

Fizyka Procesów Klimatycznych

Cykl węglowy, inne cykle biogeochemiczne.

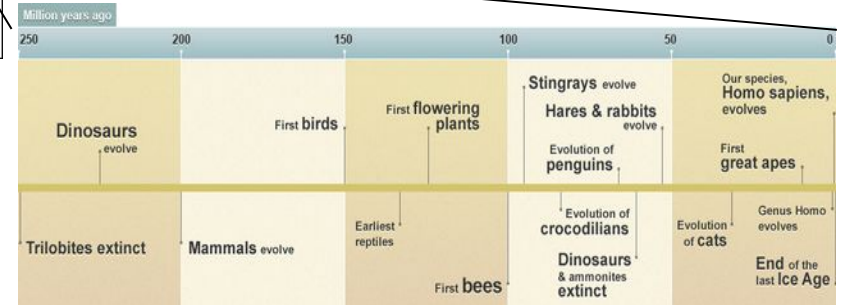
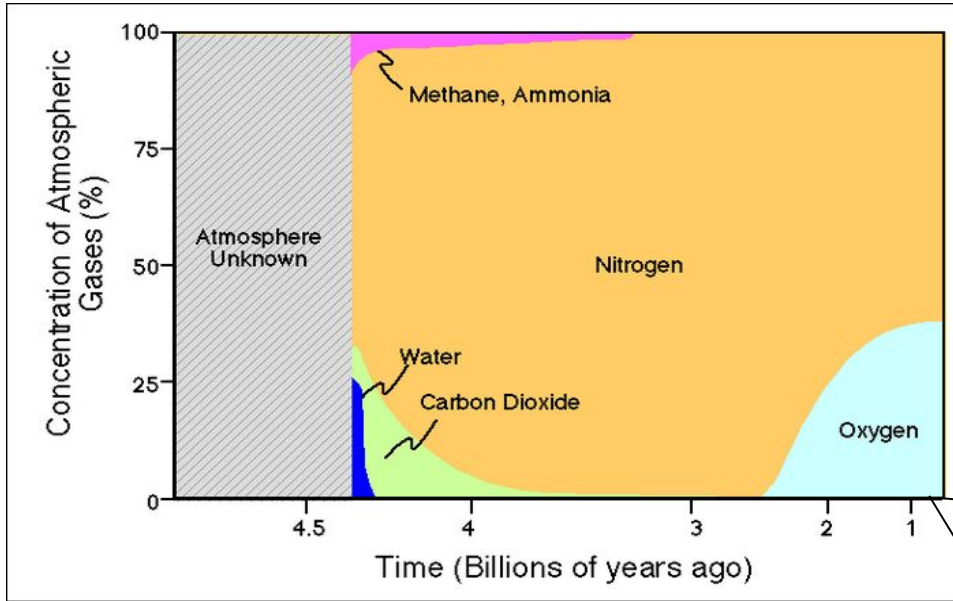
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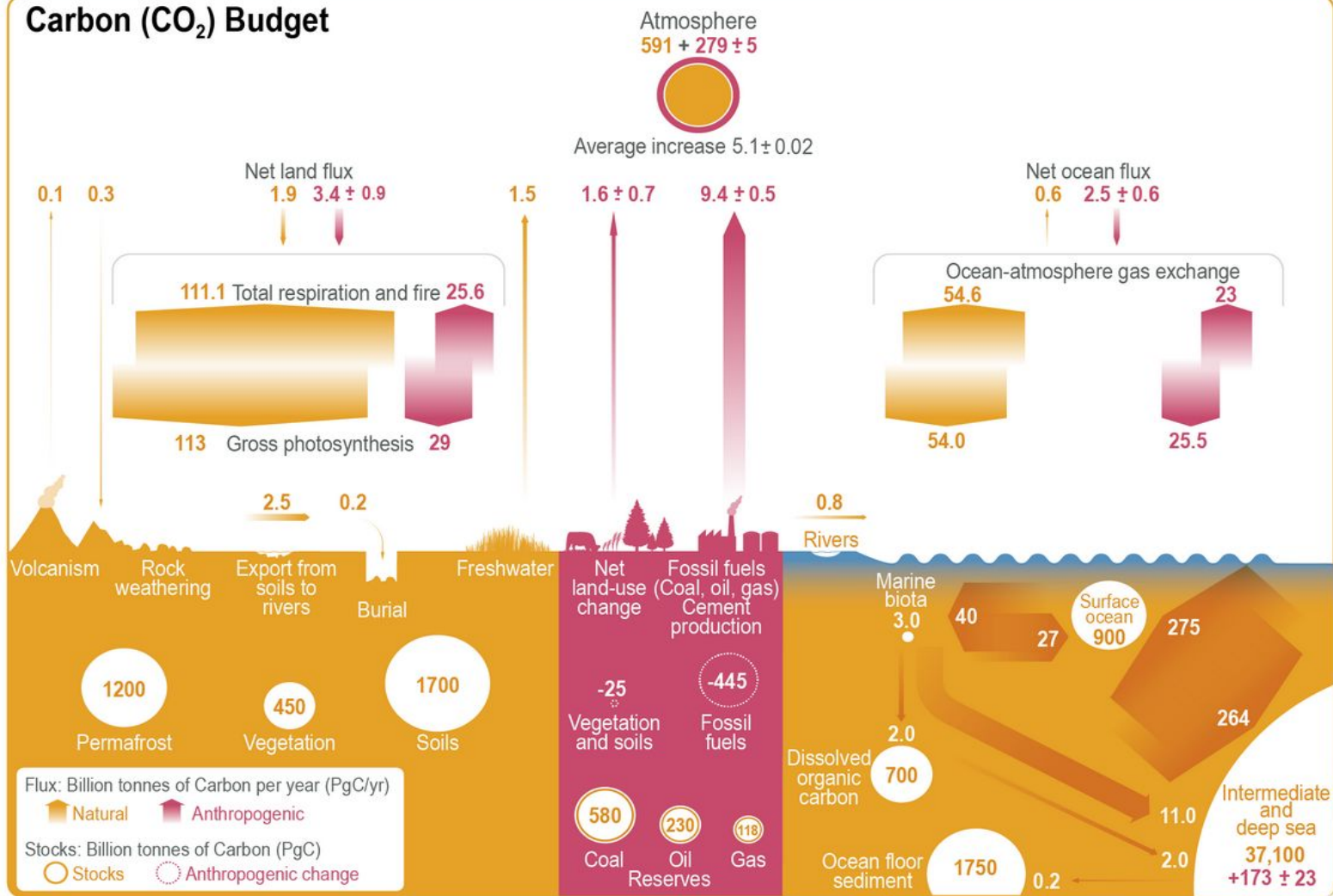
Wykorzystano slajdy dr Aleksandry Kardaś

Cykl węglowy, azotowy, zmiany w składzie atmosfery.

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



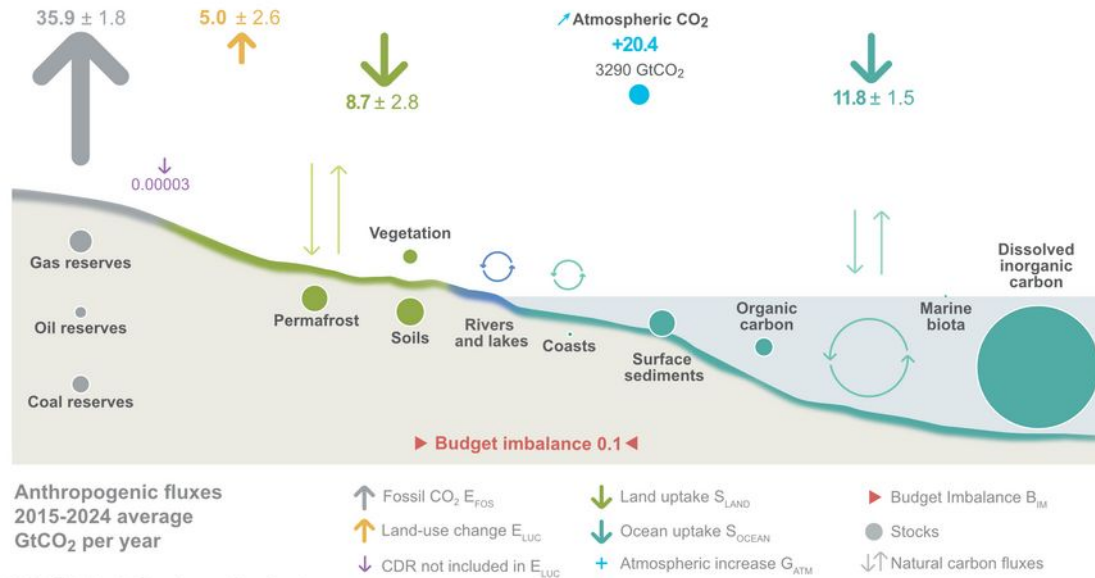
Carbon (CO₂) Budget



Anthropogenic perturbation of the global carbon cycle

Perturbation of the global carbon cycle caused by anthropogenic activities, global annual average for the decade 2015–2024 (GtCO₂/yr)

The global carbon cycle



CDR here refers to Carbo. © Global Carbon Project

r in the Land-use change

estimate.

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

Source: [NOAA-GML](#); [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Volcanic Contributions to the Global Carbon Cycle

Sustainable and Renewable Energy
Occasional Publication No. 10

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.

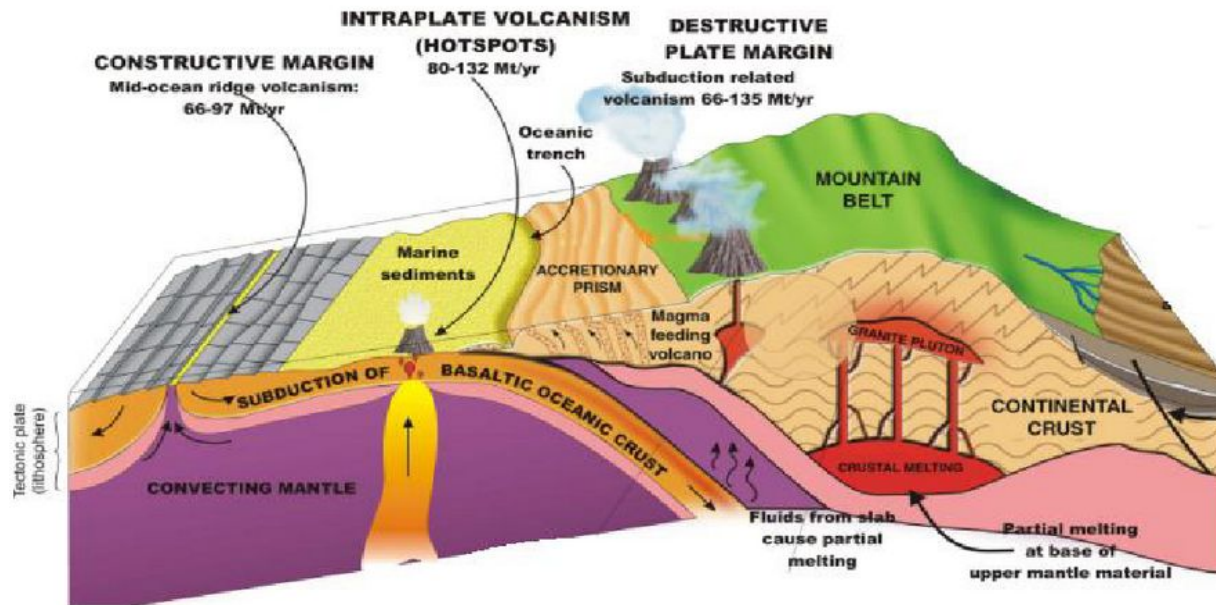
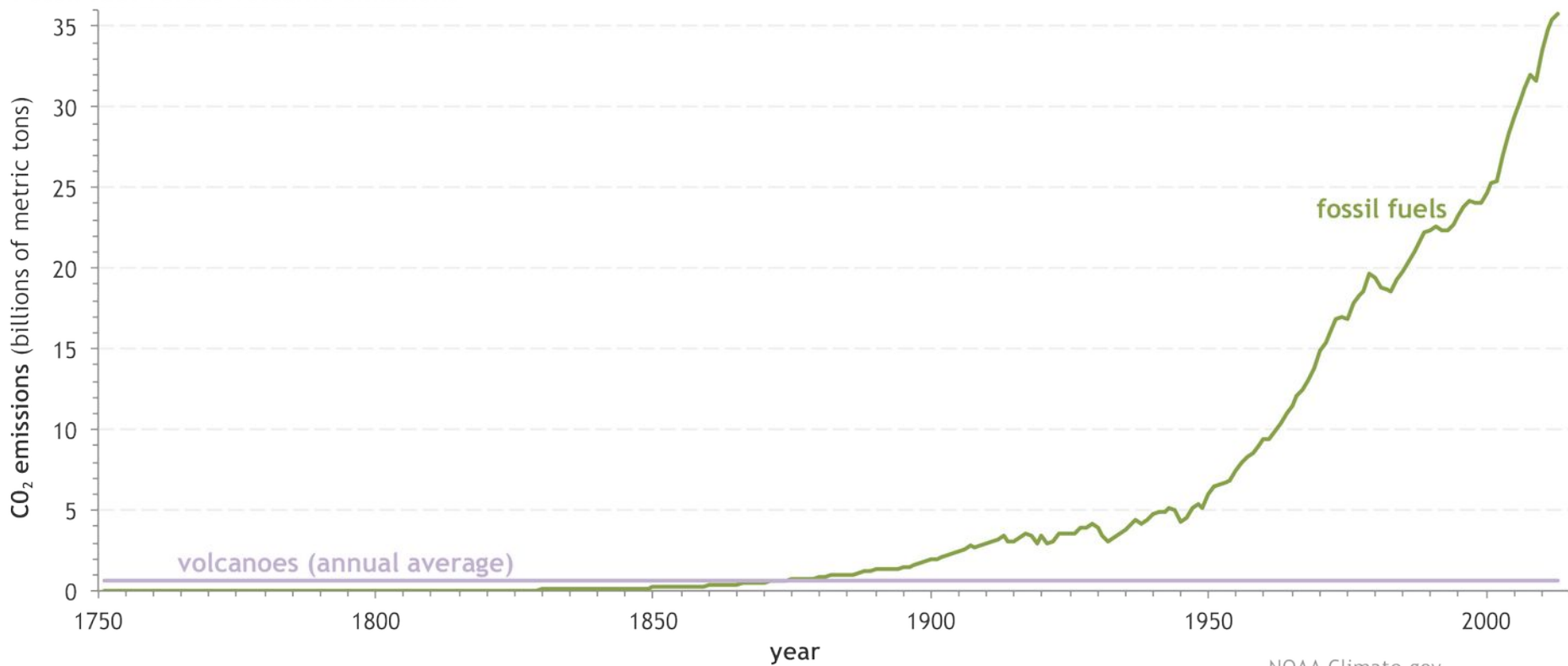


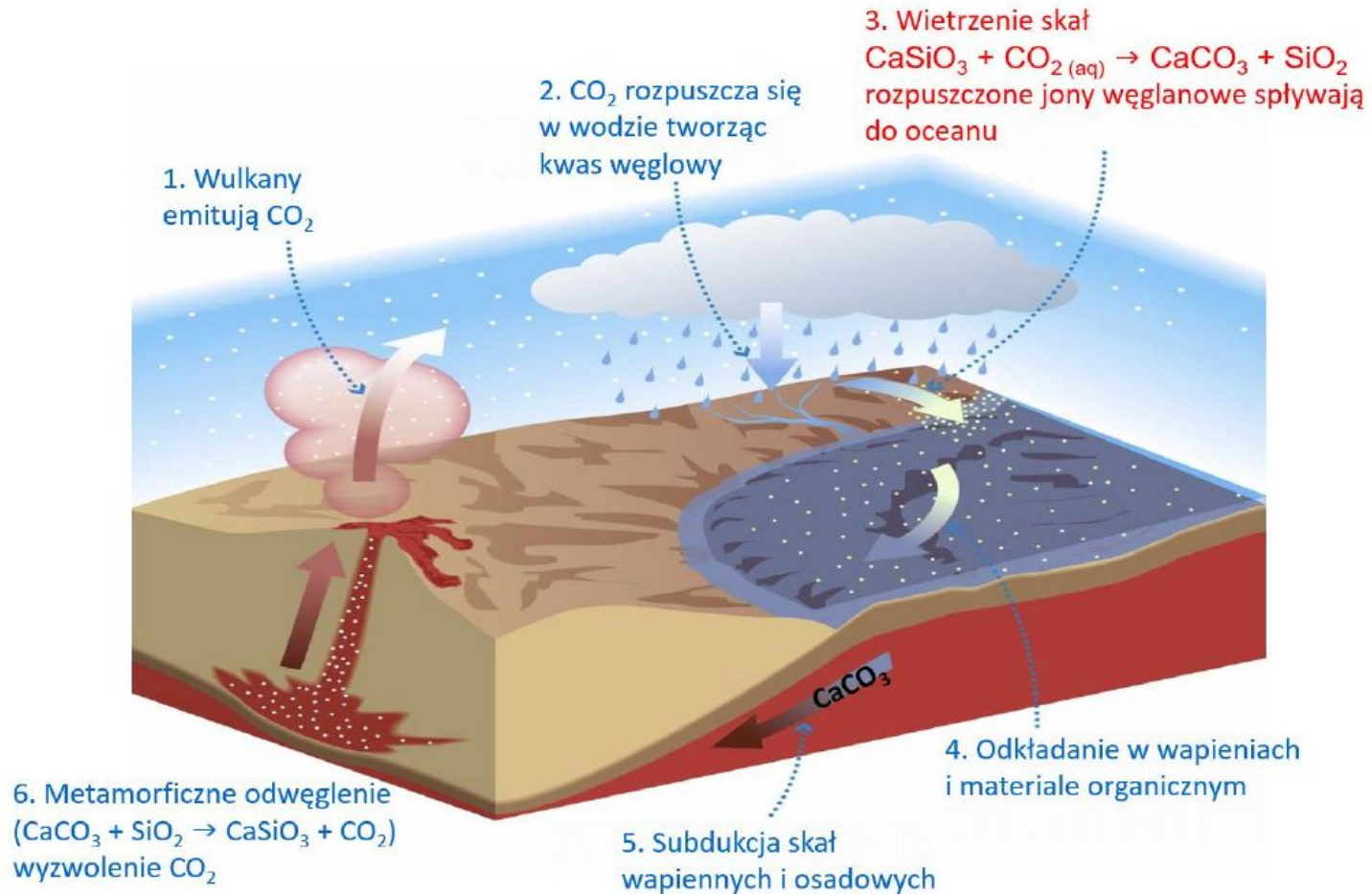
Figure 2. Diagrammatic representation of the different volcanic environments with estimates of CO₂ emission rates and their relationship to plate tectonic environment.

