In partnership with International Nitrogen Initiative

Global Nitrous Oxide Budget

2024

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Atmospheric N_2O datasets
NOAA/ESRL | AGAGE | CSIRO

Inventories
FAOSTAT | EDGAR v7.0 | UNFCCC | GFED4s

Other sources
SRNM | one nutrient budget model | Mechanistic Stochastic Modeling | Bookkeeping method

Atmospheric inversions
INVICAT | PyVAR-CAMS |MIROC4-ACTM | GEOS-Chem

Land models
CLASSIC| DLEM | ELM | ISAM| LPX-Bern | O-CN | ORCHIDEE | VISIT

Ocean models
Bern-3D | NEMOv3.6-PISCESv2-gas | NEMO-PlankTOM10 | UVic2.9

Shelf products
MEM-RF | CNRM-0.25° | ECCO2-Darwin & ECCO-Darwin

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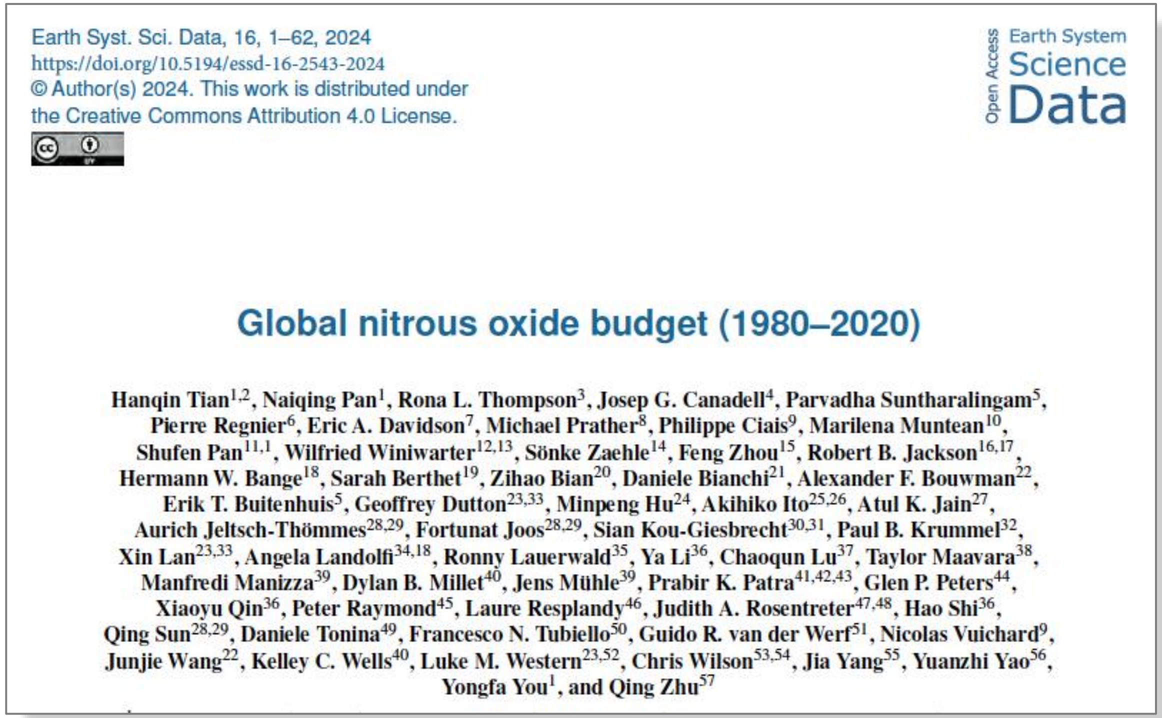
Reference:

Tian, H., Pan, N., Thompson, R. L., Canadell, J. G., Suntharalingam, P., Regnier, P., Davidson, E. A., Prather, M., Ciais, P., Muntean, M., Pan, S., Winiwarter, W., Zaehle, S., Zhou, F., Jackson, R. B., Bange, H. W., Berthet, S., Bian, Z., Bianchi, D., Bouwman, A. F., Buitenhuis, E. T., Dutton, G., Hu, M., Ito, A., Jain, A. K., Jeltsch-Thömmes, A., Joos, F., Kou-Giesbrecht, S., Krummel, P. B., Lan, X., Landolfi, A., Lauerwald, R., Li, Y., Lu, C., Maavara, T., Manizza, M., Millet, D. B., Mühle, J., Patra, P. K., Peters, G. P., Qin, X., Raymond, P., Resplandy, L., Rosentreter, J. A., Shi, H., Sun, Q., Tonina, D., Tubiello, F. N., van der Werf, G. R., Vuichard, N., Wang, J., Wells, K. C., Western, L. M., Wilson, C., Yang, J., Yao, Y., You, Y., and Zhu, Q.: Global nitrous oxide budget (1980–2020), Earth Syst. Sci. Data, 16, 2543–2604, https://doi.org/10.5194/essd-16-2543-2024, 2024.

Publication of the 2024 Global N_2O Budget



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Open Access Earth System Science Data

Global nitrous oxide budget (1980–2020)

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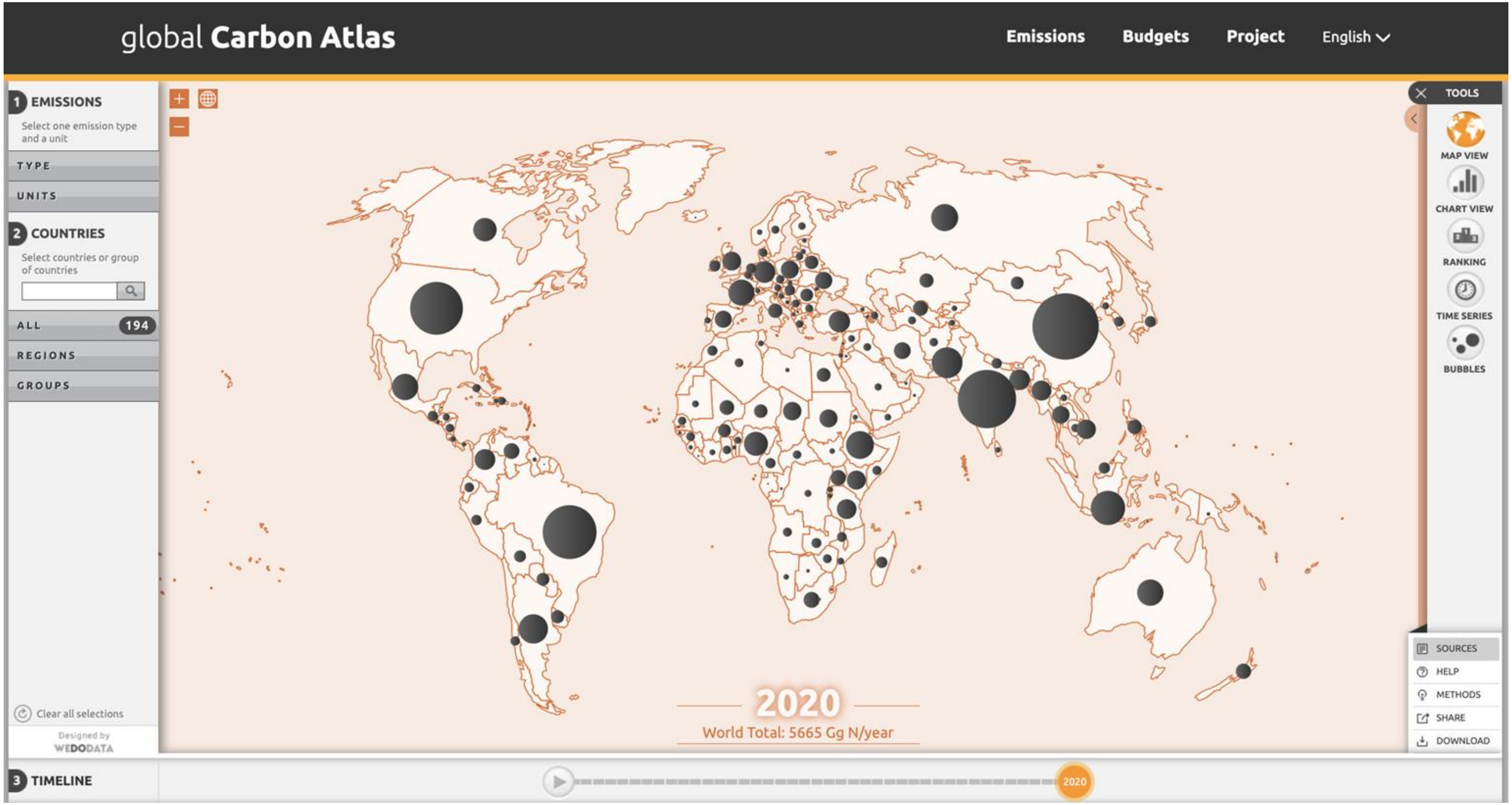
https://www.globalcarbonproject.org/nitrousoxidebudget

Global Carbon Atlas

Access country N_2O emission profiles, compare and rank countries, and download data and figures.

https://globalcarbonatlas.org



Emissions and Concentration Units and Conversions

Emissions

1 Megatonne (Mt) = 1 million (metric) tonnes = 1×10^{12}g = 1 Teragram (Tg)

1 kg nitrogen in nitrous oxide (N) = 1.57 kg nitrous oxide (N_2O)

1 Mt N = 1.57 million tonnes N_2O = 1.57 Mt N_2O

Atmospheric concentrations

1 part per billion (ppb) of atmospheric N in N_2O (N_2O-N) = 4.79 million tonnes of N_2O-N
= (x1.57) 7.5 million tonnes of N_2O

Disclaimer

The Global Carbon Budget and the information presented here are intended for those interested in learning about the carbon and nitrogen cycles, and how human activities are changing them. The information contained herein is provided as a public service and as our current best understanding, but with no warranties, either expressed or implied, concerning the accuracy, completeness, reliability, or suitability of the information.

N_2O Basics

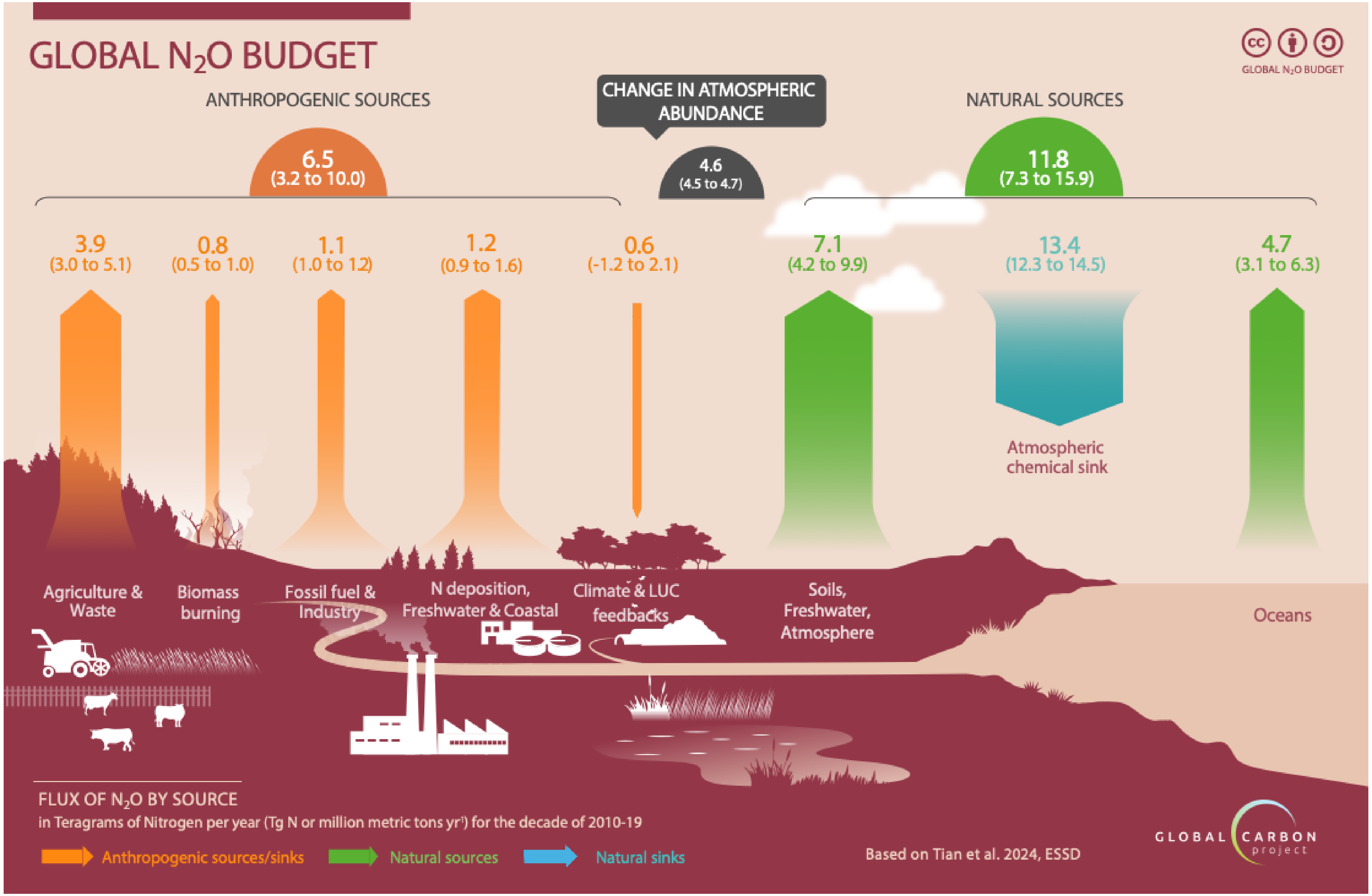
- N_2O is a powerful greenhouse gas (GHG) and a stratospheric ozone-depleting substance
- Per unit of mass, N_2O is 273 times more powerful greenhouse gas than CO_2 when integrated over 100-years.
- Once emitted, N_2O stays in the atmosphere for an average of 117 years
- N_2O is the third most important GHG contributing to human-induced global warming, after carbon dioxide (CO_2) and methane (CH_4).
- N_2O is responsible for 6.5% of the global warming due to the three most important GHGs (CO_2, CH_4 , and N_2O) (Forster et al. (2023). N_2O concentration in the atmosphere reached 336 parts per billion (ppb) in 2022, about 24% above levels around the year 1750, before the industrial era began.
- In addition to N_2O emissions, the inefficient use of synthetic nitrogen fertilizers and animal manure, also leads to the pollution of groundwater, drinking water, and inland and coastal waters.

GLOBAL CARBON PROJECT

Key Findings

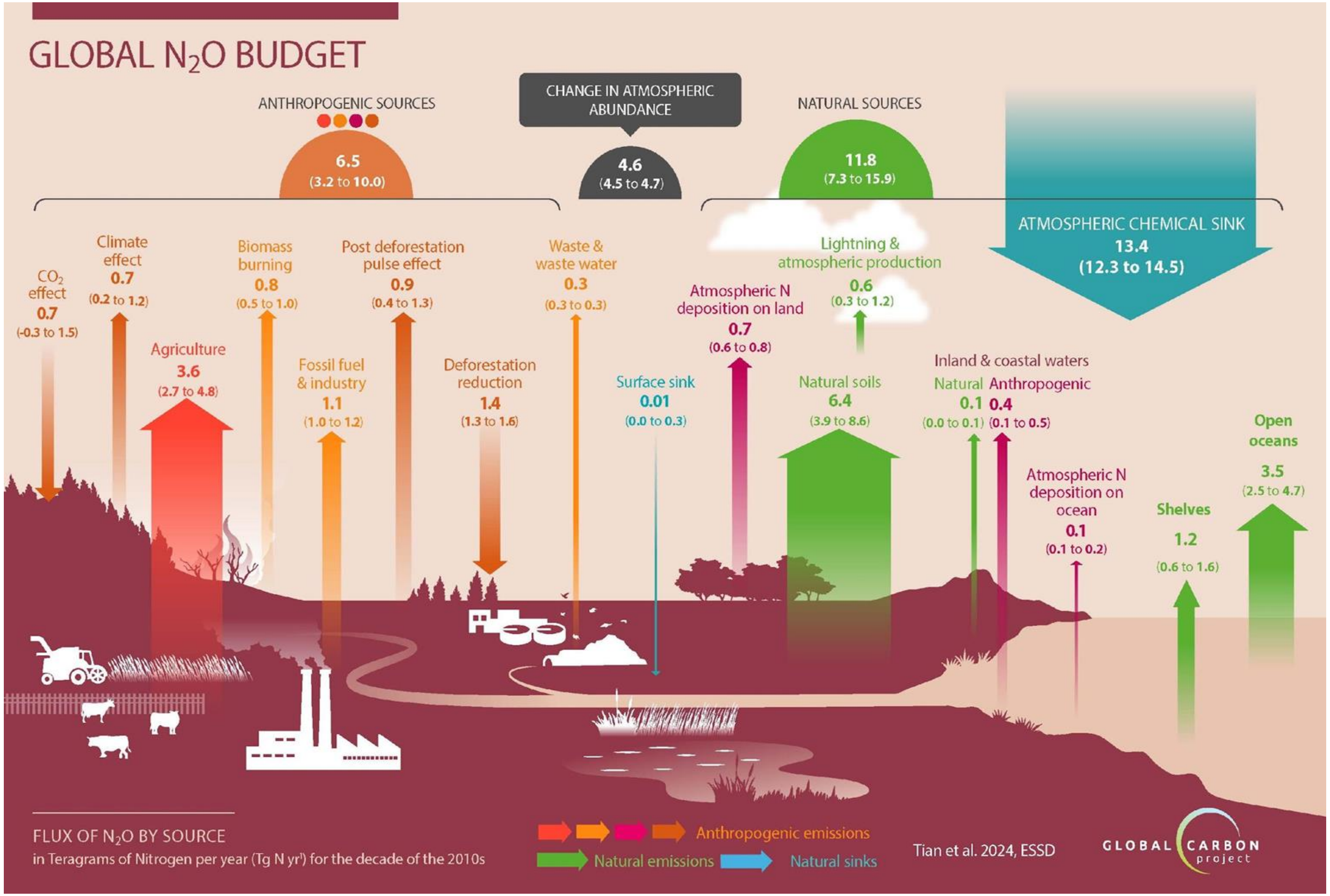
1. Global annual N_2O emissions were 17.8 (17.4–18.1) Tg N yr^{-1} from 2010 to 2019 (based on two approaches: bottom-up and top-down atmospheric inversions).
2. Global anthropogenic emissions increased by 40% from 1980 to 2020.
3. Agricultural production (due to the use of nitrogen fertilizers and animal manure) contributed 74% of the total anthropogenic N_2O emissions in the last decade.
4. The concentration of N_2O in the atmosphere reached 336 parts per billion in 2022 (25% above pre-industrial levels), and anthropogenic emissions were almost exclusively responsible for the growth.
5. N_2O accumulation in the atmosphere has accelerated in the last four decades, with growth rates over the past three years (2020-2022) higher than any previous observed year since 1980.
6. Soil N_2O emissions are increasing due to interactions between nitrogen inputs and global warming, constituting an emerging positive N_2O-climate feedback.
7. The increase in atmospheric N_2O concentrations exceeds the projections of the least optimistic scenarios used by the Intergovernmental Panel on Climate Change (IPCC AR5 and AR6), underscoring the urgent need to mitigate N_2O emissions.

