

# **Fizyka Procesów Klimatycznych**

## **Cykl węglowy, inne cykle biogeochemiczne.**

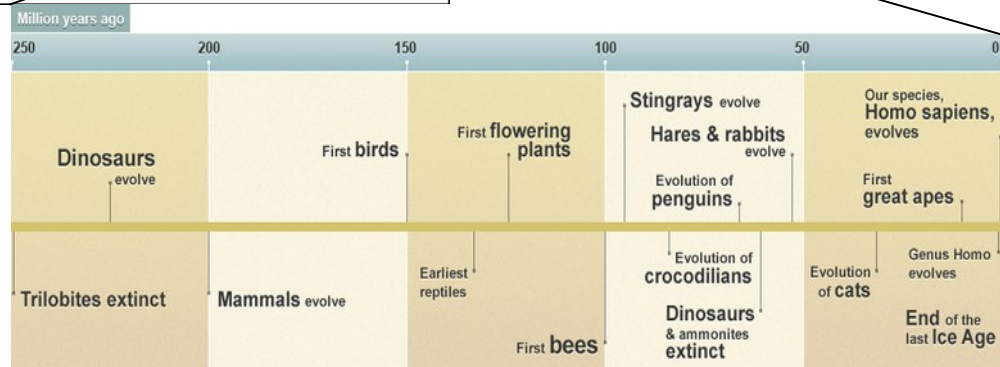
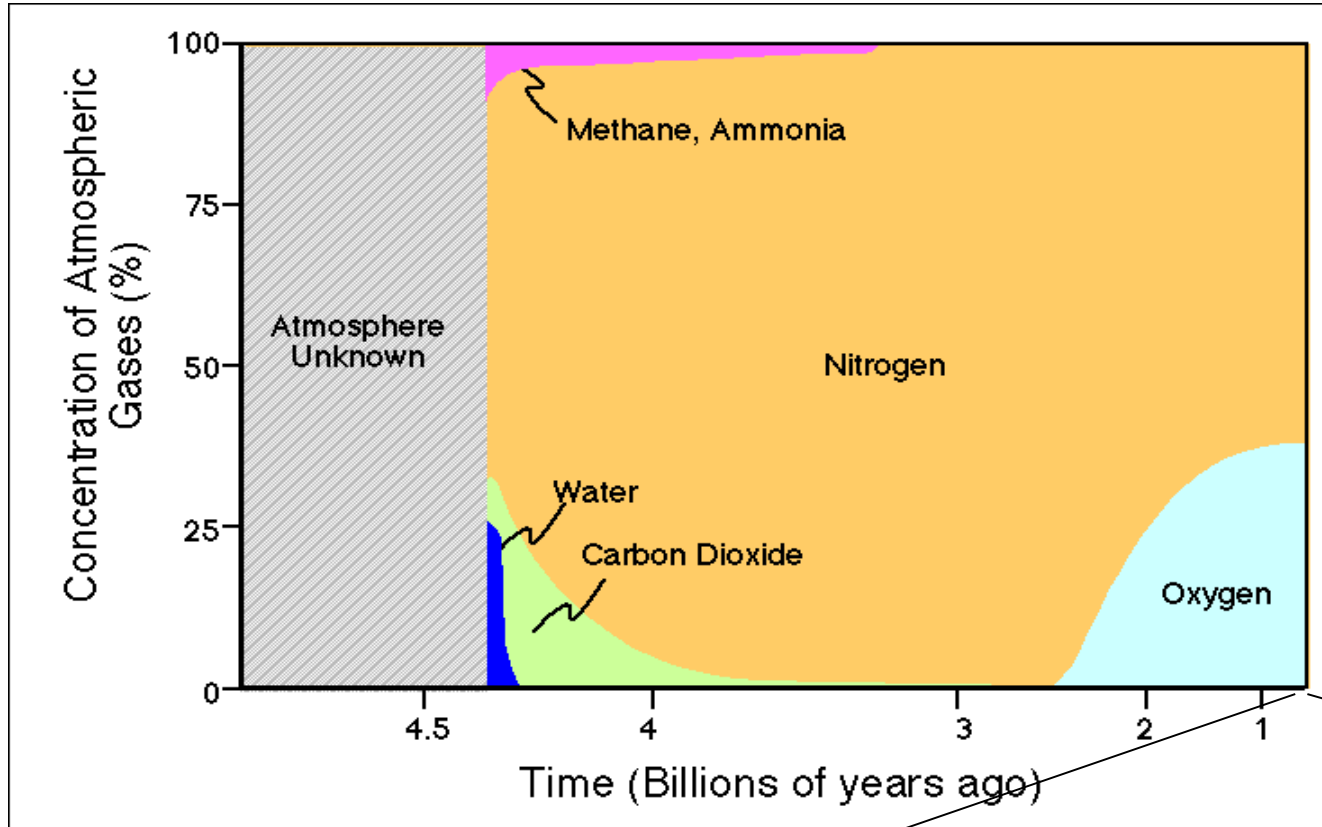
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Wykorzystano slajdy dr Aleksandry Kardaś

