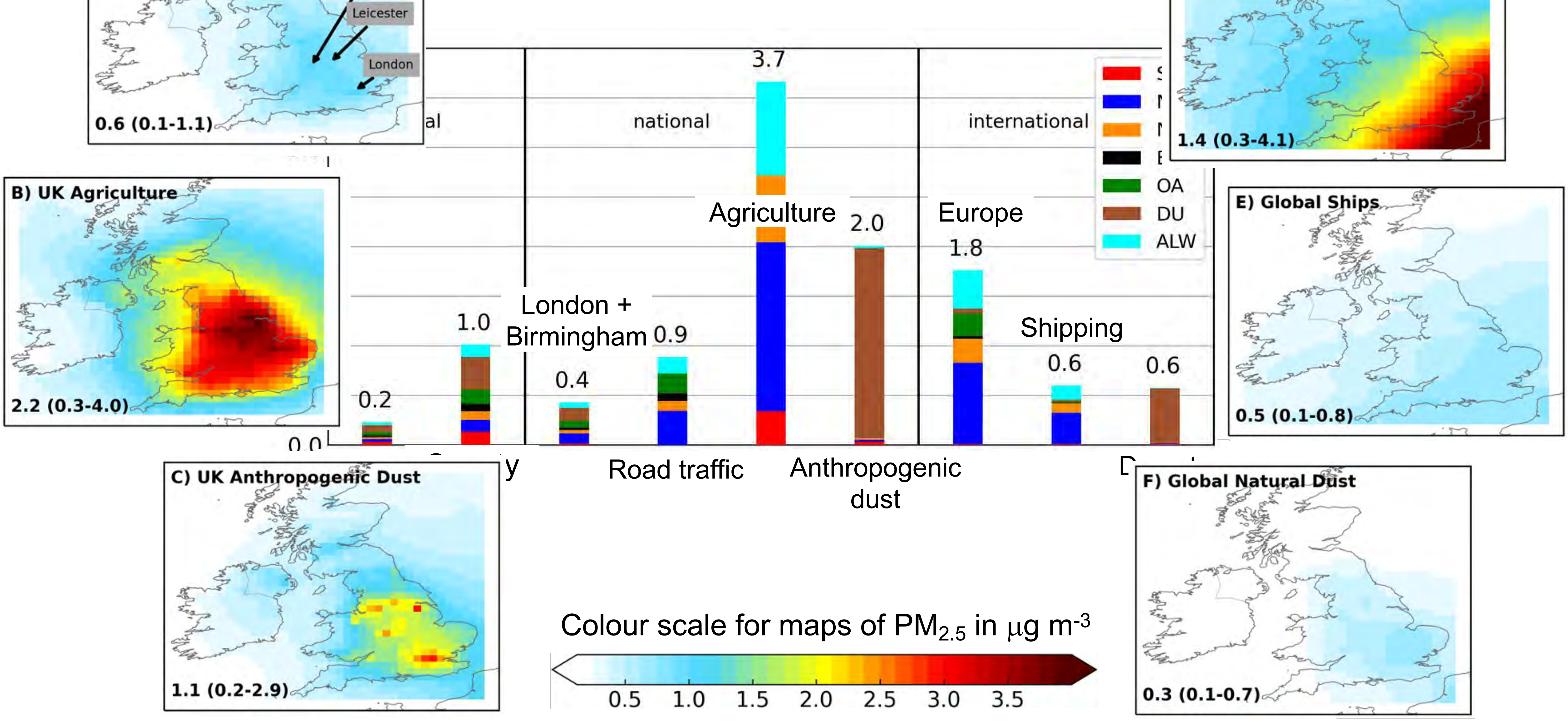
SO_4: sulfate; NO_3: nitrate; NH_4: ammonium



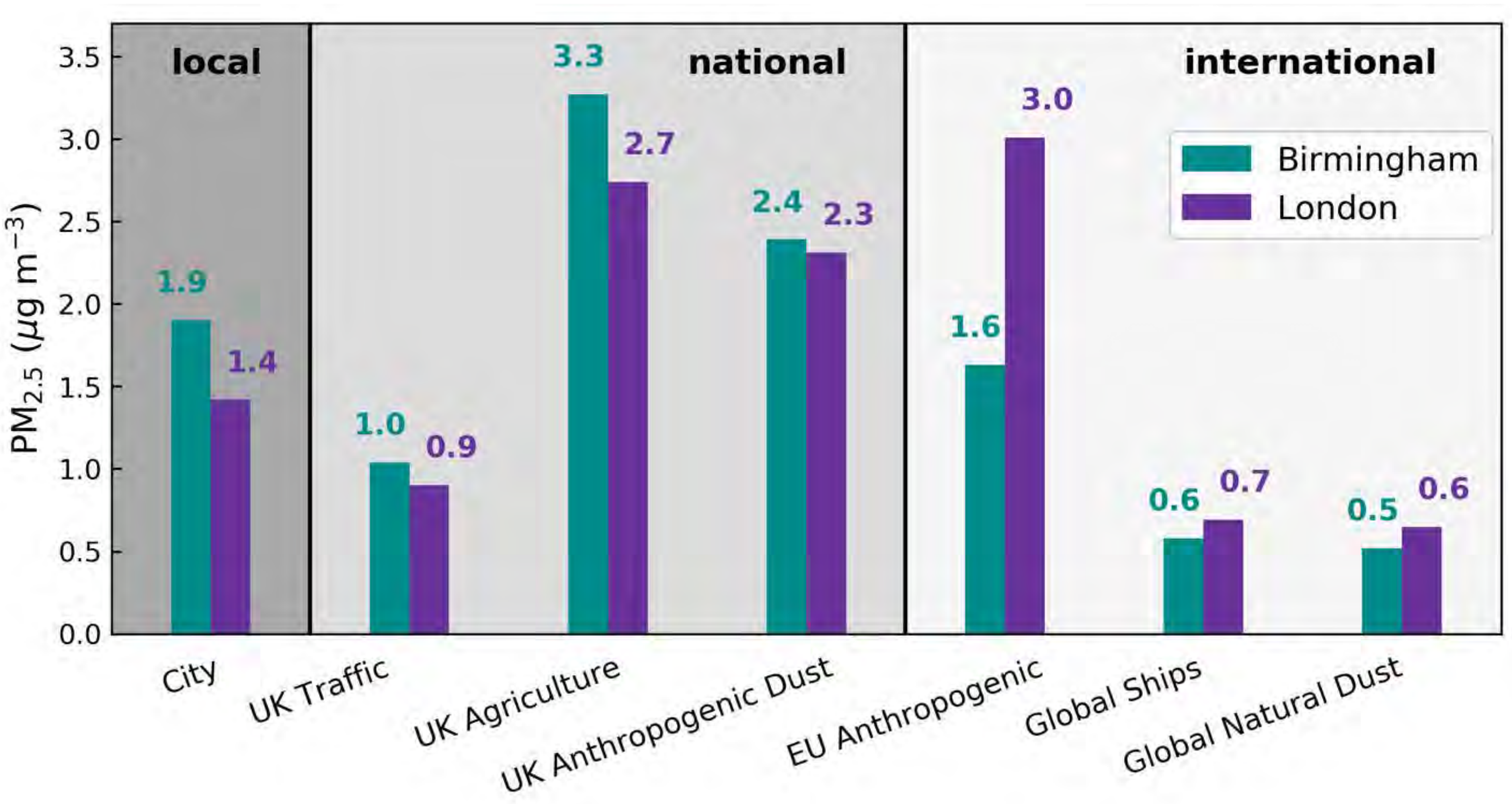
Enhancements in cold months and when ammonia emissions from agriculture peak due to application of synthetic fertilizer in March-April