Overview of the Global N_2O Budget (2010-2019)



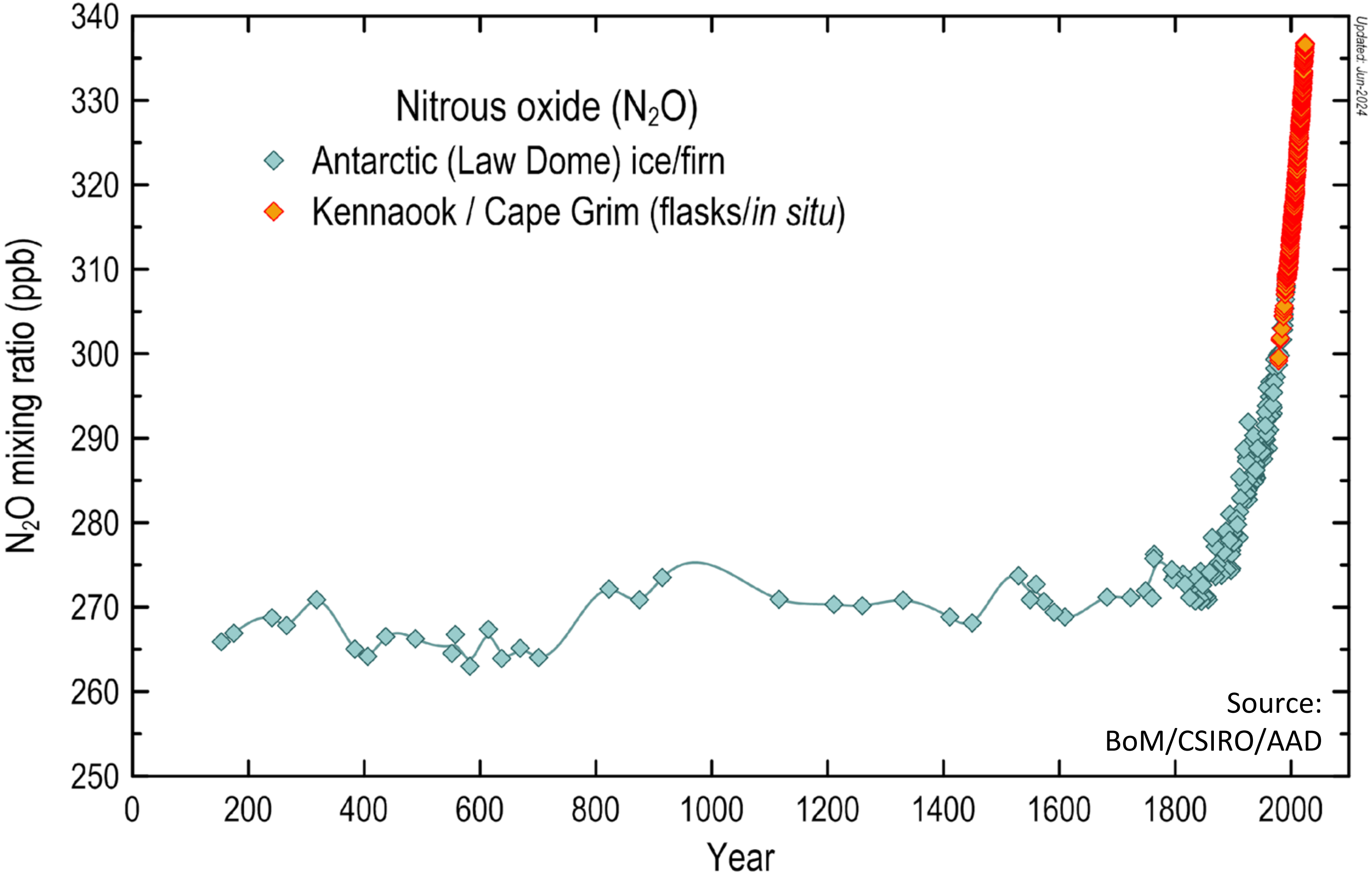
Detailed Global N_2O Budget (2010-2019)

Anthropogenic sources contributed 36% to total global N_2O emissions (median estimate)



Atmospheric N_2O Concentrations Over The Last Two Millennia

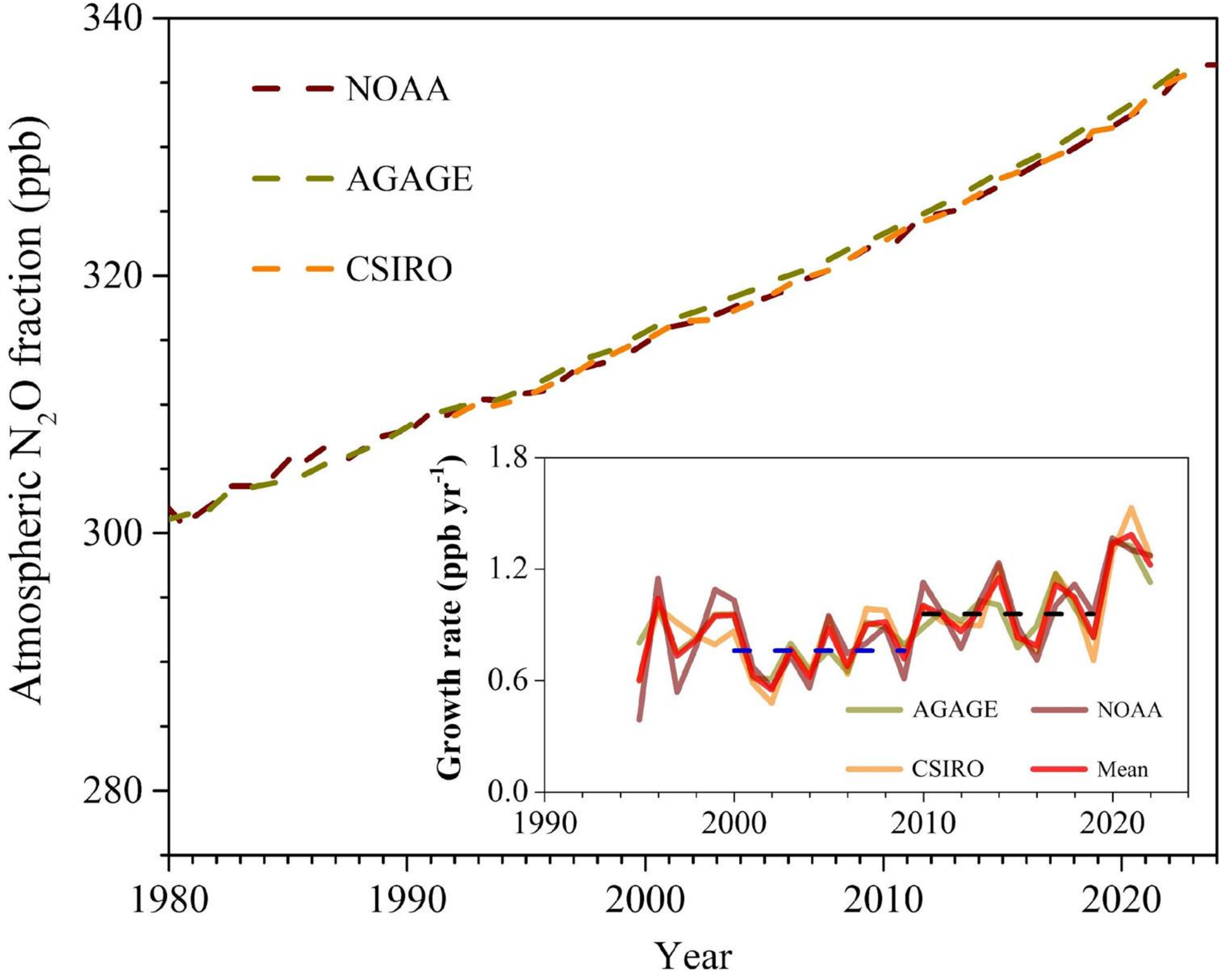
The global N_2O *concentration* has increased by about 25%, from 270 parts per billion (ppb) in 1750 to 336 ppb in 2022



Source: BoM/CSIRO/AAD

Atmospheric Concentration and Growth Rate Over the Last 40 Years

The growth in global atmospheric N_2O is accelerating. The mean growth rate for 2010-2019 was 0.96 ppb yr^{-1}.
The mean growth rate in 2020 was 30% higher than in 2010-2019, with a continuation of high growth in 2021-2022.



Global Anthropogenic N_2O Emissions

- Global anthropogenic N_2O emissions are growing at over 1% per year
- Agriculture is the single largest anthropogenic source of N_2O emissions

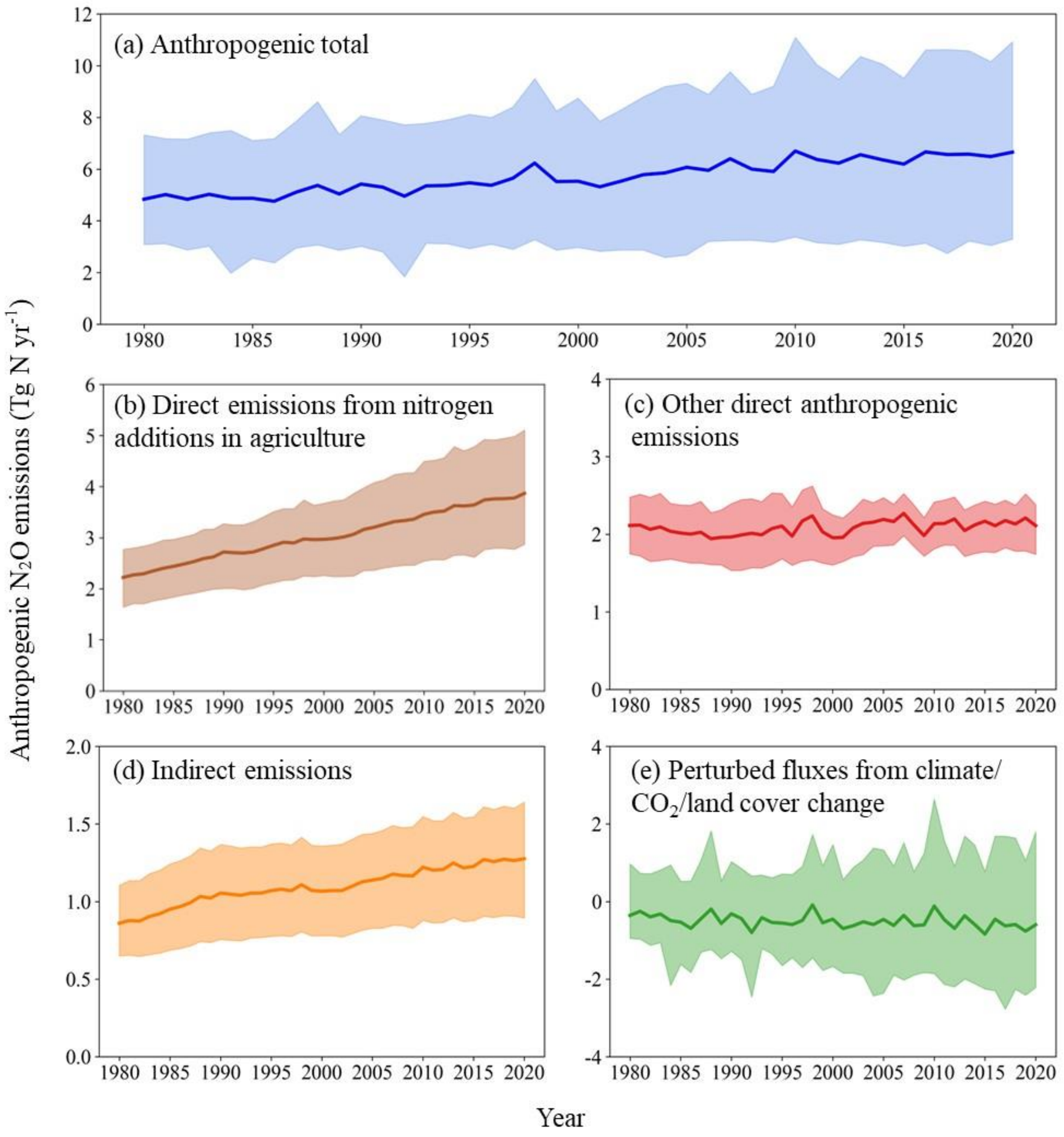
Anthropogenic Emissions Sources:

(b) Direct emissions from nitrogen additions in agriculture result from the application of synthetic N fertilizers and manure in crops and pasture lands.

(c) Other direct emissions include fossil fuel and industry, waste and wastewater, and biomass burning (both human-induced and wildfires).

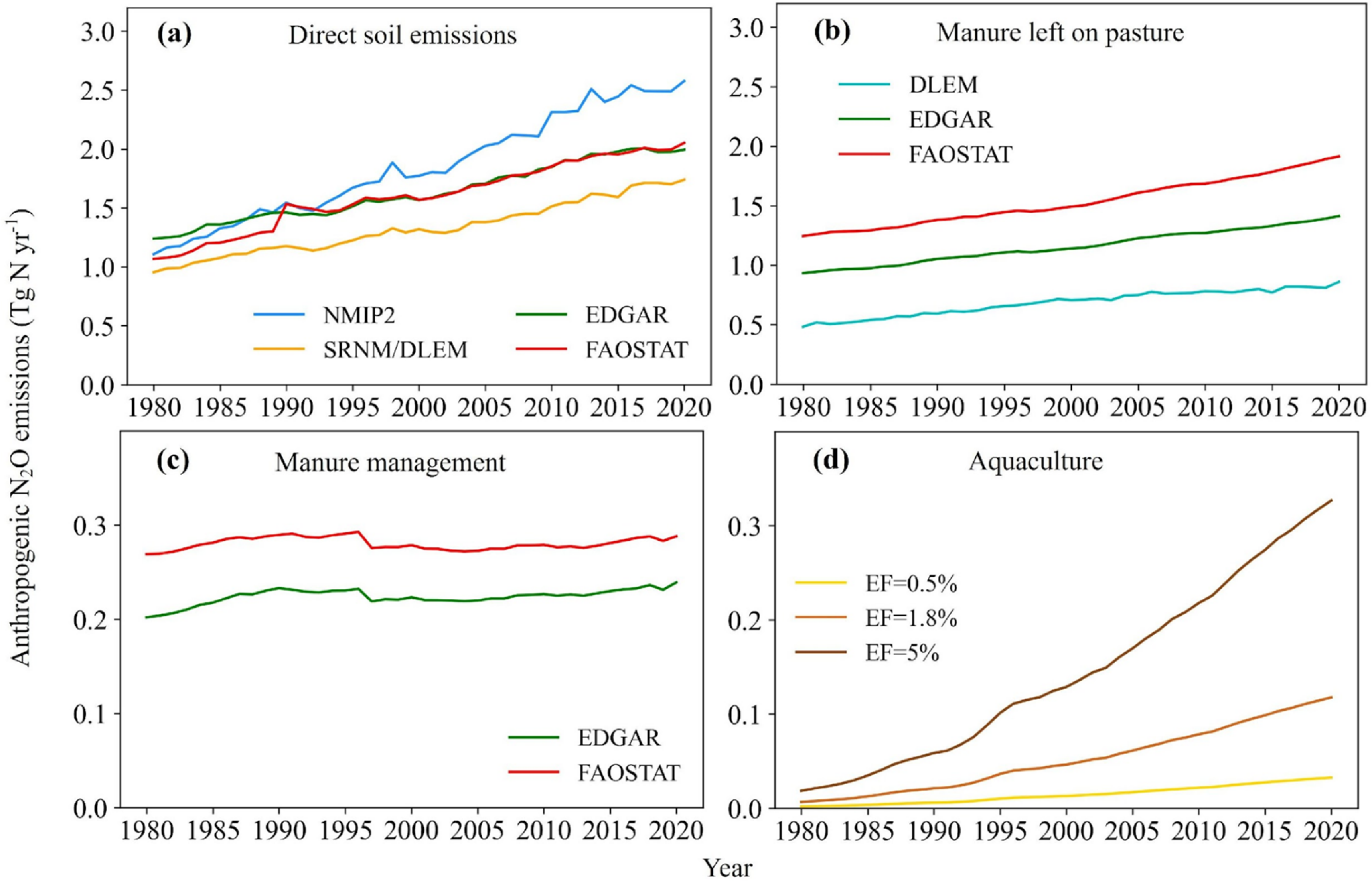
(d) Indirect emissions from anthropogenic nitrogen additions due to nitrogen deposition on land and oceans, and N loads in inland waters, estuaries, and costal vegetation.