# Cykl węglowy, azotowy, zmiany w składzie atmosfery.

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



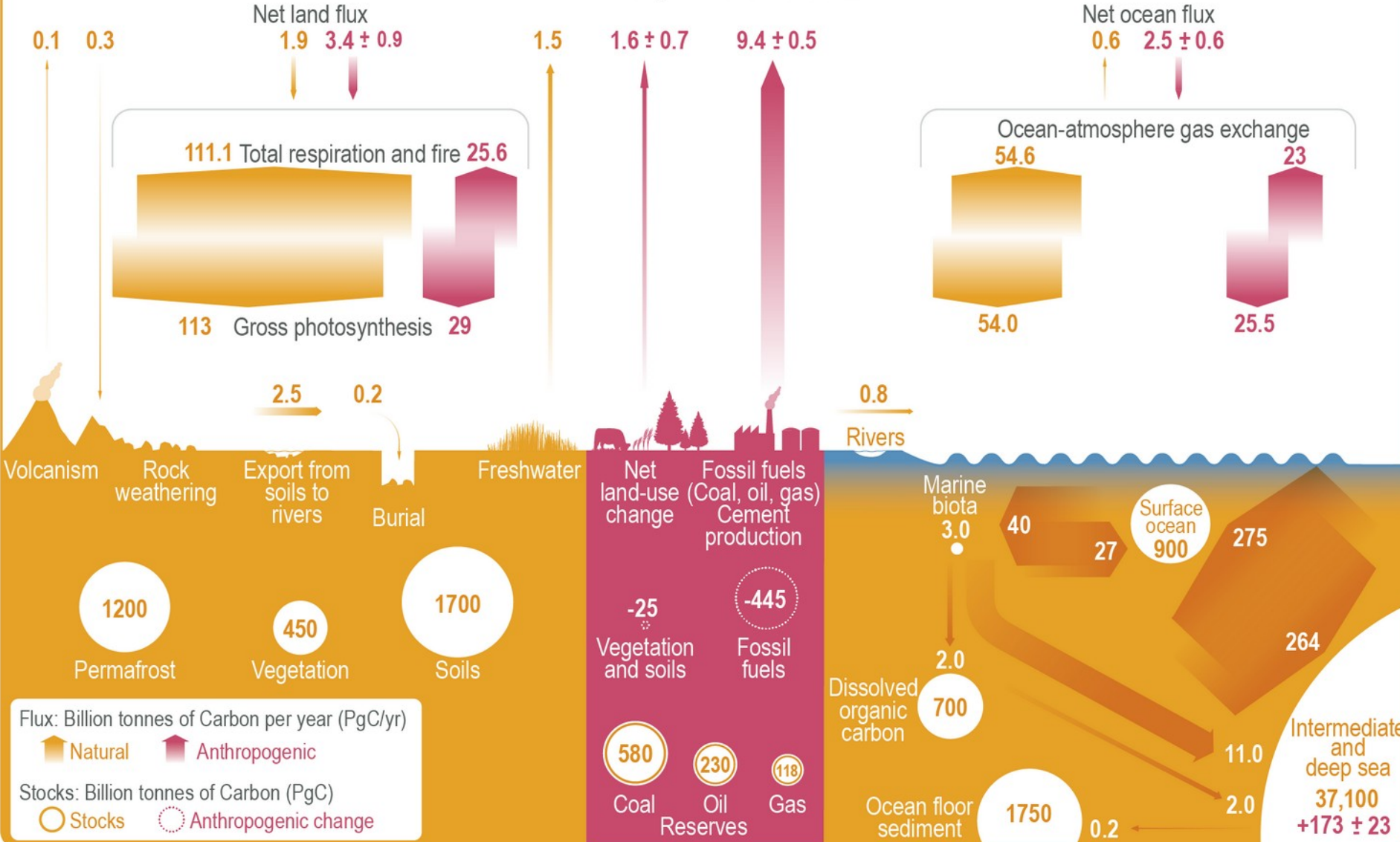
# Carbon (CO<sub>2</sub>) Budget

Atmosphere

591 + 279 ± 5

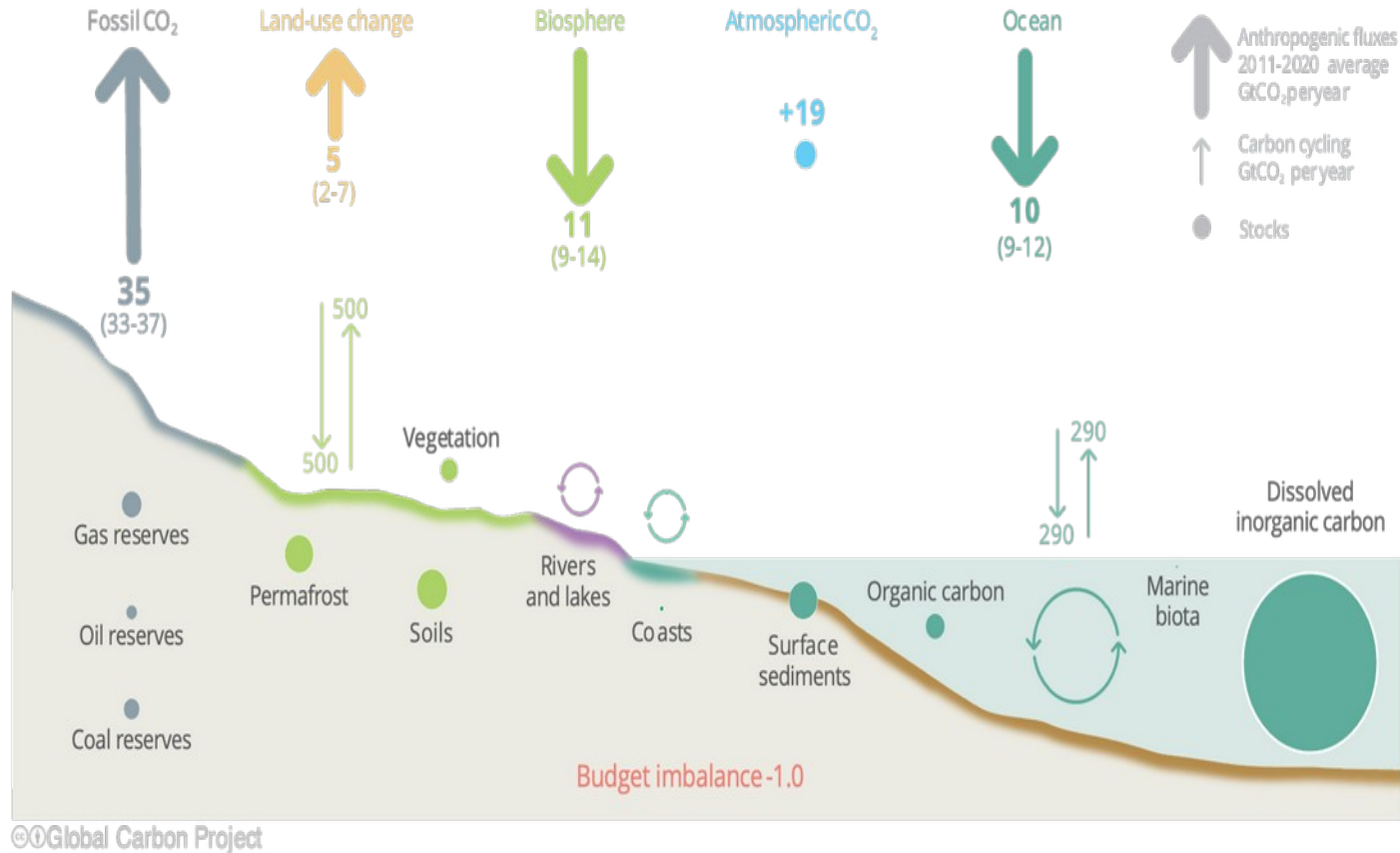


