

Fizyka Procesów Klimatycznych

Cykl węglowy, inne cykle biogeochemiczne.

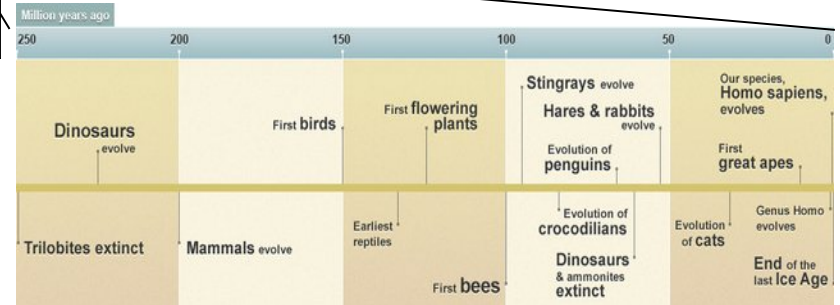
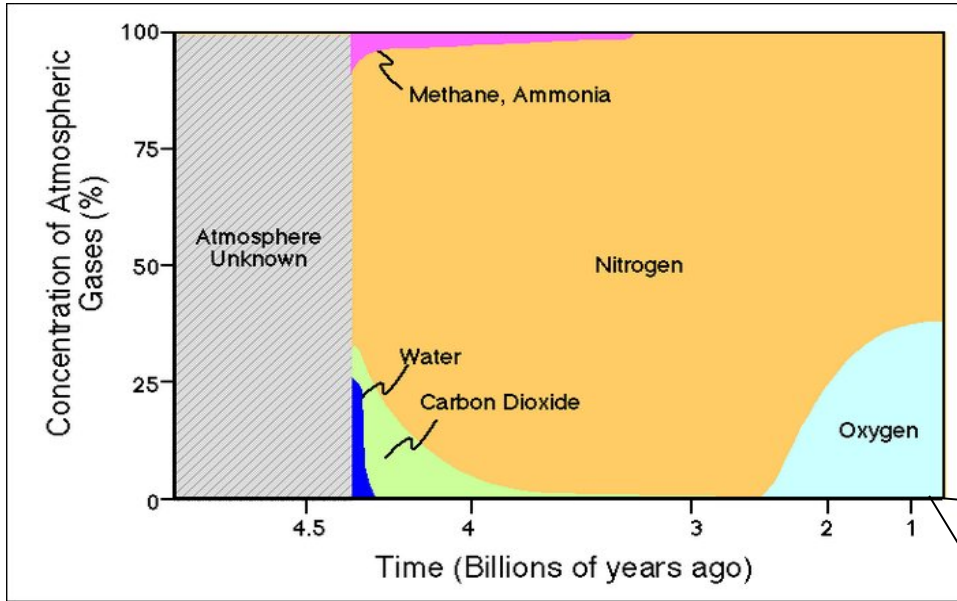
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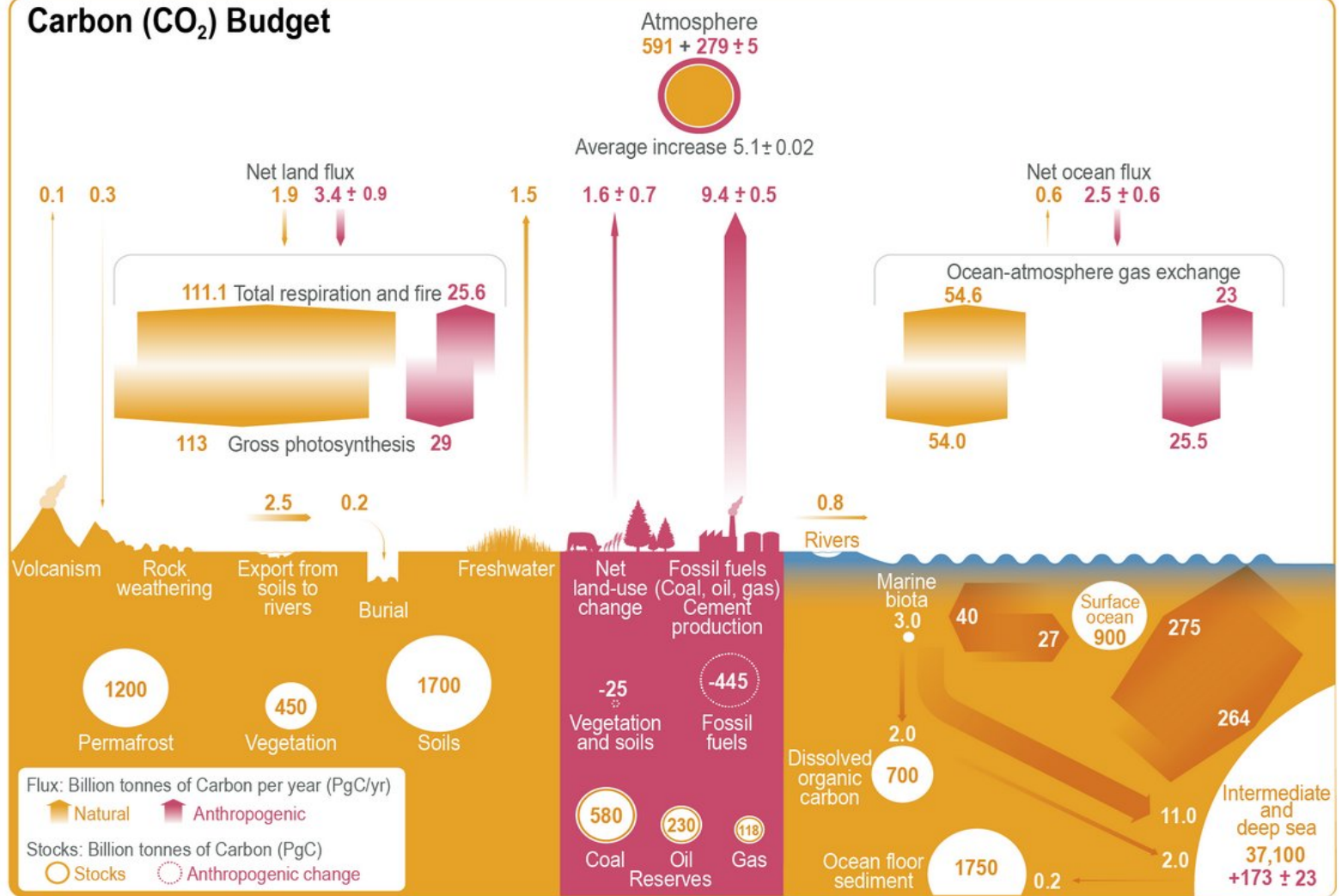
Wykorzystano slajdy dr Aleksandry Kardaś

Cykl węglowy, azotowy, zmiany w składzie atmosfery.

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



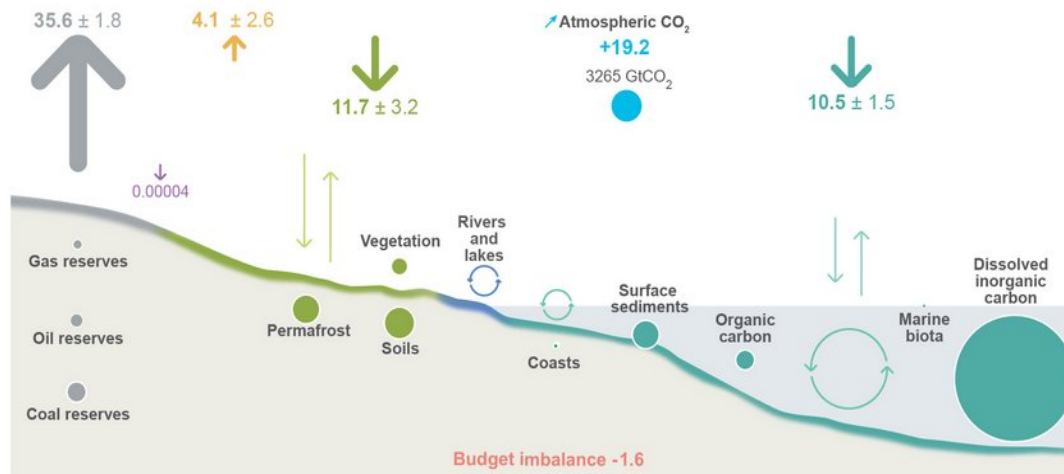
Carbon (CO₂) Budget



Anthropogenic perturbation of the global carbon cycle

Perturbation of the global carbon cycle caused by anthropogenic activities, global annual average for the decade 2014–2023 (GtCO₂/yr)

The global carbon cycle



Anthropogenic fluxes 2014–2023 average GtCO₂ per year

- ↑ Fossil CO₂ E_{FOS}
- ↓ Land uptake S_{LAND}
- Stocks GtCO₂
- ↑ Land-use change E_{LUC}
- ↓ Ocean uptake S_{OCEAN}
- + Atmospheric increase G_{ATM}
- ↓ CDR not included in E_{LUC}
- ↑ Carbon cycling GtC per year
- Budget Imbalance B_{IM}

CDR here refers to Carbon Dioxide Removal besides those associated with land-use that are accounted for in the Land-use change estimate.

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

Source: [NOAA-GML](#); [Friedlingstein et al 2024](#); [Canadell et al 2021 \(IPCC AR6 WG1 Chapter 5\)](#); [Global Carbon Project 2024](#)

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.

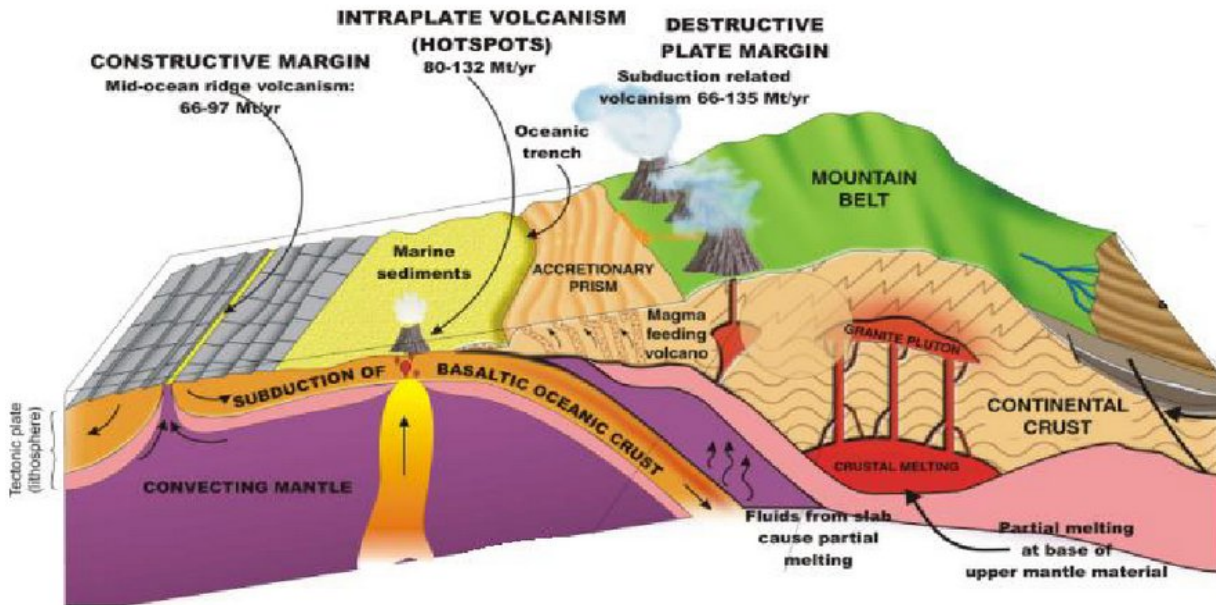
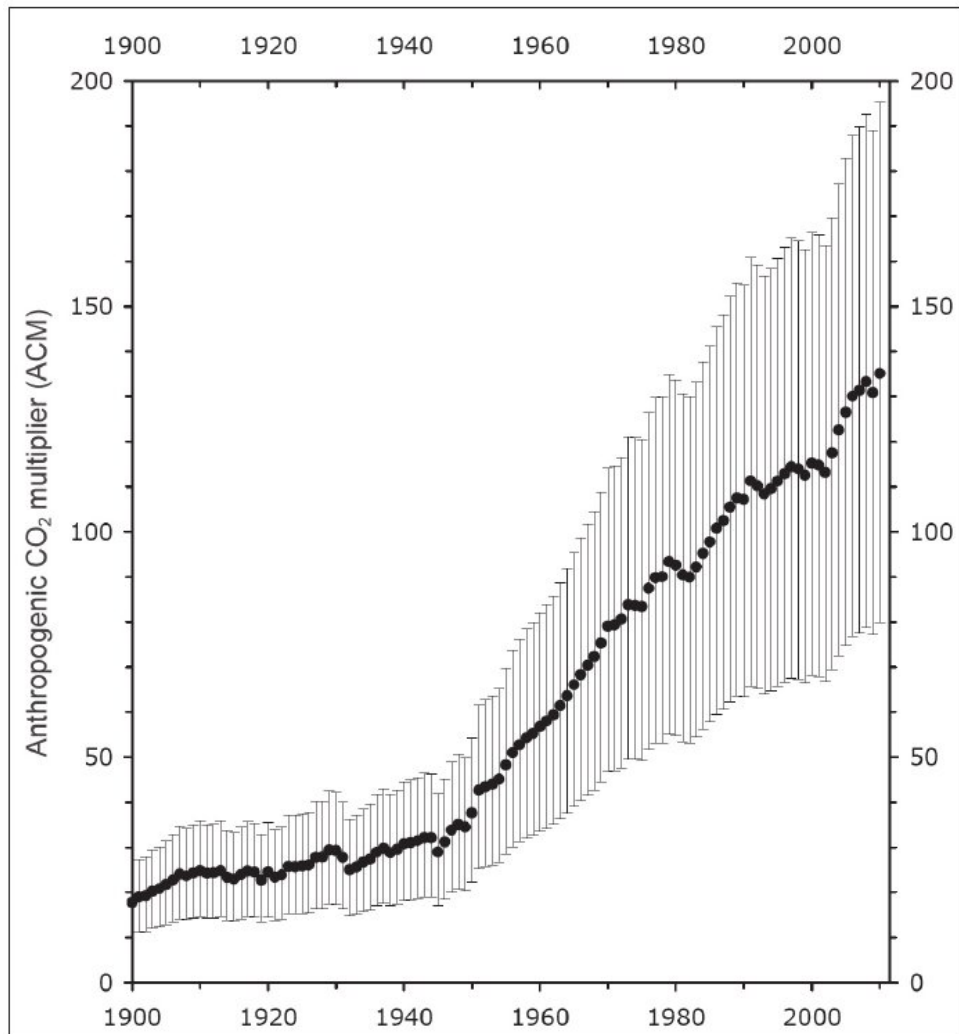


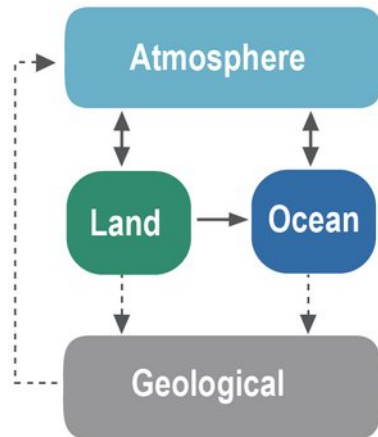
Figure 2. Diagrammatic representation of the different volcanic environments with estimates of CO₂ emission rates and their relationship to plate tectonic environment.



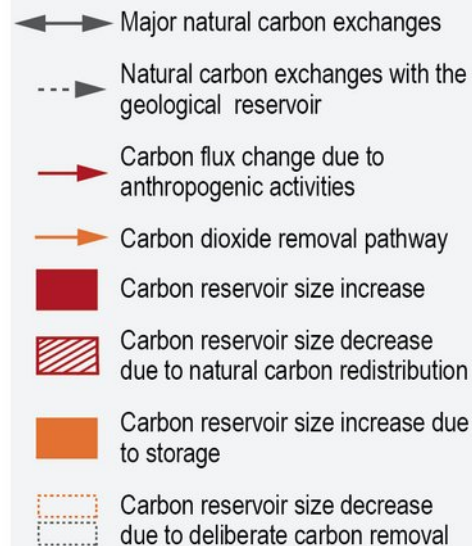
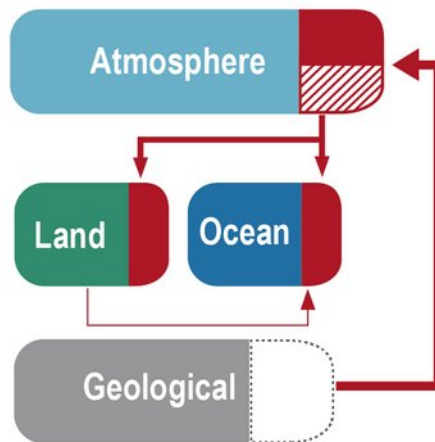
Emisje
antropogeniczne
CO₂
w stosunku
do emisji
wulkanicznych