Emisje antropogeniczne CO₂ w stosunku do emisji wulkanicznych

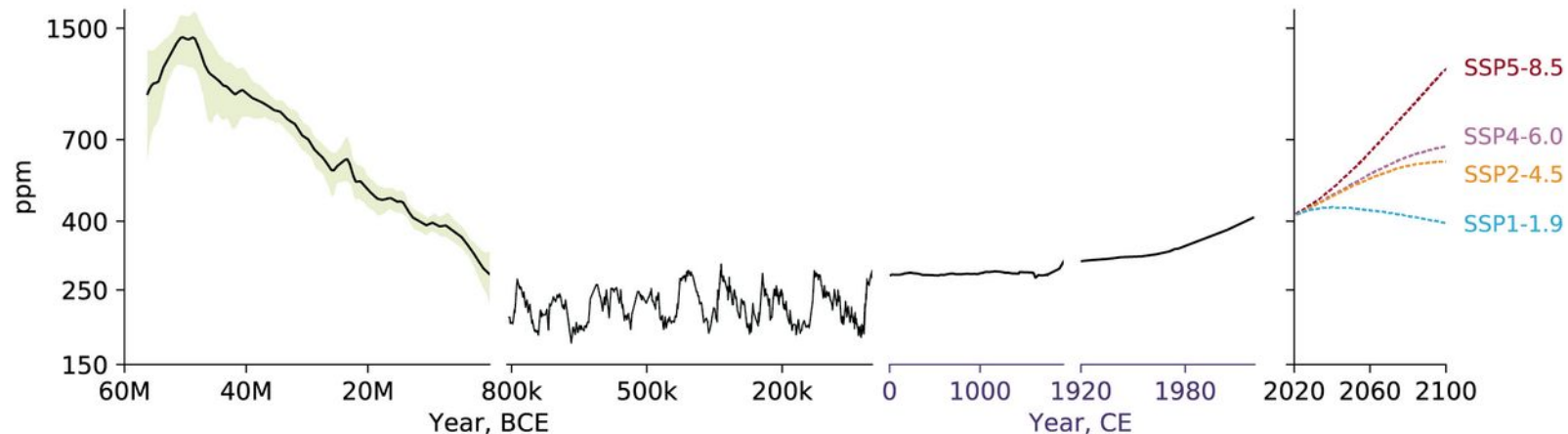
Fossil fuel versus volcanic emissions



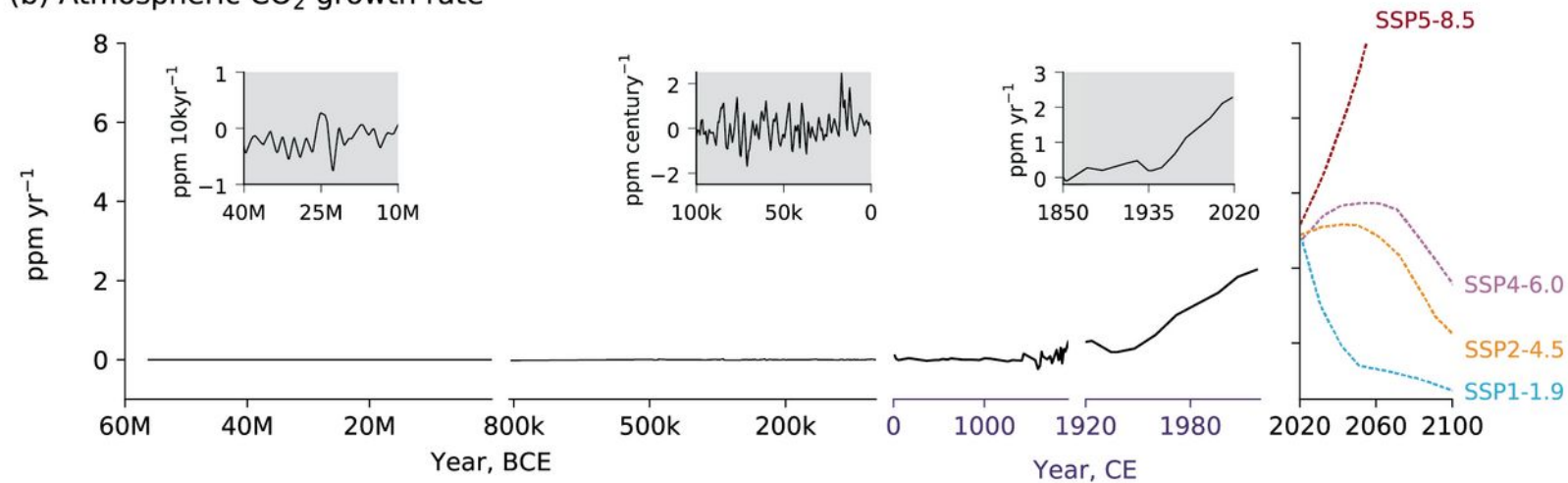
Termostat węglowy – tempo wietrzenia skał zależy od temperatury.

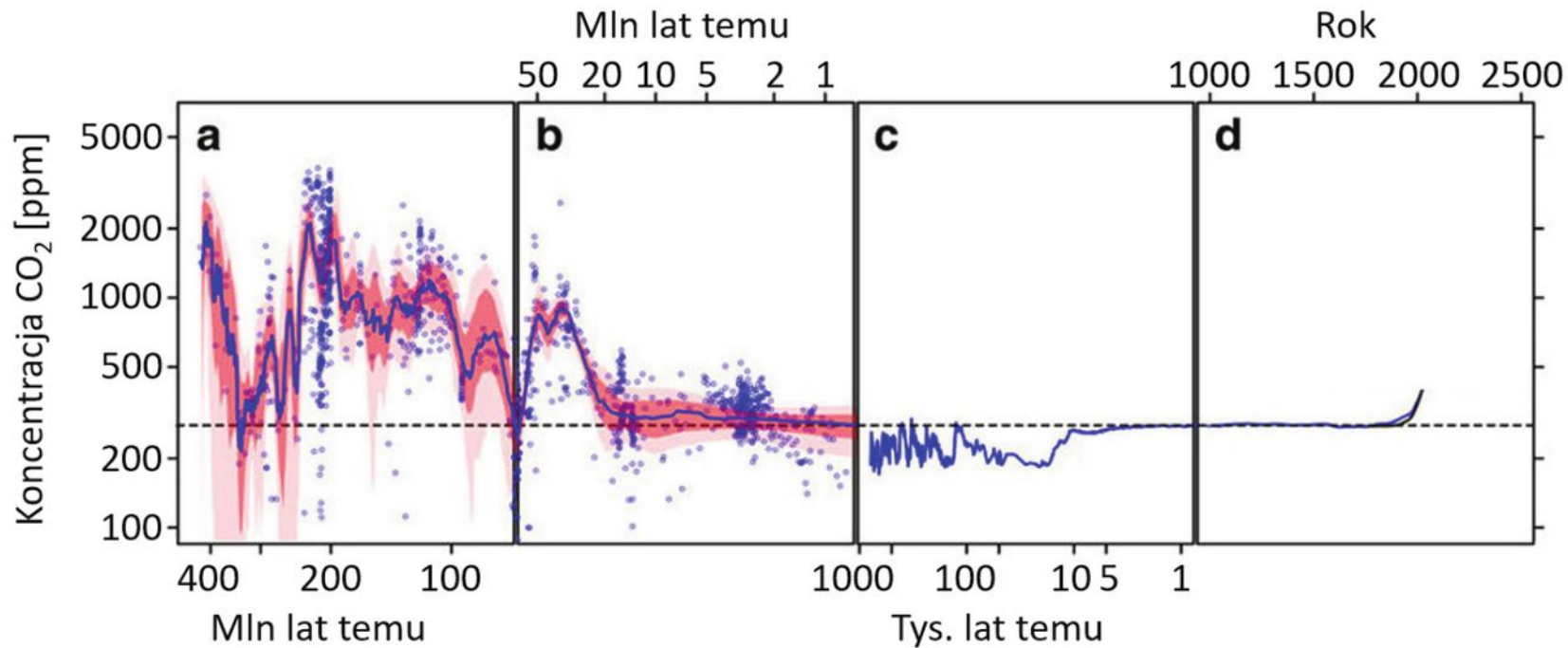


(a) Atmospheric CO₂ concentrations

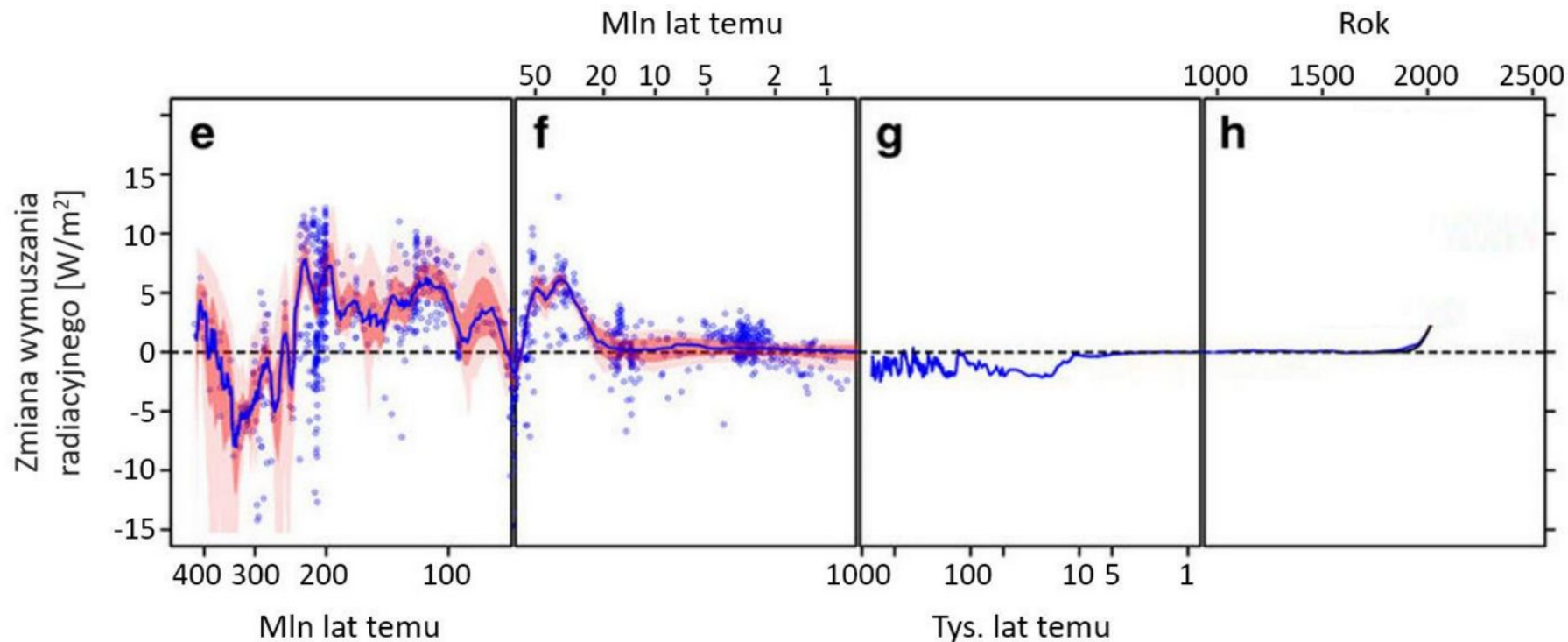


(b) Atmospheric CO₂ growth rate

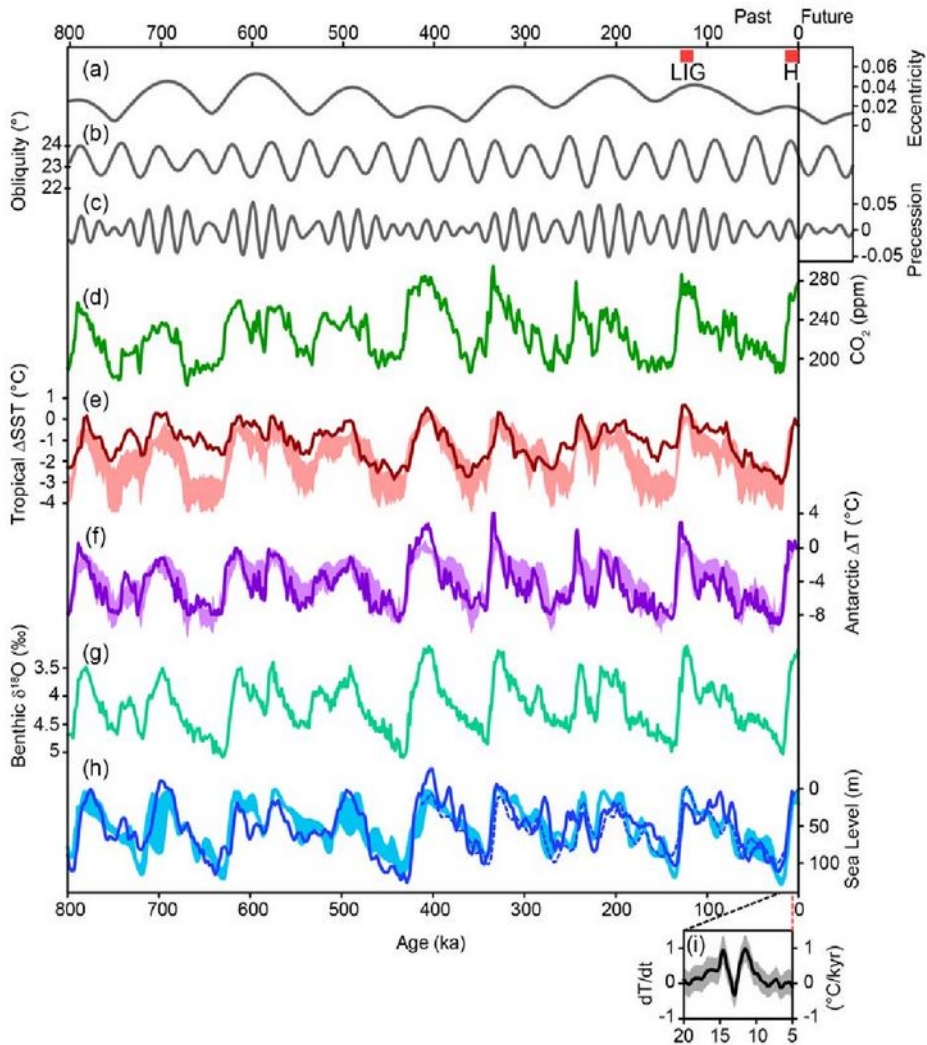




Ilustracja 1.2.11. Rekonstrukcja zmian koncentracji CO₂ w atmosferze w ostatnich 400 mln lat. UWAGA: skala czasowa nie jest liniowa. Panele a–b) na podstawie różnych wskaźników klimatycznych (niebieskie kropki odpowiadają konkretnym pomiarom, a linia – dopasowanej do nich krzywej, czerwona wstęga pokazuje 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 CO₂ i natężenia promieniowania słonecznego w ostatnich 420 mln lat. Czerwona obwódka pokazuje niepewność, z jaką wyznaczono wymuszenie, wynikającą z niepewności danych o stężeniach CO₂ 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).

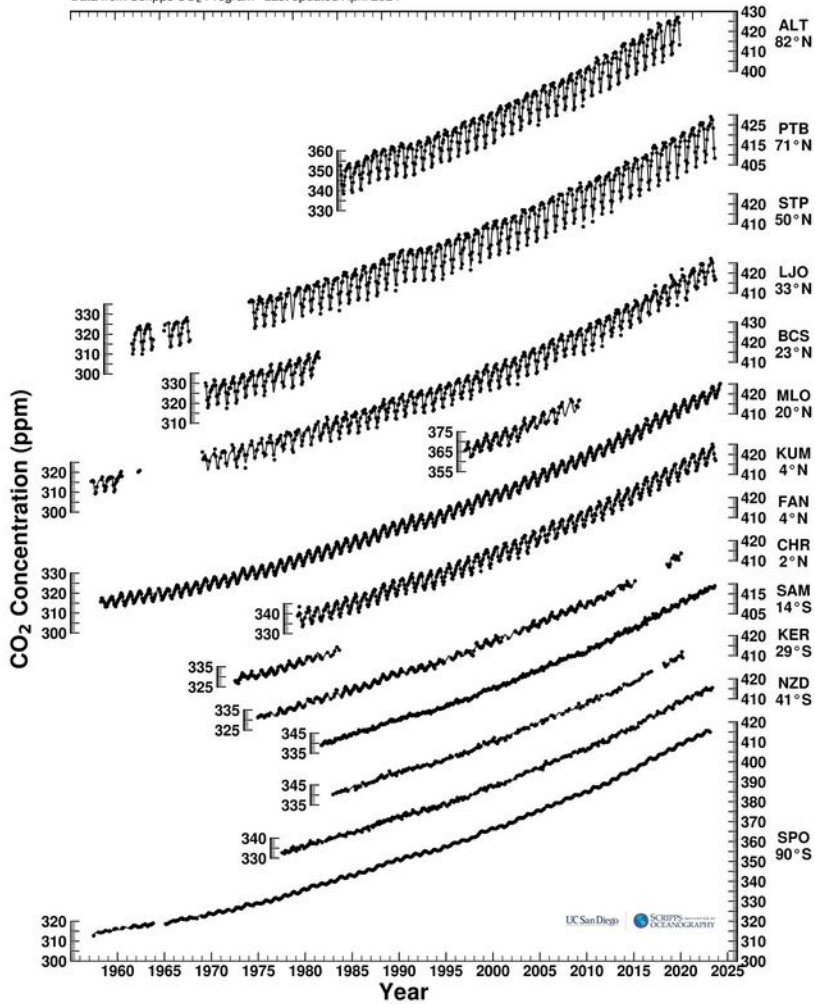
Fioletowe – temperatura Antarktydy (cienka linia – rekonstrukcje paleoklimatyczne, szerszy pas – odtworzenie w modelach klimatu).

