

Spatiotemporal distribution of N inputs drives variability in global N₂O emissions

E. Harris^{1,2}, L. Yu^{3,13}, Y. Wang⁴, J. Mohn³, S. Henne³, E. Bai⁵, M. Barthel⁶, M. Bauters⁷, P. Boeckx⁷, C. Dorich⁸, M. Farrell⁹, P. Krummel⁴, Z. Loh⁴, M. Reichstein¹⁰, J. Six⁶, M. Steinbacher³, N. Wells¹¹, C. Zellweger³, M. Bahn², P. Rayner¹²

¹Functional Ecology Research group, University of Innsbruck, Austria

²Swiss Data Science Centre, ETH Zurich, Switzerland

³Laboratory for Air Pollution & Environmental Technology, Empa, Switzerland

⁴CSIRO Ocean and Atmosphere Flagship, Aspendale, Australia

⁵Institute of Applied Ecology, Chinese Academy of Sciences

⁶Department of Environmental Systems Science, ETH Zurich, Switzerland

⁷Isotope Bioscience Laboratory, Ghent University, Belgium

⁸Natural Resource Ecology Laboratory, Colorado State University, USA

⁹CSIRO Agriculture and Food, Glen Osmond, Australia

¹⁰Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Germany

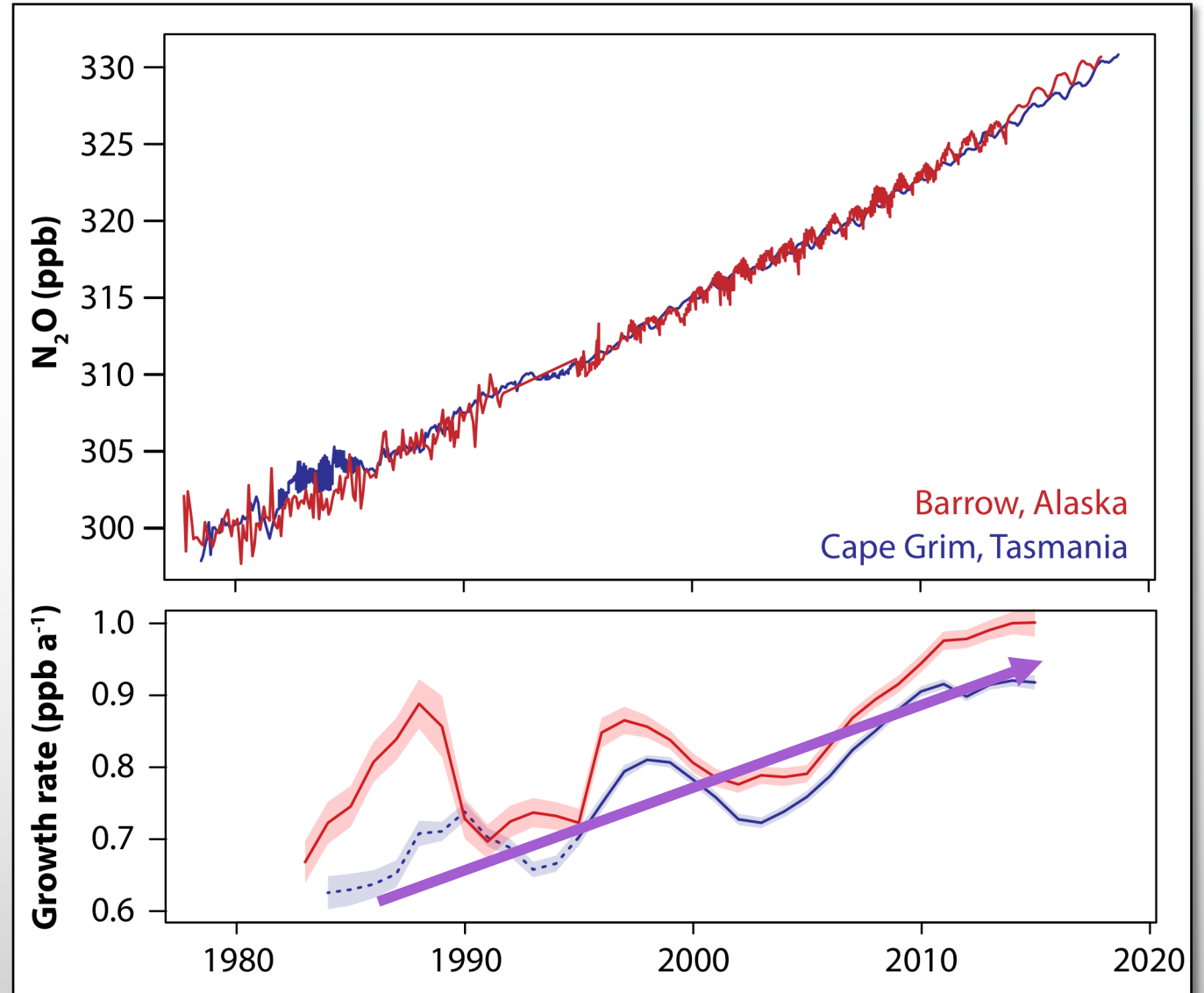
¹¹Centre for Coastal Biogeochemistry, Southern Cross University, Australia

