

Fizyka Procesów Klimatycznych

Cykl węglowy, inne cykle biogeochemiczne

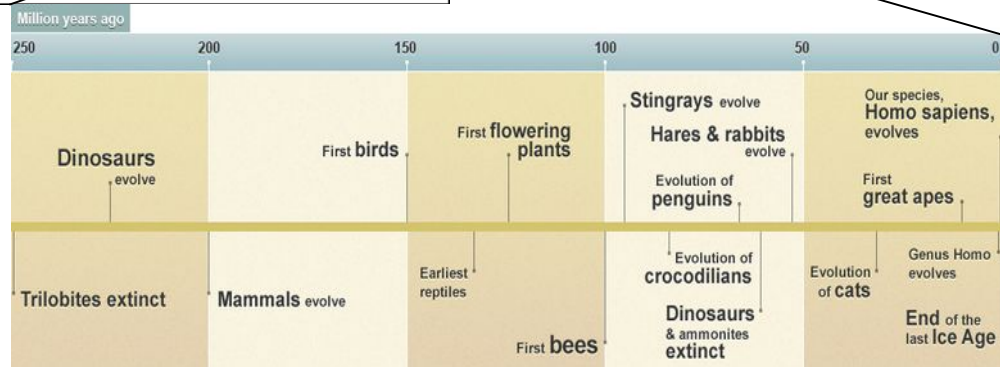
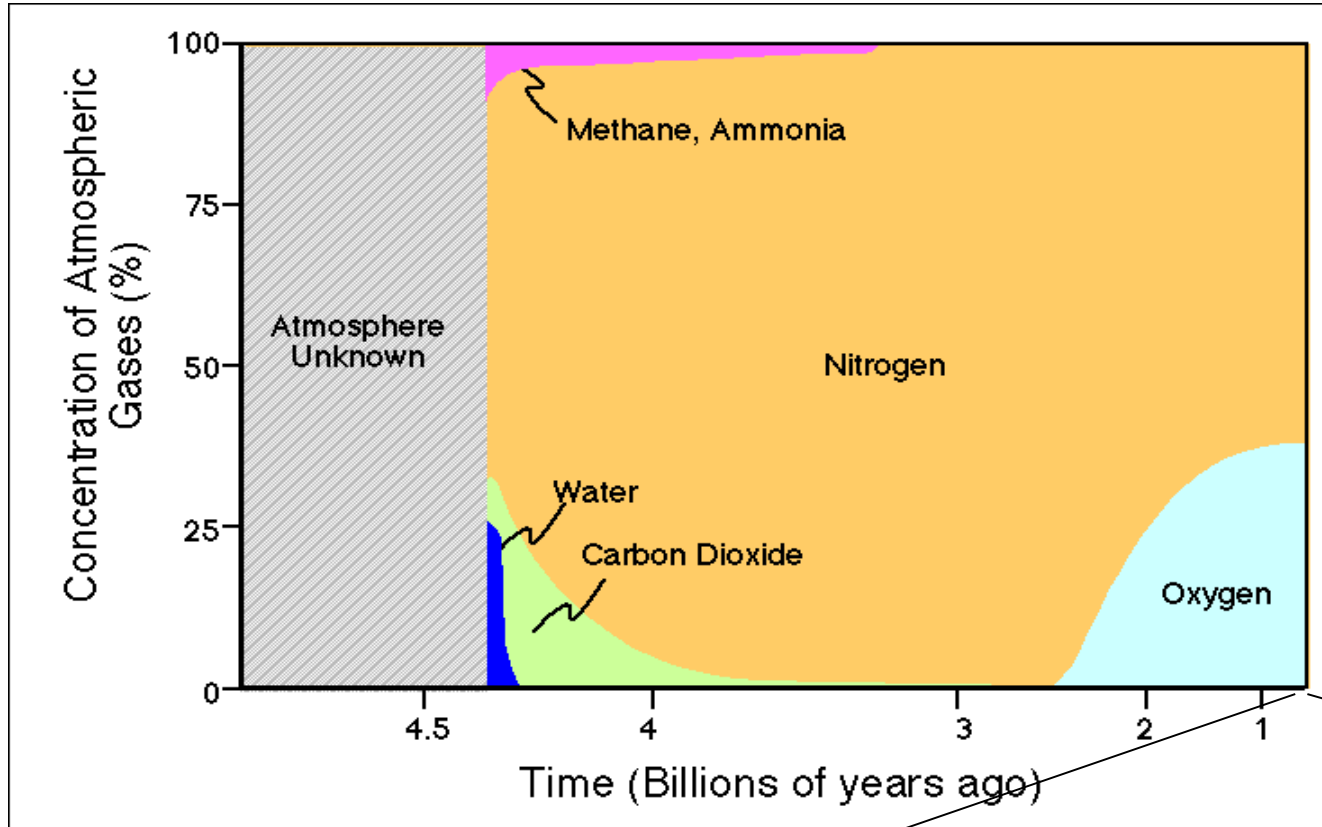
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Cykl węglowy, azotowy, zmiany w składzie atmosfery.

Skład atmosfery zmieniał się zawsze. Czy jest się czym przejmować?



Carbon (CO₂) Budget

Atmosphere
591 + 279 ± 5

Average increase 5.1 ± 0.02

Net land flux
1.9 3.4 ± 0.9

Net ocean flux
0.6 2.5 ± 0.6

111.1 Total respiration and fire 25.6

113 Gross photosynthesis 29

Ocean-atmosphere gas exchange

54.0

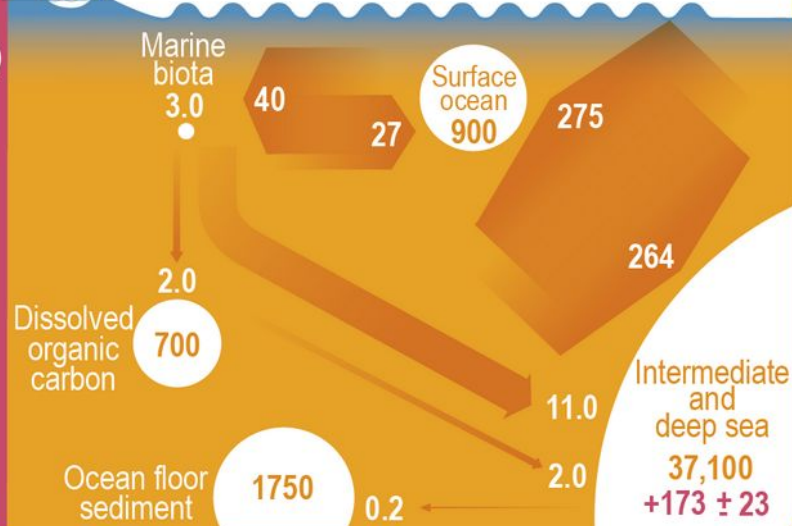
25.5

2.5

0.2

0.8

Rivers



1200

Permafrost

450

Vegetation

1700

Soils

-25

Vegetation and soils

-445

Fossil fuels

580

Coal

230

Oil

118

Gas

Reserves

3.0

2.0

40

27

700

11.0

2.0

0.2

275

264

11.0

2.0

0.2

Flux: Billion tonnes of Carbon per year (PgC/yr)



Natural



Anthropogenic

Stocks: Billion tonnes of Carbon (PgC)



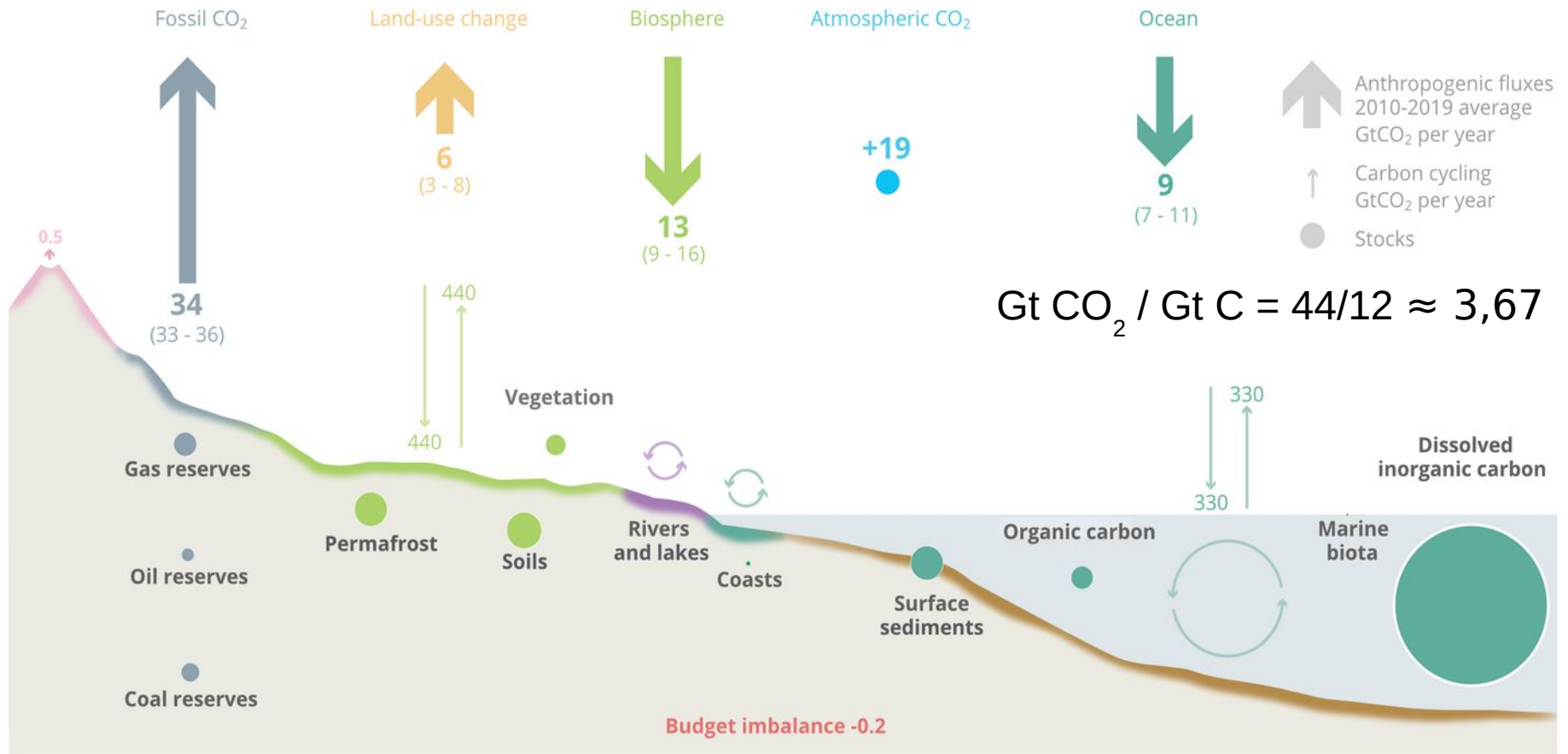
Stocks



Anthropogenic change

Anthropogenic perturbation of the global carbon cycle

Perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2010-2019 (GtCO₂/yr)



The budget imbalance is the difference between the estimated emissions and sinks.

Source: [CDIAC](#); [NOAA-ESRL](#); [Friedlingstein et al 2020](#); [Ciais et al. 2013](#);

[Global Carbon Budget 2020](#)

5 Present day volcanic carbon flux estimates

Terrestrial volcanism occurs within both the hydrosphere and atmosphere. Submarine and subaerial volcanism originate almost entirely within different tectonic environments (as outlined above), tapping different, although not entirely exclusive volatile sources, shown schematically in Figure 2, below.

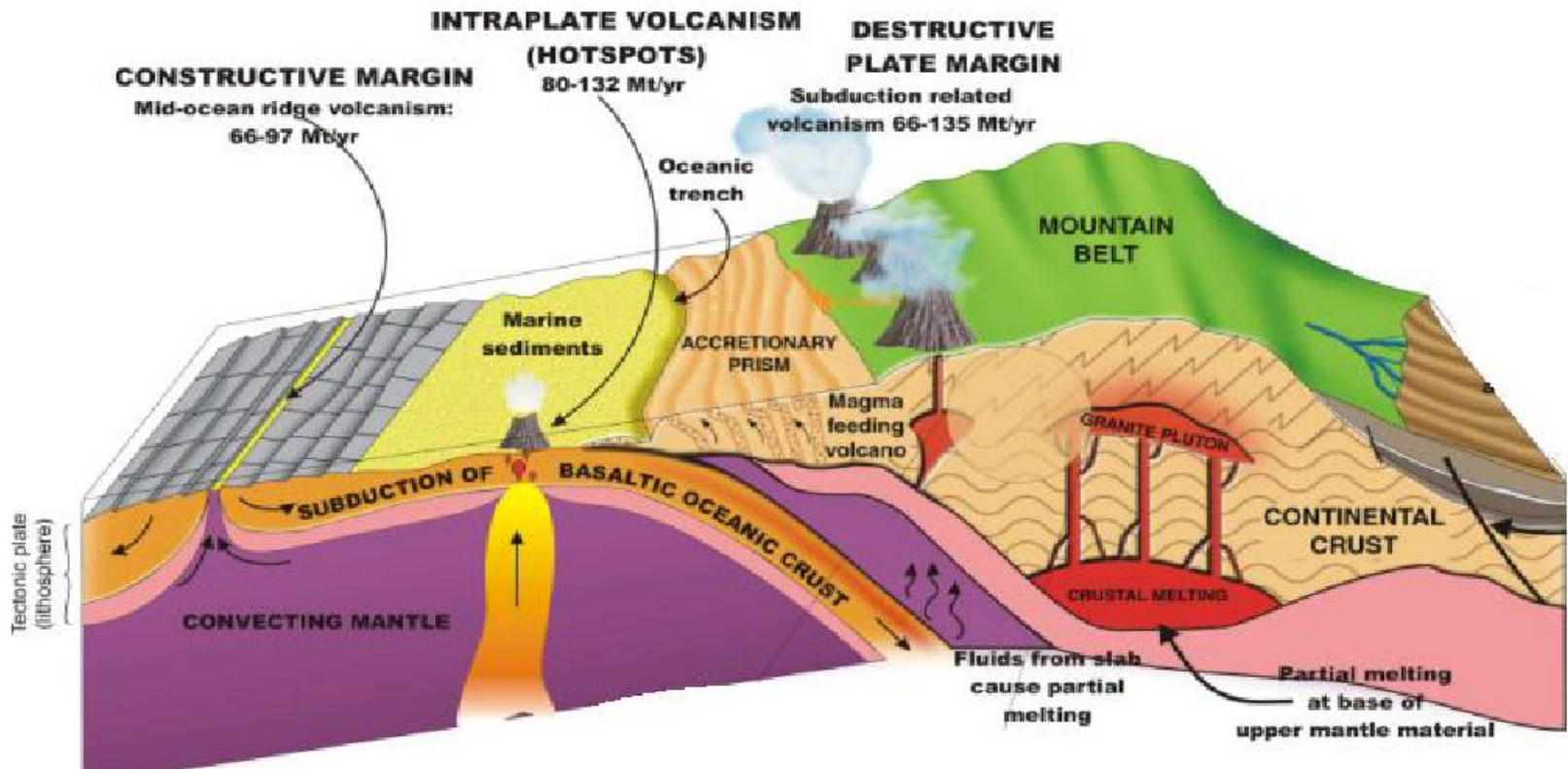
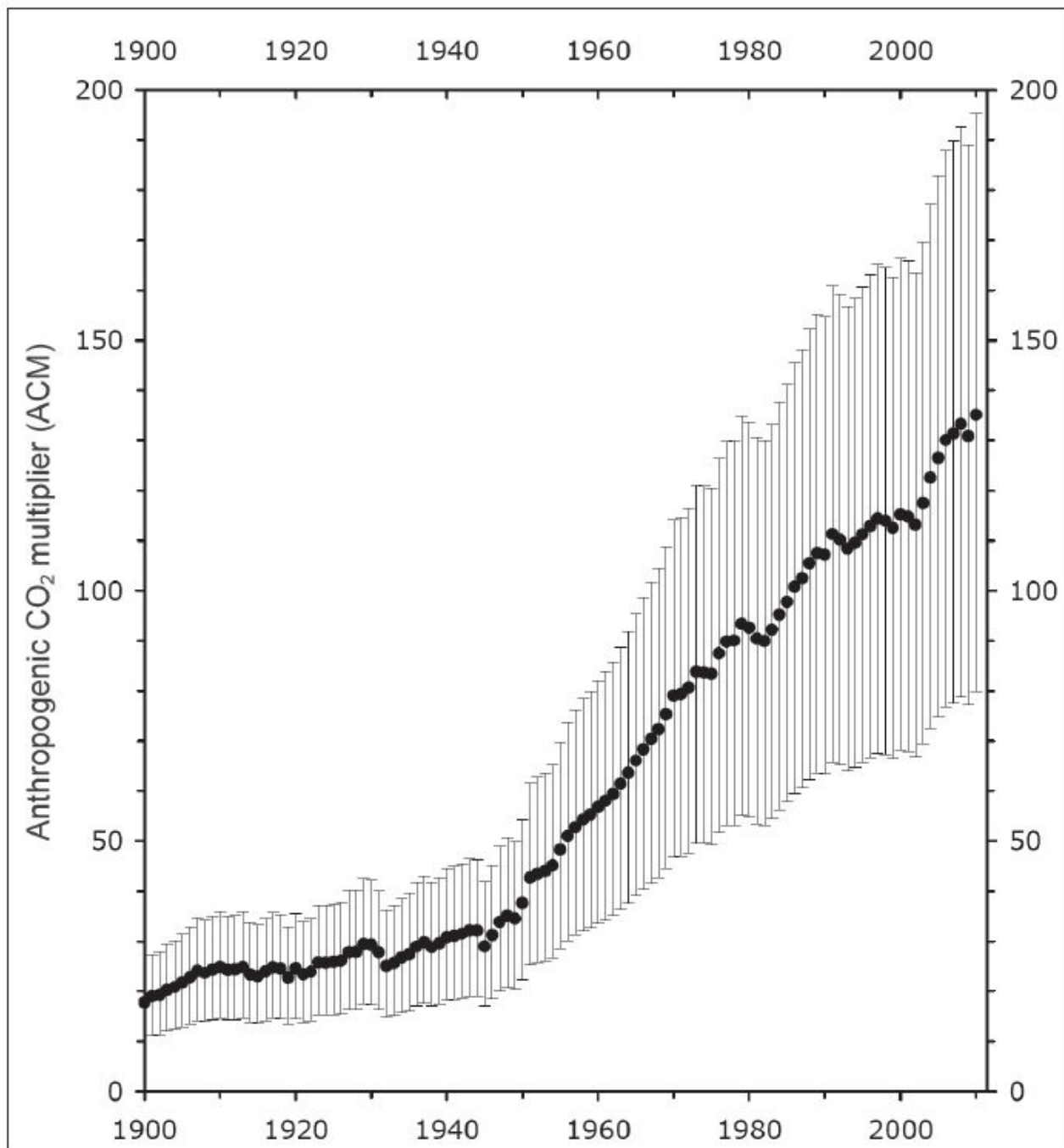


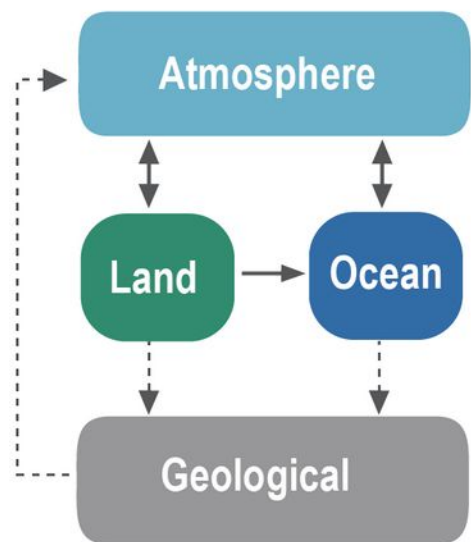
Figure 2. Diagrammatic representation of the different volcanic environments with estimates of CO₂ emission rates and their relationship to plate tectonic environment.



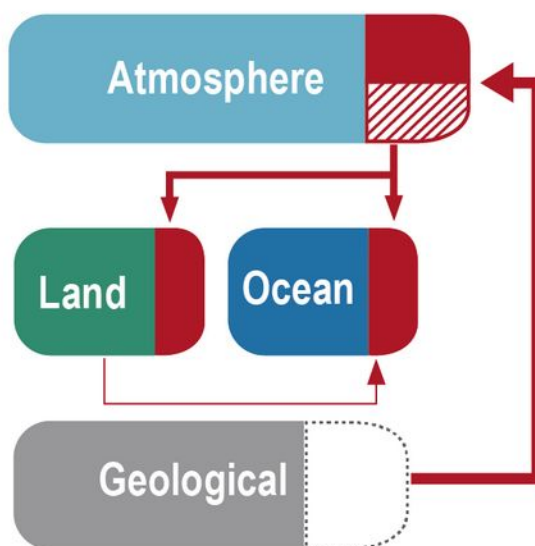
Emisje antropogeniczne CO₂ w stosunku do emisji wulkanicznych

Gerlach, T. (2011): "Volcanic Versus Anthropogenic Carbon Dioxide", EOS, Trans. AGU, 92:24, 201-208

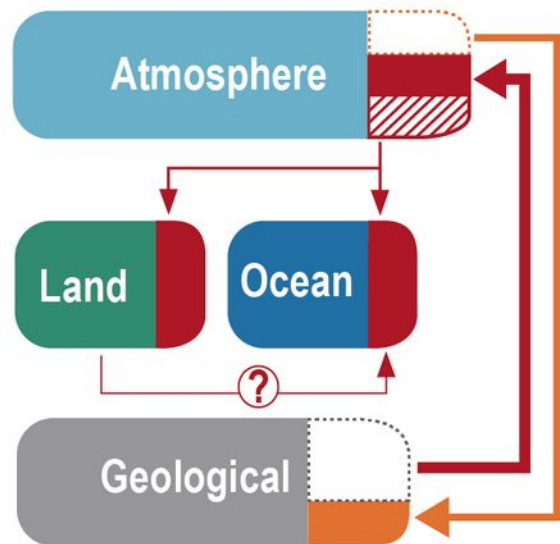
(a) Unperturbed carbon cycle fluxes



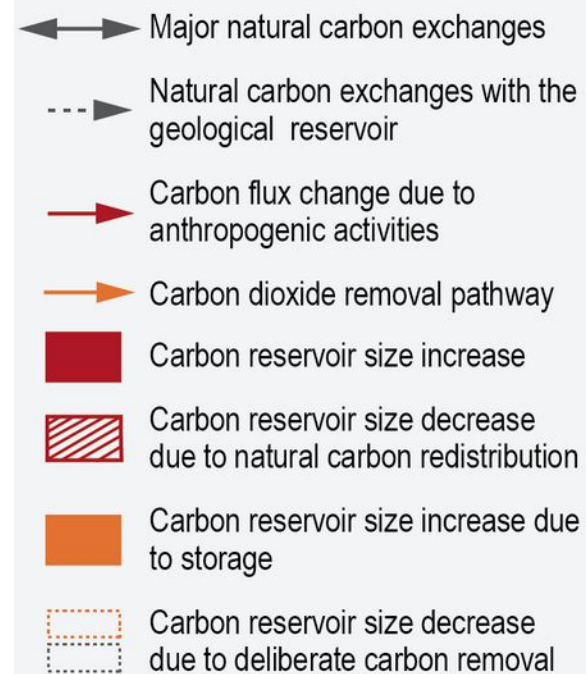
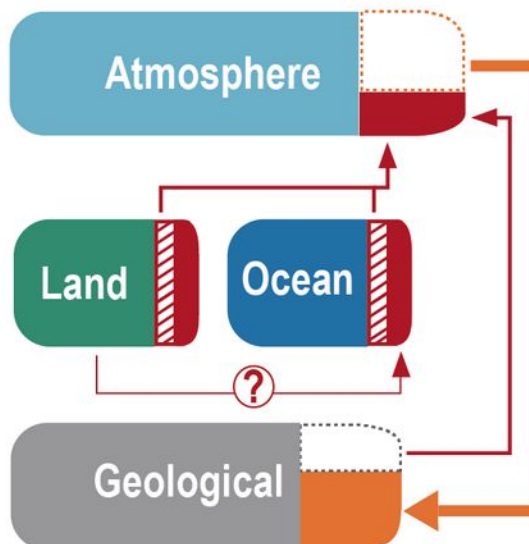
(b) Industrial era CO₂ emissions