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

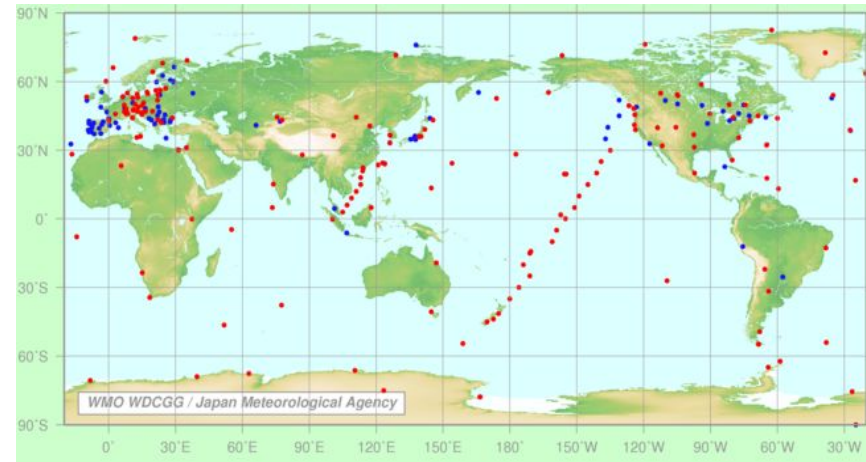
Data from Scripps CO₂ Program Last updated April 2024

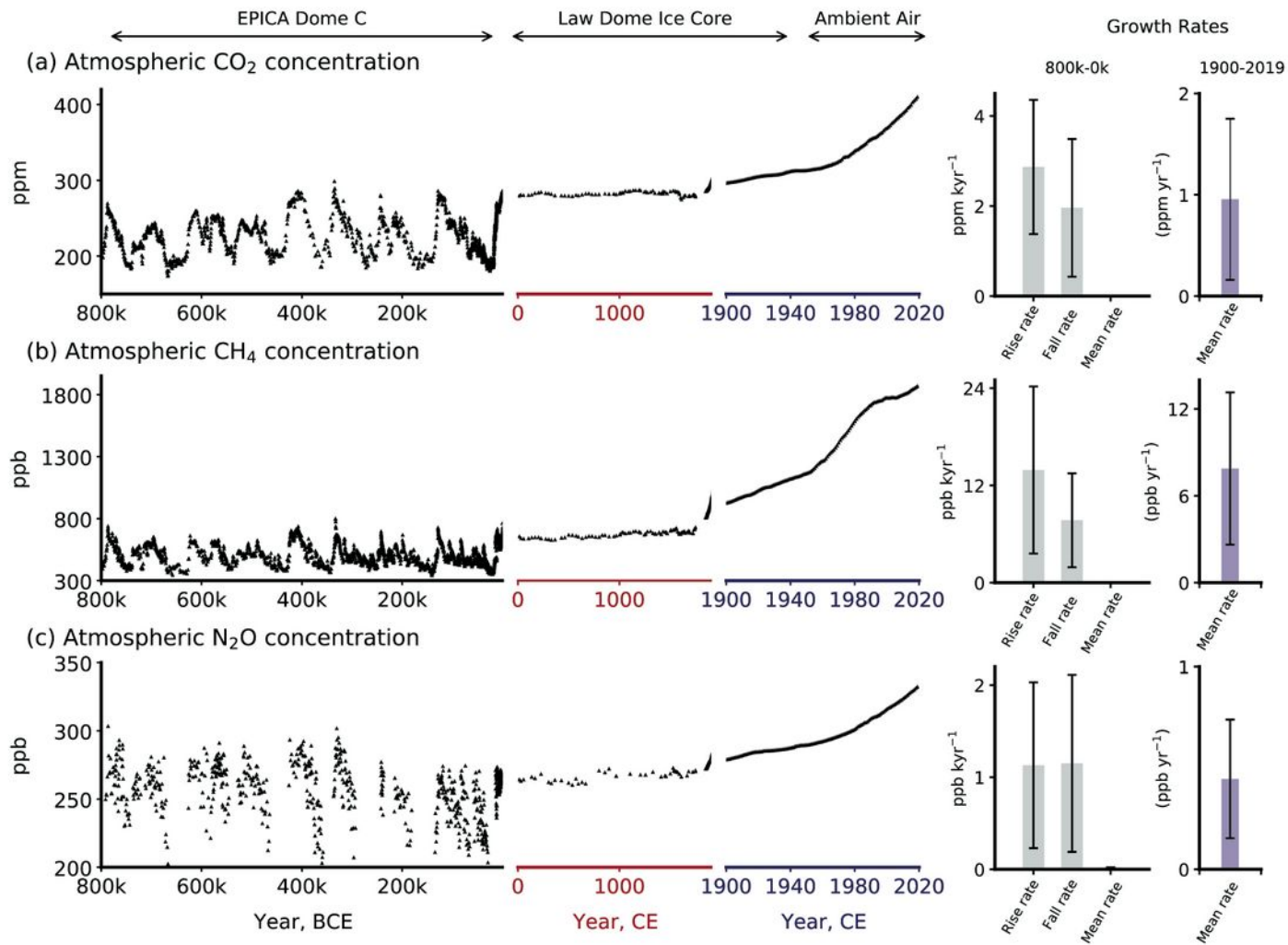


Regularne pomiary CO₂ i innych gazów atmosferycznych są zbierane w WMO World Data Centre for Greenhouse Gases (WDCGG)

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

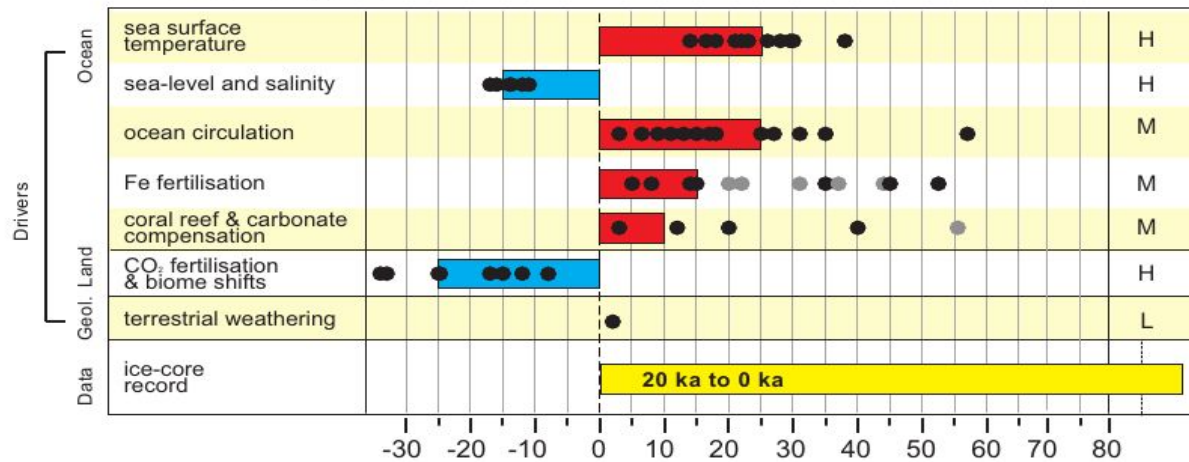
<http://scrippsco2.ucsd.edu/>



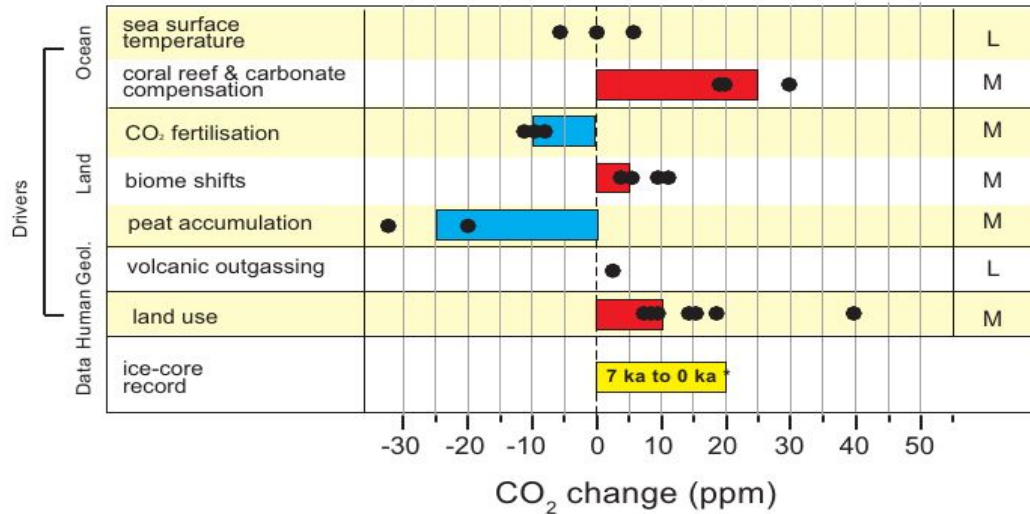


Zmiany w koncentracji atmosferycznych CO₂, CH₄ i N₂O

Glacial to Interglacial



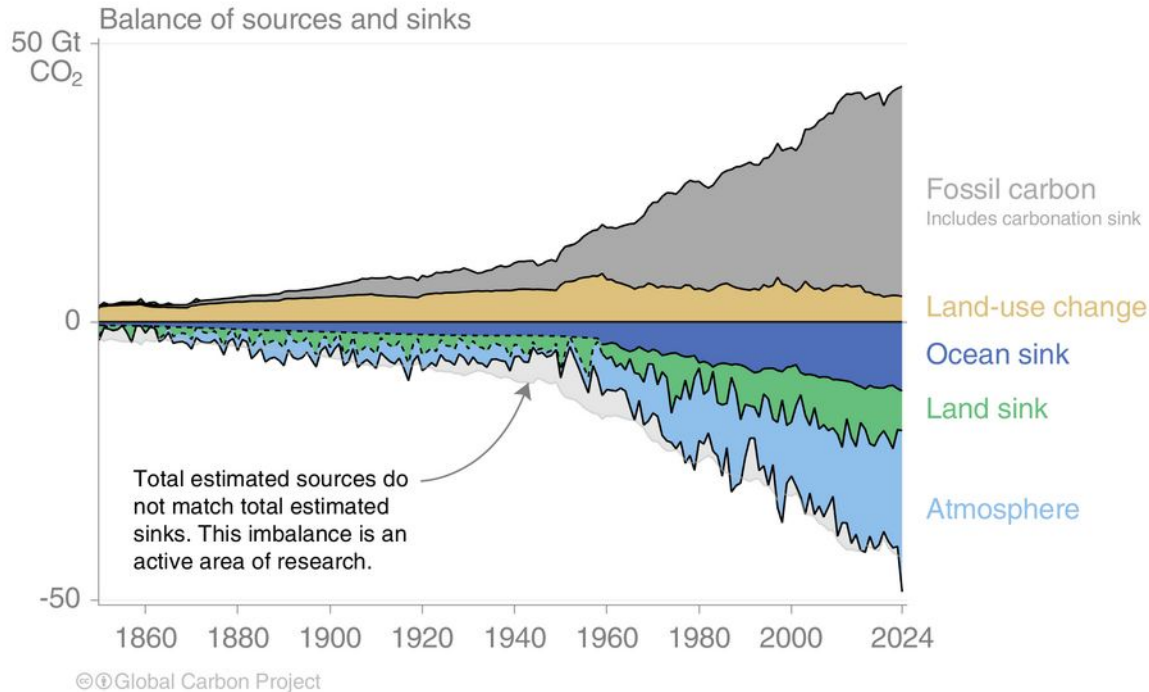
Holocene



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

Global carbon budget

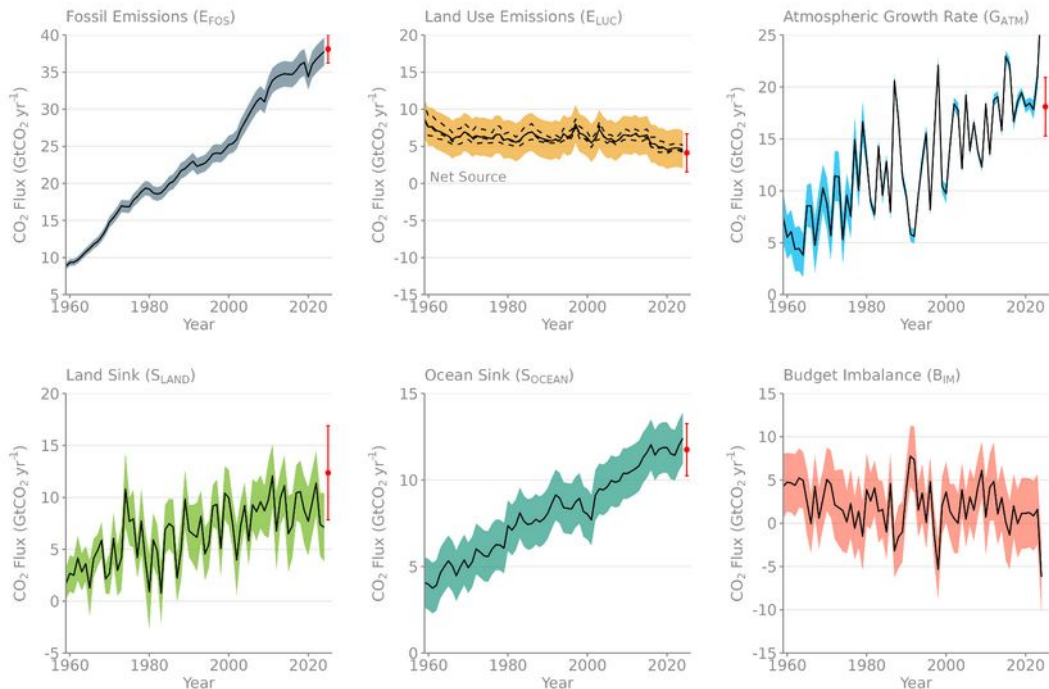
Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean
 The “imbalance” between total emissions and total sinks is an active area of research



Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Changes in the budget over time

The sinks have continued to grow with increasing emissions, but climate change affects carbon cycle processes in a way that will exacerbate the increase of CO₂ in the atmosphere



The budget imbalance is the total emissions minus the estimated growth in the atmosphere, land and ocean.

It reflects the limits of our understanding of the carbon cycle.

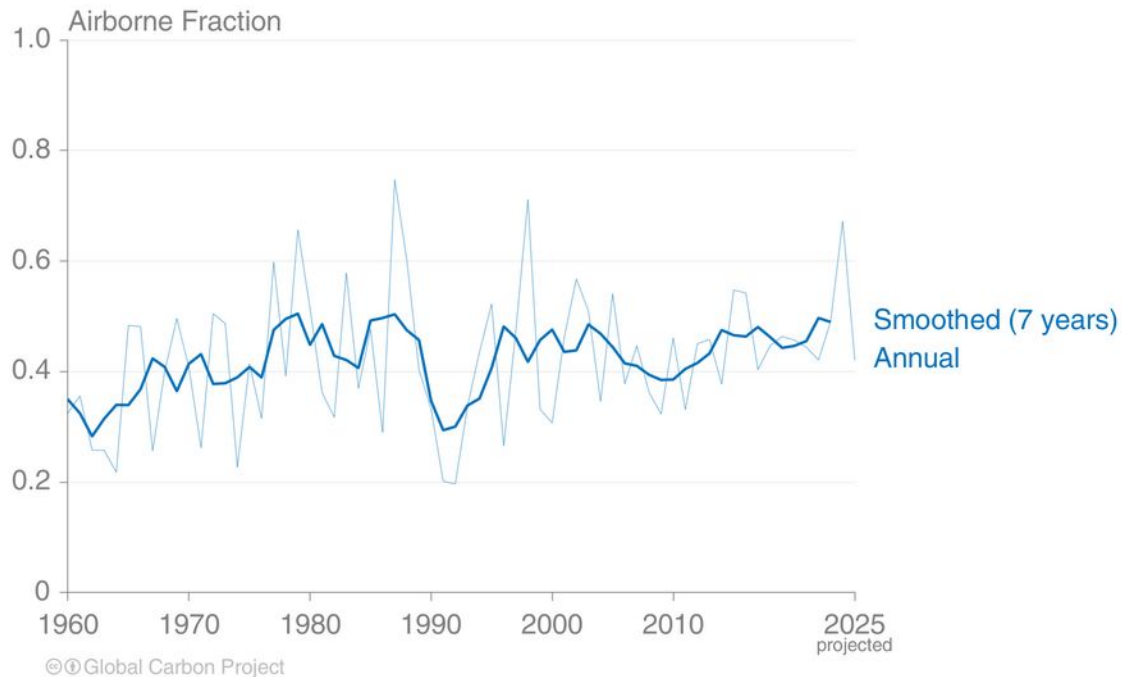
Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Airborne Fraction

The airborne fraction is the proportion of the total annual CO₂ emissions that remains in the atmosphere.

The rest of the CO₂ emissions are removed by the land and ocean sinks.

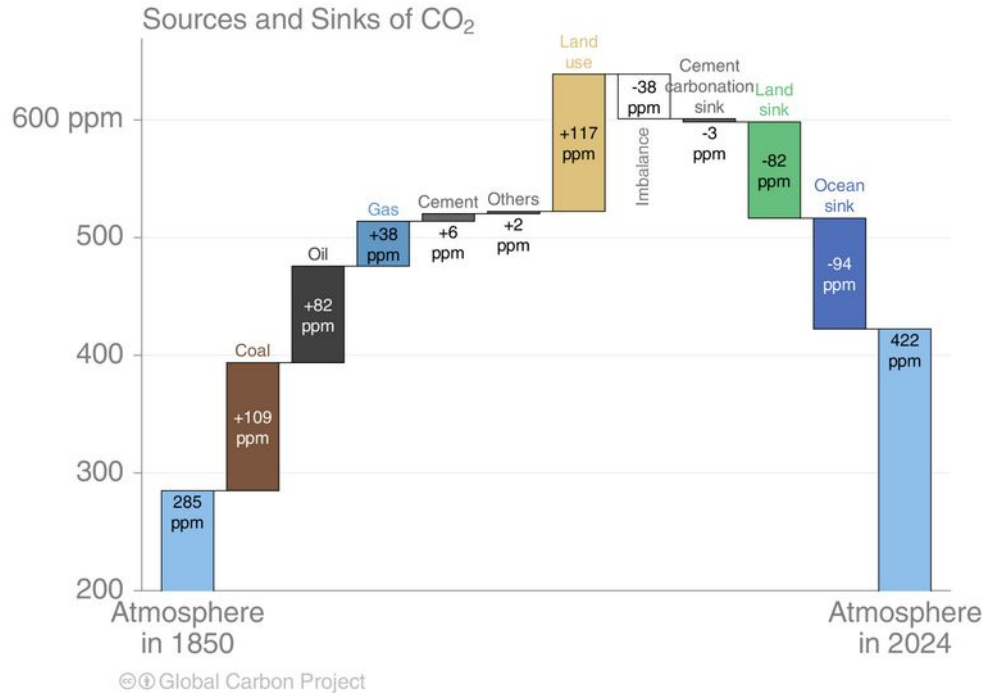
Around 45% of CO₂ emissions remain in the atmosphere despite sustained growth in CO₂ emissions.



Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Global carbon budget

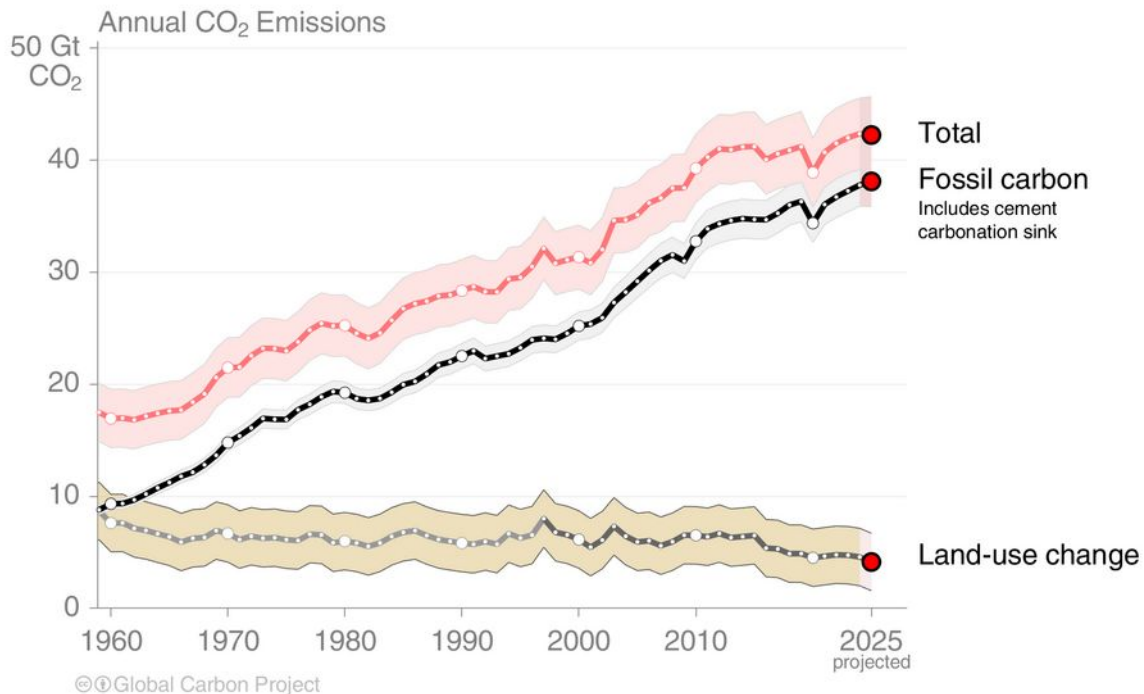
The cumulative contributions to the global carbon budget from 1850
 The carbon imbalance represents the gap in our current understanding of sources & sinks



Total global emissions

Total global emissions, projected to reach 42.2 ± 3.2 GtCO₂ in 2025, 49% over 1990

Percentage land-use change: 45% in 1960, 12% averaged 2015–2024

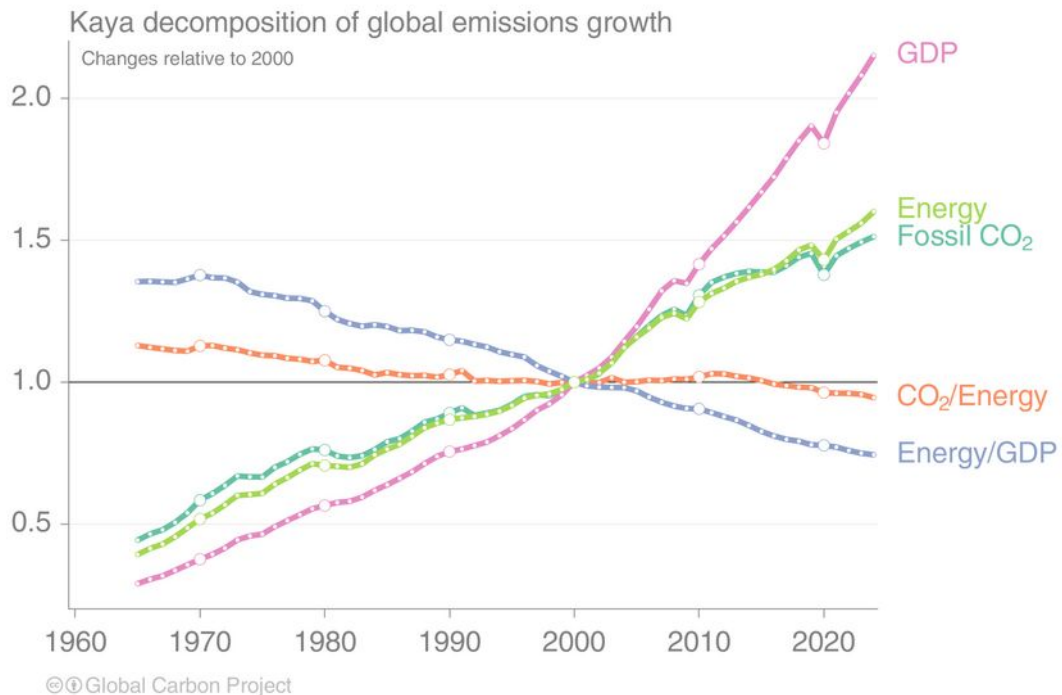


Land-use change estimates from four bookkeeping models, using fire-based variability from 1997

Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Kaya decomposition

The Kaya decomposition illustrates that relative decoupling of economic growth from CO₂ emissions is driven by improved energy intensity (Energy/GDP) and, recently, carbon intensity of energy (CO₂/Energy)

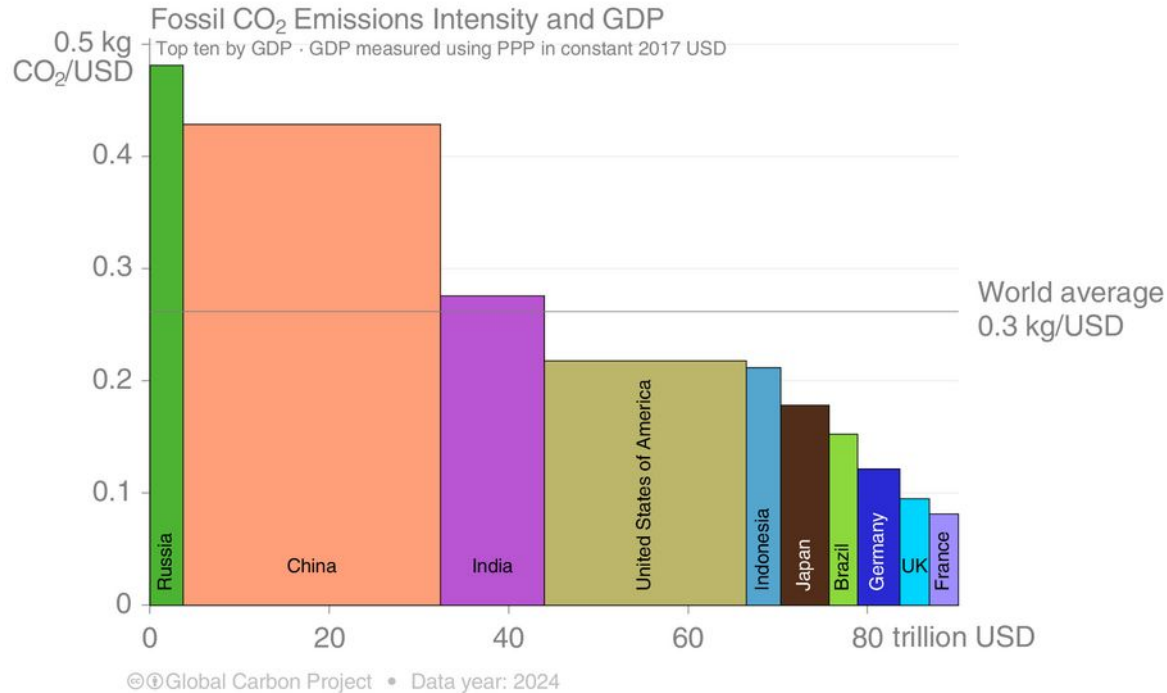


GDP: Gross Domestic Product (economic activity)

Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Fossil CO₂ emission intensity

The 10 largest economies have a wide range of emission intensity of economic activity

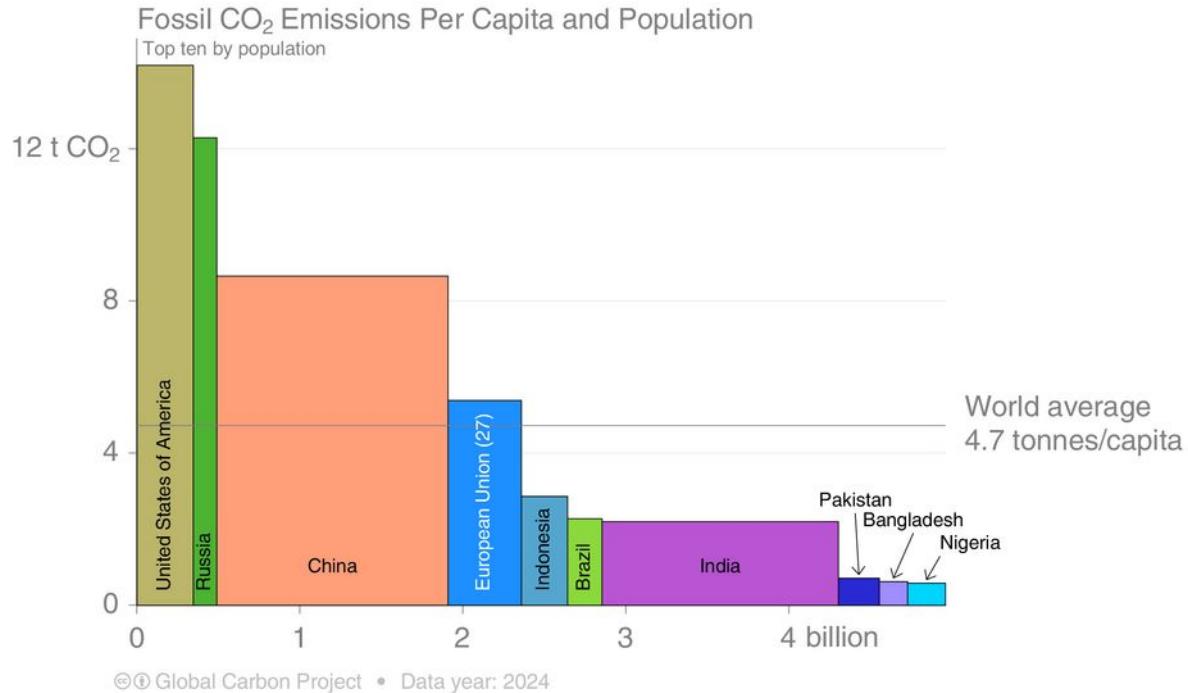


Emission intensity: Fossil CO₂ emissions divided by Gross Domestic Product (GDP)

Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Fossil CO₂ Emissions per capita

The 10 most populous countries span a wide range of development and emissions per capita

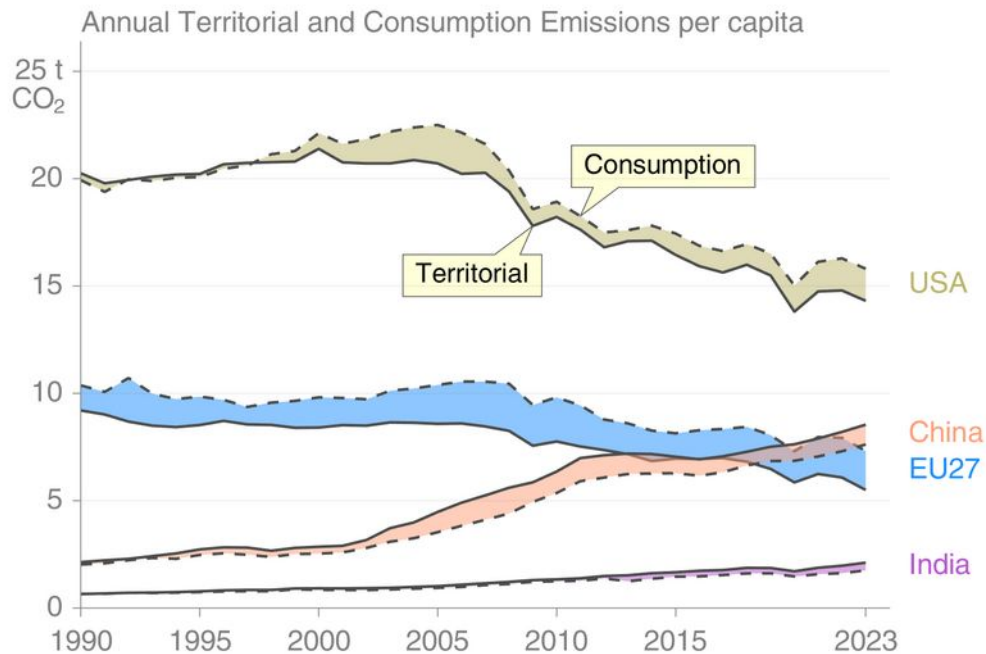


Emission per capita: Fossil CO₂ emissions divided by population

Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Consumption-based emissions per person

The differences between fossil CO₂ emissions per capita is larger than the differences between consumption and territorial emissions.



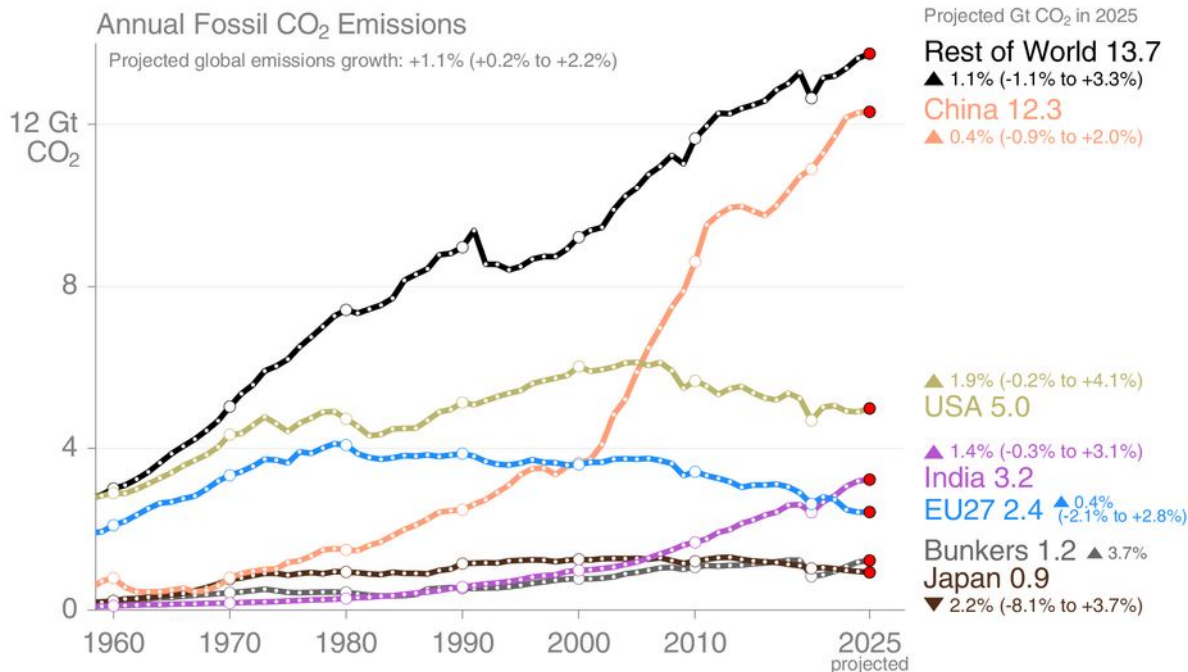
© Global Carbon Project

Consumption-based emissions are calculated by adjusting the standard emissions estimates to account for international trade

Source: [Peters et al 2011](#); [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

Emissions Projections for 2025

Fossil CO₂ emissions growth is from different regions in 2025 compared to 2024:
 The USA rising, and EU27 flat, reversing recent declines. China flat, India low growth,



© Global Carbon Project • Global growth rate includes cement carbonation sink

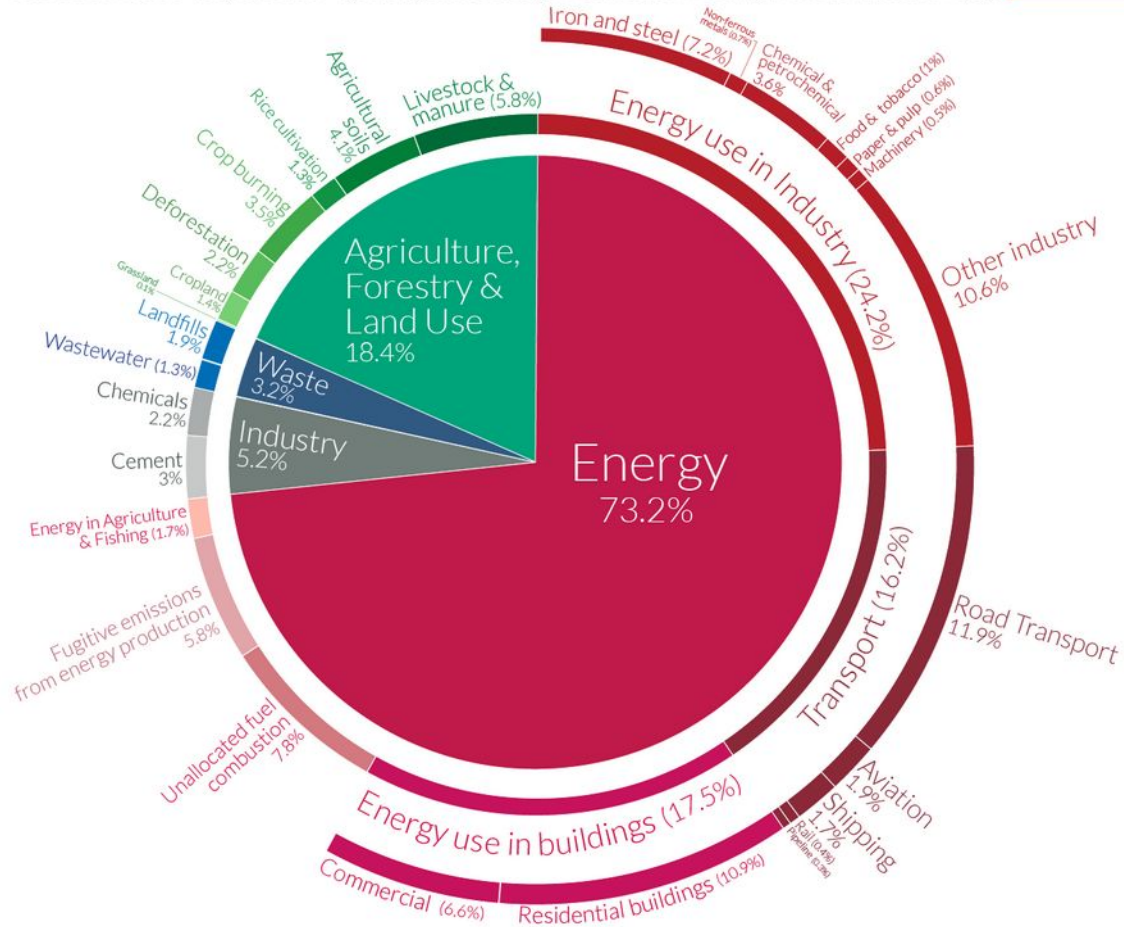
The 2025 projections are based on preliminary data and modelling.

'Bunkers' are fossil fuels used for international shipping and aviation

Source: [Friedlingstein et al 2025](#); [Global Carbon Project 2025](#)

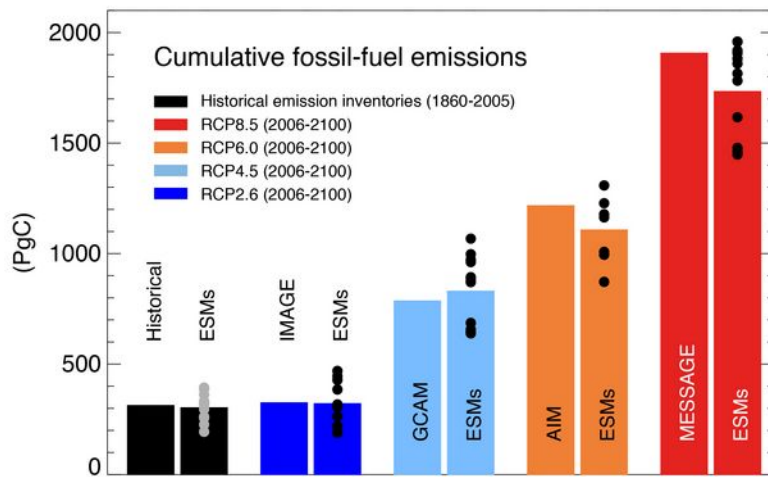
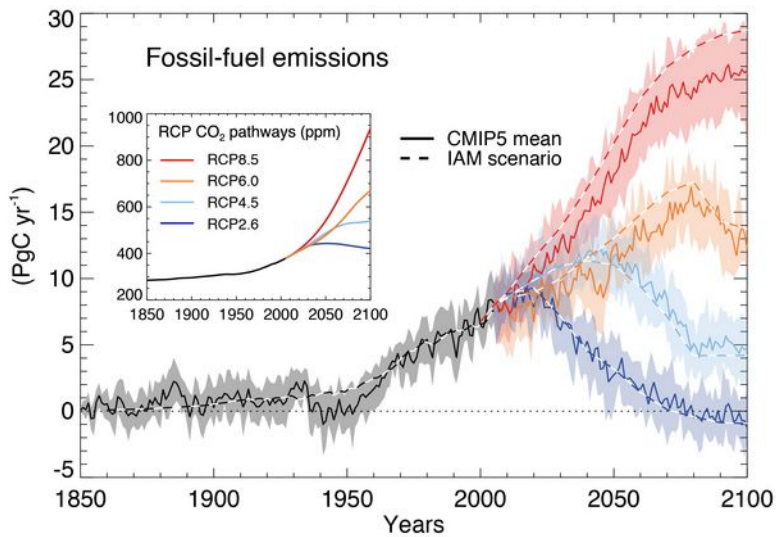
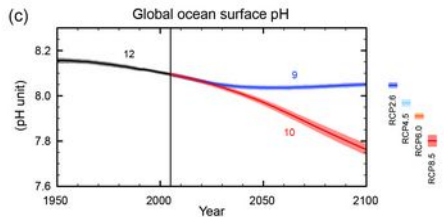
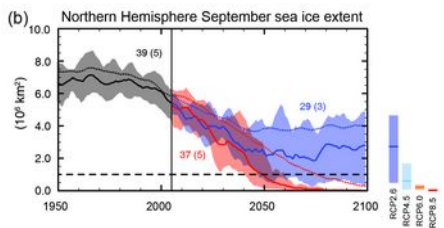
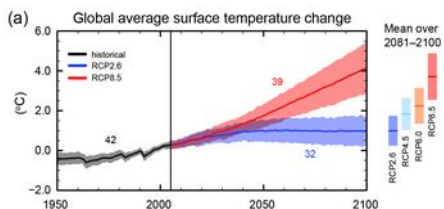
Global greenhouse gas emissions by sector

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO₂eq.