Average increase 5.1 ± 0.02



# Anthropogenic perturbation of the global carbon cycle

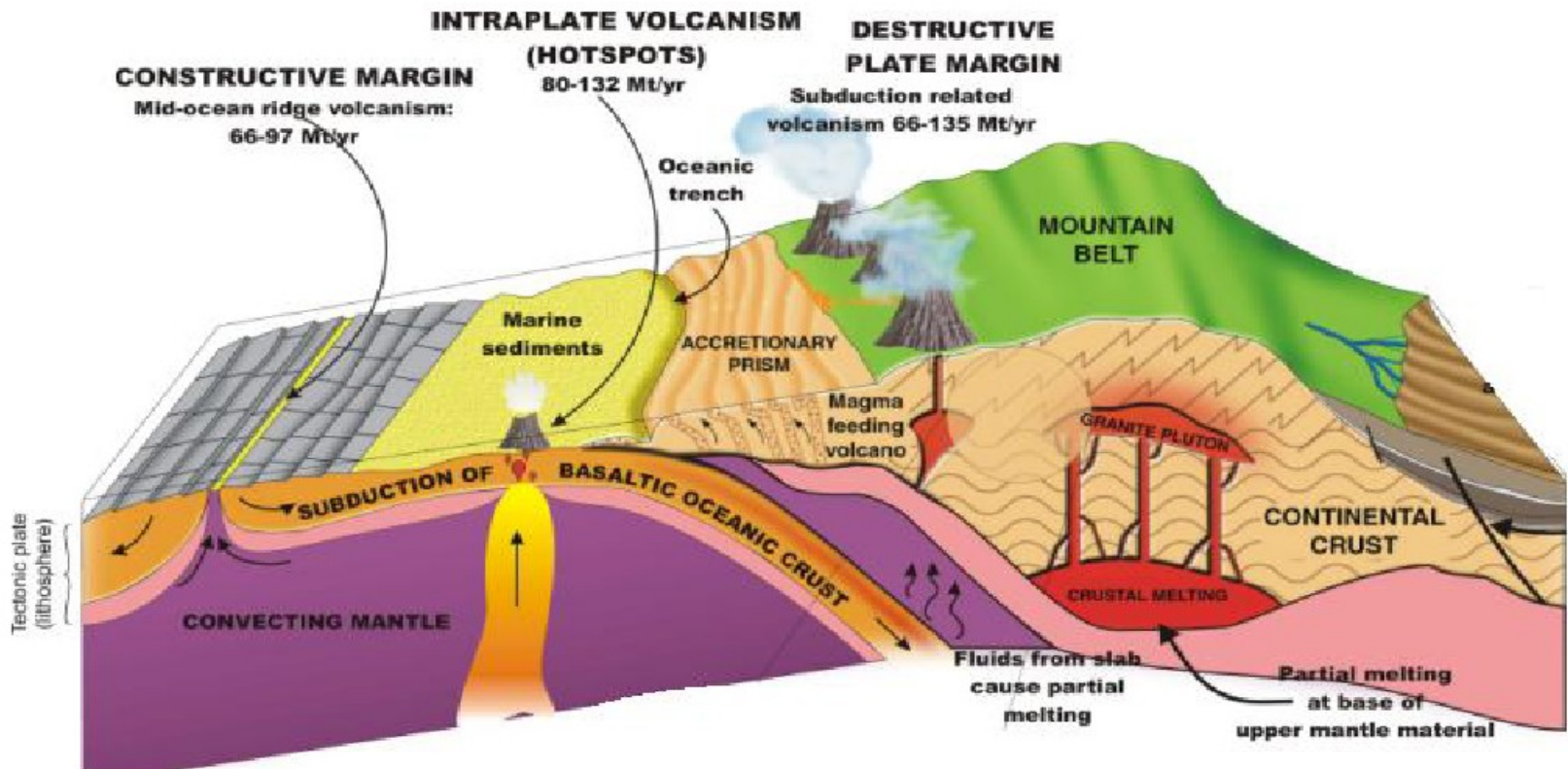
Perturbation of the global carbon cycle caused by anthropogenic activities, global annual average for the decade 2012–2021 (GtCO<sub>2</sub>/yr)