¹²Department of Earth Sciences, University of Melbourne, Australia

¹³Now at: Institute of Groundwater and Earth Sciences, Jinan University, China

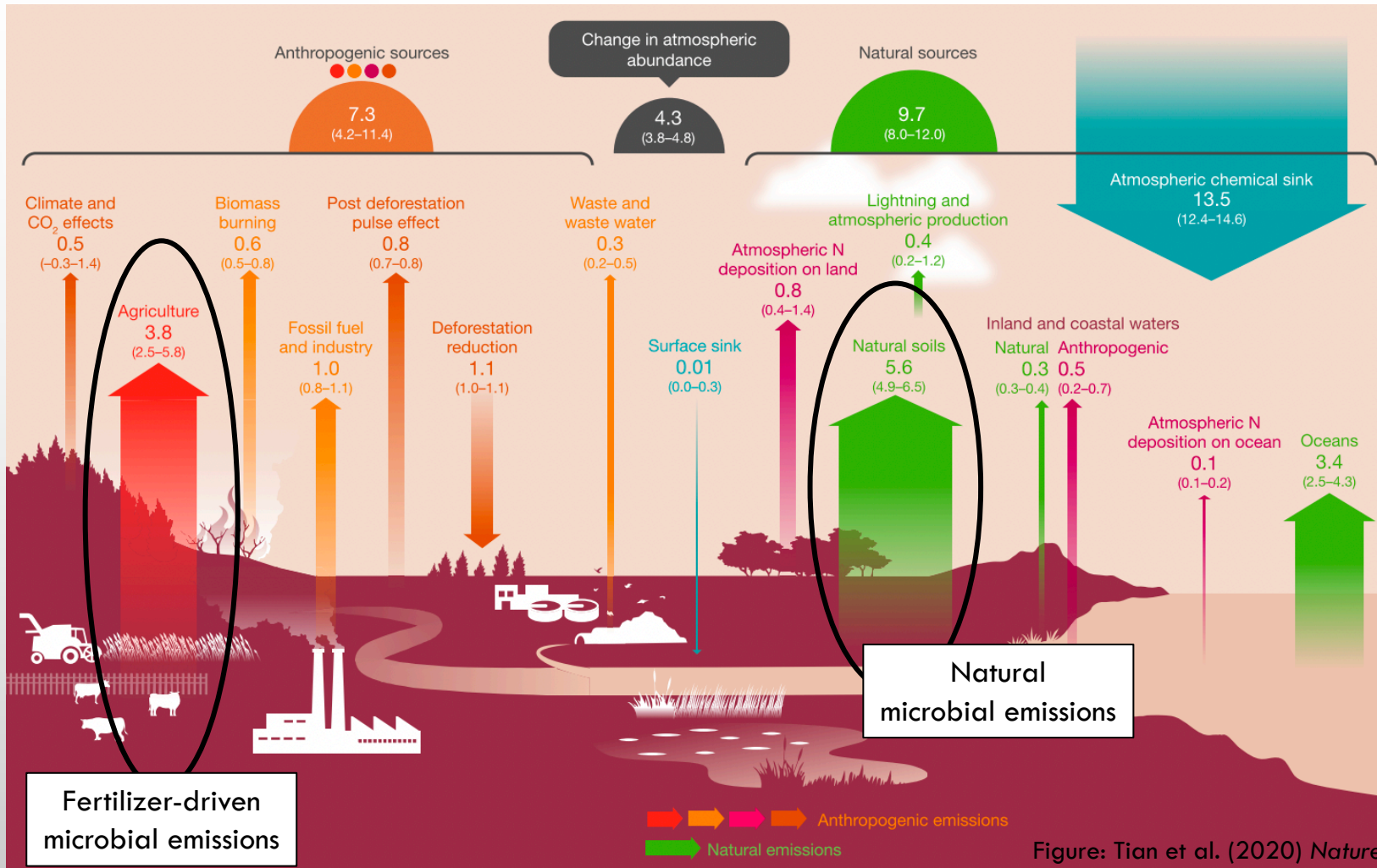
N₂O: Rising globally, impacting climate

- Nitrous oxide (N₂O) is a strong greenhouse gas and ozone-depleting substance
- N₂O mole fraction is rapidly increasing around the world
- Particularly concerning:
Growth rate is accelerating



Data: NOAA HATS/CCGG and AGAGE. Figure: Harris et al. (2021) *Science Advances*.

What drives N₂O emissions?

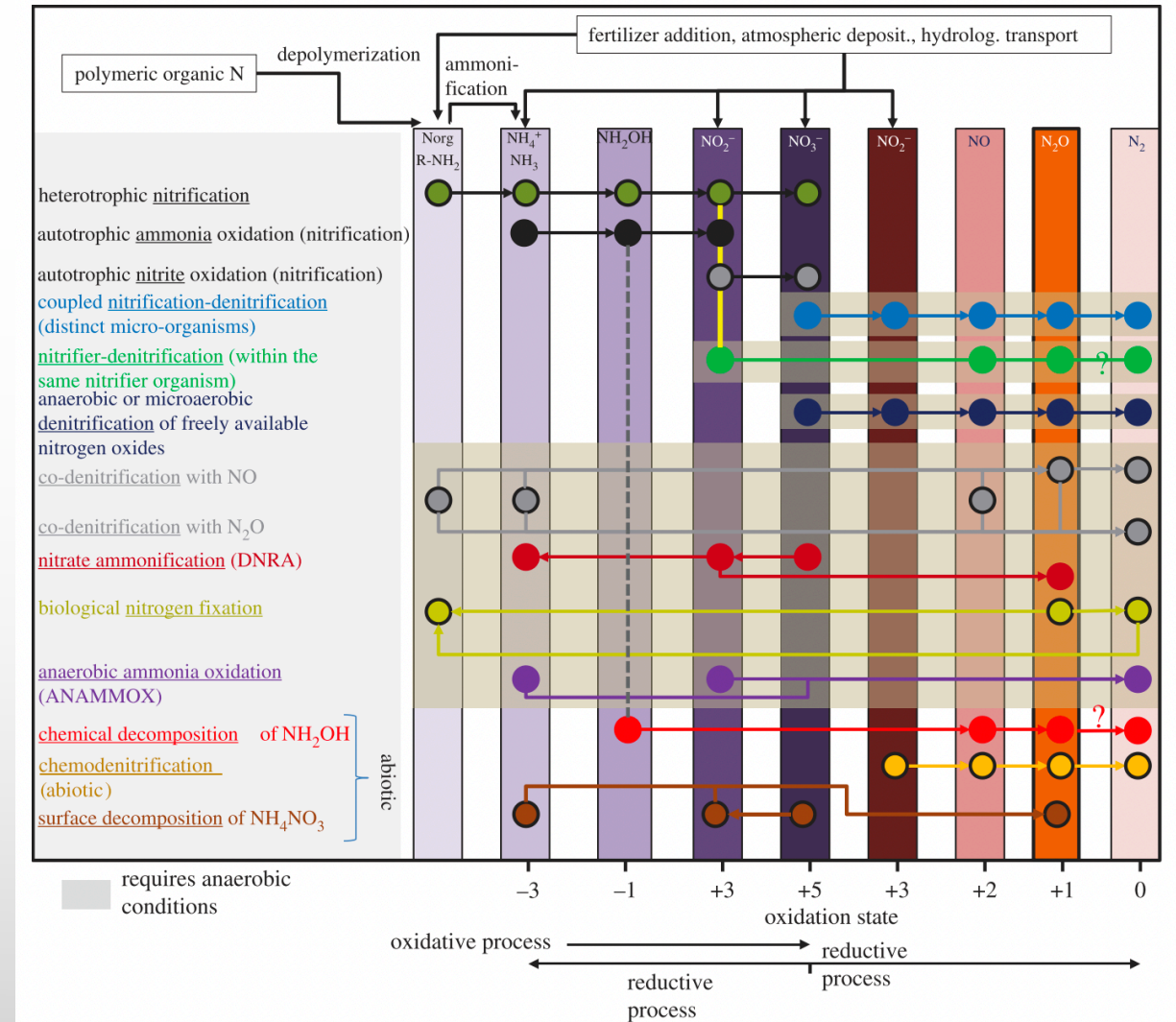


- *N inputs...*
- *N outputs:* Leaching, volatilization, N gas production
- Climate warming accelerates N cycling
- Many drivers impact N₂O emissions: soil texture, moisture, microbes...