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

RCP – Representative Concentration Pathways



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.

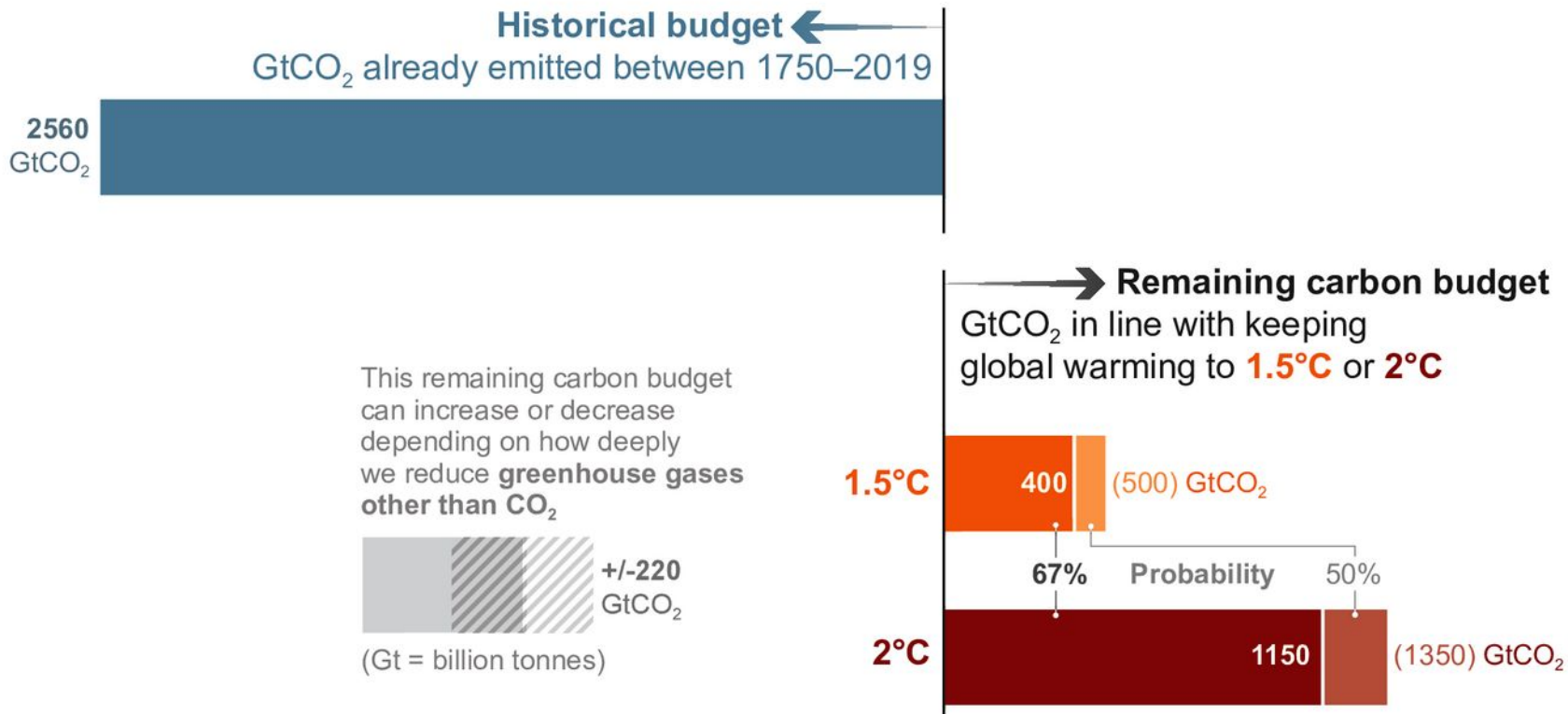
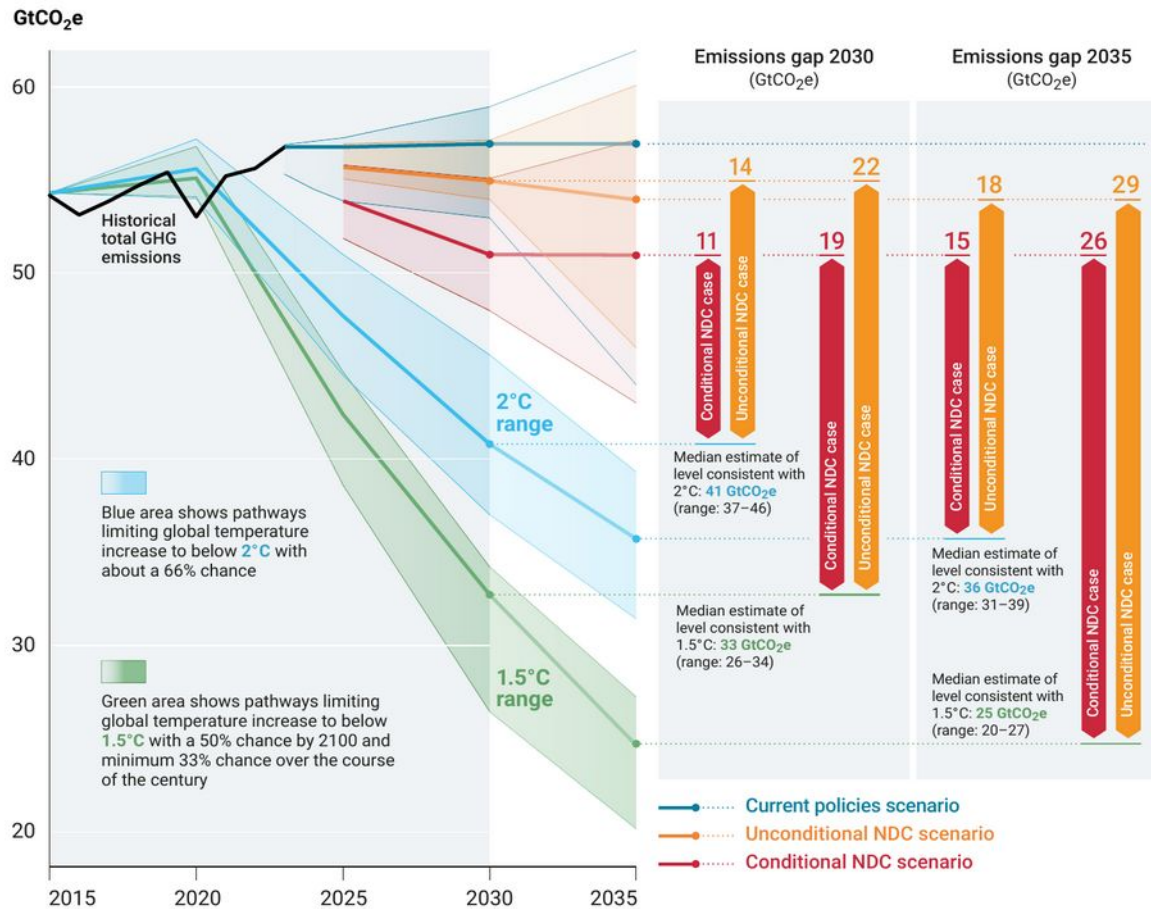
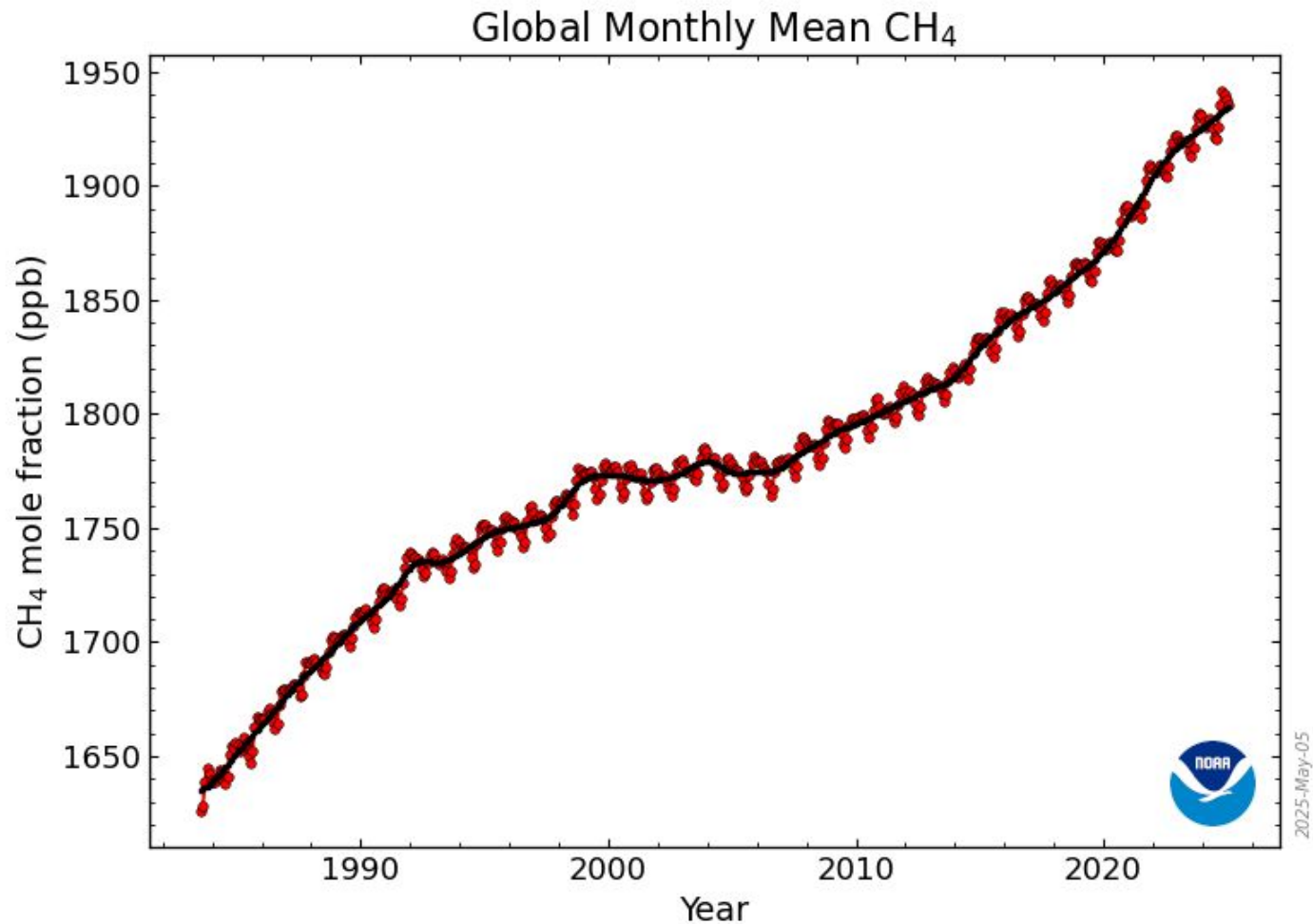


Figure ES.3 Global GHG emissions under different scenarios and the emissions gap in 2030 and 2035



Nie tylko CO₂:

Wzrost koncentracji
metanu w atmosferze



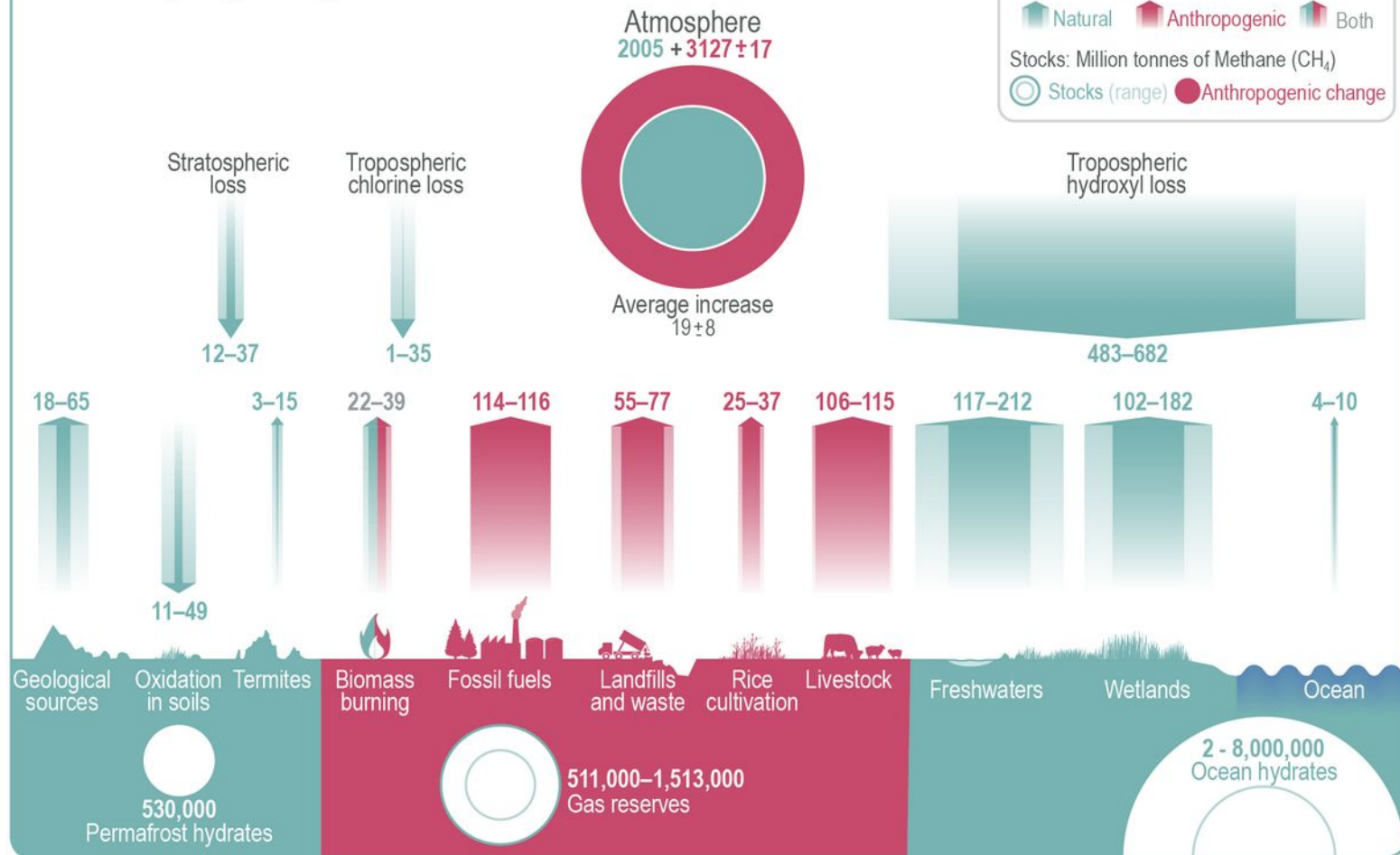
Methane (CH₄) Budget

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

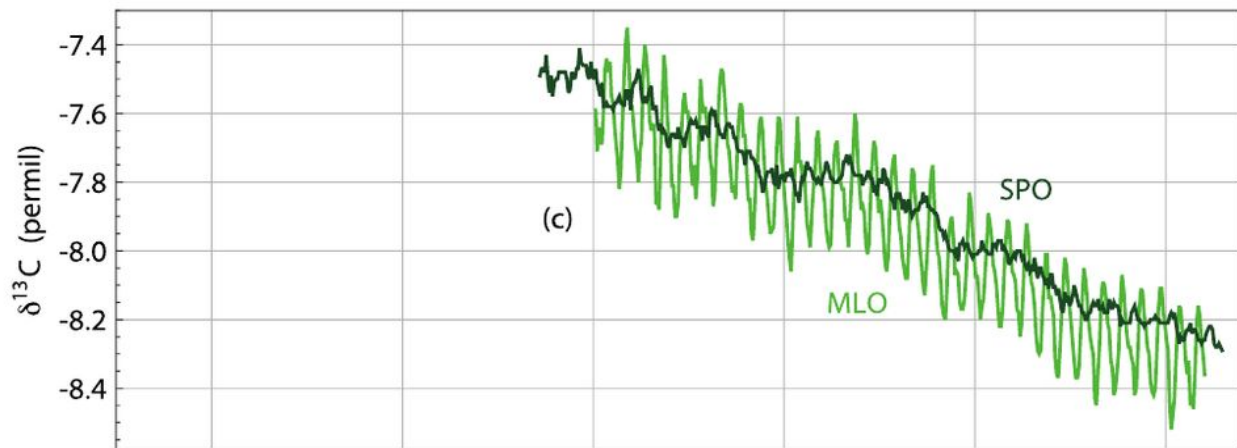
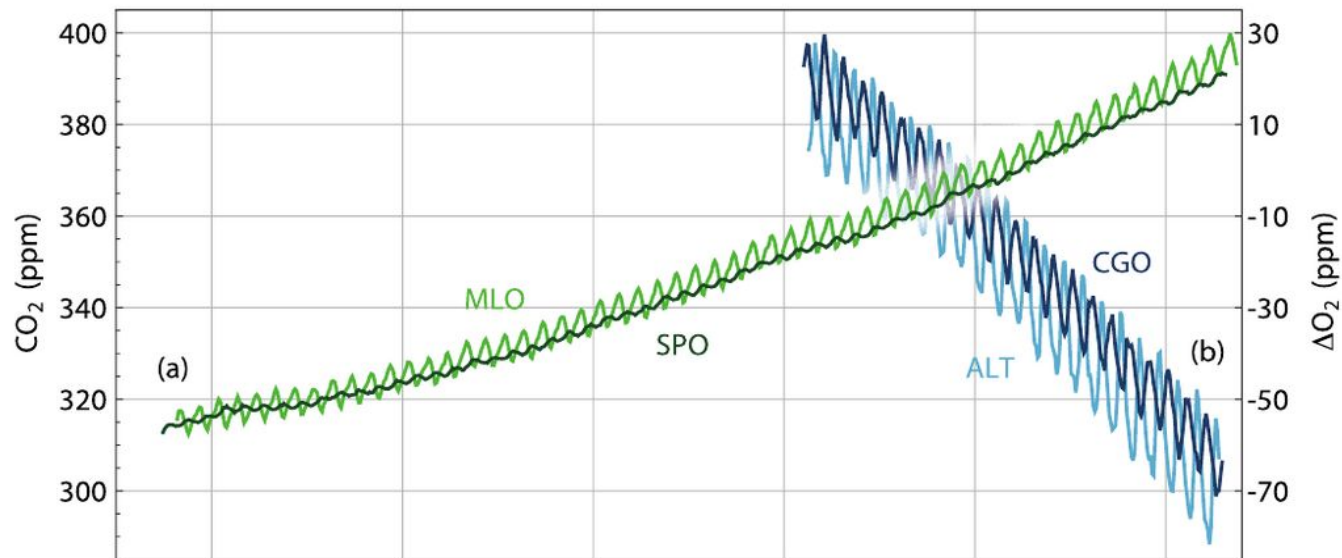
▮ Natural
 ▮ Anthropogenic
 ▮ Both