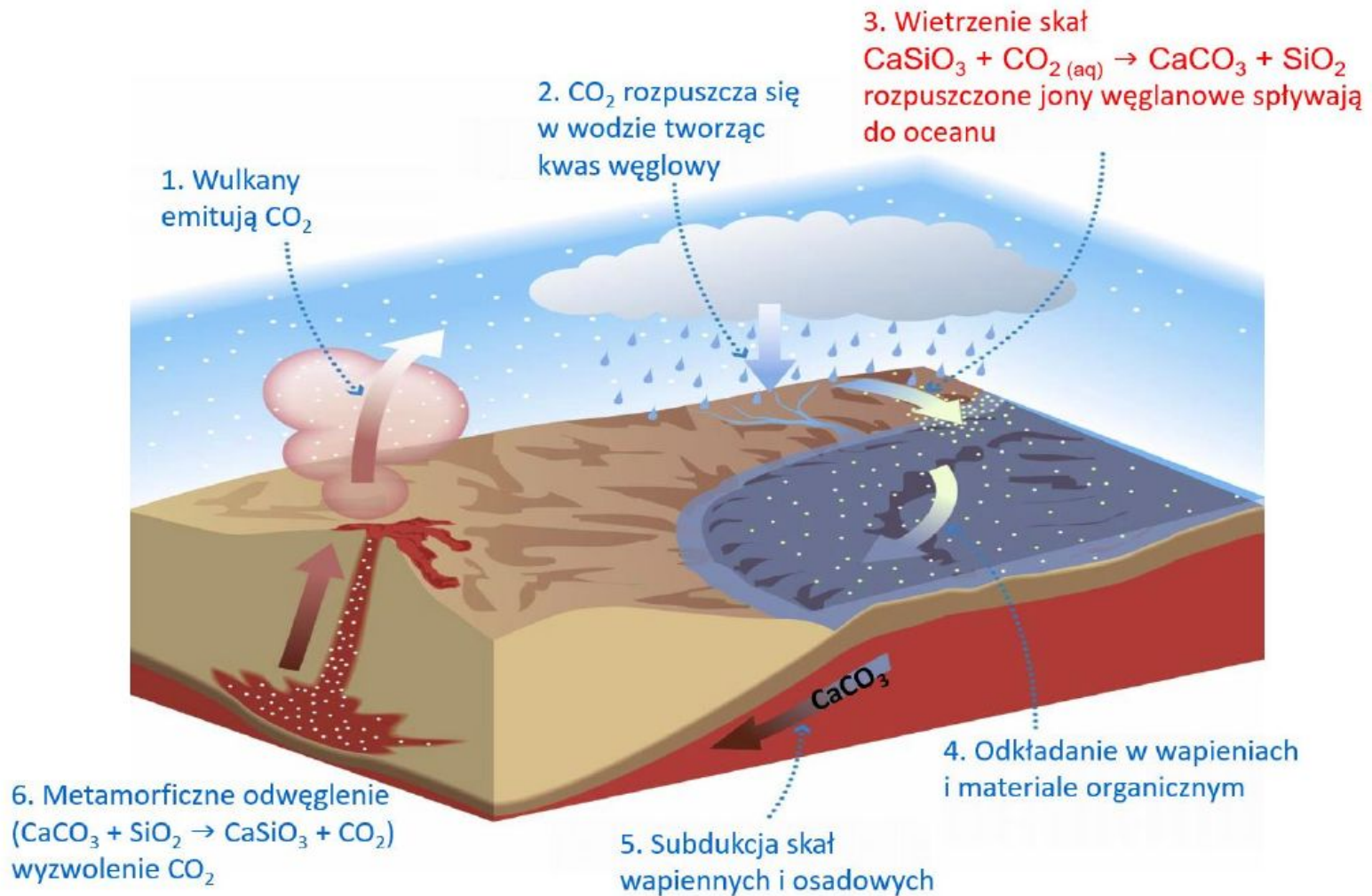
(c) Net positive CO₂ emissions with CDR



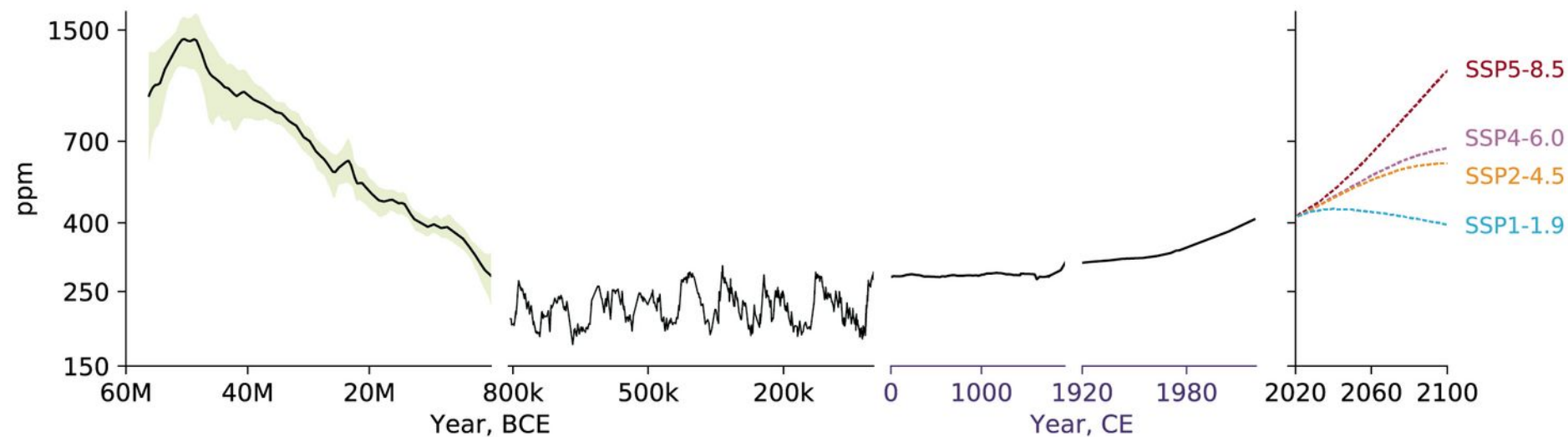
(d) Net negative CO₂ emissions



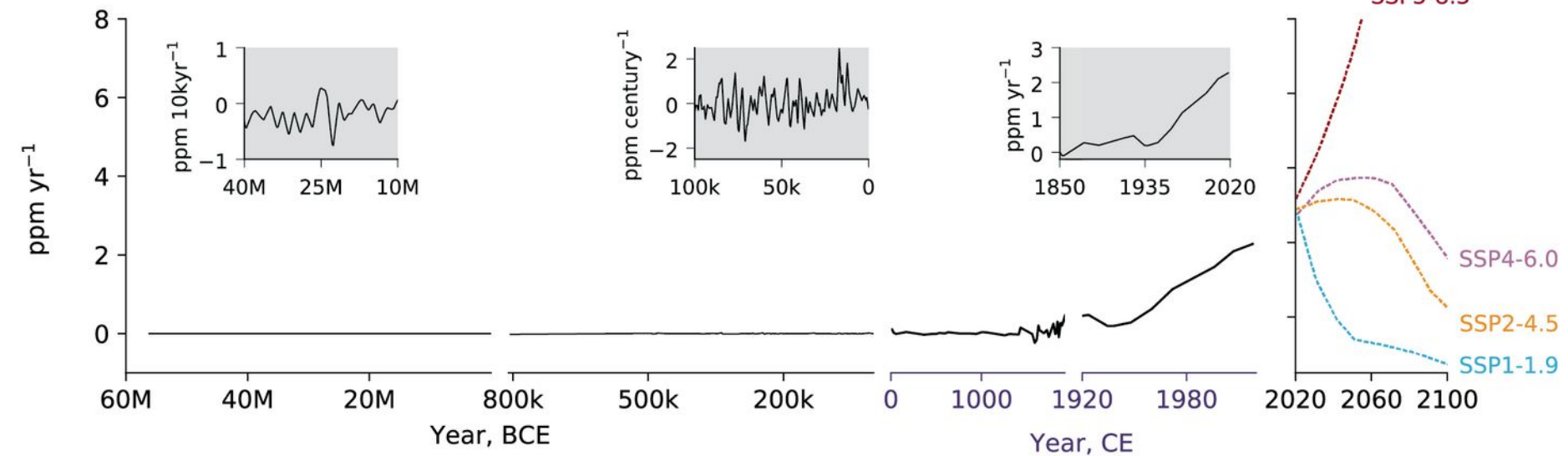
Termostat węglowy – tempo wietrzenia skał zależy od temperatury.

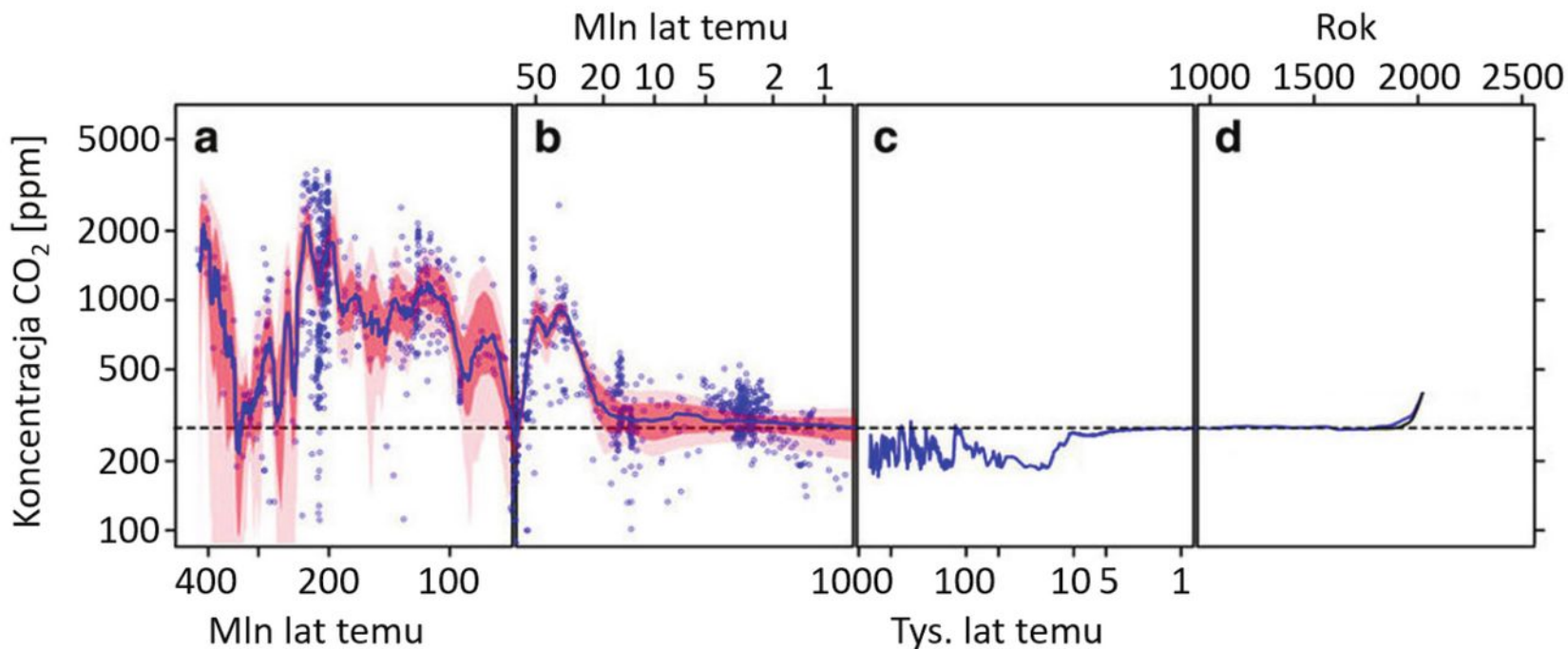


(a) Atmospheric CO₂ concentrations

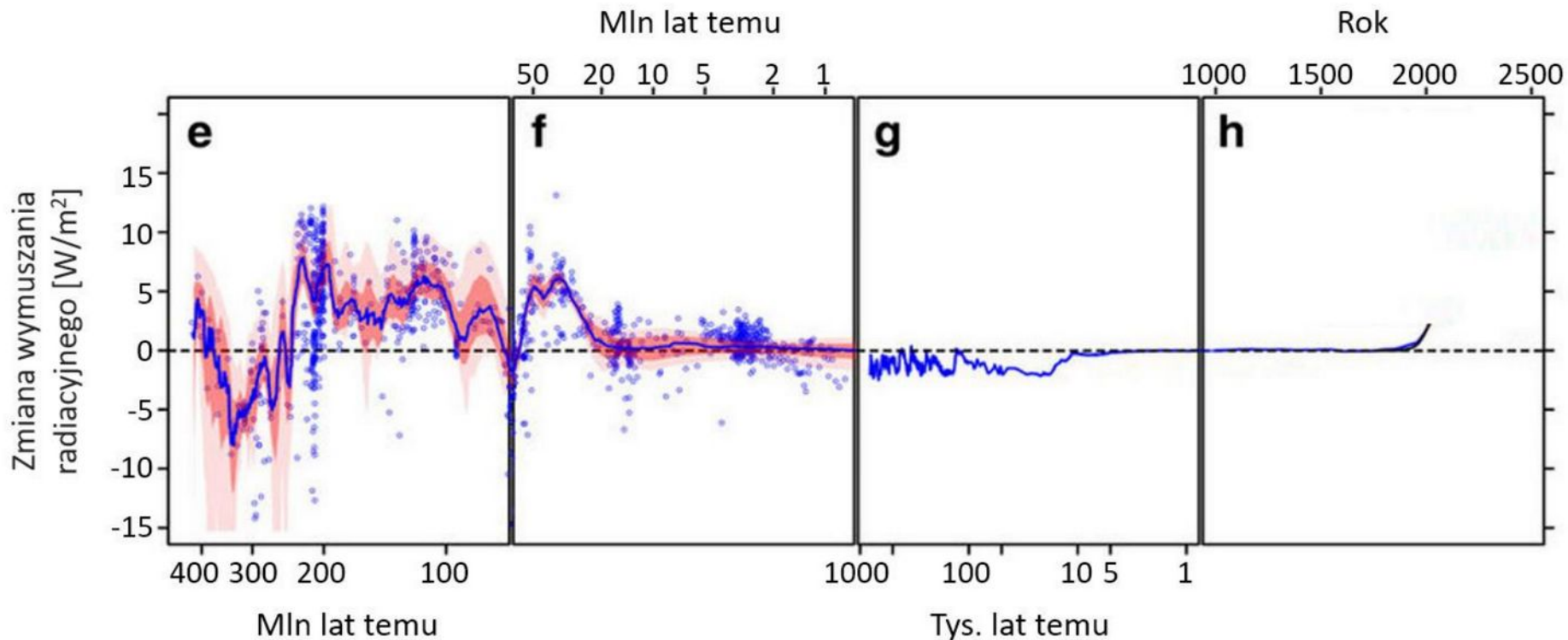


(b) Atmospheric CO₂ growth rate

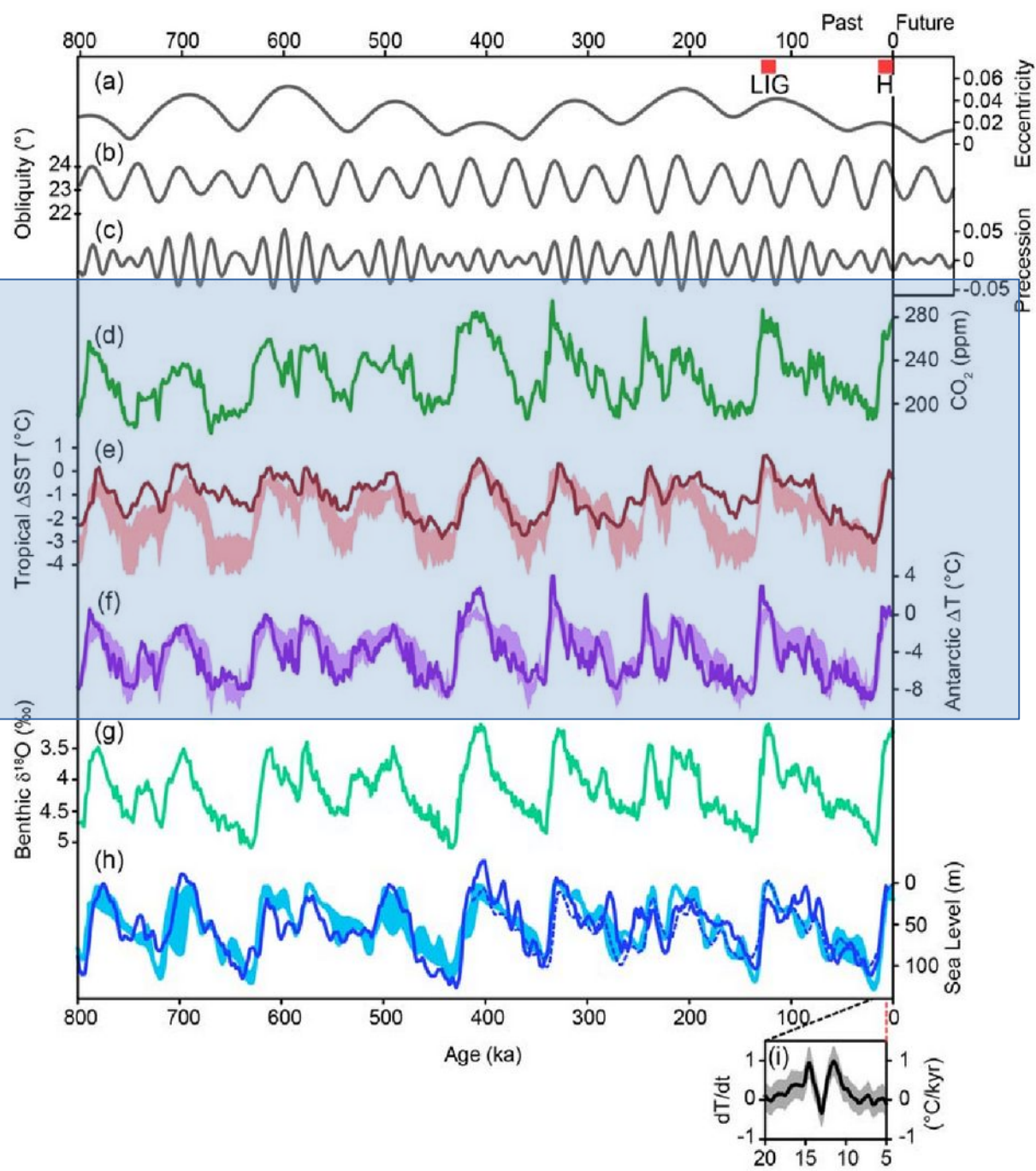




Ilustracja 1.2.11. Rekonstrukcja zmian koncentracji CO₂ w atmosferze w ostatnich 400 mln lat. UWAGA: skala czasowa nie jest liniowa. Panele a–b) na podstawie różnych wskaźników klimatycznych (niebieskie kropki odpowiadają konkretnym pomiarom, a linia – dopasowanej do nich krzywej, czerwona wstęga pokazuje zakres, w którym faktyczny przebieg zmian temperatury mieści się z prawdopodobieństwem 68%, a wstęga różowa odpowiada prawdopodobieństwu 95%, panel c) rdzenie lodowe, panel d) rdzenie lodowe i obserwacje.



Ilustracja 2.18.2. Wymuszenie radiacyjne ziemskiego systemu klimatycznego powodowane zmianami stężenia CO_2 i natężenia promieniowania słonecznego w ostatnich 420 mln lat. Czerwona obwódka pokazuje niepewność, z jaką wyznaczono wymuszenie, wynikającą z niepewności danych o stężeniach CO_2 jak na ilustracji 1.2.11 Uwaga: skala czasowa nie jest liniowa.



Rekonstrukcje paleoklimatyczne:

Czarne – wymuszenia orbitalne,
 Zielone – wymuszenia CO₂ (na podstawie rdzeni lodowych)

Czerwone – temperatura w tropikach (cienka linia – rekonstrukcje paleoklimatyczne, szerszy pas – odtworzenie w modelach klimatu).

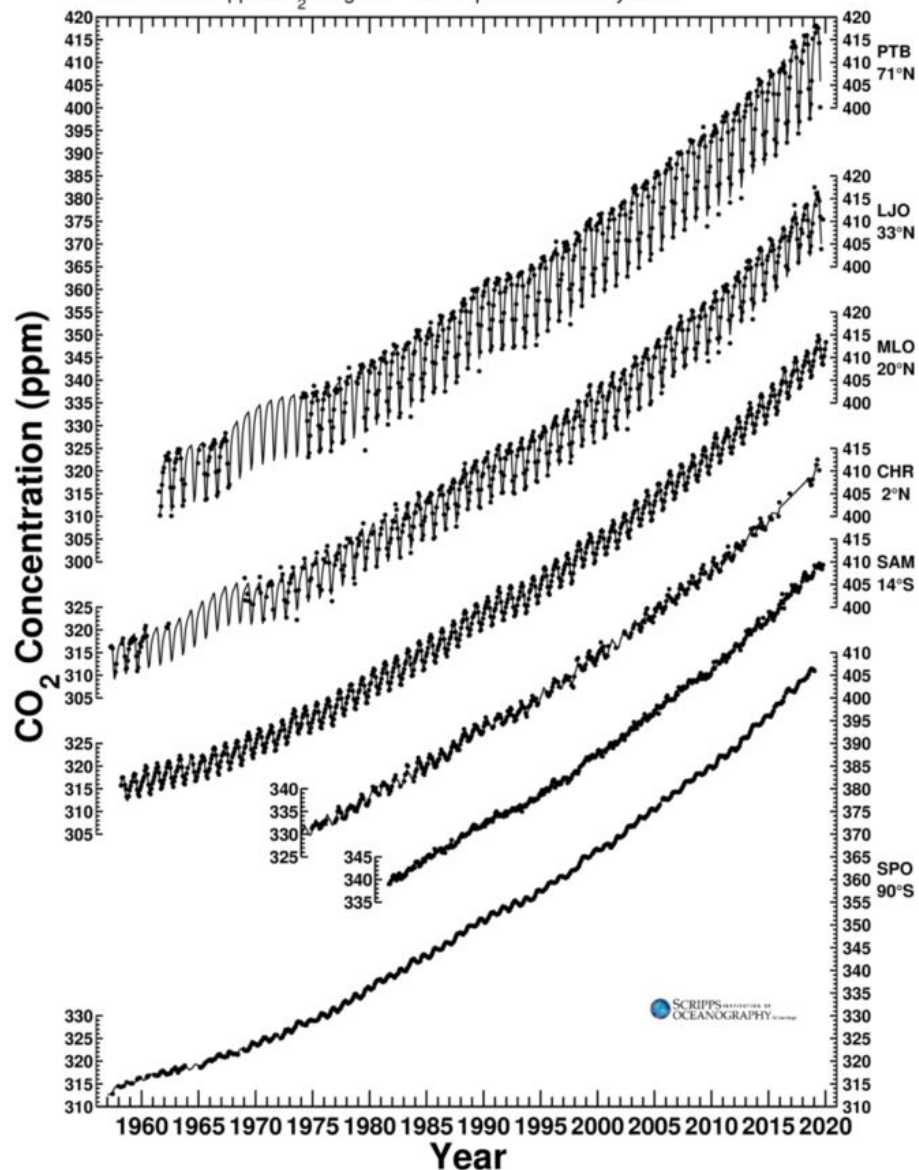
Fioletowe – temperatura Antarktydy (cienka linia – rekonstrukcje paleoklimatyczne, szerszy pas – odtworzenie w modelach klimatu).