How are anthropogenic activities impacting N₂O emissions?

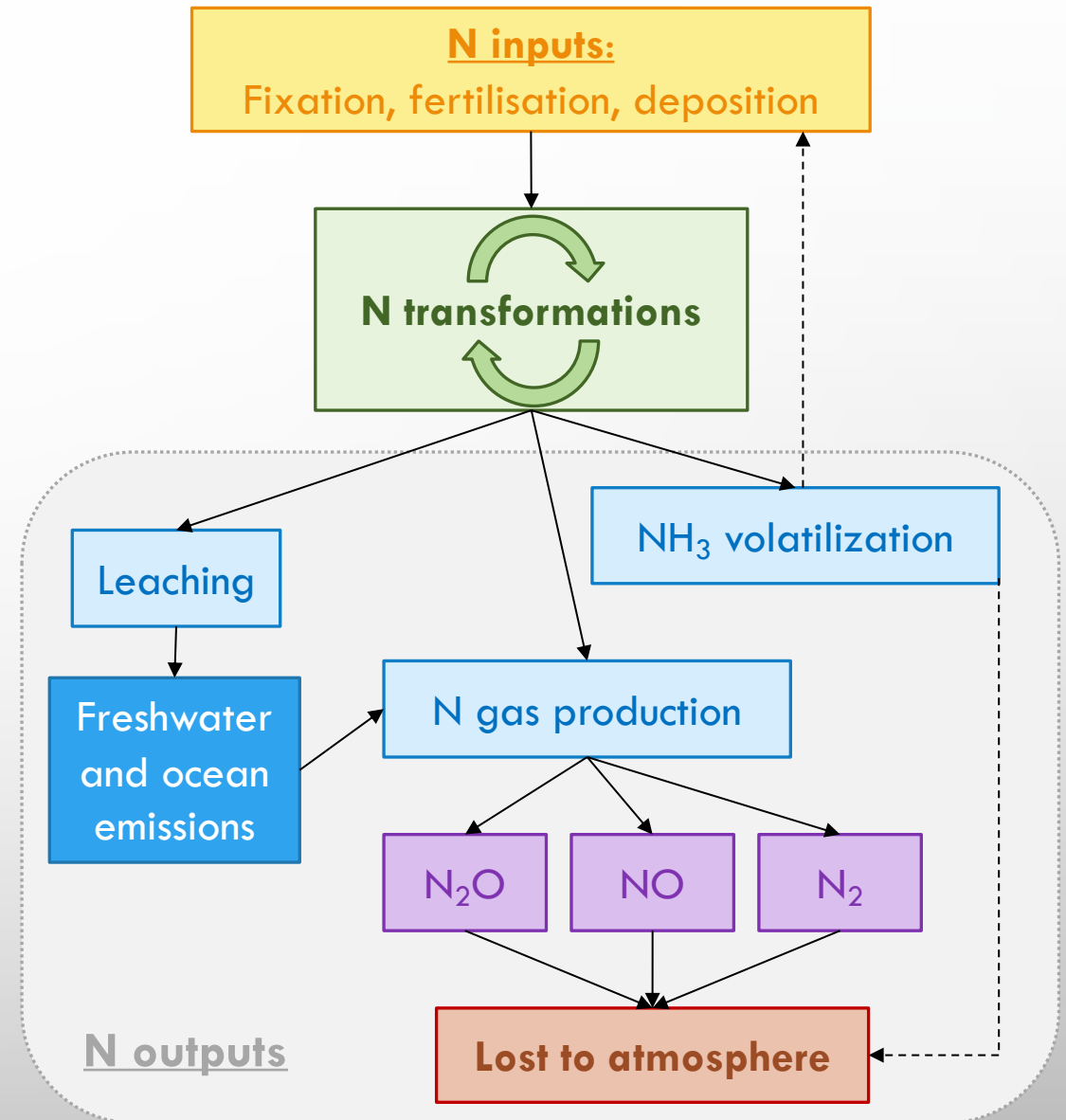
Modelling N₂O emissions and the N cycle

- Process-based modelling of the N cycle is complicated...



Modelling N₂O emissions and the N cycle

- Process-based modelling of the N cycle is complicated...
- Isotopes can act as an 'integrated' signature of numerous processes
- At steady state:
 - N inputs = N outputs
 - ¹⁵N inputs = ¹⁵N outputs
- **Can we use N isotopes as a simple constraint for the global N₂O budget?**



The IsoTONE model

- **I**sotopic **T**racing **O**f **N**itrogen in the **E**nvironment
- Estimates N losses based on steady state assumption:

$$f_{leach} + f_{NH_3} + f_{gas} = 1$$

1) N losses

$$\delta^{15}N_{soil} = \delta^{15}N_{input} - f_{leach} \cdot \epsilon_{leach} - f_{NH_3} \cdot \epsilon_{NH_3} - f_{gas} \cdot \epsilon_{gas}$$

