GLOBAL CARBON PROJECT

In partnership with International Nitrogen Initiative

Global Nitrous Oxide Budget

2020

The GCP is a Global Research Project of futurearth Research. Innovation. Sustainability.

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Published on 7 October 2020

PowerPoint version 1.0 (released 7 October 2020)

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Acknowledgements

The work presented here has been possible thanks to the enormous observational and modelling efforts of the institutions and networks below

Atmospheric N_2O datasets
NOAA/ESRL | AGAGE | CSIRO

Inventories
FAOSTAT | GAINS | EDGAR 4.3.2 | GFED v4.0

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

Atmospheric inversions
INVICAT | PyVAR |MIROC4-ACTM | GEOSChem

Land models
DLEM | LPJ-GUESS | LPX-Bern | OCN | ORCHIDEE | ORCHIDEE-CNP | VISIT

Ocean models
Bern-3D | NEMOv3.6-PISCESv2-gas | NEMO-PlankTOM10 | UVic2.9 | NEMO-PISCES 3.2

Full acknowledgements provided in Tian et al. (2020) Nature

Contributors 57 people | 48 organisations | 14 countries

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Publications of the Global N_2O Budget Activity

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Article

A comprehensive quantification of global nitrous oxide sources and sinks

https://doi.org/10.1038/s41586-020-2780-0

Received: 28 December 2019

Accepted: 14 August 2020

[redacted]

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https://doi.org/10.1038/s41586-020-2780-0

nature climate change

ARTICLES

https://doi.org/10.1038/s41558-019-0613-7

Acceleration of global N_2O emissions seen from two decades of atmospheric inversion

R. L. Thompson[1]*, L. Lassaletta[2], P. K. Patra[3], C. Wilson[4,5], K. C. Wells[6], A. Gressent[7], E. N. Koffi[8], M. P. Chipperfield[4,5], W. Winiwarter[9,10], E. A. Davidson[11], H. Tian[12] and J. G. Canadell[13]

Nitrous oxide (N_2O) is the third most important long-lived GHG and an important stratospheric ozone depleting substance. Agricultural practices and the use of N-fertilizers have greatly enhanced emissions of N_2O. Here, we present estimates of N_2O emissions determined from three global atmospheric inversion frameworks during the period 1998–2016. We find that global N_2O emissions increased substantially from 2009 and at a faster rate than estimated by the IPCC emission factor approach. The regions of East Asia and South America made the largest contributions to the global increase. From the inversion-based emissions, we estimate a global emission factor of 2.3 ± 0.6%, which is significantly larger than the IPCC Tier-1 default for combined direct and indirect emissions of 1.375%. The larger emission factor and accelerating emission increase found from the inversions suggest that N_2O emission may have a nonlinear response at global and regional scales with high levels of N-input.

https://doi.org/10.1038/s41558-019-0613-7

AMERICAN METEOROLOGICAL SOCIETY JUNE 2018 BAMS

THE GLOBAL N_2O MODEL INTERCOMPARISON PROJECT

Hanqin Tian, Jia Yang, Chaoqun Lu, Rongting Xu, Josep G. Canadell, Robert B. Jackson, Almut Arneth, Jinfeng Chang, Guangsheng Chen, Philippe Ciais, Stefan Gerber, Akihiko Ito, Yuanyuan Huang, Fortunat Joos, Sebastian Lienert, Palmira Messina, Stefan Olin, Shufen Pan, Changhui Peng, Eri Saikawa, Rona L. Thompson, Nicolas Vuichard, Wilfried Winiwarter, Sönke Zaehle, Bowen Zhang, Kerou Zhang, and Qiuan Zhu

The N_2O Model Intercomparison Project (NMIP) aims at understanding and quantifying the budgets of global and regional terrestrial N_2O fluxes, environmental controls, and uncertainties associated with input data, model structure, and parameters.

https://doi.org/10.1175/BAMS-D-17-0212.1

Emissions are shown in Mega tonnes N

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

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

1 MtN = 1.57 million tonnes N_2O = 1.57 MtN_2O

Disclaimer

N_2O Basics

- N_2O is both a powerful greenhouse gas (GHG) and a ozone-depleting substance.
- Per unit of mass, N_2O is considered 298 times as effective as a greenhouse gas as CO_2 when integrating over 100-years.
- Once emitted, N_2O stays in the atmosphere for longer than a human life, about 116 ±9 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 three most important GHGs (CO_2, CH_4 and N_2O) (Updated to 2019 from Etminan et al. 2016, GRL)
- N_2O concentration in the atmosphere reached 331 parts per billion (ppb) in 2018 (WMO 2020, United in Science), about 22% above levels around the year 1750, before the industrial era began.

Highlights

- Global N_2O emissions were about 17.0 (15.9–17.7) Tg N yr^{-1} over the 10-year period 2007-2016 (based on two approaches).

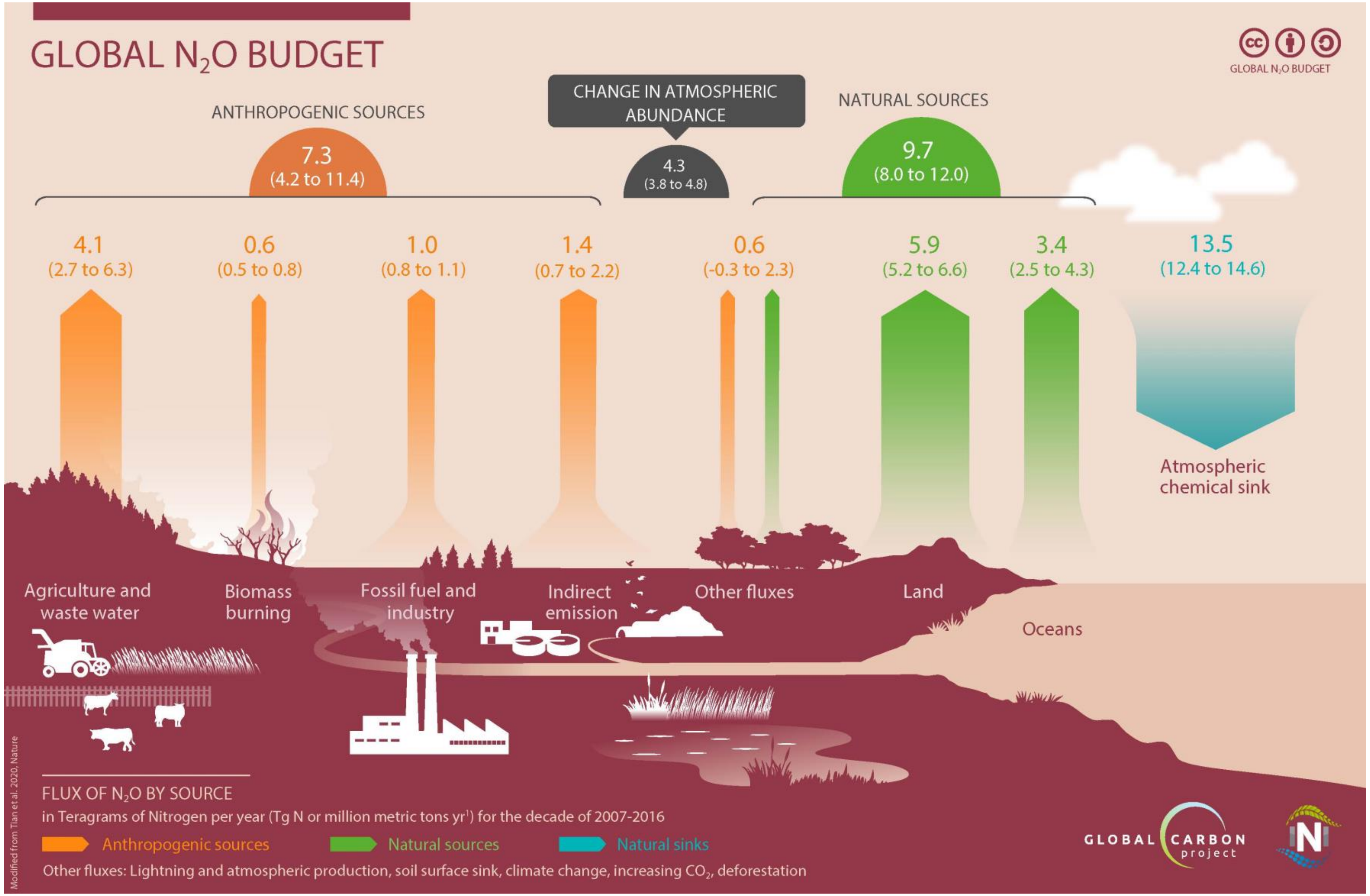
- Global anthropogenic emissions increased by 30% since 1980, dominated by nitrogen fertilization in croplands. The anthropogenic emission increase is almost exclusively responsible for the growth in atmospheric N_2O.

- Soil N_2O emissions are increasing due to interactions between nitrogen inputs and global warming, constituting an emerging positive N_2O-climate feedback.

- The recent increase in global N_2O emissions exceeds the emission trends of the least optimistic scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), underscoring the urgent need to mitigate N_2O emissions.

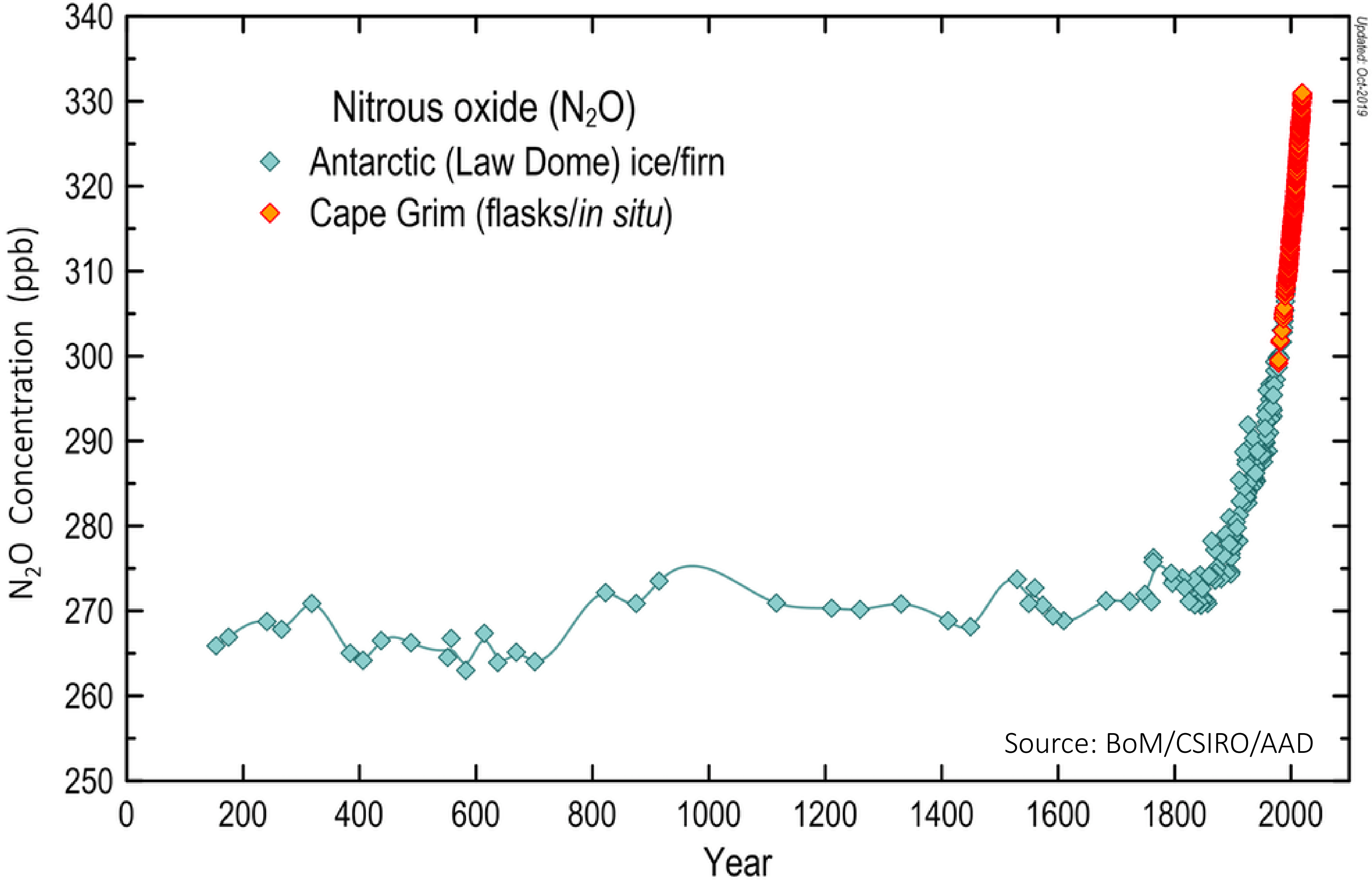
The Global N_2O Budget (simplified)

Anthropogenic sources contribute, for the central estimate, 43% to total global N_2O emissions.