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

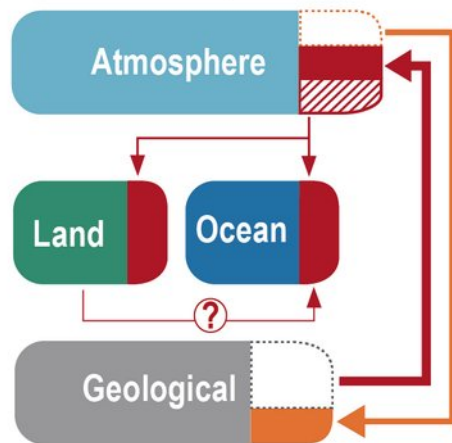
(a) Unperturbed carbon cycle fluxes



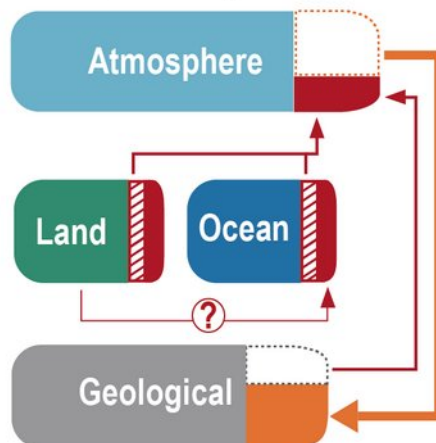
(b) Industrial era CO₂ emissions



(c) Net positive CO₂ emissions with CDR

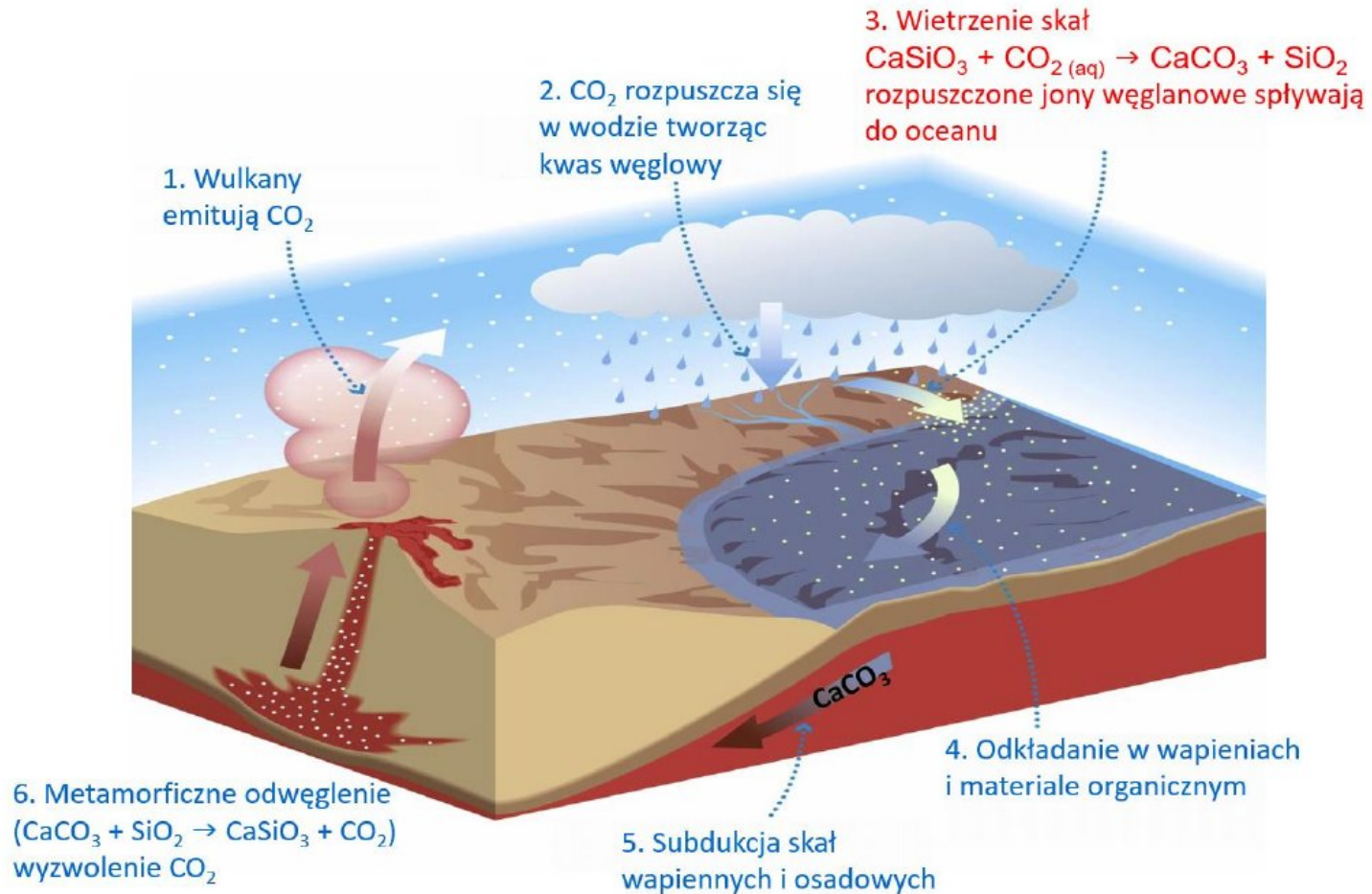


(d) Net negative CO₂ emissions

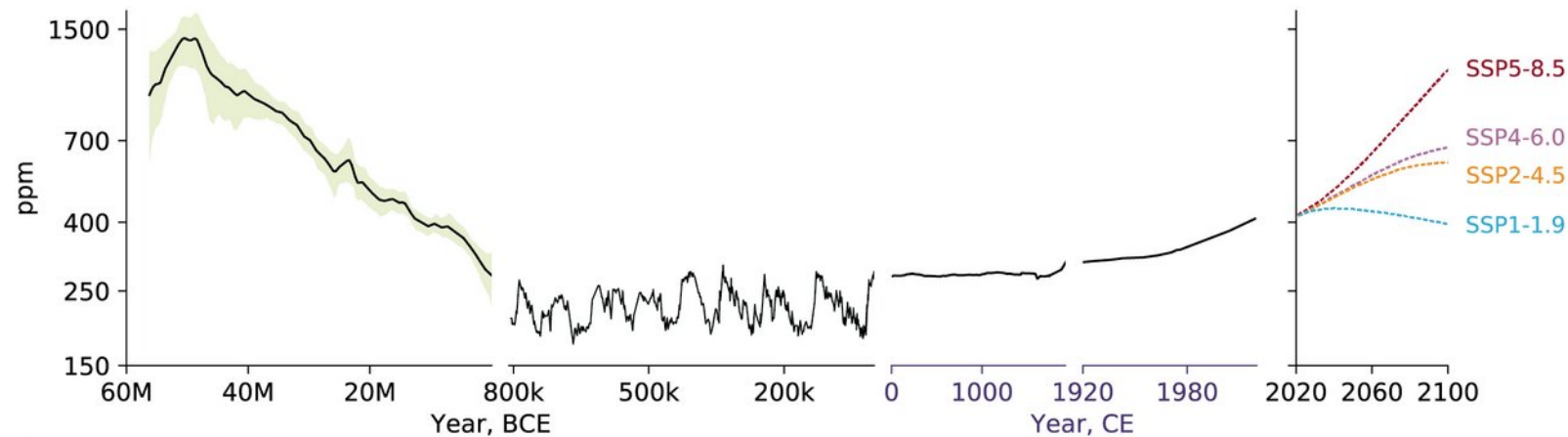


IPCC 6AR
WG1

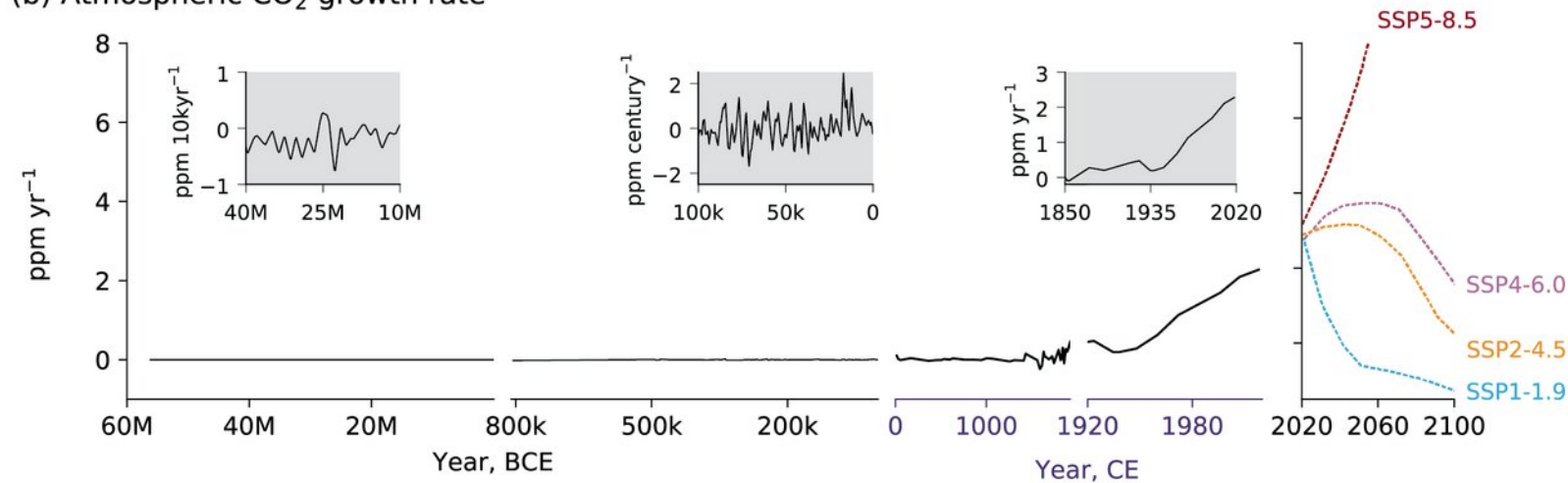
Termostat węglowy – tempo wietrzenia skał zależy od temperatury.

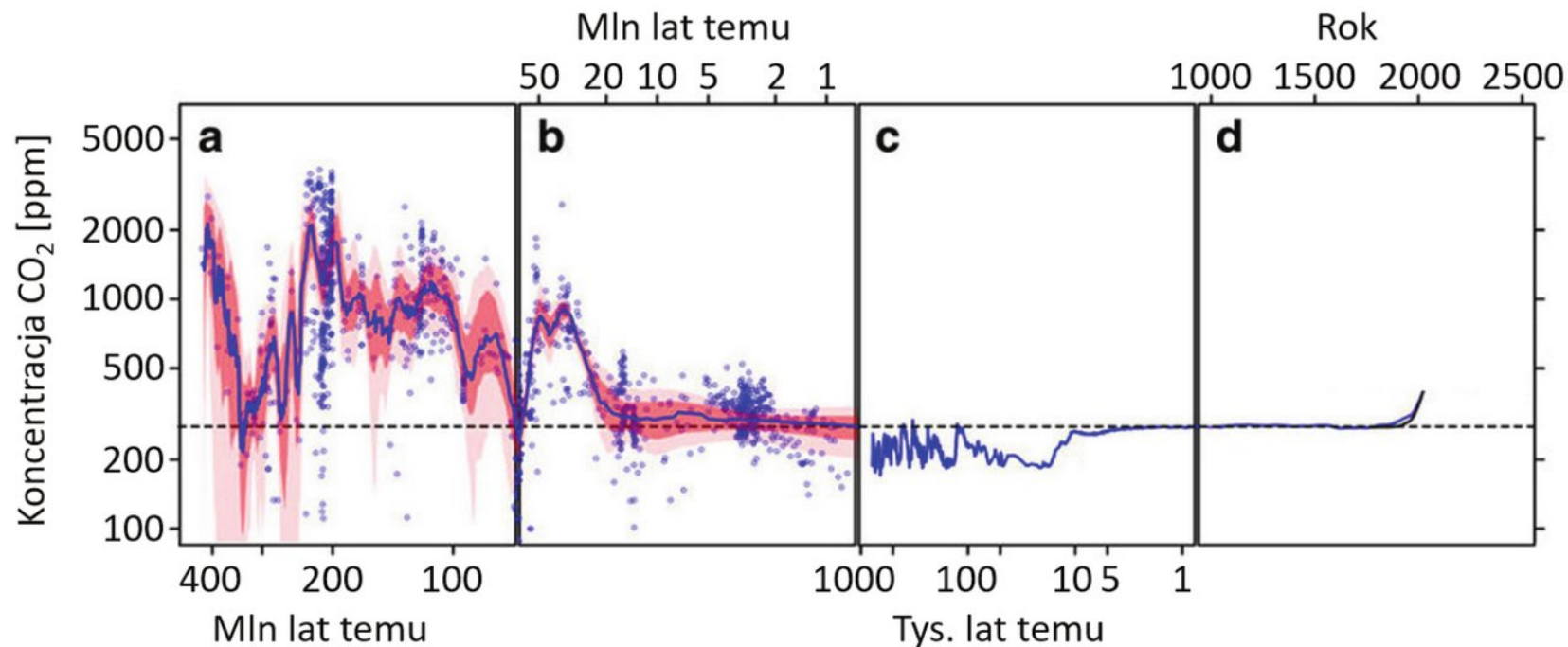


(a) Atmospheric CO₂ concentrations

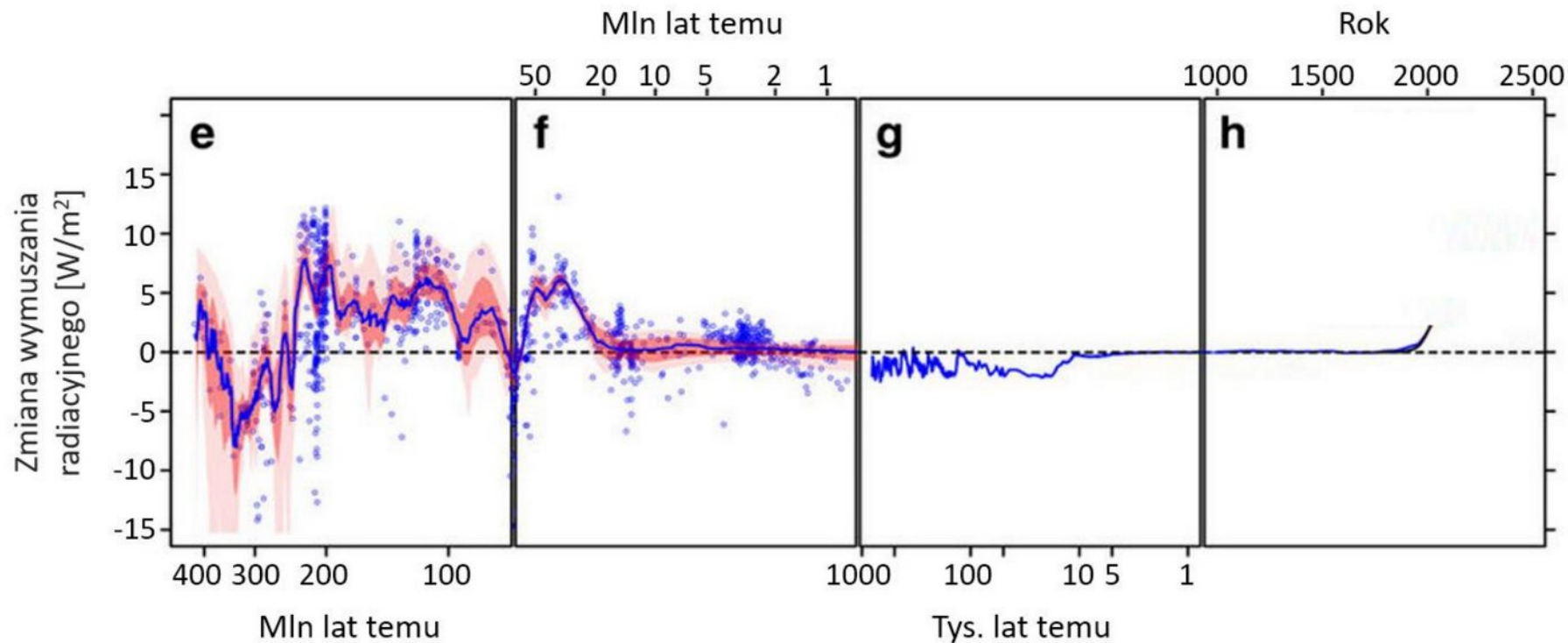


(b) Atmospheric CO₂ growth rate

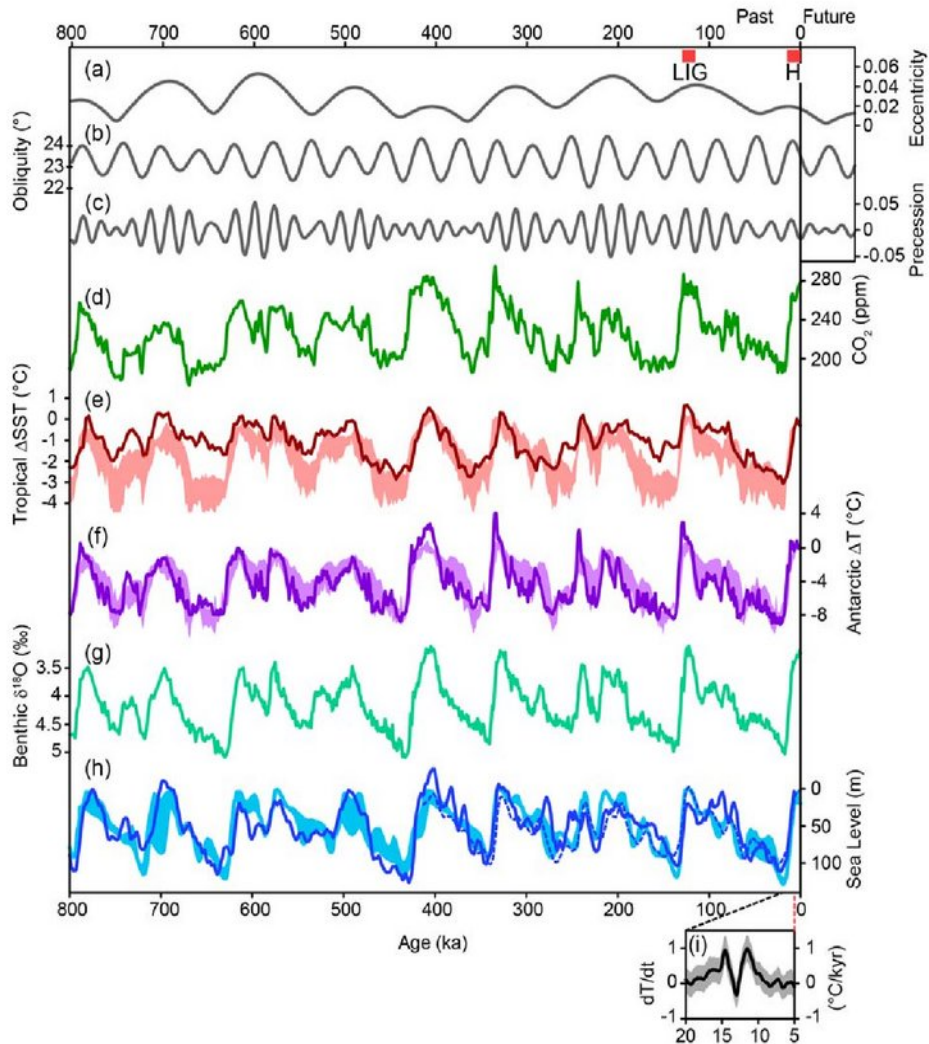




Ilustracja 1.2.11. Rekonstrukcja zmian koncentracji CO₂ w atmosferze w ostatnich 400 mln lat. UWAGA: skala czasowa nie jest liniowa. Panele a–b) na podstawie różnych wskaźników klimatycznych (niebieskie kropki odpowiadają konkretnym pomiarom, a linia – dopasowanej do nich krzywej, czerwona wstęga pokazuje 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:

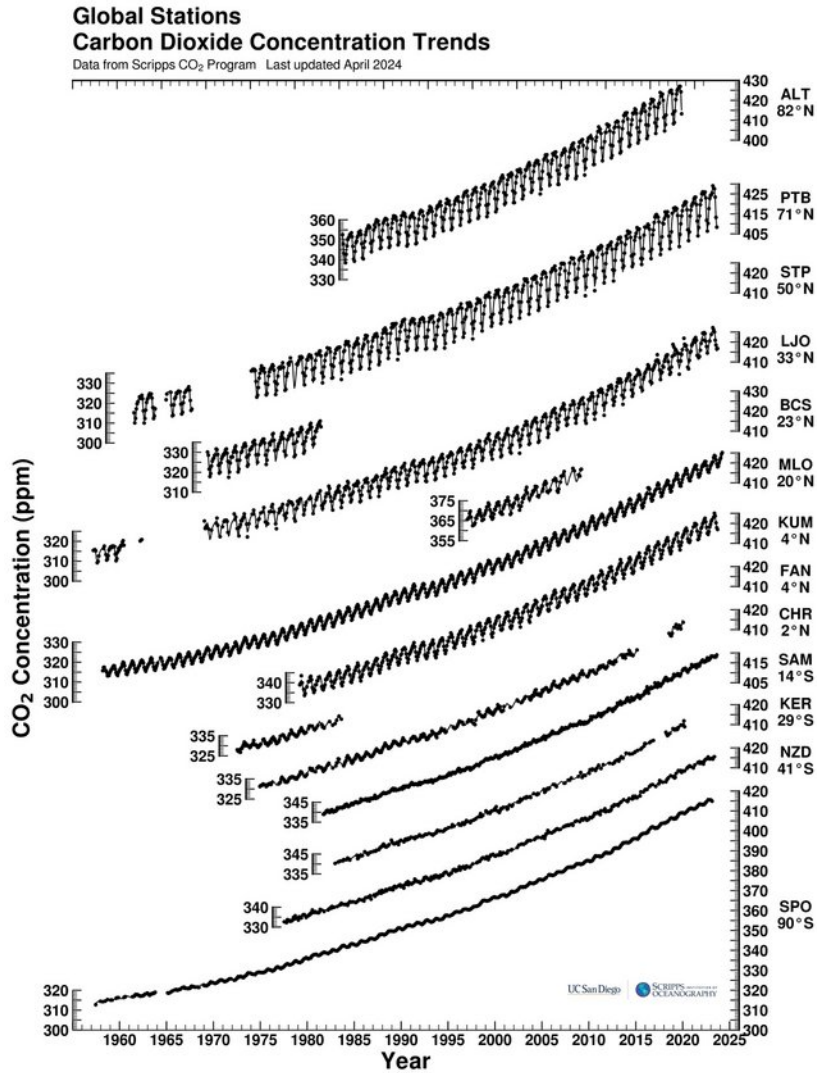
Czarne – wymuszenia orbitalne,
Zielone – wymuszenia CO₂ (na podstawie rdzeni lodowych)

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 $\delta^{18}\text{O}$ w osadach dennych)

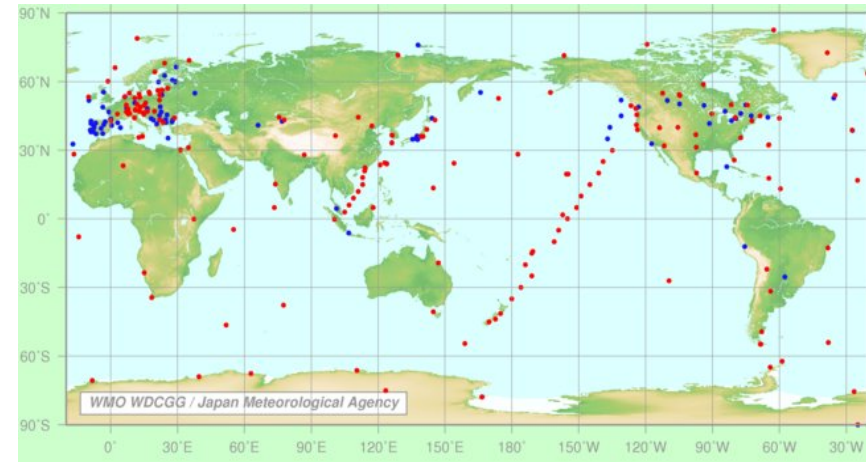
Niebieskie – poziom morza (cienka linia – rekonstrukcje paleoklimatyczne, szerszy pas – odtworzenie w modelach klimatu).