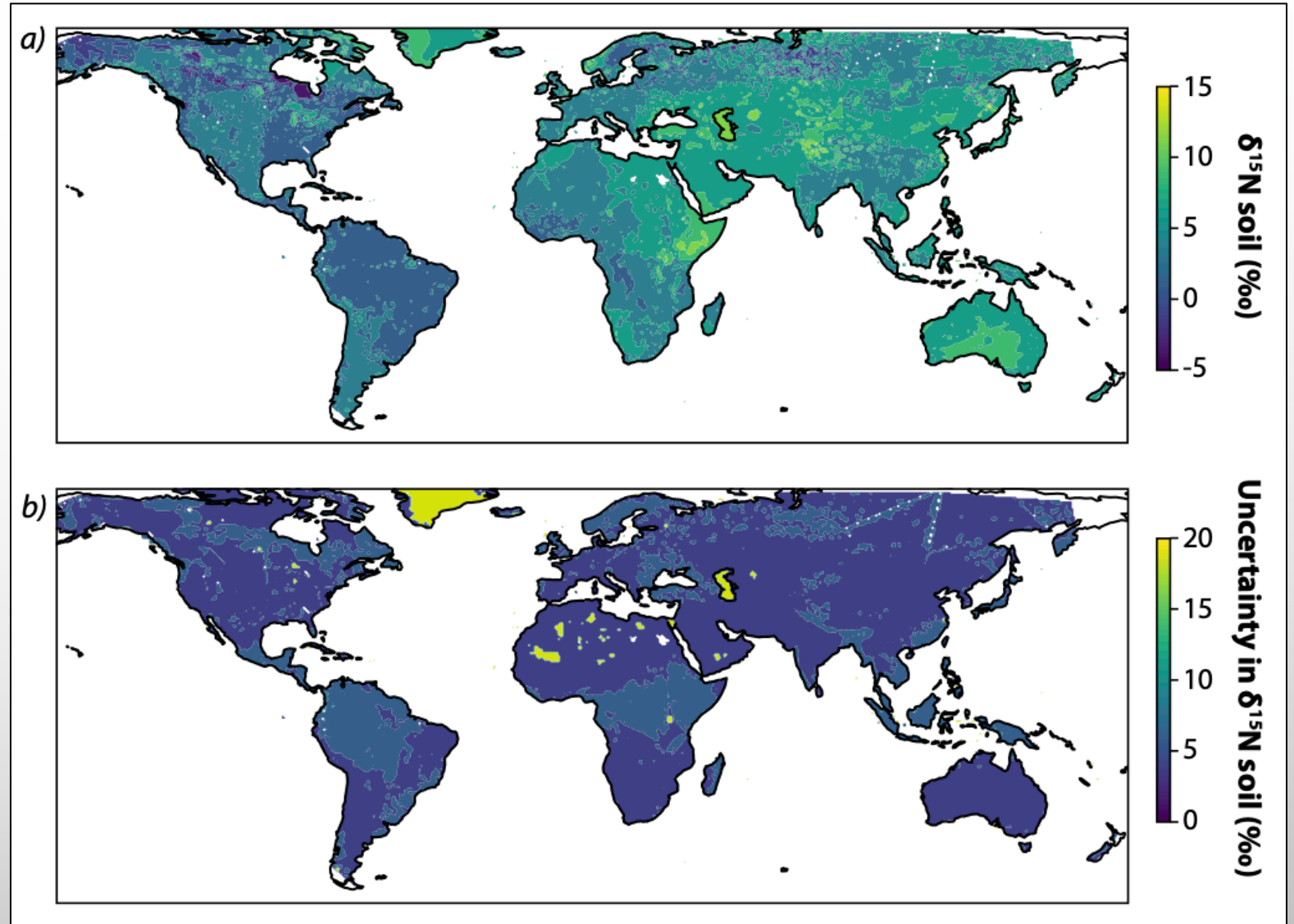
2) N isotopes

- NH_3 volatilization is estimated by a land surface model (CABLE); $f_{NH_3} < 0.05$
- Gas production strongly favours ^{14}N , causing ^{15}N enrichment in soil N pool
- Leaching produces weak fractionation, therefore:

$$\text{Low } \delta^{15}N_{soil} = \text{leaching} \quad \Leftrightarrow \quad \text{High } \delta^{15}N_{soil} = \text{gas production}$$

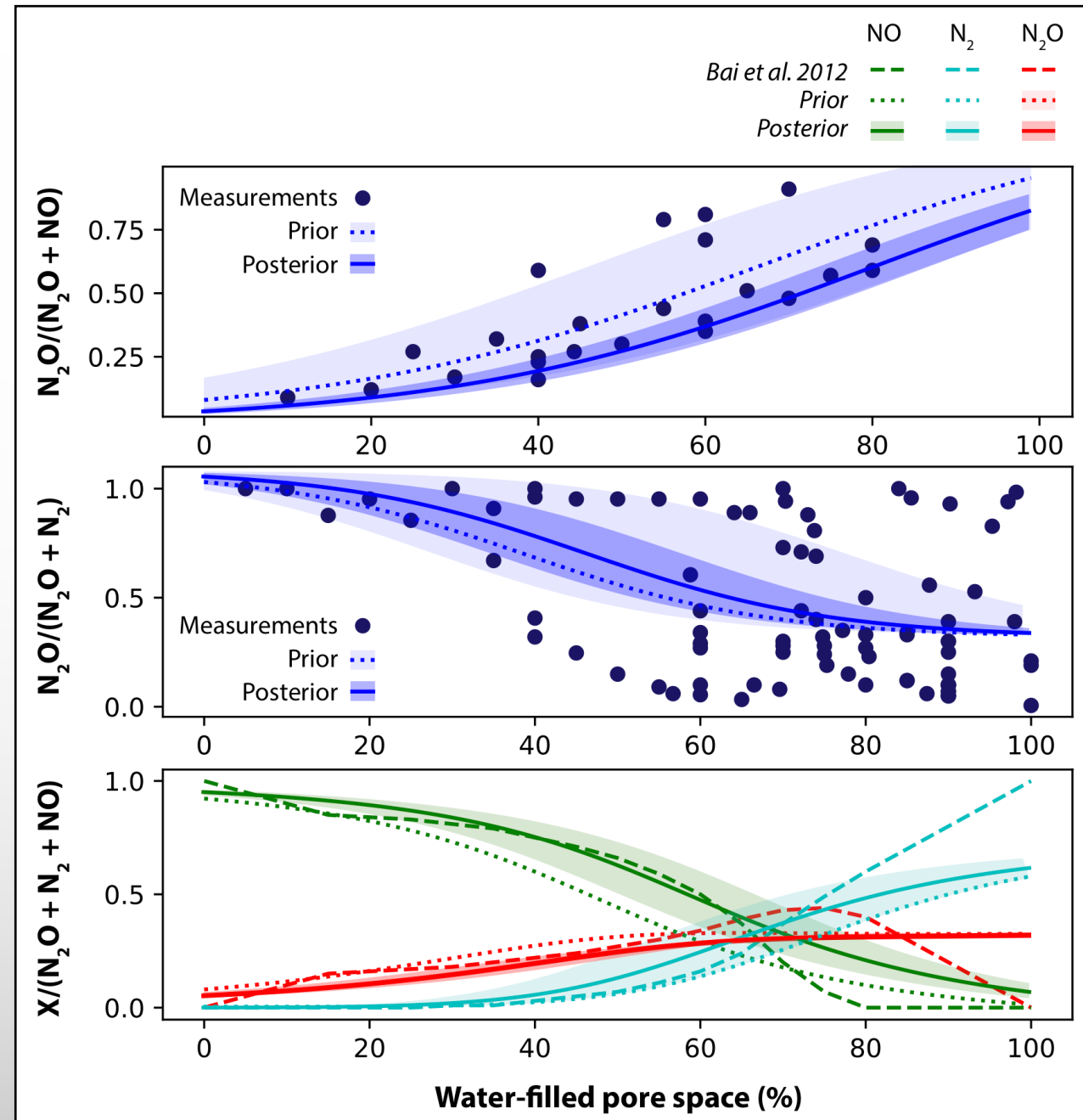
Global soil nitrogen isotopic composition