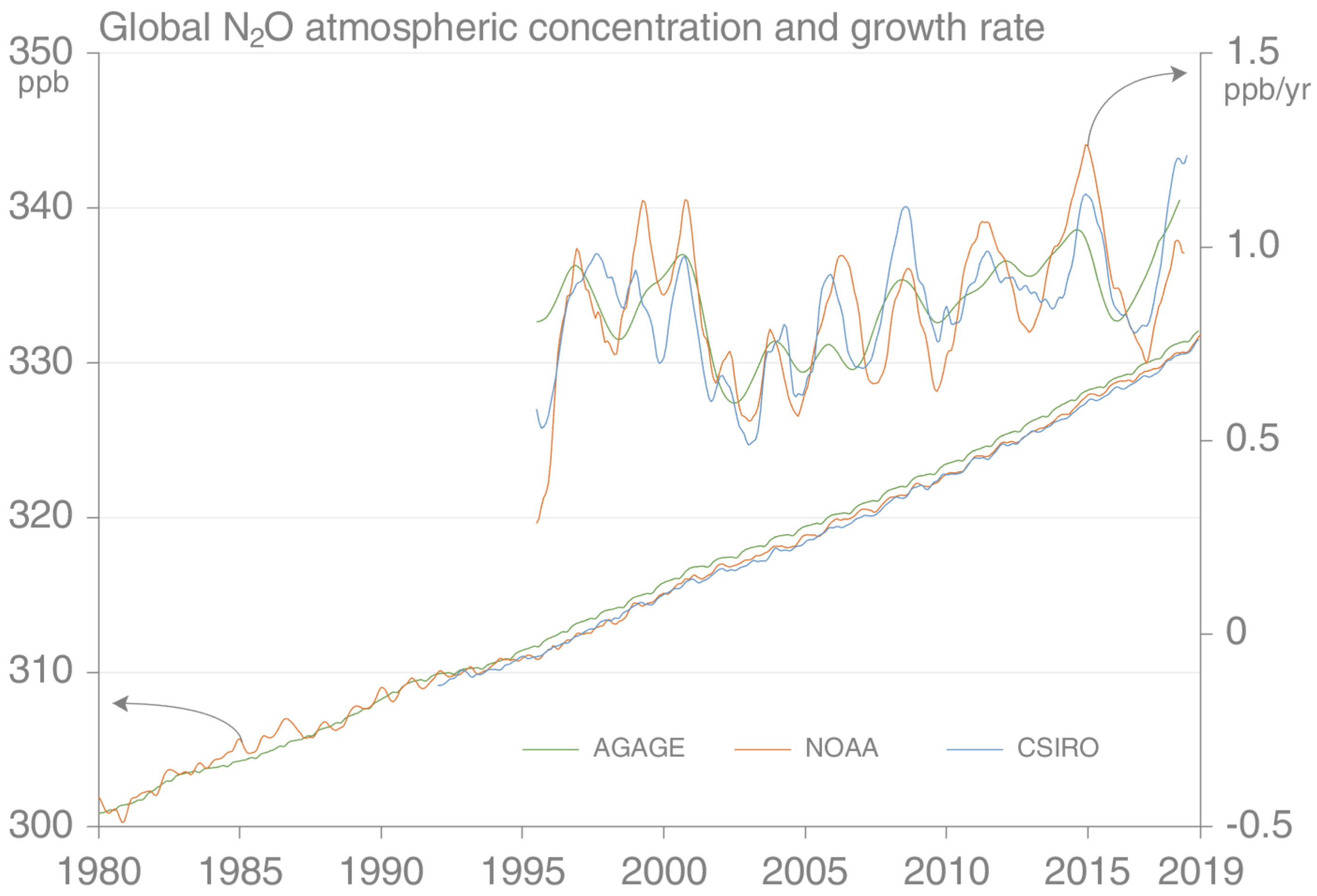
Atmospheric N_2O concentrations over the last two millennia

The global N_2O *concentration* has increased by about 22%, from 270 parts per billion (ppb) in 1750 to 331 ppb in 2018.



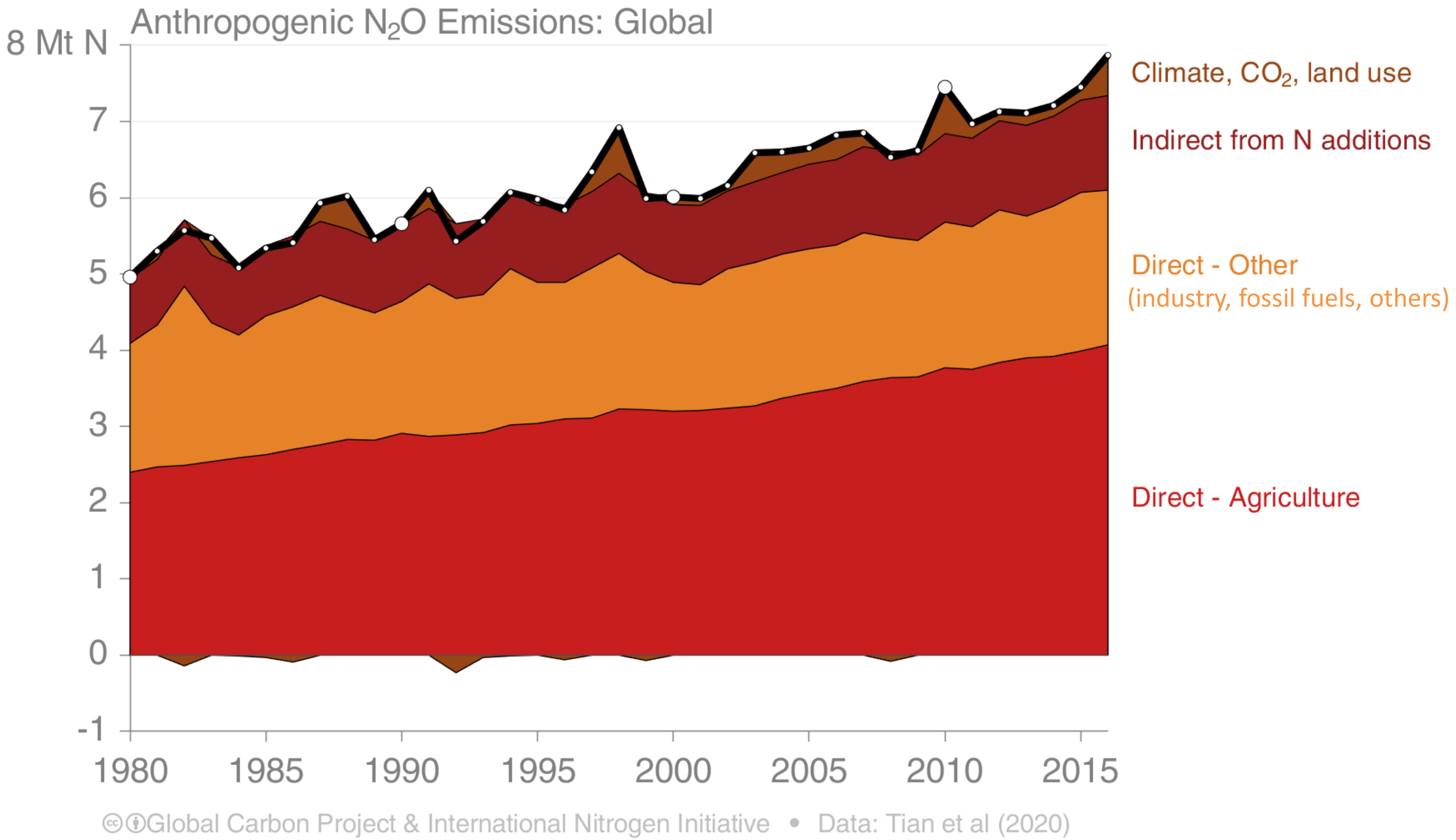
Atmospheric concentration and growth rate over the last 40 years

The growth in global atmospheric N_2O is accelerating
The mean growth rate since 2000 is 0.84 ppb/yr



Global Anthropogenic N_2O Emissions

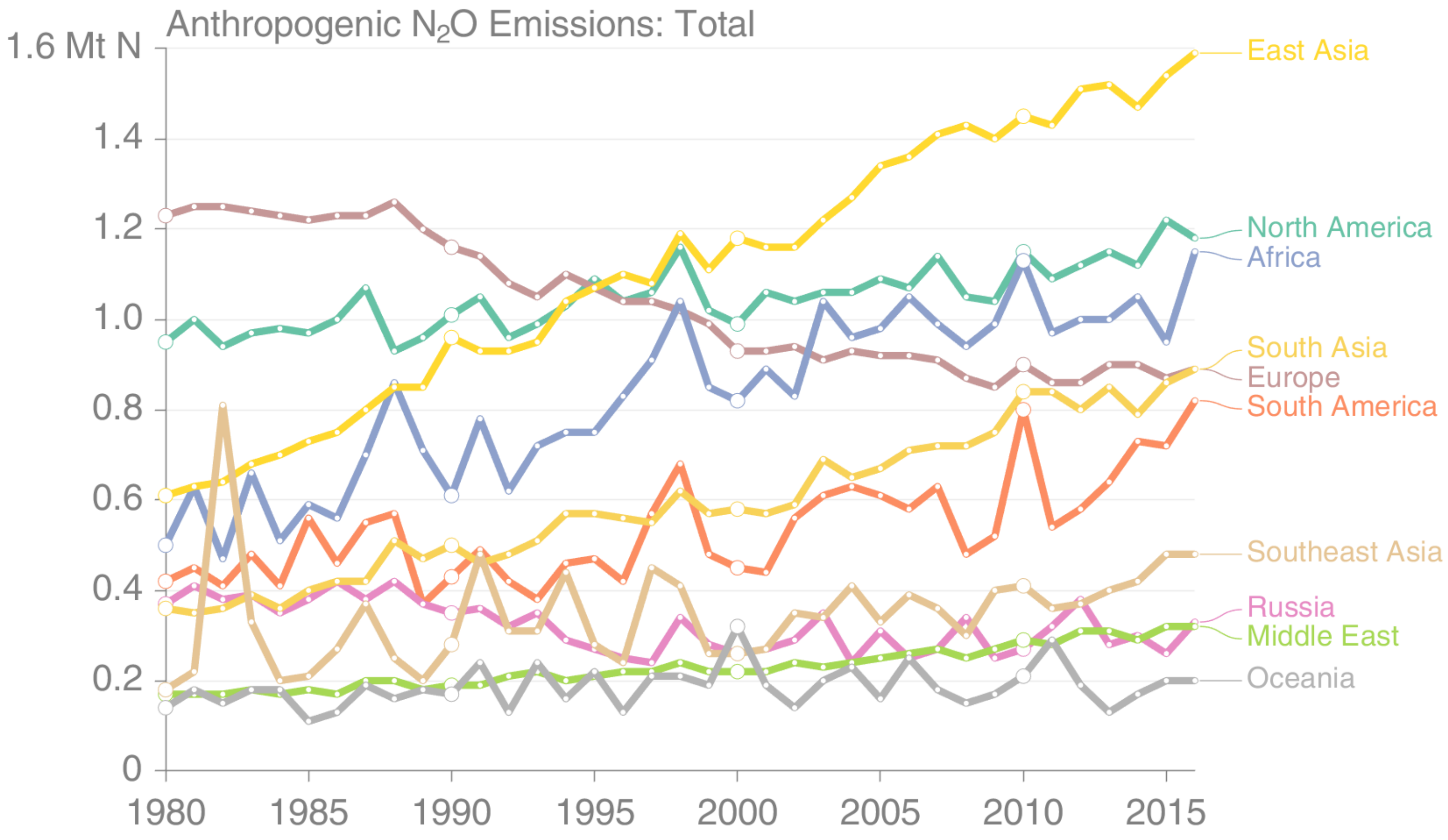
Global anthropogenic N_2O emissions are growing at over 1% pear year.
Agriculture is the single largest anthropogenic source of N_2O emissions.