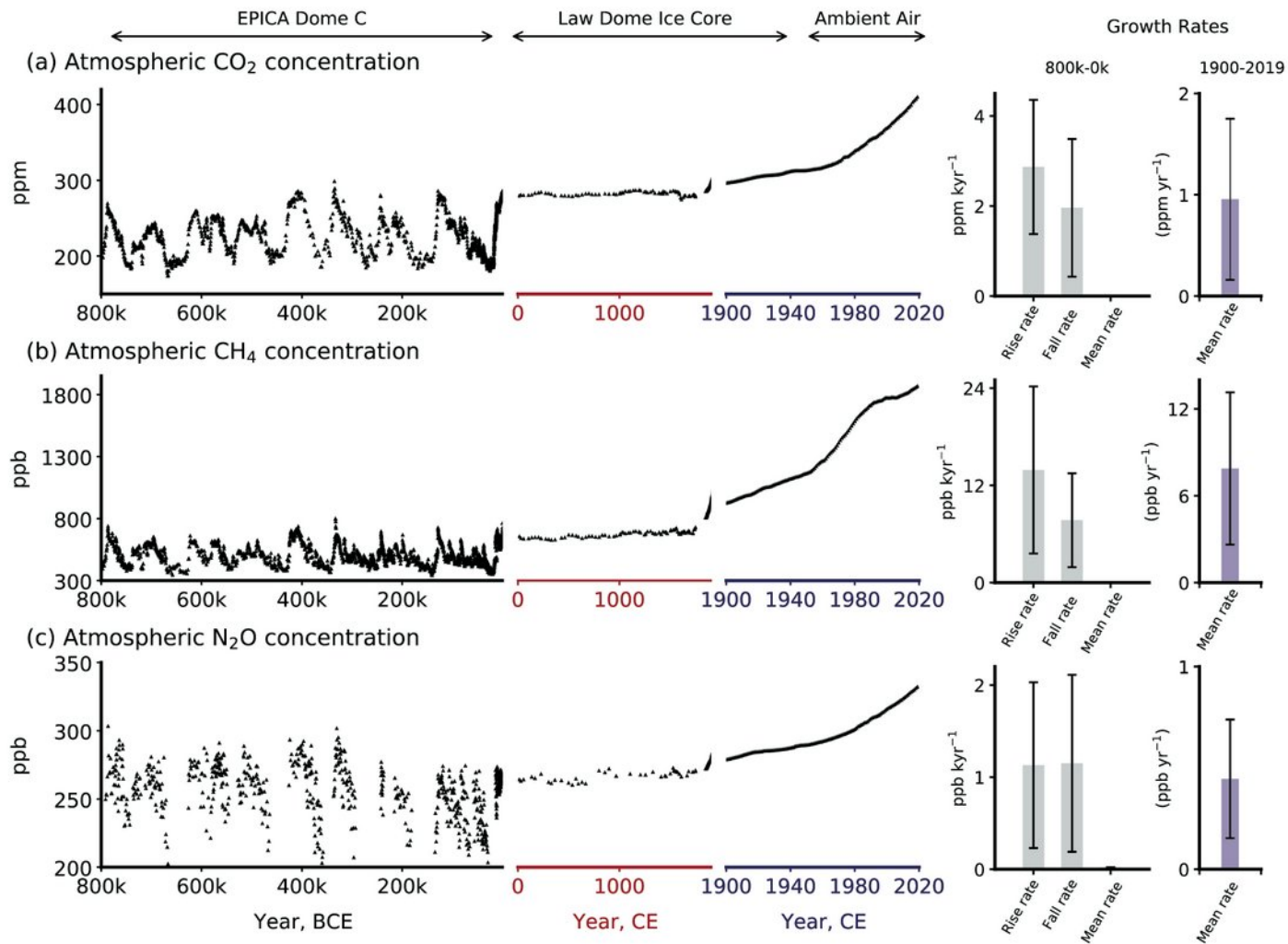


Regularne pomiary CO₂ i innych gazów atmosferycznych są zbierane w WMO World Data Centre for Greenhouse Gases (WDCGG)

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

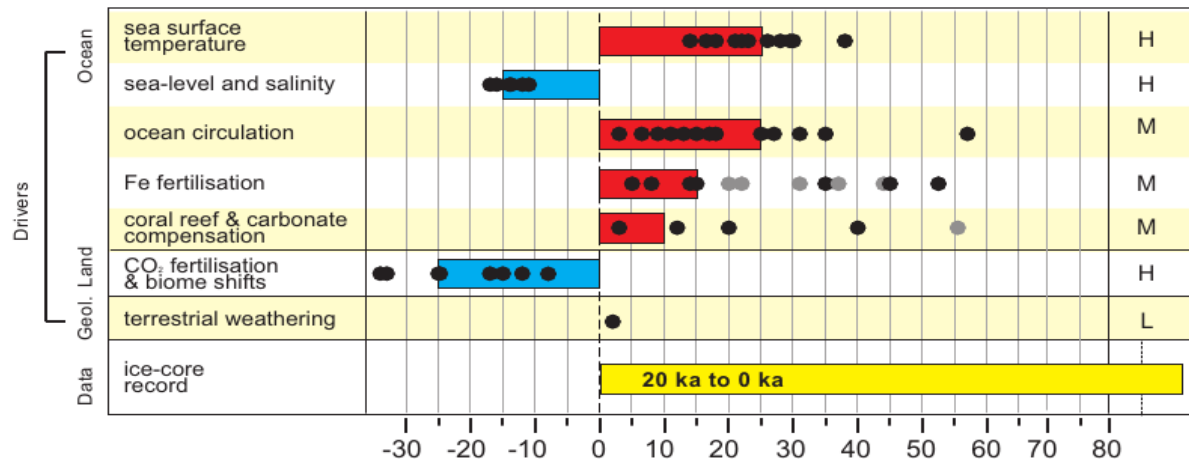
<http://scrippsco2.ucsd.edu/>



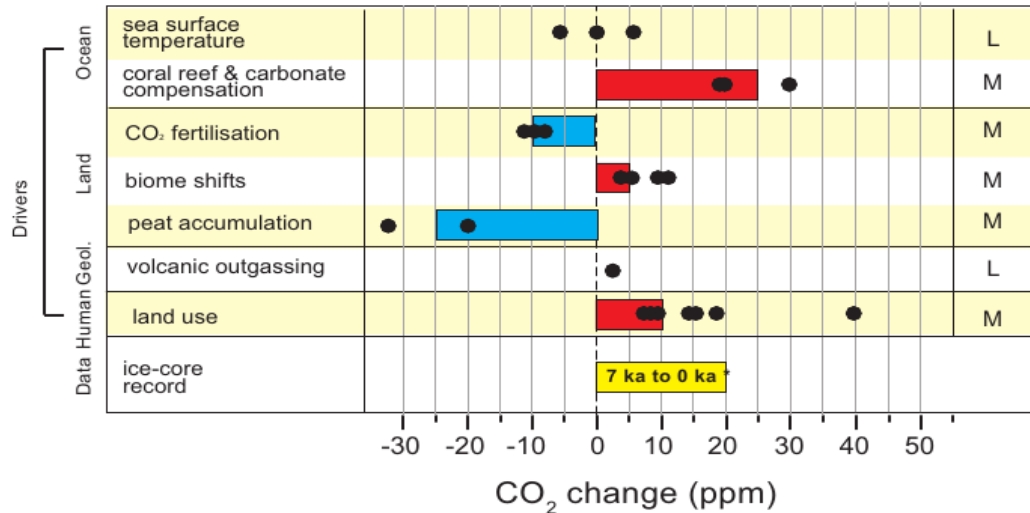


Zmiany w koncentracji atmosferycznych CO₂, CH₄ i N₂O

Glacial to Interglacial



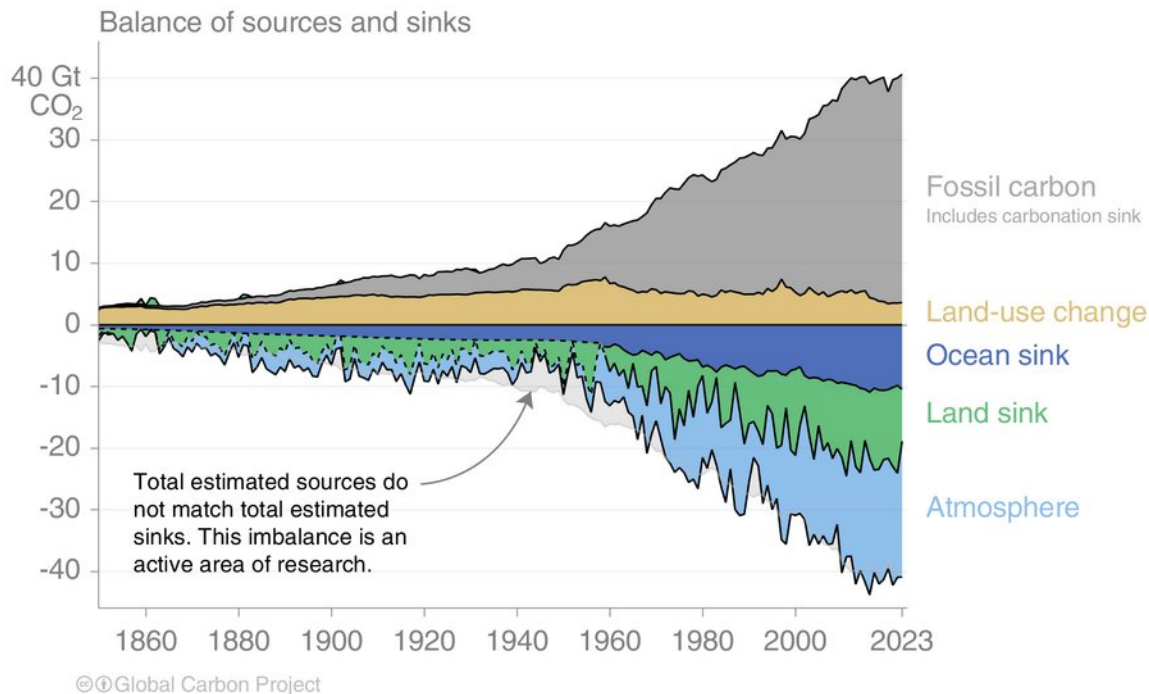
Holocene



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

Global carbon budget

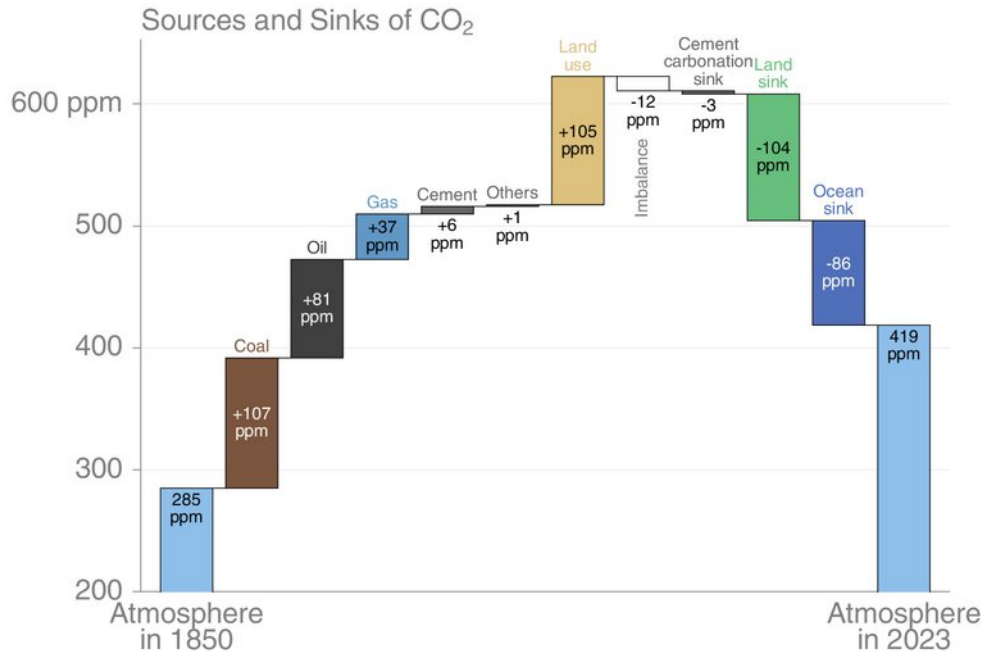
Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean
The “imbalance” between total emissions and total sinks is an active area of research



Source: [Friedlingstein et al 2024](#); [Global Carbon Project 2024](#)

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

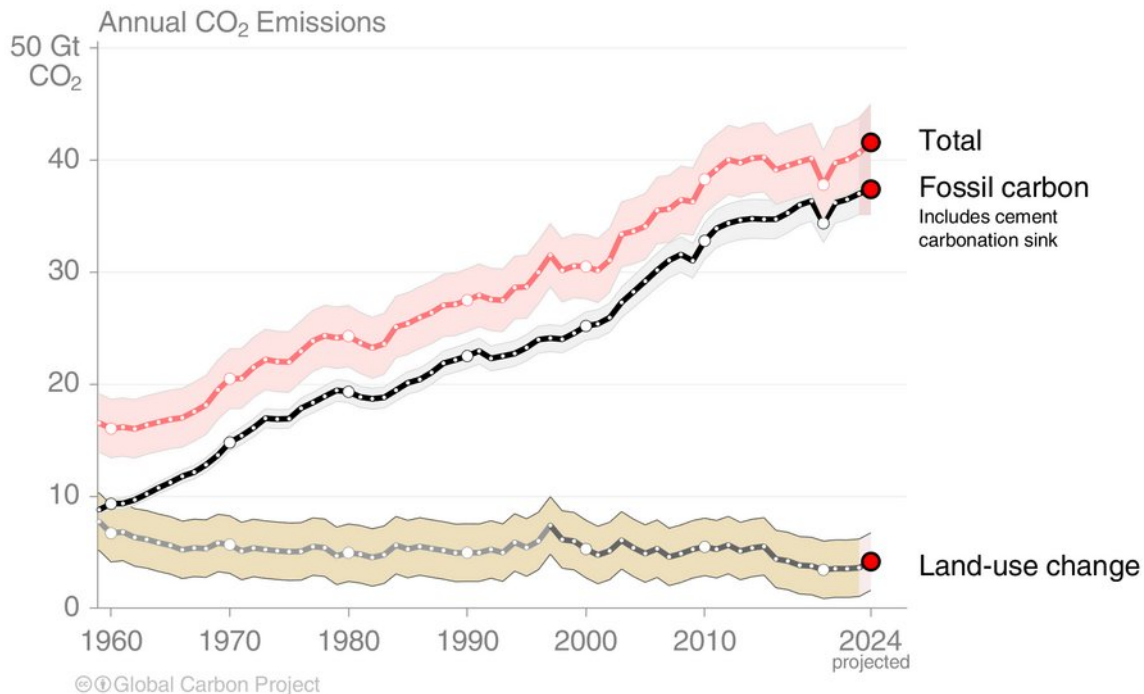


© 2024 Global Carbon Project

Source: [Friedlingstein et al 2024](#); [Global Carbon Project 2024](#)

Total global emissions

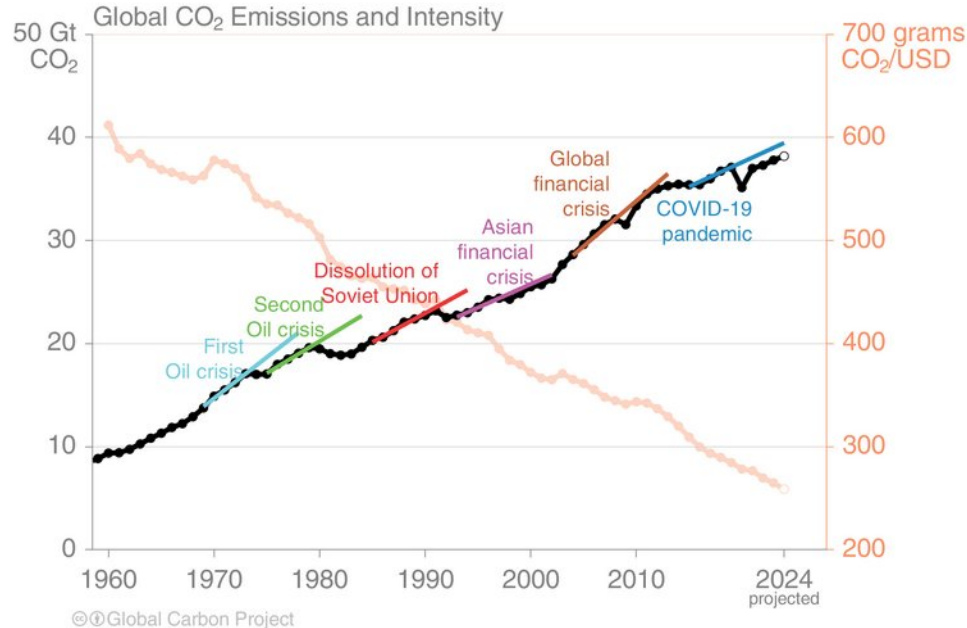
Total global emissions, projected to reach 41.6 ± 3.2 GtCO₂ in 2024, 51% over 1990
 Percentage land-use change: 42% in 1960, 10% averaged 2014–2023



Land-use change estimates from four bookkeeping models, using fire-based variability from 1997
 Source: [Friedlingstein et al 2024](#); [Global Carbon Project 2024](#)

Fossil CO₂ emission intensity

Global CO₂ emissions growth has generally resumed quickly from global crises. Emission intensity has steadily declined but not sufficiently to offset economic growth.