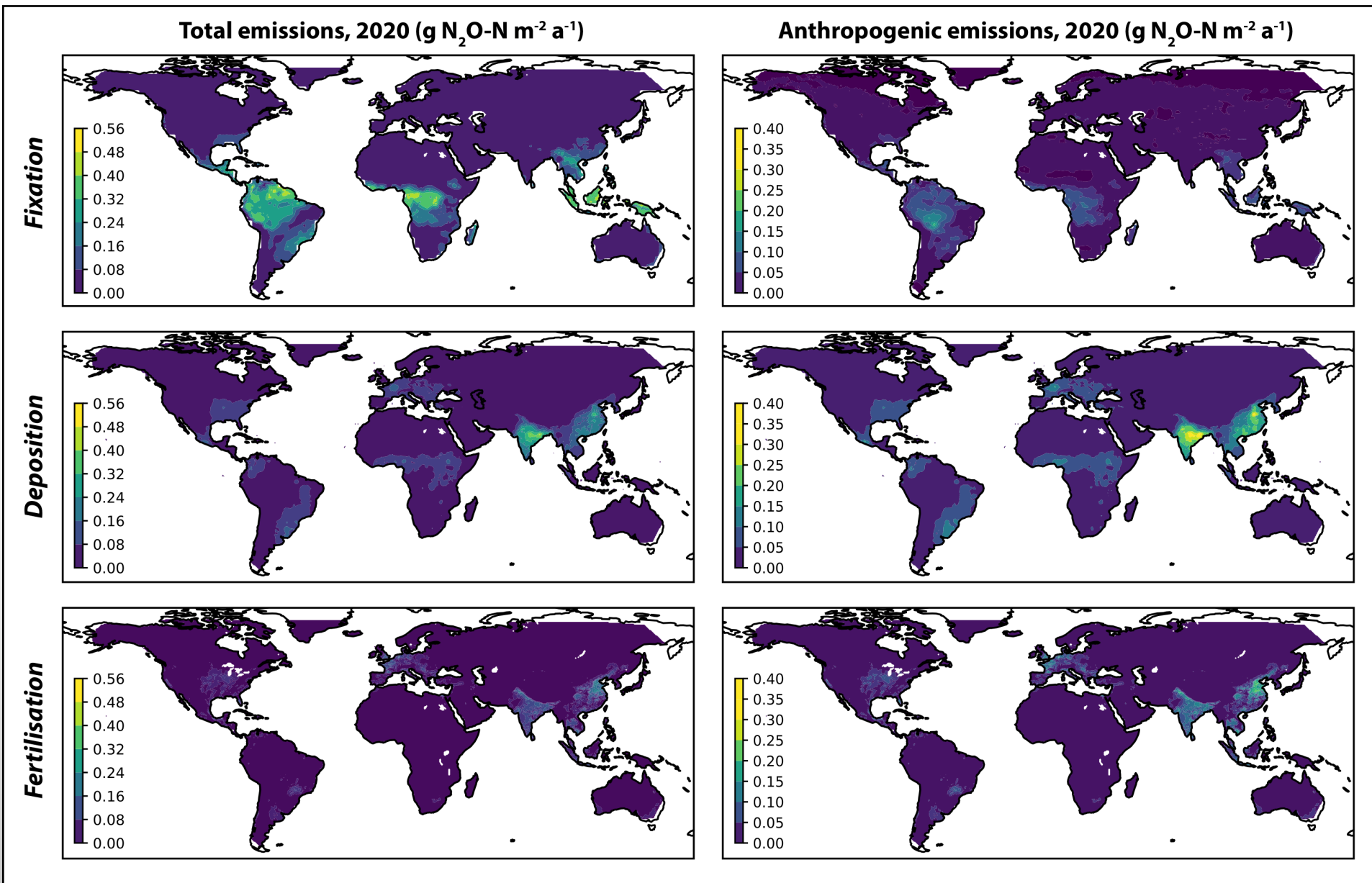
- Soil $\delta^{15}\text{N}$ was interpolated globally from ~7000 available data points using an artificial neural network
- Total N gas production (f_{gas}) and leaching (f_{leach}) were estimated for each grid cell ($0.5^\circ \times 0.5^\circ$)



Calculating N₂O emissions

- f_{gas} can be broken down into NO, N₂ and N₂O emission factors based on a sigmoid fit to soil moisture (WFPS)
- N₂O emissions and isotopic composition are calculated for each grid cell
 - **N inputs:** Fertilization, fixation, deposition