Zielone – odwrotność masy czap lodowych (rekonstrukcja paleoklimatyczna na podstawie δ¹⁸O w osadach dennych)

Niebieskie – poziom morza (cienka linia – rekonstrukcje paleoklimatyczne, szerszy pas – odtworzenie w modelach klimatu).

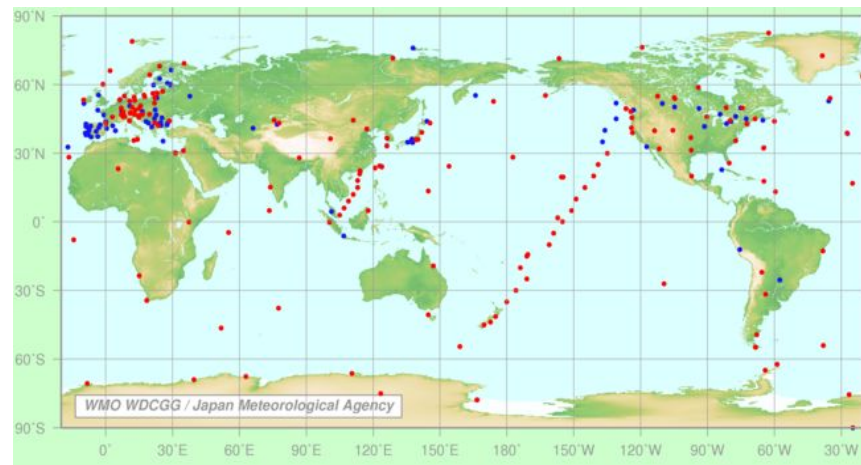
Global Stations Carbon Dioxide Concentration Trends

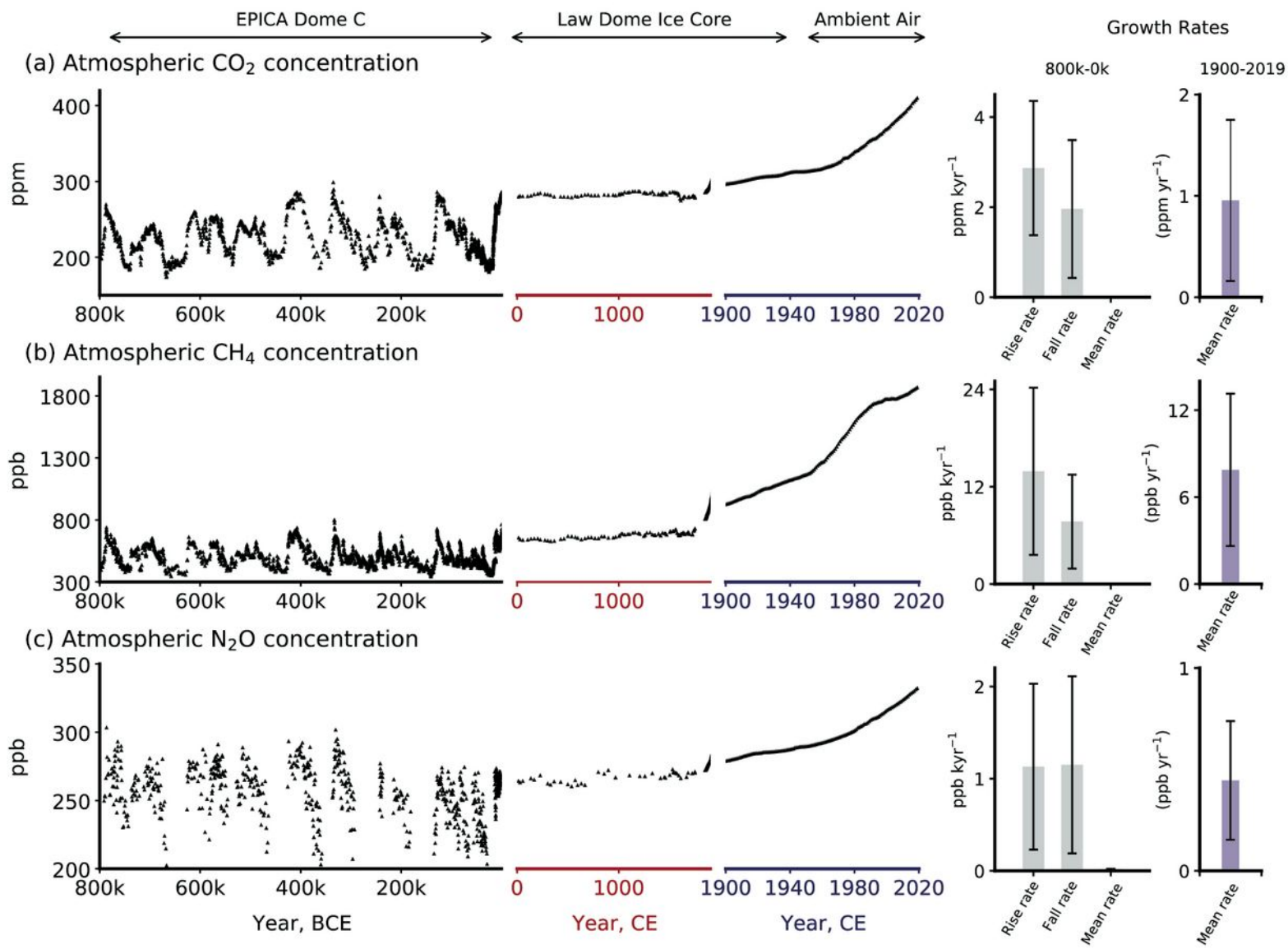
Data from Scripps CO₂ Program Last updated February 2020



Regularne pomiary CO₂ i innych gazów atmosferycznych są zbierane w WMO World Data Centre for Greenhouse Gases (WDCGG)

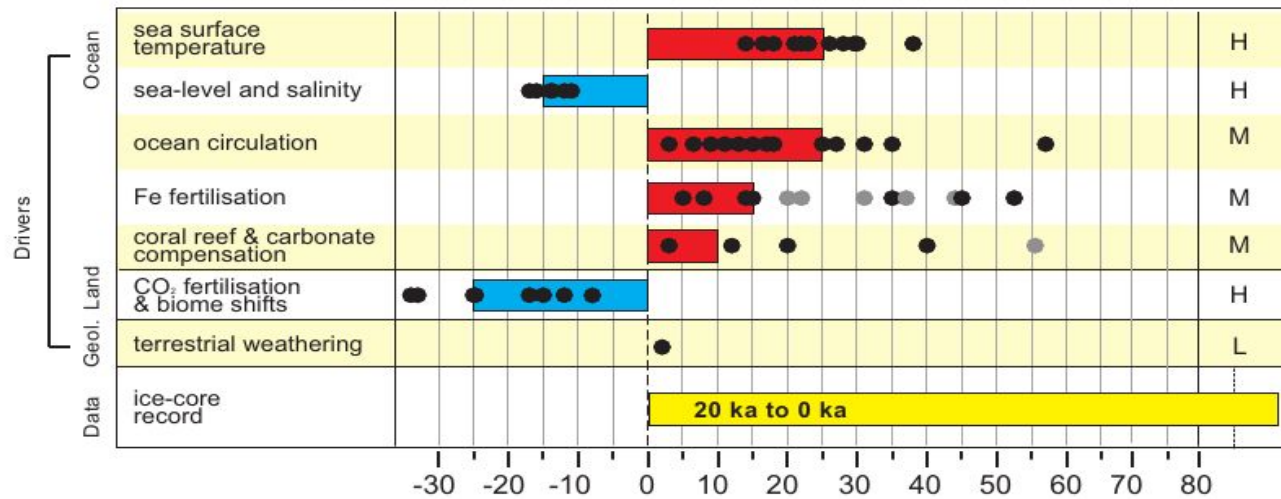
<http://ds.data.jma.go.jp/gmd/wdogg/>



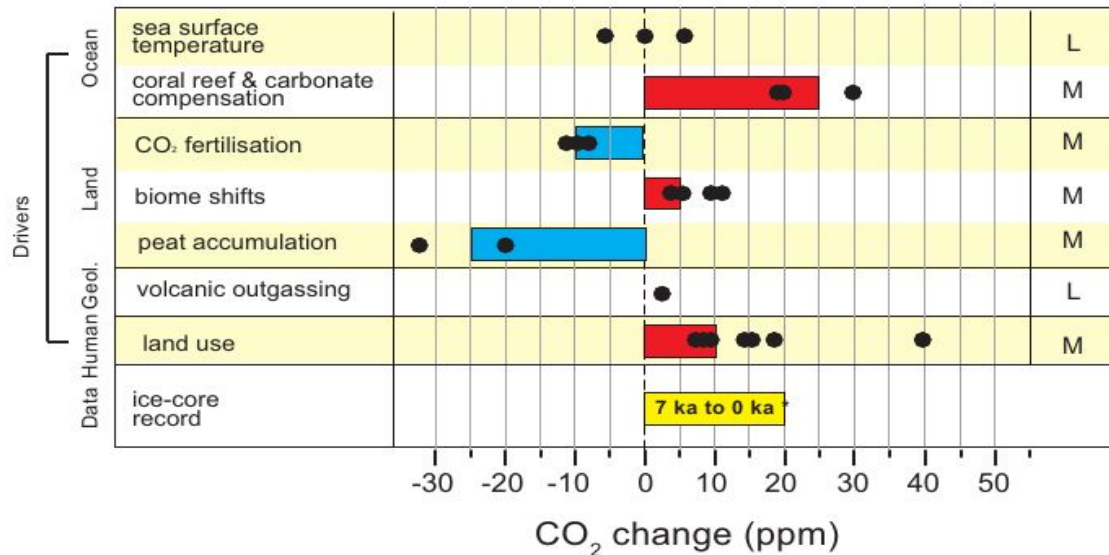


Zmiany w koncentracji atmosferycznych CO₂, CH₄ i N₂O .

Glacial to Interglacial



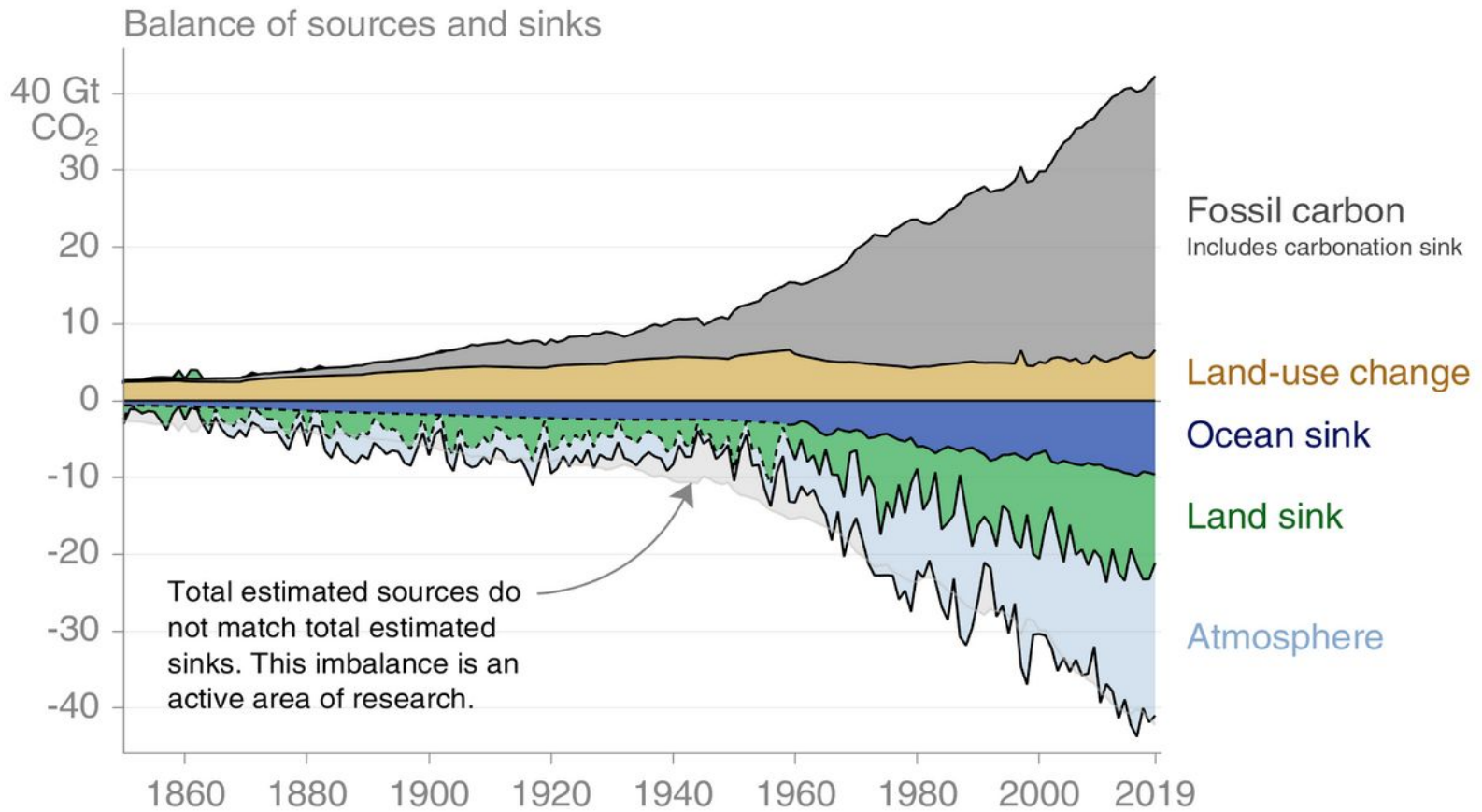
Holocene



Czynniki odpowiedzialne za naturalne zmiany koncentracji CO₂ w atmosferze:
 górny panel – od poprzedniego maksimum lodowego do Holocenu
 dolny panel: w Holocenie.

Global carbon budget

Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean
 The “imbalance” between total emissions and total sinks is an active area of research

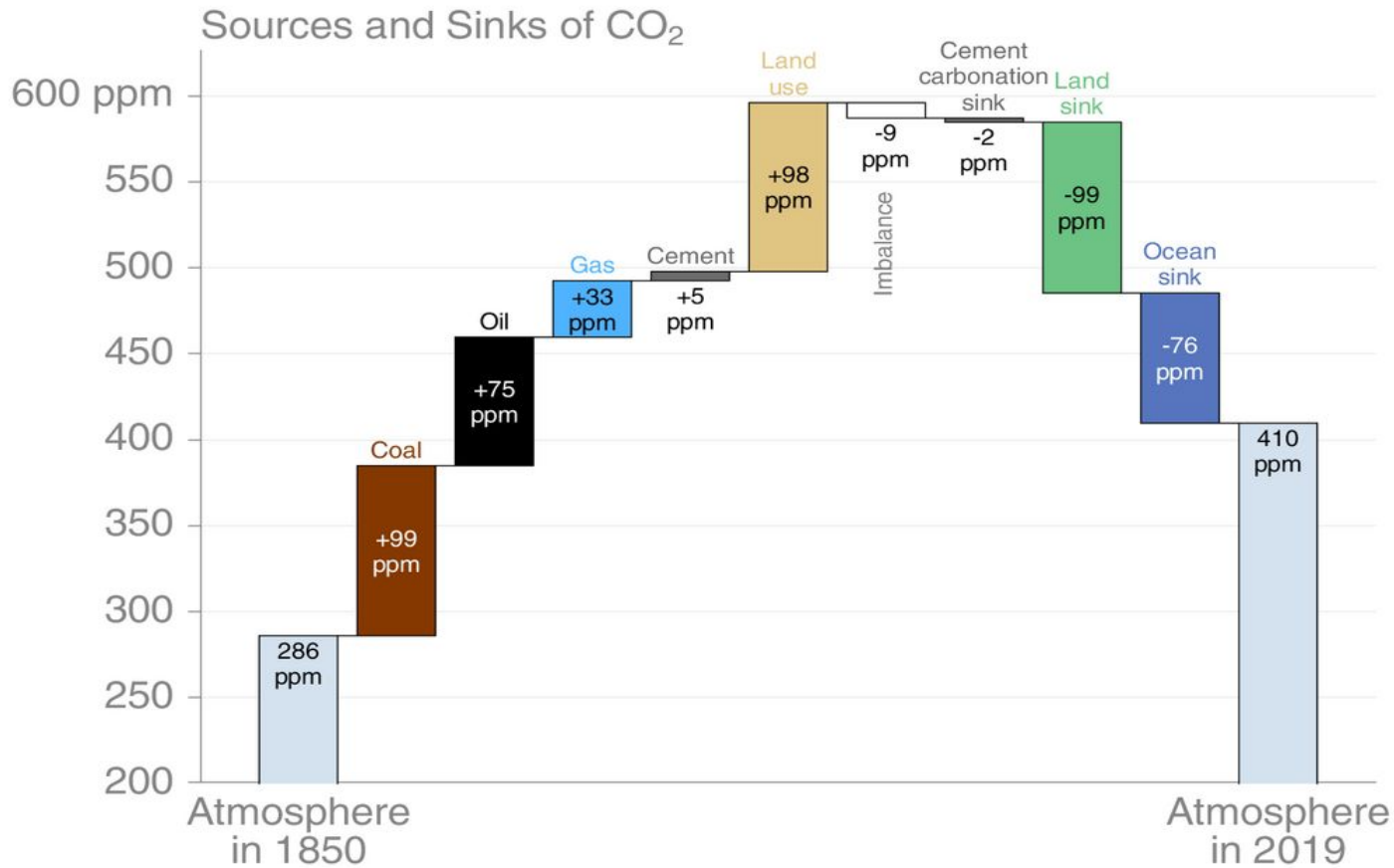


© Global Carbon Project • Data: GCP/CDIAC/NOAA-ESRL/UNFCCC

Source: [Friedlingstein et al 2020](#); [Global Carbon Budget 2020](#)

Global carbon budget

The cumulative contributions to the global carbon budget from 1850
 The carbon imbalance represents the gap in our current understanding of sources & sinks

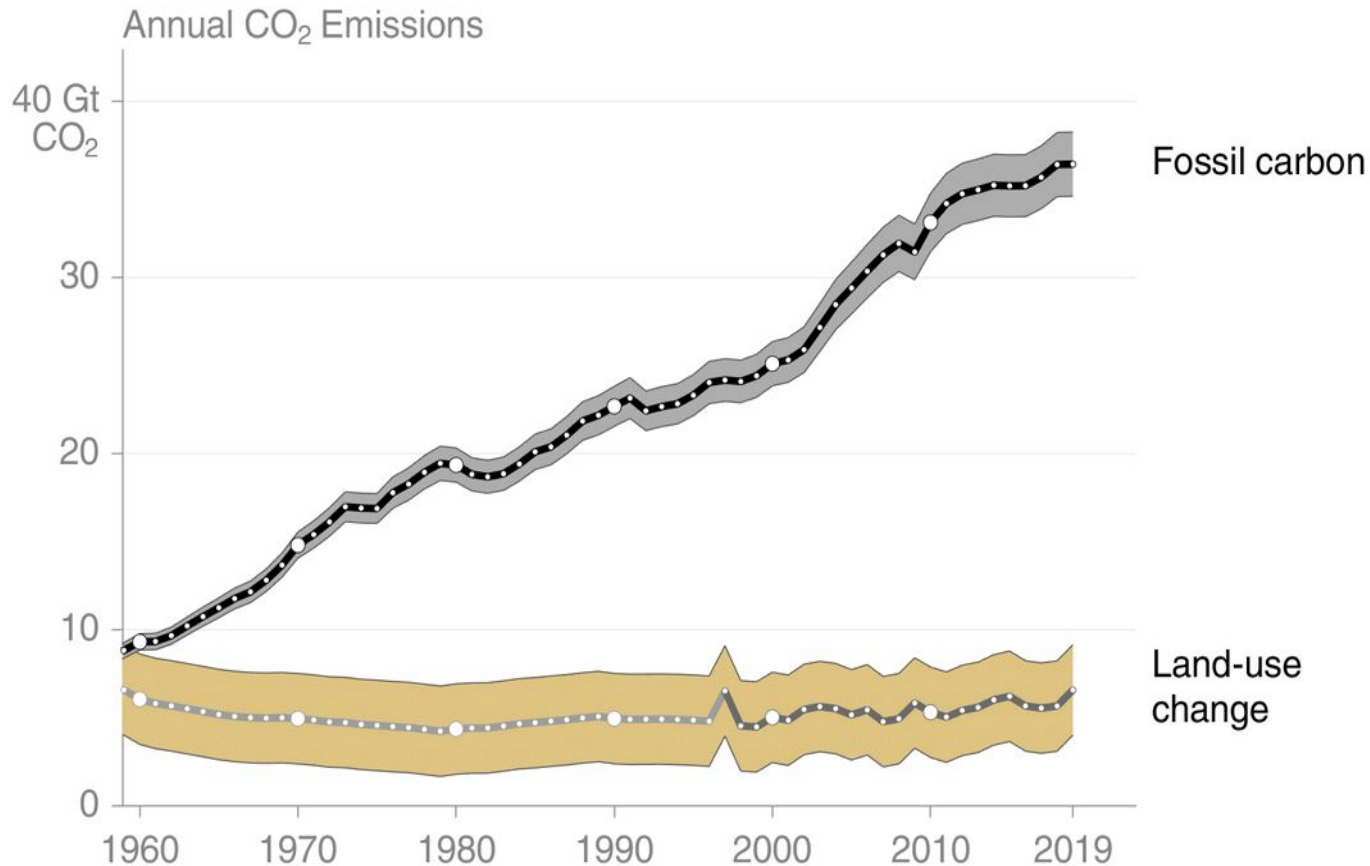


© Global Carbon Project • Data: GCP/CDIAC/NOAA-ESRL/UNFCCC

Source: [Friedlingstein et al 2020](#); [Global Carbon Budget 2020](#)

Total global emissions

Total global emissions: 43.0 ± 3.3 GtCO₂ in 2019, 56% over 1990
 Percentage land-use change: 39% in 1960, 14% averaged 2010–2019