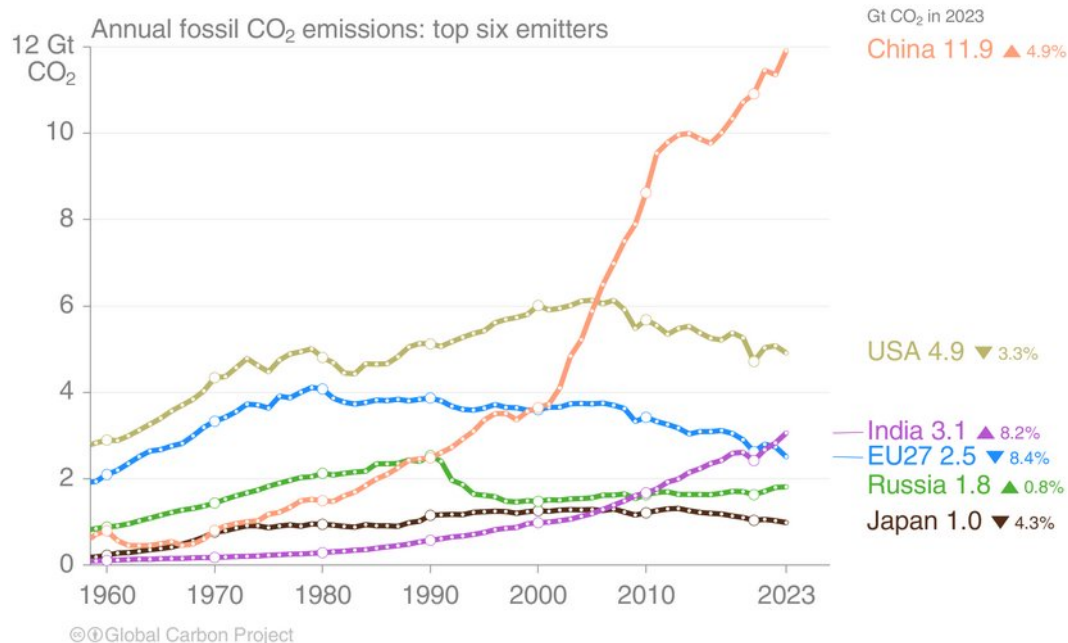


Each trend line is based on the five years before the crisis and extended to five years after. Economic activity is measured in purchasing power parity (PPP) terms in 2017 US dollars.

Source: [Friedlingstein et al 2024](#); [Global Carbon Project 2024](#)

Top emitters: Fossil CO₂ emissions to 2023

The top six emitters in 2023 covered 68% of global emissions
China 32%, United States 13%, India 8%, EU 7%, Russia 5%, and Japan 3%

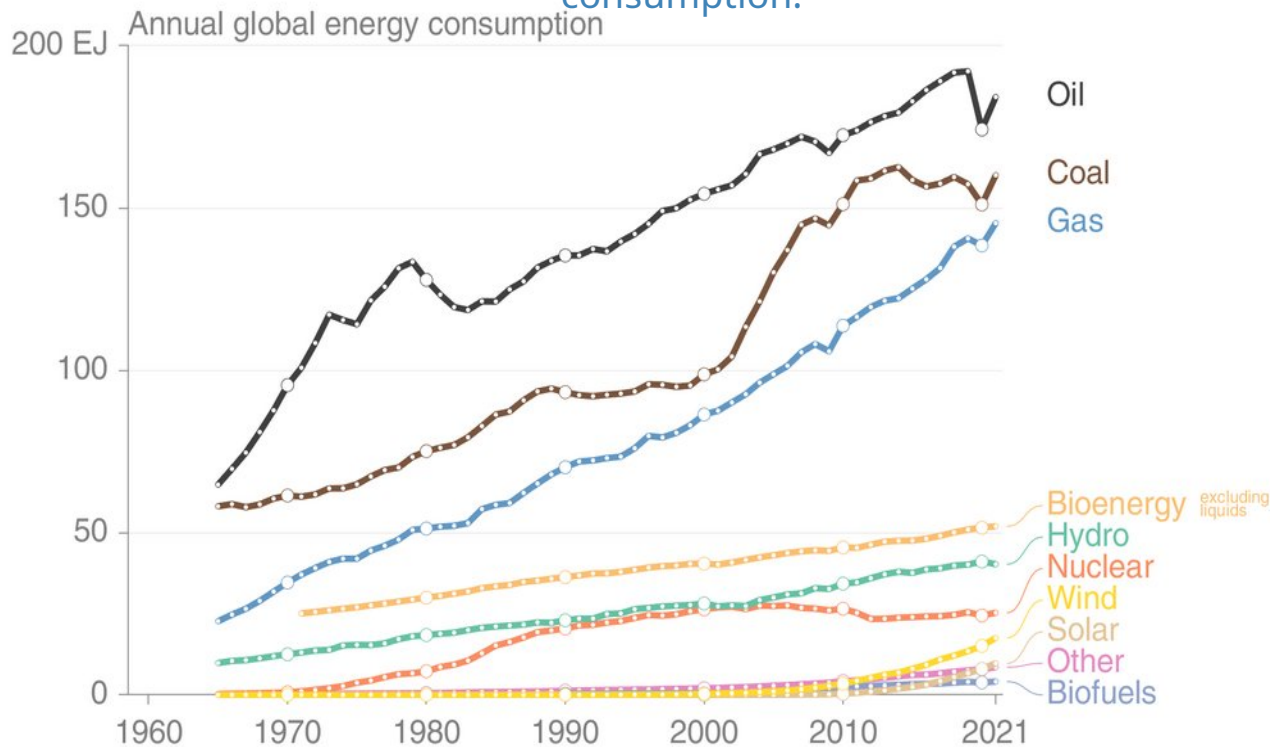


International aviation and maritime shipping (bunker fuels) contributed 3.0% of global emissions in 2023.

Source: [Friedlingstein et al 2024](#); [Global Carbon Project 2024](#)

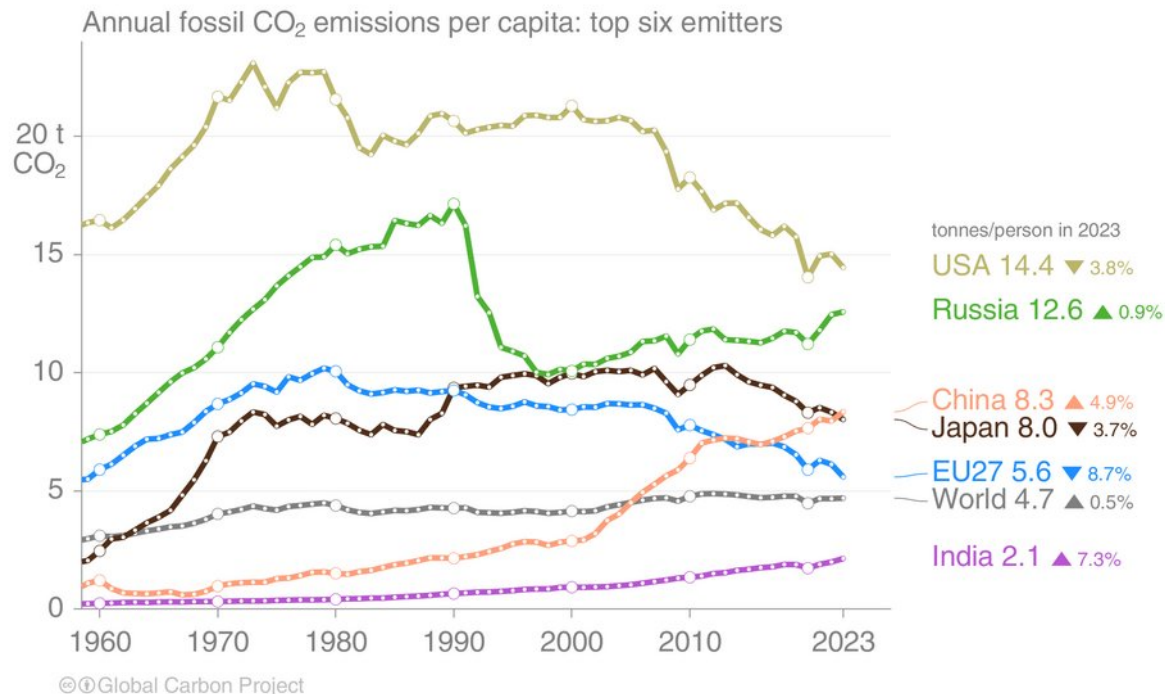
Energy use by source

Consumption of energy from fossil sources bounced back in 2021, but oil is still subdued. Renewable energy continued to grow, but needs to grow even faster to replace fossil energy consumption.



Top emitters: Fossil CO₂ emissions per capita to 2023

Countries have a broad range of per capita emissions reflecting their national circumstances

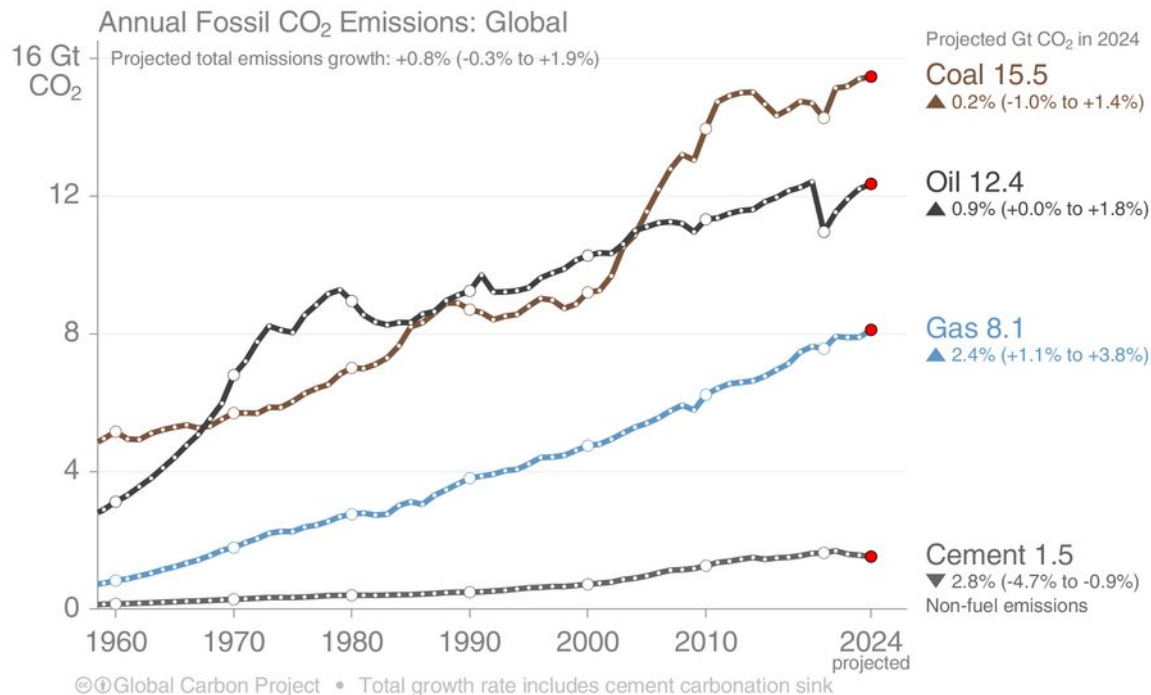


International aviation and maritime shipping (bunker fuels) contributed 3.0% of global emissions in 2023.

Source: [Friedlingstein et al 2024](#); [Global Carbon Project 2024](#)

Fossil CO₂ emissions by source

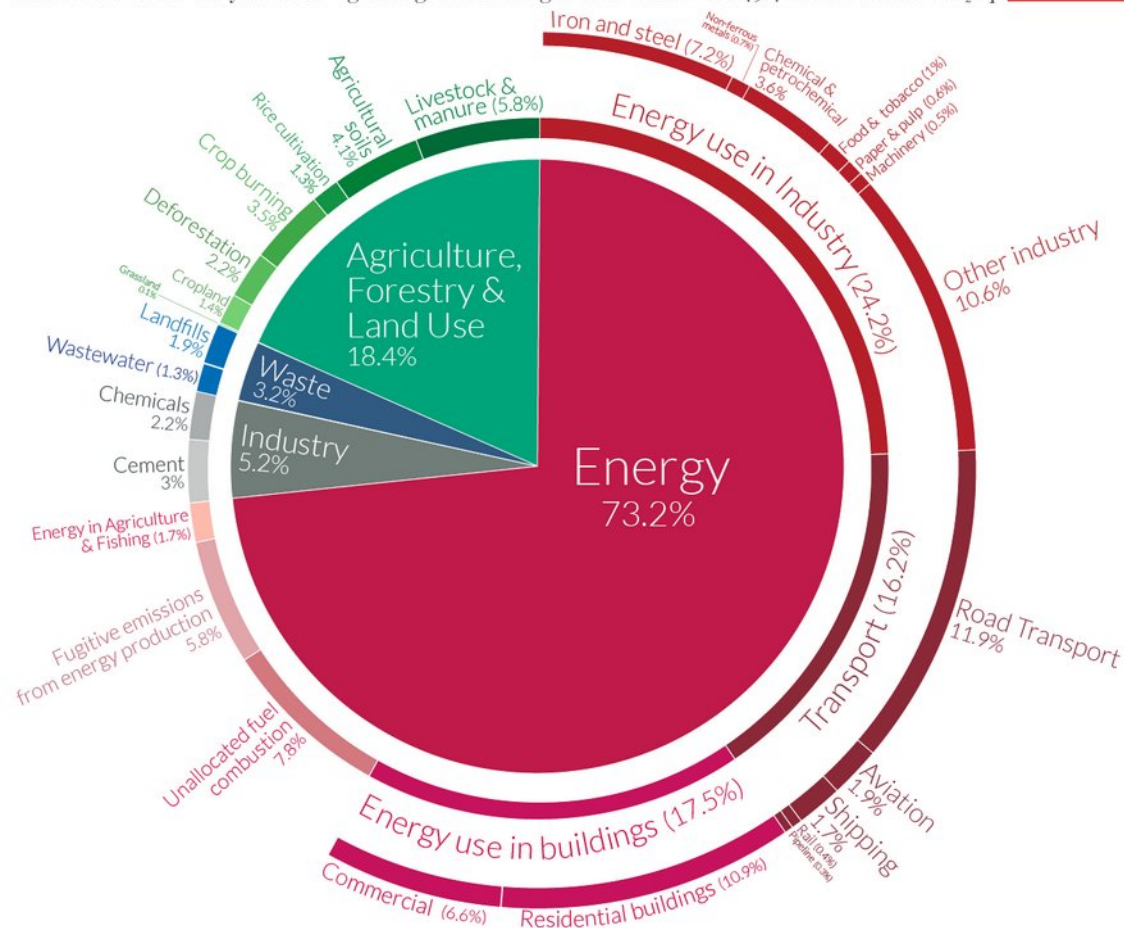
Share of global fossil CO₂ emissions in 2024: coal (41%), oil (32%), gas (21%), cement (4%), flaring and others (2%, not shown)



The 2024 projection is based on preliminary data and modelling.
Source: [Friedlingstein et al 2024](#); [Global Carbon Project 2024](#)

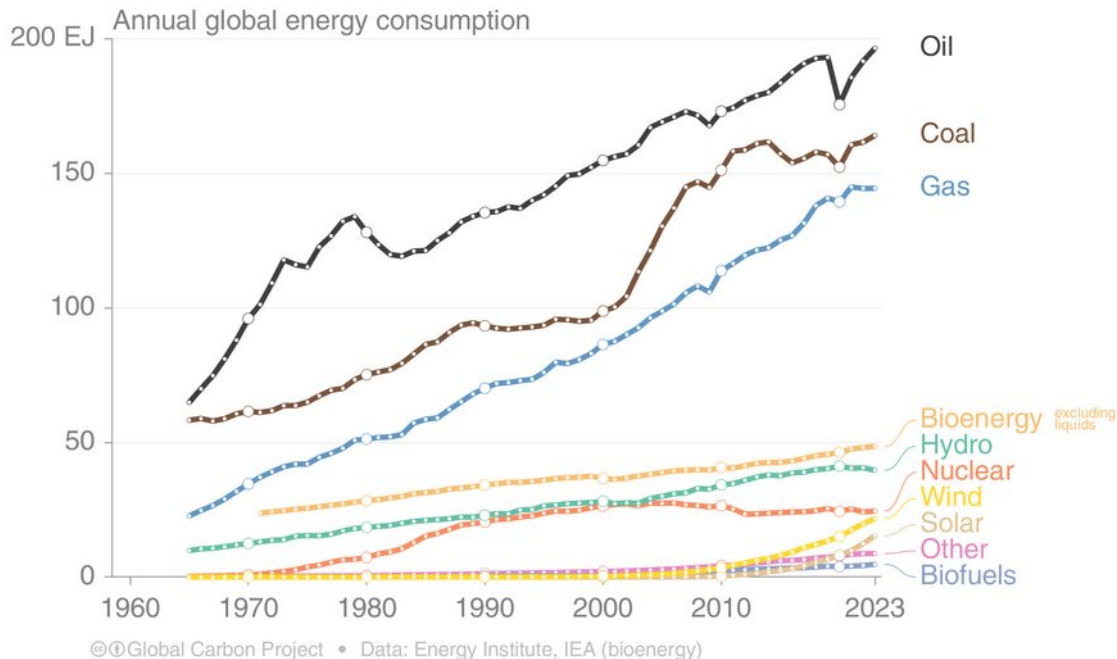
Global greenhouse gas emissions by sector

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



Energy use by source

Consumption of natural gas was flat in 2023, but oil exceeded its pre-pandemic level. Renewable energy continued to grow, but needs to grow even faster to replace fossil energy consumption.