Direct sources are those occurring where nitrogen additions are made, while indirect sources are those occurring down-stream or downwind

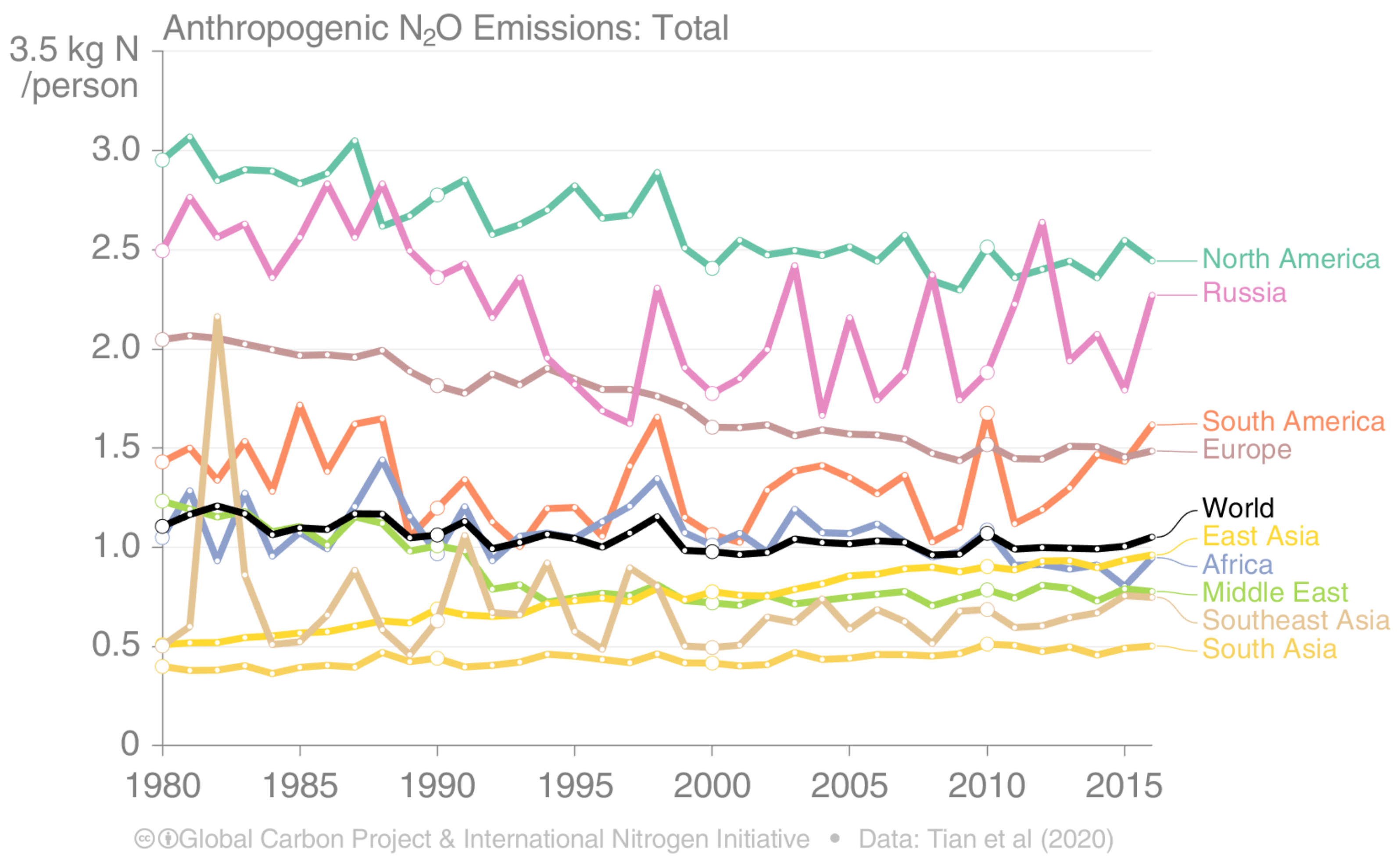
Anthropogenic Emissions by World Region

The recent global increase in N_2O emissions is driven by Asia, followed by South America and Africa, while emissions in Europe have decreased since 1990



Anthropogenic Emissions per Person by World Region

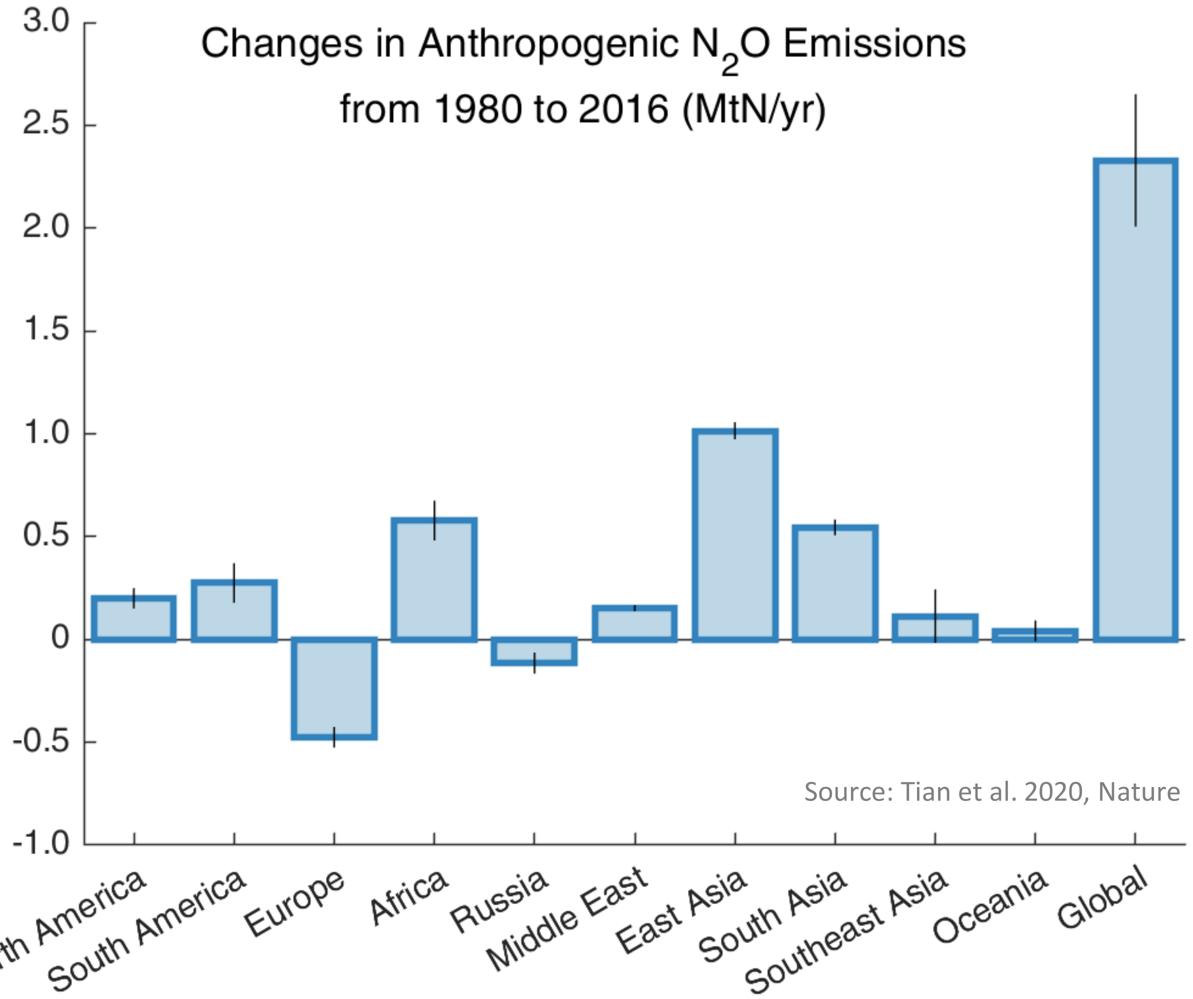
There is a broad range of N_2O emissions per person, with wealthier regions generally above the world average



Oceania excluded to make figure clearer. Oceania emits around 6kgN per person

Changes in anthropogenic N_2O emissions

Emissions from Europe and Russia decreased by a total of 0.6 (0.5–0.7) TgN/yr over 1980-2016, while emissions from the remaining regions increased by a total of 2.9 (2.4–3.4) TgN/yr

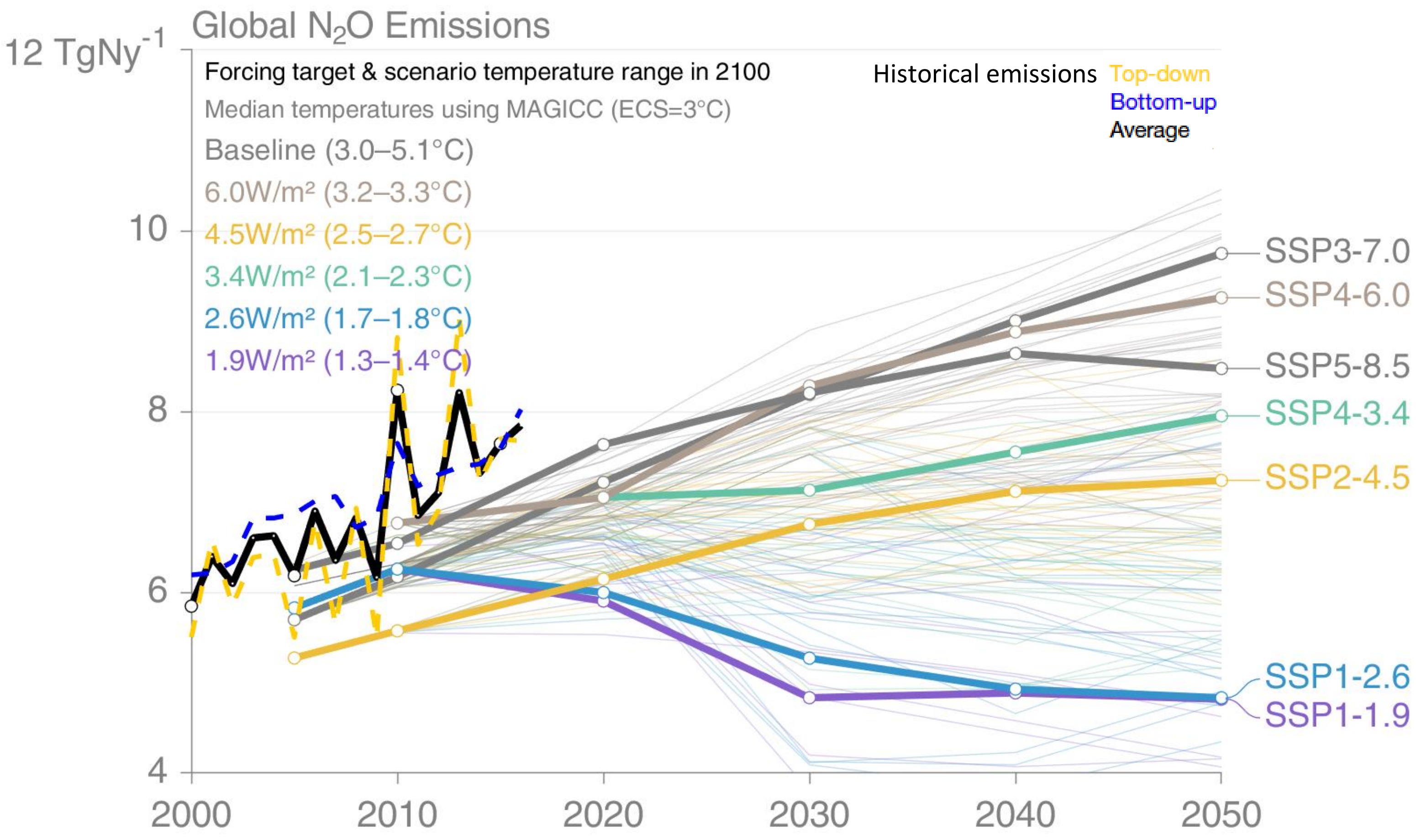


Source: Tian et al. 2020, Nature

Shared Socioeconomic Pathways (SSPs)

The SSPs lead to a broad range in baselines (grey), with more aggressive mitigation leading to lower temperature outcomes.
The bold lines are scenarios that will be analysed in CMIP6 and the results assessed in the IPCC AR6 process.