Fossil carbon



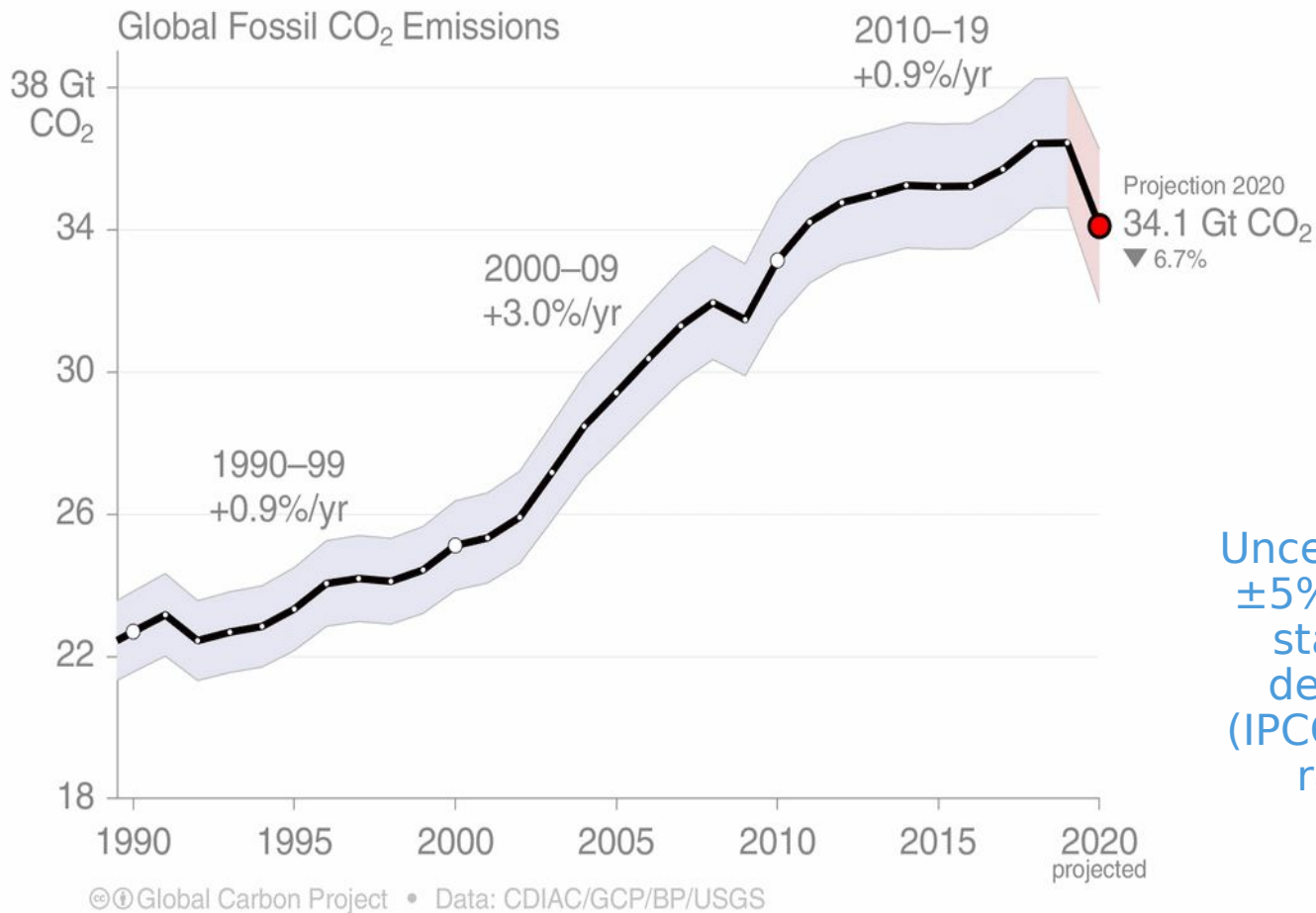
Land-use change

© Global Carbon Project • Data: CDIAC/UNFCCC/BP/USGS/GCP

Land-use change estimates from three bookkeeping models, using fire-based variability from 1997
 Source: [CDIAC](#); [Houghton and Nassikas 2017](#); [Hansis et al 2015](#); [Gasser et al 2020](#);
[van der Werf et al. 2017](#);
[Friedlingstein et al 2020](#); [Global Carbon Budget 2020](#)

Global Fossil CO₂ Emissions

Global fossil CO₂ emissions: 36.4 ± 2 GtCO₂ in 2019, 61% over 1990
 Projection for 2020: 34.1 ± 2 GtCO₂, about 7% lower than 2019



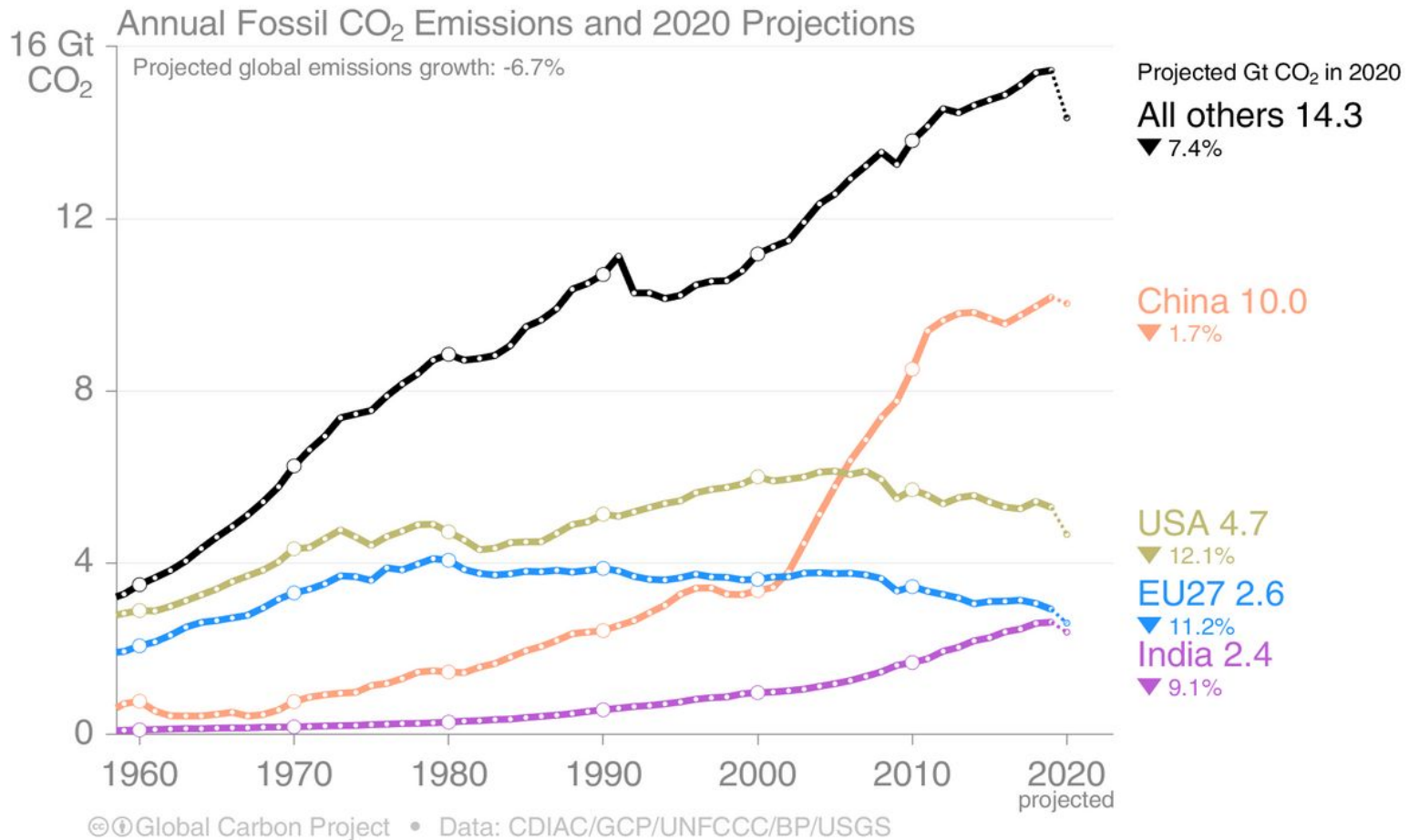
Uncertainty is
 ±5% for one
 standard
 deviation
 (IPCC “likely”
 range)

The 2020 projection is based on preliminary data and modelling, and is the median of the four studies.

Source: [CDIAC](#); [Friedlingstein et al 2020](#); [Global Carbon Budget 2020](#)

Emissions Projections for 2020

Global fossil CO₂ emissions are projected to decline by about 7% in 2020
Based on the median of four different estimates

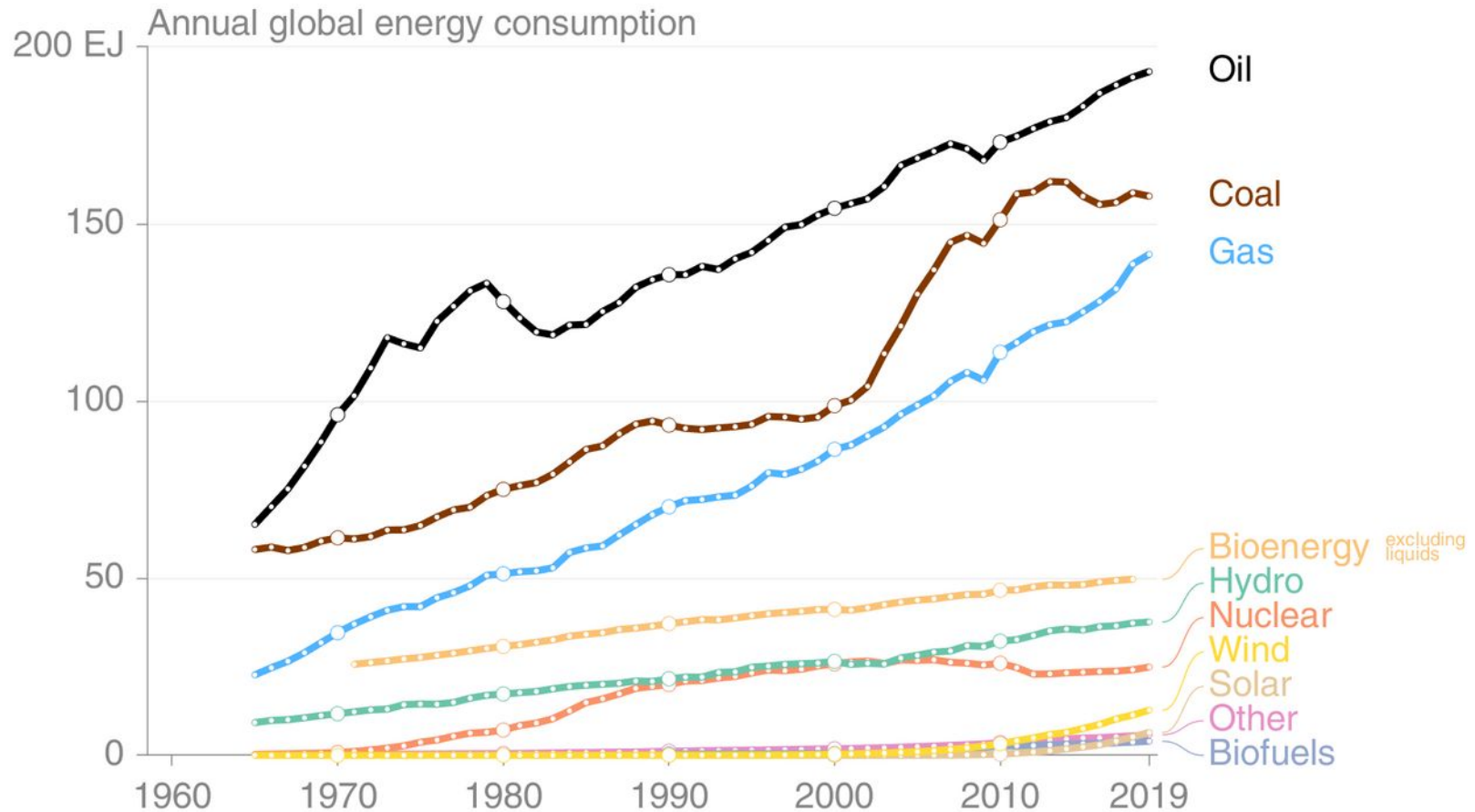


The 2020 projections are based on preliminary data and modelling, and is the median of the four studies.

Source: [CDIAC](#); [Friedlingstein et al 2020](#); [Global Carbon Budget 2020](#)

Energy use by source

Renewable energy is growing exponentially, but this growth has so far been too low to offset the growth in fossil energy consumption.



© Global Carbon Project • Data: BP, IEA (bioenergy)

This figure shows “primary energy” using the BP substitution method (non-fossil sources are scaled up by an assumed fossil efficiency of 0.38)

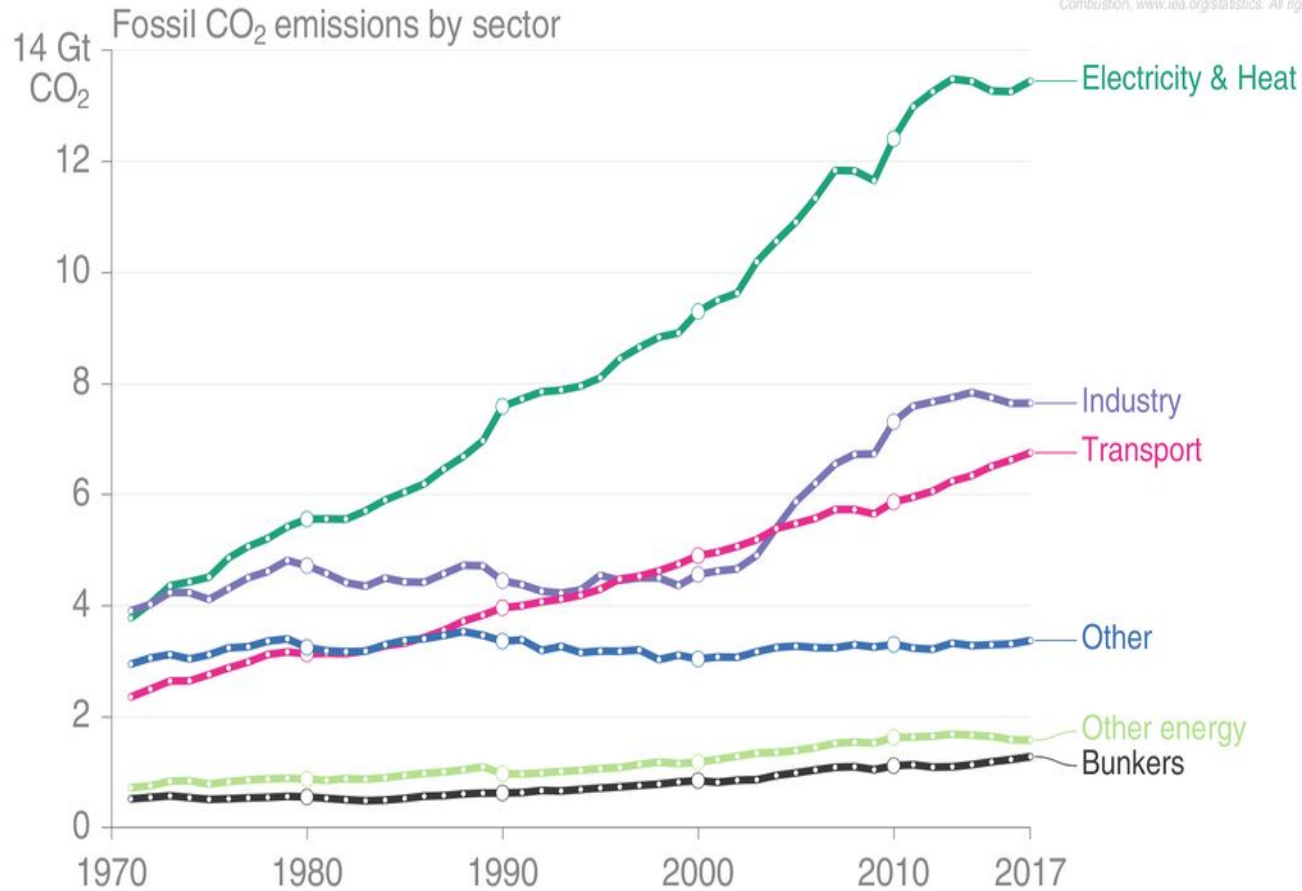
Source: [BP 2020](#); [Global Carbon Budget 2020](#)

Fossil CO₂ Emissions by Sector

Global fossil CO₂ emissions are dominated by electricity, heat, & energy (45%), industry (23%), & national transport (19%).

International aviation and marine bunkers are 3.5% & remaining sectors 10%.

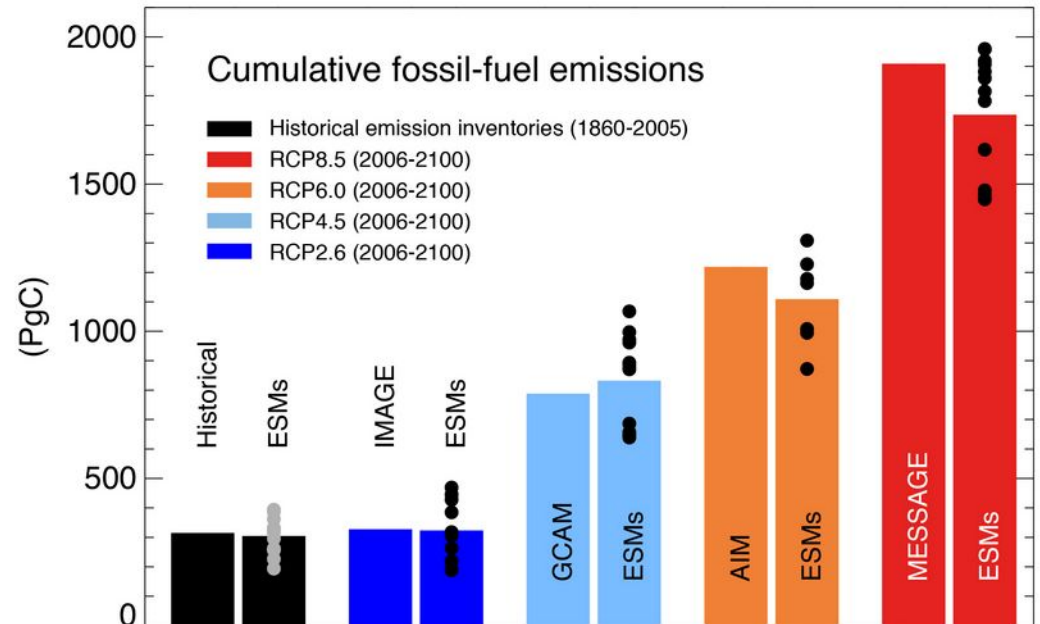
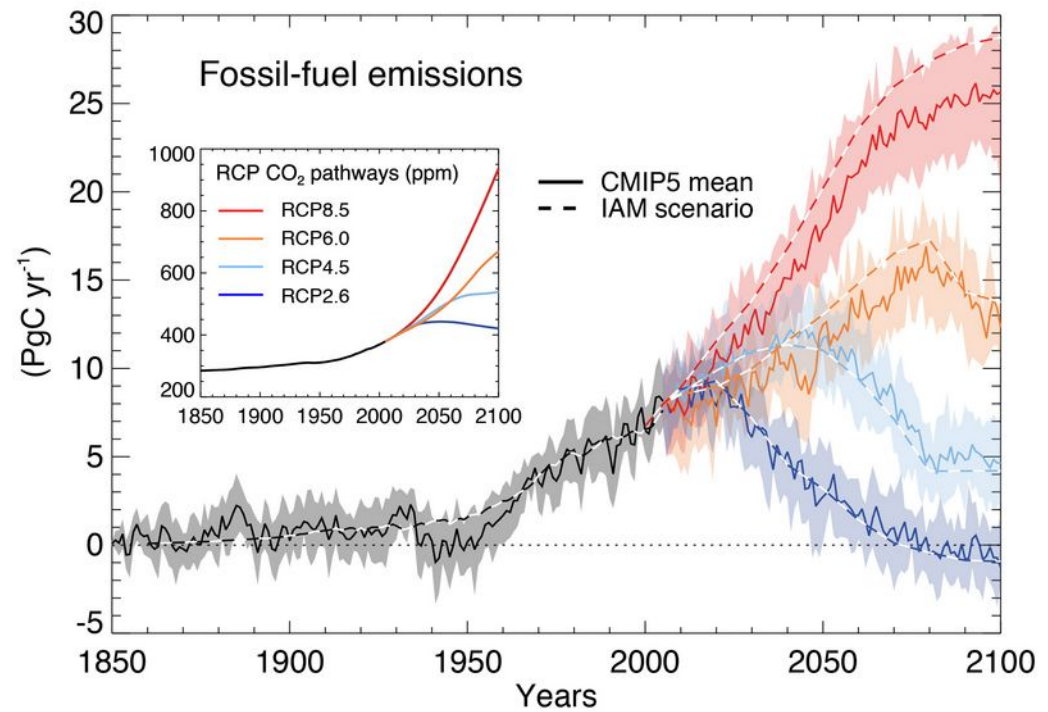
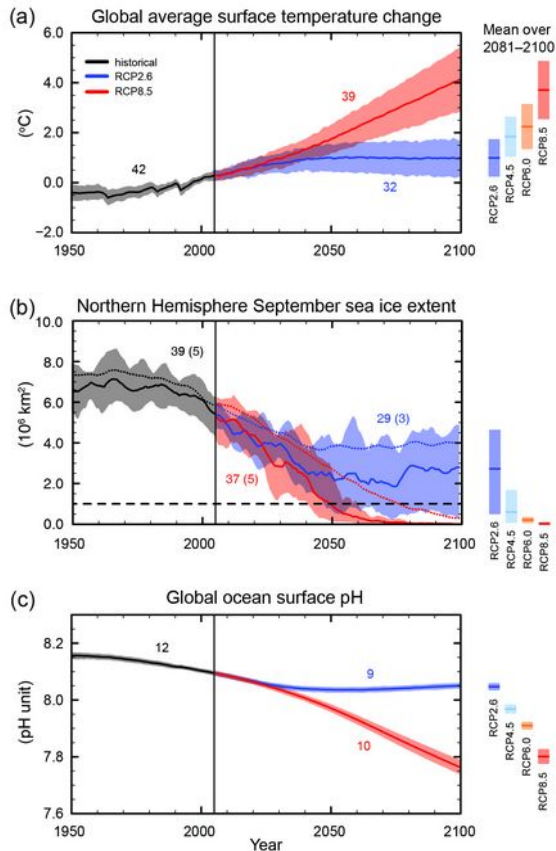
Based on IEA data from the IEA (2019) CO₂ Emissions from Fuel Combustion, www.iea.org/statistics. All rights reserved.



© Global Carbon Project • Data: IEA (2019), Andrew (2019)

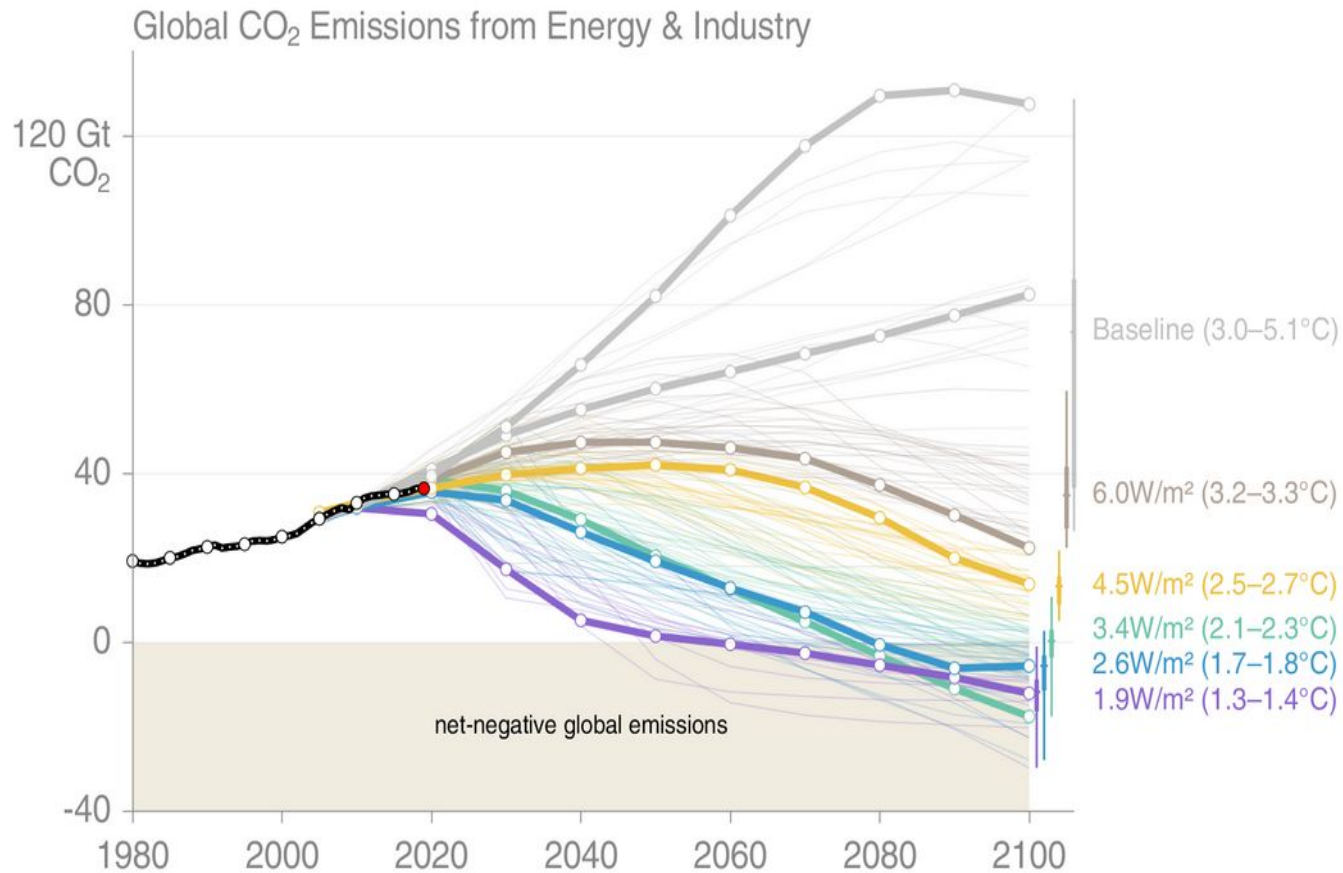
Przyszłe emisje z paliw kopalnych według różnych scenariuszy w modelach klimatu: rozkład w czasie w wartości skumulowane.