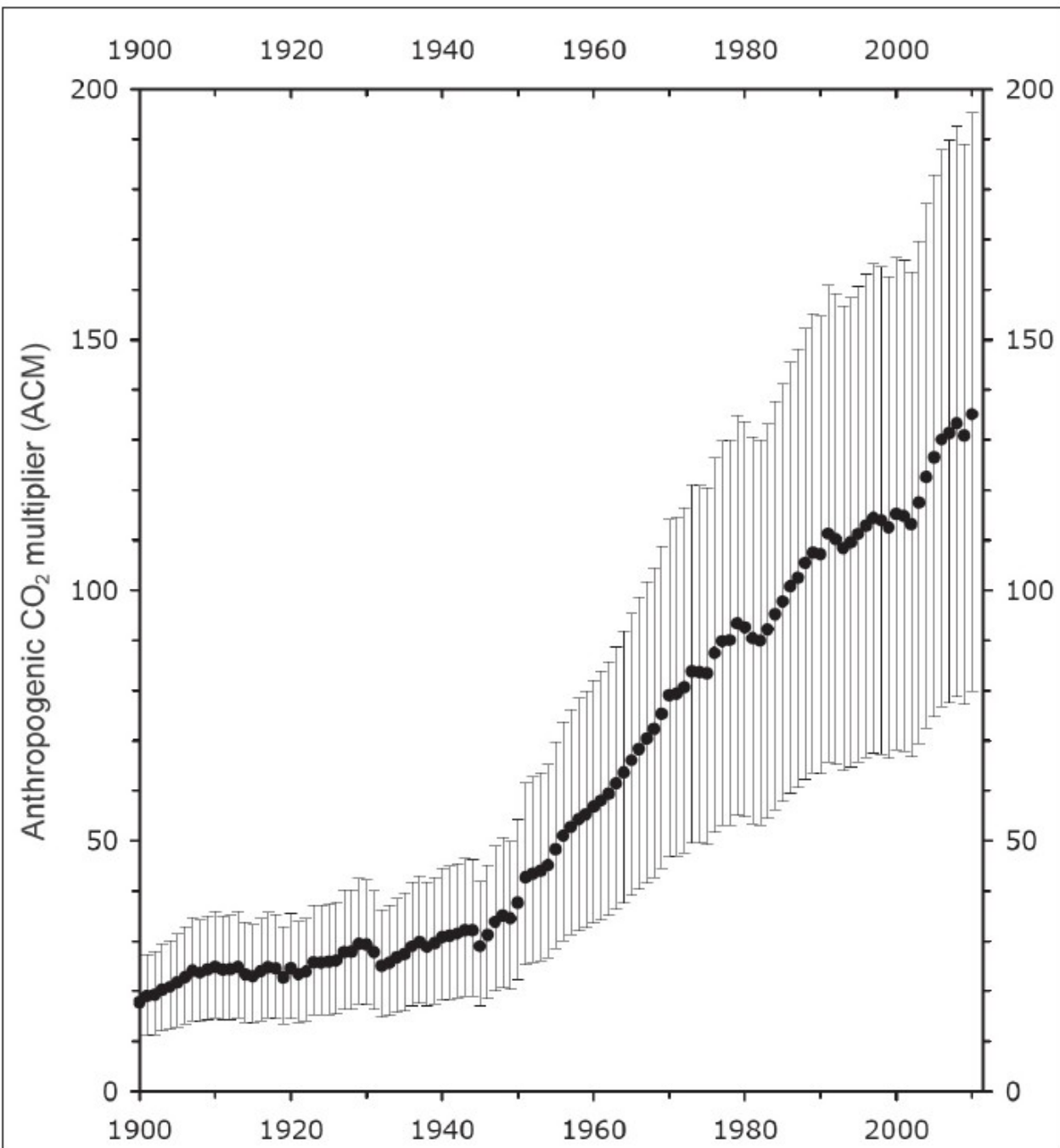
The budget imbalance is the difference between the estimated emissions and sinks.

## 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.



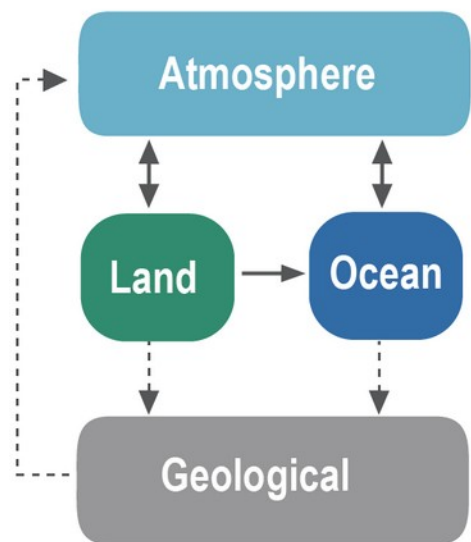
**Figure 2.** Diagrammatic representation of the different volcanic environments with estimates of CO<sub>2</sub> emission rates and their relationship to plate tectonic environment.



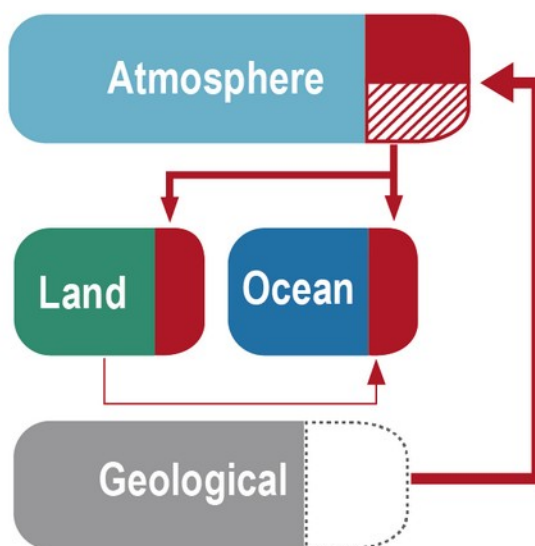
Emisje antropogeniczne CO<sub>2</sub> w stosunku do emisji wulkanicznych