(e) Perturbed fluxes result from the impacts of anthropogenic climate change, CO_2 fertilization on vegetation, and changes in land cover (e.g., deforestation)



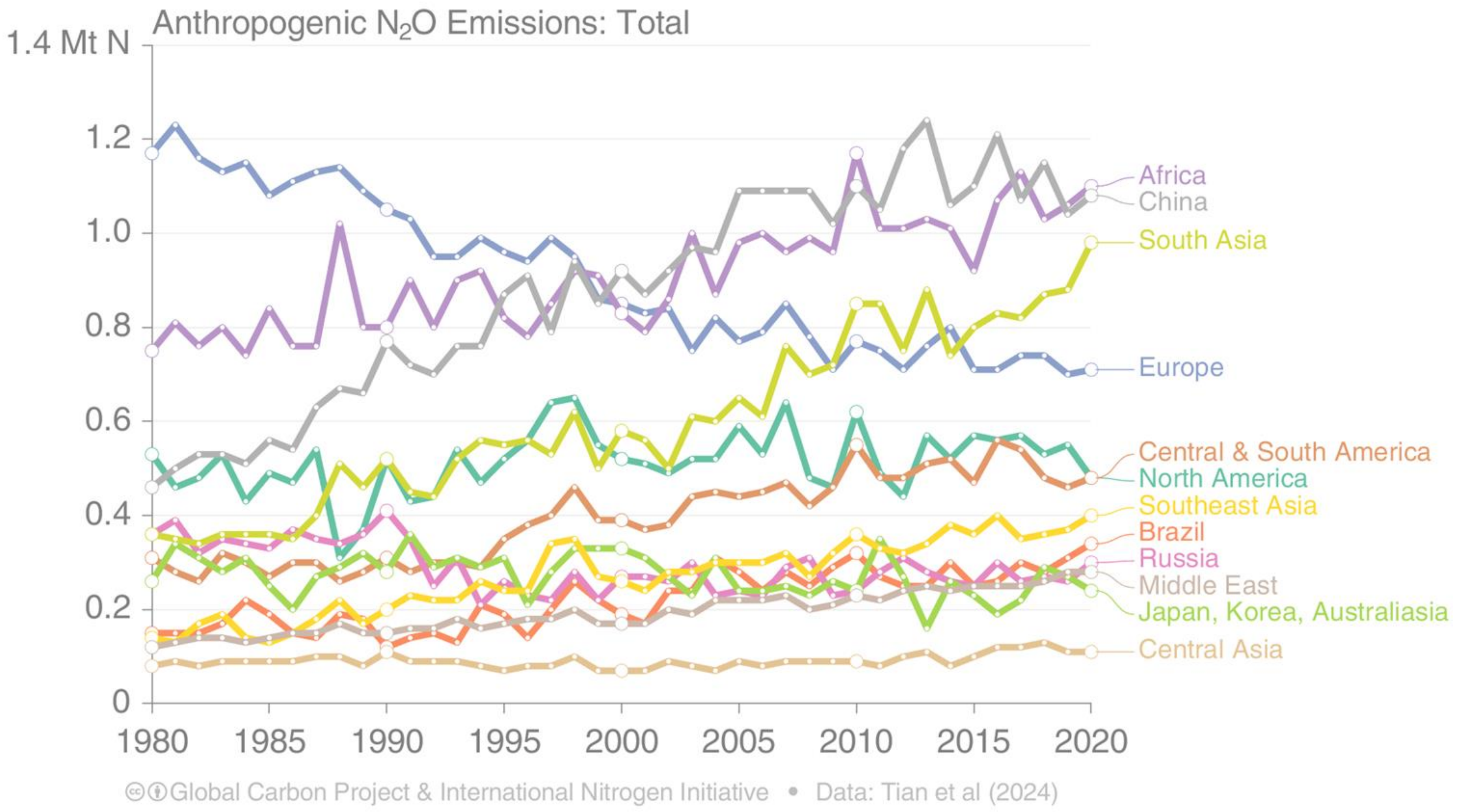
Global Agricultural Emissions From Bottom-Up Models

Biogeochemical models (NMIP2) show increasing direct soil emissions at a higher rate than inventory models. Aquaculture emissions are highly uncertain.



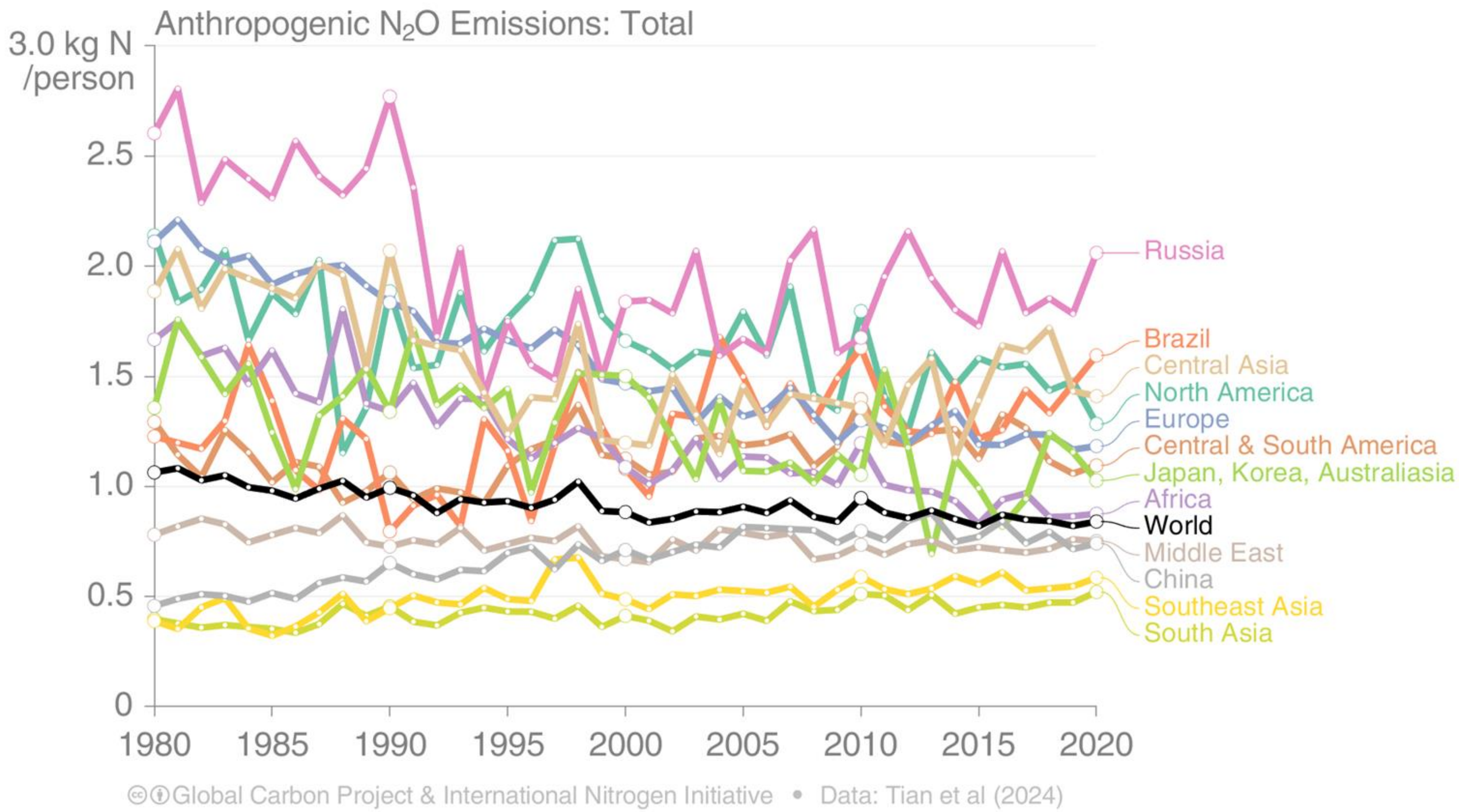
Anthropogenic Emissions by World Region

The recent global increase in N_2O emissions is driven by Asia, followed by Africa and Central & South America, while emissions in Europe have significantly decreased (this figure includes biomass burning from anthropogenic fires and wildfires).



Anthropogenic Emissions per Person by World Region

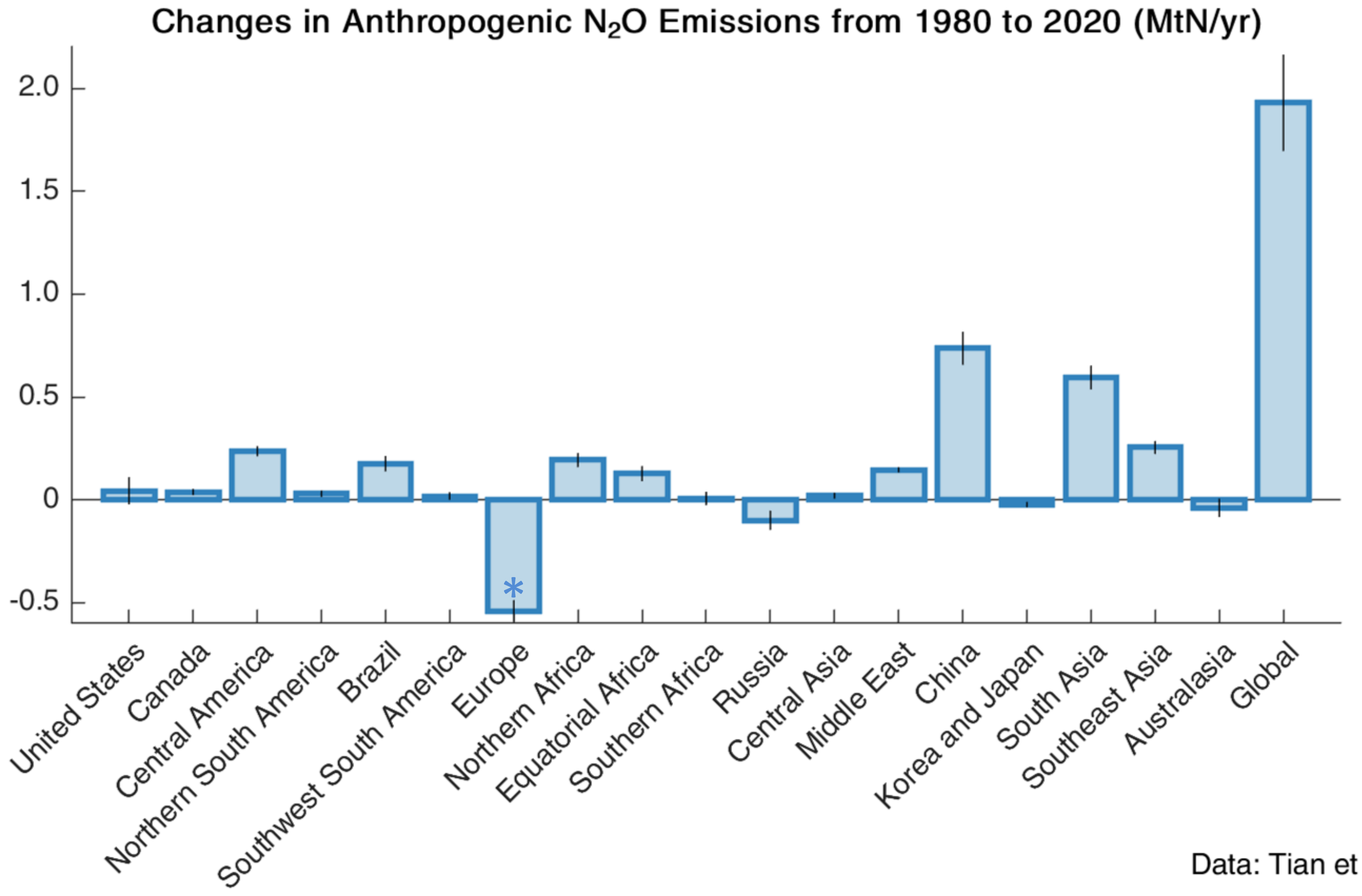
There is a broad range of N_2O emissions per person, with wealthier regions generally above the world average (this figure includes biomass burning). Per capita emissions are also influenced by how much food and N_2O-generating products are exported or imported.



Changes in Anthropogenic N_2O Emissions

Emissions from Europe and Russia decreased by a total of 0.6 TgN/yr over 1980-2020, while emissions from the remaining regions increased by a total of 2.5 TgN/yr.

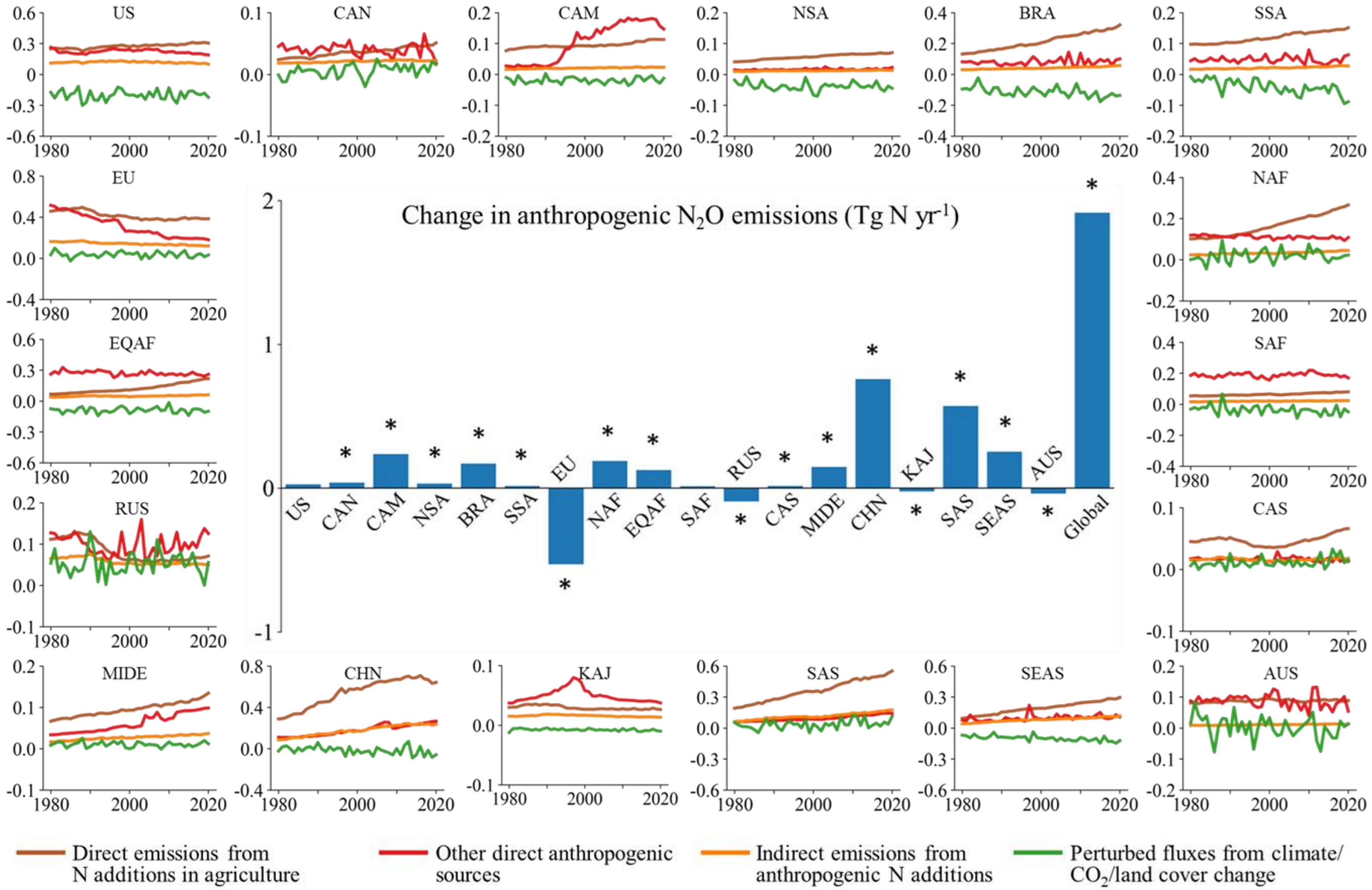
*Europe's strong N_2O emissions decline were due to a decrease in industry emissions; agricultural emissions have remained constant for the past two decades.