RCP – Representative Concentration Pathways



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.



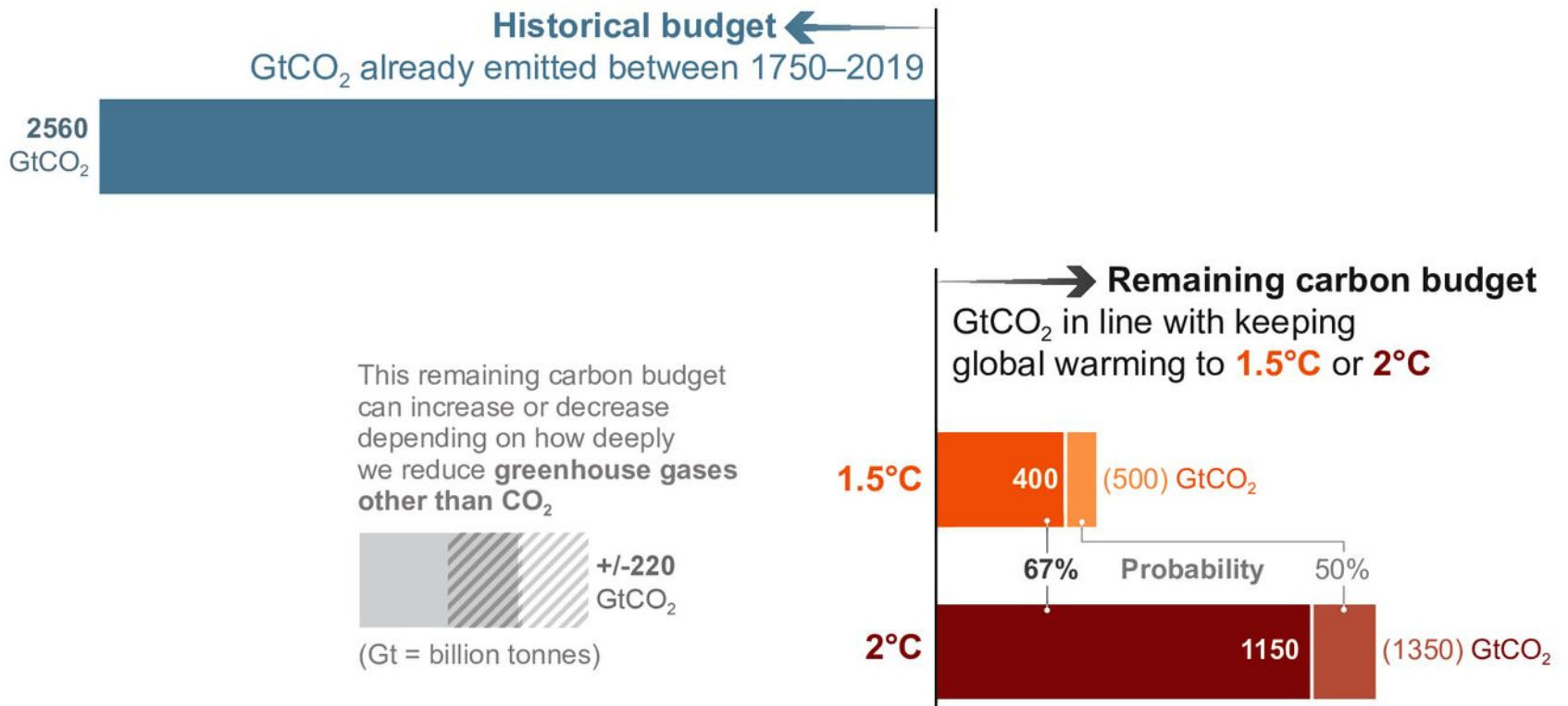
© Global Carbon Project • Data: Riahi et al (2017), Rogelj et al (2018), SSP Database (version 2)

This set of quantified SSPs are based on the output of six Integrated Assessment Models (AIM/CGE, GCAM, IMAGE, MESSAGE, REMIND, WITCH). Net emissions include those from land-use change and bioenergy with CCS.

Source: [Riahi et al. 2016](#); [Rogelj et al. 2018](#); [IIASA SSP Database](#); [IAMC](#); [Global Carbon Budget 2019](#)

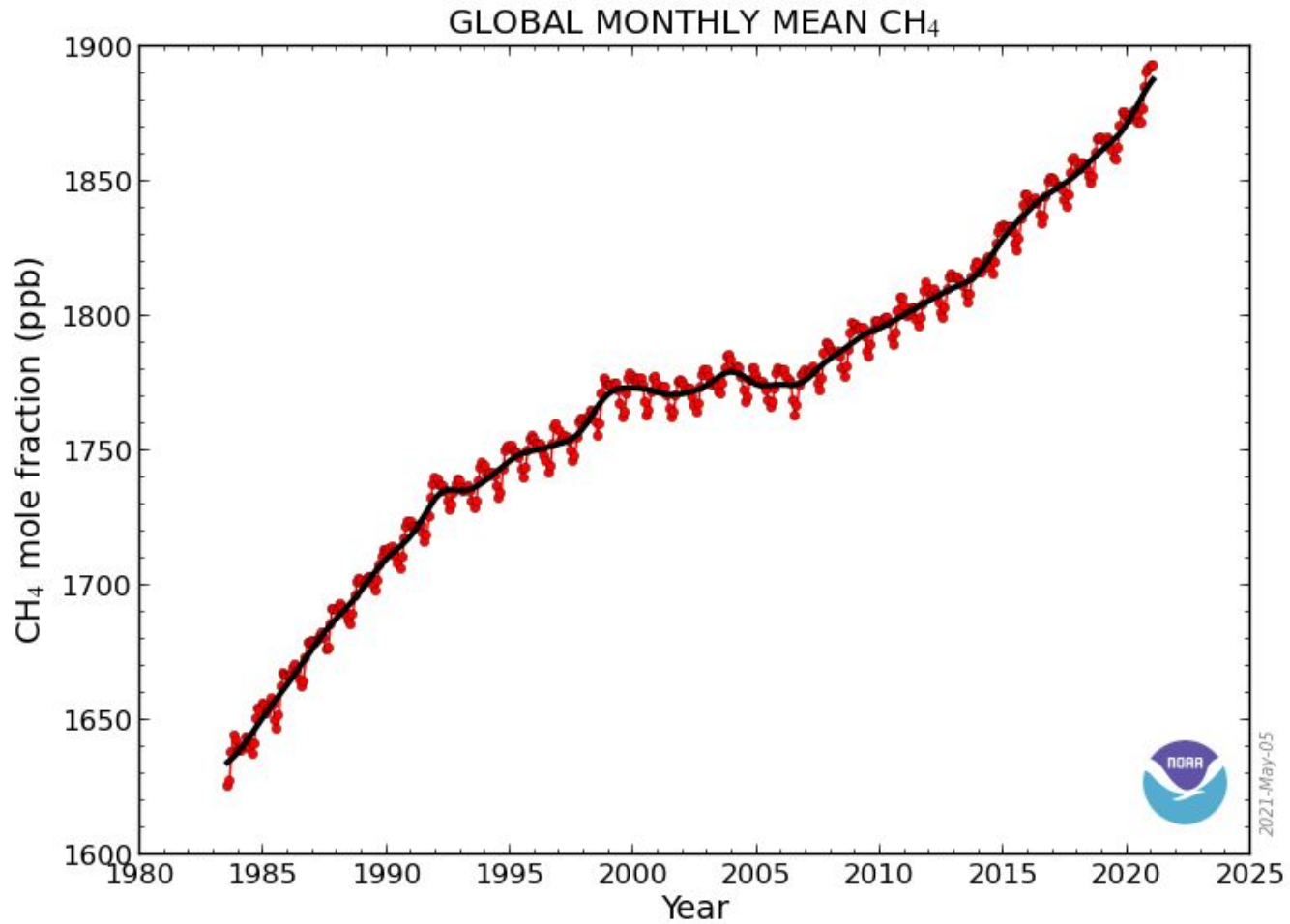
FAQ 5.4: What are Carbon Budgets?

The term carbon budget is used in several ways. Most often the term refers to the total net amount of carbon dioxide (CO₂) that can still be emitted by human activities while limiting global warming to a specified level.



Nie tylko CO₂:

Wzrost koncentracji metanu w atmosferze



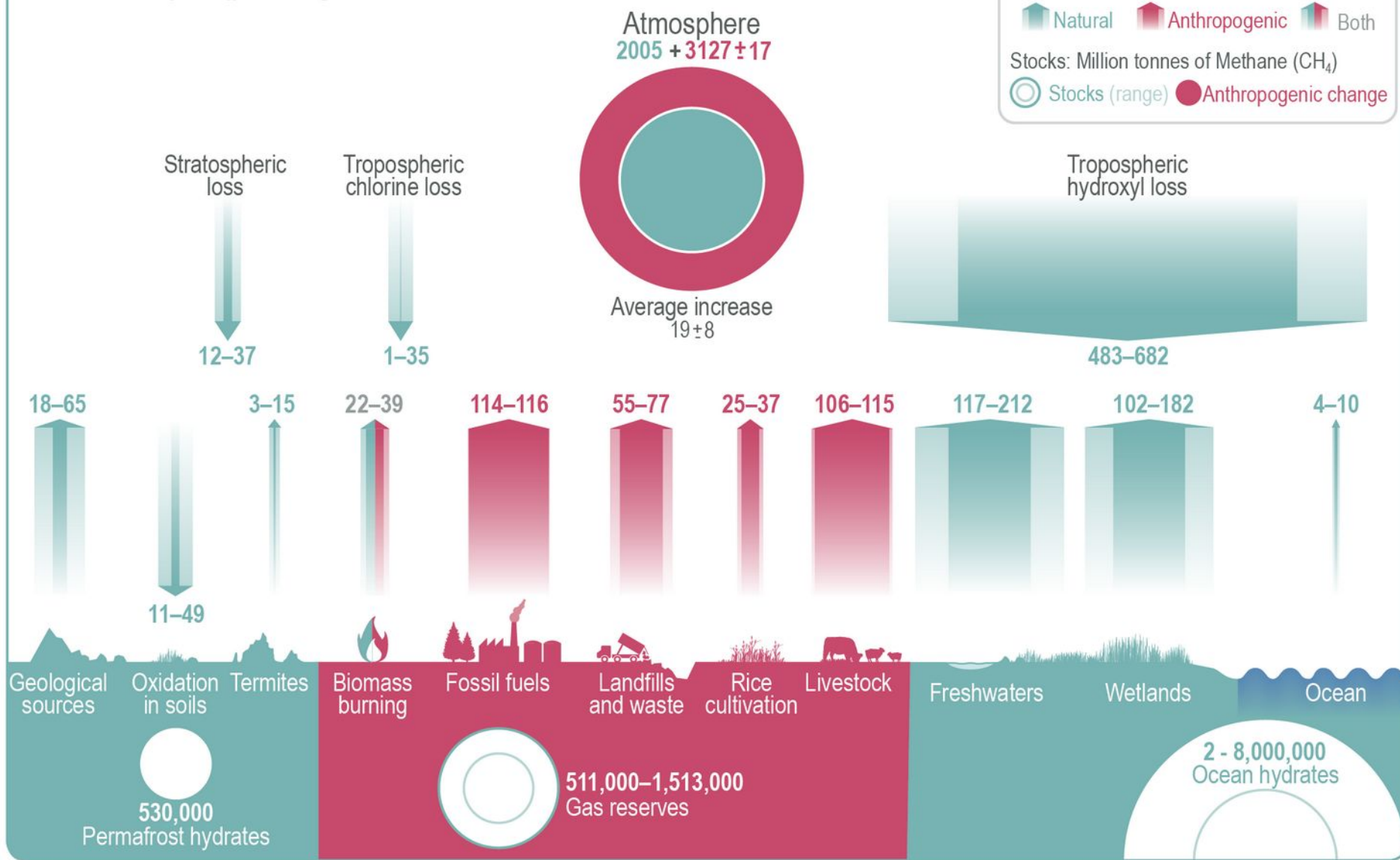
Methane (CH₄) Budget

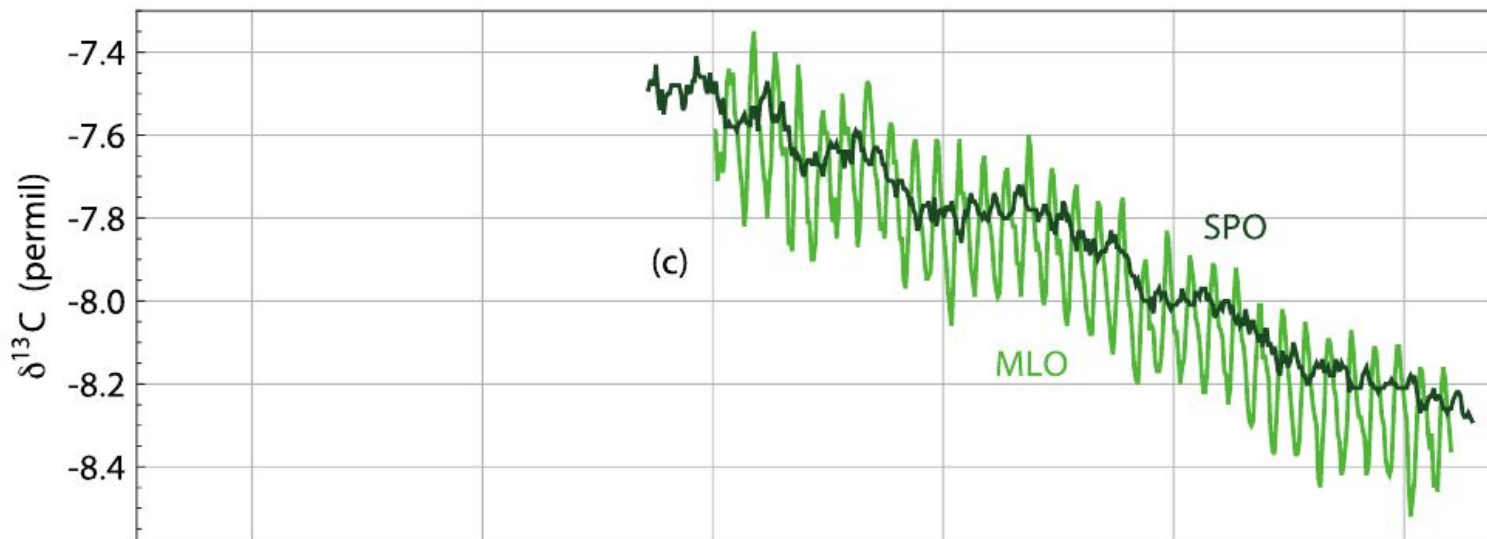
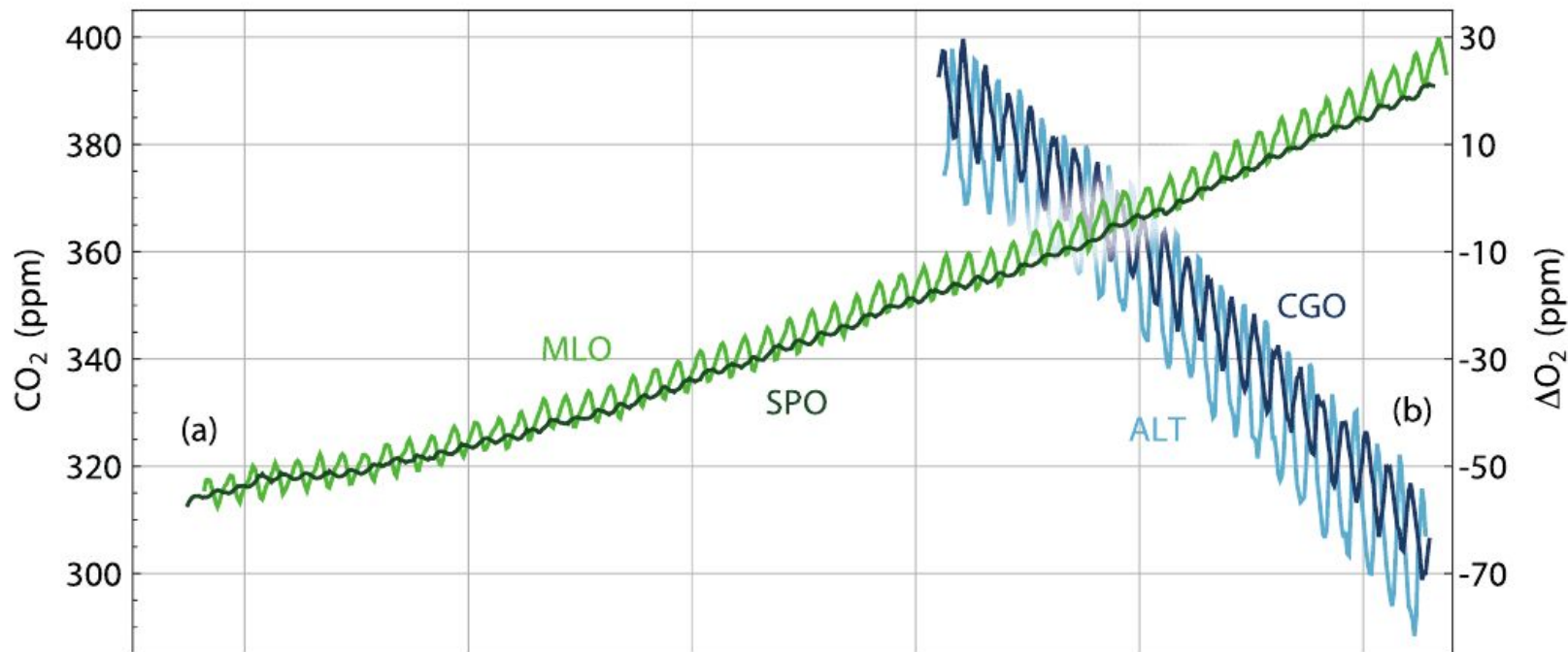
Flux: Million tonnes of CH₄ per year (Tg CH₄/yr)

▮ Natural
 ▮ Anthropogenic
 ▮ Both

Stocks: Million tonnes of Methane (CH₄)

○ Stocks (range)
 ● Anthropogenic change



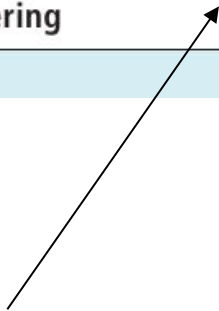


Inne dowody (poza bilansem węgla) na to że wzrost koncentracji CO₂ w atmosferze pochodzi ze spalania paliw kopalnych

Główne procesy naturalne odpowiedzialne za usuwanie dwutlenku węgla z atmosfery po nagłym wzroście koncentracji tego gazu w atmosferze.

Box 6.1, Table 1 | The main natural processes that remove CO₂ consecutive to a large emission pulse to the atmosphere, their atmospheric CO₂ adjustment time scales, and main (bio)chemical reactions involved.