Stocks: Million tonnes of Methane (CH₄)

○ Stocks (range)
 ● Anthropogenic change

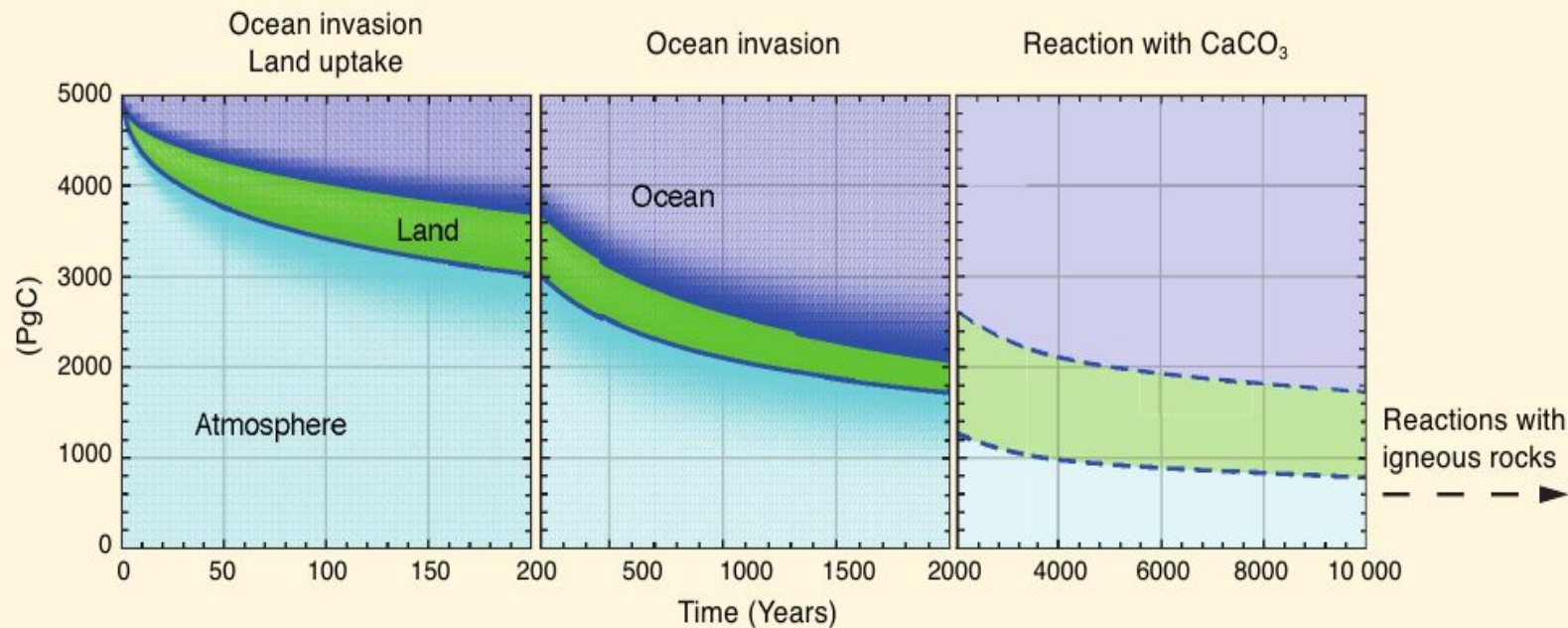


Inne dowody (poza bilansem węgla) na to że wzrost koncentracji CO₂ w atmosferze pochodzi ze spalania paliw kopalnych



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).

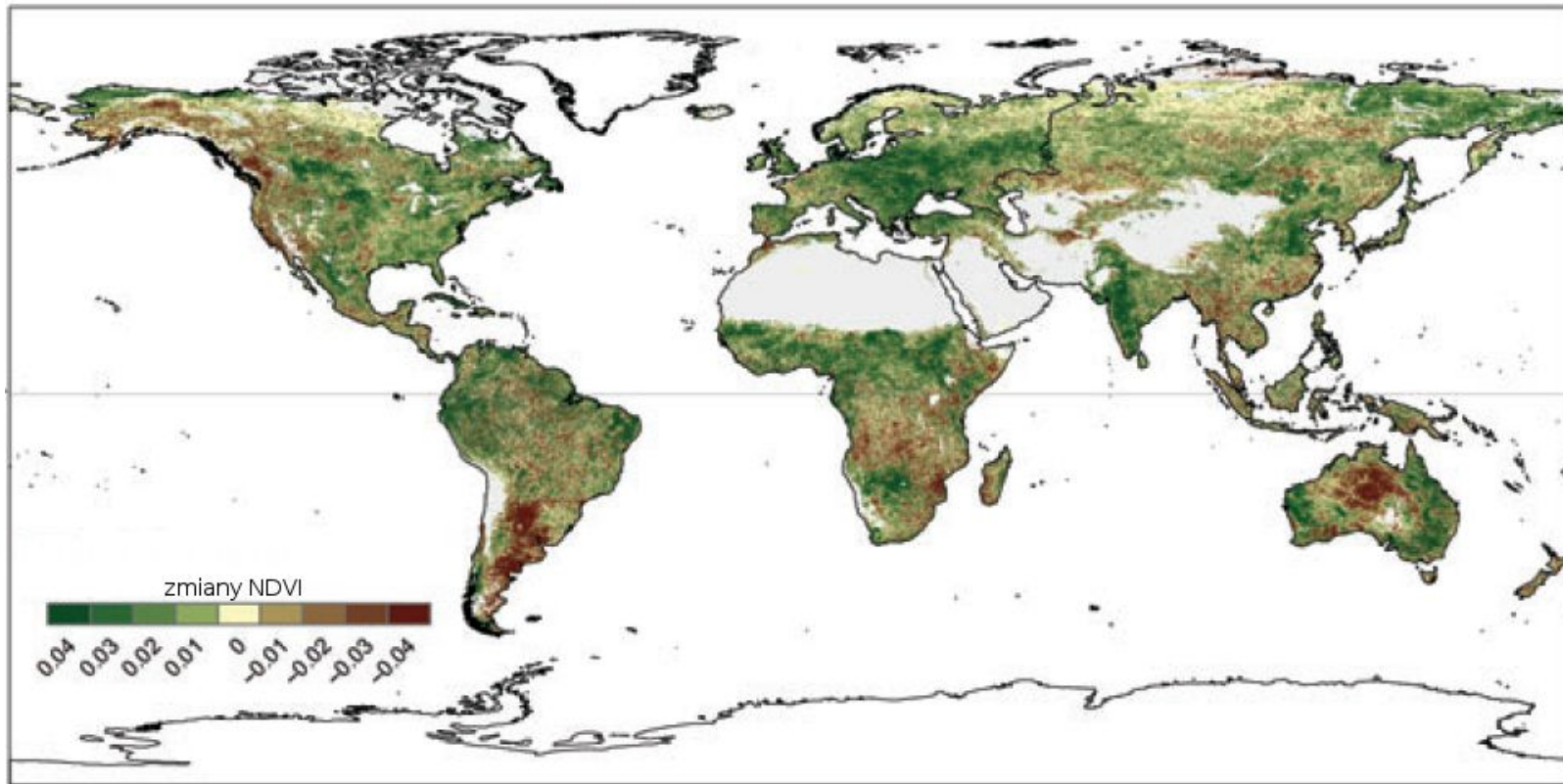
Główne procesy naturalne odpowiedzialne za usuwanie dwutlenku węgla z atmosfery po nagłym wzroście koncentracji tego gazu w atmosferze.

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.

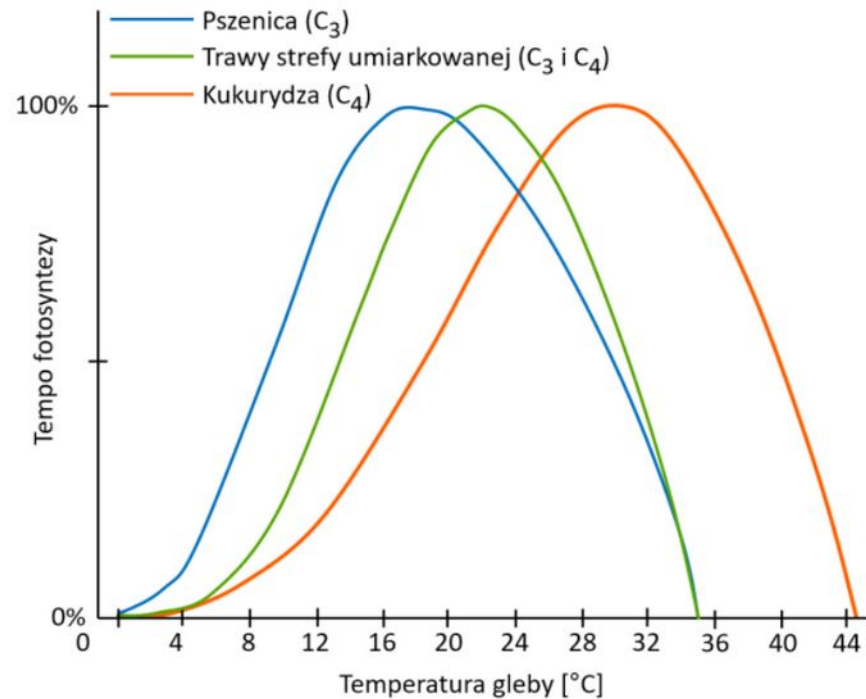
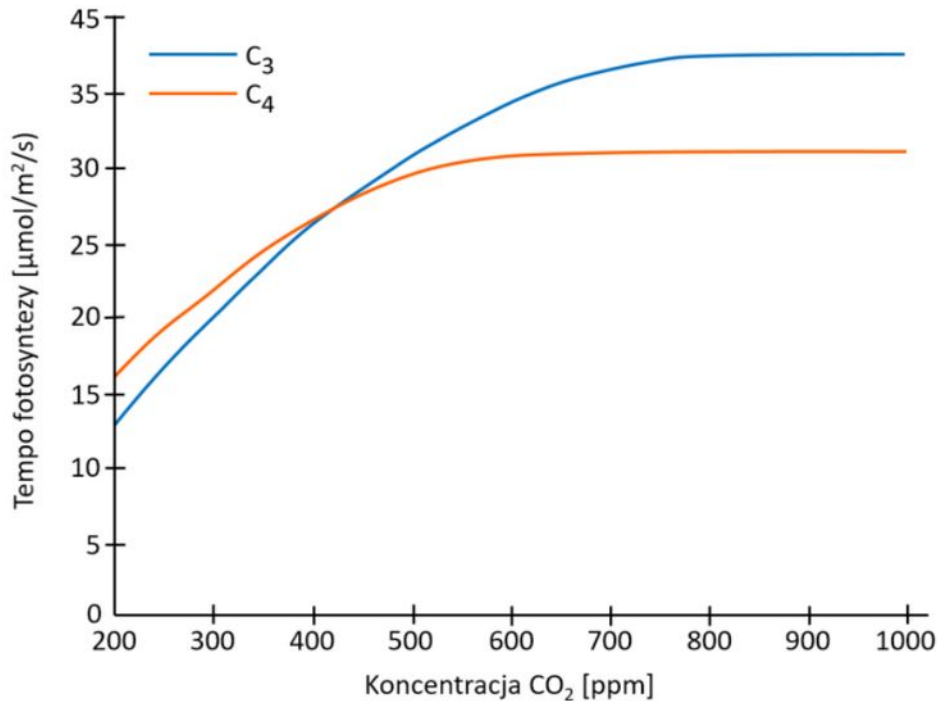
Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	1–10 ²	$6\text{CO}_2 + 6\text{H}_2\text{O} + \text{photons} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$ $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{heat}$
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

Czy więcej CO₂ w atmosferze oznacza większą produkcję roślinną?

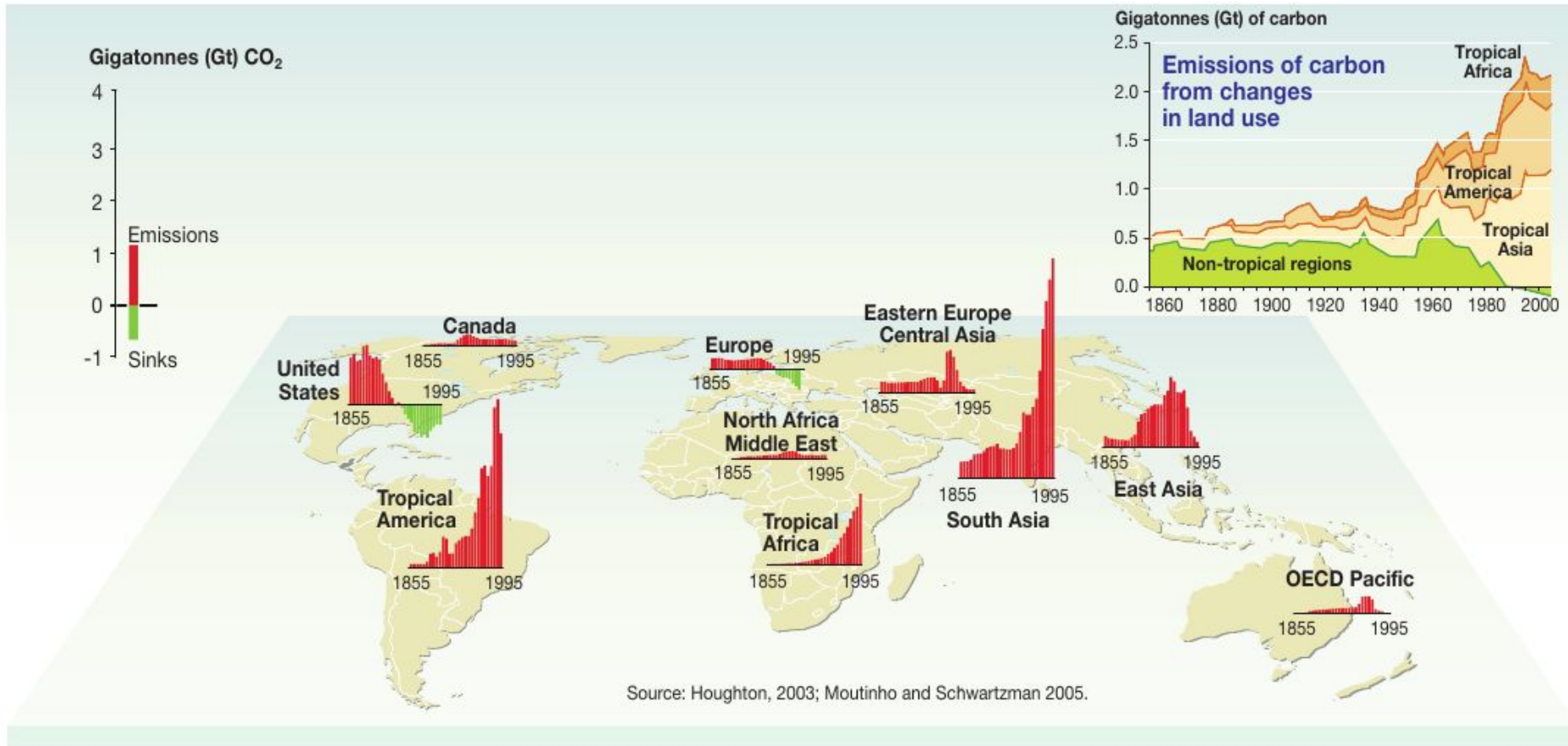


Zmiany wskaźnika NDVI (Normalized Difference Vegetation Index) w okresie 1982-2008. Globalne ocieplenie zmniejsza produktywność roślin. W miarę jak przybywa dwutlenku węgla, na półkuli północnej rosną wartości wskaźnika NDVI (obszary oznaczone na mapie kolorem zielonym), co oznacza zdrową i rozwijającą 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.