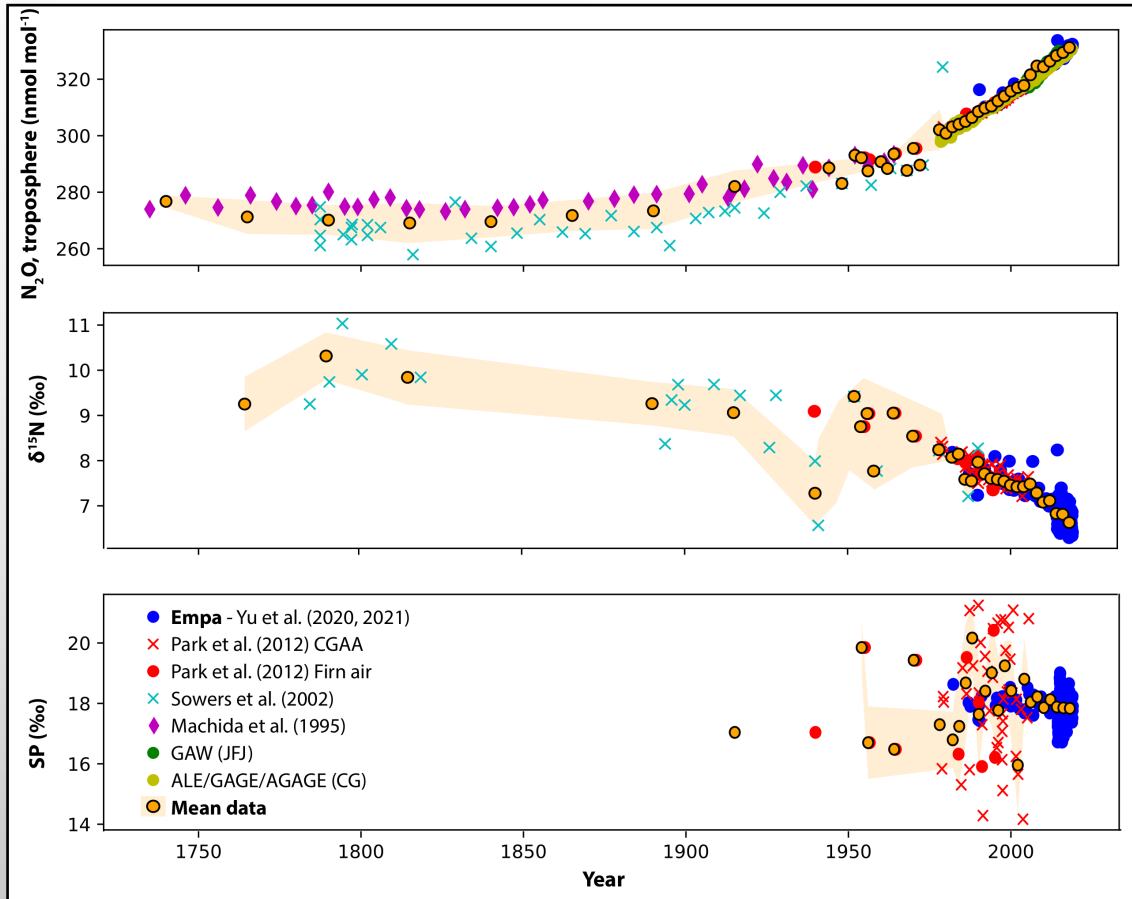




However, there is very little representative emission data to test the model...

Modelling atmospheric N₂O

- High precision atmospheric time series for N₂O have been measured

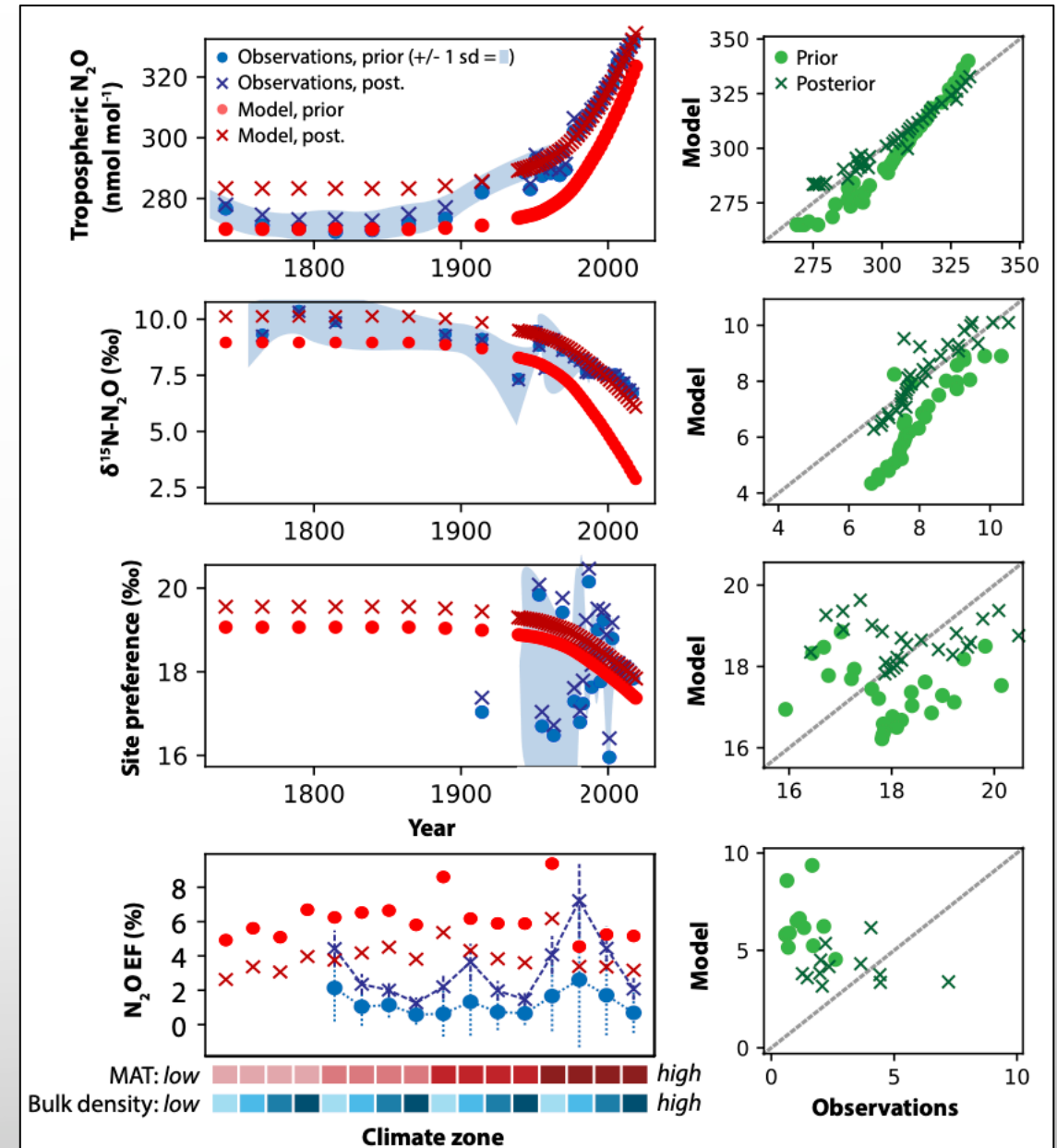


- Annual N₂O emissions per grid cell are estimated for 1850-2020
- N₂O is emitted into a well-mixed troposphere
- Stratospheric destruction is estimated, assuming steady state in the preindustrial