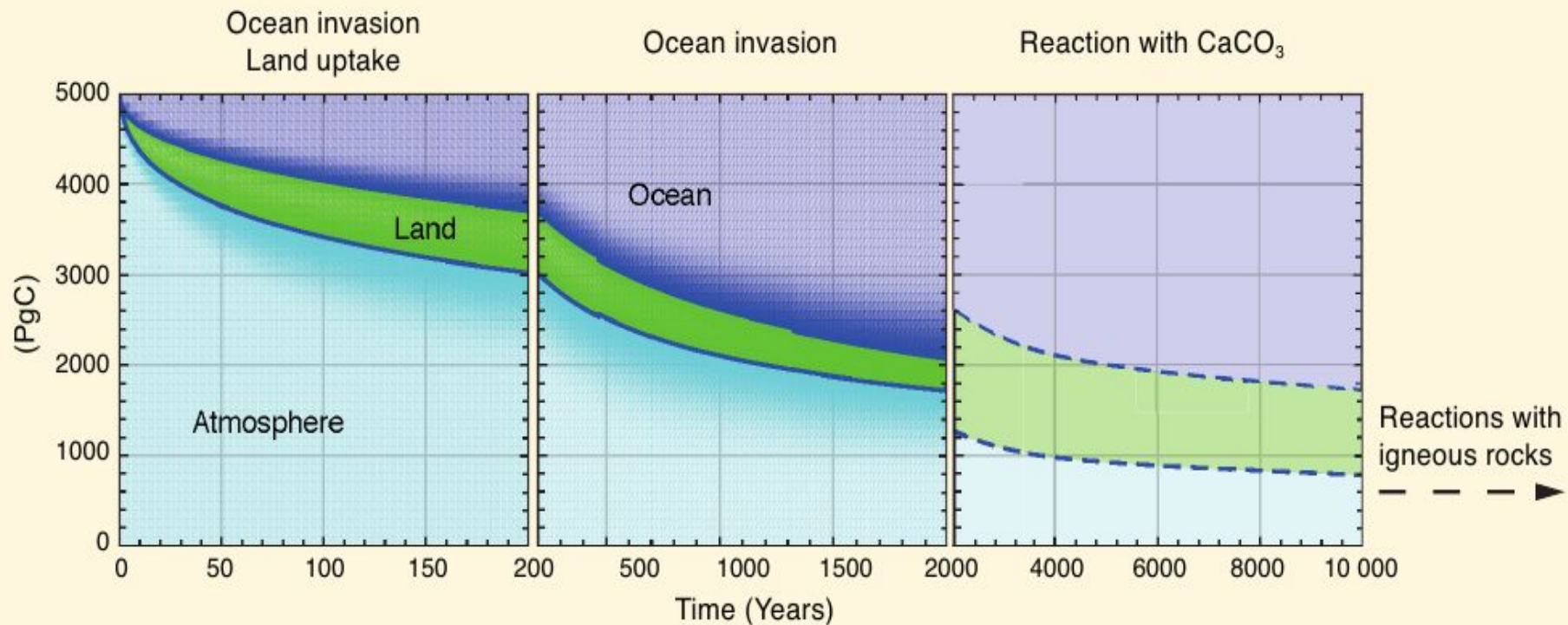
Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	1–10 ²	$6\text{CO}_2 + 6\text{H}_2\text{O} + \text{photons} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$ $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{heat}$
Ocean invasion: Seawater buffer	10–10 ³	$\text{CO}_2 + \text{CO}_3^{2-} + \text{H}_2\text{O} \rightleftharpoons 2\text{HCO}_3^-$
Reaction with calcium carbonate	10 ³ –10 ⁴	$\text{CO}_2 + \text{CaCO}_3 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-$
Silicate weathering	10 ⁴ –10 ⁶	$\text{CO}_2 + \text{CaSiO}_3 \rightarrow \text{CaCO}_3 + \text{SiO}_2$



to + emisje wulkaniczne + tworzenie pokładów węgla organicznego = wolny cykl węglowy

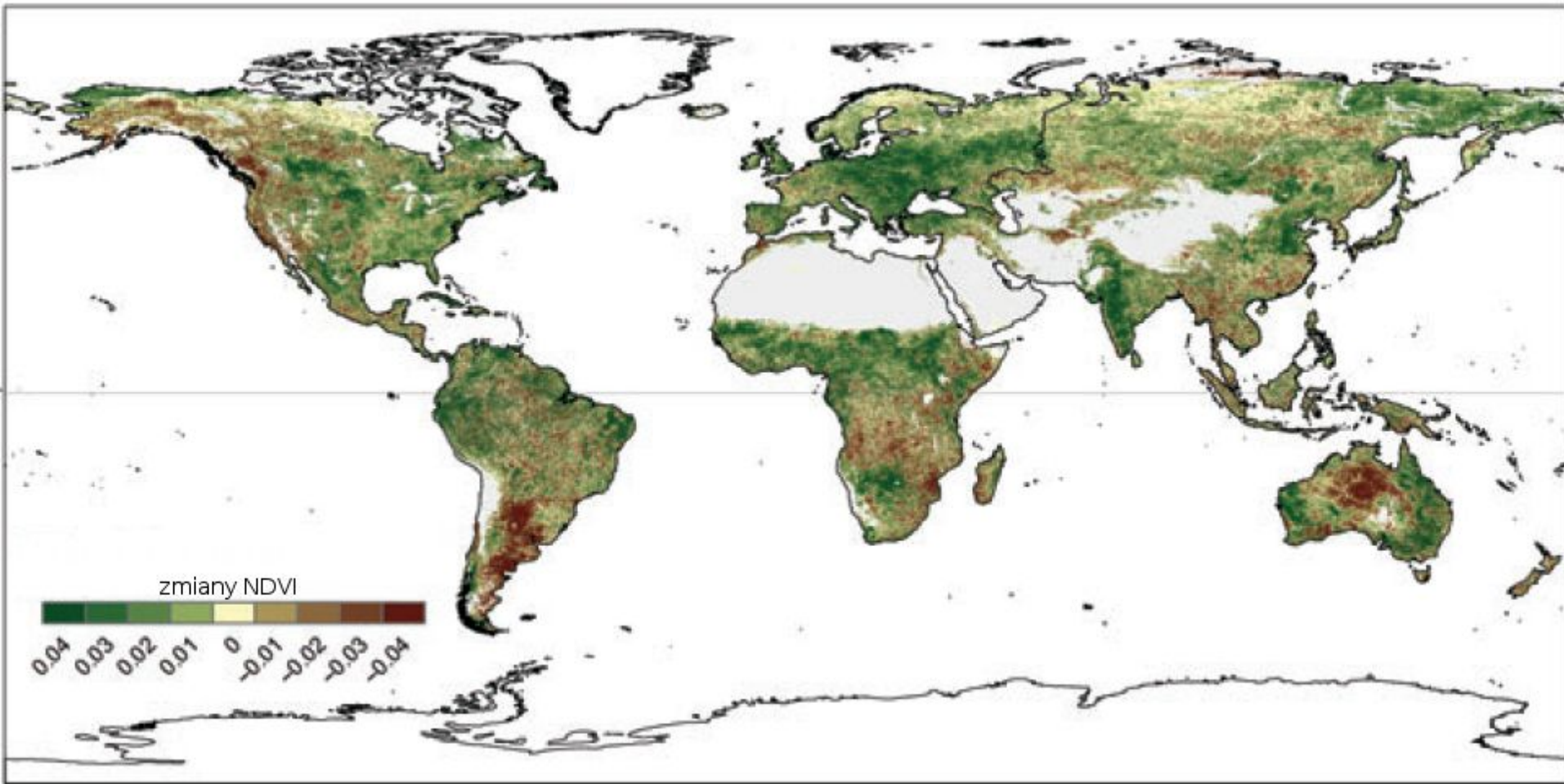
Tempo (skale czasu) usuwania dwutlenku węgla z atmosfery.

Sposób oszacowania: stała czasowa spadku CO₂ po nagłym wzroście koncentracji tego gazu w atmosferze.

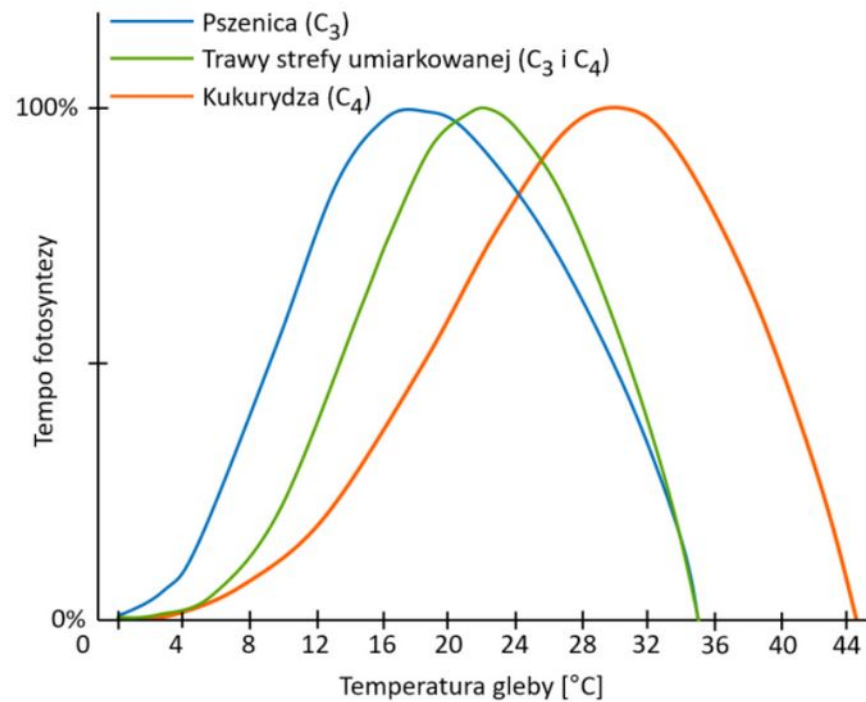
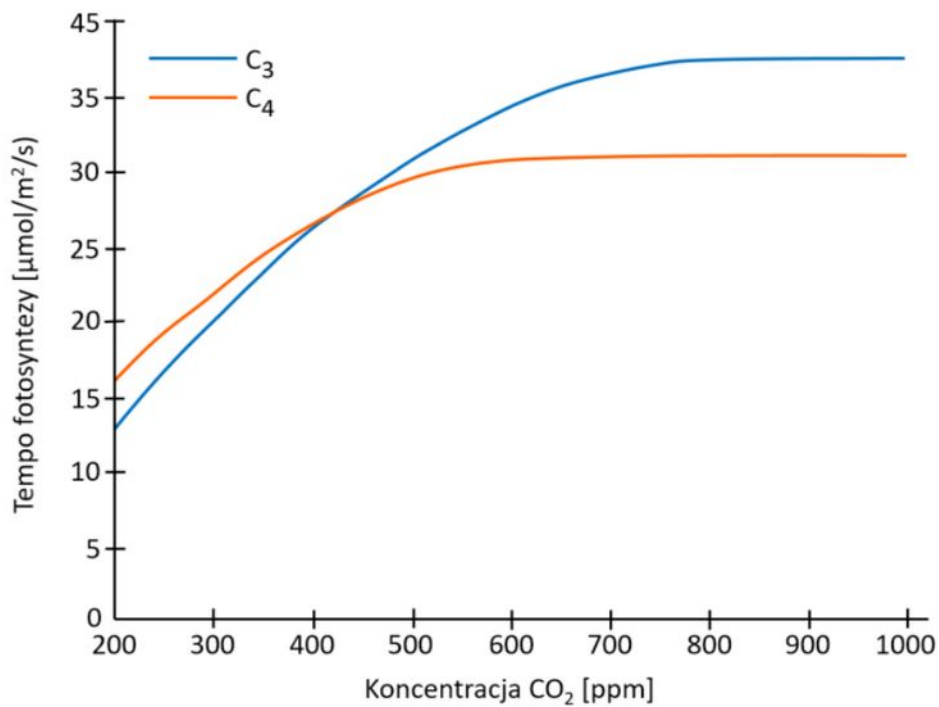


FAQ 6.2, Figure 2 | Decay of a CO₂ excess amount of 5000 PgC emitted at time zero into the atmosphere, and its subsequent redistribution into land and ocean as a function of time, computed by coupled carbon-cycle climate models. The sizes of the colour bands indicate the carbon uptake by the respective reservoir. The first two panels show the multi-model mean from a model intercomparison project (Joos et al., 2013). The last panel shows the longer term redistribution including ocean dissolution of carbonaceous sediments as computed with an Earth System Model of Intermediate Complexity (after Archer et al., 2009b).

Czy więcej CO₂ w atmosferze oznacza większą produkcję roślinną?

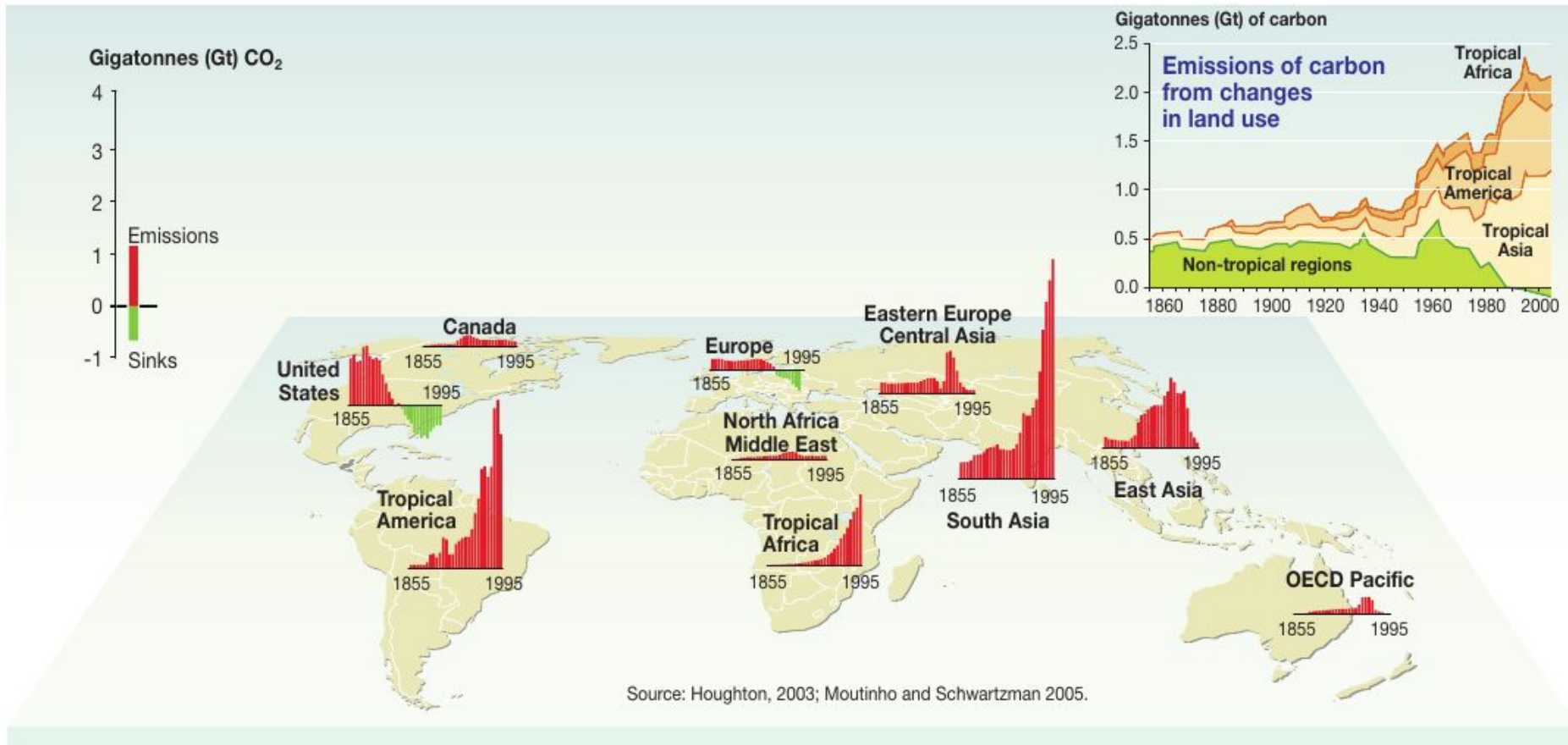


Zmiany wskaźnika NDVI (Normalized Difference Vegetation Index) w okresie 1982-2008. Globalne ocieplenie zmniejsza produktywność roślin. W miarę jak przybywa dwutlenku węgla, na półkuli północnej rosną wartości wskaźnika NDVI (obszary oznaczone na mapie kolorem zielonym), co oznacza zdrową i rozwijającą się pokrywę roślinną. Jednak zjawisko to nie wystarcza, by skompensować ubytek pokrywy roślinnej na półkuli południowej (obszary malejących wartości NDVI, oznaczone na mapie kolorem brązowym). Globalnie roślinności na świecie ubywa. Źródło: de Jong i in. (2012).

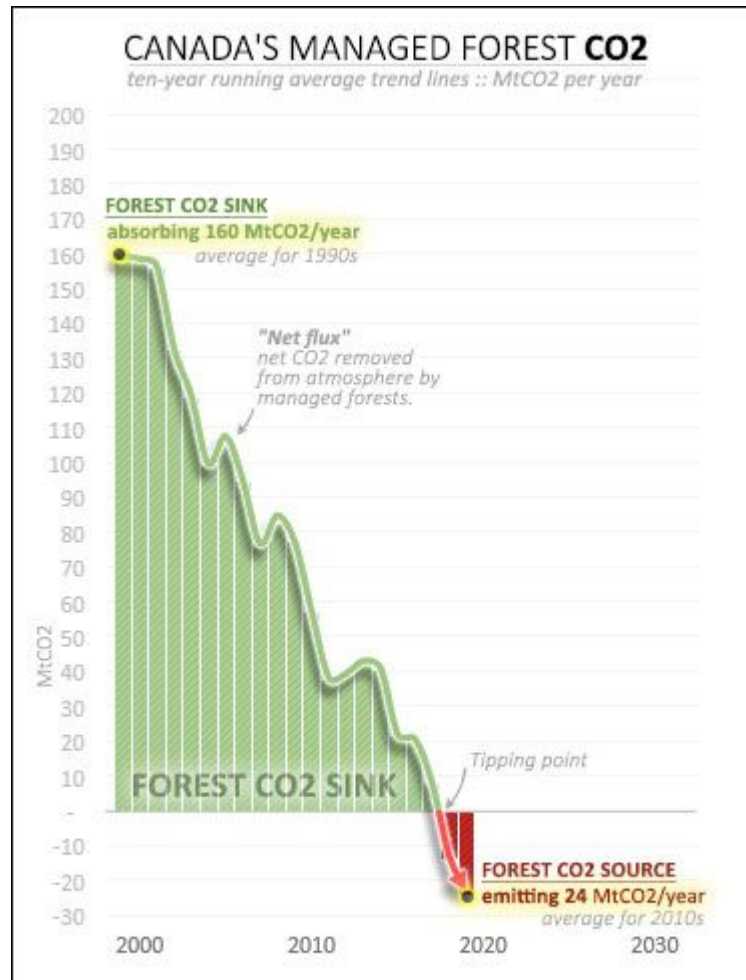


Ilustracja 2.17.11. Po lewej: Poglądowo przedstawiona zależność tempa fotosyntezy od koncentracji CO_2 dla różnych typów fotosyntezy. Po prawej: Zależność tempa fotosyntezy dla różnych roślin od temperatury powierzchniowej warstwy gleby.

Historical forest carbon balance, 1855-1995



Rola lasów w bilansie węgla



CANADA MANAGED FOREST & LOGGING CO₂ – Data from Canada's National Inventory Reports. All lines are 10-year running averages. Green line & area is net CO₂ absorbed by Canada's managed forest lands (net flux in Table 6-3). Solid brown line is carbon content of harvested wood each year, expressed as CO₂ ("Instant oxidation accounting" for HWP pool inputs in Table 6-7). This is how Canada used to report HWP emissions. The dashed brown line is CO₂ emitted each year by wood harvested in the past ("End of use accounting" now listed as "HWP"). Dotted brown line is projections from NRCan. CHART by Barry Saxifrage at VisualCarbon.org & NationalObserver.com. April 2021

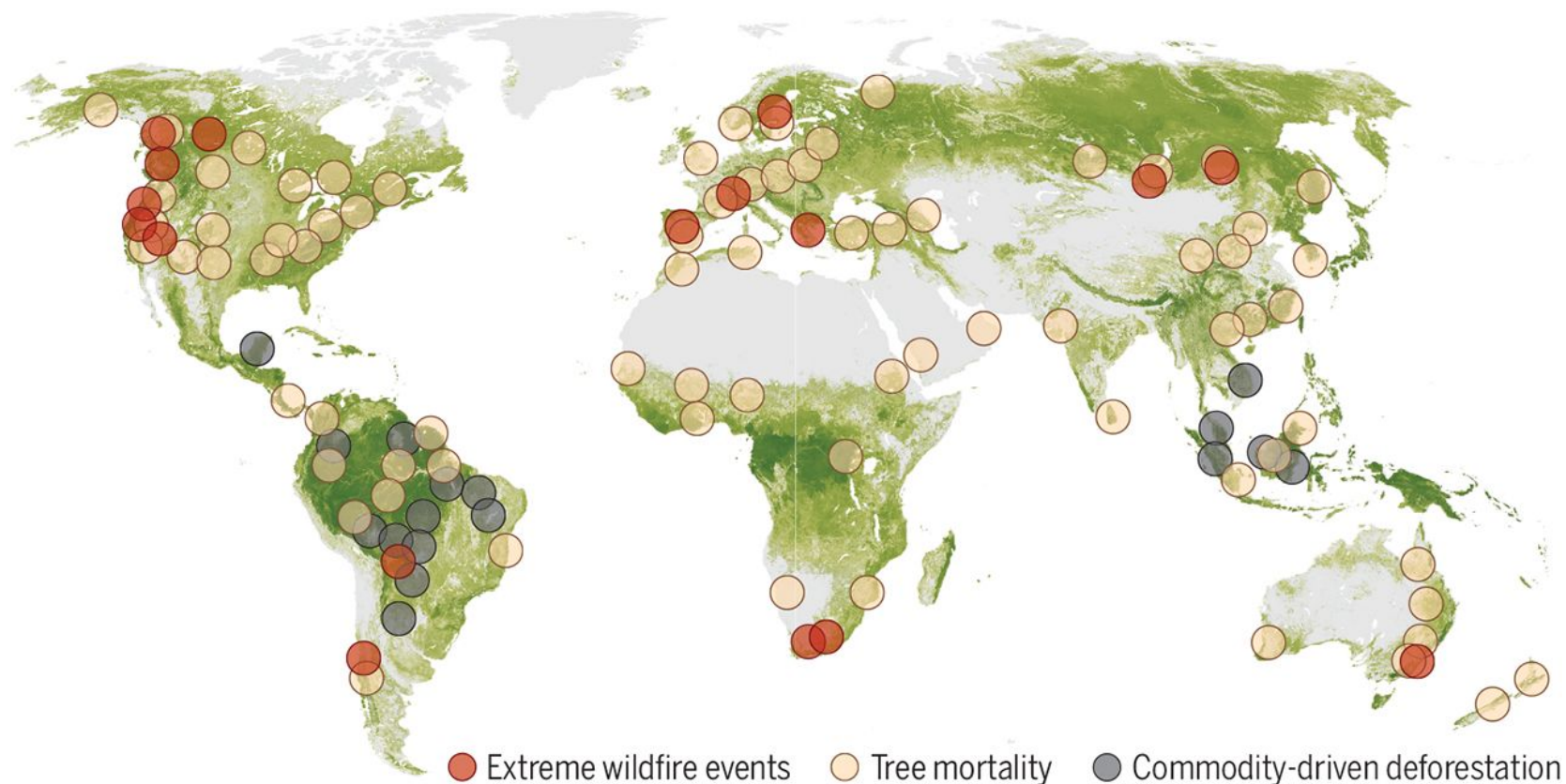
Jonathan T. Overpeck¹, David D. Breshears²

+ See all authors and affiliations

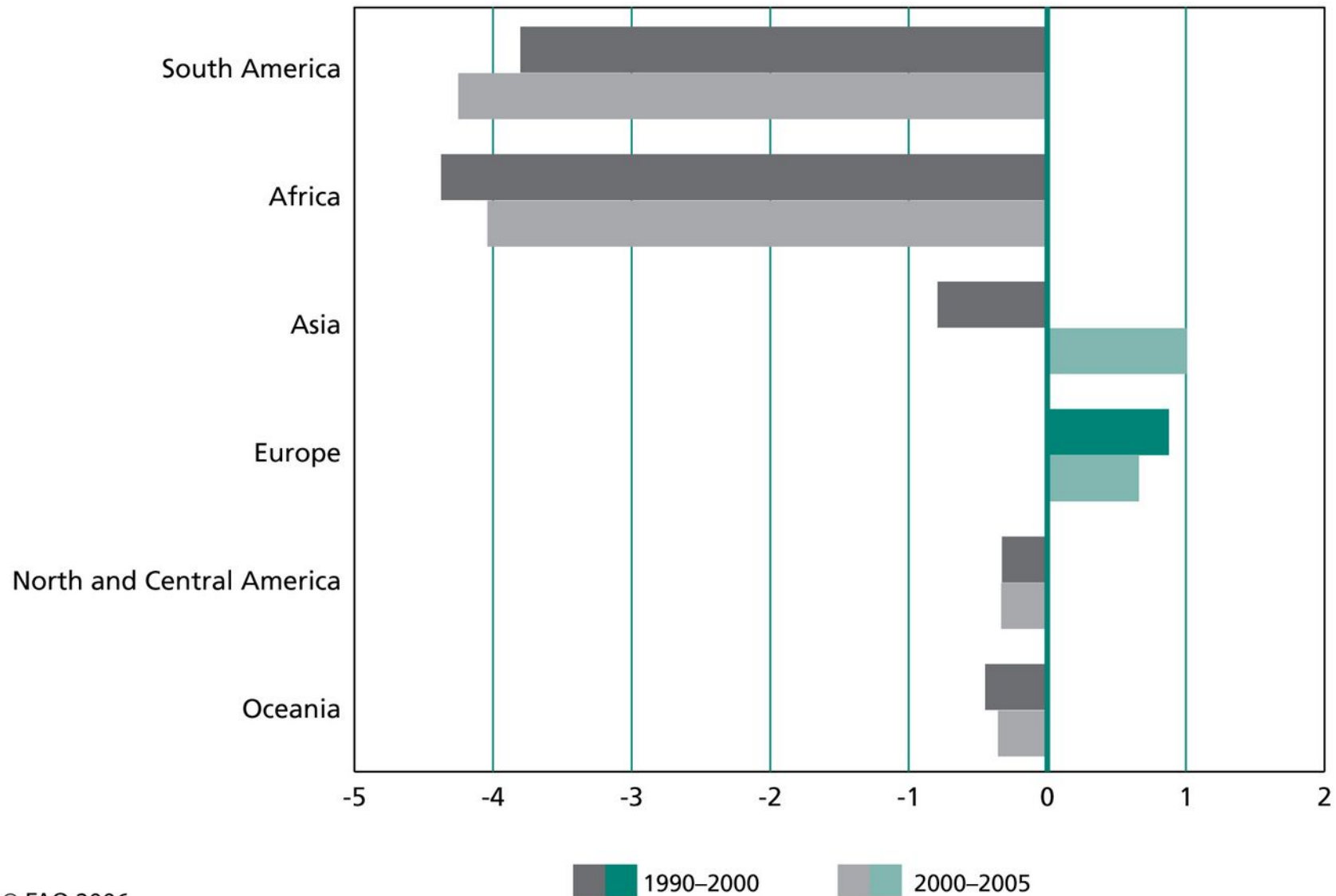
Science 21 May 2021:
Vol. 372, Issue 6544, pp. 786-787
DOI: 10.1126/science.abb9902