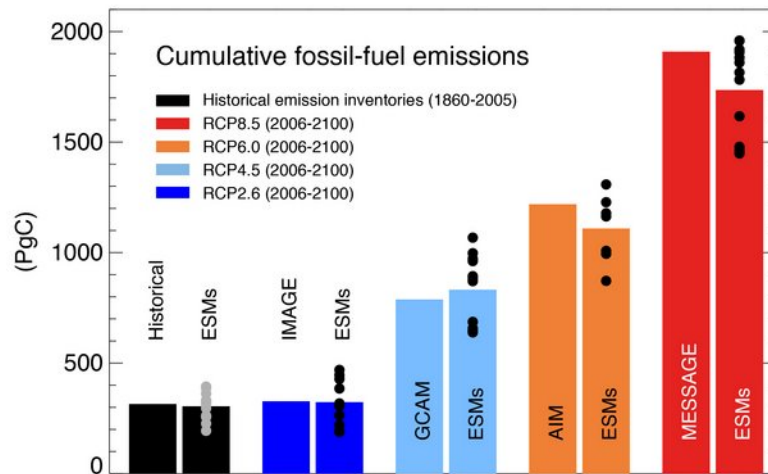
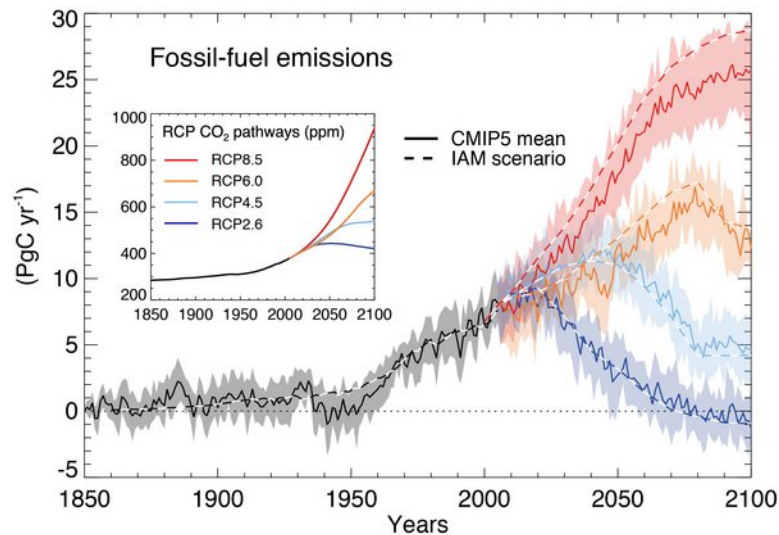
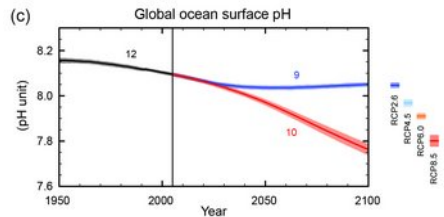
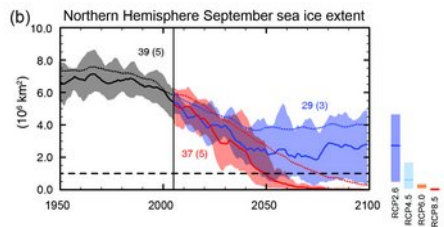
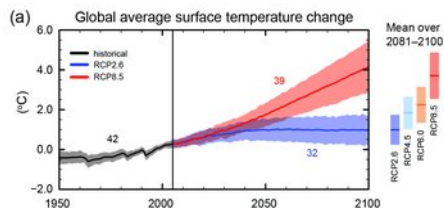


This figure shows “primary energy” using the substitution method (non-fossil sources are scaled up by an assumed fossil efficiency of approximately 0.38)

Source: [Energy Institute 2024](#); [Global Carbon Project 2024](#)

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.



This remaining carbon budget can increase or decrease depending on how deeply we reduce **greenhouse gases other than CO₂**

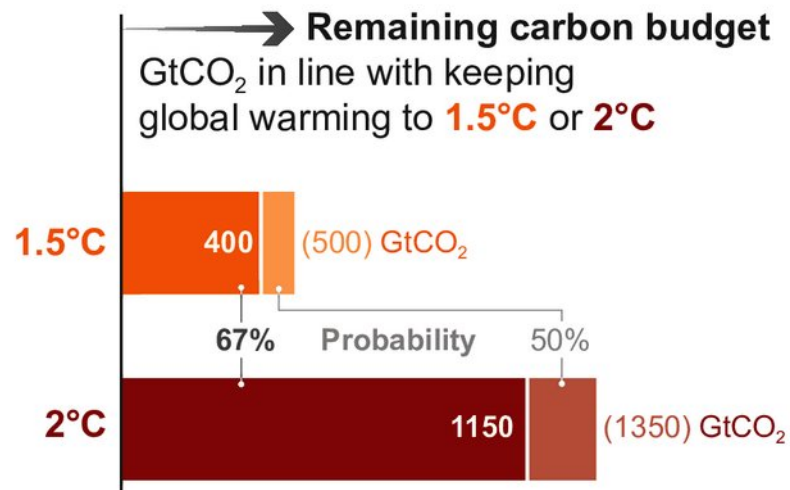
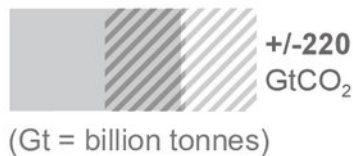
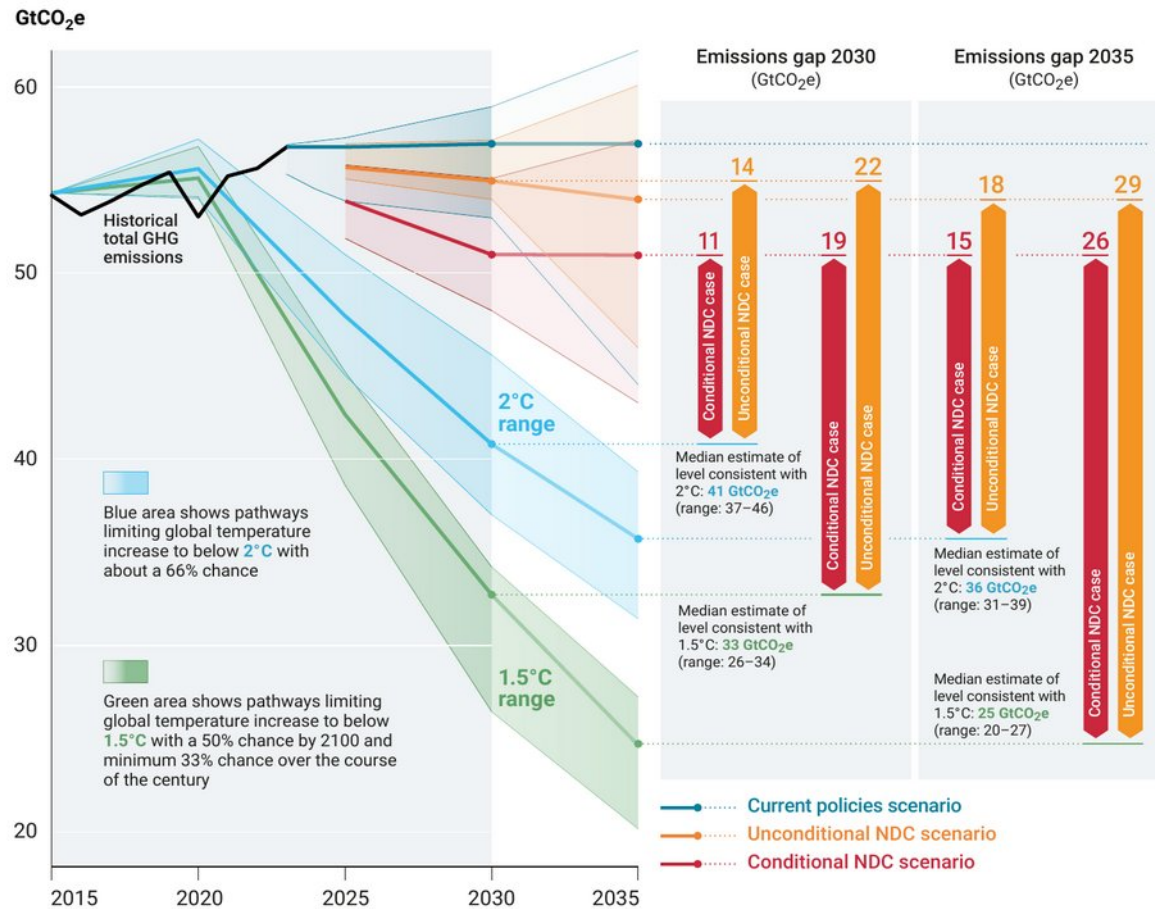
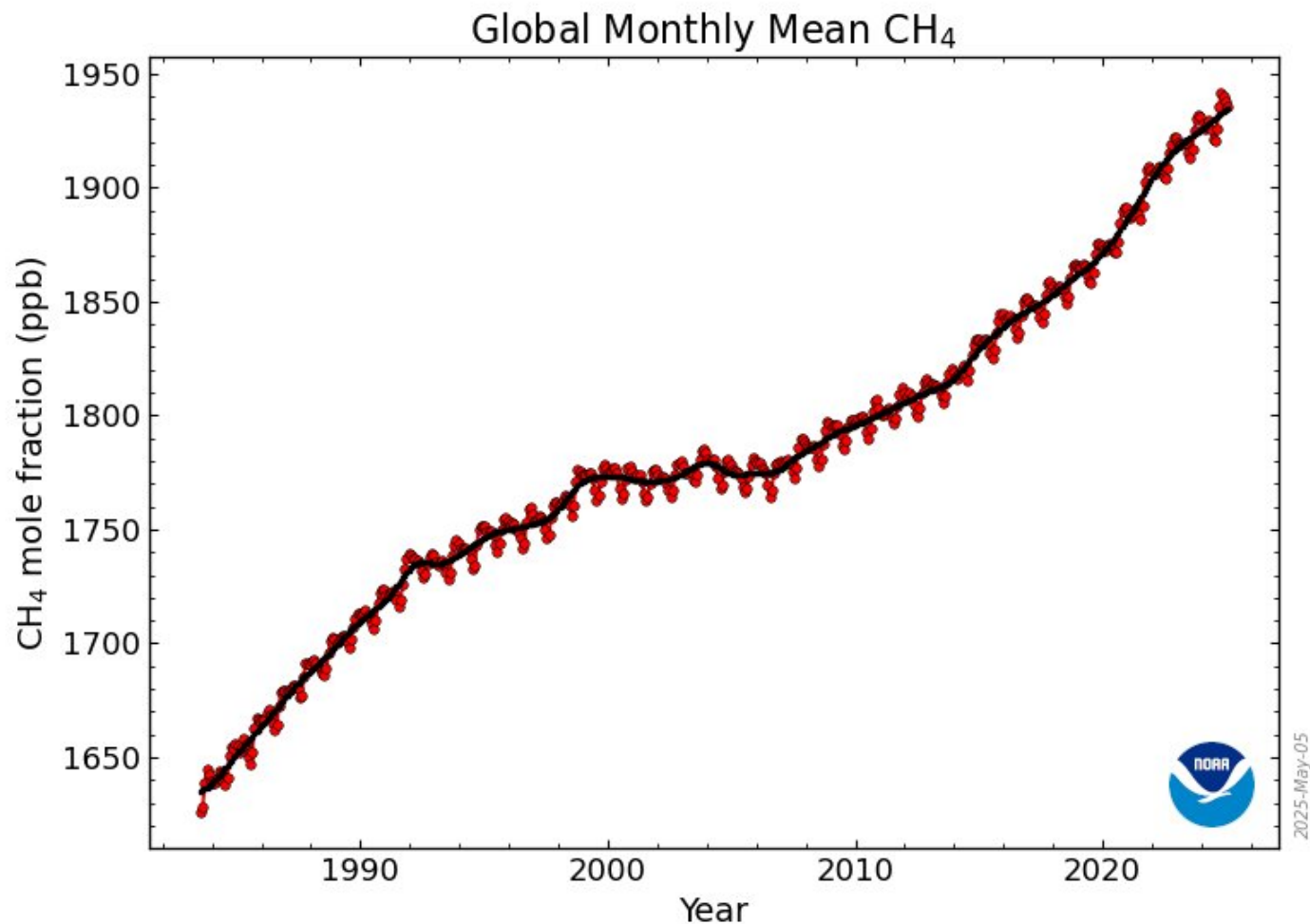


Figure ES.3 Global GHG emissions under different scenarios and the emissions gap in 2030 and 2035



Nie tylko CO₂:

Wzrost koncentracji
metanu w atmosferze



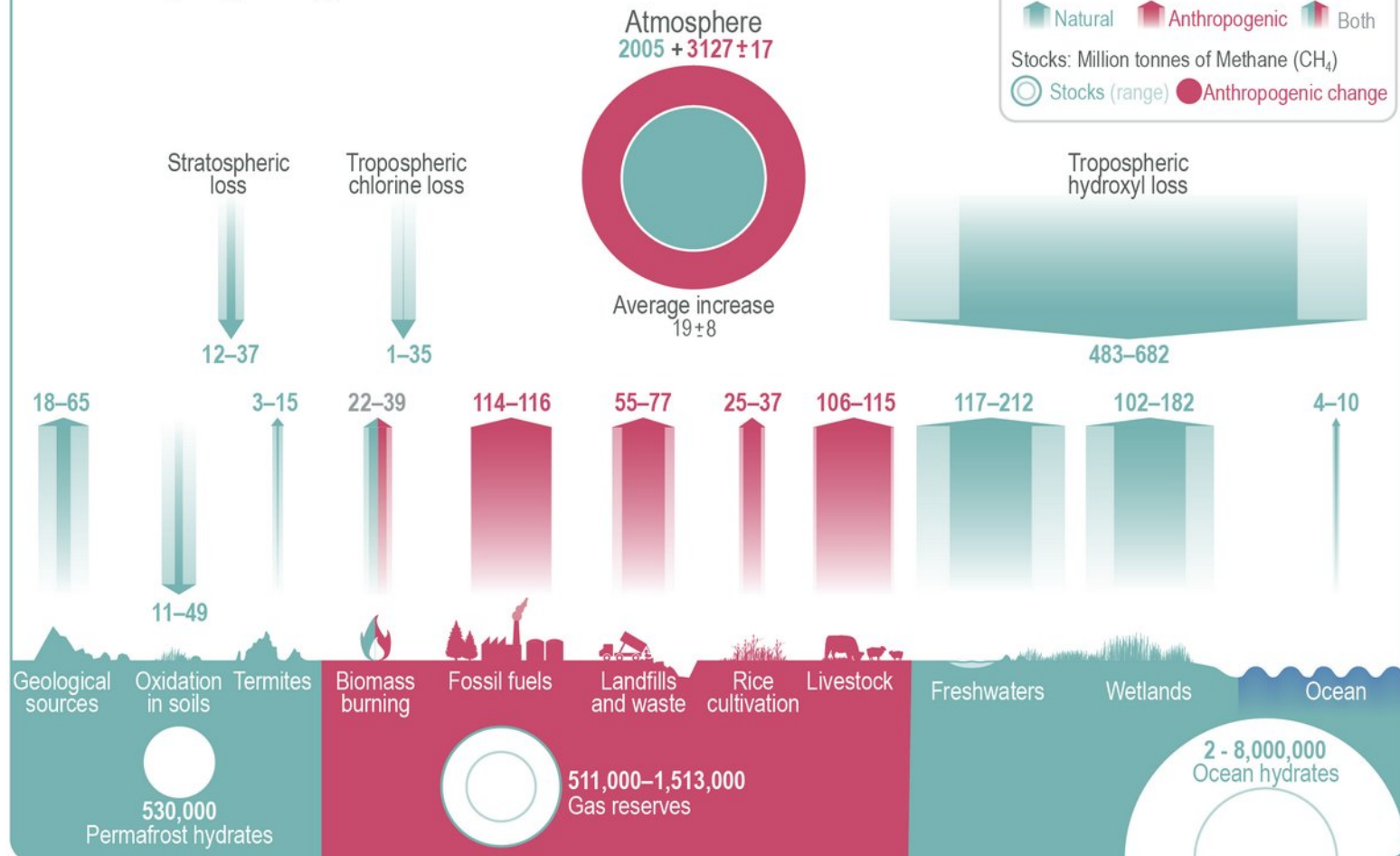
Methane (CH₄) Budget

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

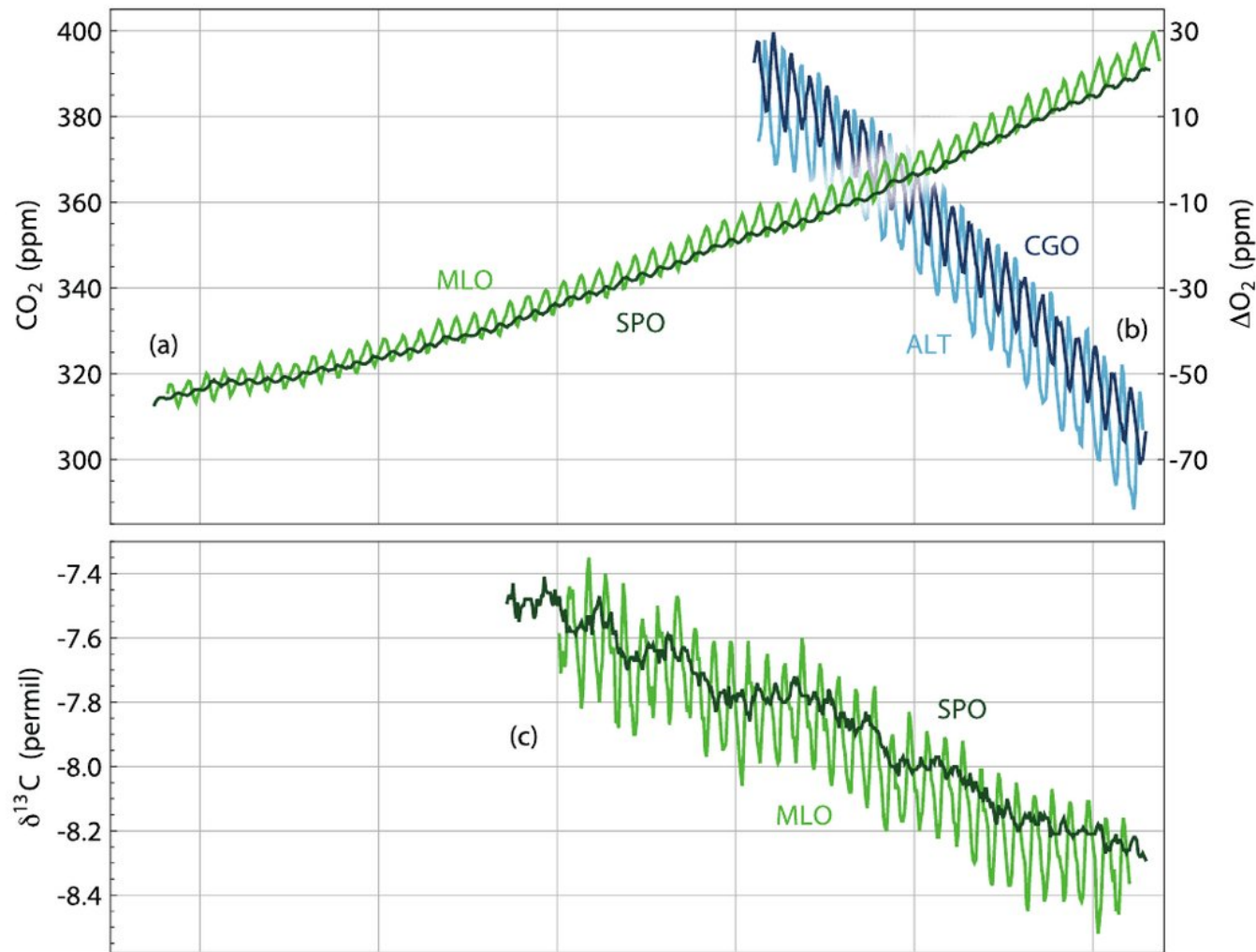
 Natural
  Anthropogenic
  Both

Stocks: Million tonnes of Methane (CH₄)

 Stocks (range)
  Anthropogenic change

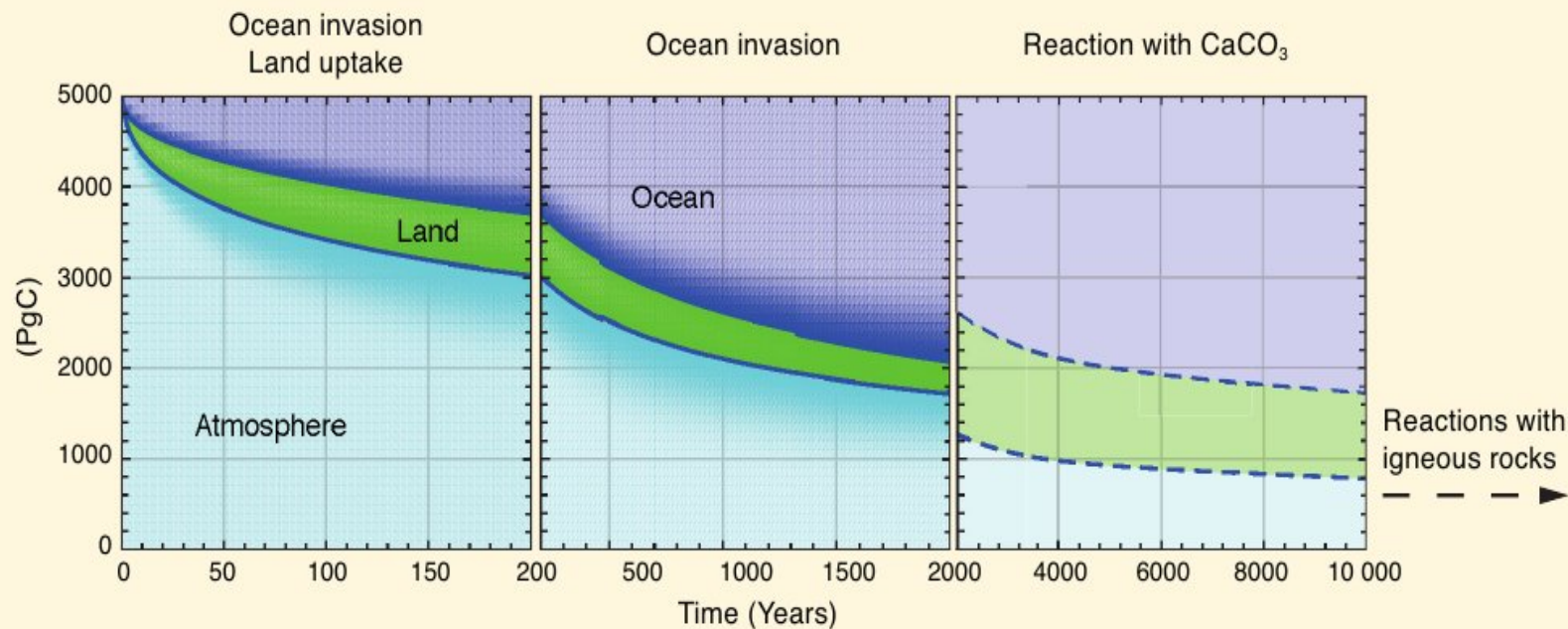


Inne dowody (poza
bilansem węgla) na to
że wzrost koncentracji
CO₂ w atmosferze
pochodzi ze spalania
paliw kopalnych



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).