The bold black and dashed blue and yellow lines are the estimated actual emissions



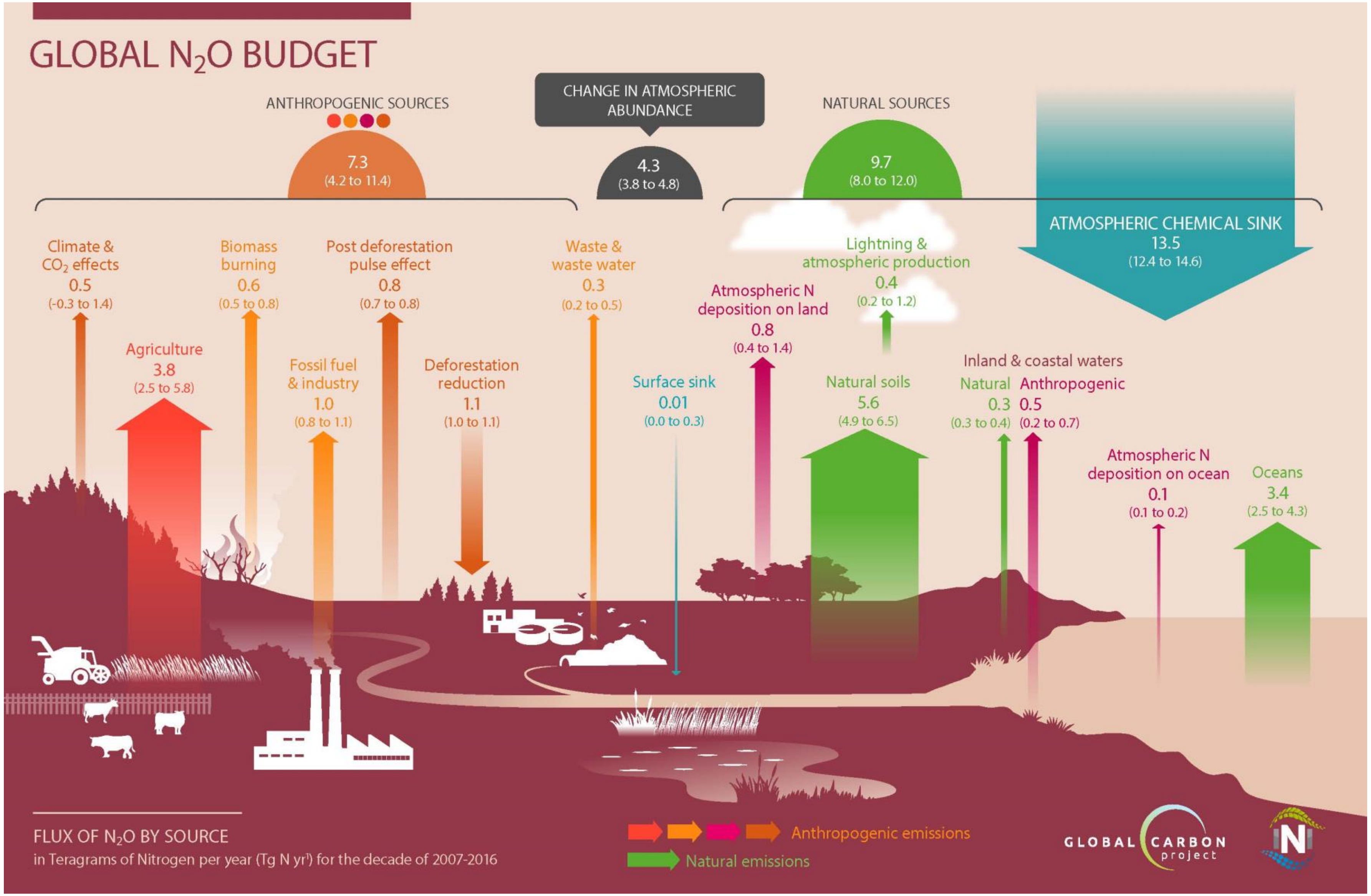
This set of quantified SSPs are based on the output of six Integrated Assessment Models (AIM/CGE, GCAM, IMAGE, MESSAGE, REMIND, WITCH).
Model and Data Sources: Riahi et al. 2016; Rogelj et al. 2018; IIASA SSP Database; IAMC; Global Carbon Budget 2019

Global N_2O sources and sinks in the past four decades

The budget includes **21** natural and anthropogenic source categories. Global N_2O emissions have increased significantly since the 1980s, driven primarily by anthropogenic sources.

		the 1980s			the 1990s			the 2000s			2007-2016		
Anthropogenic sources		**mean**	min	max	**mean**	min	max	**mean**	min	max	**mean**	min	max
Direct emissions of N additions in the agricultural sector (Agriculture)	Direct soil emissions	1.5	0.9	2.6	1.7	1.1	3.1	2.0	1.3	3.4	2.3	1.4	3.8
	Manure left on pasture	0.9	0.7	1.0	1.0	0.7	1.1	1.1	0.8	1.2	1.2	0.9	1.3
	Manure management	0.3	0.2	0.4	0.3	0.2	0.4	0.3	0.2	0.5	0.3	0.2	0.5
	Aquaculture	0.01	0.00	0.03	0.03	0.01	0.1	0.1	0.02	0.2	0.1	0.02	0.2
	sub-total	2.6	1.8	4.1	3.0	2.1	4.8	3.4	2.3	5.2	3.8	2.5	5.8
Other direct anthropogenic sources	Fossil fuel and industry	0.9	0.8	1.1	0.9	0.9	1.0	0.9	0.8	1.0	1.0	0.8	1.1
	Waste and waste water	0.2	0.1	0.3	0.3	0.2	0.4	0.3	0.2	0.4	0.3	0.2	0.5
	Biomass burning	0.7	0.7	0.7	0.7	0.6	0.8	0.6	0.6	0.6	0.6	0.5	0.8
	sub-total	1.8	1.6	2.1	1.9	1.7	2.1	1.8	1.6	2.1	1.9	1.6	2.3
Indirect emissions from anthropogenic N additions	Inland waters, estuaries, coastal zones	0.4	0.2	0.5	0.4	0.2	0.5	0.4	0.2	0.6	0.5	0.2	0.7
	Atmospheric N deposition on land	0.6	0.3	1.2	0.7	0.4	1.4	0.7	0.4	1.3	0.8	0.4	1.4
	Atmospheric N deposition 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
	sub-total	1.1	0.6	1.9	1.2	0.7	2.1	1.2	0.6	2.1	1.3	0.7	2.2
Perturbed fluxes from climate/CO2/land cover change	CO_2 effect	-0.2	-0.3	0.0	-0.2	-0.4	0.0	-0.3	-0.5	0.1	-0.3	-0.6	0.1
	Climate effect	0.4	0.0	0.8	0.5	0.1	0.9	0.7	0.3	1.2	0.8	0.3	1.3
	Post-deforestation pulse effect	0.7	0.6	0.8	0.7	0.6	0.8	0.7	0.7	0.8	0.8	0.7	0.8
	Long-term effect of reduced mature forest area	-0.8	-0.8	-0.9	-0.9	-0.8	-1.0	-1.0	-0.9	-1.1	-1.1	-1.0	-1.1
	sub-total	0.1	-0.4	0.7	0.1	-0.5	0.7	0.2	-0.4	0.9	0.2	-0.6	1.1
Anthropogenic total		5.6	3.6	8.7	6.2	3.9	9.7	6.7	4.1	10.3	7.3	4.2	11.4
Natural fluxes													
Natural soils baseline		5.6	4.9	6.6	5.6	4.9	6.5	5.6	5.0	6.5	5.6	4.9	6.5
Ocean baseline		3.6	3.0	4.4	3.5	2.8	4.4	3.5	2.7	4.3	3.4	2.5	4.3
Natural (Inland waters, estuaries, coastal zones)		0.3	0.3	0.4	0.3	0.3	0.4	0.3	0.3	0.4	0.3	0.3	0.4
Lightning and atmospheric production		0.4	0.2	1.2	0.4	0.2	1.2	0.4	0.2	1.2	0.4	0.2	1.2
Surface sink		-0.01	0.00	-0.3	-0.01	0.00	-0.3	-0.01	0.00	-0.3	-0.01	0.00	-0.3
Natural total		9.9	8.5	12.2	9.8	8.3	12.1	9.8	8.2	12.0	9.7	8.0	12.0
Bottom-up total source		15.5	12.1	20.9	15.9	12.2	21.7	16.4	12.3	22.4	17.0	12.2	23.5
Top-down Ocean								5.1	3.1	7.2	5.1	3.4	7.1
Top-down Land								10.8	9.3	12.5	11.8	10.6	13.8
Top-down total source								15.9	15.1	16.9	16.9	15.9	17.7
Top-down Statospheric sink								12.1	11.4	13.1	12.4	11.7	13.3
Observed atmospheric chemical sink*								13.3	12.2	14.4	13.5	12.4	14.6
Change in atmospheric abundance**								**3.7**	3.2	**4.2**	**4.3**	3.8	**4.8**
Atmospheric burden		1462	1442	1482	1493	1472	1514	1531	1510	1552	1555	1533	1577

Global N_2O Budget (complete)



Source: Tian et al. 2020, Nature

Methodology overview

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

Key uncertainties

- ✓ Current data analysis and synthesis of long-term N_2O fluxes are based on a wide variety of top-down and bottom-up approaches.
- ✓ Top-down approaches provide a range of estimates, due to systematic errors in the modelled atmospheric transport and stratospheric loss of N_2O, as well as large uncertainty in prior ocean flux estimates.
- ✓ Bottom-up approaches are subject to large uncertainties in various sources from land and oceans. For process-based land and ocean models, the uncertainty is associated with differences in model configuration as well as process parameterization.
- ✓ GHG inventories using default Emission Factors show large uncertainties at the global scale, especially for agricultural N_2O emissions due to the spatial divergence in climate, management, and soil conditions.
- ✓ A large range of Emission Factors have been used to estimate aquaculture N_2O emissions and long-term estimates of N flows in freshwater and marine aquaculture are scarce.
- ✓ Missing fluxes from permafrost thawing and the freeze-thaw.
- ✓ The relative proportion of ocean N_2O from oxygen-minimum zones, Oxic versus sub-oxic ocean zones, is highly uncertain.

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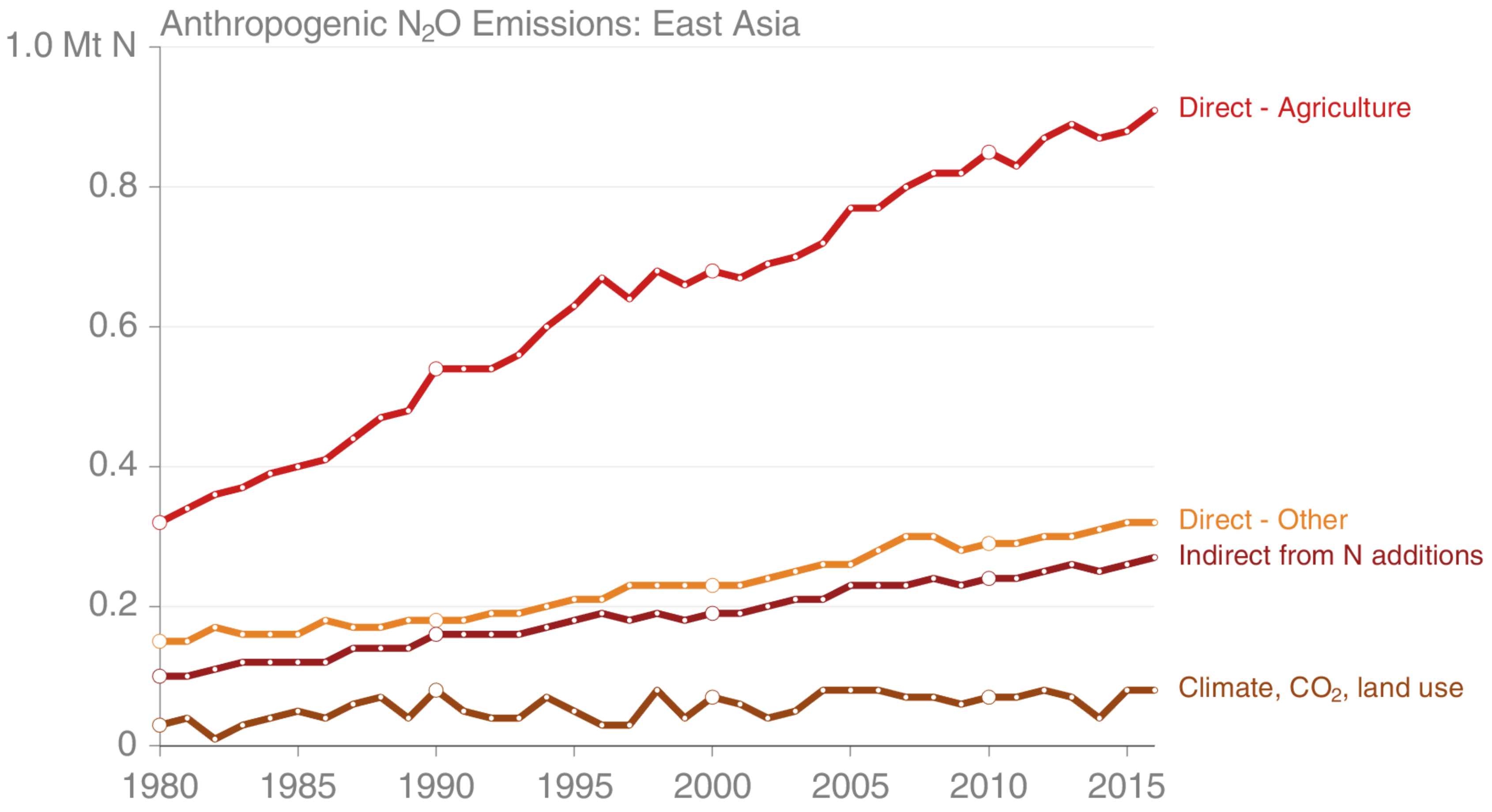
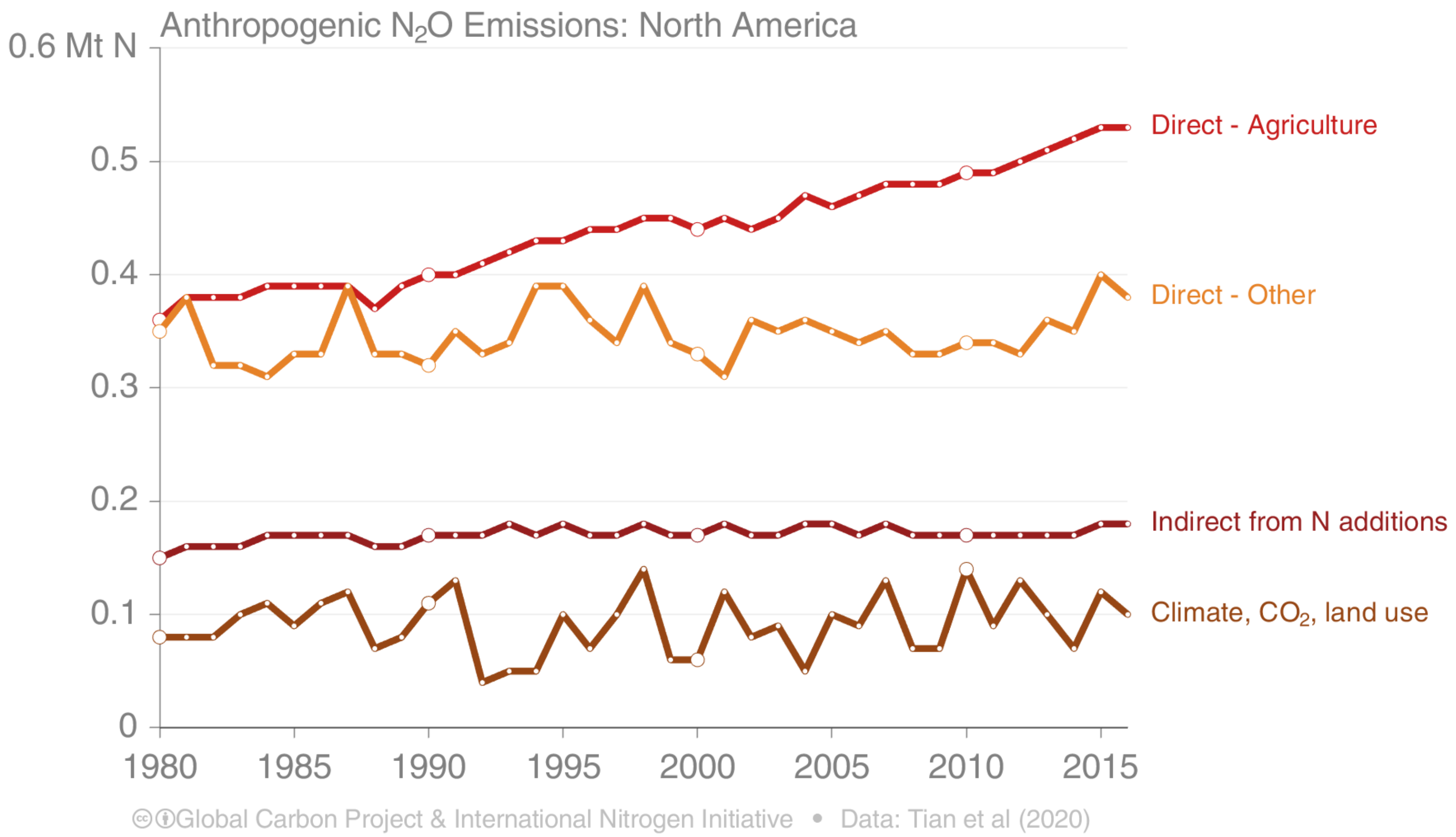
Emissions from key regions