Rapid tree loss around the world

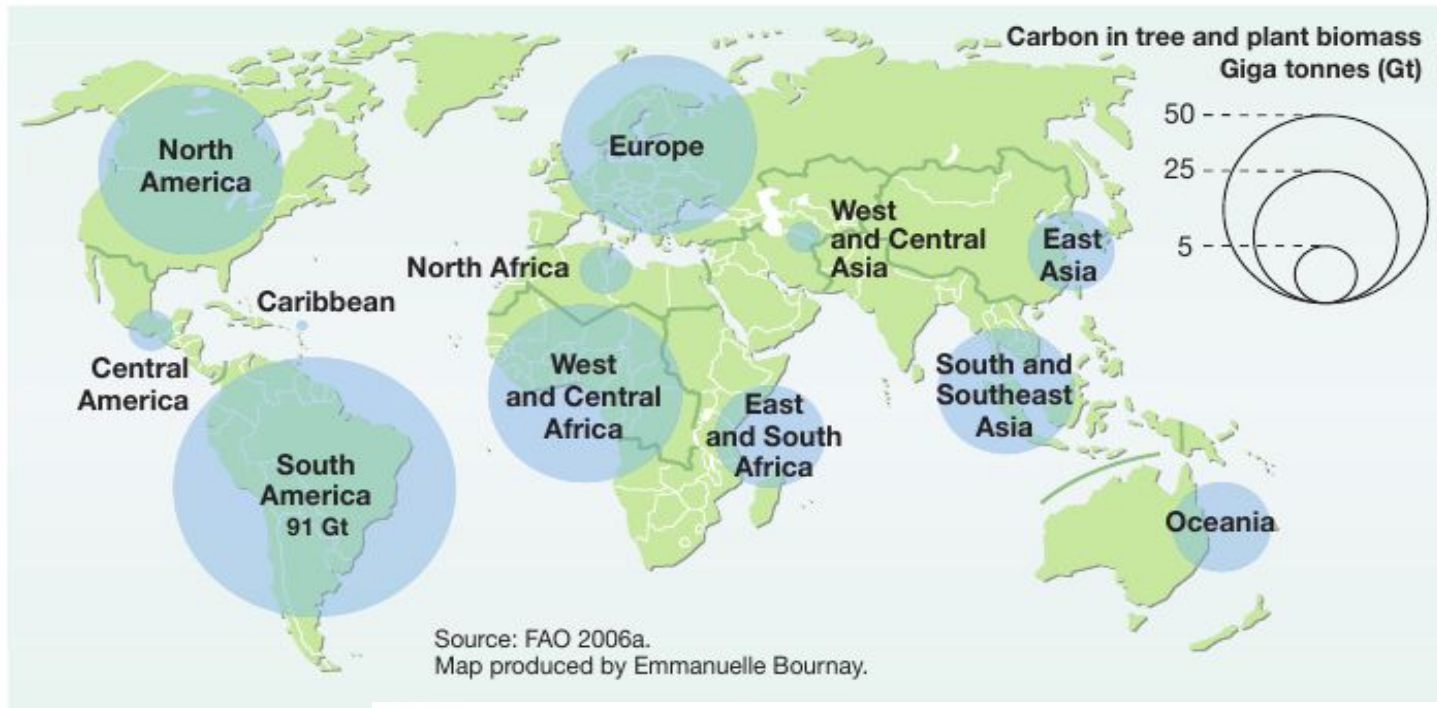
Global tree decline is attributed to commodity-driven deforestation (9), loss by wildfire (1), and drought- and heat-related mortality (often associated with pests and pathogens). The latter two are affected by increasing atmospheric moisture demand that drives forest stress. Forested areas are shown with tree heights ranging from 5 m (lightest green) to greater than 60 m (darkest green).



Annual net change in forest area by region 1990–2005 (million ha per year)



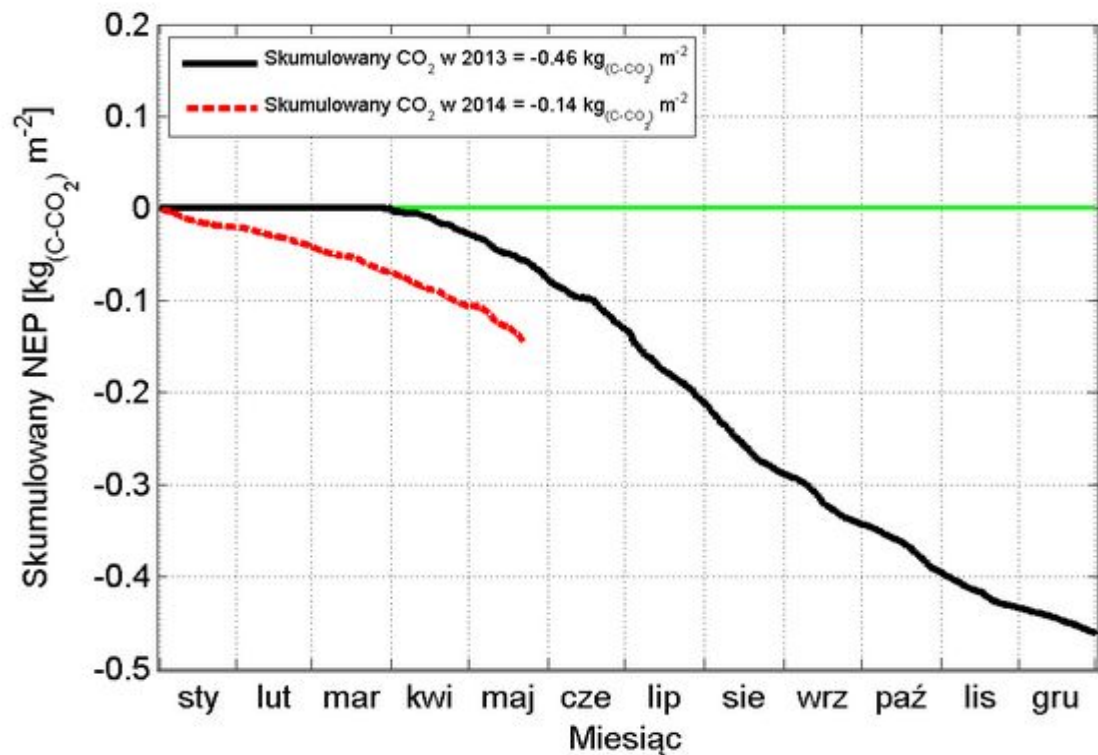
Forest carbon stock per region



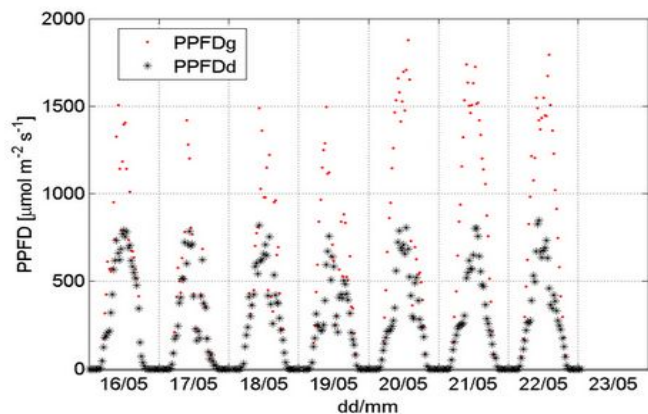
Breakdown of carbon storage by region



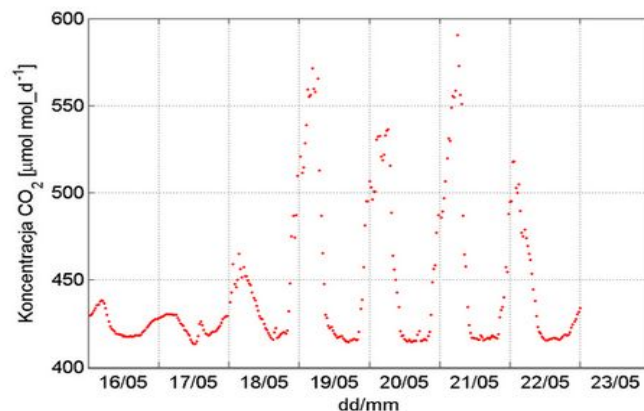
Stacja badawcza Tleń- las iglasty po przejściu tornado (od 29 Marca 2013r.)



Cummulation of CO_2 estimated by EC



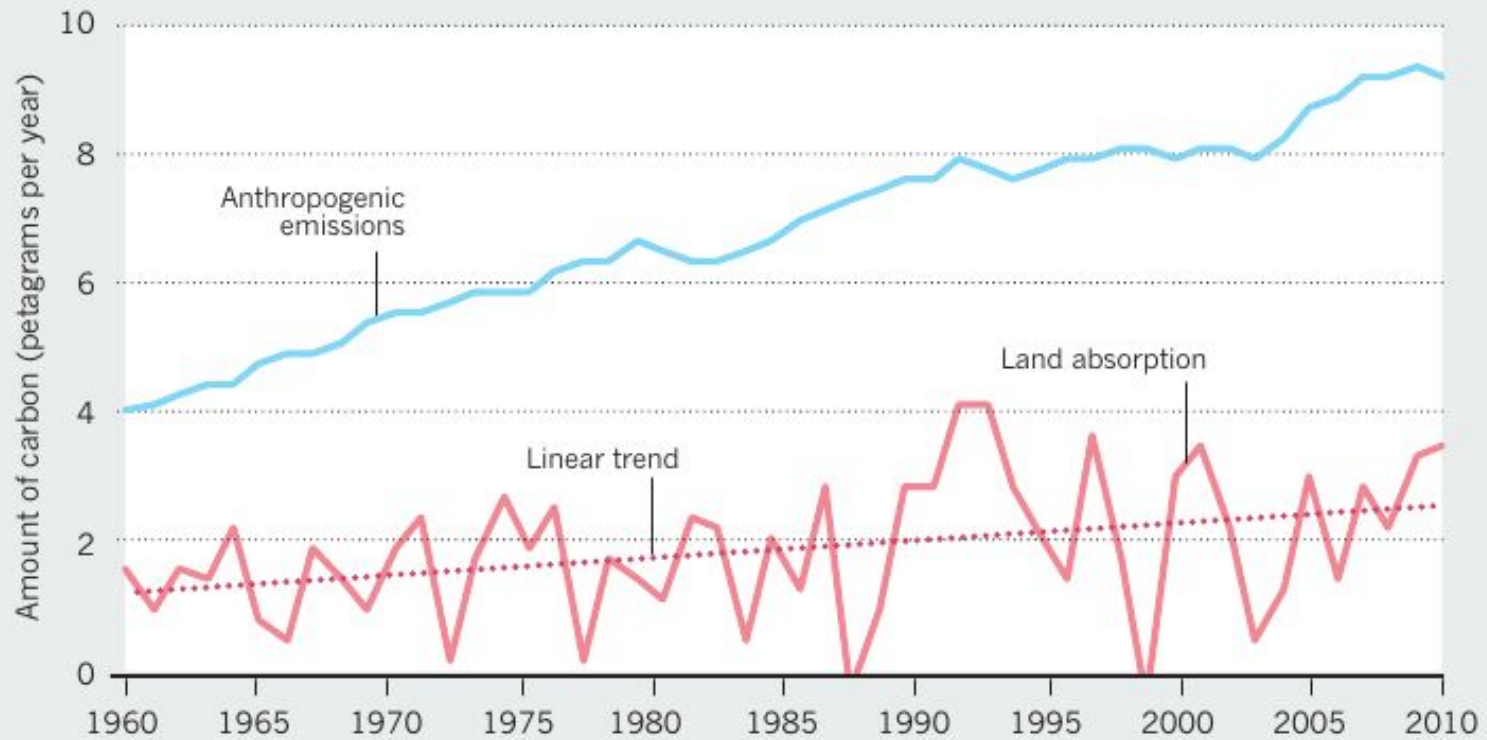
Photosynthetic Photon Flux Density (data from BF5), in last 7 days



CO_2 mixing ratio runs in last 7 days

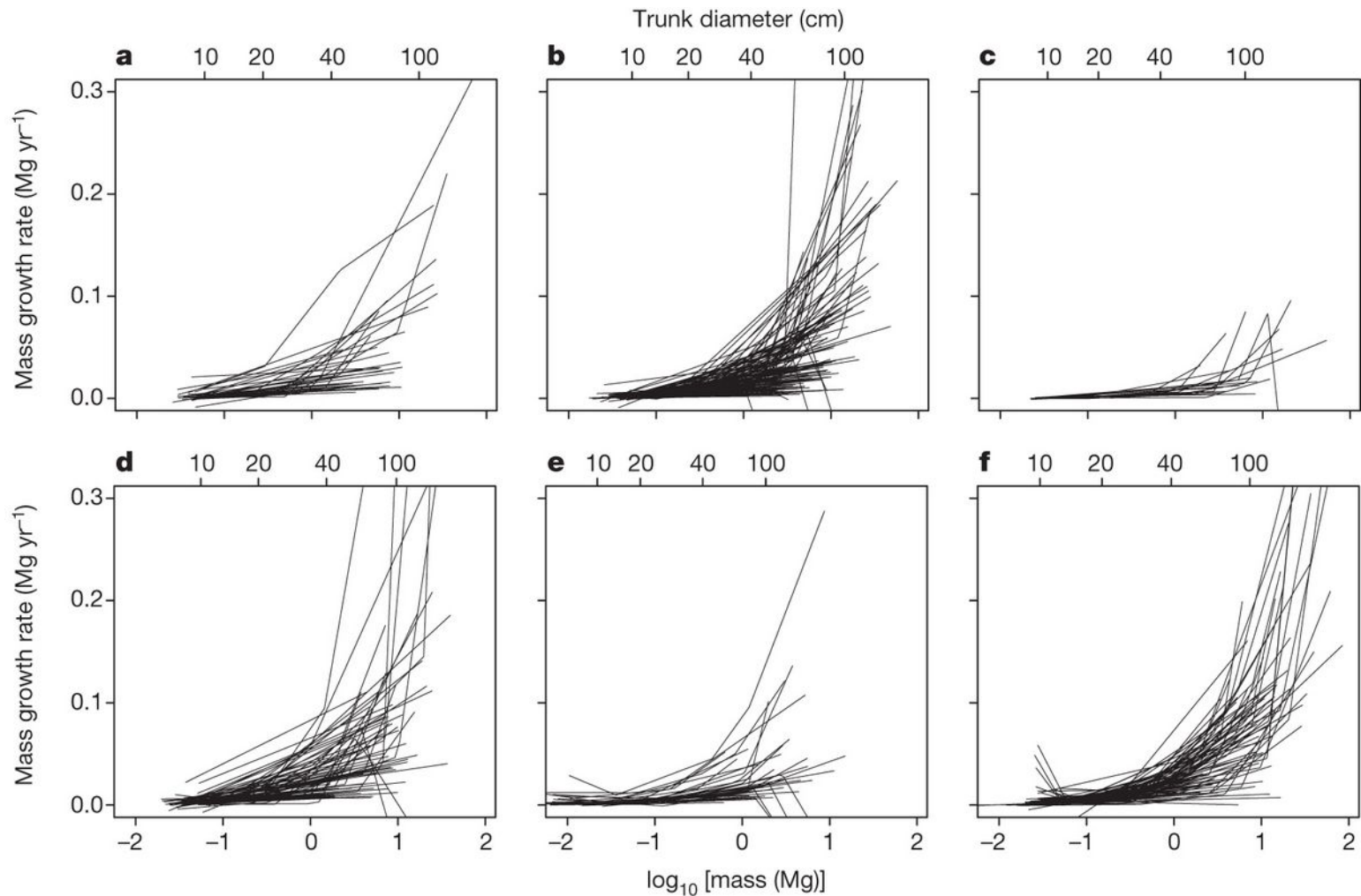
GLOBAL LAND SINK

The quantity of carbon absorbed by trees and other types of vegetation per hectare of land has risen in the past 50 years as anthropogenic carbon dioxide and nitrogen emissions have grown. This is despite the world's forest area falling by around 2% since 1990.



I jak to jest z gospodarką leśną:

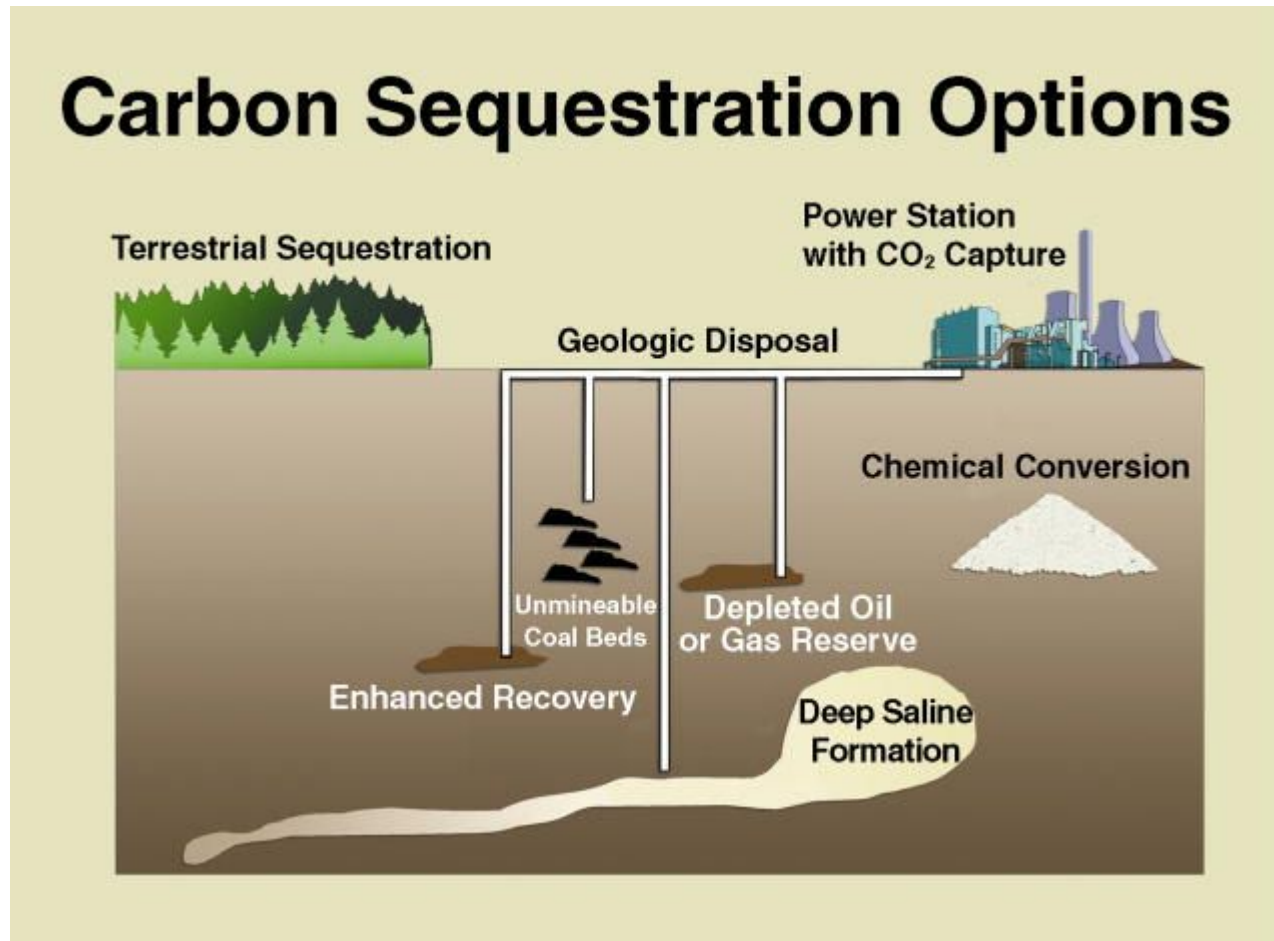
Above ground mass growth rates for the 403 tree species, by continent.

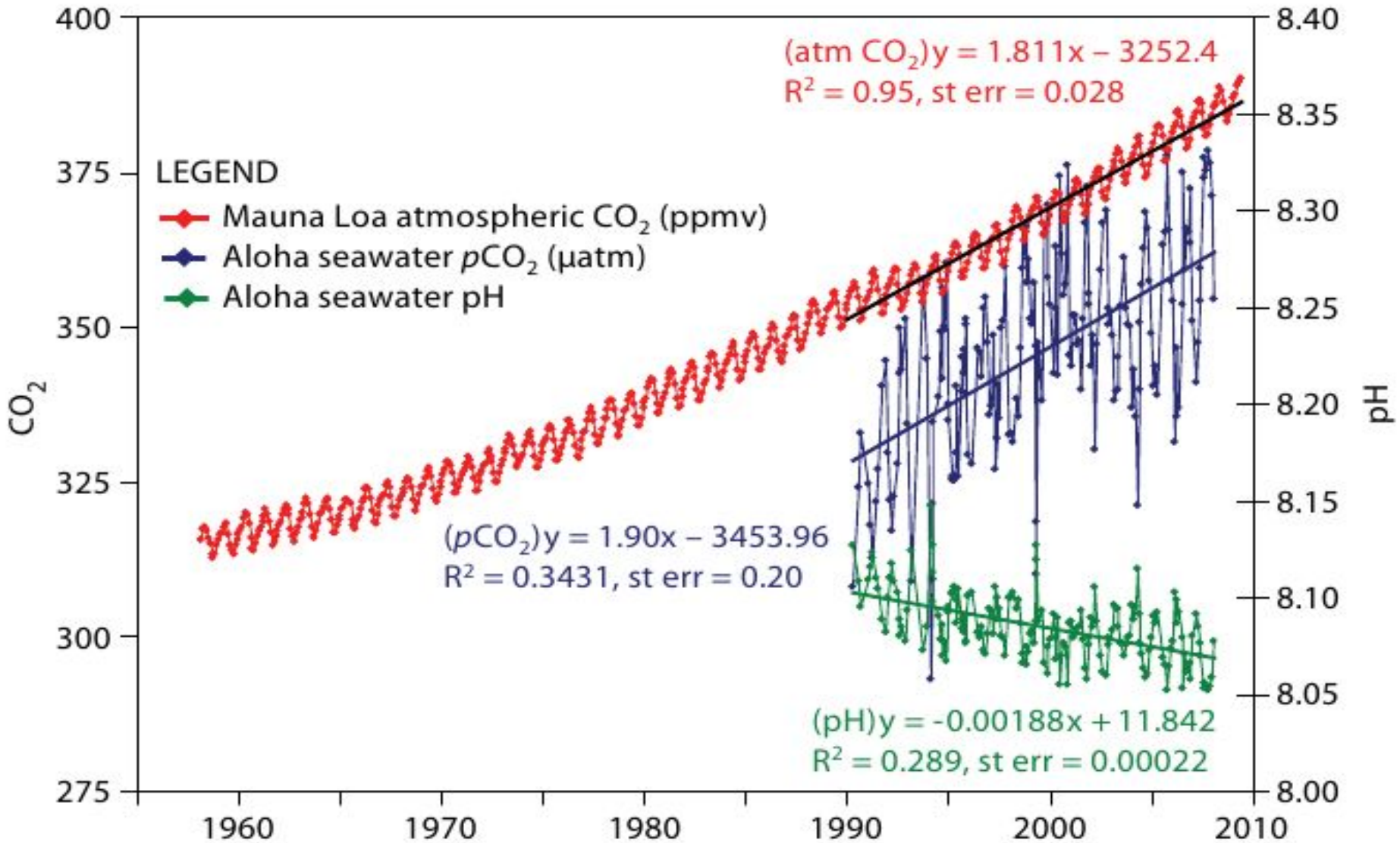


NL Stephenson *et al.* *Nature* **000**, 1-4 (2014) doi:10.1038/nature12914

nature

Nie tylko lasy – opcje sekwestracji węgla.