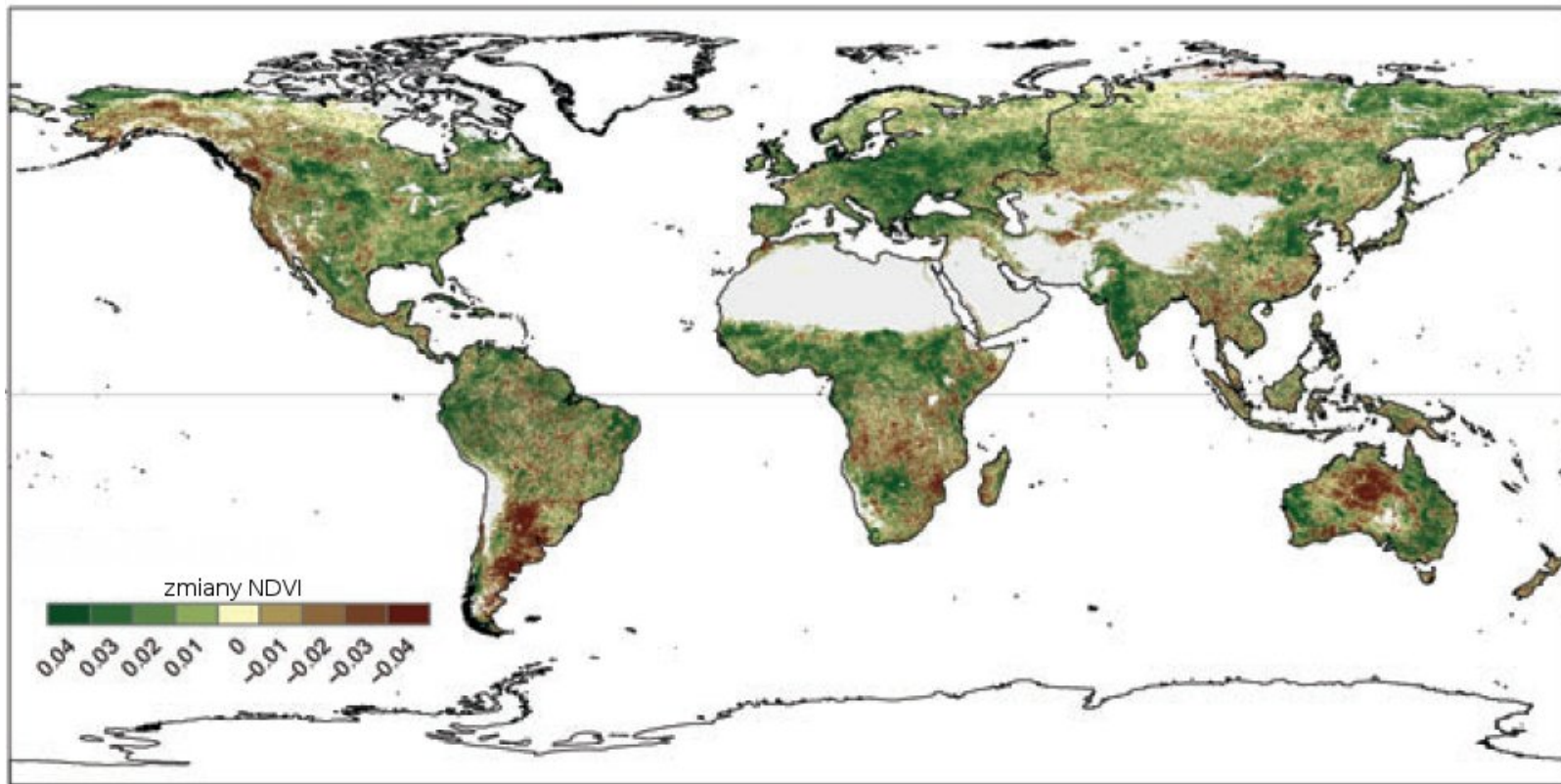
Główne procesy naturalne odpowiedzialne za usuwanie dwutlenku węgla z atmosfery po nagłym wzroście koncentracji tego gazu w atmosferze.

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.

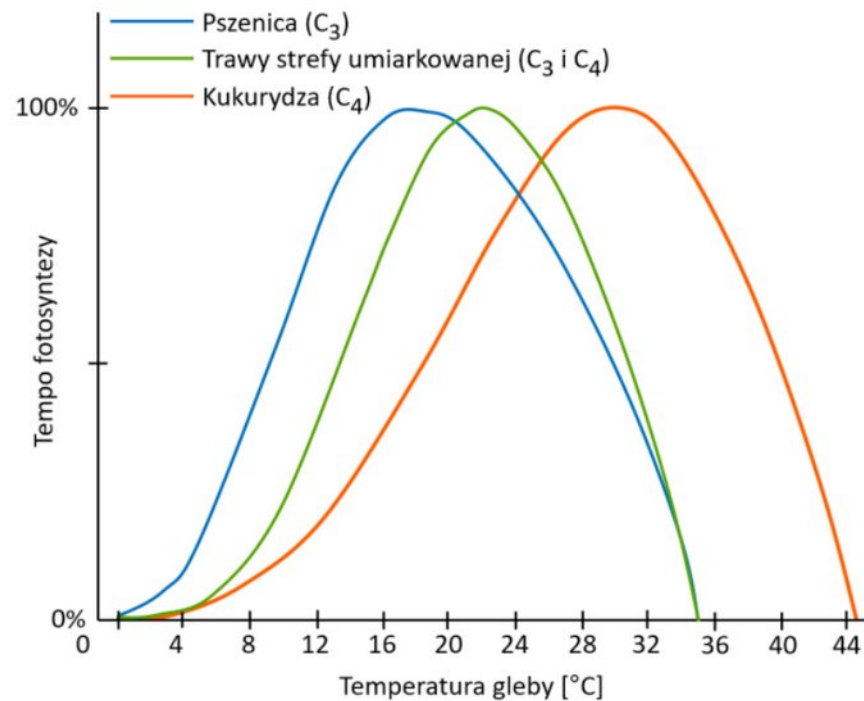
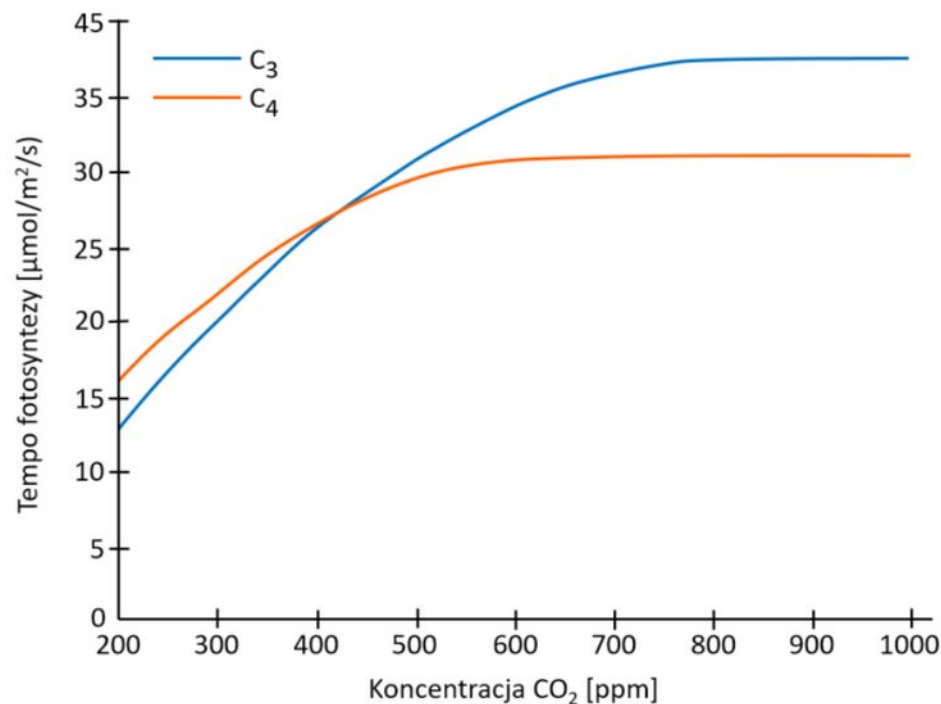
Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	1–10 ²	$6\text{CO}_2 + 6\text{H}_2\text{O} + \text{photons} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$ $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O} + \text{heat}$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

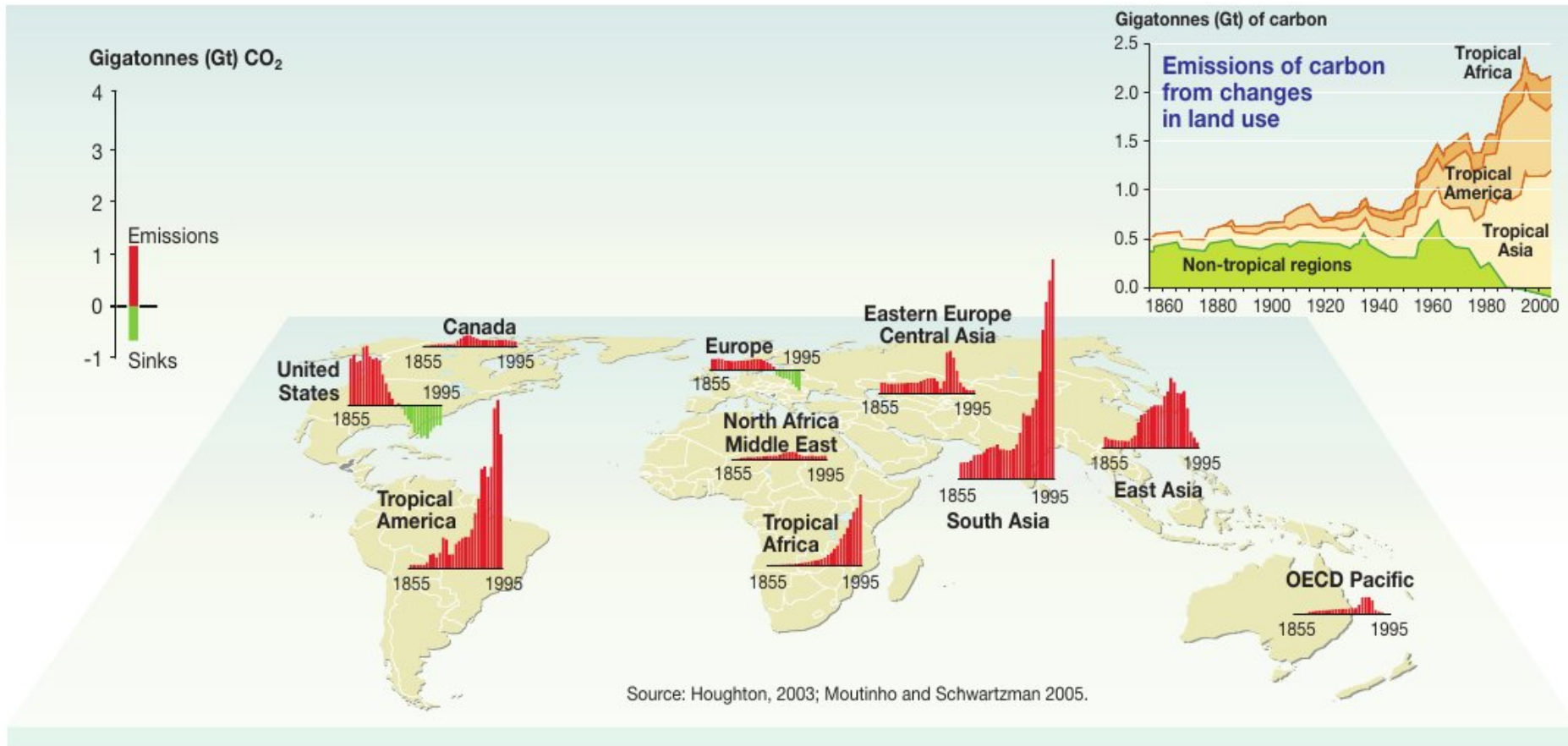


Zmiany wskaźnika NDVI (Normalized Difference Vegetation Index) w okresie 1982-2008. Globalne ocieplenie zmniejsza produktywność roślin. W miarę jak przybywa dwutlenku węgla, na półkuli północnej rosną wartości wskaźnika NDVI (obszary oznaczone na mapie kolorem zielonym), co oznacza zdrową i rozwijającą 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 CO₂ dla różnych typów fotosyntezy. Po prawej: Zależność tempa fotosyntezy dla różnych roślin od temperatury powierzchniowej warstwy gleby.

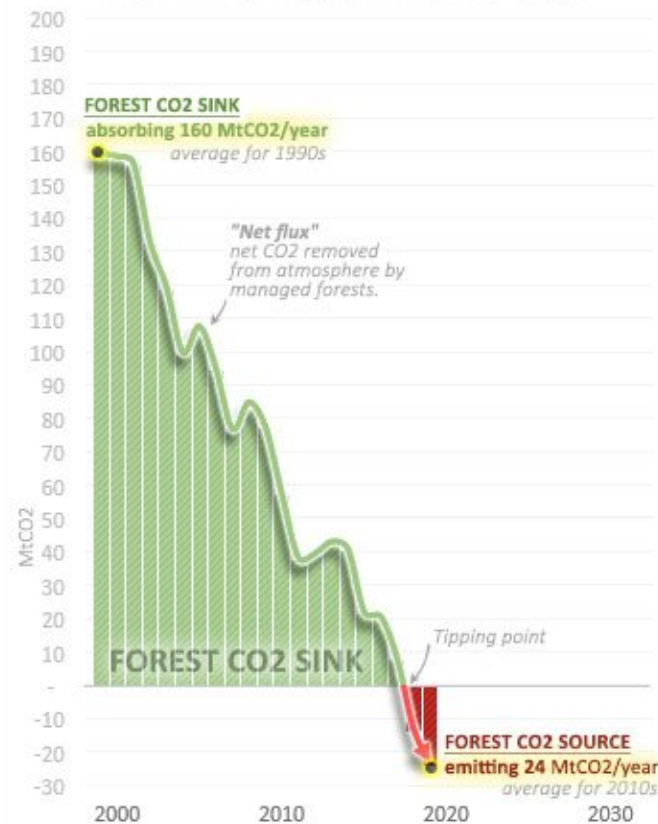
↓ Historical forest carbon balance, 1855-1995



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

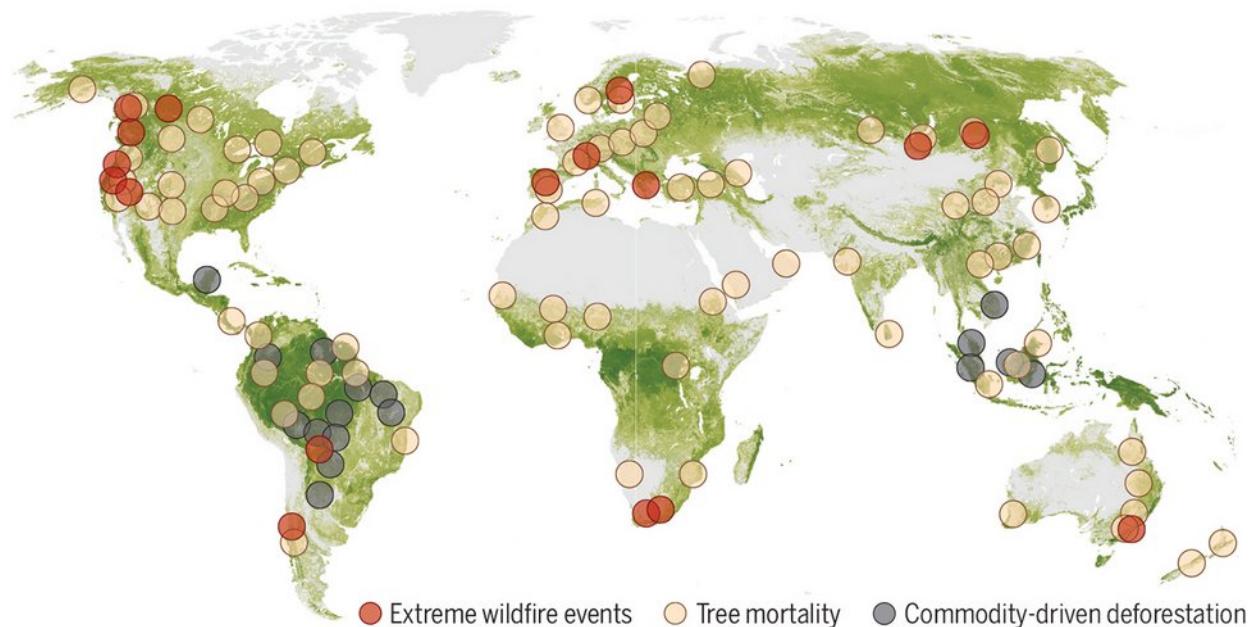
Jonathan T. Overpeck¹, David D. Breshears²