⇒ N₂O background mixing ratio and isotopic composition are simulated

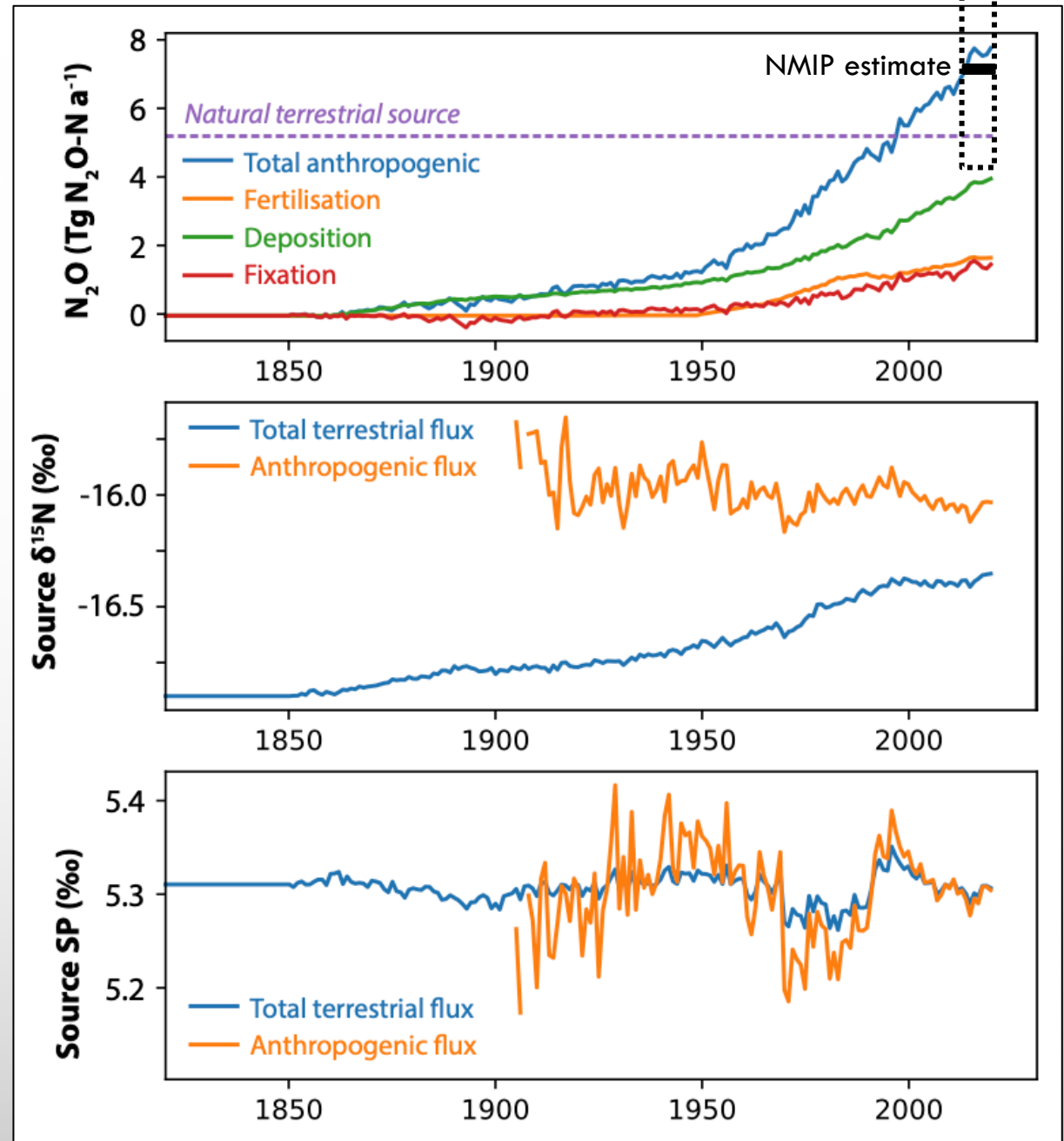
Results: Model optimization

- 12 model parameters were optimized in an MCMC with 150 000 iterations
- Using the posterior parameters, RMSE was reduced from:
 - 12.9 to 4.3 ppb for mixing ratio
 - 2.2 to 0.6 ‰ for $\delta^{15}\text{N}^{\text{bulk}}$
 - 1.2 to 1.1 ‰ for $\delta^{15}\text{N}^{\text{SP}}$
- Prior emission factors were too uncertain to constrain the MCMC
 - More representative emission factor estimates are needed



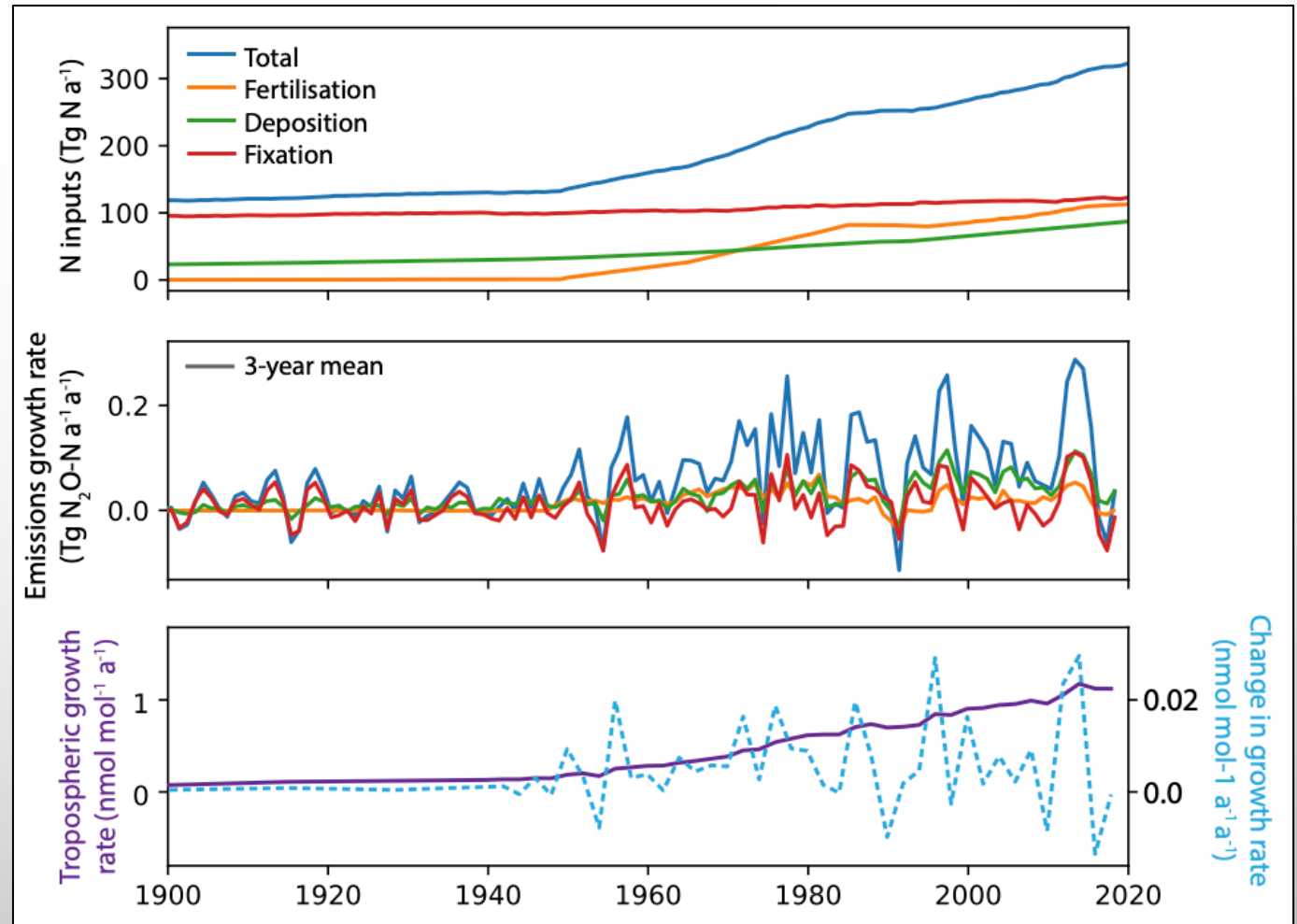
Results: N₂O emissions

- Anthropogenic emissions were calculated assuming natural emissions have not changed
 - Total anthropogenic N₂O agrees well with the recent NMIP estimate
- Emissions are increasing from all input categories: **fixation**, **fertilization** and **deposition**
- $\delta^{15}\text{N}^{\text{SP}}$ suggests major changes in the anthropogenic source