Data: Tian et al (2024)

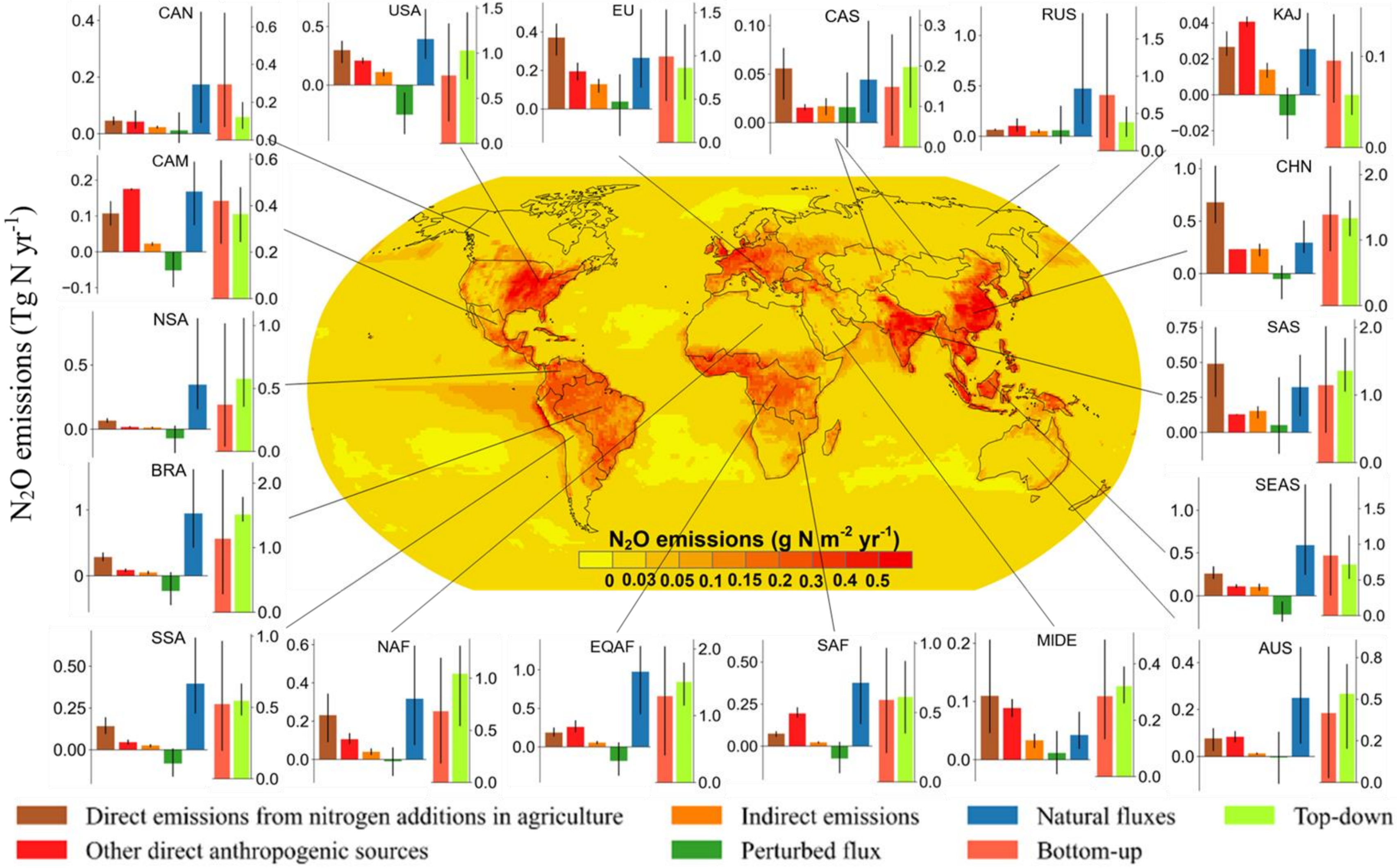
Regional Trends in Anthropogenic N_2O Emissions

Europe and Russia show a net decrease in emissions from 1980 to 2020, while China, South Asia and Southeast Asia show substantial increases



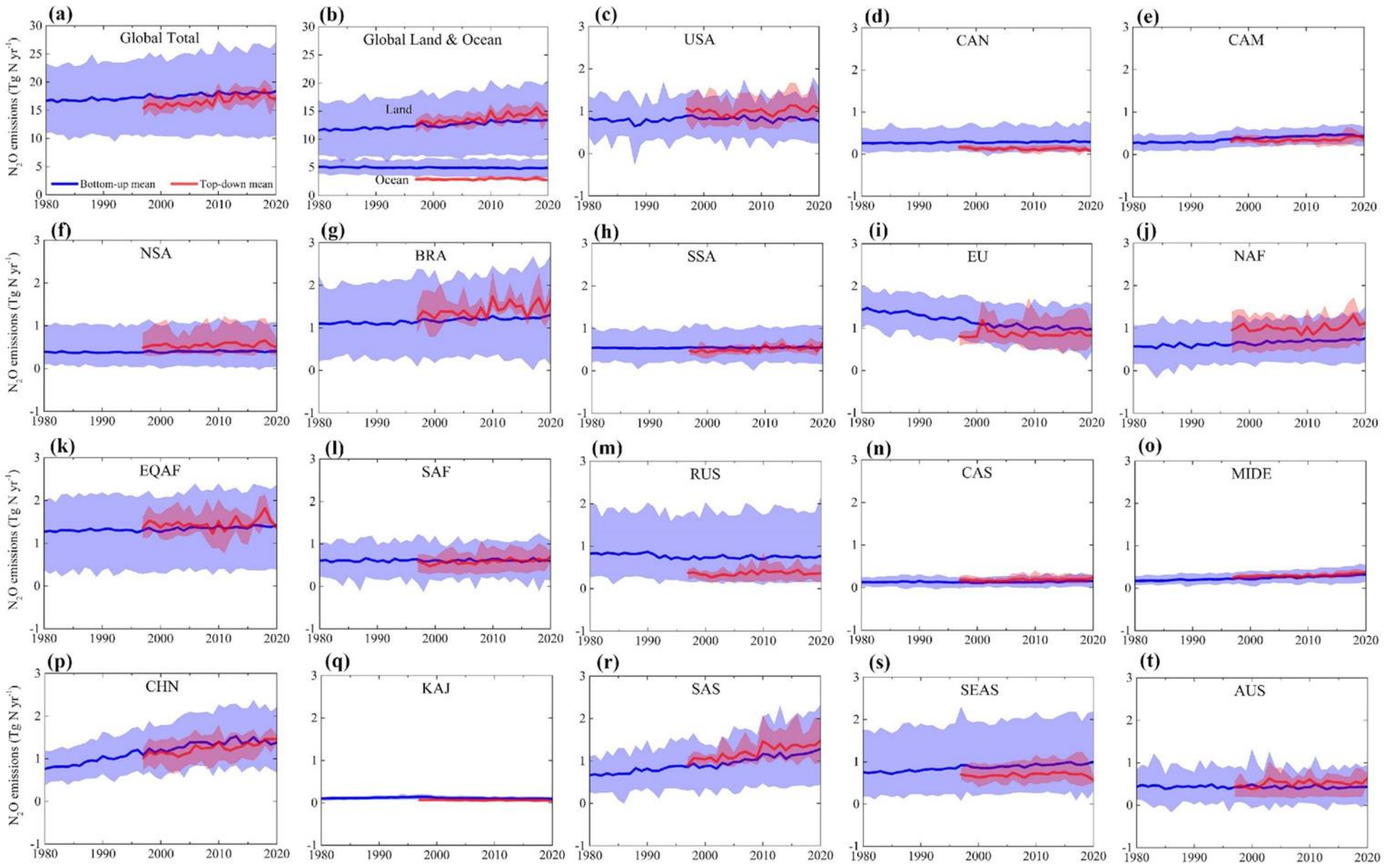
Regional N_2O Budgets for 2010-2019

In China, Europe, USA, Southern Asia, and Middle East agricultural emissions far exceed natural emissions.
Agricultural emissions are exceeded by other anthropogenic emissions in Korea + Japan, Central America, and South Africa



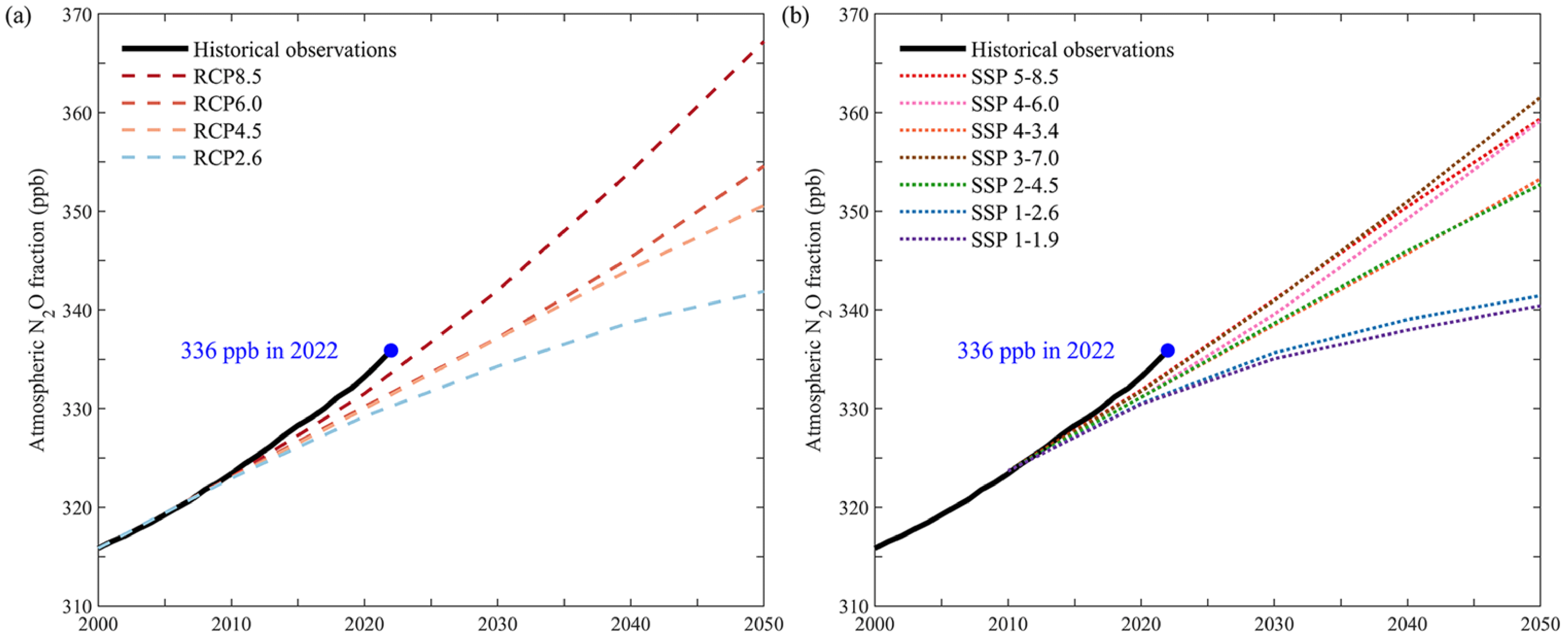
Annual Comparison of Bottom-Up and Top-Down Estimates

Global total N_2O emission estimates from BU and TD are comparable in magnitude and trend for 1998-2020



Observed Atmospheric N_2O Higher than Predicted

The observed atmospheric N_2O concentrations in the past decade have exceeded the most pessimistic illustrative future GHG scenarios used by the IPCC.



Global N_2O Sources and Sinks in the Past Four Decades

The budget includes **21** natural and anthropogenic source categories

		1980-1989			1990-1999			2000-2009			2010-2019			2020		
Anthropogenic sources		mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max
Direct agricultural	Direct soil emission	1.2	1.1	1.3	1.5	1.2	1.6	1.7	1.4	2.0	2.0	1.6	2.4	2.1	1.7	2.6
	Manure left on pasture	0.9	0.5	1.3	1.1	0.6	1.4	1.2	0.7	1.6	1.3	0.8	1.8	1.4	0.9	1.9
	Manure management	0.2	0.2	0.3	0.3	0.2	0.3	0.2	0.2	0.3	0.3	0.2	0.3	0.3	0.2	0.3
	Aquaculture	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.2	0.1	0.0	0.3	0.1	0.0	0.3
	subtotal	2.4	1.8	3.0	2.8	2.1	3.4	3.2	2.3	4.0	3.6	2.7	4.8	3.9	2.9	5.1
Other direct anthropogenic	Fossil fuel and industry	1.0	1.0	1.0	1.0	0.9	1.1	1.1	1.0	1.1	1.1	1.0	1.2	1.1	1.0	1.1
	Waste and waste water	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
	Biomass burning	0.9	0.5	1.2	0.9	0.5	1.2	0.8	0.5	1.0	0.8	0.5	1.0	0.8	0.5	0.9
	subtotal	2.0	1.7	2.4	2.1	1.6	2.4	2.1	1.8	2.4	2.1	1.8	2.4	2.1	1.7	2.4
Indirect emissions from anthropogenic N additions	Inland waters, estuaries, coastal zones	0.3	0.1	0.4	0.3	0.1	0.4	0.4	0.1	0.5	0.4	0.1	0.5	0.4	0.1	0.6
	Atmos. N dep. on land	0.5	0.5	0.6	0.6	0.5	0.7	0.7	0.6	0.8	0.7	0.6	0.8	0.8	0.6	0.9
	Atmos. N dep. on ocean	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2
	subtotal	0.9	0.7	1.2	1.1	0.8	1.4	1.1	0.8	1.4	1.2	0.9	1.6	1.3	0.9	1.6
Perturbed fluxes from climate/CO_2/land cover change	CO_2 effect	-0.4	-0.8	0.2	-0.5	-1.0	0.2	-0.6	-1.3	0.3	-0.7	-1.5	0.3	-0.8	-1.6	0.3
	Climate effect	0.4	0.1	0.8	0.5	0.2	0.7	0.6	0.1	0.8	0.7	0.2	1.2	0.9	0.4	1.8
	Post-deforestation pulse effect	0.8	0.6	1.1	0.9	0.6	1.2	0.9	0.5	1.3	0.9	0.4	1.3	0.8	0.4	1.3
	Long-term effect of reduced mature forest area	-1.2	-1.1	-1.4	-1.3	-1.2	-1.5	-1.4	-1.2	-1.5	-1.4	-1.3	-1.6	-1.5	-1.4	-1.6
	subtotal	-0.4	-1.1	0.7	-0.5	-1.4	0.6	-0.6	-1.9	0.8	-0.6	-2.1	1.2	-0.6	-2.2	1.8
Anthropogenic total		5.0	3.0	7.3	5.5	3.1	7.9	5.8	3.1	8.6	6.5	3.2	10.0	6.7	3.3	10.9
Natural sources																
Natural soils baseline		6.4	3.9	8.5	6.4	3.8	8.6	6.4	3.9	8.5	6.4	3.9	8.6	6.4	3.8	8.7
Open ocean baseline		3.7	3.0	4.6	3.6	2.8	4.5	3.6	2.7	4.7	3.5	2.5	4.7	3.5	2.5	4.7
Continental shelves		1.2	0.6	1.6	1.2	0.6	1.6	1.2	0.6	1.6	1.2	0.6	1.6	1.2	0.6	1.6
Natural (inland waters, estuaries, coastal vegetation)		0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1
Lightning and atmospheric production		0.6	0.3	1.2	0.6	0.3	1.2	0.6	0.3	1.2	0.6	0.3	1.2	0.6	0.3	1.2
Surface sink		0.0	0.0	-0.3	0.0	0.0	-0.3	0.0	0.0	-0.3	0.0	0.0	-0.3	0.0	0.0	-0.3
Natural total		12.0	7.9	15.8	11.9	7.7	15.8	11.9	7.5	15.9	11.8	7.3	15.9	11.8	7.4	16.1
BU total		16.9	10.9	23.1	17.4	10.7	23.6	17.7	10.6	24.5	18.2	10.6	25.9	18.5	10.6	27.0
TD ocean								2.8	2.6	3.2	3.0	2.7	3.3	2.7	2.7	2.7
TD land								13.2	12.1	14.3	14.5	13.0	15.9	14.3	13.9	14.7
TD total net flux								16.0	14.9	17.5	17.4	15.8	19.2	17.0	16.6	17.4
TD stratospheric sink								12.2	11.7	12.6	12.6	12.3	12.9	12.9	12.5	13.2
Atmospheric chemical sink								12.8	11.7	13.8	13.4	12.3	14.5	14.0	12.8	15.2
Change in atmospheric abundance								3.6	3.6	3.7	4.6	4.5	4.7	6.4	6.2	6.5
Atmospheric burden								1528			1570			1592		
Lifetime (from MLS)								119			117					