Contribution of Sources to annual $PM_{2.5}$ in Leicester

SO_4: sulfate; NO_3: nitrate; NH_4: ammonium
BC: black carbon; OC: organic carbon; DU: dust



Results for Large Cities like London and Birmingham



London: 1,600 km^2

Birmingham: 270 km^2

Leicester: 70 km^2

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

Takehome Messages So Far

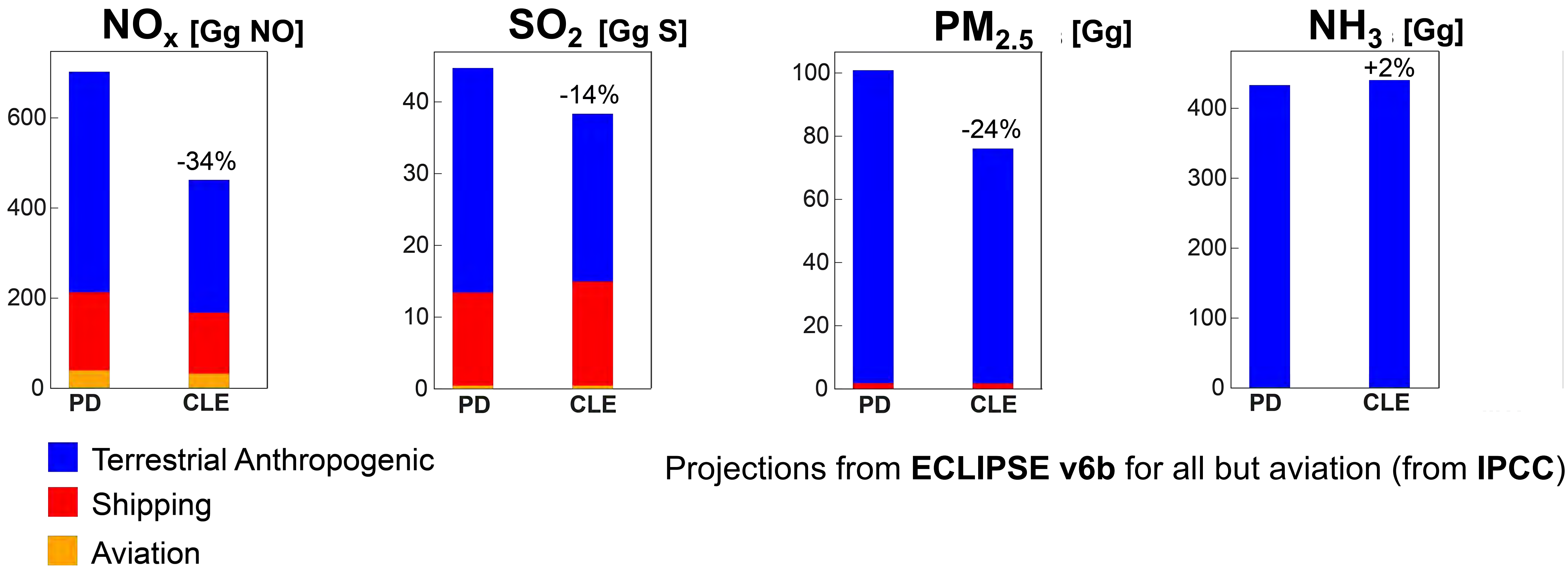
- Spring and Summer peak in NH_3 emissions
- Inventories may underestimate NH_3 emissions, as missing summer peak
- Rural NH_3 large or dominant contributor to $PM_{2.5}$ in UK cities.
- Local controls have limited efficacy at addressing $PM_{2.5}$ pollution

How effective are current measures at decreasing $PM_{2.5}$?

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**)



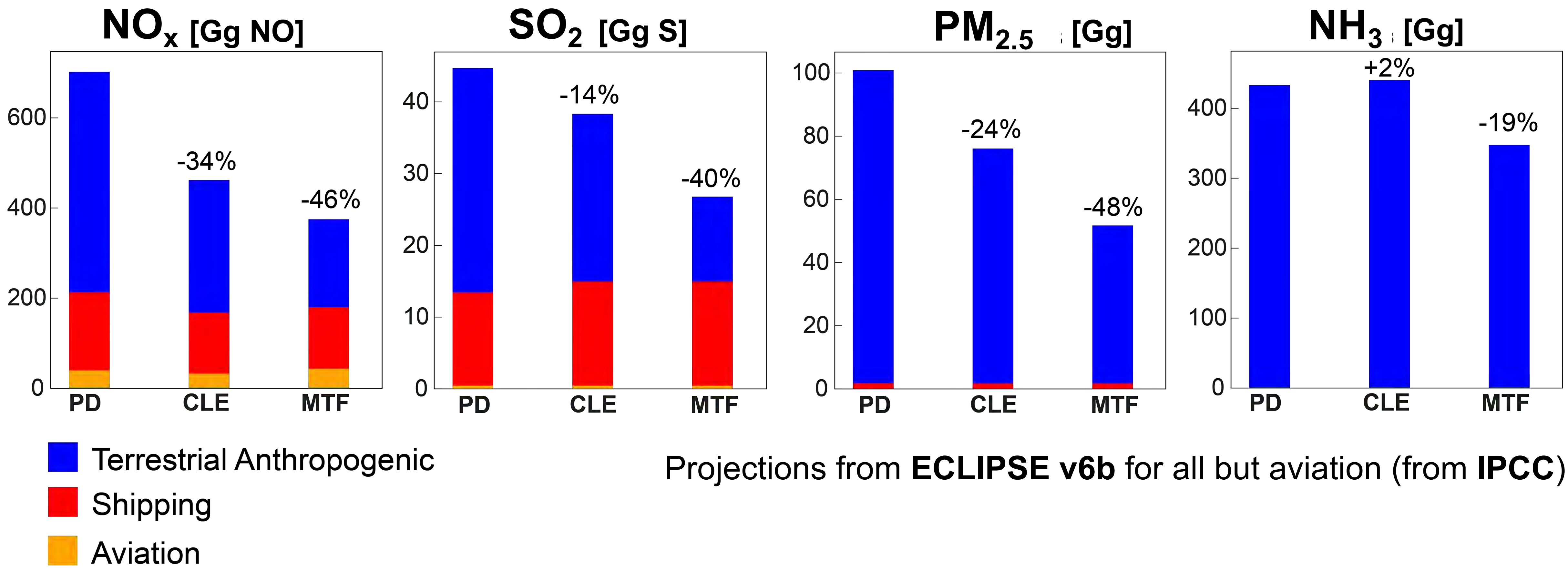
Projections from **ECLIPSE v6b** for all but aviation (from **IPCC**)

NH_3 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**)