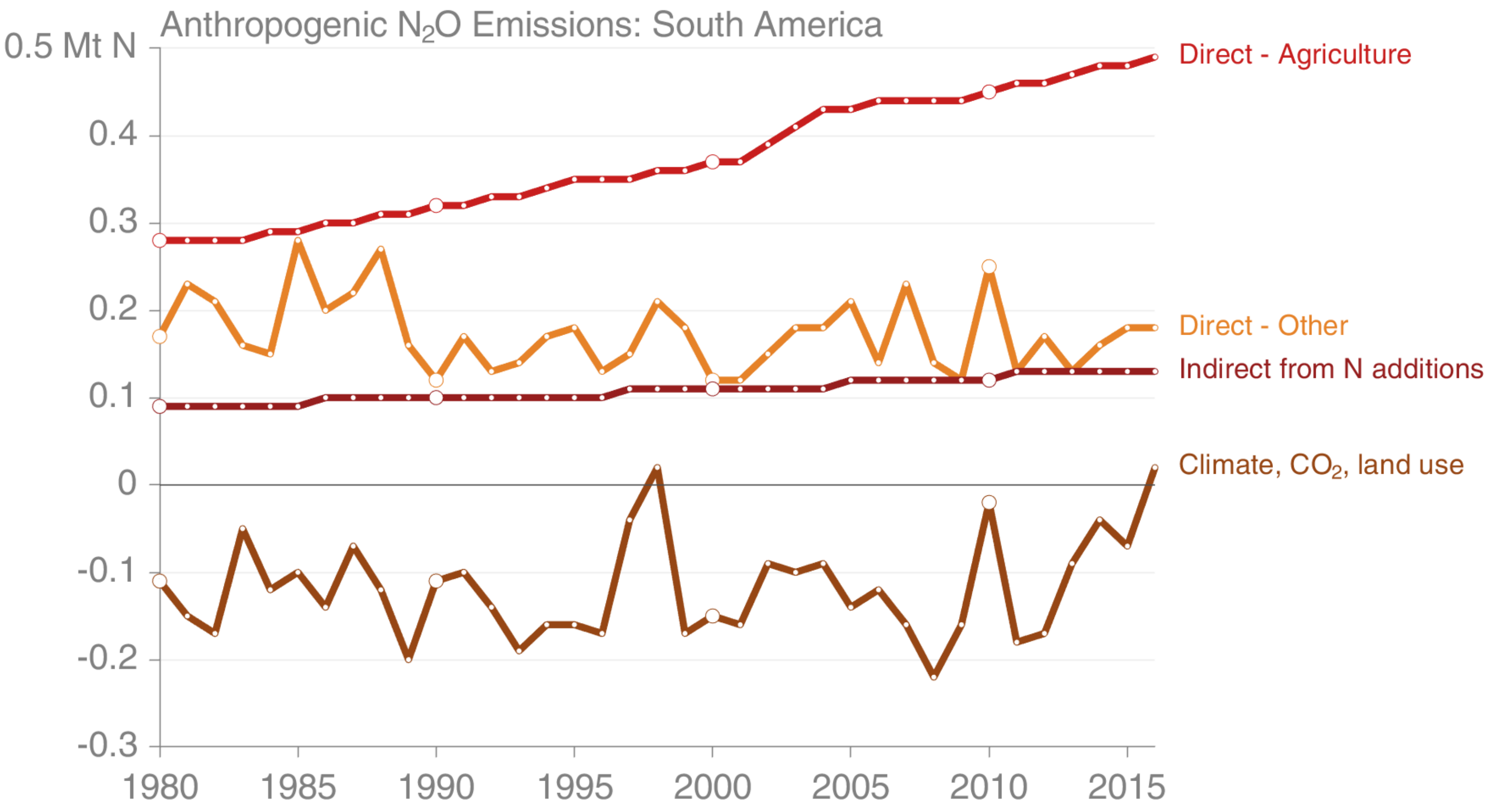
East Asia: Anthropogenic N_2O Emissions



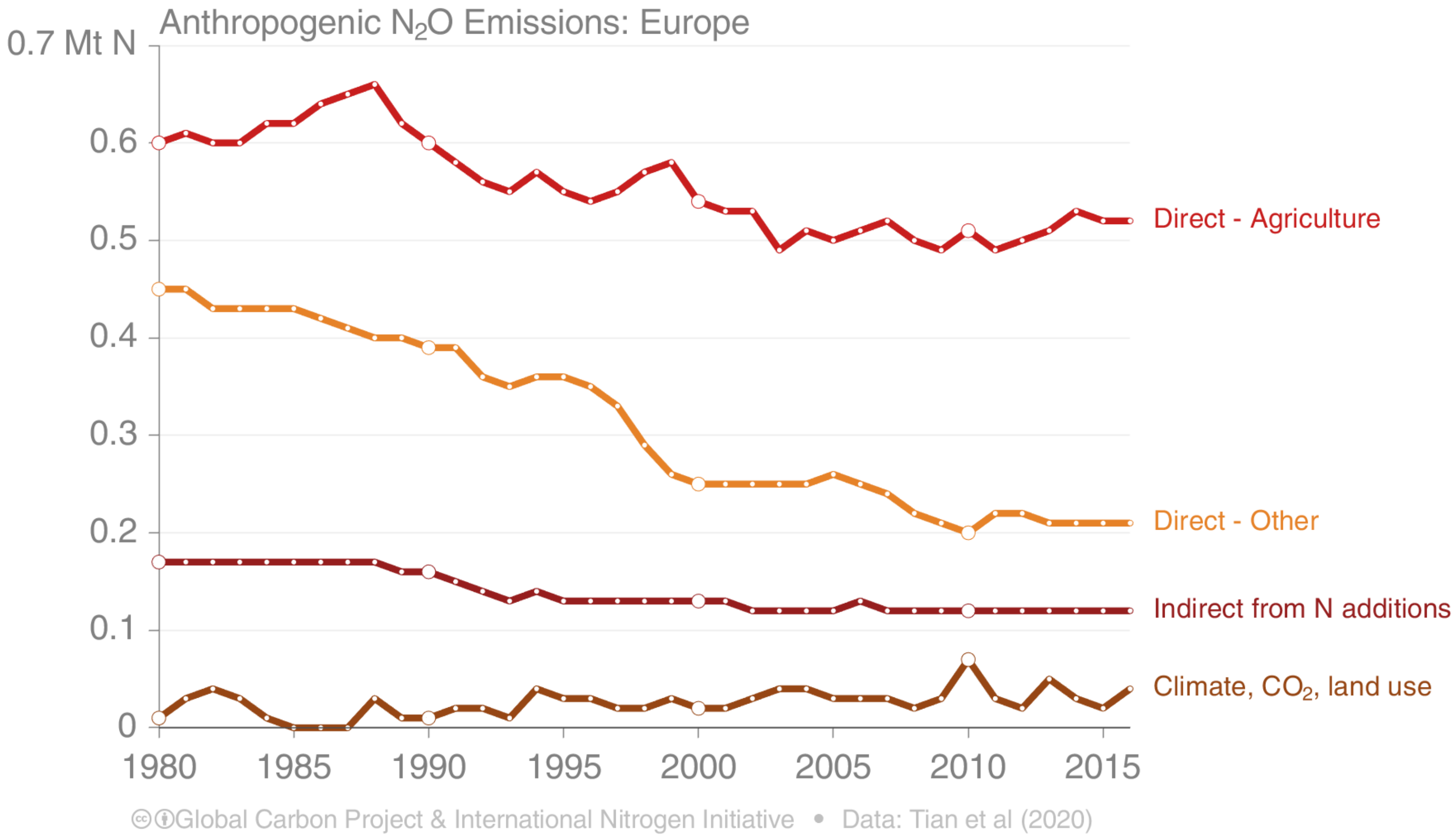
North America: Anthropogenic N_2O Emissions



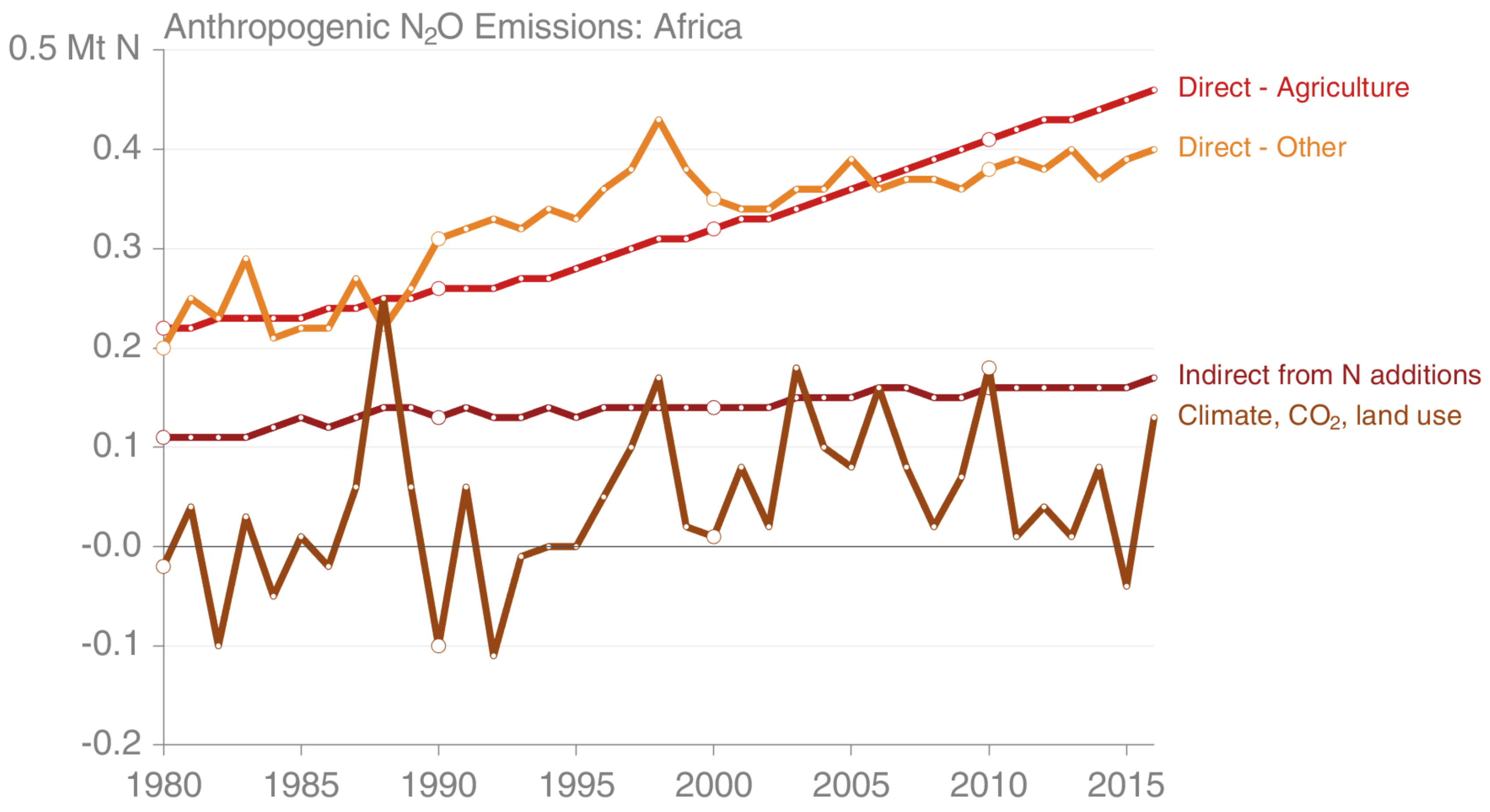
South America: Anthropogenic N_2O Emissions