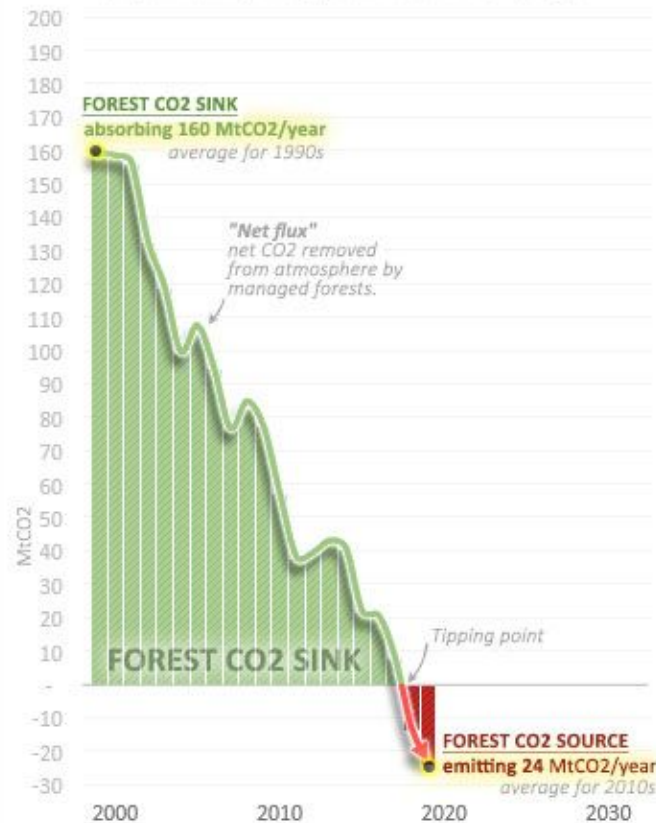
Historical forest carbon balance, 1855-1995



Rola lasów w bilansie węgla

CANADA'S MANAGED FOREST CO₂

ten-year running average trend lines :: MtCO₂ per year



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 6-5). 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

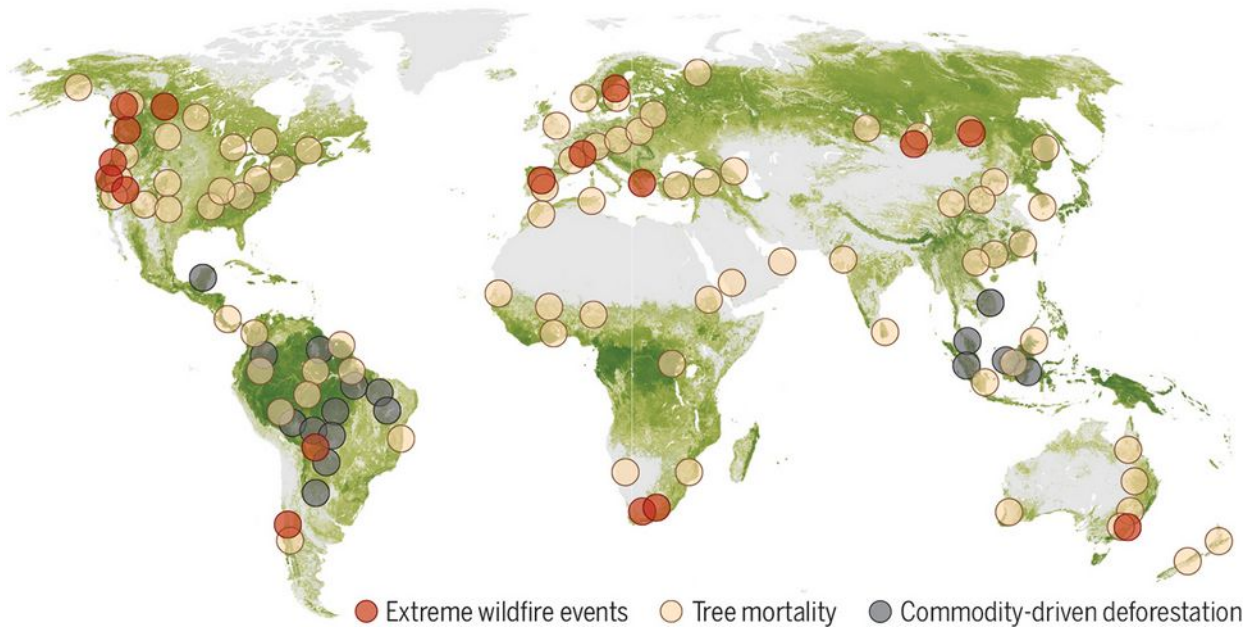
Jonathan T. Overpeck¹, David D. Breshears²

+ See all authors and affiliations

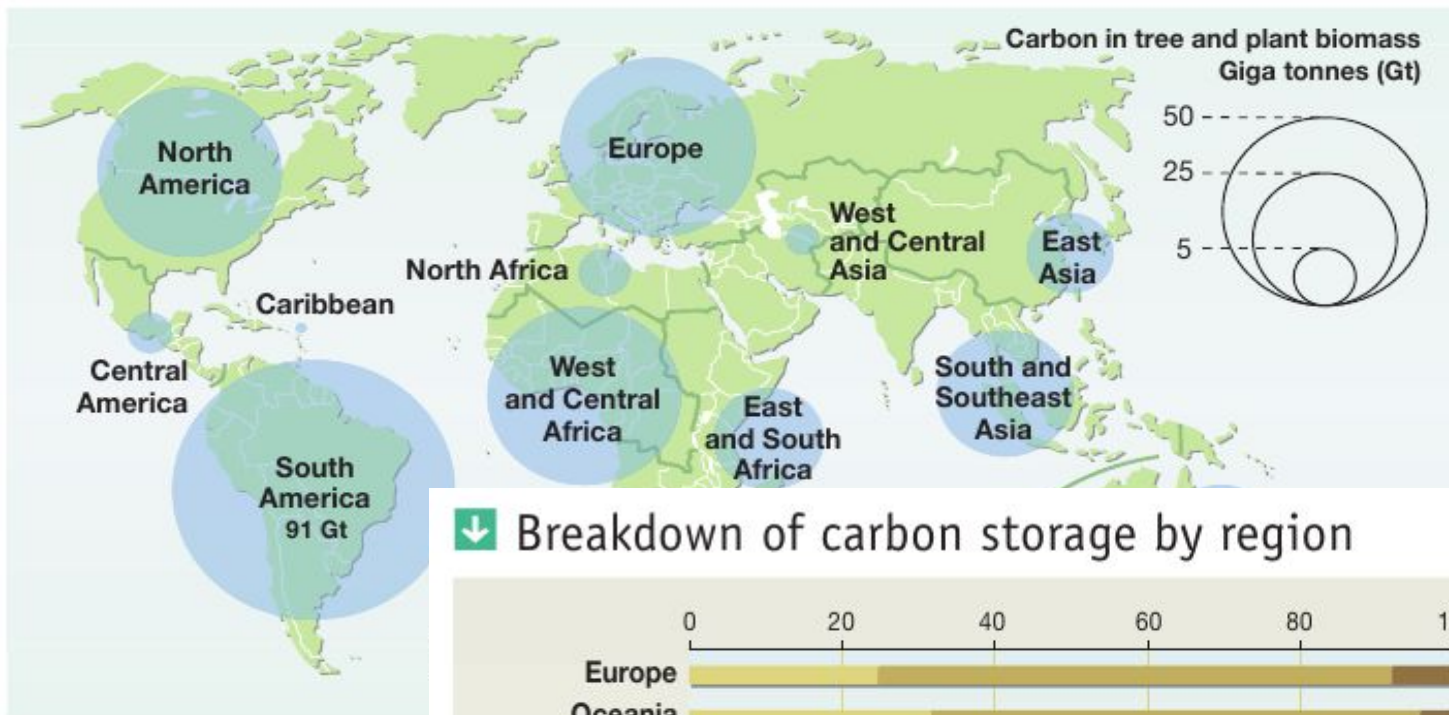
Science 21 May 2021;
Vol. 372, Issue 6544, pp. 786-787
DOI: 10.1126/science.abi9902

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).



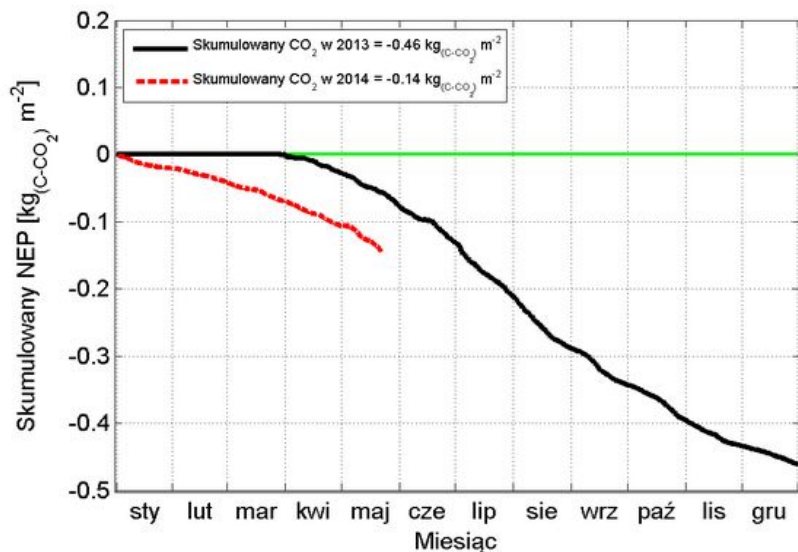
↓ Forest carbon stock per region



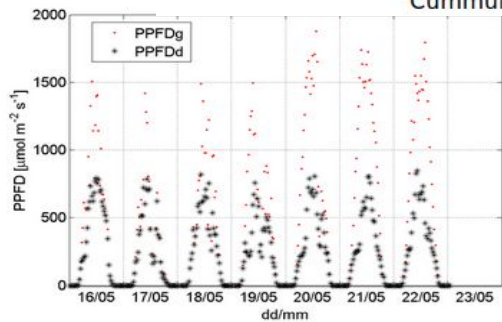
↓ Breakdown of carbon storage by region



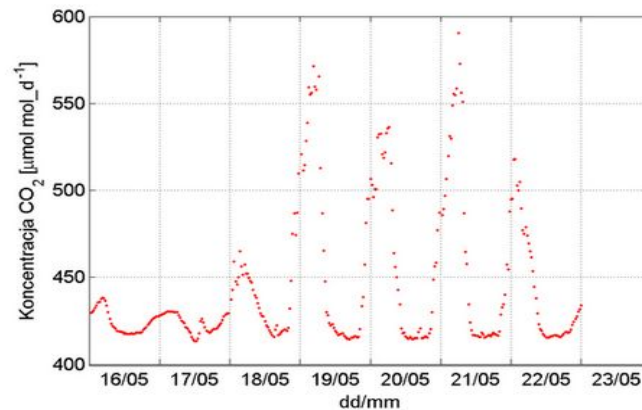
Stacja badawcza Tleń- las iglasty po przejściu tornado (od 29 Marca 2013r.)



Cummulation of CO₂ estimated by EC



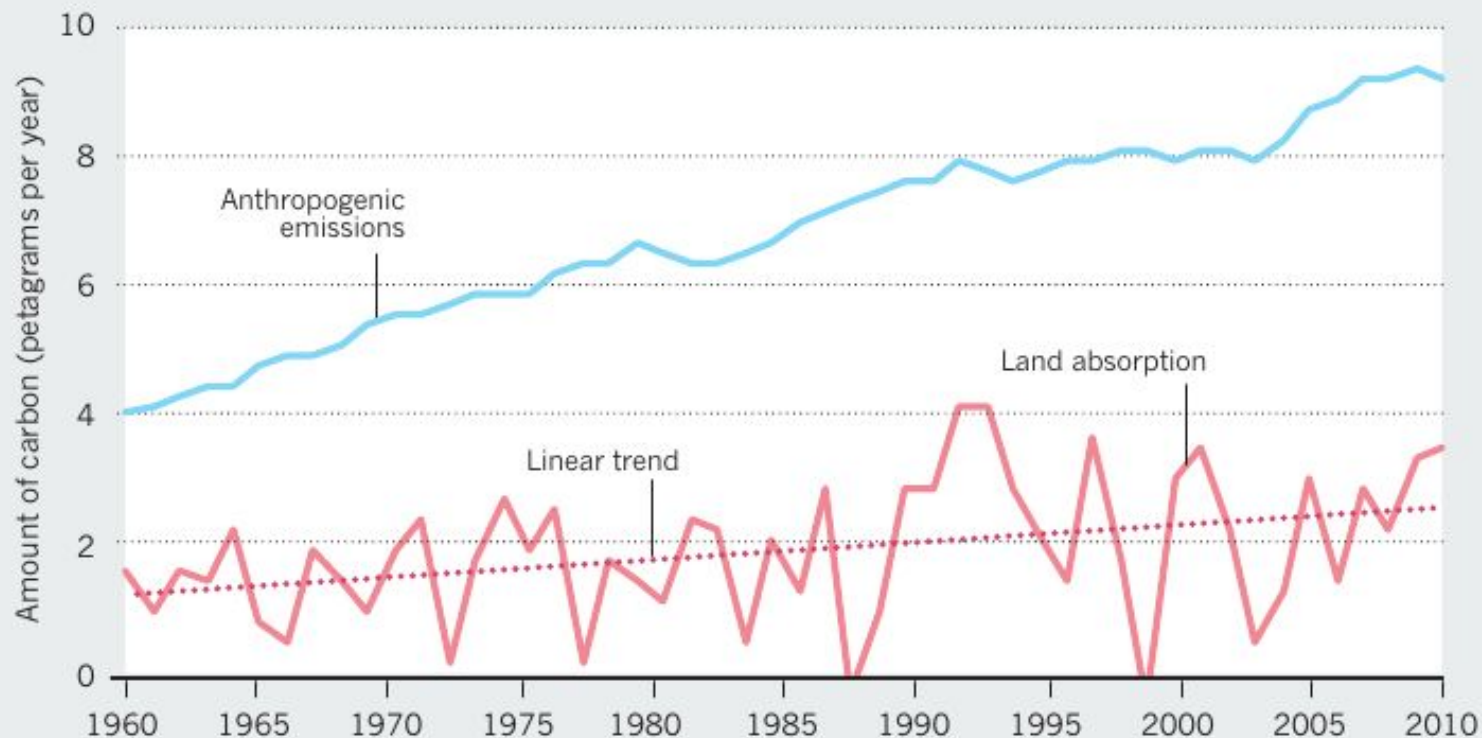
Photosynthetic Photon Flux Density (data from BF5), in last 7 days



CO₂mixing ratio runs in last 7 days

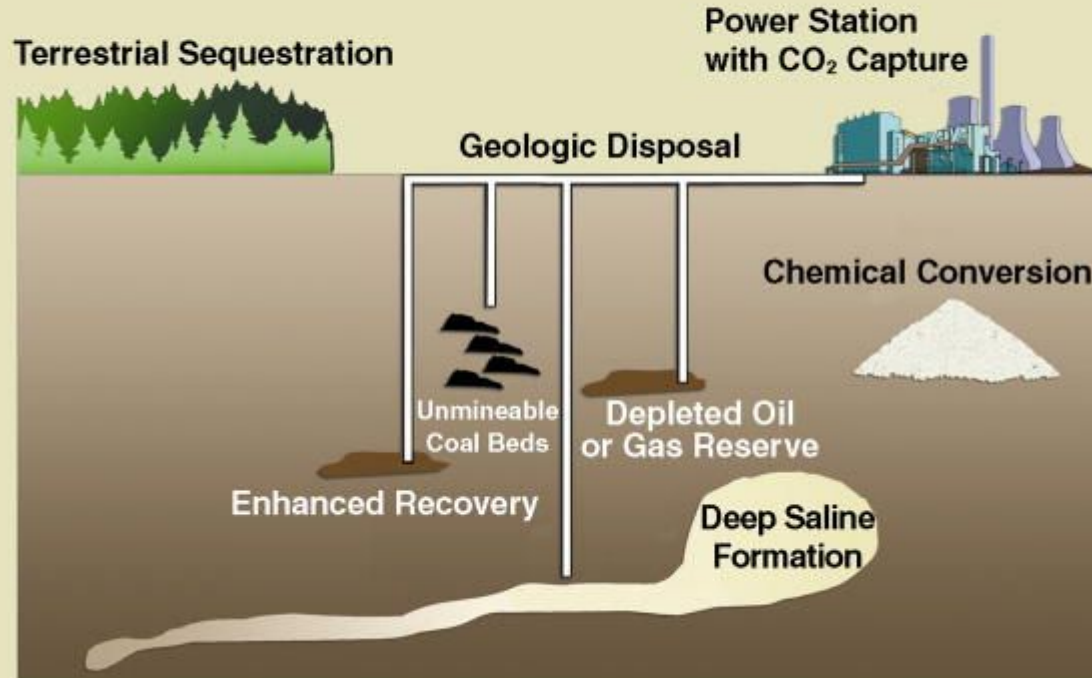
GLOBAL LAND SINK

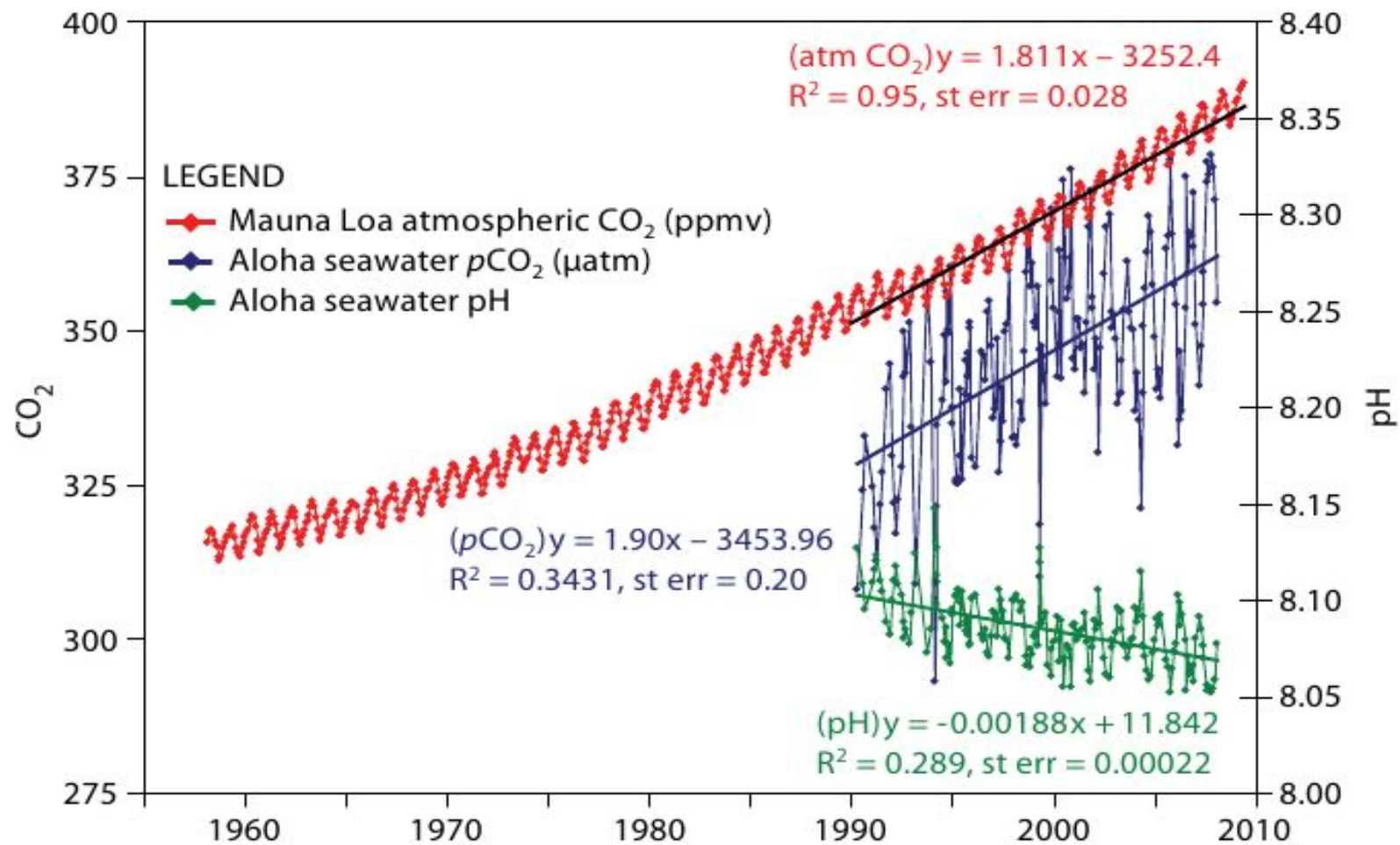
The quantity of carbon absorbed by trees and other types of vegetation per hectare of land has risen in the past 50 years as anthropogenic carbon dioxide and nitrogen emissions have grown. This is despite the world's forest area falling by around 2% since 1990.



Nie tylko lasy – opcje sekwestracji węgla.