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

Best technology decreases all precursors except ammonia (NH_3) by 40-48%

NH_3 controls limited to suggested rather than enforced measures

Influence of emissions controls on $PM_{2.5}$, NH_3, and N deposition

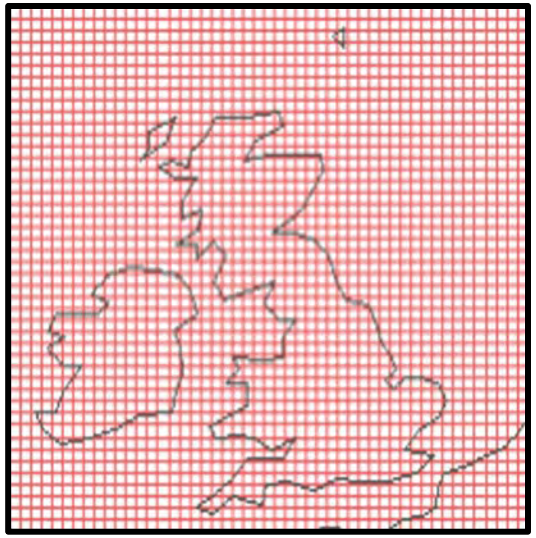
Emissions

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°



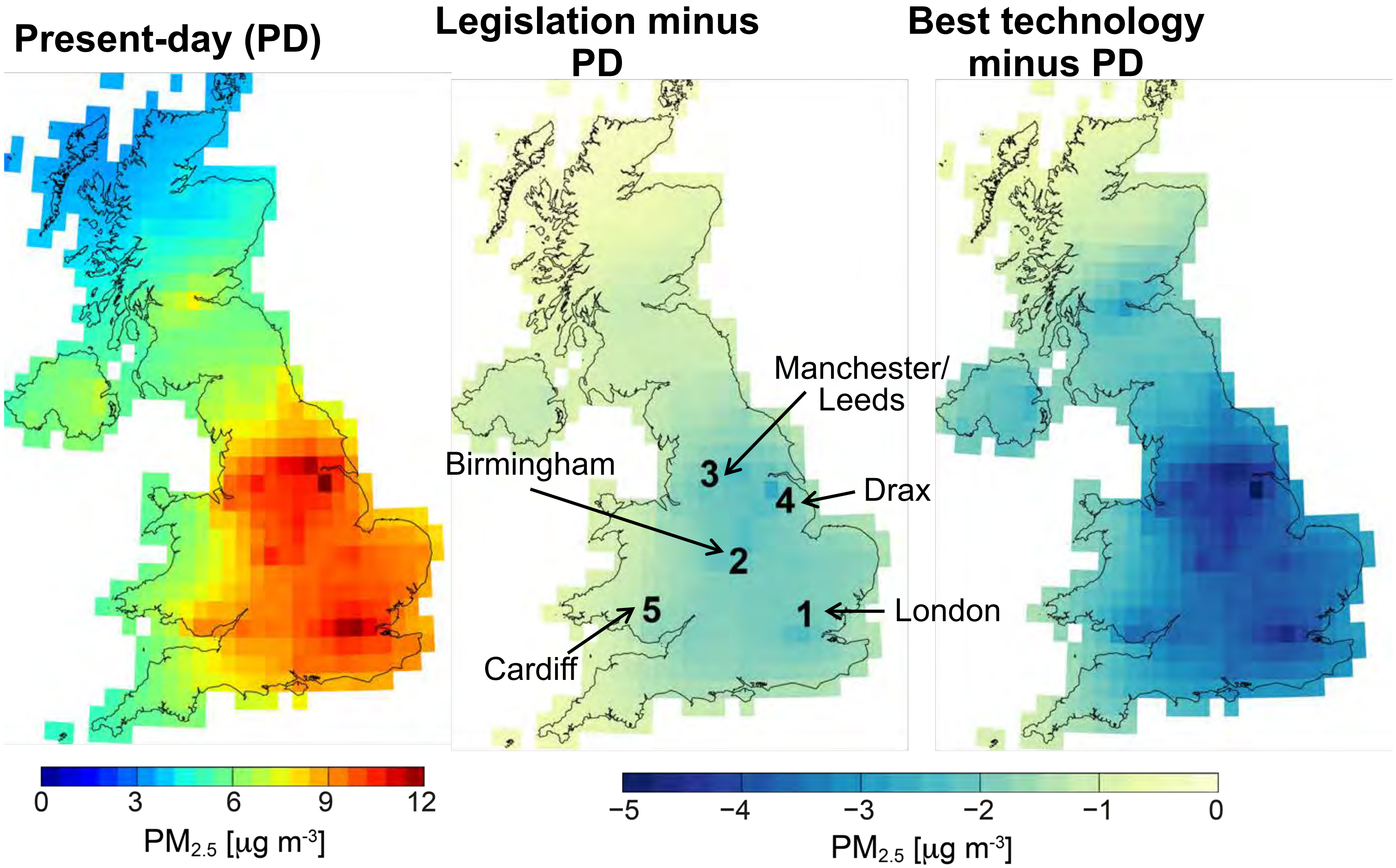
Gas- and aerosol-phase chemistry, transport, wet+dry deposition

Surface NH_3 and $PM_{2.5}$ components
Nitrogen wet and dry deposition

NASA GEOS-FP Meteorology

2019 throughout

Influence of emission controls on $PM_{2.5}$



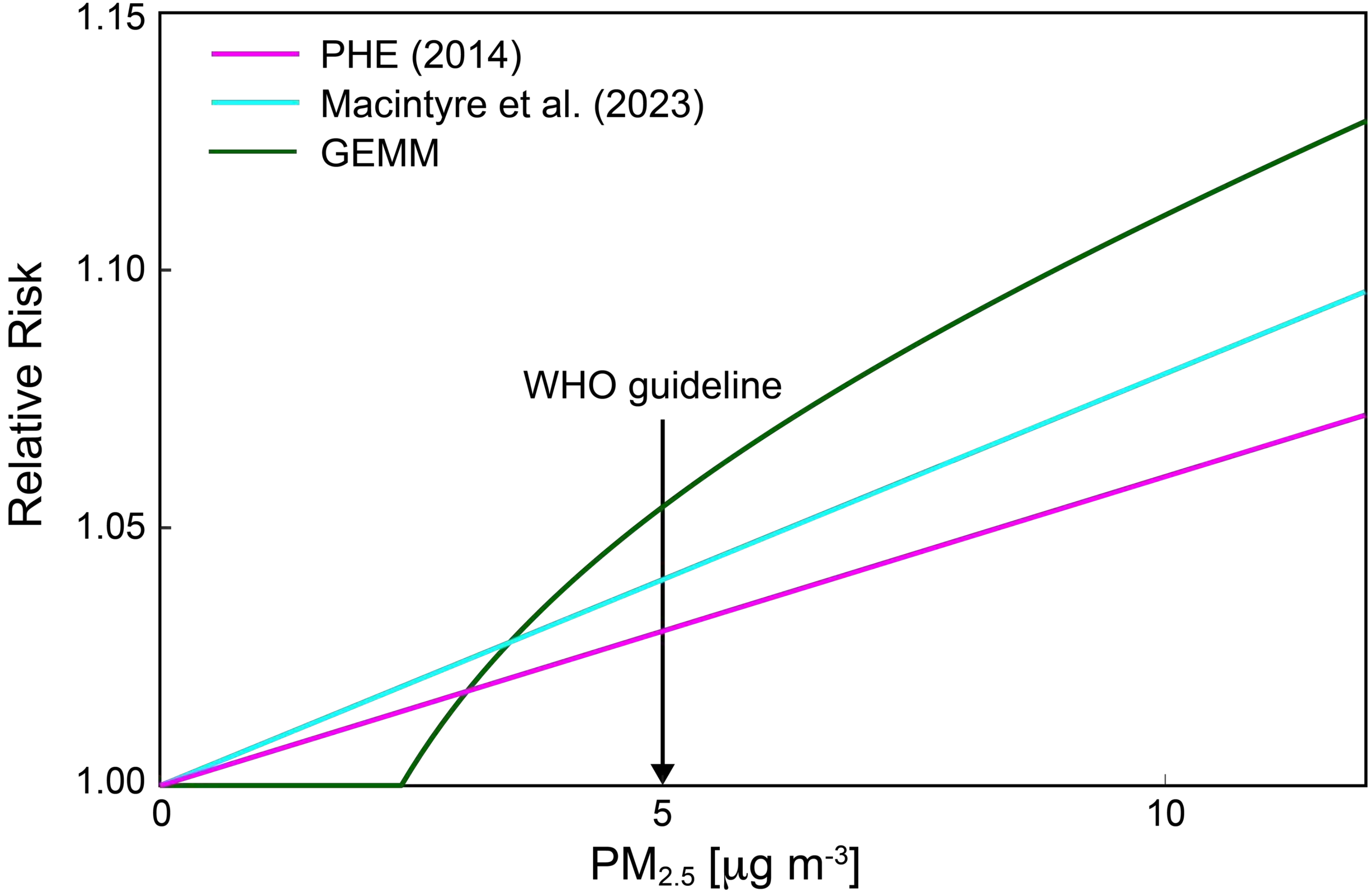
Current legislation controls cause $PM_{2.5}$ decline of at most **2 μg m^{-3}** compared to **5 μg m^{-3}** for best technology