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

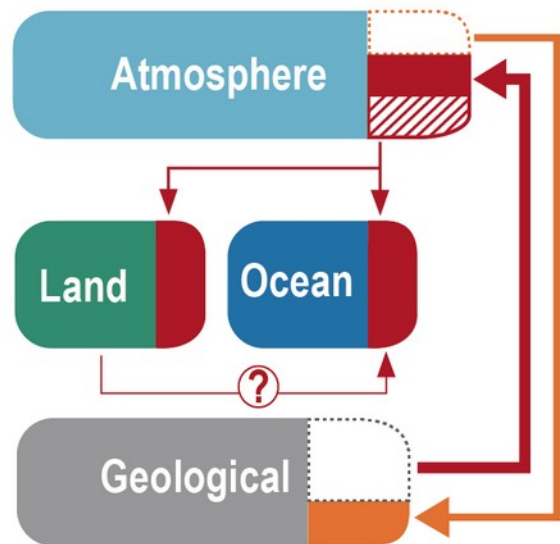
(a) Unperturbed carbon cycle fluxes



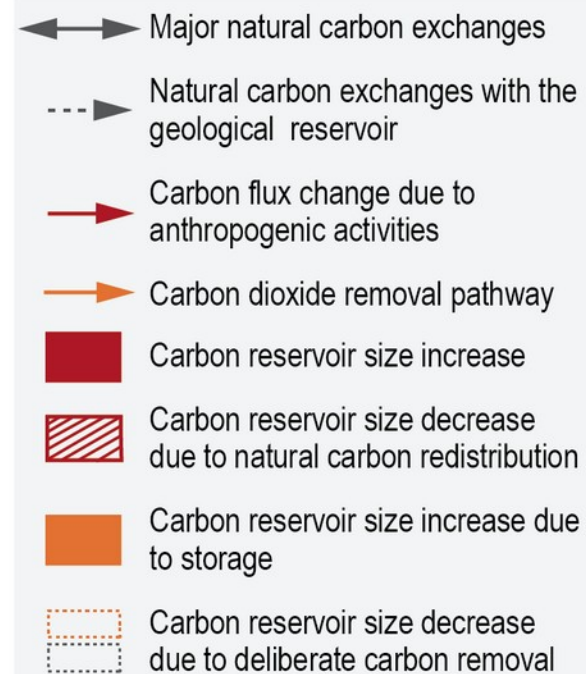
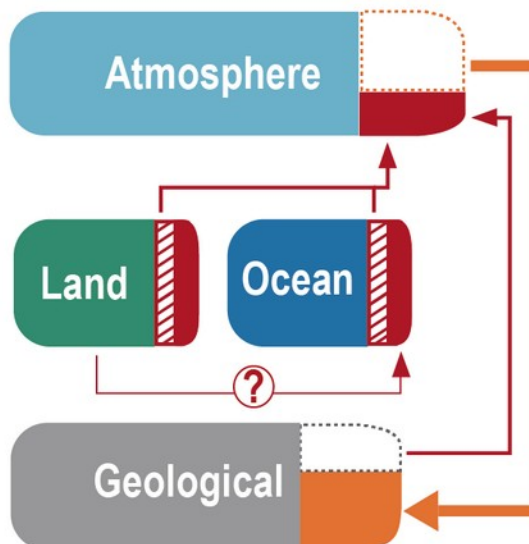
(b) Industrial era CO<sub>2</sub> emissions



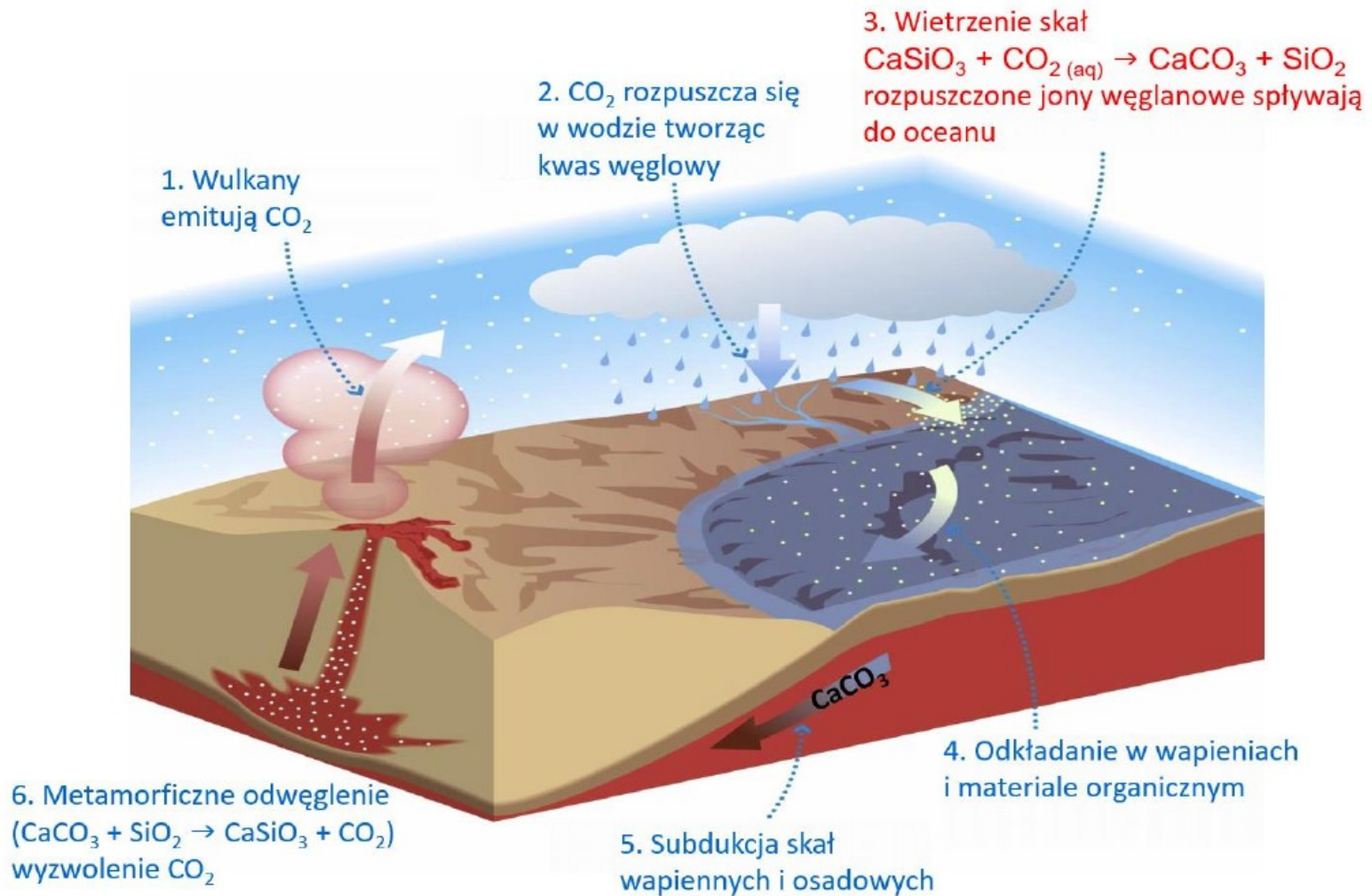
(c) Net positive CO<sub>2</sub> emissions with CDR