Europe: Anthropogenic N_2O Emissions



Africa: Anthropogenic N_2O Emissions

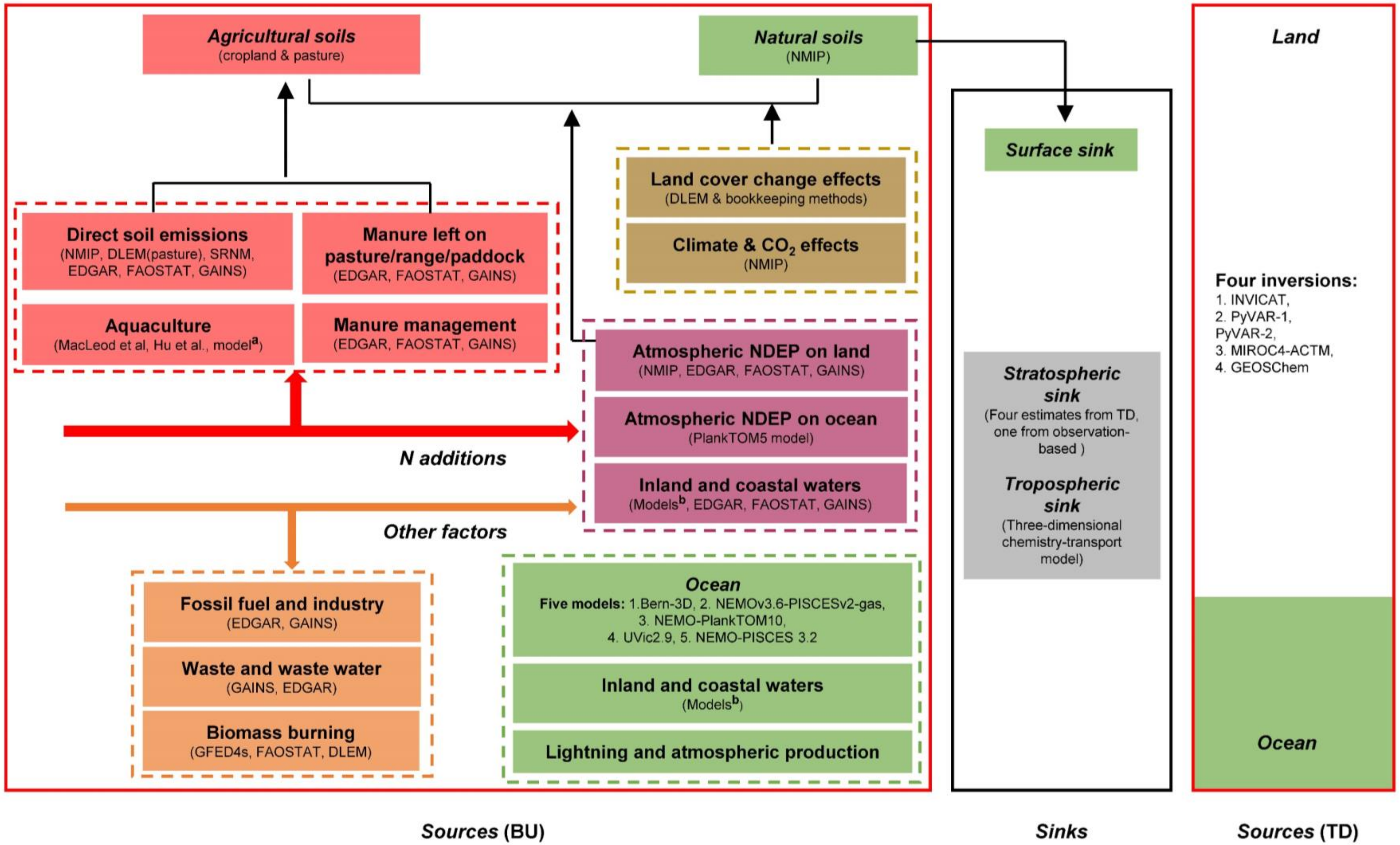


Additional figures

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)

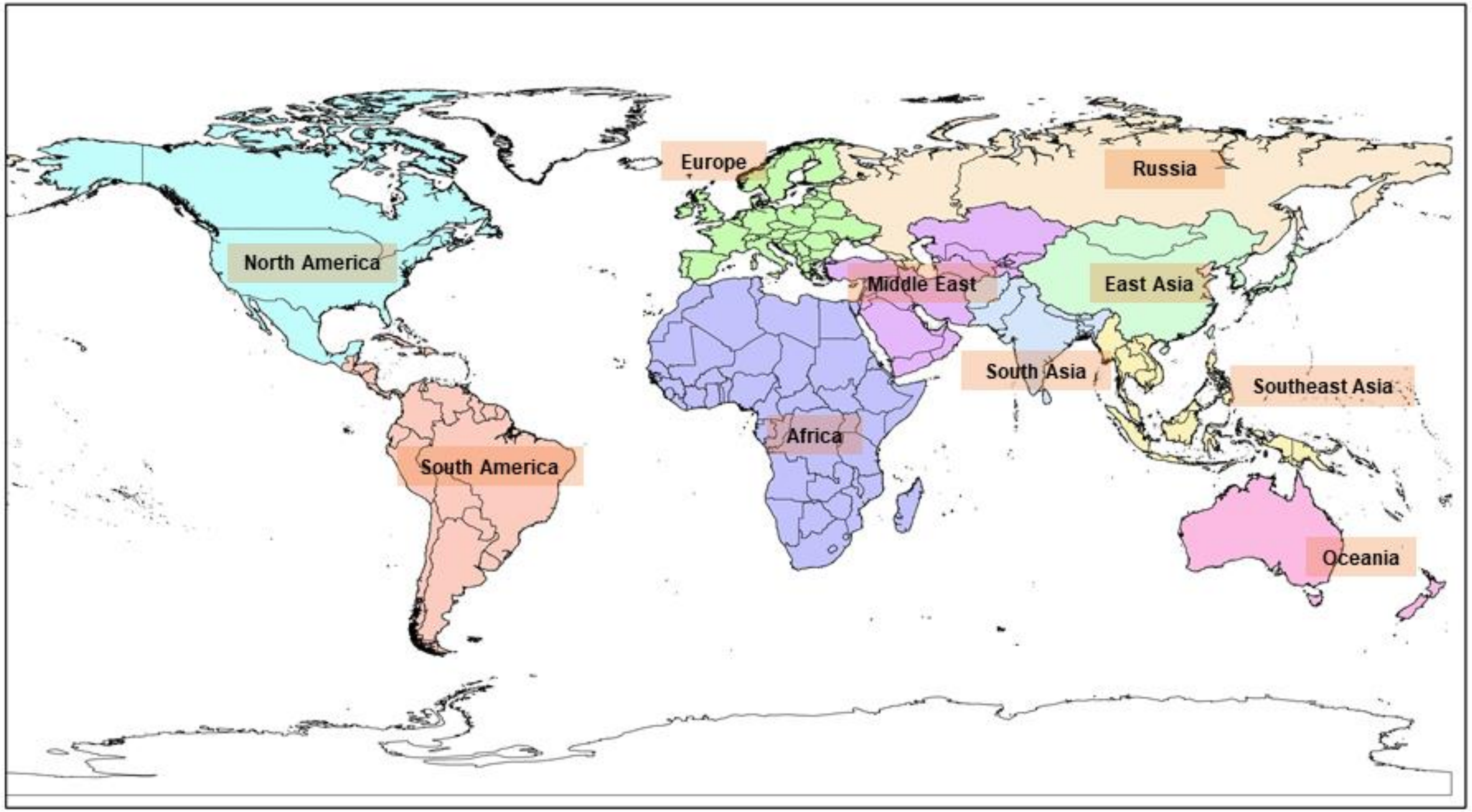


Source: Tian et al. 2020, Nature

[a]MacLeod et al. and Hu et al. provide global aquaculture N_2O emissions in 2013 and in 2009, respectively; and the nutrient budget model provides N flows in global freshwater and marine aquaculture over the period 1980–2016. [b]Model-based estimates of N_2O emissions from 'Inland and coastal waters' include rivers and reservoirs, lakes, estuaries, coastal zones (i.e., seagrasses, mangroves, saltmarsh and intertidal saltmarsh), and coastal upwelling.

Ten study regions for regional N_2O budgets

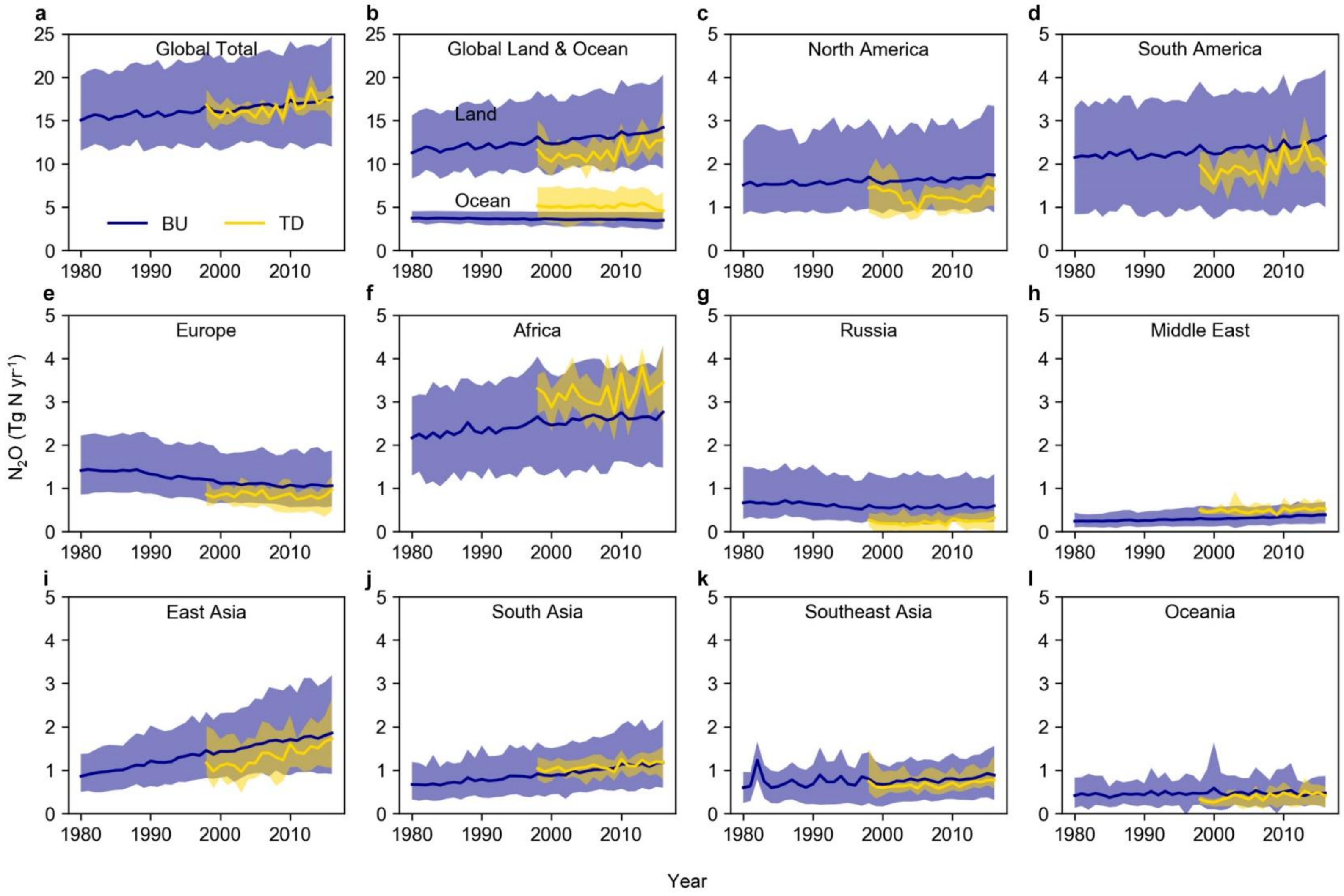
The Earth's ice-free land was partitioned into ten regions