UK grids > **5 μg m^{-3}**: 79% in the PD, 58% with legislated controls, and 36% with best technology

Relating long-term exposure to $PM_{2.5}$ to adverse health outcomes

Available curves relating $PM_{2.5}$ to premature mortality unconstrained at $PM_{2.5} < 5$ μg m^{-3}

UK $PM_{2.5}$ range is 2.5-12 μg m^{-3}



PHE (2014):
Public Health England report

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

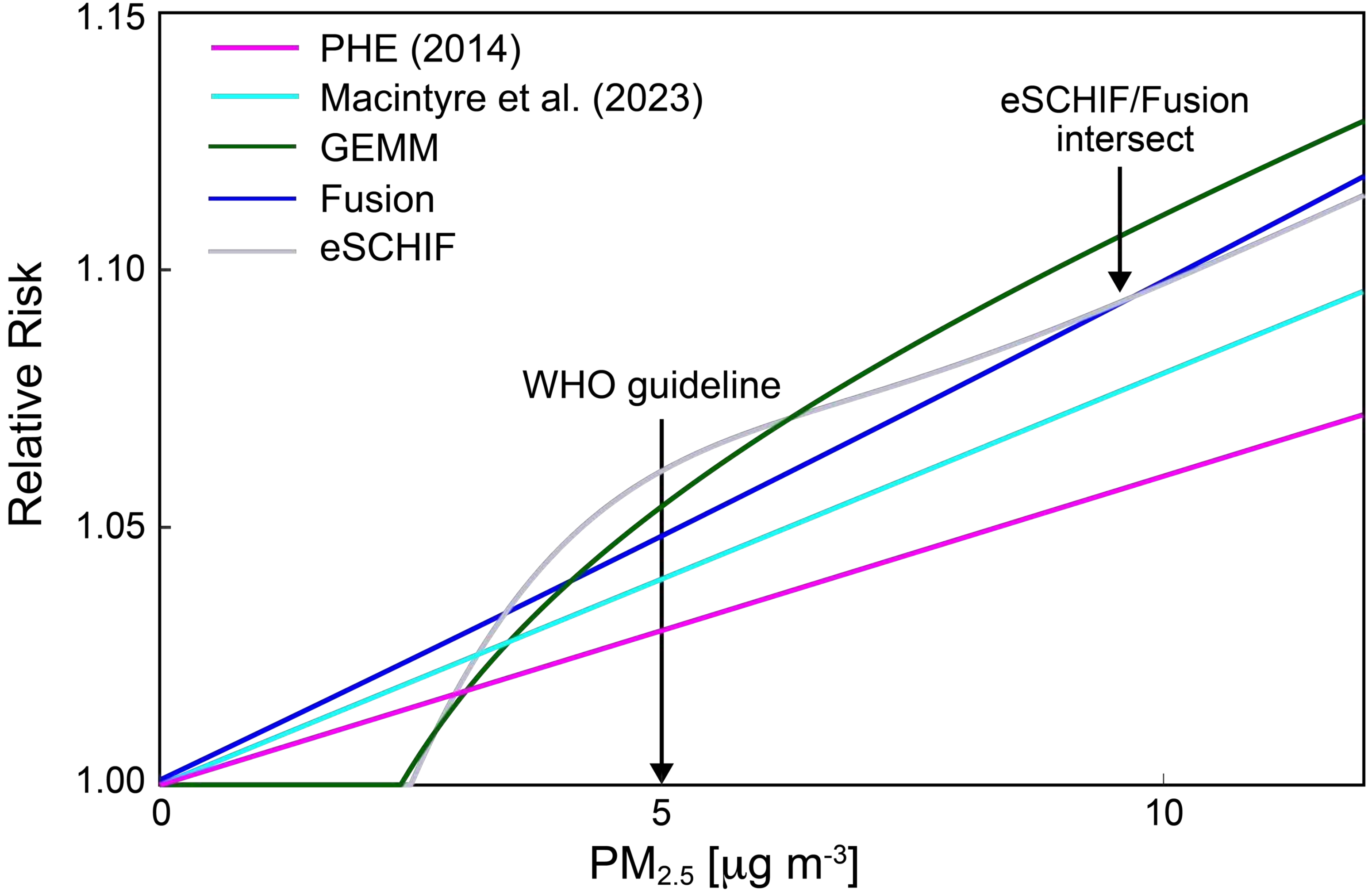
GEMM:
Global Exposure Mortality Model

All curves relate adult (mostly 25+ years old) premature mortality and annual mean $PM_{2.5}$

Relating long-term exposure to $PM_{2.5}$ 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

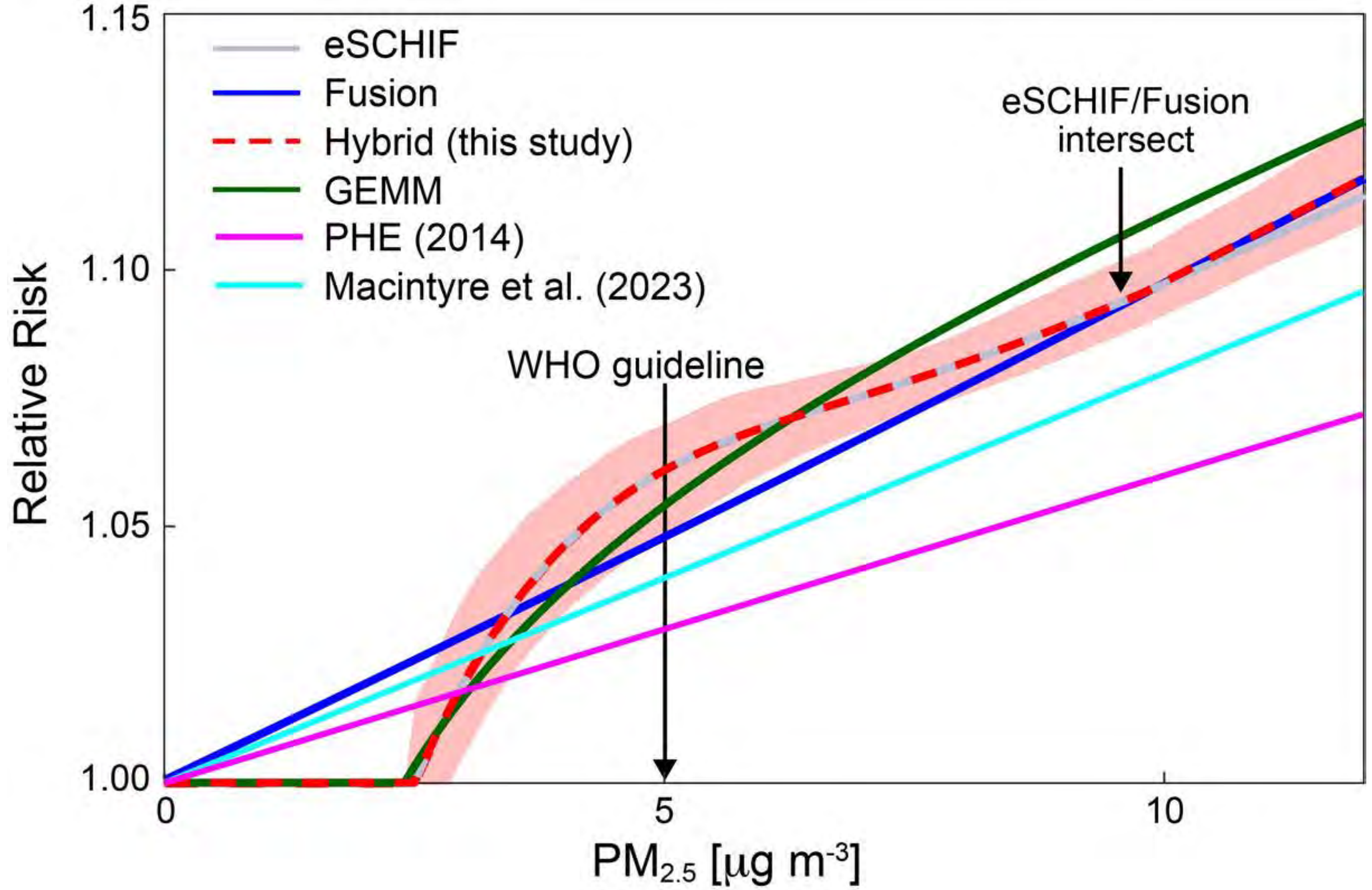
eSCHIF:
extended Shape Constrained Health Impact Function (Brauer et al., 2022 US HEI report)