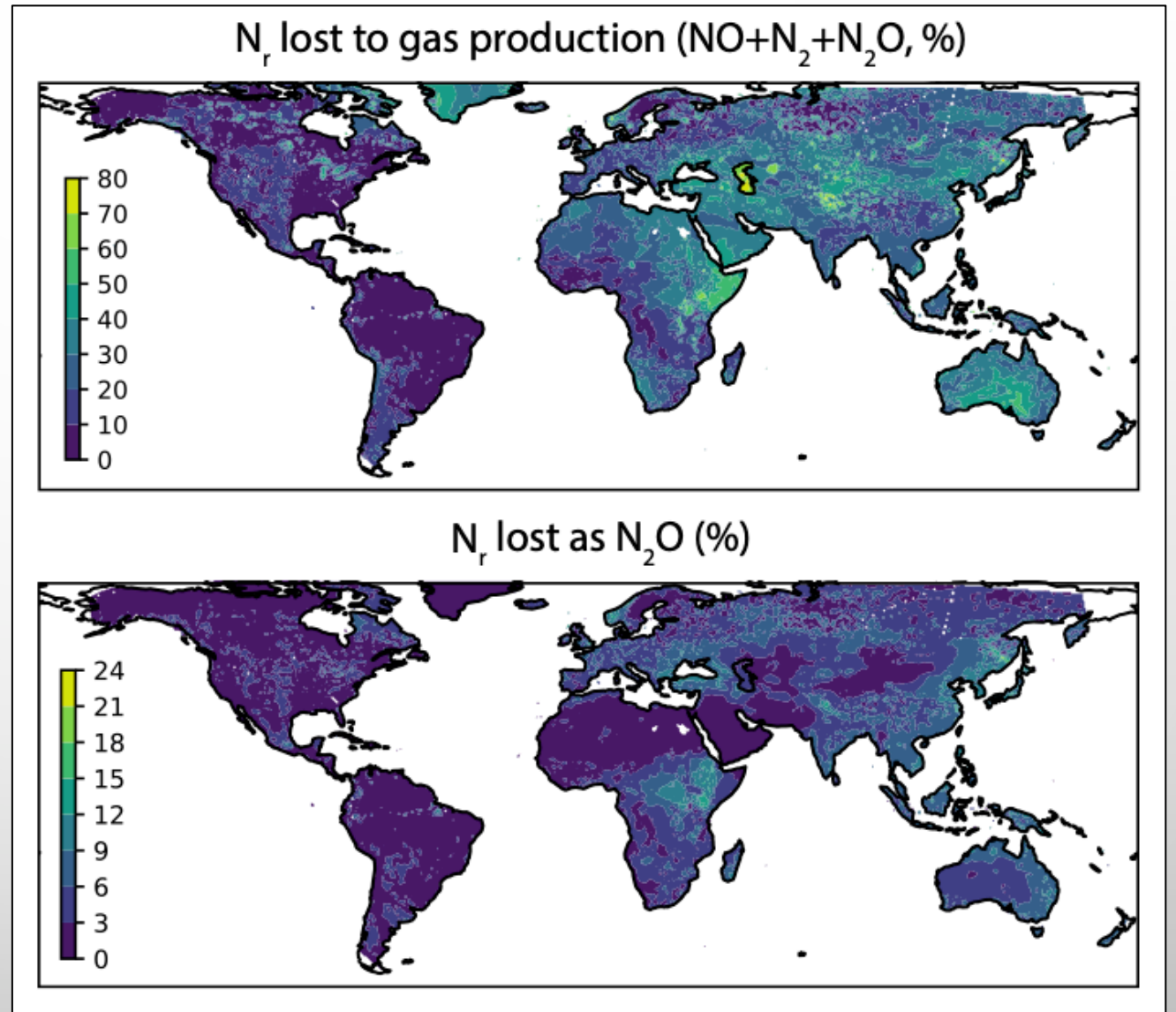
Results: N₂O emissions growth rate

- N inputs drive variability in total global N₂O emissions
- Subdecadal variability in N₂O is dominated by variability in **fixation**
- Decadal variability is dominated by **fertilizer N inputs**
- **Deposition N₂O** is steadily increasing but not highly variable



Results: N₂O emission factor

- N₂O emission factor shows strong spatial variability
 - Temperature, soil moisture and texture, nutrient availability
- Area-weighted global mean EF is 1.0%, in good agreement with IPCC's 1.4%
- However, N-input-weighted global mean EF is 3.8% in 2020
- Mean EF has increased by >0.5% since 1960



Conclusions

- N isotopes can be used as an integrated estimate of N loss pathways to allow simple and fast modelling of N₂O emissions
- The IsoTONE model combines soil and atmosphere modules within an MCMC optimization framework
 - Total emissions agree well with the recent NMIP N₂O budget estimate
- N fixation responds to climate, causing subdecadal variability in N₂O growth rate, while fertilisation drives longterm increases
- N₂O emission factors show strong spatial variability, and an increasing trend as N inputs move to areas with higher EF
 - Soil $\delta^{15}\text{N}$ could be used to estimate regional EFs for GHG inventories

A scenic mountain landscape with a valley and a town in the distance. The foreground shows a grassy slope with some evergreen trees. The middle ground features a deep valley with a small town or village nestled in it. The background consists of high, rugged mountains under a clear blue sky.

Thank you for listening!

- *Thanks to the Austrian Science Foundation (FWF), and the Swiss National Science Foundation (SNF) for financing this work*
- *Thanks to the OECD Cooperative Research Program for Sustainable Agriculture for funding my stay in Melbourne*
- *This work was only possible thanks to support from many Bachelor, PhD and Masters students, as well as countless supervisors and mentors*

Simulating N₂O emissions based on N isotopes: The **IsoTONE** model

E. Harris et al.