(d) Net negative CO<sub>2</sub> emissions

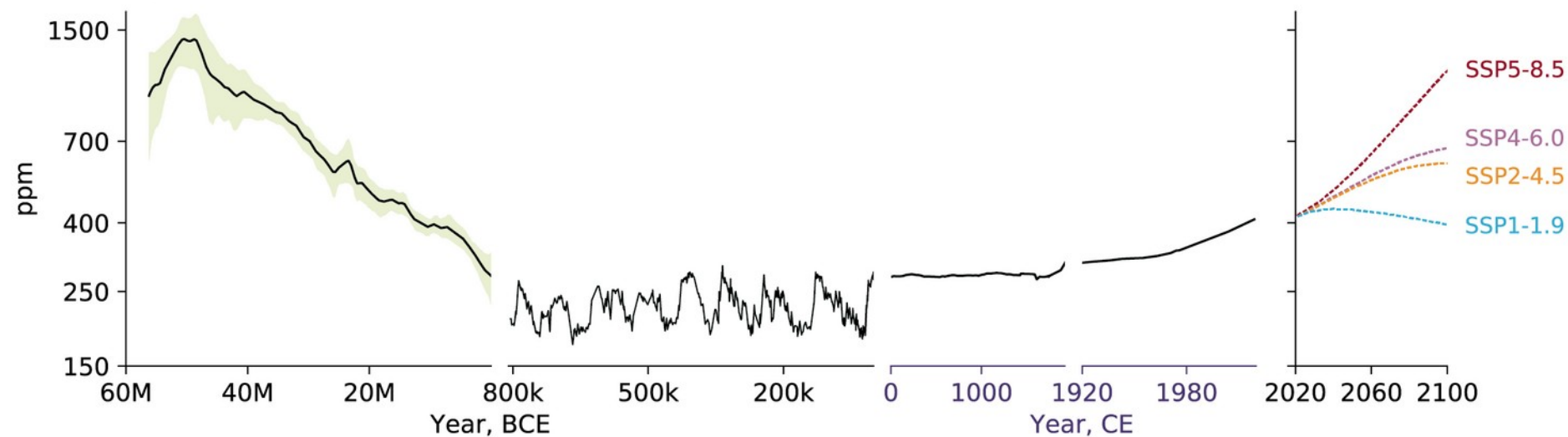


# Termostat węglowy – tempo wietrzenia skał zależy od temperatury.

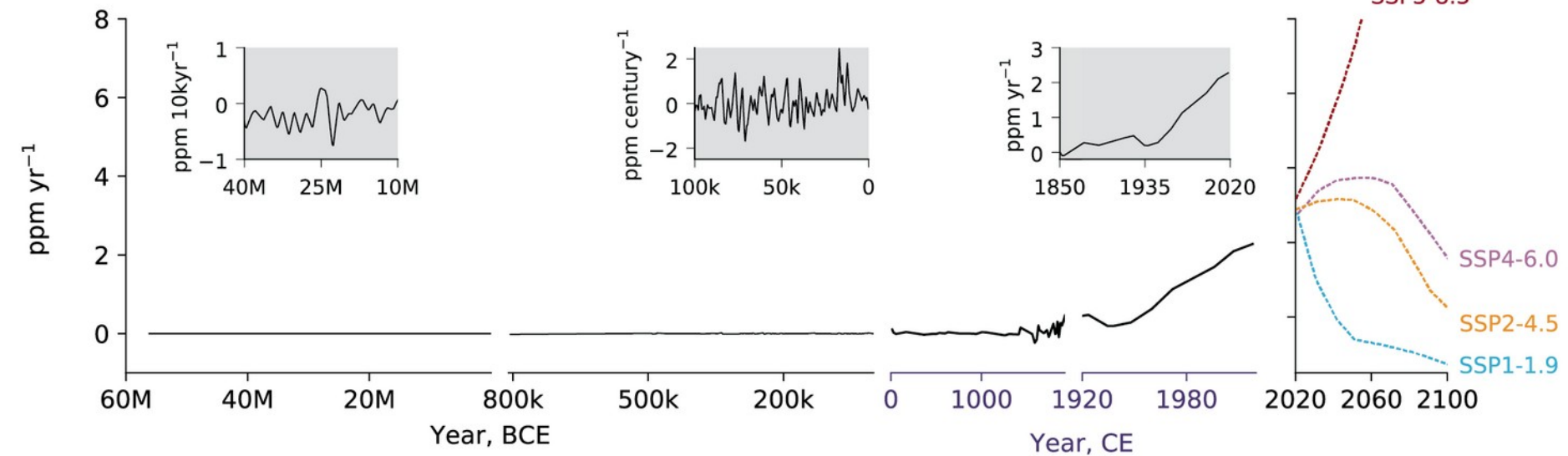


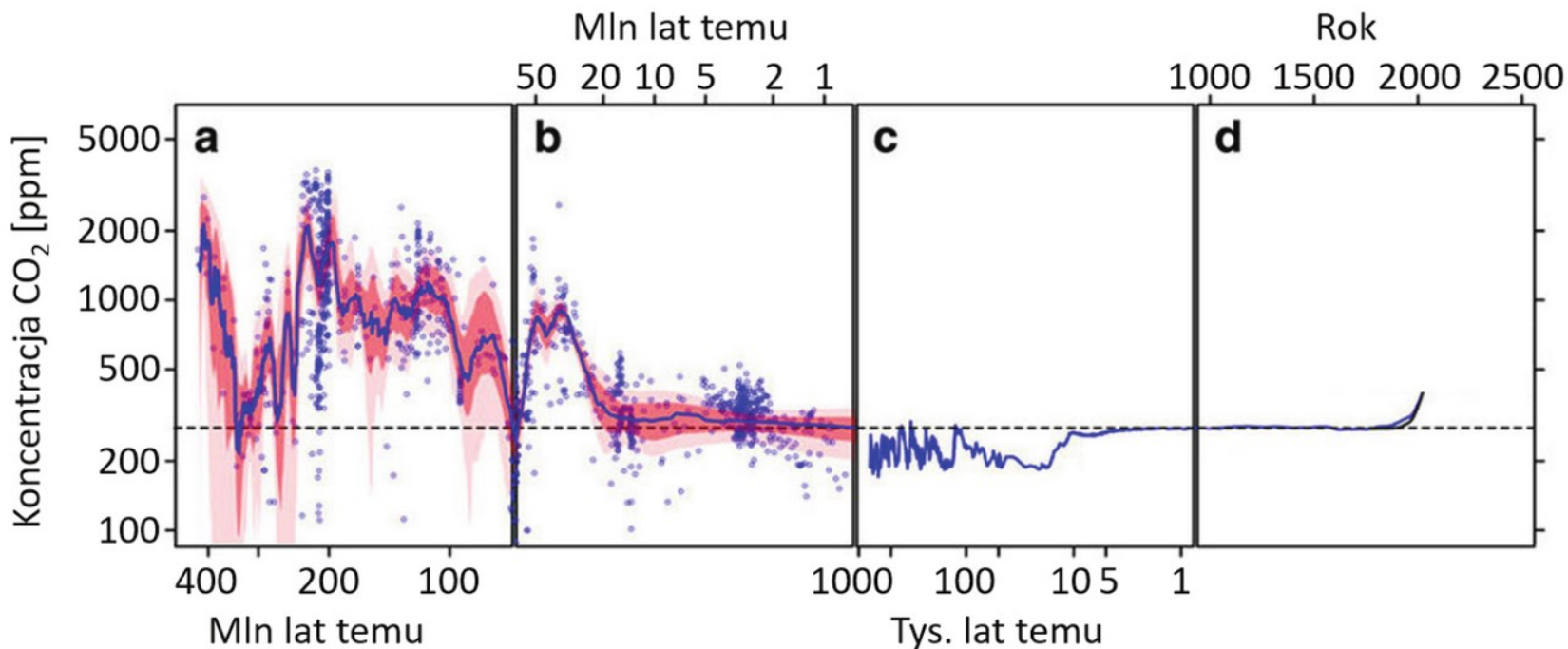


(a) Atmospheric CO<sub>2</sub> concentrations

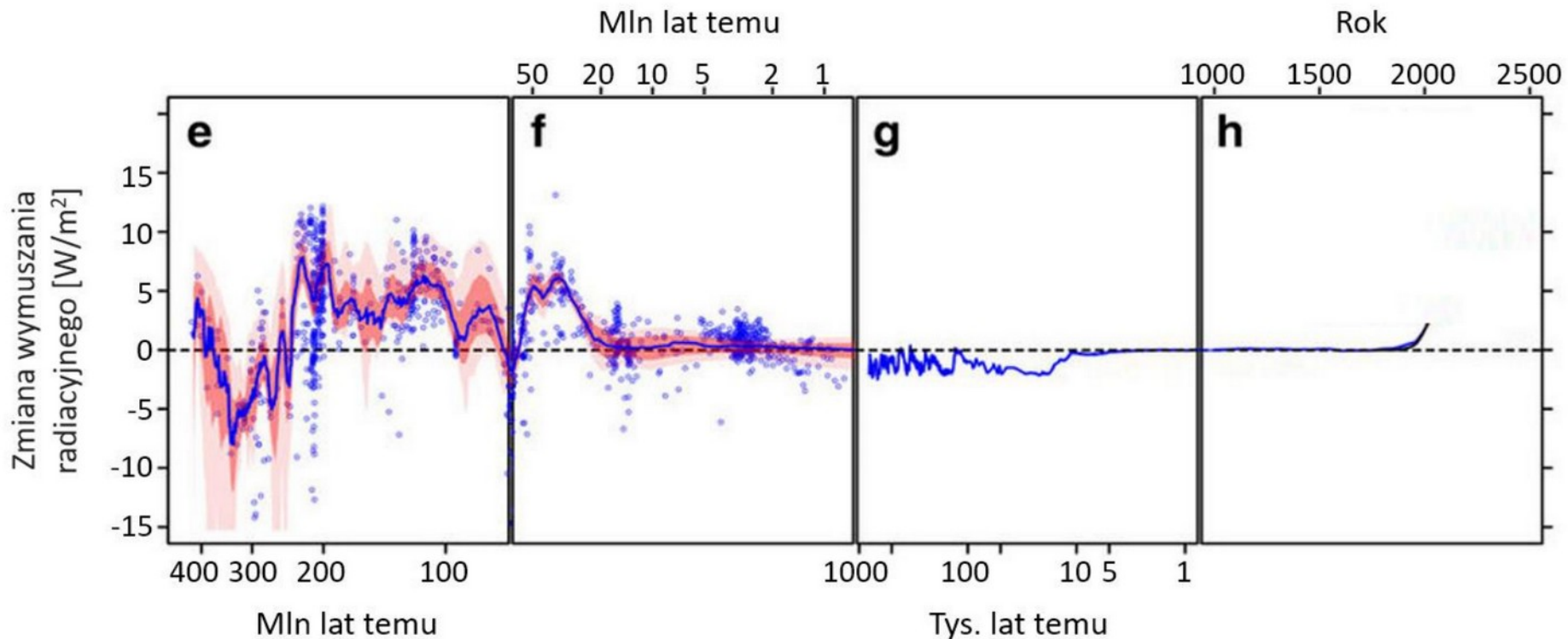


(b) Atmospheric CO<sub>2</sub> growth rate

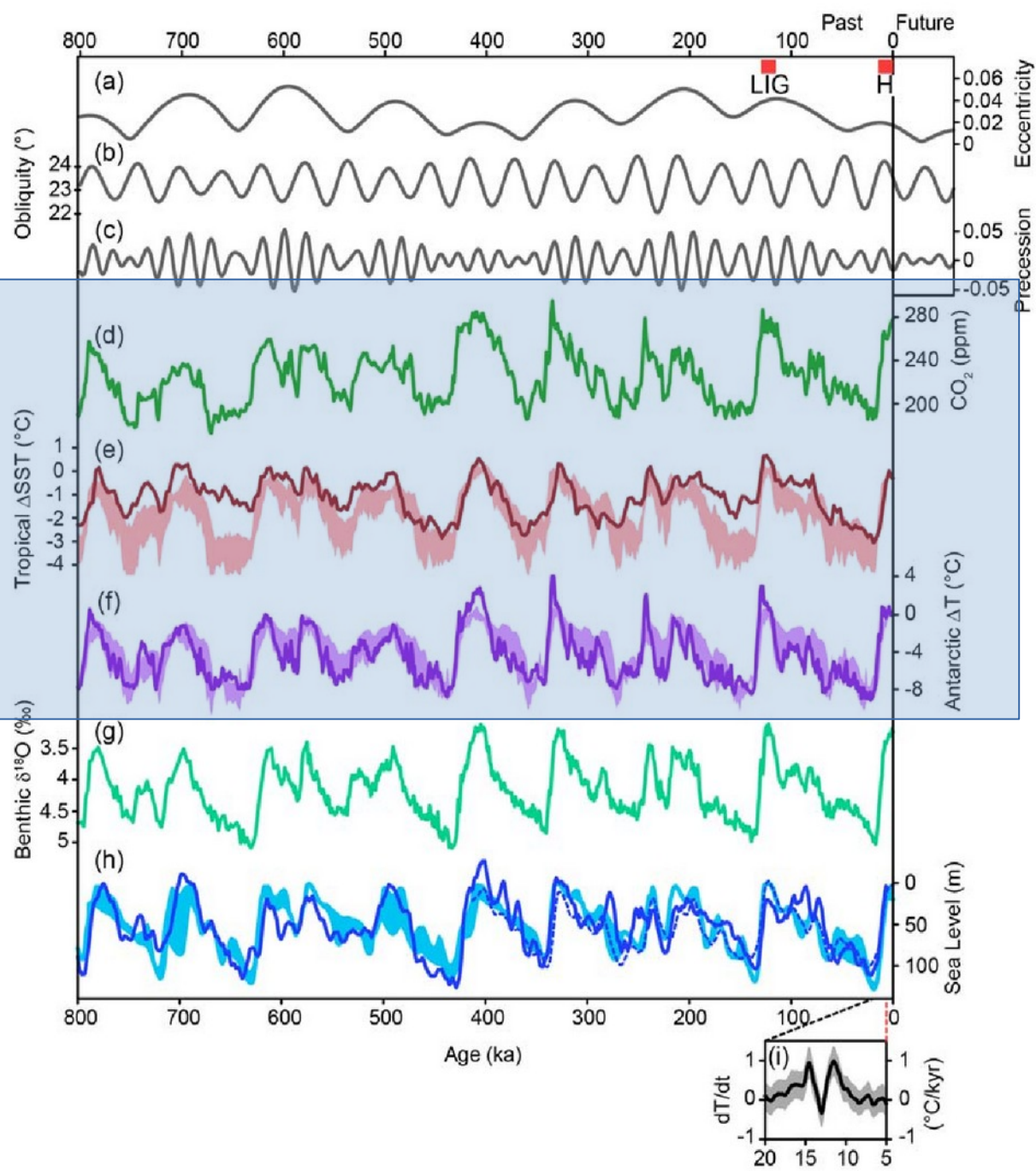