Fusion addresses deficiencies in individual curves

Relating long-term exposure to $PM_{2.5}$ to adverse health outcomes

Hybrid curve combines Fusion and CanCHEC

Approach motivated by Weichenthal et al. (2022)



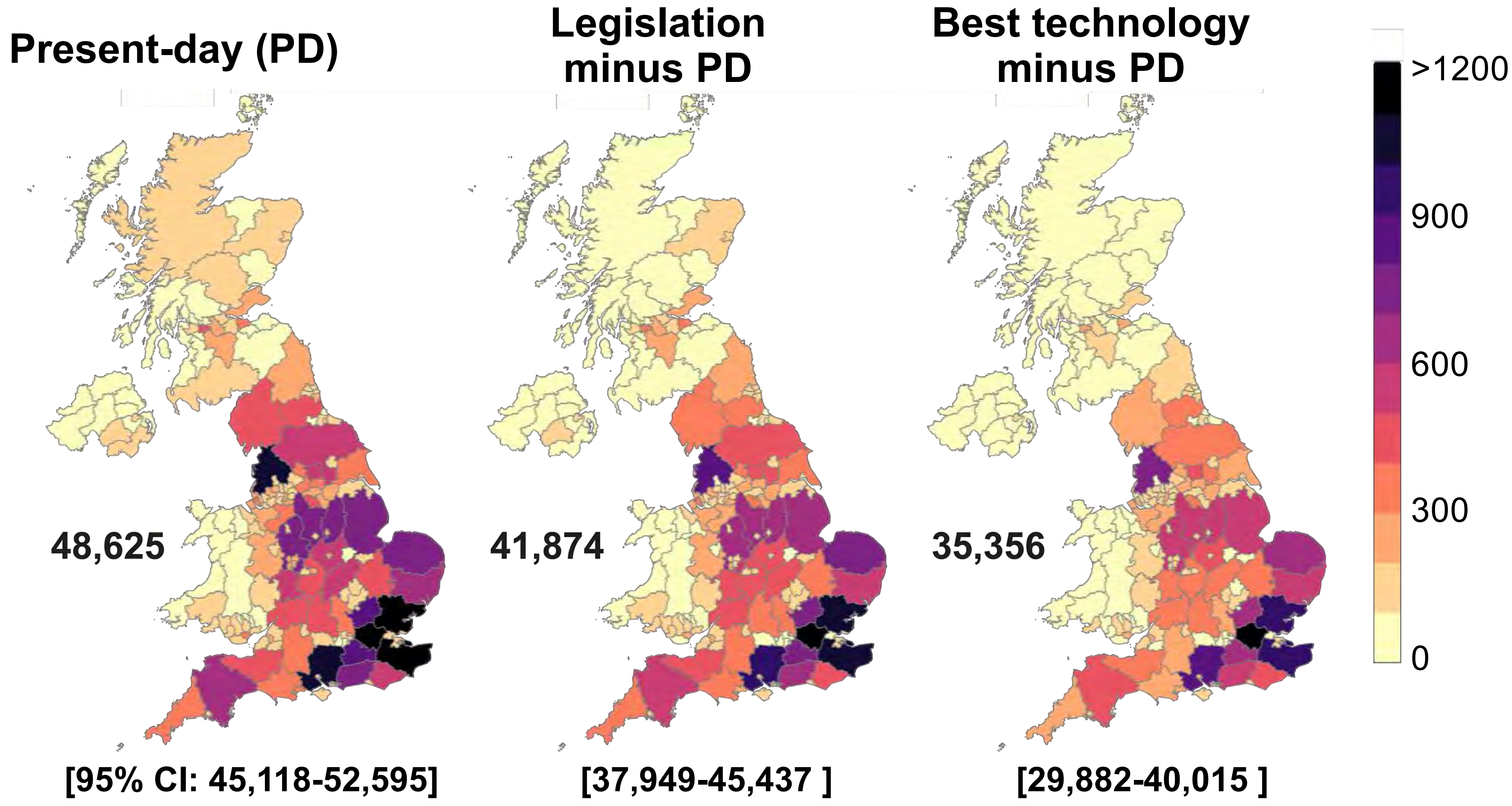
Hybrid:
eSCHIF at 2.5-9.8 μg m^{-3} and Fusion beyond 9.8 μg m^{-3}

Weichenthal et al. (2022) transition between curves at 5 μg 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 μg m^{-3}

Adult premature mortality from long-term exposure to $PM_{2.5}$

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

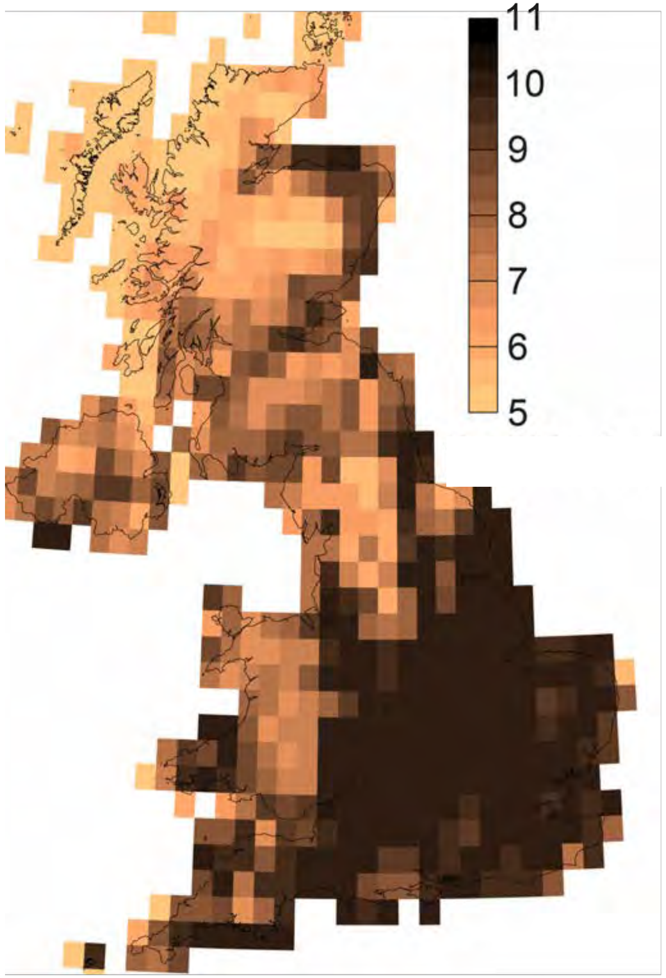


6,751 avoided early deaths with legislated controls, double that (13,269) with best available technology