Methodology Overview

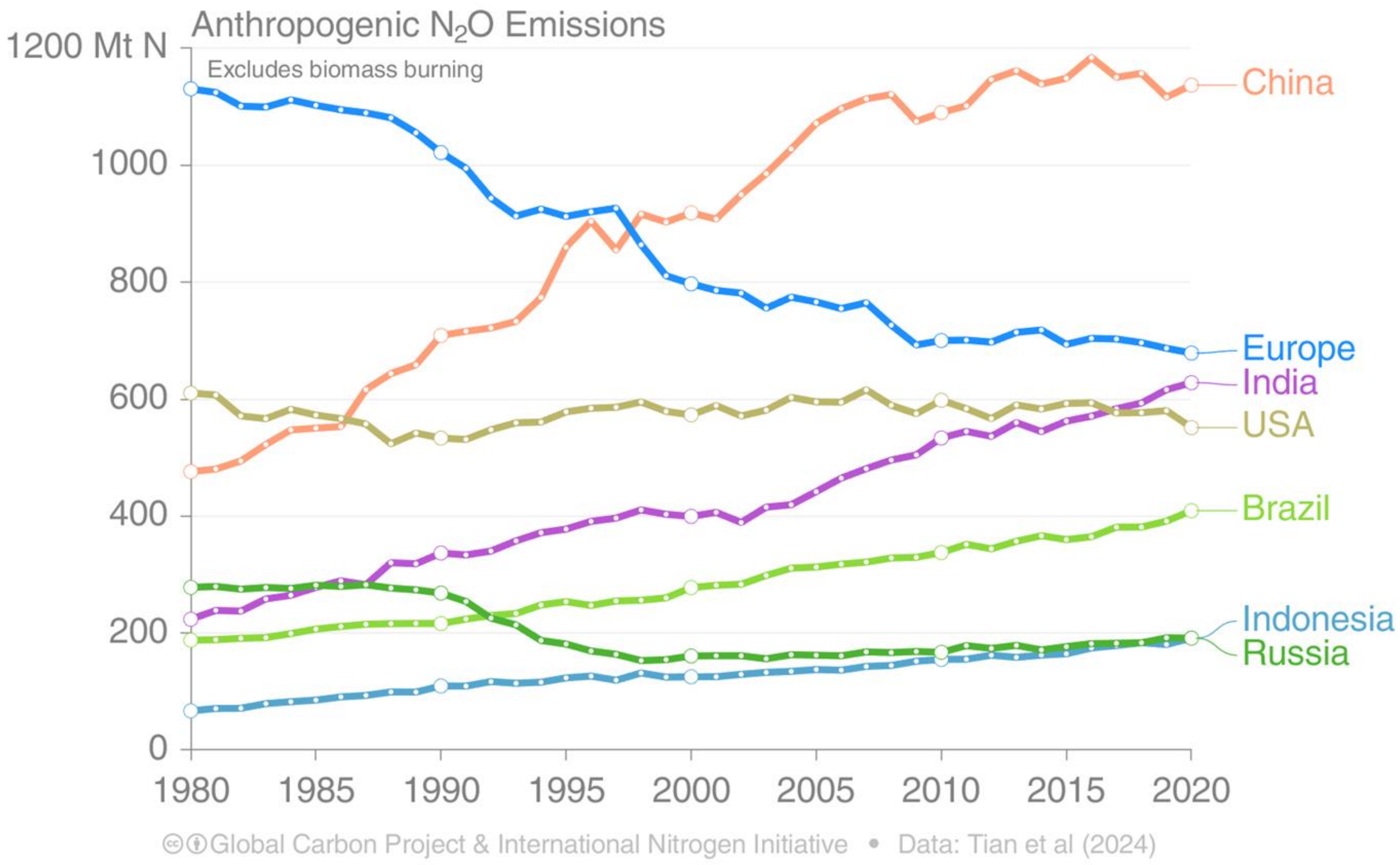
- The global N_2O budget is constructed with 43 independent flux estimates, including emission inventories, process-based and empirical models ("bottom-up" estimates), and atmospheric measurements and inverse modeling ("top-down" estimates).
- Process-based models were used to estimate emissions from agriculture and land-use change, as well as natural emissions from soils, inland waters, and oceans.
- Process-based models were used to determine the interactions between nitrogen additions and climate showing a positive N_2O-climate feedback.
- Empirical models were used to estimate emissions from agriculture, waste, fossil fuel combustion, industry, biomass burning, and aquaculture.
- Measurements of atmospheric N_2O were used in statistical models to optimize independent emissions estimates with multiple atmospheric inversion frameworks. This approach estimates the sum of N_2O sources over land and ocean.
- Atmospheric chemistry transport models were used to estimate the stratospheric N_2O sink.

Key Uncertainties

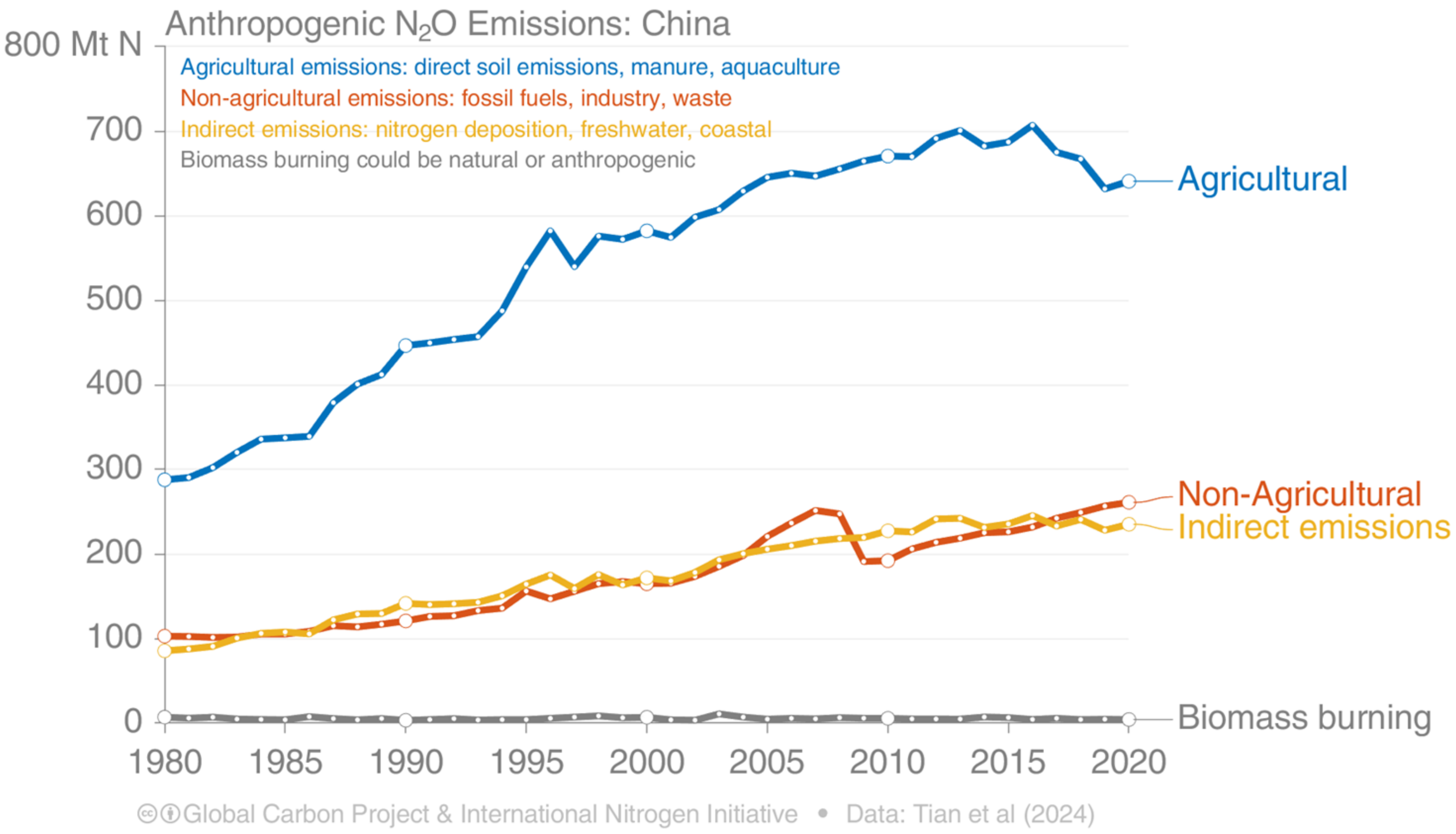
- Top-down approaches have uncertainties due to errors in the modelled atmospheric transport and stratospheric loss of N_2O, as well as due to the limited coverage of atmospheric observations, especially in the tropics and Southern Hemisphere.
- Process-based models are subject to large uncertainties in various sources from land and oceans. These are mostly associated with the model configuration and process parameterization. For land models, the lack of representation of human management (e.g. tillage) also contributes to the uncertainty.
- GHG inventories using default Emission Factors (EFs) have large uncertainties at the global scale, especially for agricultural N_2O emissions due to the poorly captured dependence of EFs on regional climate, land management, and soil biophysical properties.
- Aquacultural emissions have large uncertainties due to the large uncertainty in EFs owing to the scarcity of measurements of N flows in freshwater and marine aquaculture.
- Missing fluxes from permafrost thawing and freeze-thaw cycles.
- The relative proportion of ocean N_2O from oxygen-minimum zones, oxic versus sub-oxic ocean zones, is highly uncertain.