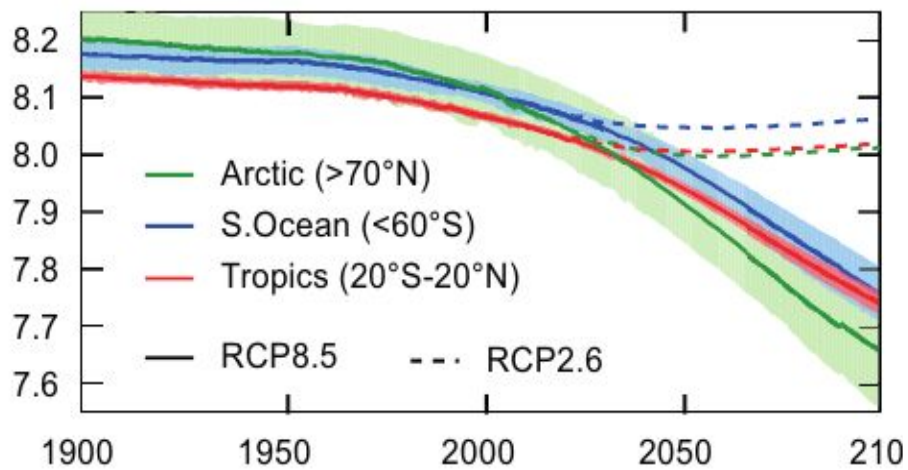


Ocean zmienia odczyn na bardziej kwaśny

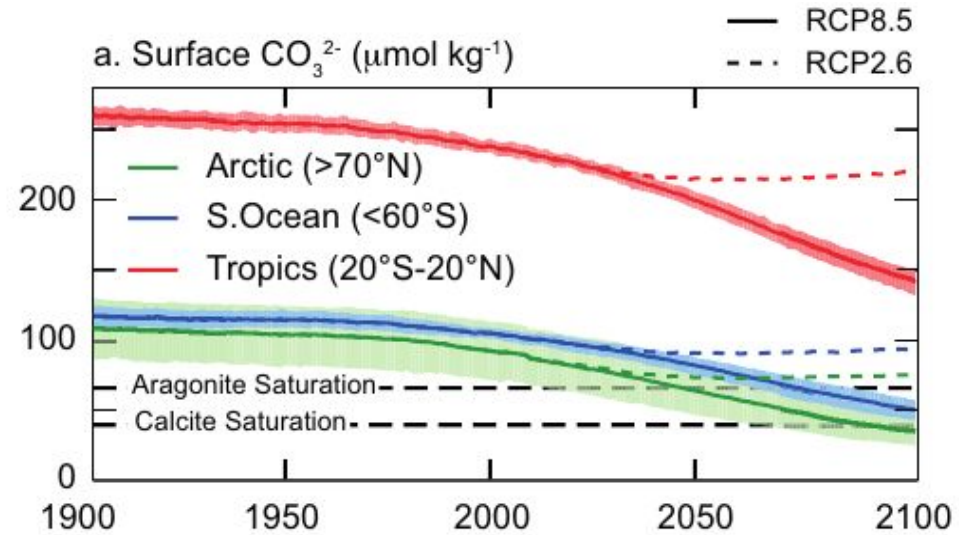
Feely, R.A., S.C. Doney, and S.R. Cooley. 2009. Ocean acidification: Present conditions and future changes in a high-CO₂ world. *Oceanography* 22(4):36–47, <http://dx.doi.org/10.5670/oceanog.2009.95>.

Zakwaszenie oceanów

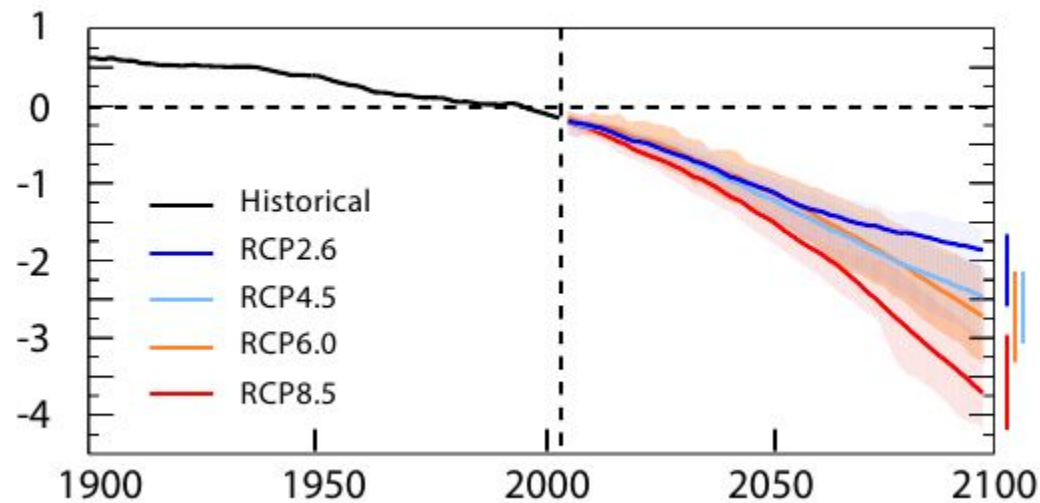
a. Surface pH

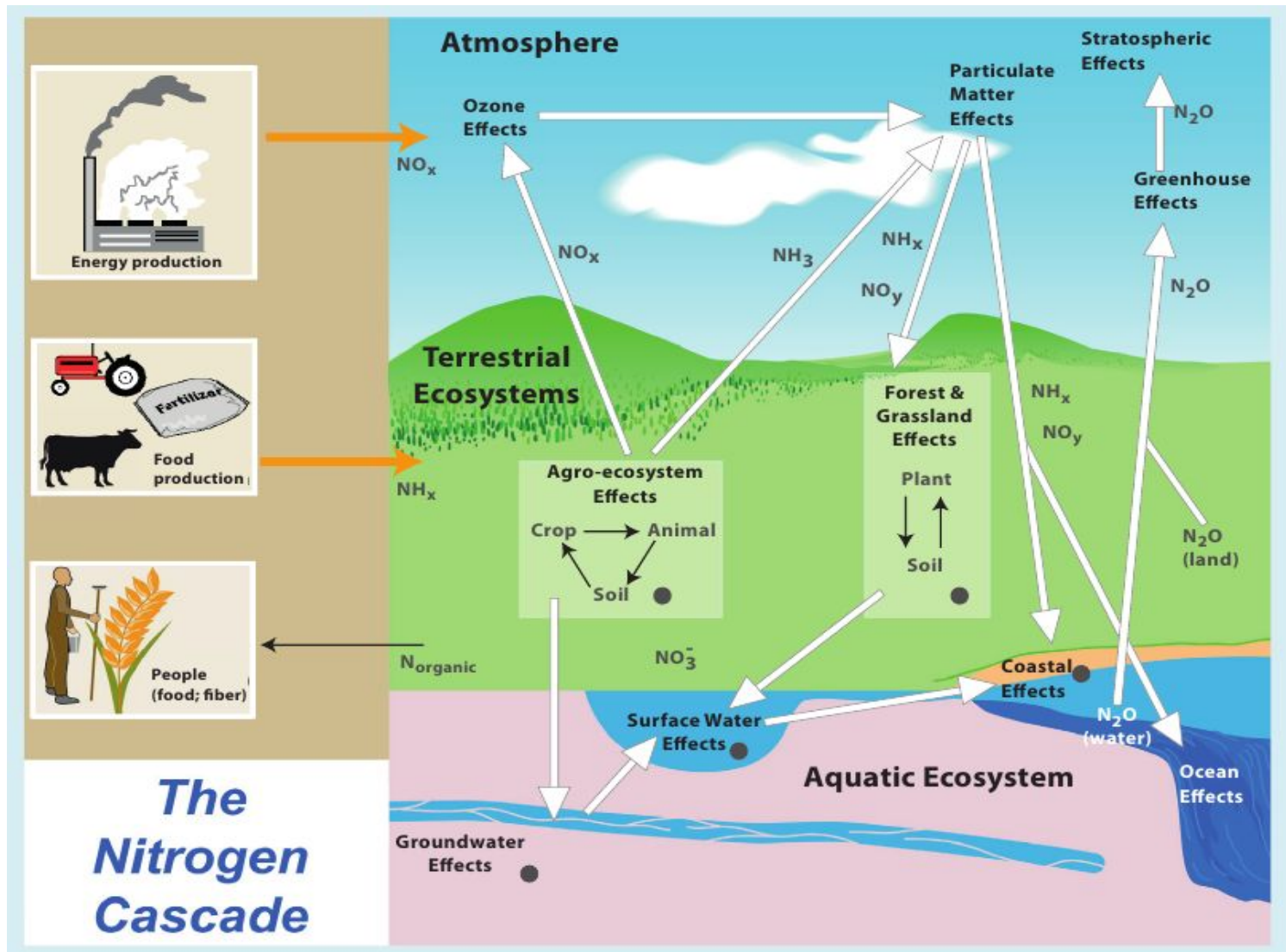


a. Surface CO_3^{2-} ($\mu\text{mol kg}^{-1}$)



a. Ocean oxygen content change (%)

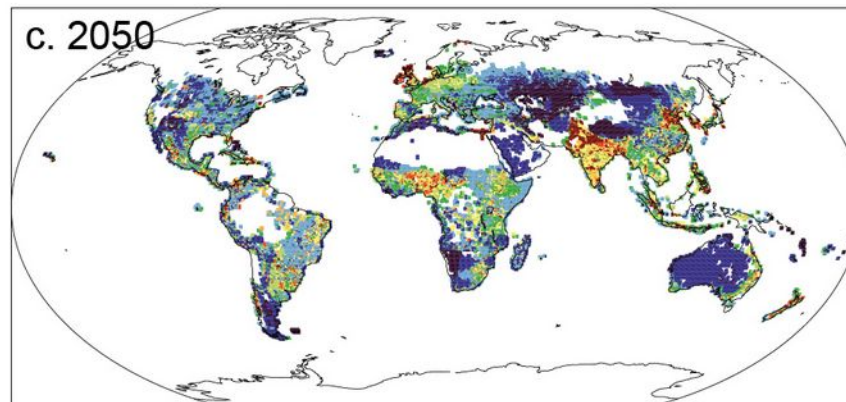
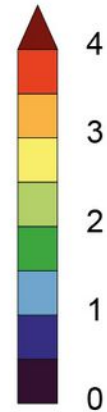
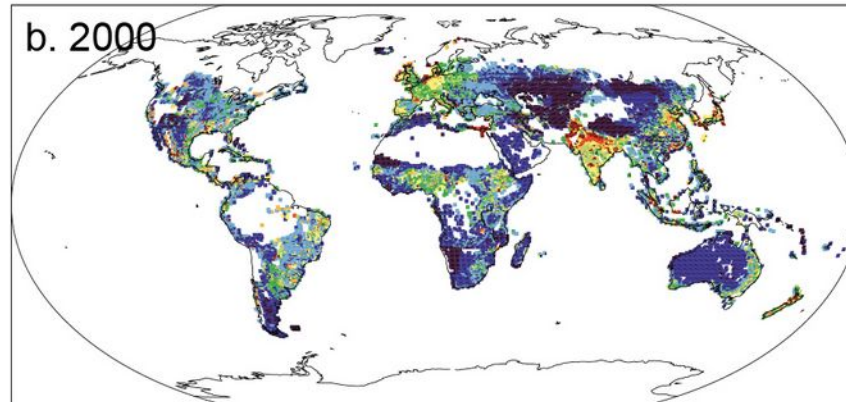
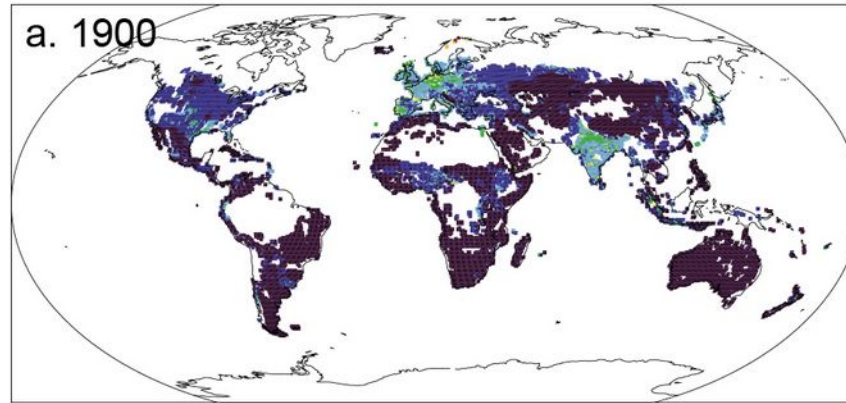




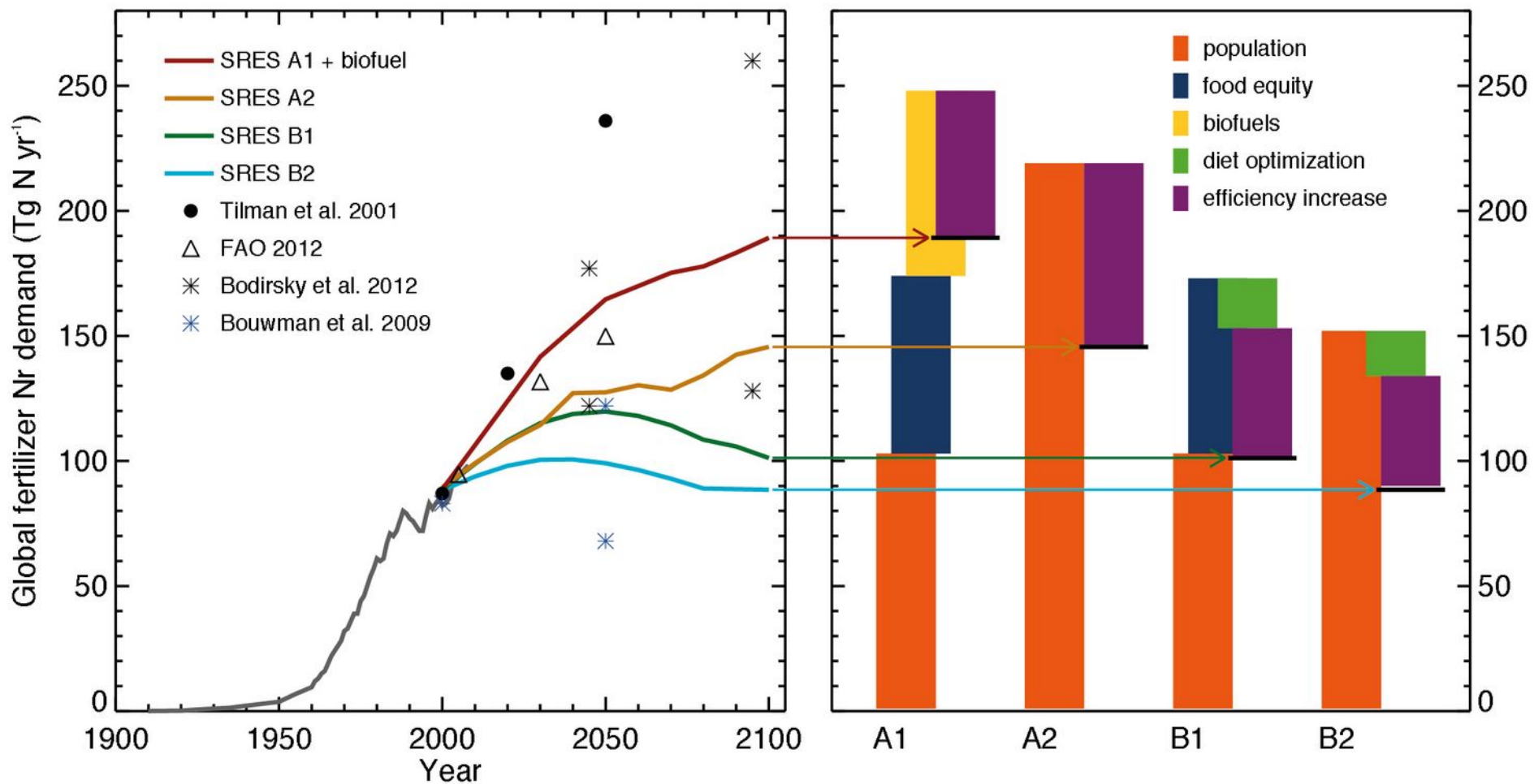
“Kaskada azotowa” - zmiany jakie powoduje w cyklu azotowym każdy atom przekształcony z nieaktywnej formy N_2 do formy reaktywnej chemicznie – biorącej udział w procesach biologicznych i chemicznych w systemie klimatycznym

N₂O emissions (kgN km⁻² y⁻¹)

Emisje podtlenku azotu – estymacje geograficzne.



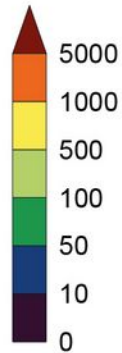
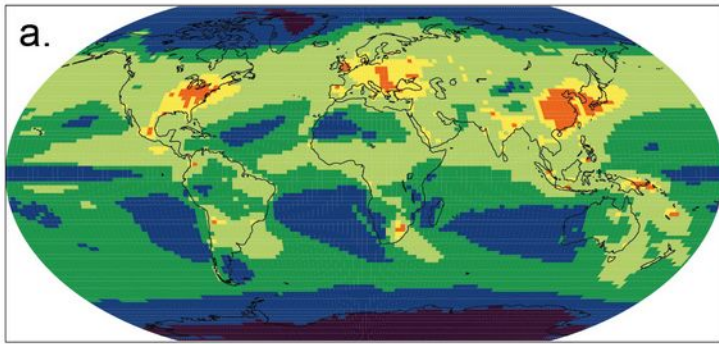
Zaburzenia w cyklu azotowym wskutek działania rolnictwa – rozkład czasowy emisji i wartości skumulowane.



Jak będzie się zmieniać depozycja związków siarki i azotu.

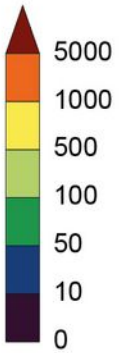
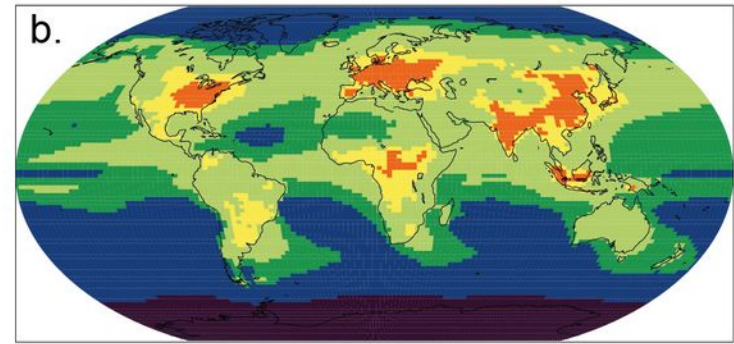
SO_x deposition (kgS km⁻² y⁻¹)

1990s

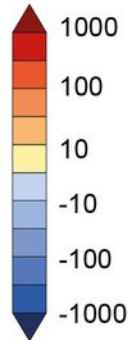
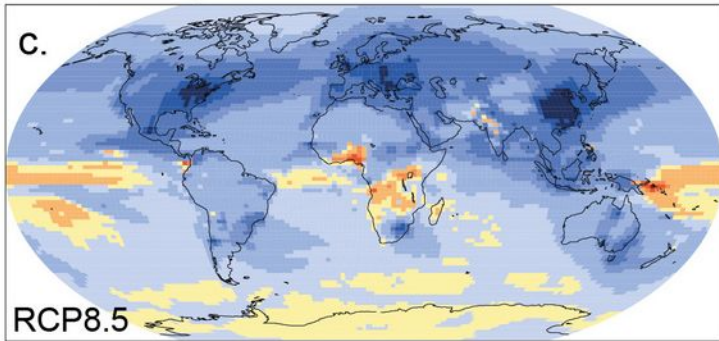


N deposition (kgN km⁻² y⁻¹)

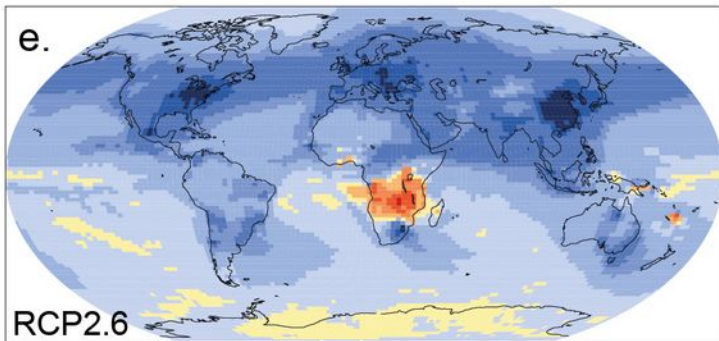
1990s



2090s, changes from 1990s

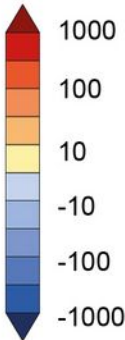
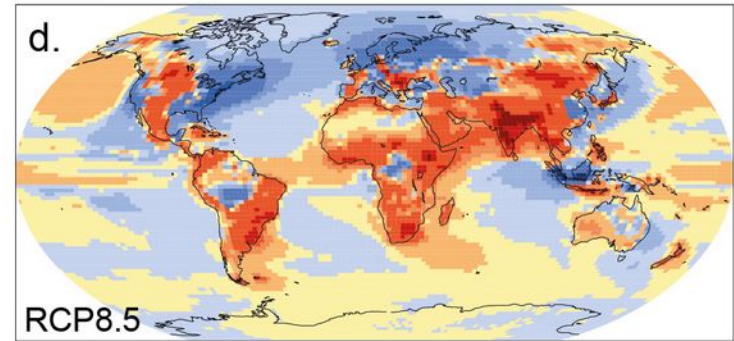


RCP8.5

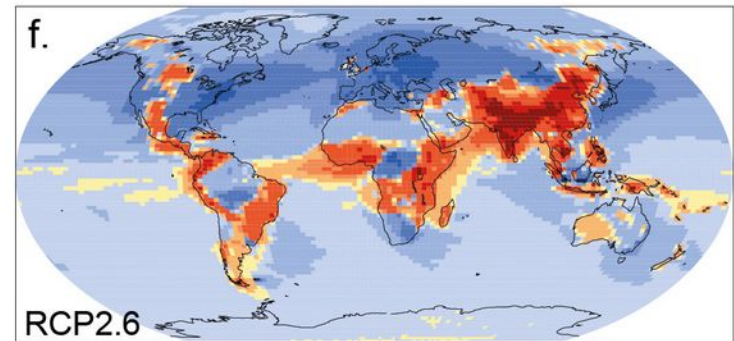


RCP2.6

2090s, changes from 1990s



RCP8.5



RCP2.6

Podsumowanie:

Problem z węglem: CO₂ i CH₄ poważny.

Ale nie jedyny...