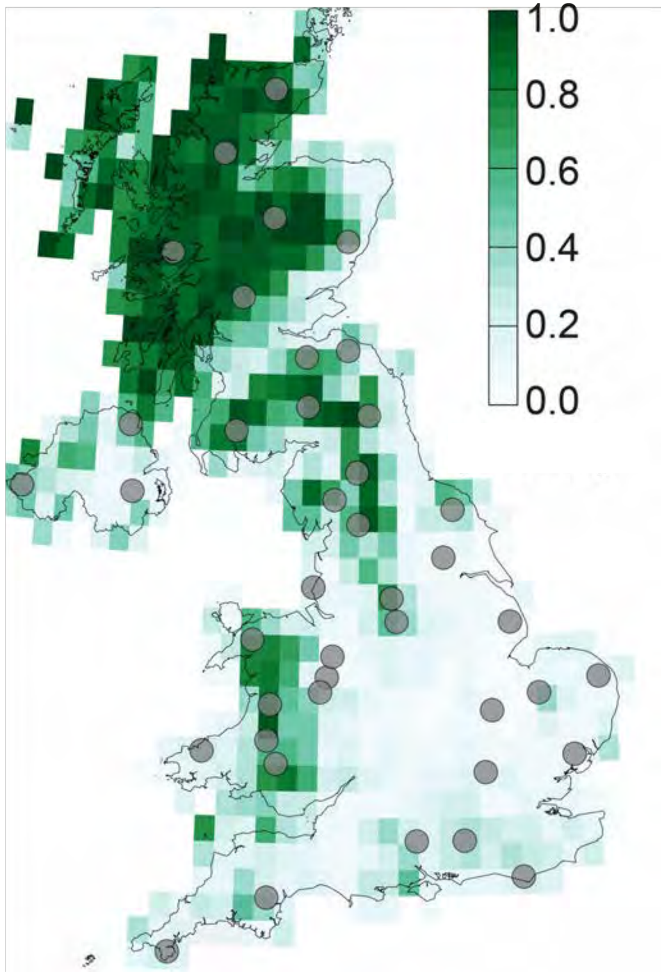
Burden of disease estimates greater than past UK-focused studies and similar to those obtained with GEMM curve

Assessing Adverse Effects on Ecosystem Health

Nitrogen critical loads
[kg N (ha sensitive habitat)$^{-1}$ a^{-1}]



Sensitive habitat cover
[fraction]



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

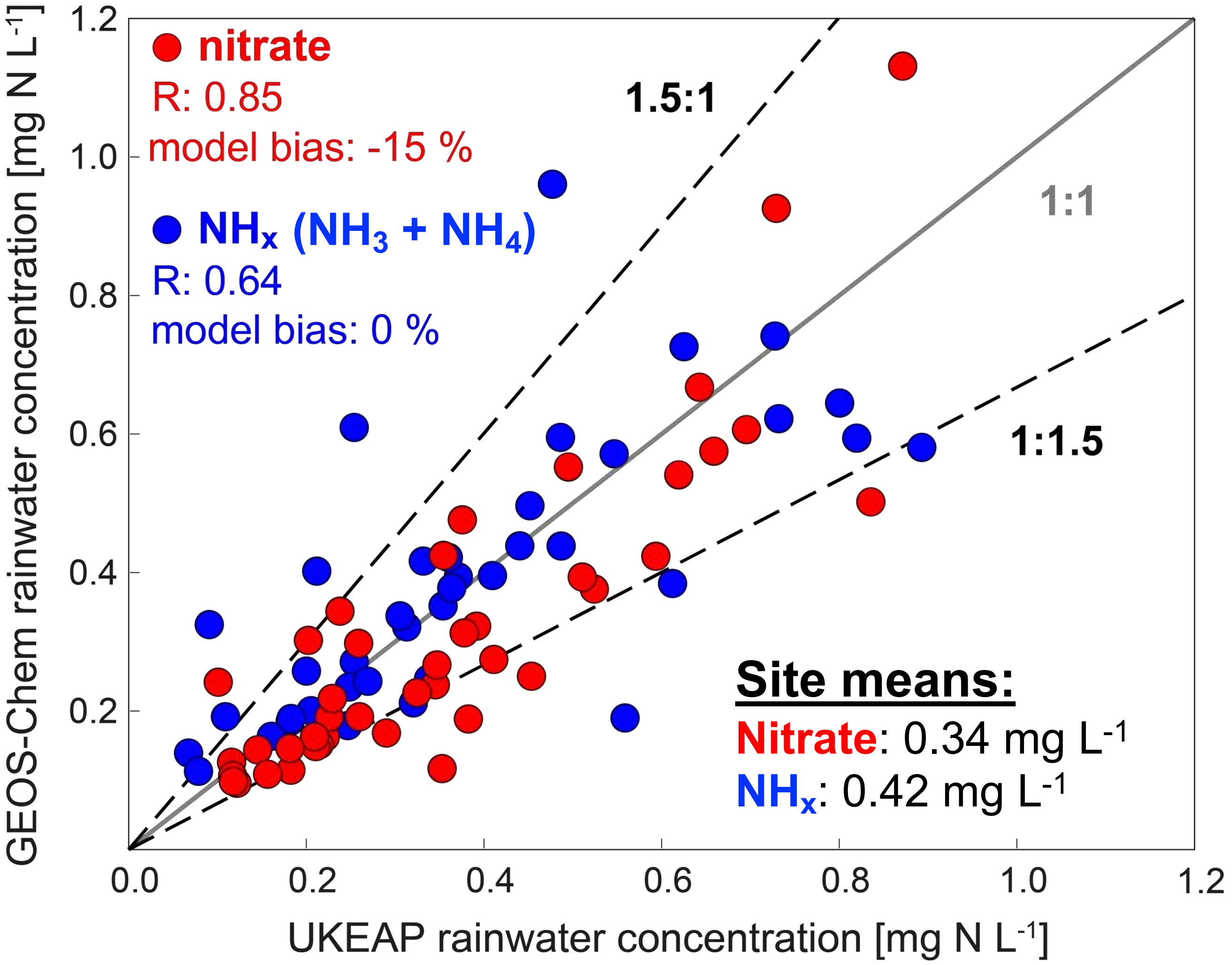
Critical load and sensitive habitat maps from Ed C. Rowe & N. Hina at the UK Centre for Ecology & Hydrology (**UKCEH**)

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

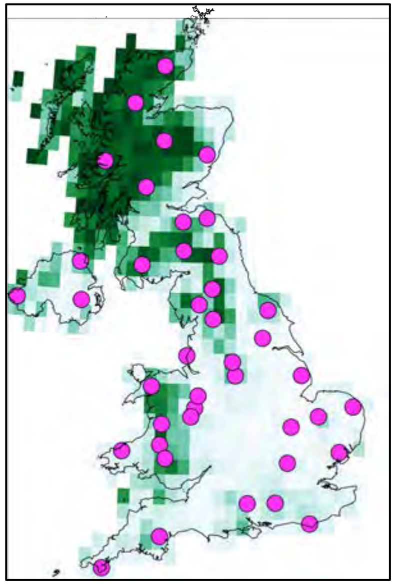
Also assess impact of ambient NH_3 on bryophytes (NH_3 > 1 μg m^{-3})

Evaluate GEOS-Chem nitrogen wet deposition

Modelled vs observed rainwater concentrations of oxidized and reduced nitrogen



Precip-Net sites



Dashed lines bound 50% difference

Requires correction to monthly total GEOS-FP precipitation

Ranges from 40-50% increase to 23-26% decrease.