✦ See all authors and affiliations

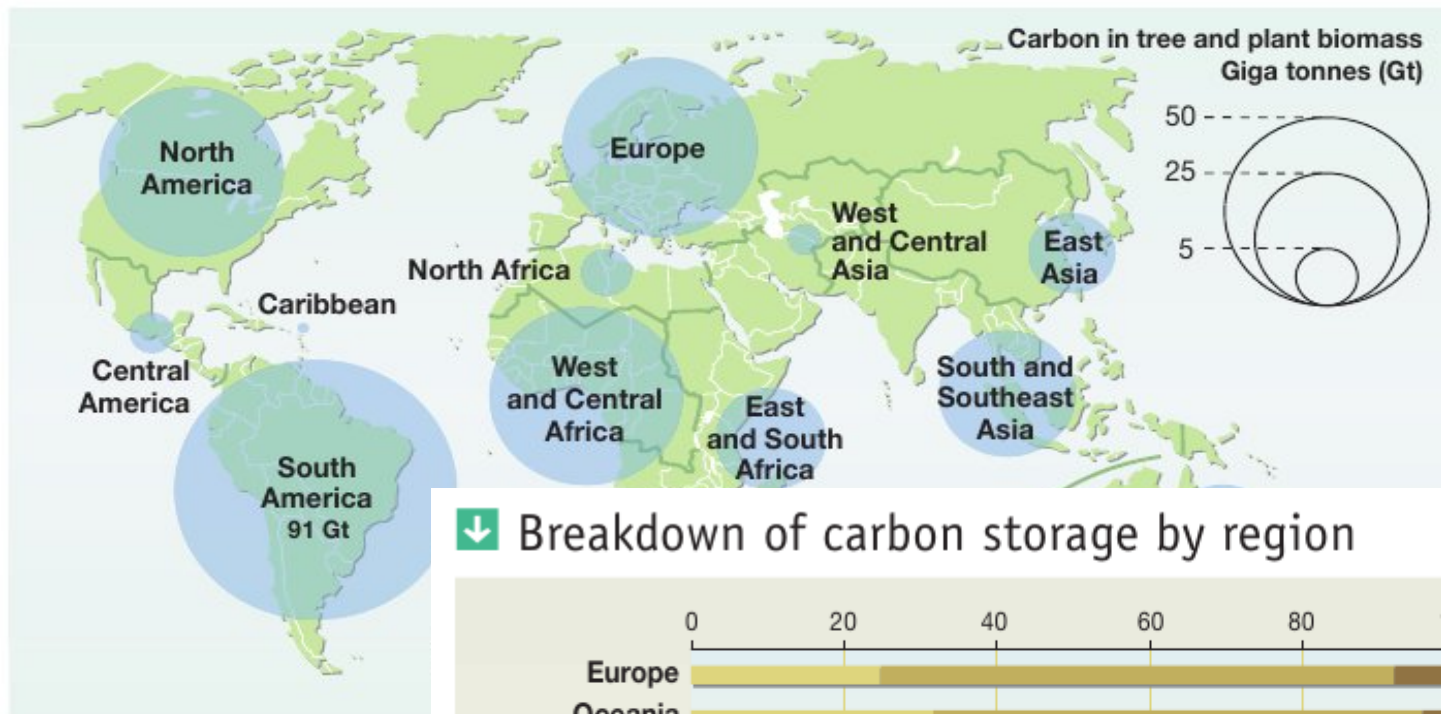
Science 21 May 2021:
Vol. 372, Issue 6544, pp. 786-787
DOI: 10.1126/science.abi9902

Rapid tree loss around the world

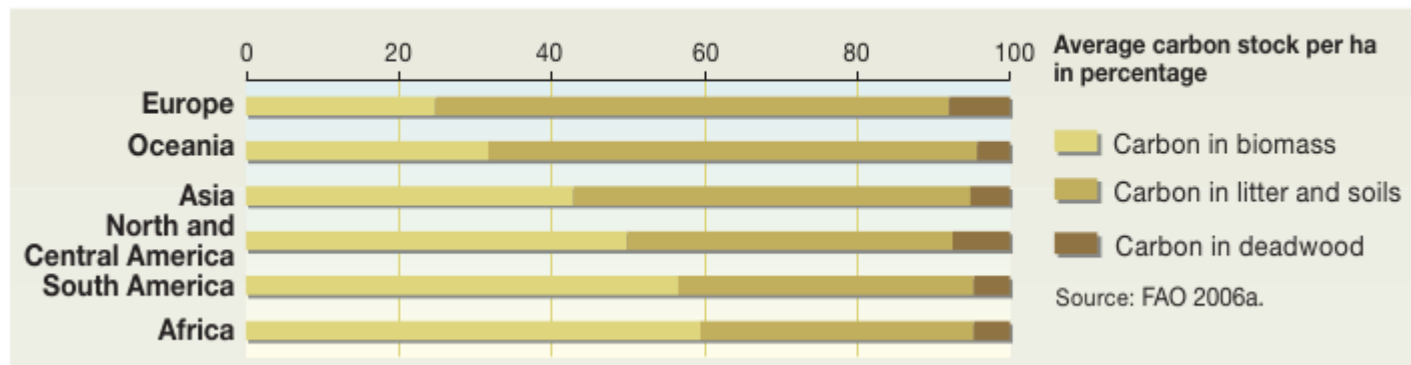
Global tree decline is attributed to commodity-driven deforestation (9), loss by wildfire (1), and drought- and heat-related mortality (often associated with pests and pathogens). The latter two are affected by increasing atmospheric moisture demand that drives forest stress. Forested areas are shown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



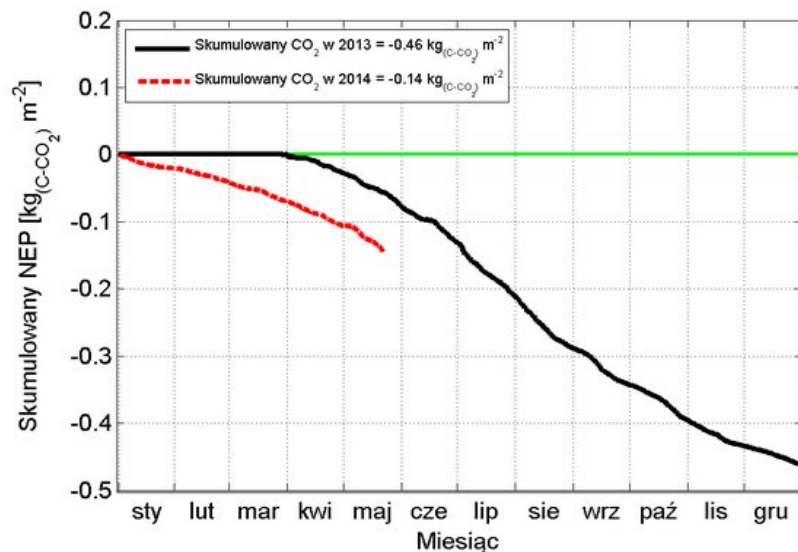
↓ Forest carbon stock per region



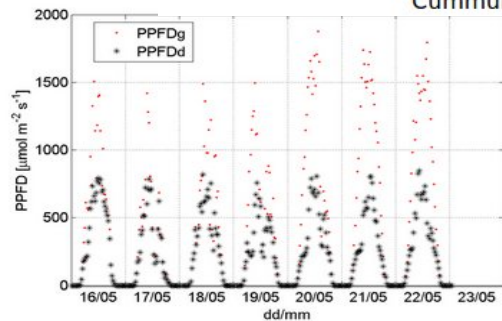
↓ Breakdown of carbon storage by region



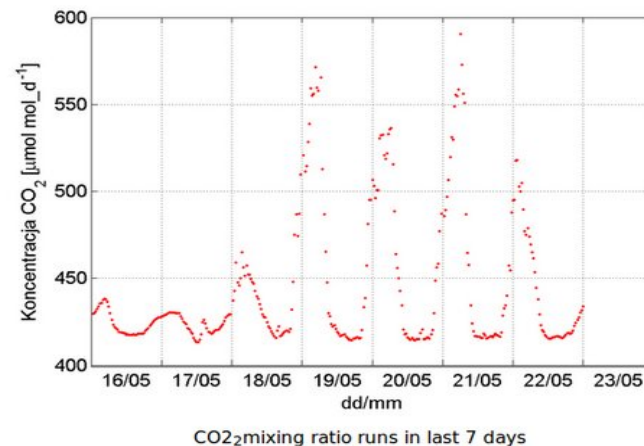
Stacja badawcza Tleń- las iglasty po przejściu tornado (od 29 Marca 2013r.)



Cummulation of CO_2 estimated by EC

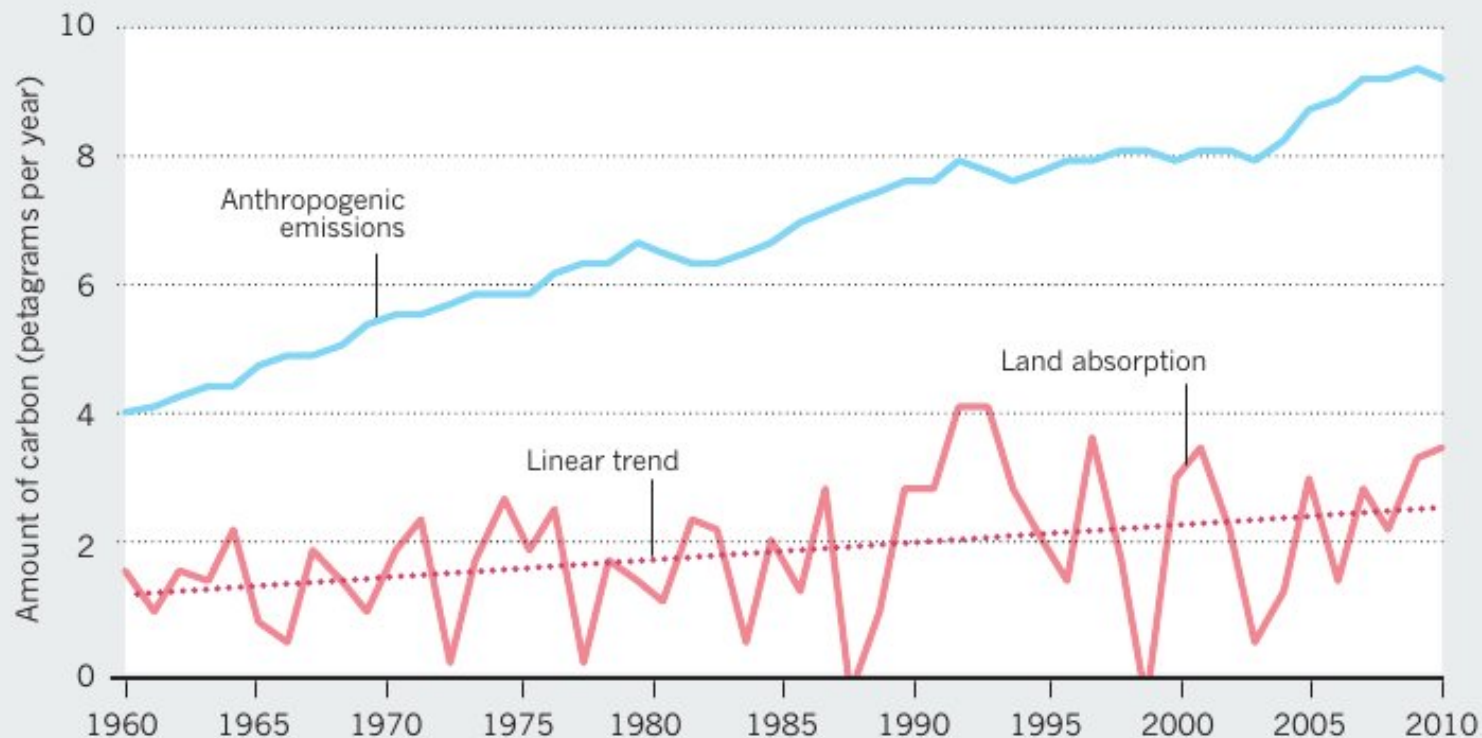


Photosynthetic Photon Flux Density (data from BF5), in last 7 days



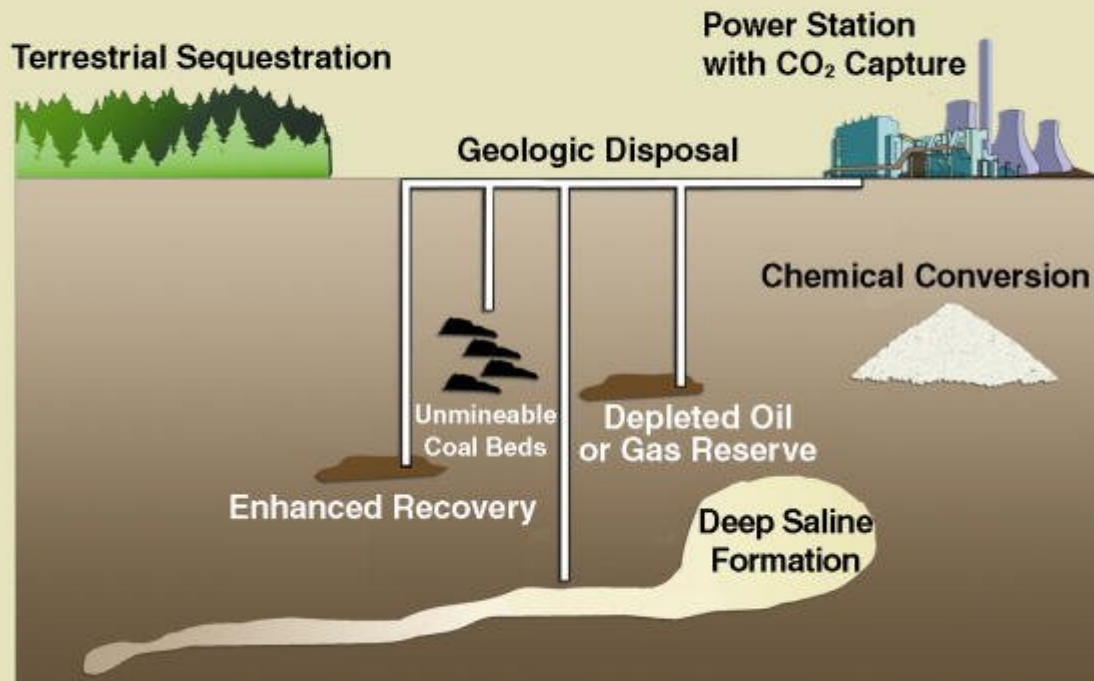
GLOBAL LAND SINK

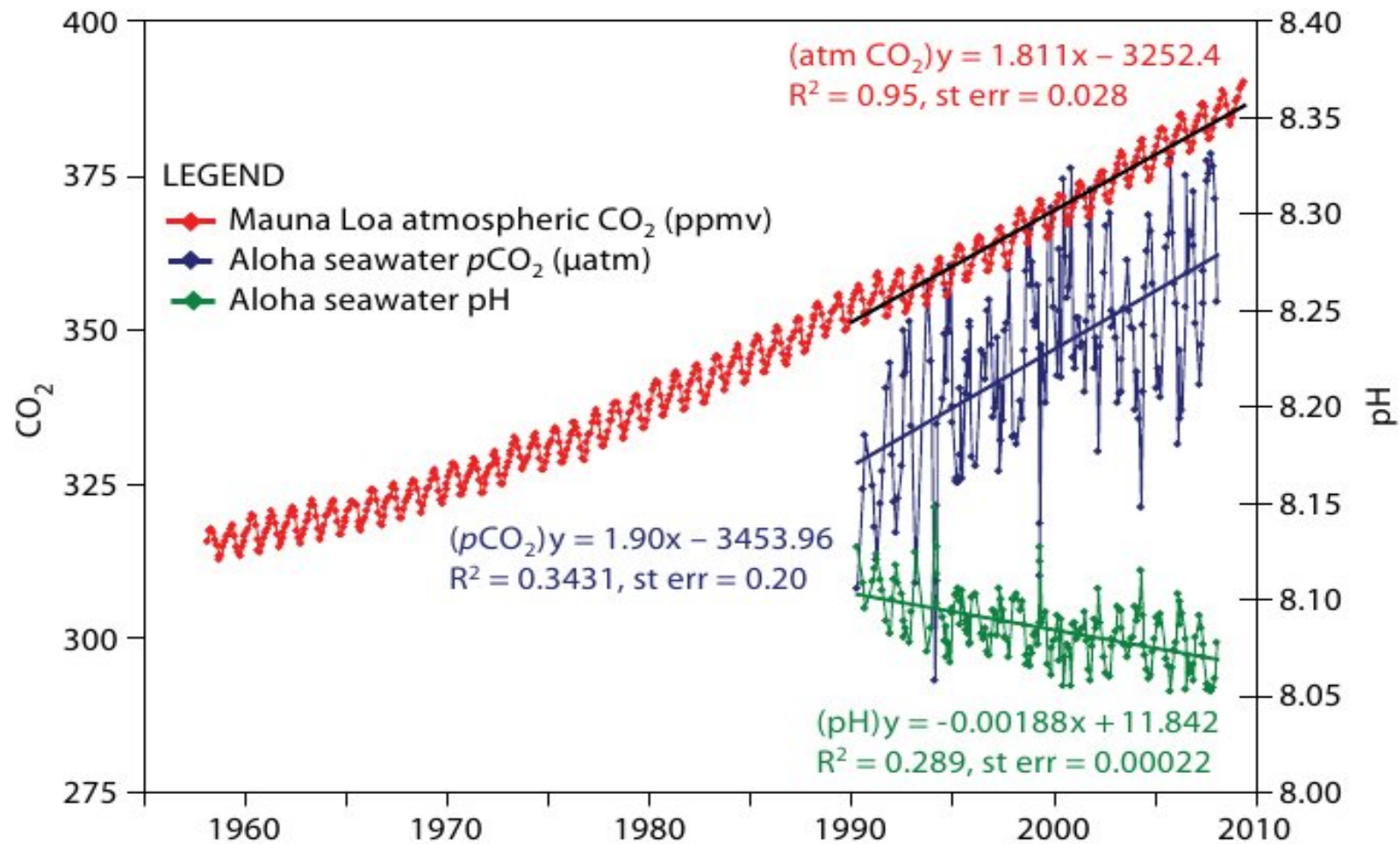
The quantity of carbon absorbed by trees and other types of vegetation per hectare of land has risen in the past 50 years as anthropogenic carbon dioxide and nitrogen emissions have grown. This is despite the world's forest area falling by around 2% since 1990.



Nie tylko lasy – opcje sekwestracji węgla.