Source: Tian et al. 2020, Nature

Annual comparison of Bottom-Up (BU) and Top-Down (TD) estimates

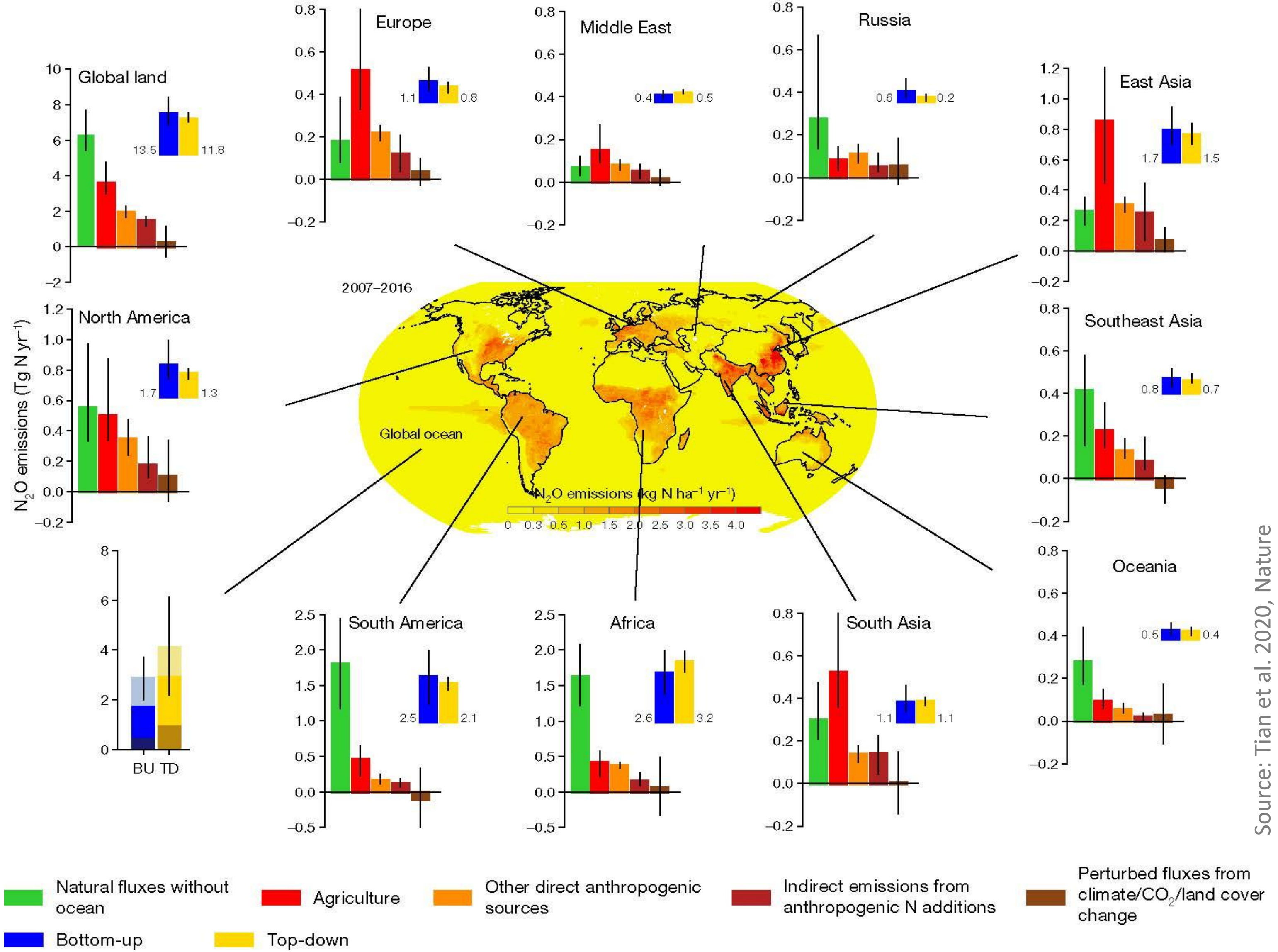
Global N_2O emission estimates from BU and TD are comparable in magnitude and trend for 1998-2016.
TD estimates show larger inter-annual variability but have smaller land and larger ocean emissions.



Source: Tian et al. 2020, Nature

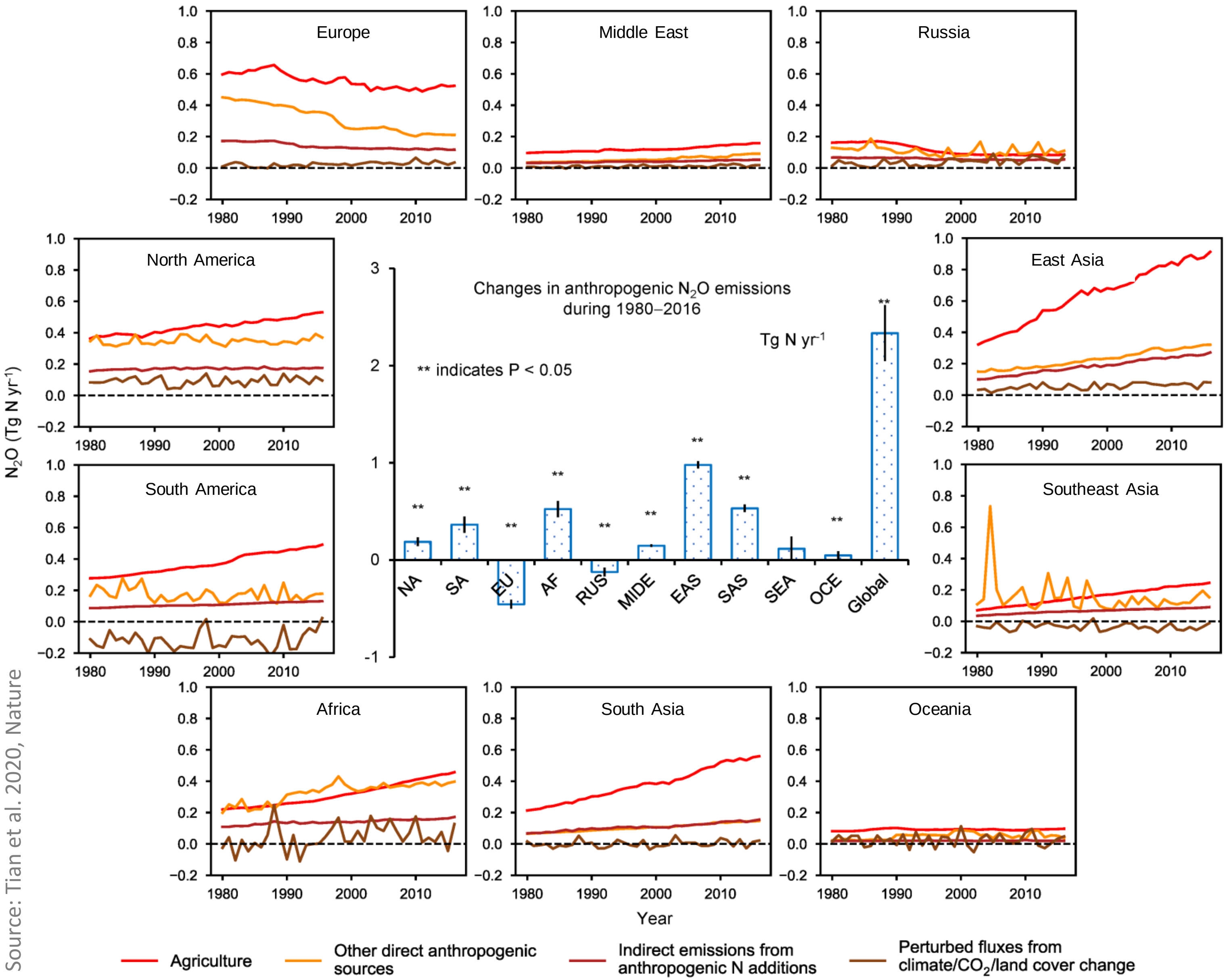
Regional N_2O Budgets for 2007-2016

Bottom-up and top-down approaches indicate that Africa was the largest N_2O land source in the last decade, followed by South America. The tropical oceans contribute over 50% to the global oceanic source.



Source: Tian et al. 2020, Nature

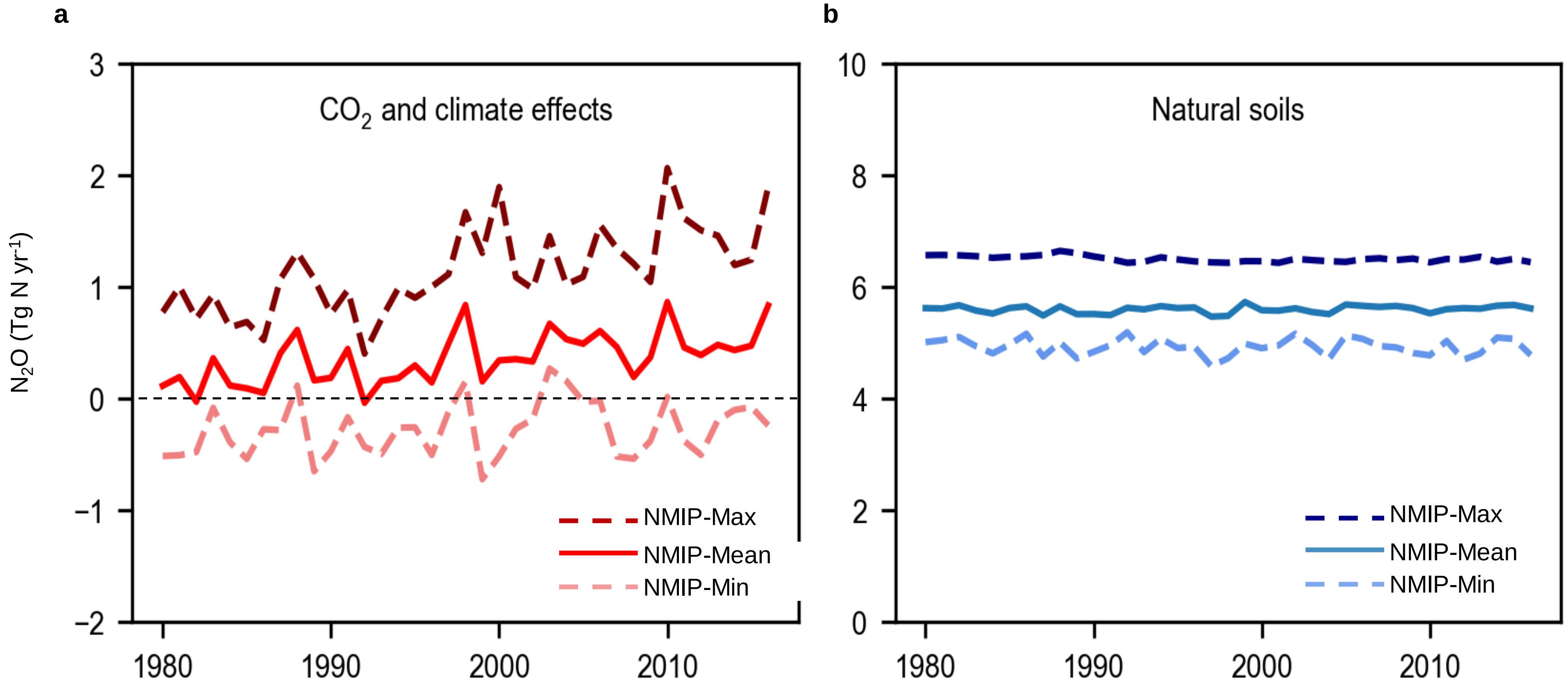
Regional trends in anthropogenic N_2O emissions



Source: Tian et al. 2020, Nature

Estimates of CO_2, climate, & soil effects

A large inter-annual N_2O variability is attributable to the effect of environmental factors (i.e., climate).