GEOS-FP annual total increases by 4%

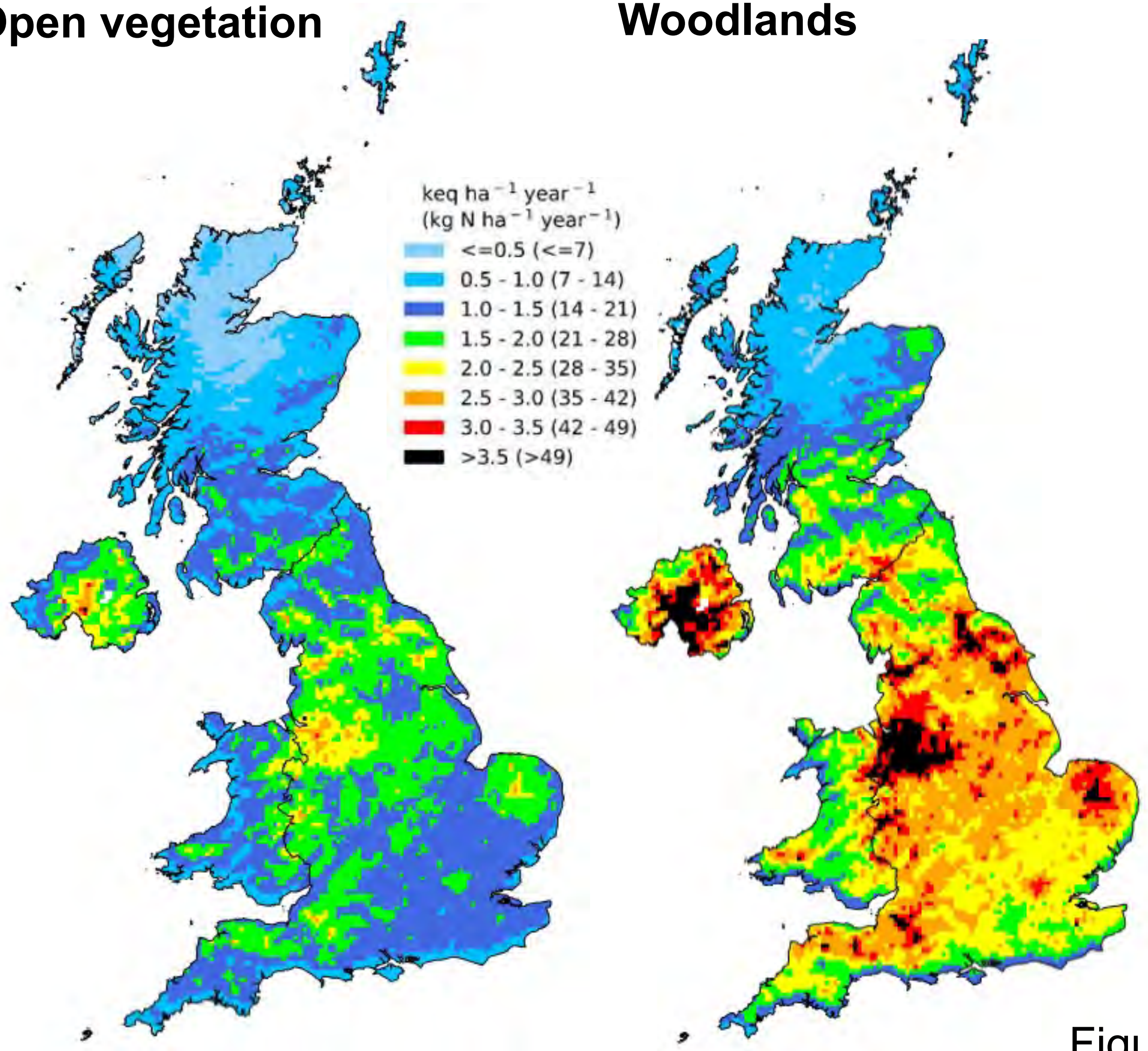
Model 15% underestimate in nitrate may be due to low bias in NO_x emissions

Wet deposition ~60% of total deposition. Unvalidated ~40% dry deposition mostly (64%) 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

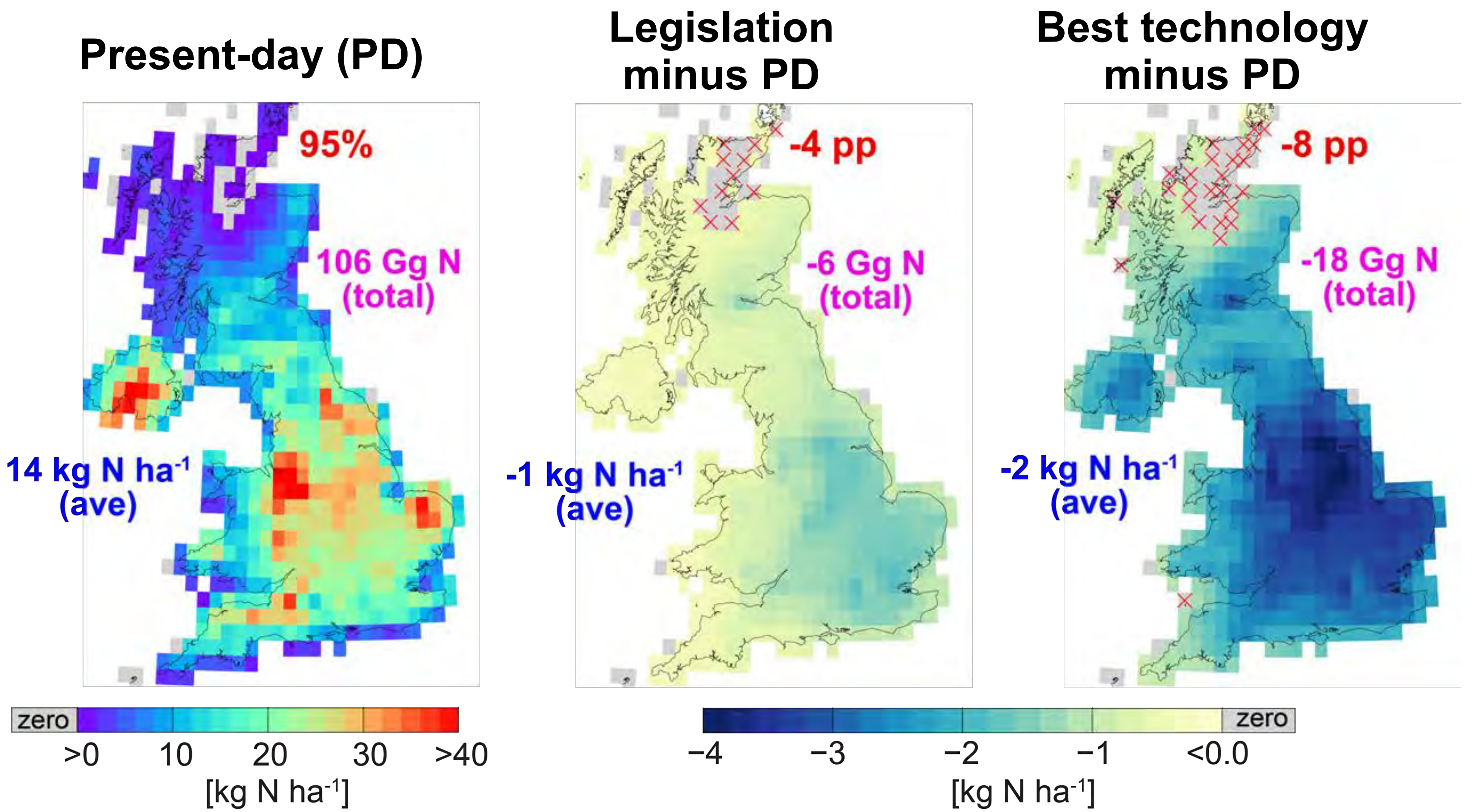
GEOS-Chem also doesn't account for enhanced washout over upland areas or deposition of cloud droplets to vegetation.