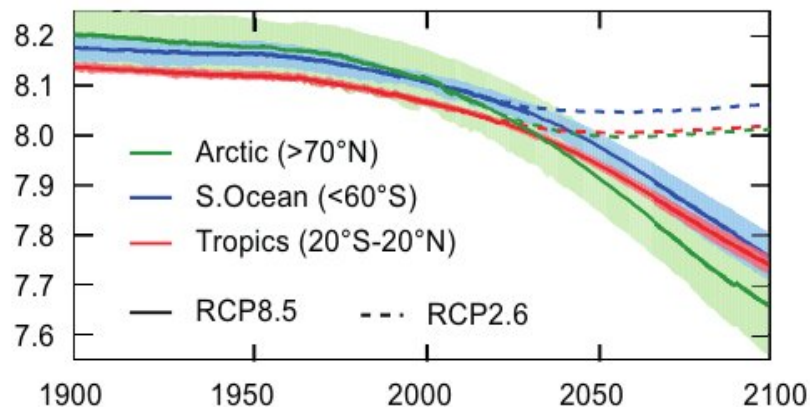
Carbon Sequestration Options



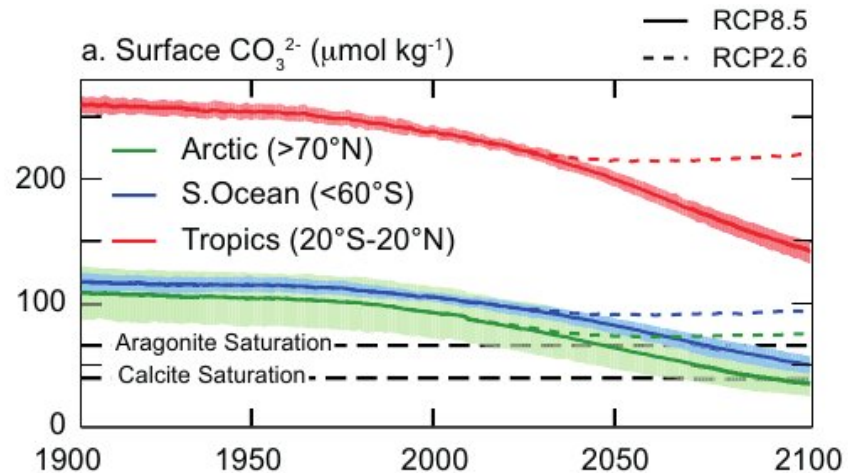


Zakwaszenie oceanów

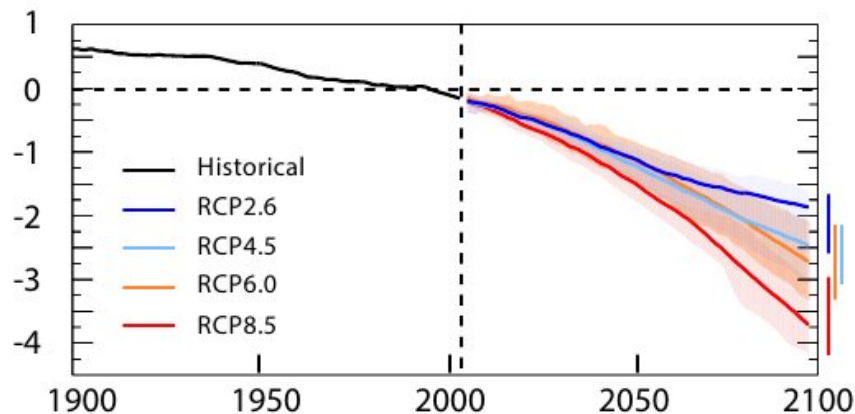
a. Surface pH

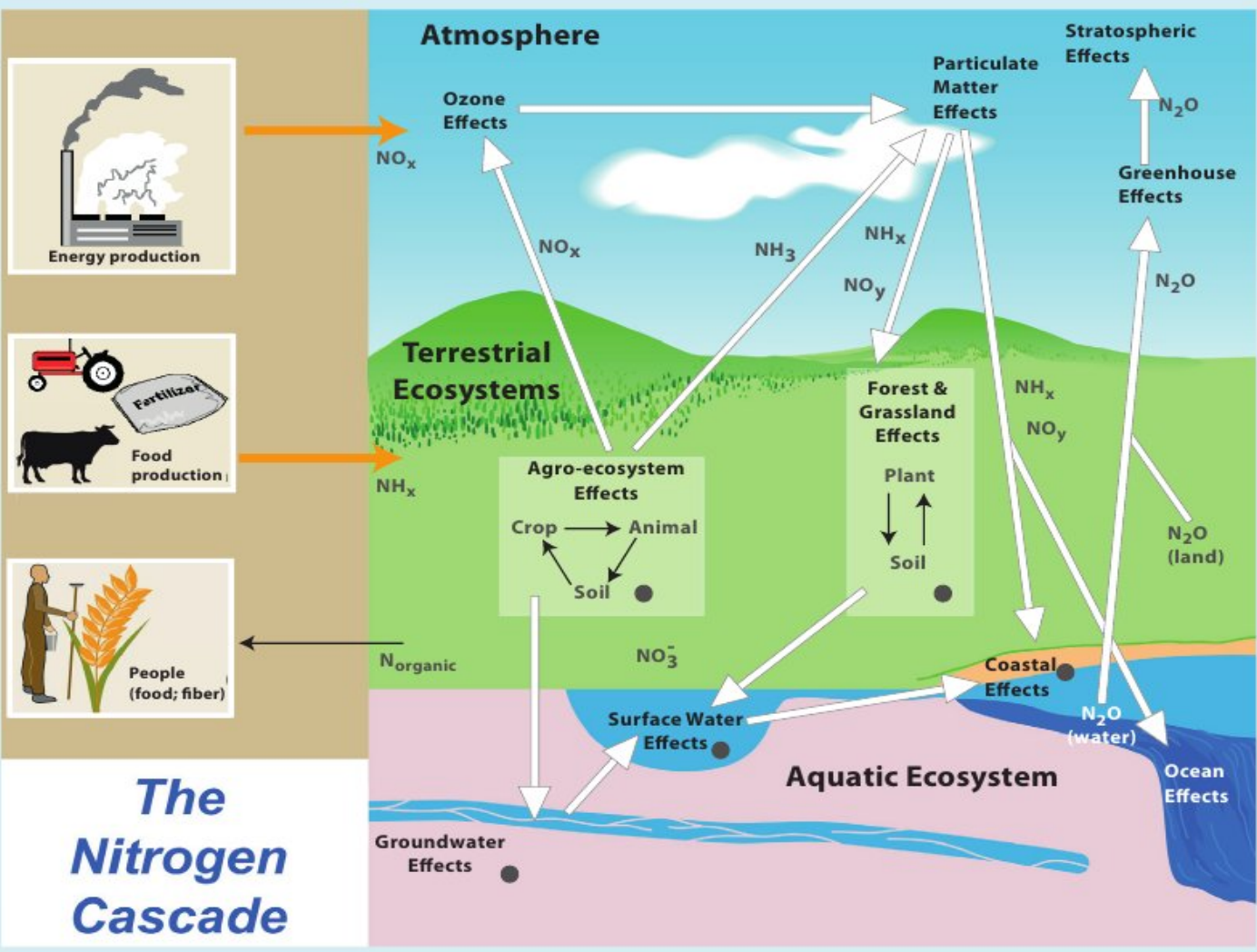


a. Surface CO_3^{2-} ($\mu\text{mol kg}^{-1}$)



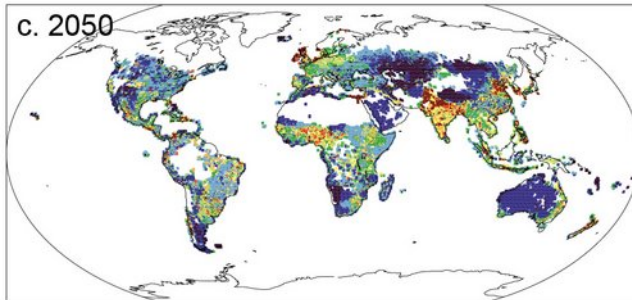
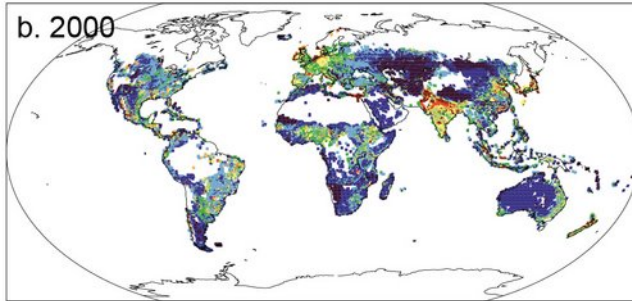
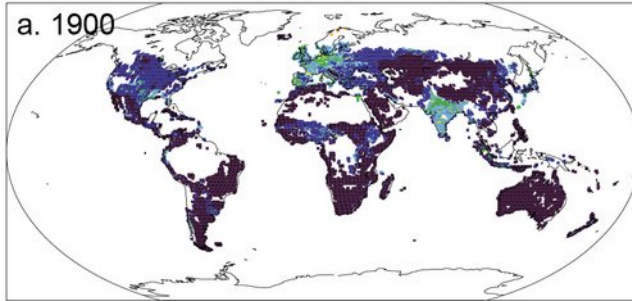
a. Ocean oxygen content change (%)





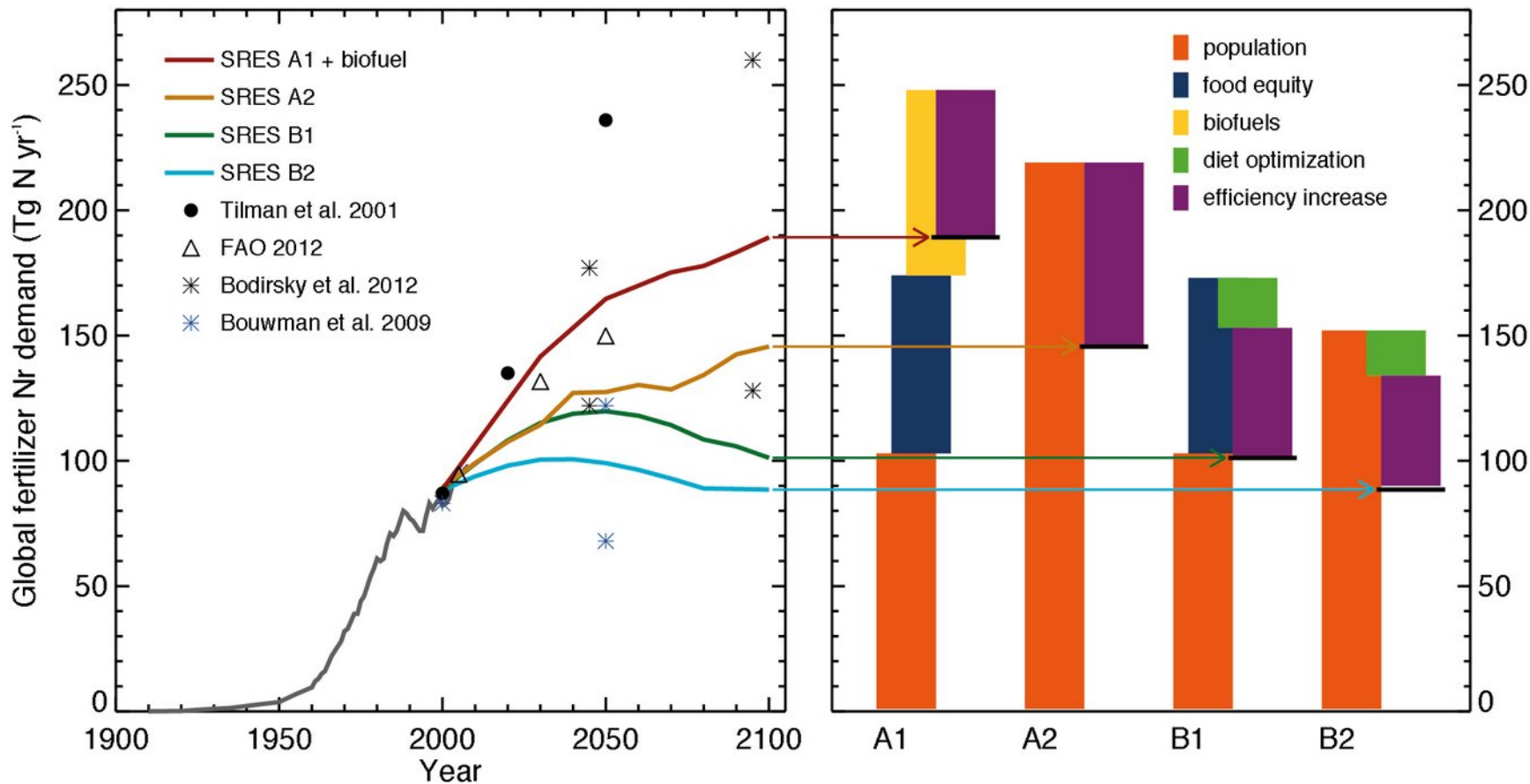
“Kaskada azotowa” - zmiany jakie powoduje w cyklu azotowym każdy atom przekształcony z nieaktywnej formy N_2 do formy reaktywnej chemicznie – biorącej udział w procesach biologicznych i chemicznych w systemie klimatycznym

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.

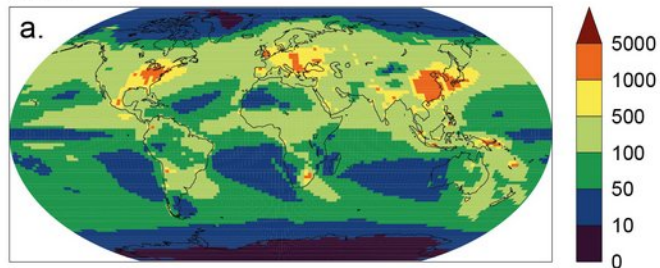


Jak będzie się zmieniać depozycja związków siarki i azotu.

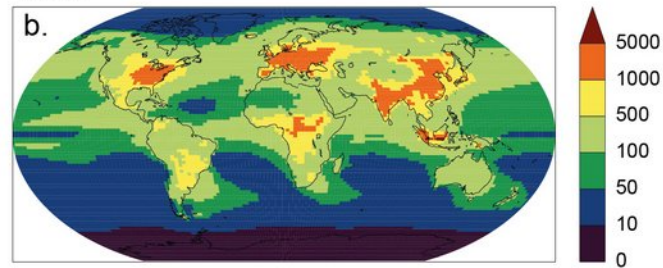
SO_x deposition (kgS km⁻² y⁻¹)

N deposition (kgN km⁻² y⁻¹)

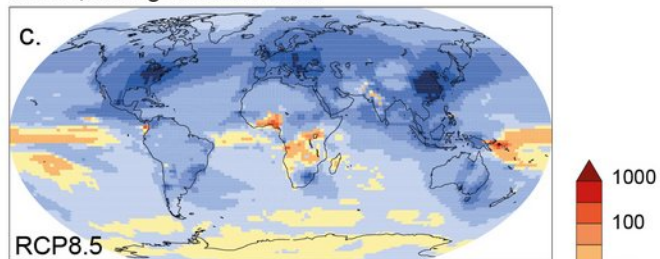
1990s



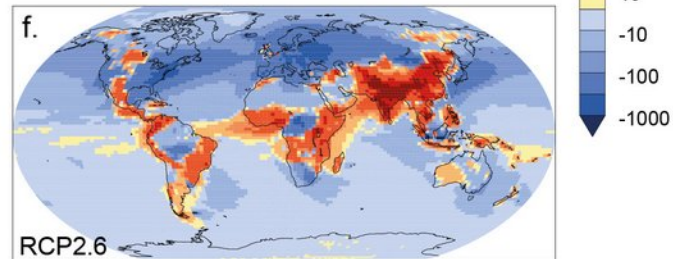
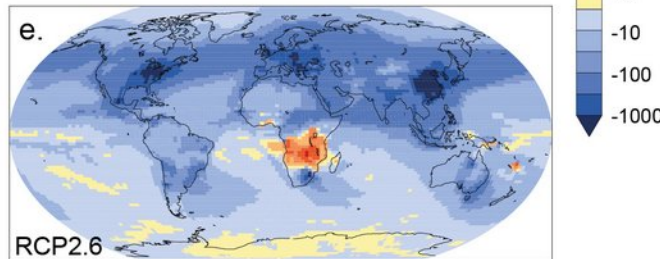
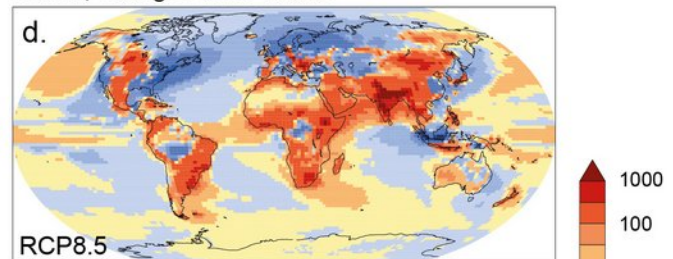
1990s



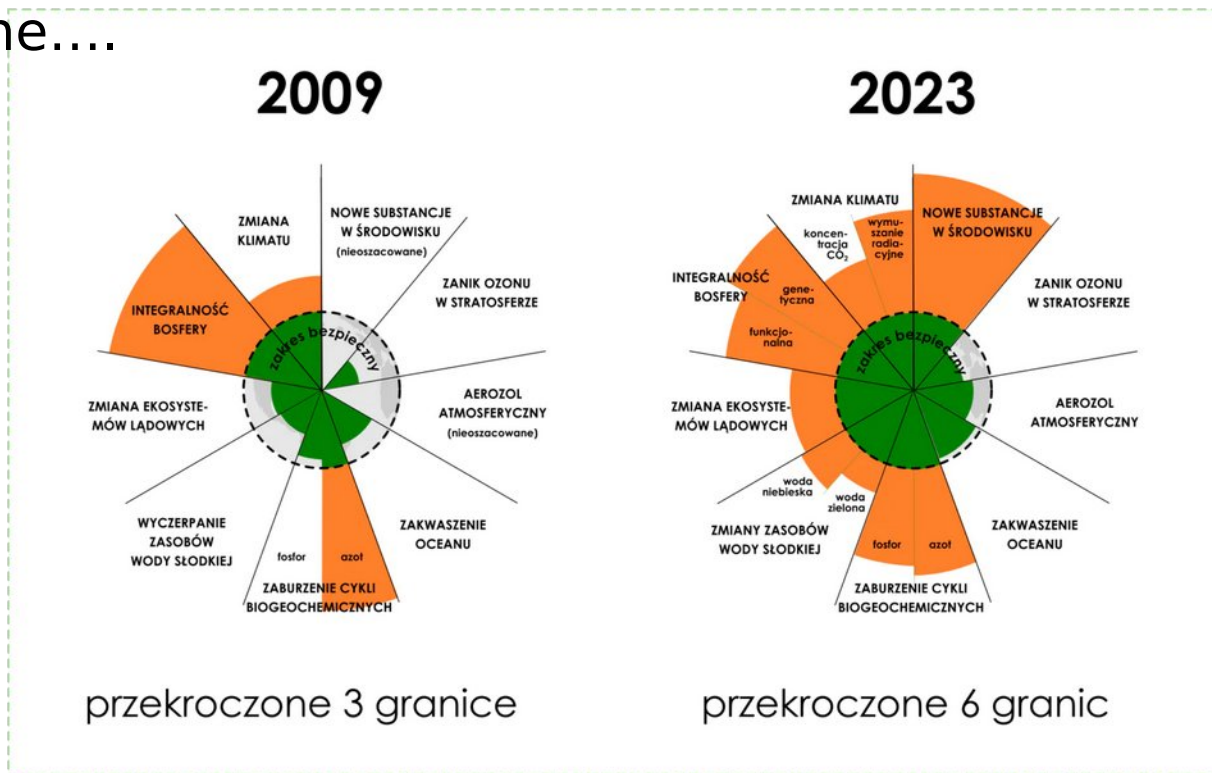
2090s, changes from 1990s



2090s, changes from 1990s



Szybko przekraczamy granice planetarne....



Earth beyond six of nine planetary boundaries

KATHERINE RICHARDSON · WILL STEFFEN · WOLFGANG LUKHT · JÜRGEN BERNHARDT · SARAH E. CORNELL · JONATHAN F. DONGES · MARKUS DÖRIG · INGO FELTZER · GOVINDASAMY BALA · J. I. AND JONAS ROCKSTRÖM · +19 authors · [Authors Info & Affiliations](#)

Podsumowanie:

Problem z węglem: CO_2 i CH_4 poważny.

Ale nie jedyny...