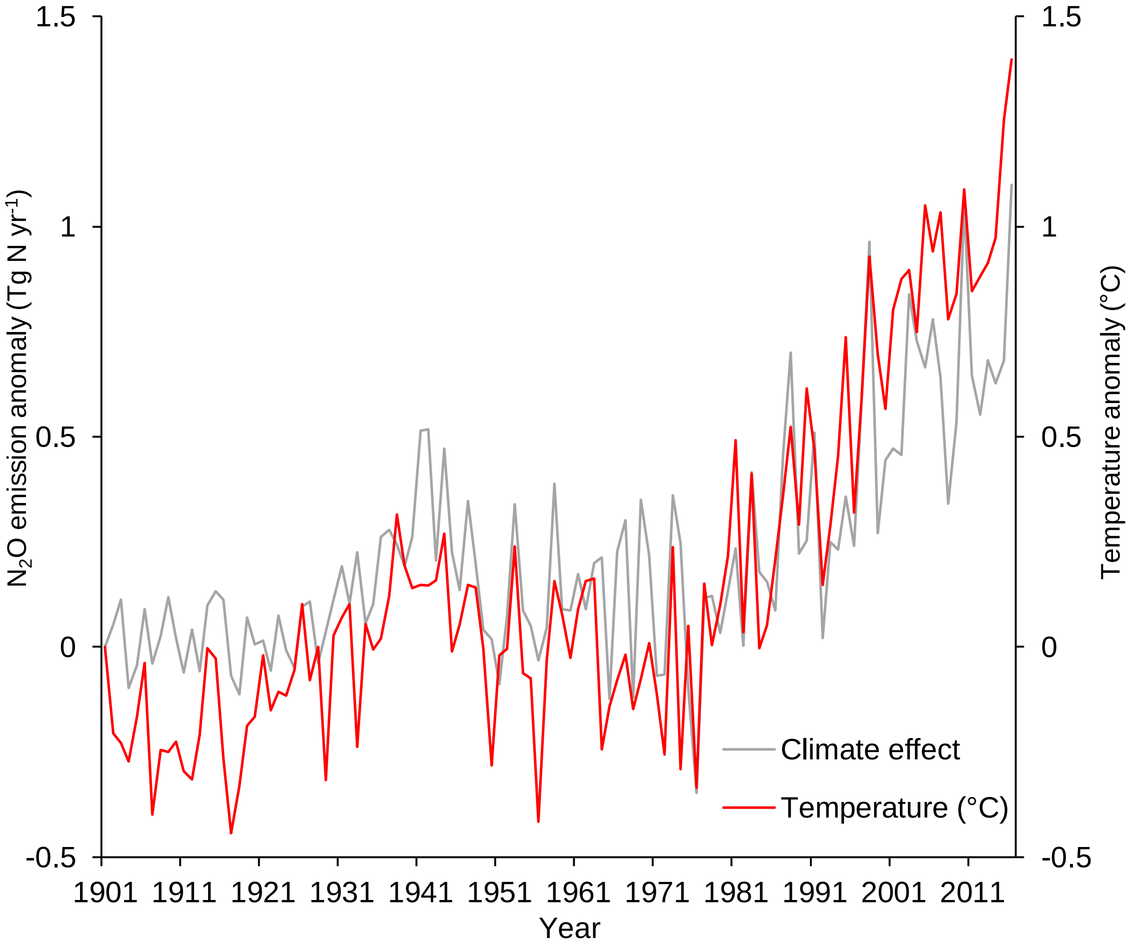


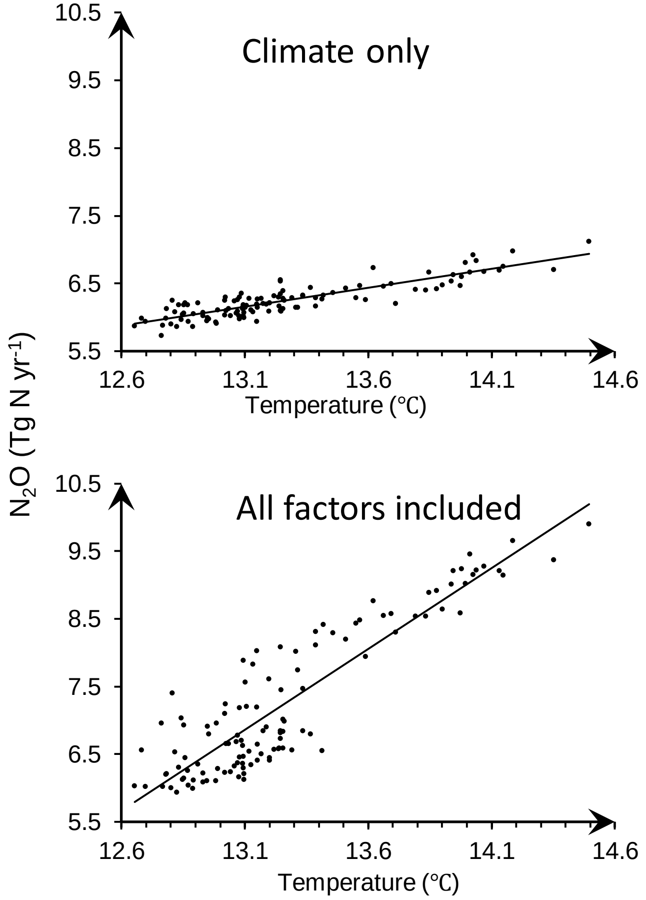
Source: Modified from Tian et al. 2020, Nature

Results from six terrestrial biosphere models (Global N_2O Model Intercomparison Project, NMIP)
a) change in global land N_2O emissions due to CO_2 and climate effects, **b**) variability in global natural soil N_2O emissions.
(Note: global natural soil N_2O emissions were defined as without consideration of land use change (e.g., deforestation) and without consideration of indirect anthropogenic effects via global change (i.e., climate, elevated CO_2, and atmospheric N deposition)

Climate effects based on terrestrial biosphere model simulations

Process-based model estimates show that soil N_2O emissions increased substantially due to climate change since the early 1980s constituting a positive nitrogen-climate feedback.



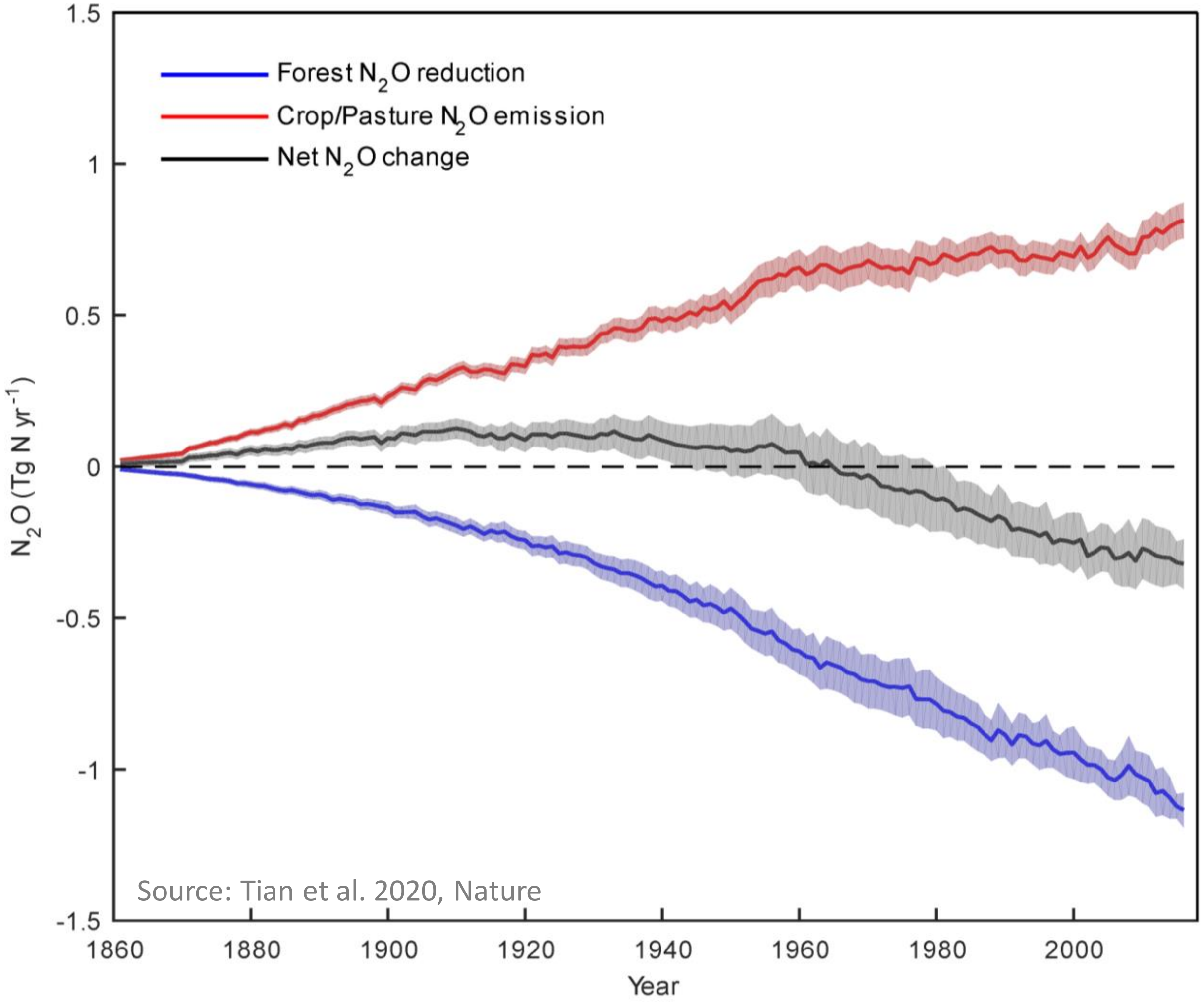


Source: Modified from Tian et al. 2020, Nature

Changes in natural N_2O emissions from global deforestation

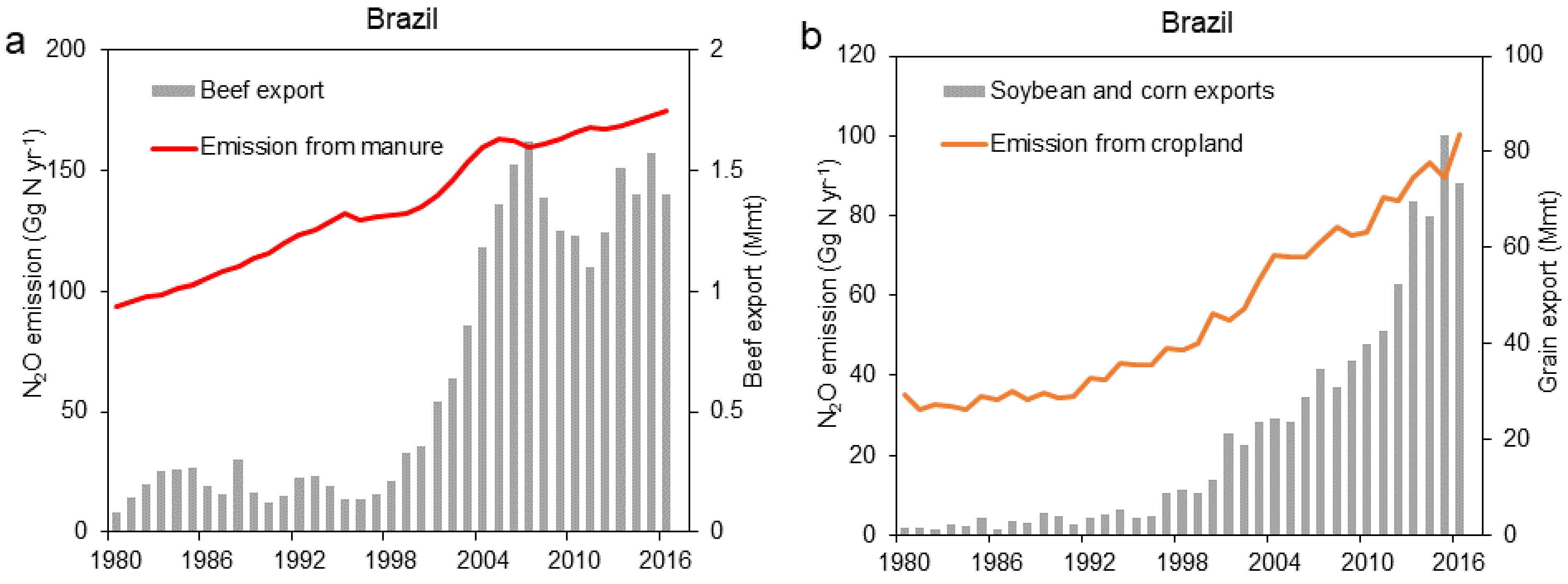
The global net effect of deforestation is first an increase and then gradually a reduction of N_2O emissions, reaching -0.34 ± 0.11 TgN/yr in 2016.

(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)



Direct soil emissions and agricultural product trades in Brazil

Agricultural N_2O emissions for Brazil increased by 120% from 1980 to 2016 due to increases in livestock and N-fertilizer use



Source: Tian et al. 2020, Nature

In (a), the red line shows the direct N_2O emissions from livestock manure based on EDGARv4.3.2, GAINS, and FAOSTAT (the sum of 'manure left on pasture' and 'manure management'). The gray columns show the amount of beef exported by Brazil. In (b), the orange line shows the direct N_2O emissions from croplands due to N-fertilization based on NMIP and SRNM. The gray columns show the amount of soybean and corn exported by Brazil.