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

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

Figures from Rowe et al. (2022) annual UKCEH report

Ecosystem health benefits of emission controls



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_3: 73% today, 75% with legislated controls, 69% with best technology

Takehome Messages

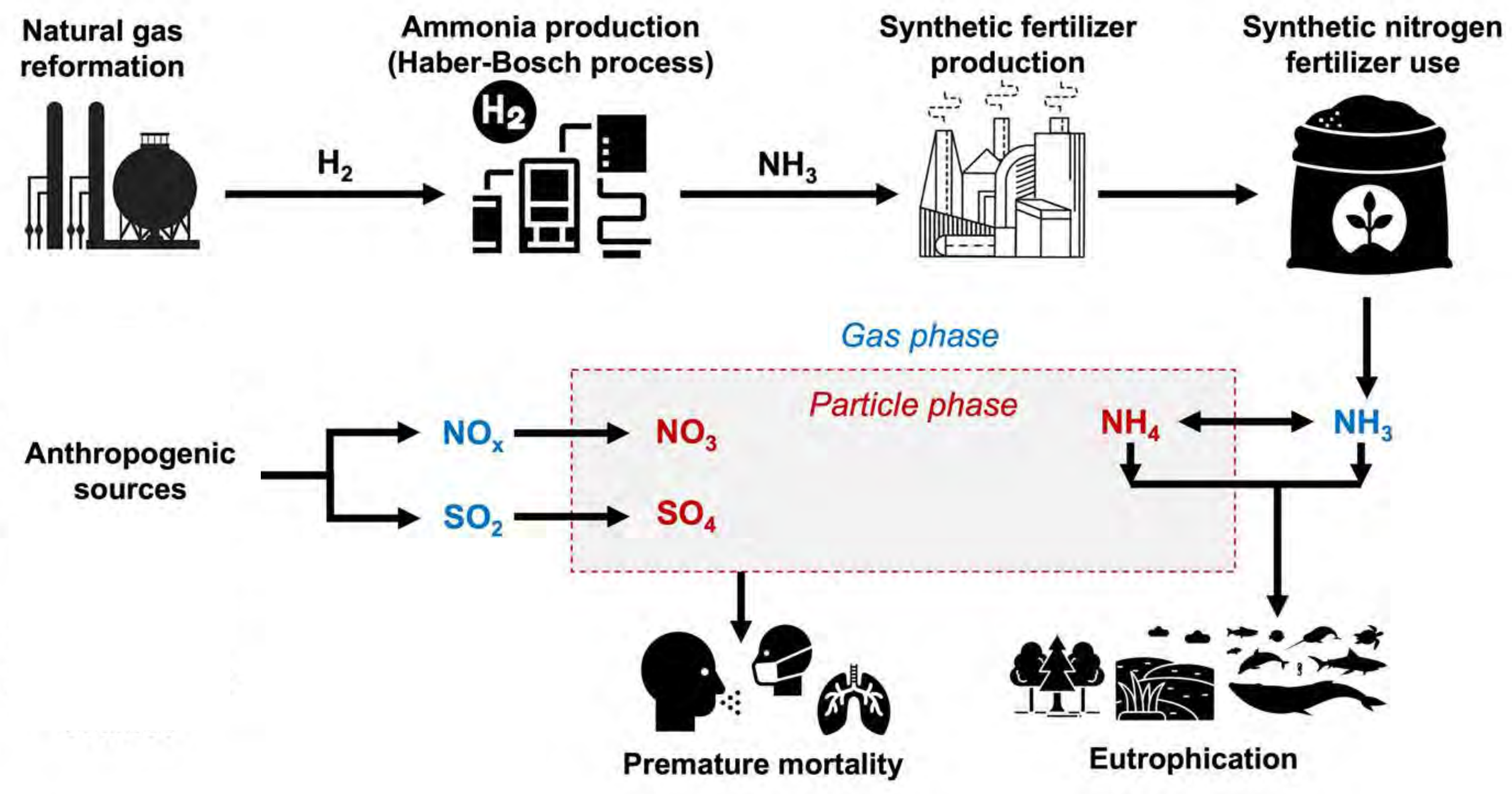
- Spring and Summer peak in NH_3 emissions
- Inventories may underestimate NH_3 emissions, as missing summer peak
- Rural NH_3 large or dominant contributor to $PM_{2.5}$ in UK cities.
- Local controls have limited efficacy at addressing $PM_{2.5}$ pollution
- Substantial improvements to public health 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 $PM_{2.5}$: City & Environment Interactions, 2023 (doi:10.1016/j.cacint.2023.100100)

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

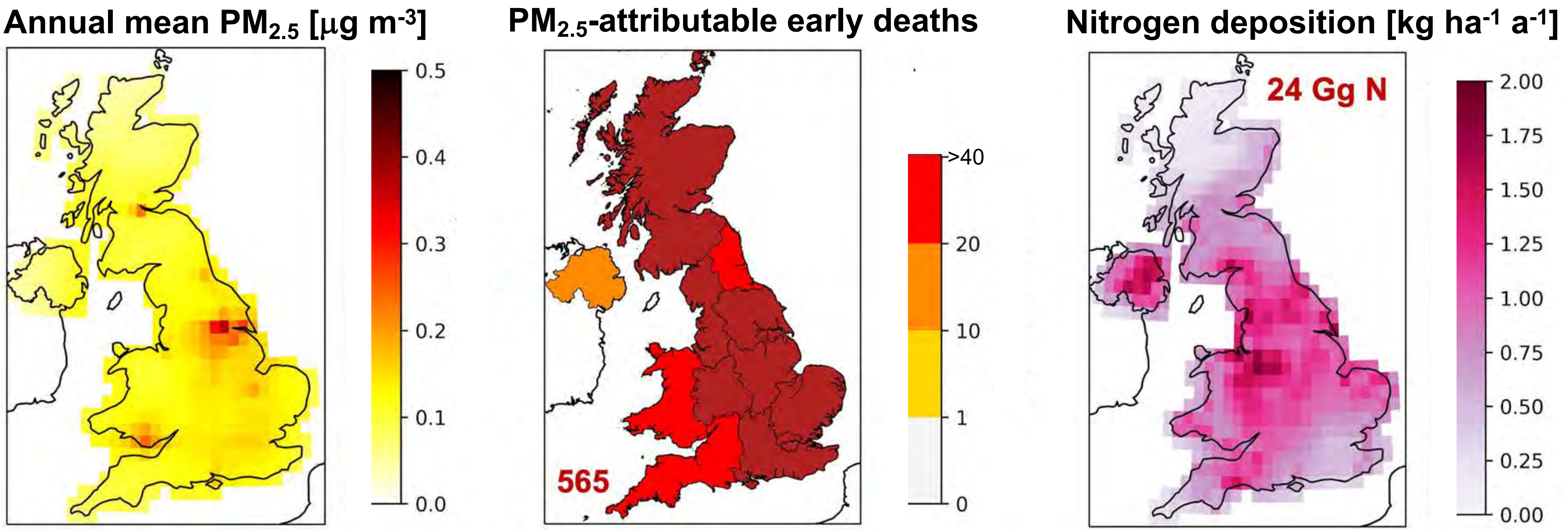
Health burden of fossil-fuel derived synthetic nitrogen fertilizer



Overwhelming majority of synthetic nitrogen fertilizer from natural gas

[*Vohra et al., in progress*]

Health burden of fossil-fuel derived synthetic nitrogen fertilizer



Total attributable to $PM_{2.5}$ 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