Anthropogenic Emissions from key Nations/Regions

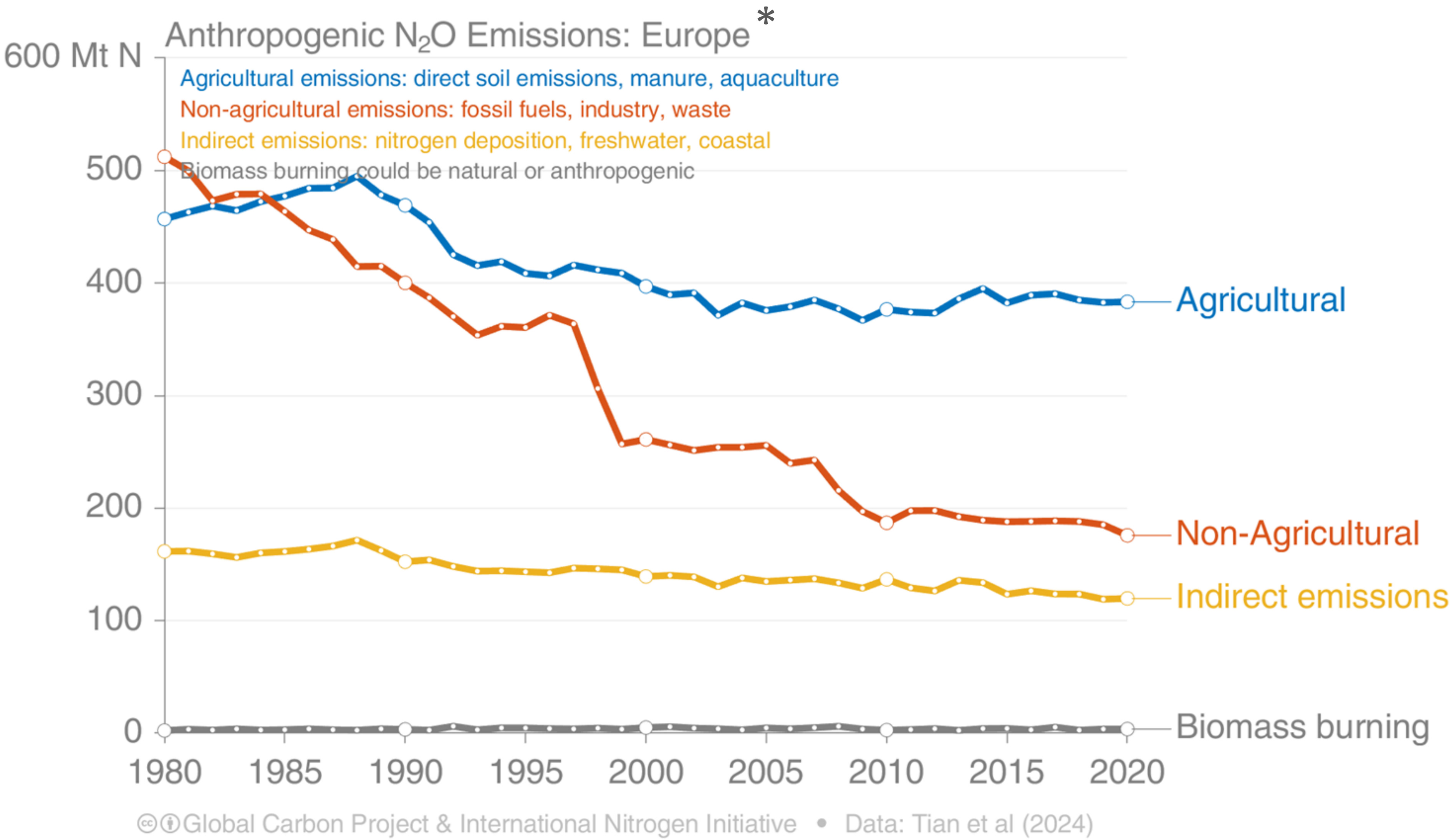
Top National Emitters



China: Anthropogenic N_2O Emissions

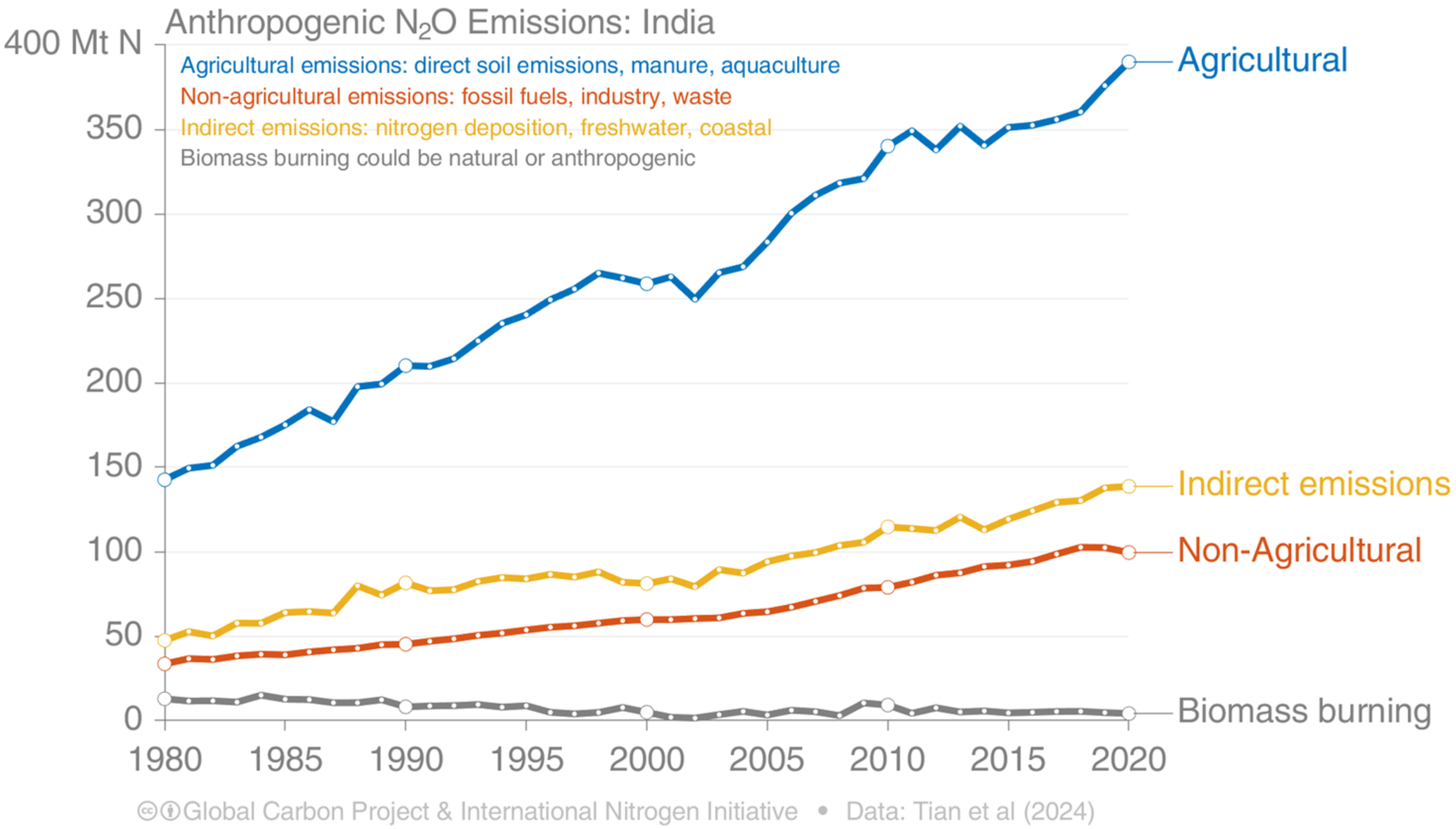


Europe: Anthropogenic N_2O Emissions

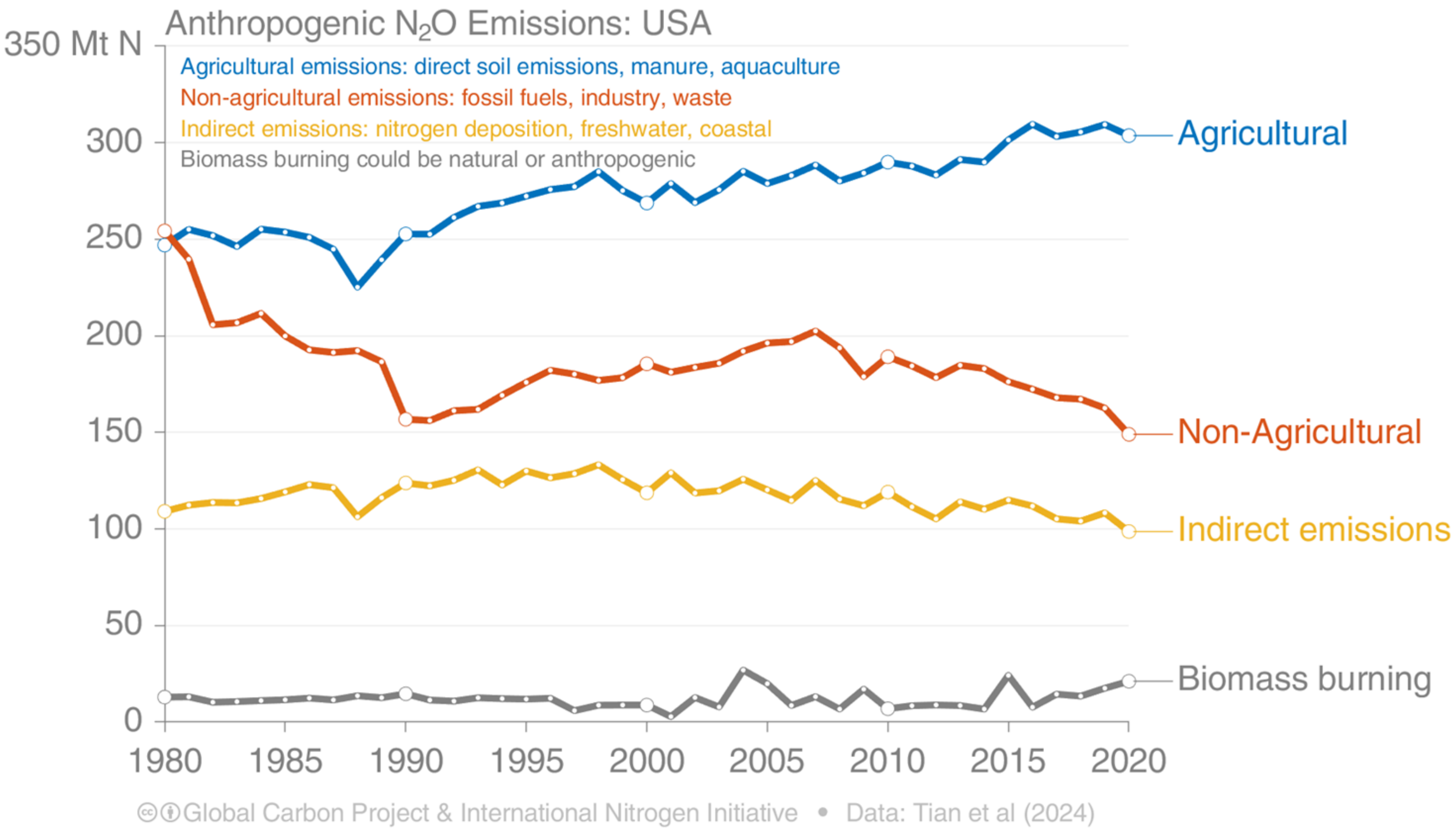


*Europe includes EU27+UK+18 other countries. See Tian et al. 2024 for the full list of countries.

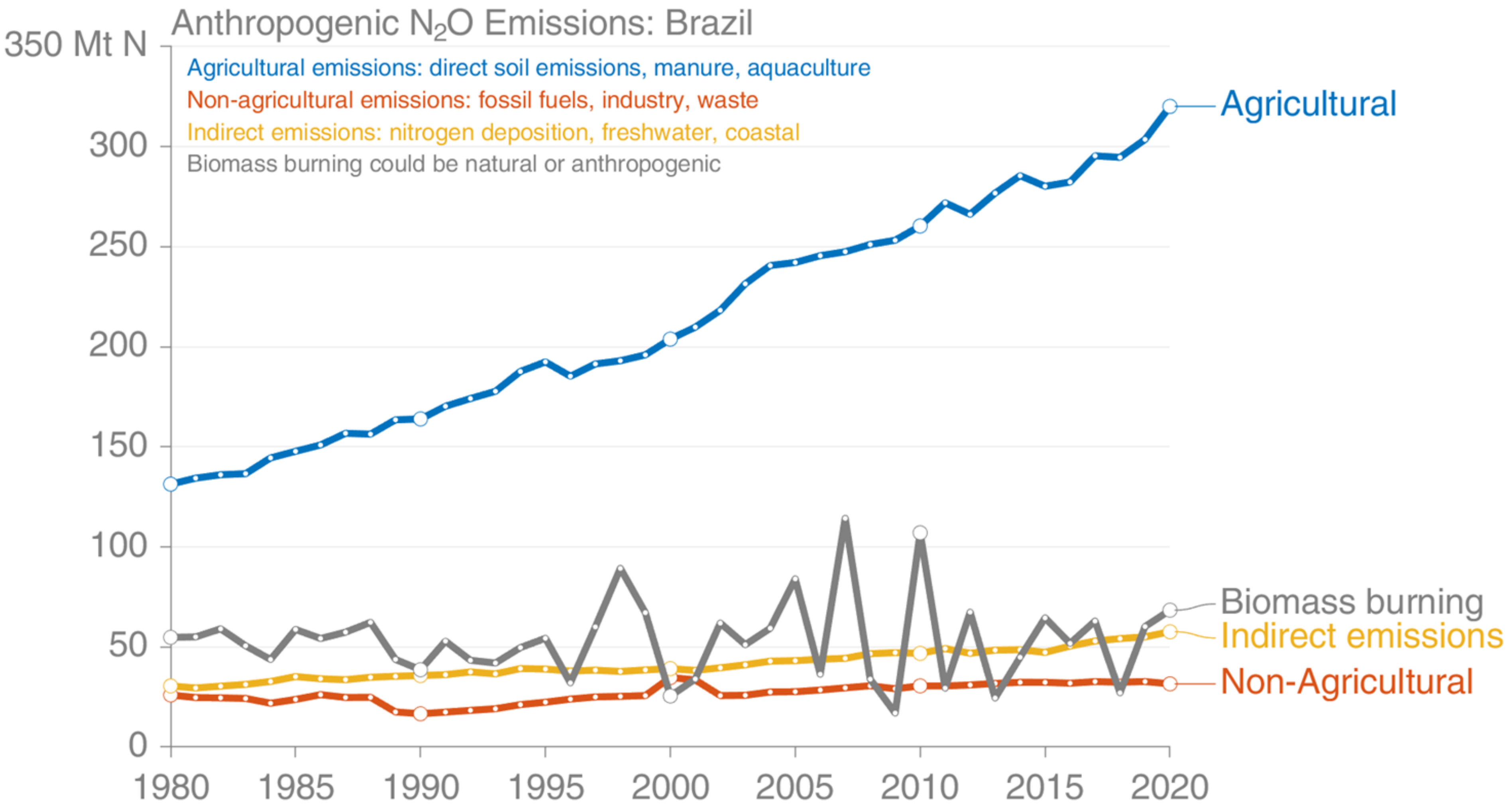
India: Anthropogenic N_2O Emissions



USA: Anthropogenic N_2O Emissions

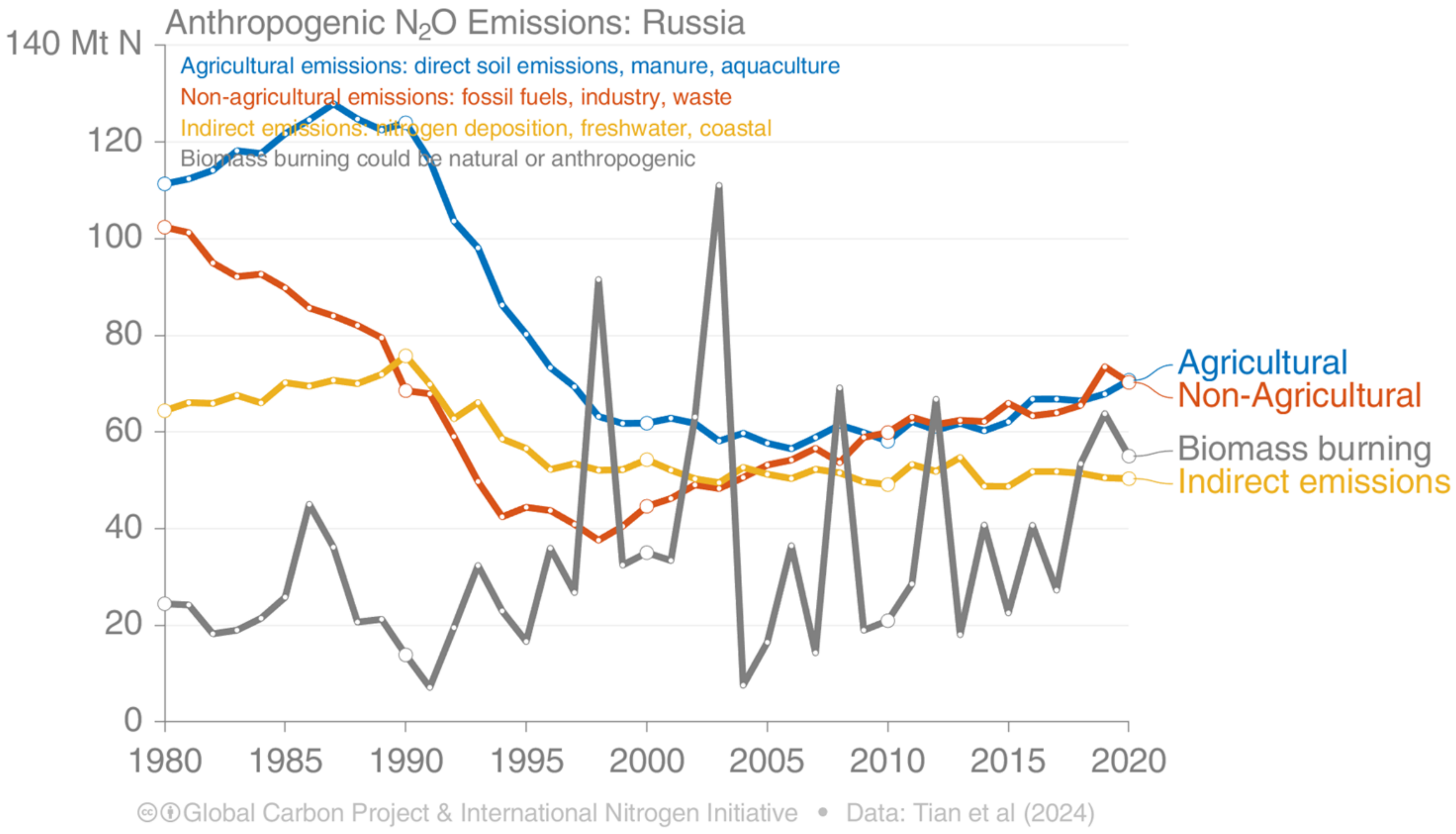


Brazil: Anthropogenic N_2O Emissions

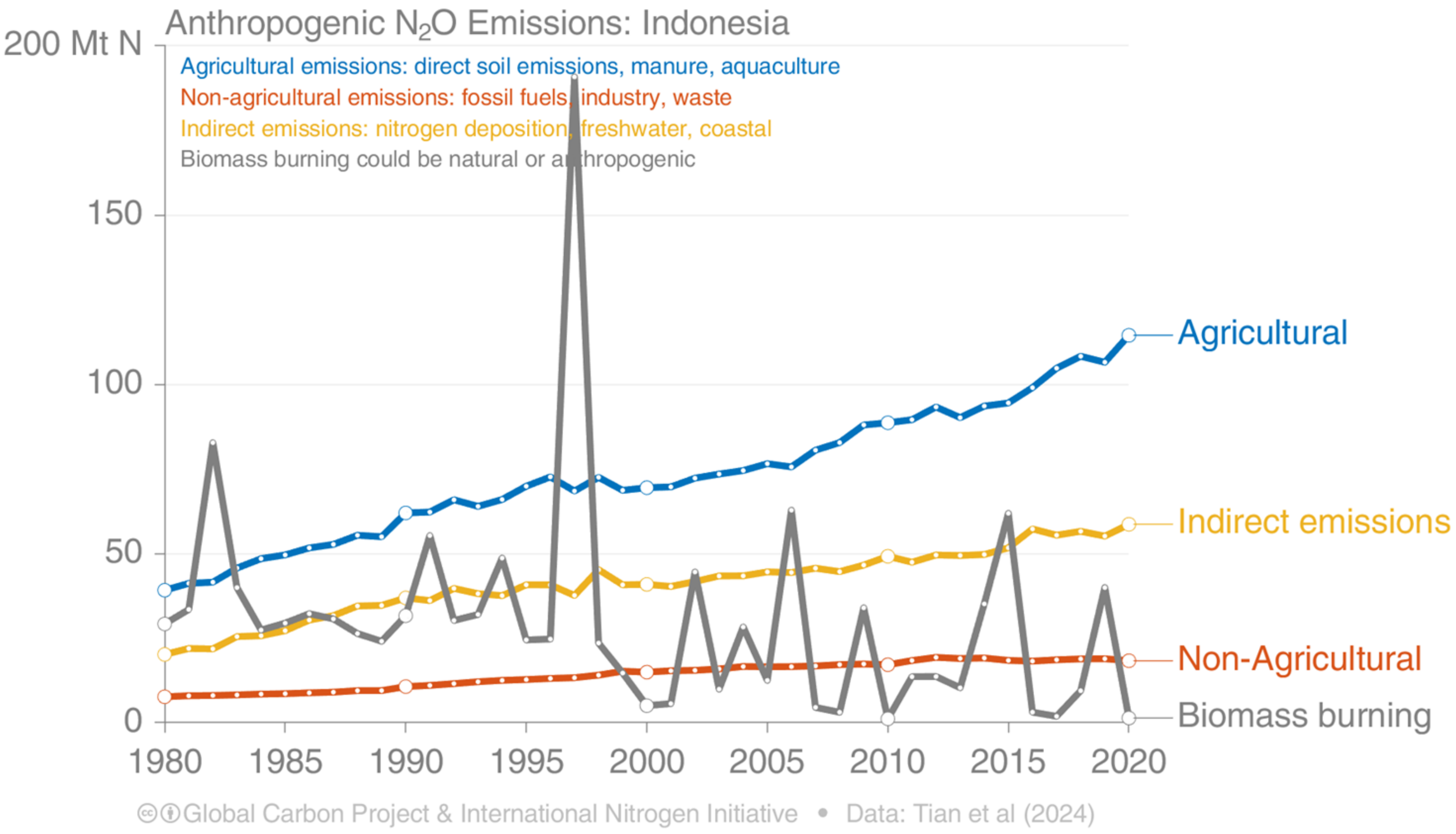


Global Carbon Project & International Nitrogen Initiative • Data: Tian et al (2024)