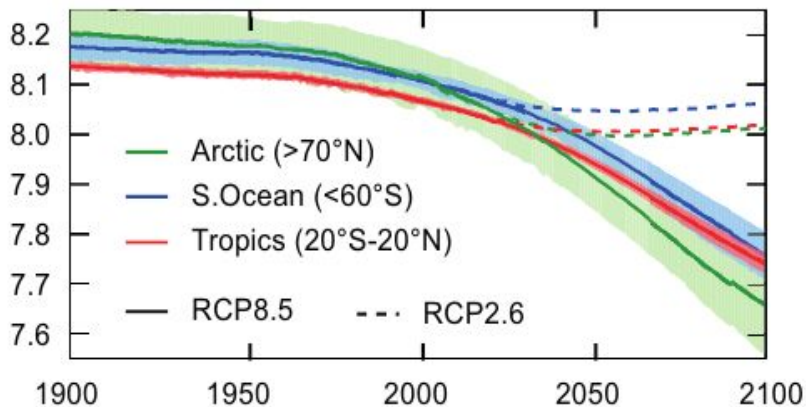
Carbon Sequestration Options



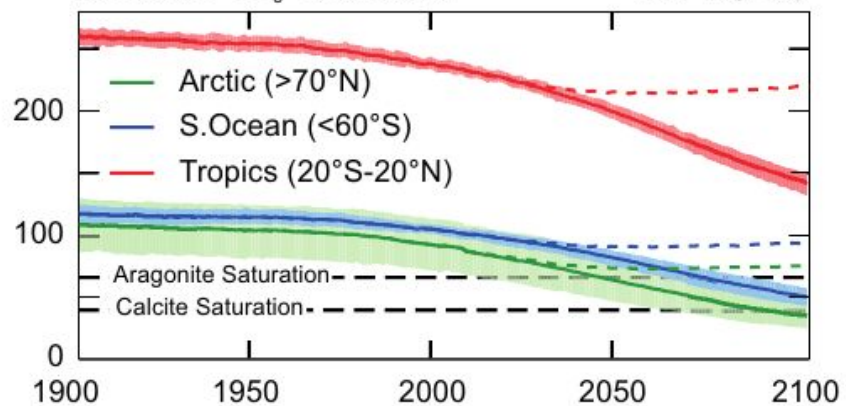


Zakwaszenie oceanów

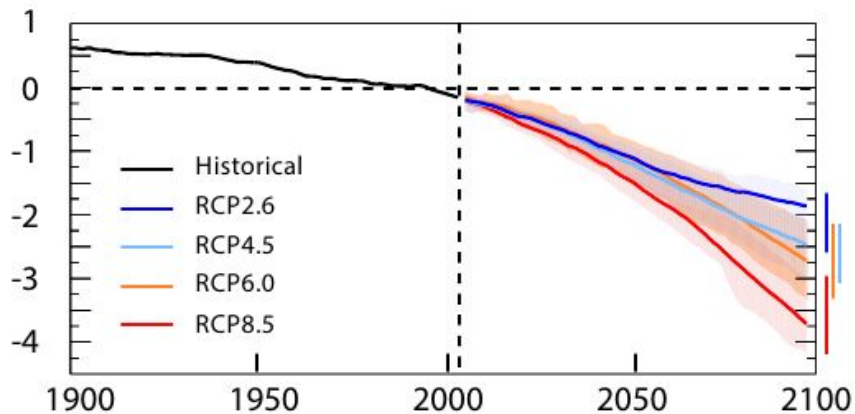
a. Surface pH

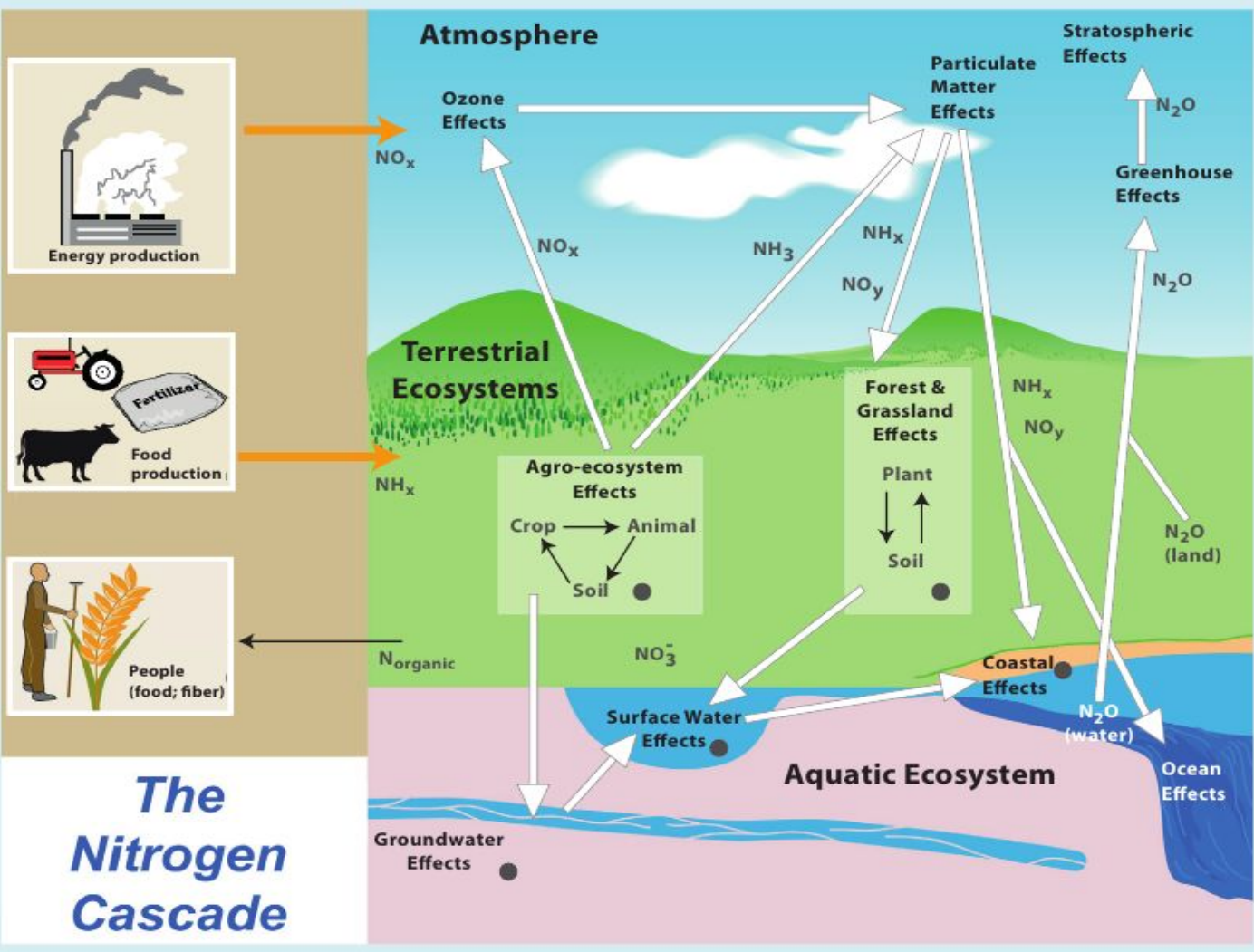


a. Surface CO_3^{2-} ($\mu\text{mol kg}^{-1}$)



a. Ocean oxygen content change (%)

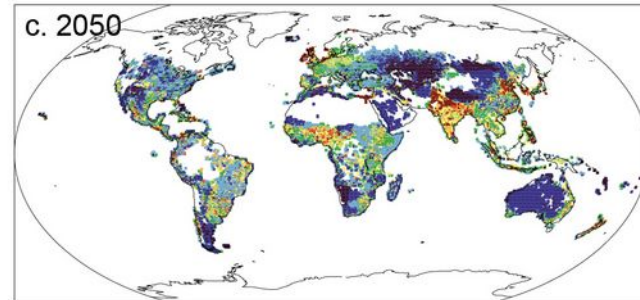
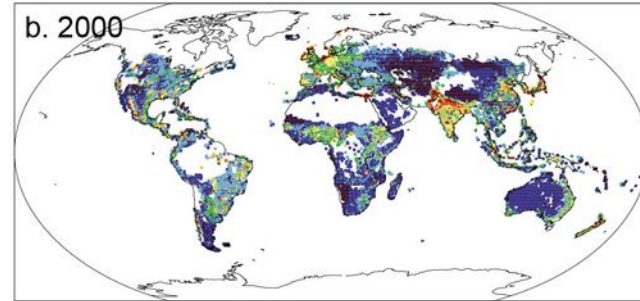
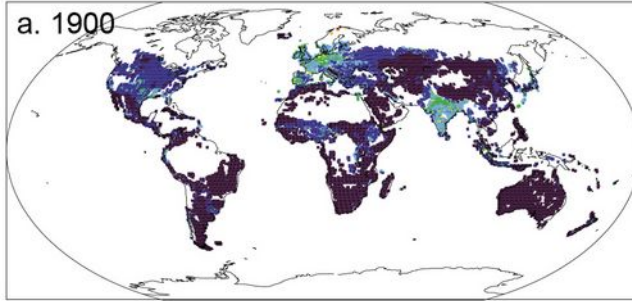




“Kaskada azotowa” - zmiany jakie powoduje w cyklu azotowym każdy atom przekształcony z nieaktywnej formy N_2 do formy reaktywnej chemicznie – biorącej udział w procesach biologicznych i chemicznych w systemie klimatycznym

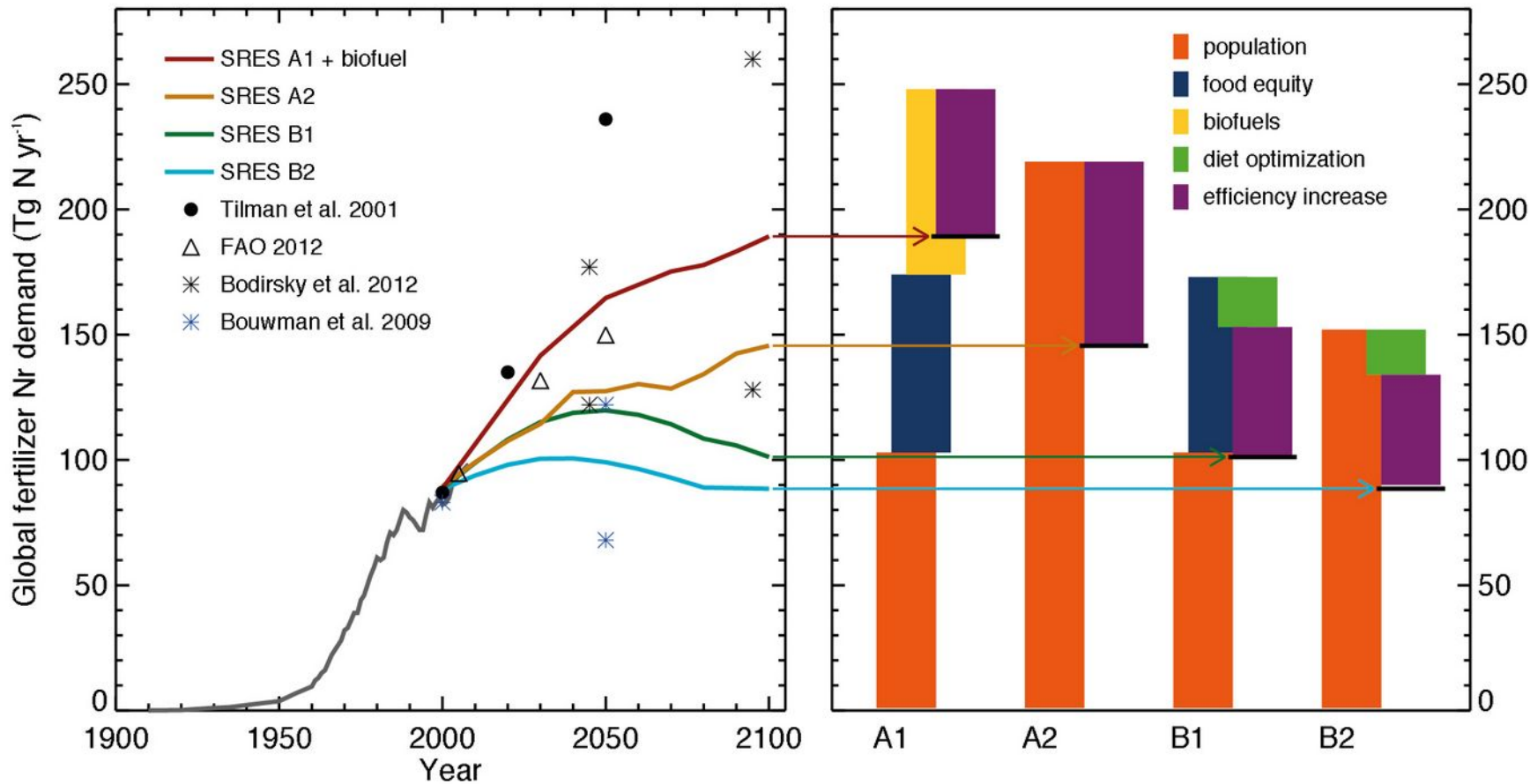
The Nitrogen Cascade

N_2O emissions ($\text{kgN km}^{-2} \text{y}^{-1}$)



Emisje podtlenku
azotu – estymacje
geograficzne.

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

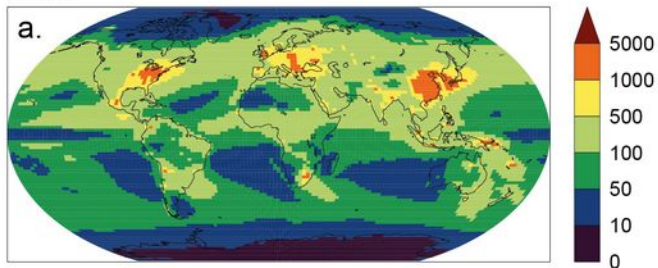


Jak będzie się zmieniać depozycja związków siarki i azotu.

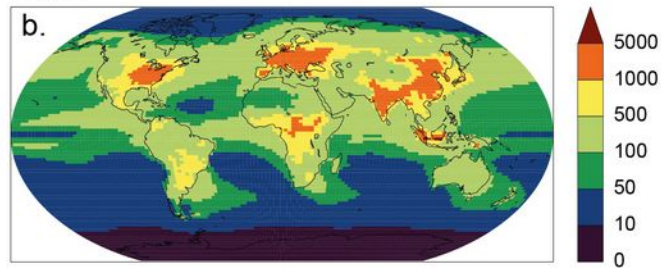
SO_x deposition (kgS km⁻² y⁻¹)

N deposition (kgN km⁻² y⁻¹)

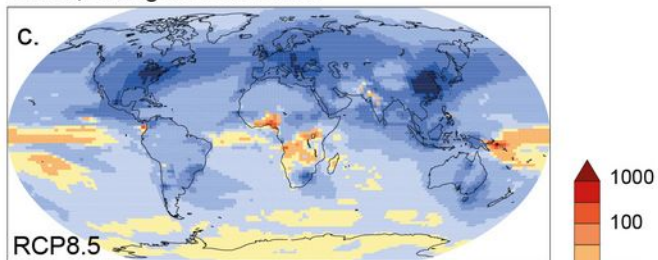
1990s



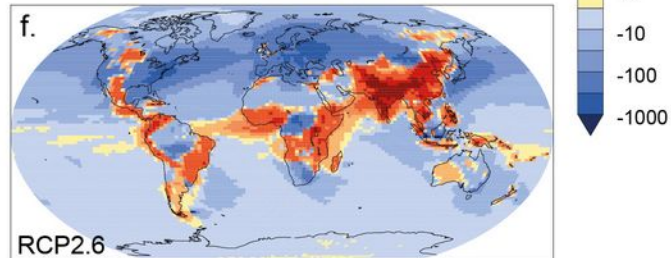
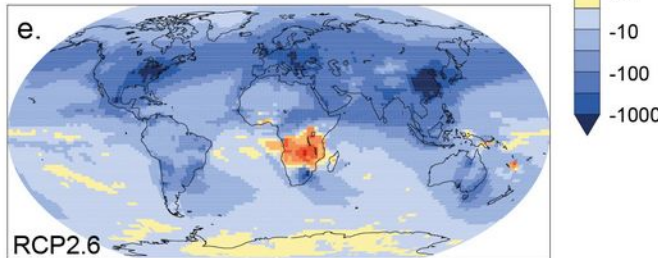
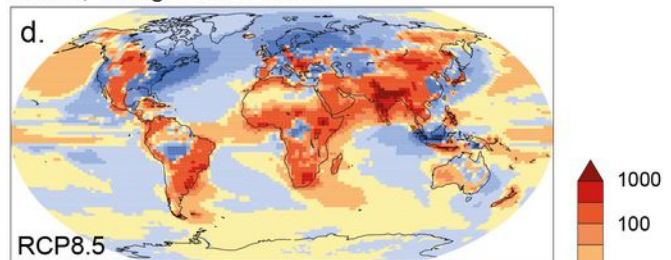
1990s



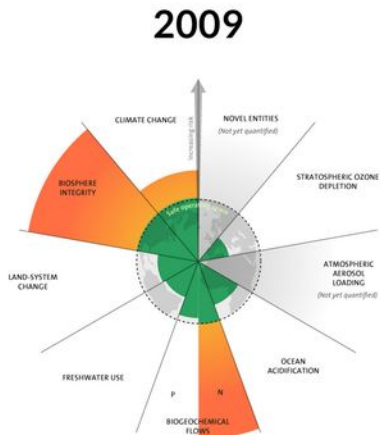
2090s, changes from 1990s



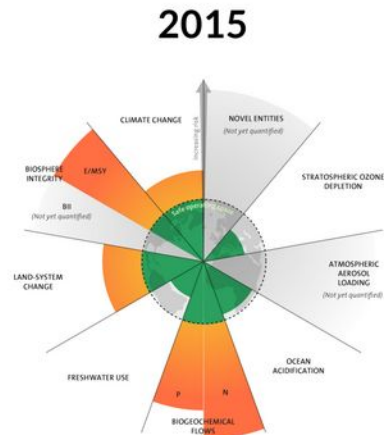
2090s, changes from 1990s



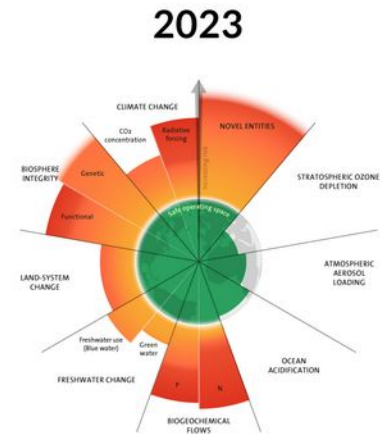
Szybko przekraczamy granice planetarne....



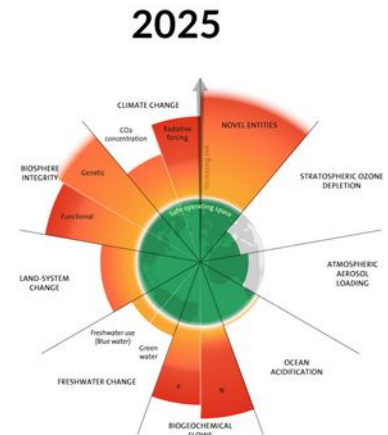
7 boundaries assessed,
3 crossed



7 boundaries assessed,
4 crossed



9 boundaries assessed,
6 crossed



9 boundaries assessed,
7 crossed

Earth beyond six of nine planetary boundaries

KATHERINE RICHARDSON · WILL STEFFEN · WOLFGANG LUCHT · JØRGEN BENJØRSEN · SARAH E. CORNELIS · JONATHAN F. DONGES · MARCUS DRINK · INGO FETZER · GOVINDASAMY BALL · L. J. AND JOHAN ROCKSTRÖM · +19 authors [Authors Info & Affiliations](#)

<https://www.stockholmresilience.org/research/planetary-boundaries.html>

Podsumowanie:

Problem z węglem: CO₂ i CH₄ poważny.

Ale nie jedyny...