Russia: Anthropogenic N_2O Emissions

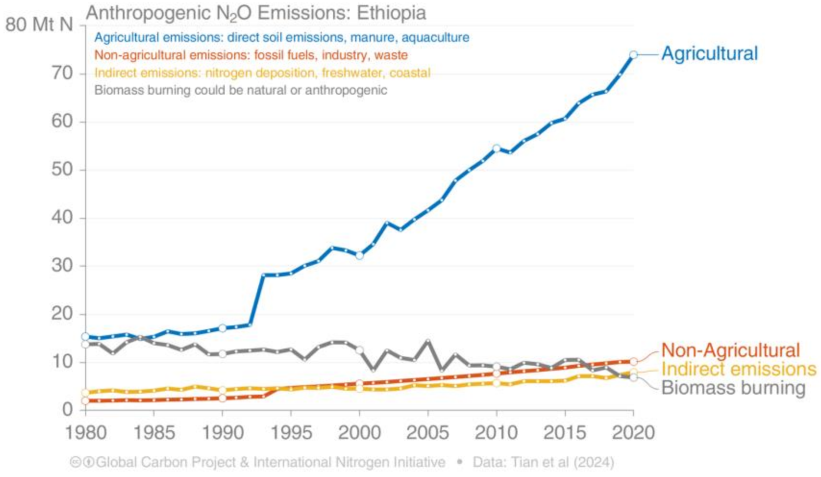


Indonesia: Anthropogenic N_2O Emissions

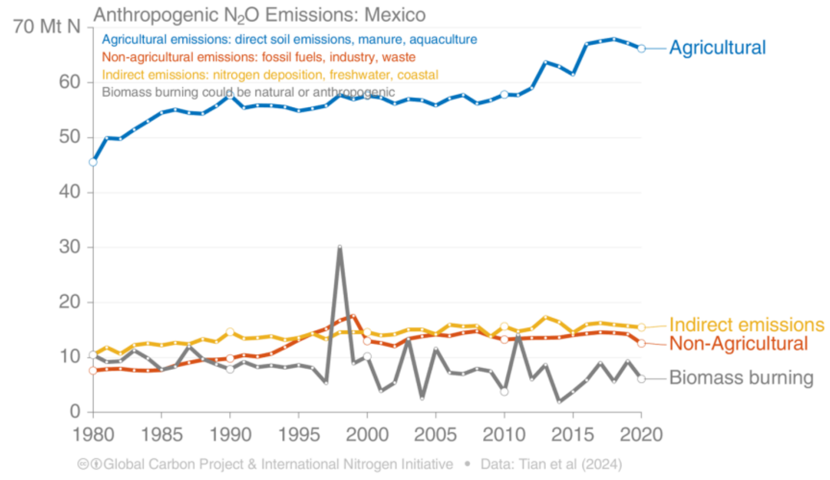


Other Major National Emitters

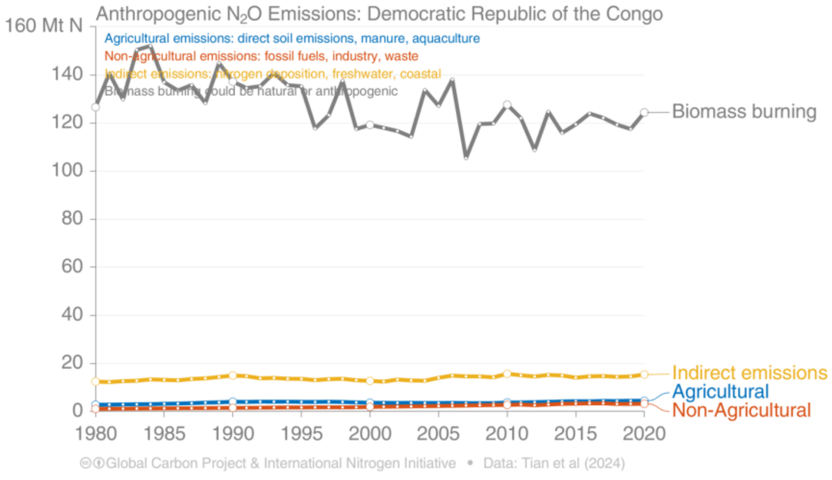
Ethiopia



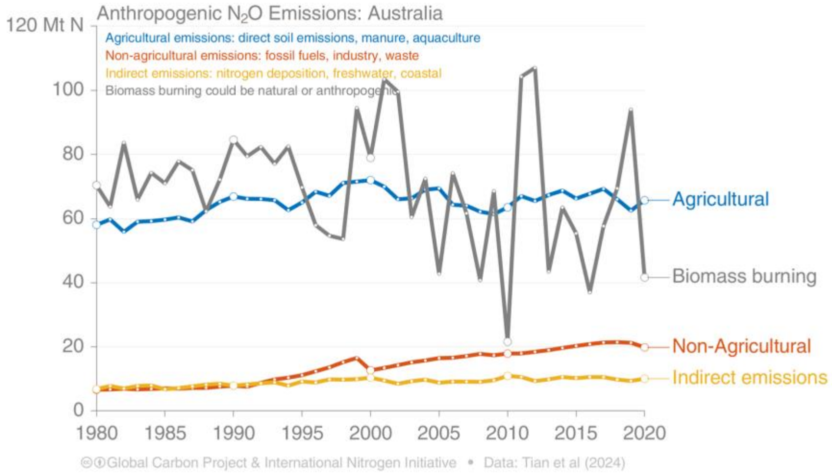
Mexico



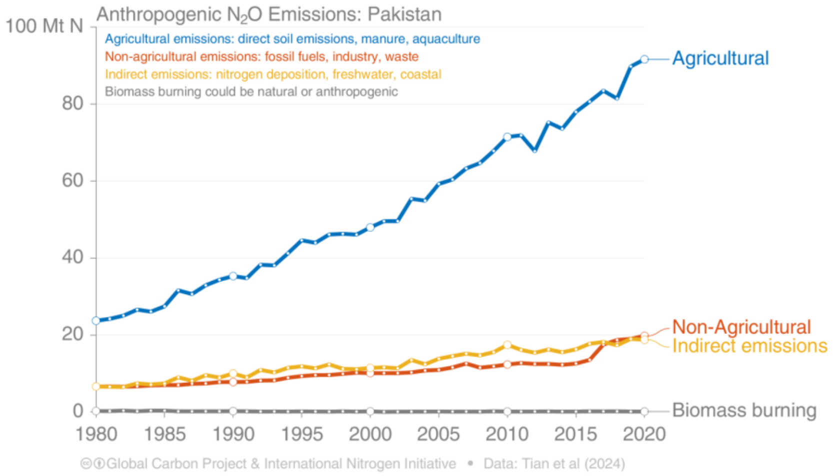
Democratic Republic of the Congo



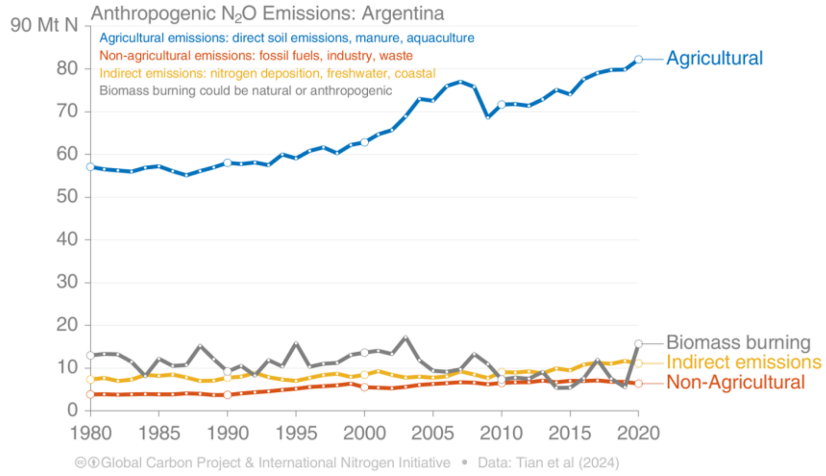
Australia



Pakistan



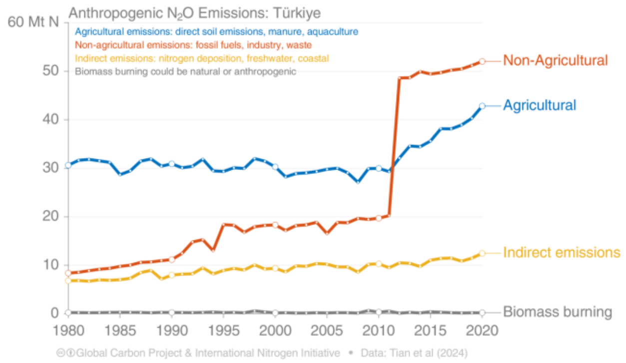
Argentina



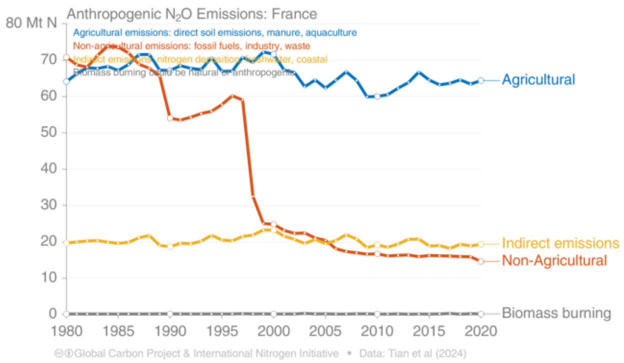
GLOBAL CARBON PROJECT

Other Major National Emitters

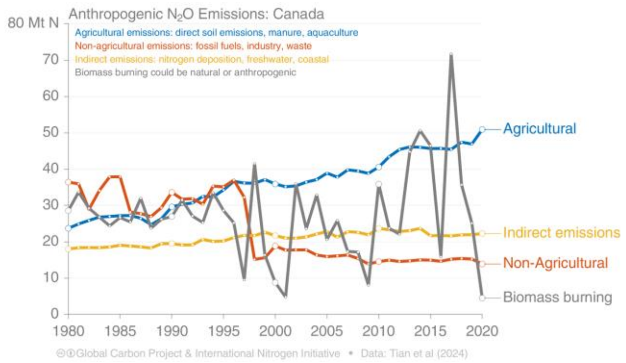
Türkiye



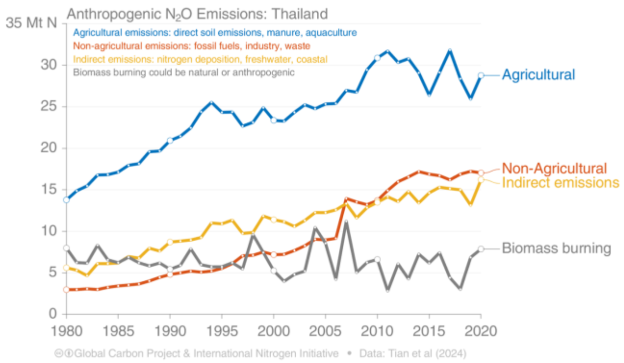
France



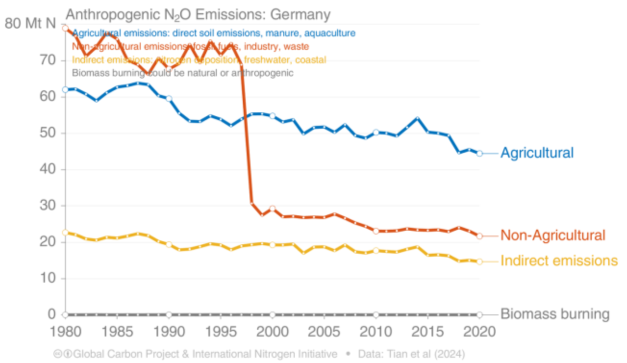
Canada



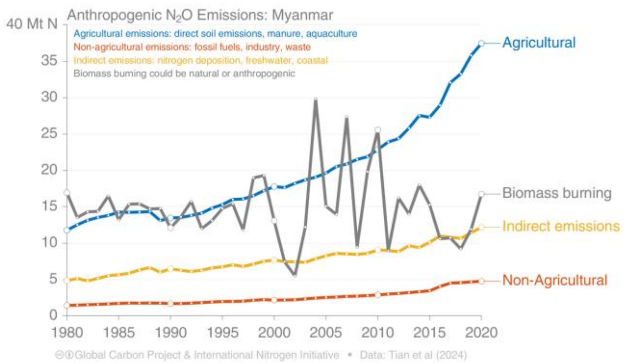
Thailand



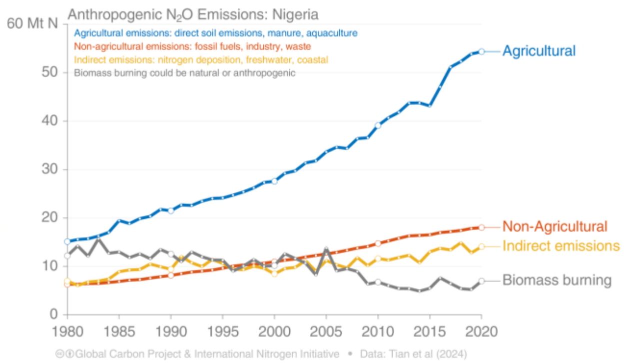
Germany



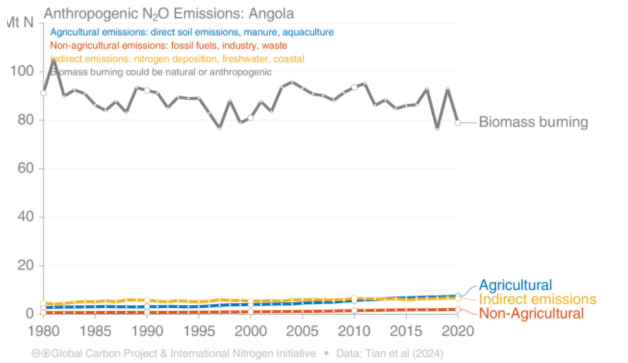
Myanmar



Nigeria



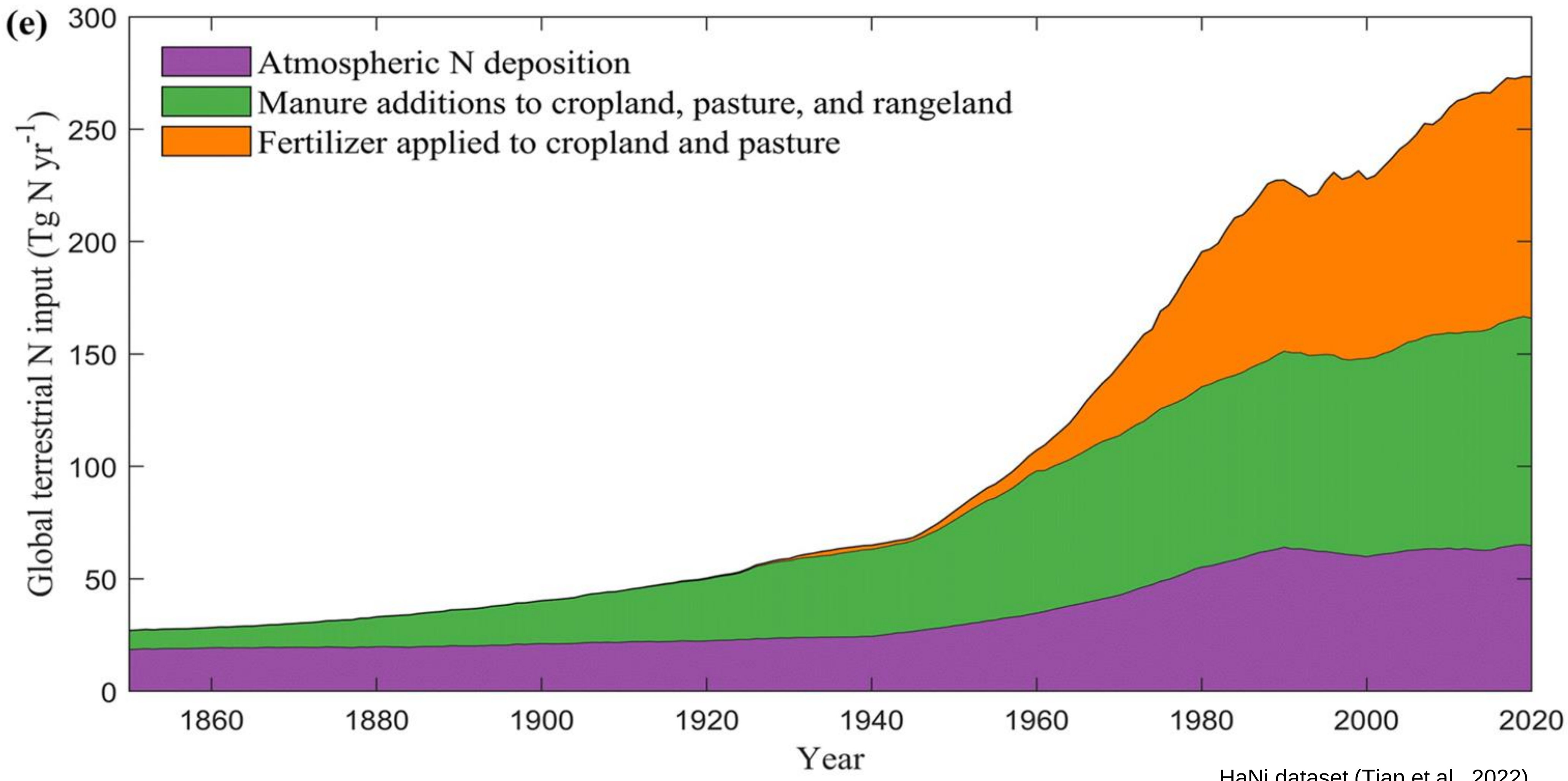
Angola



Additional Figures

Anthropogenic N Additions to Terrestrial Ecosystems

Temporal changes in fertilizer N and manure N applications, and atmospheric N deposition to global terrestrial ecosystems.

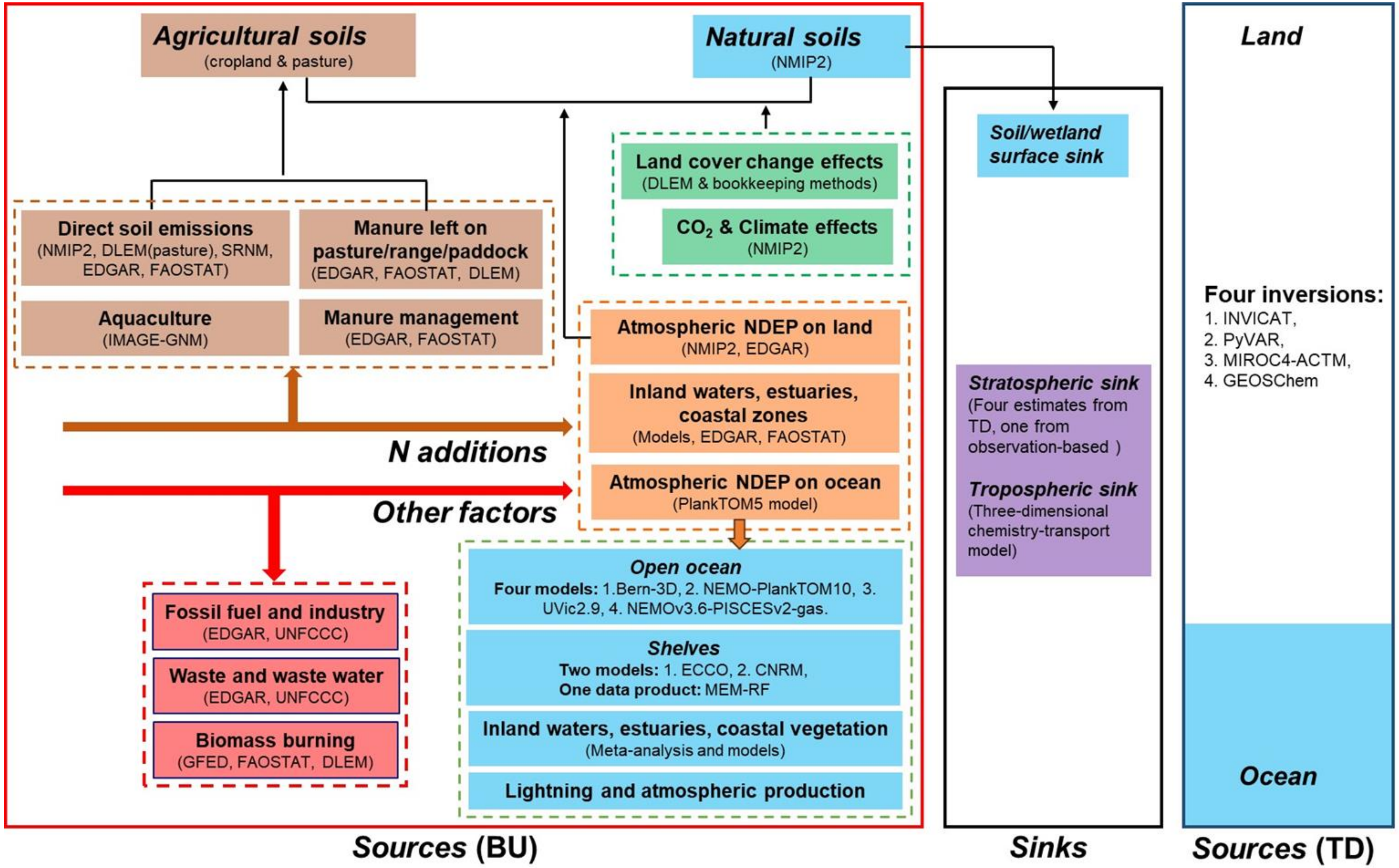


HaNi dataset (Tian et al., 2022)

The Methodology for Preparing the N_2O Budget

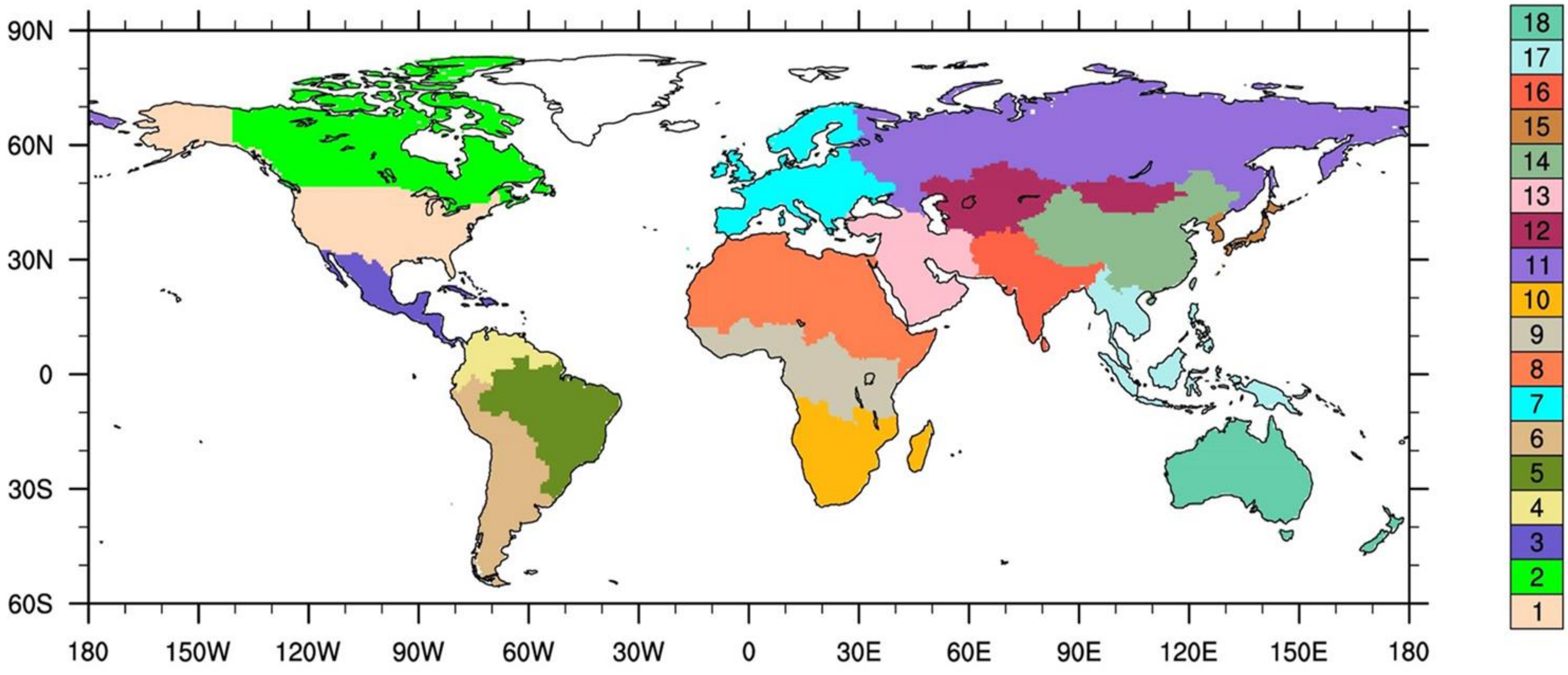
The global N_2O budget is synthesized from **43** independent estimates

(Bottom-up (BU) are from statistical and process-based models, Top-down (TD) are derived from atmospheric observations)



Study Regions for Regional N_2O Budgets

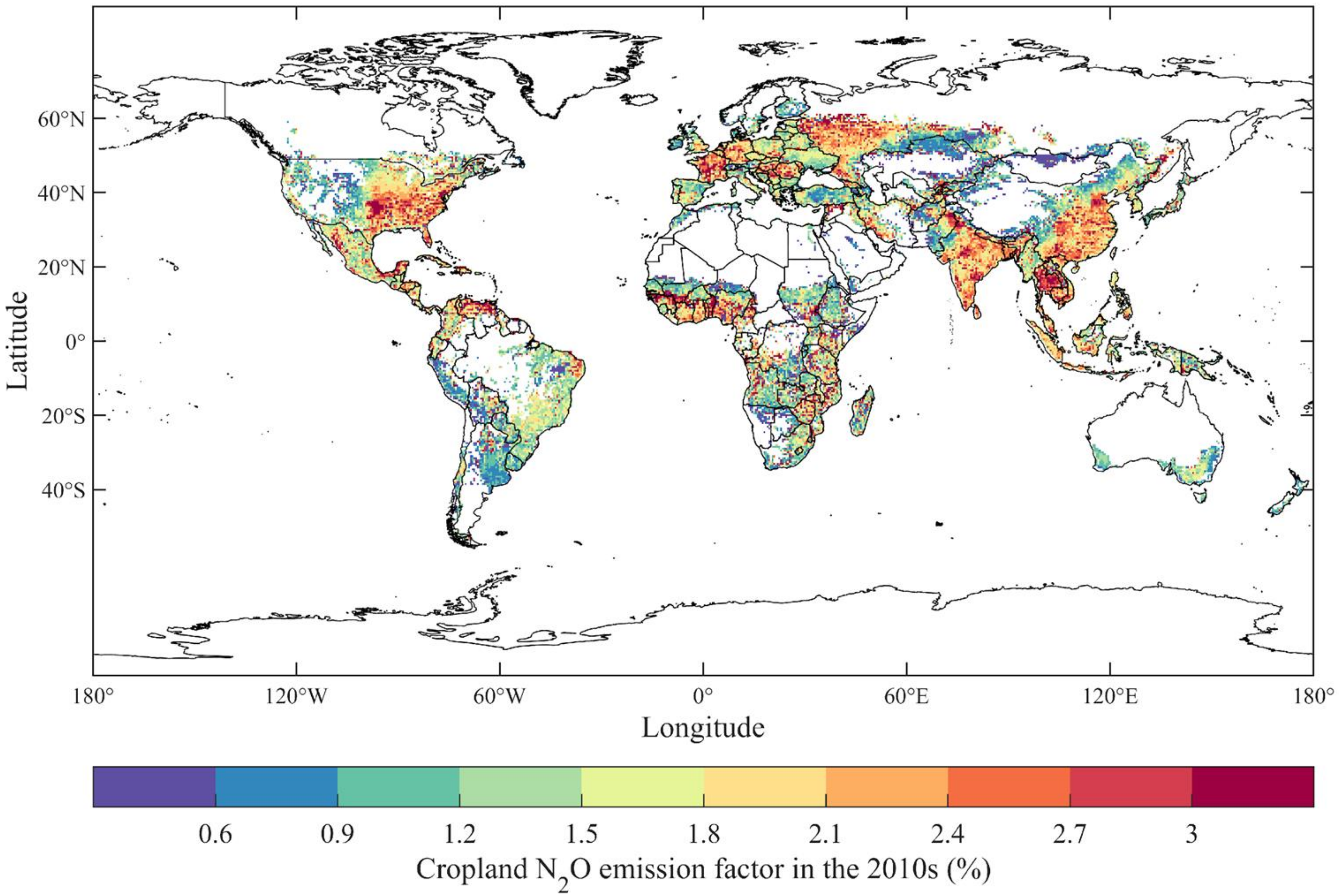
The Earth's ice-free land was partitioned into eighteen regions



1. USA
2. Canada
3. Central America
4. Northern South America
5. Brazil
6. Southwest South America
7. Europe
8. Northern Africa
9. Equatorial Africa
10. Southern Africa
11. Russia
12. Central Asia
13. Mideast
14. China
15. Korea and Japan
16. South Asia
17. Southeast Asia
18. Australasia

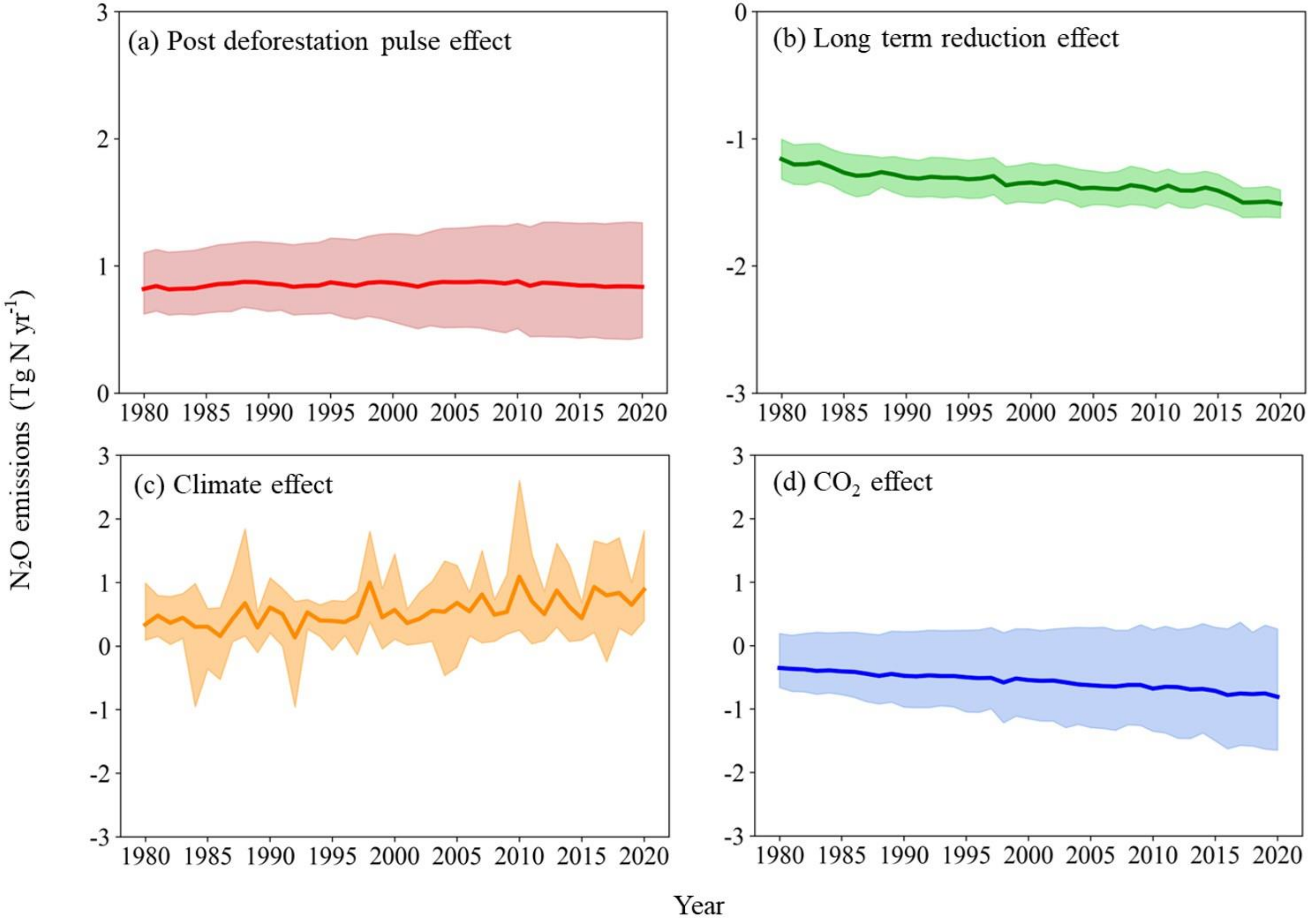
Cropland N_2O Emission Factors

Emission Factors describe the mass of N_2O emitted relative to the amount of anthropogenic nitrogen input.
Emission Factors were calculated from the NMIP2 process-based models



Changes in N_2O Emissions from Deforestation and Climate

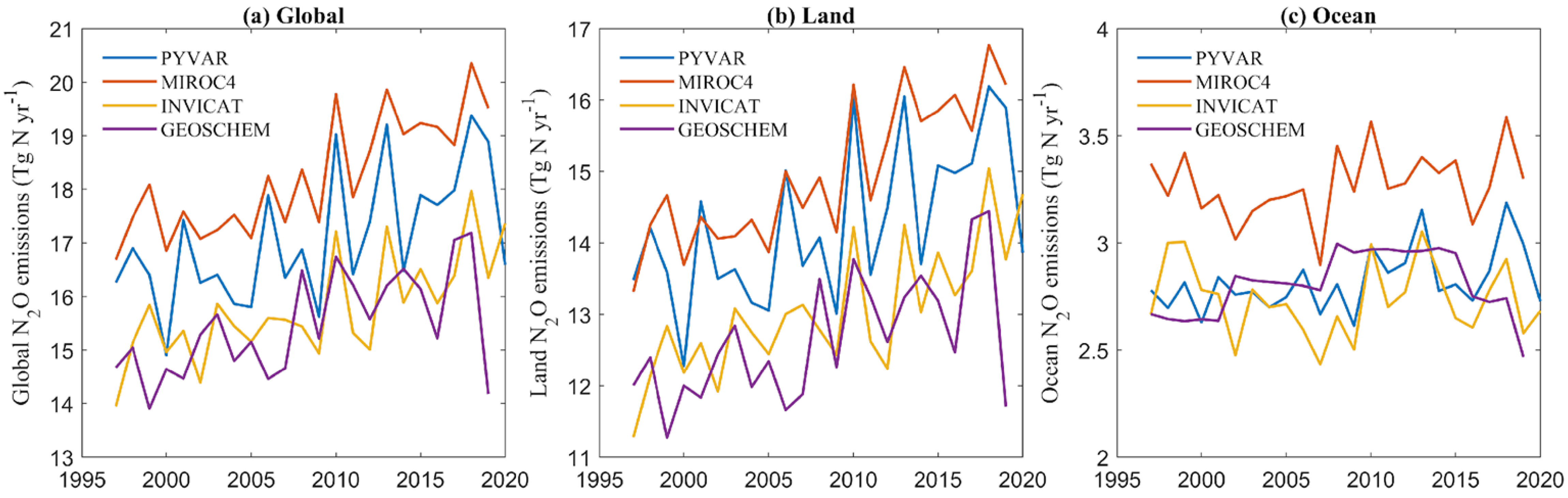
- The global net effect of deforestation is first an increase and then gradually a reduction of N_2O emissions and was -0.6 ± 0.5 TgN/yr in 2020*
- The effect of climate change on N_2O emissions is positive and increased over the past four decades
- The effect of increasing atmospheric CO_2 on N_2O emissions in negative and is due to its effect of increasing the nitrogen use efficiency of plants



*Note: changes in crop/pasture emissions are calculated in the absence of N-fertilizer and manure use, when this is considered the crop/pasture emissions are significantly higher and the net N_2O change is positive

Top-Down N_2O Emission Estimates

Four top-down estimates were used and are from independent atmospheric inversion frameworks. The inversions are very consistent in the trends and partially also in the inter-annual variations, but differ in the magnitudes of global, land and ocean sources



Estimates of the Stratospheric N_2O Sink

- Estimates from four atmospheric inversions and one based on satellite observations and a model of photolysis
- Differences in the stratospheric estimate among atmospheric inversions partly explains the differences in the magnitudes of their source estimates