Ilustracja 1.2.11. Rekonstrukcja zmian koncentracji CO<sub>2</sub> w atmosferze w ostatnich 400 mln lat. UWAGA: skala czasowa nie jest liniowa. Panele a–b) na podstawie różnych wskaźników klimatycznych (niebieskie kropki odpowiadają konkretnym pomiarom, a linia – dopasowanej do nich krzywej, czerwona 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  $\text{CO}_2$  i natężenia promieniowania słonecznego w ostatnich 420 mln lat. Czerwona obwódka pokazuje niepewność, z jaką wyznaczono wymuszenie, wynikającą z niepewności danych o stężeniach  $\text{CO}_2$  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).

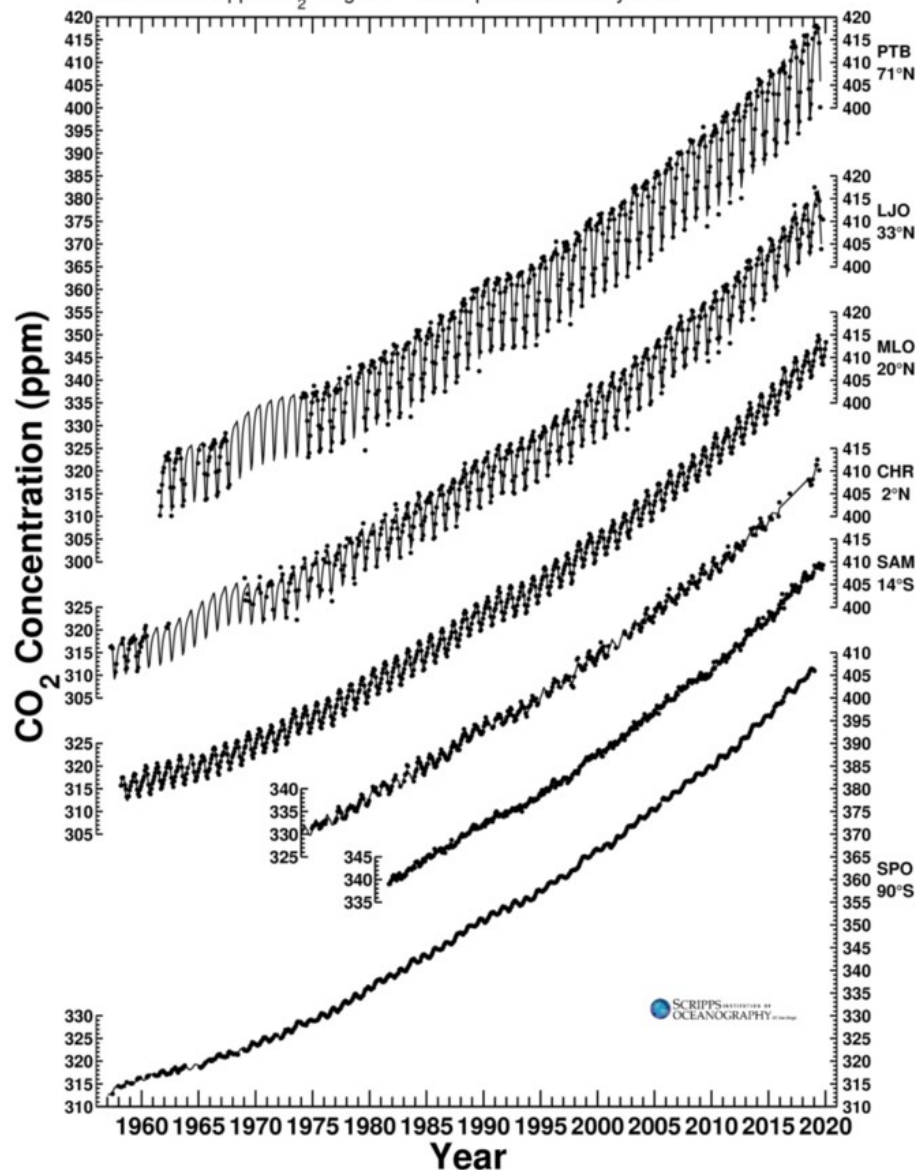
Fioletowe – temperatura Antarktydy (cienka linia – rekonstrukcje paleoklimatyczne, szerszy pas – odtworzenie w modelach klimatu).

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).

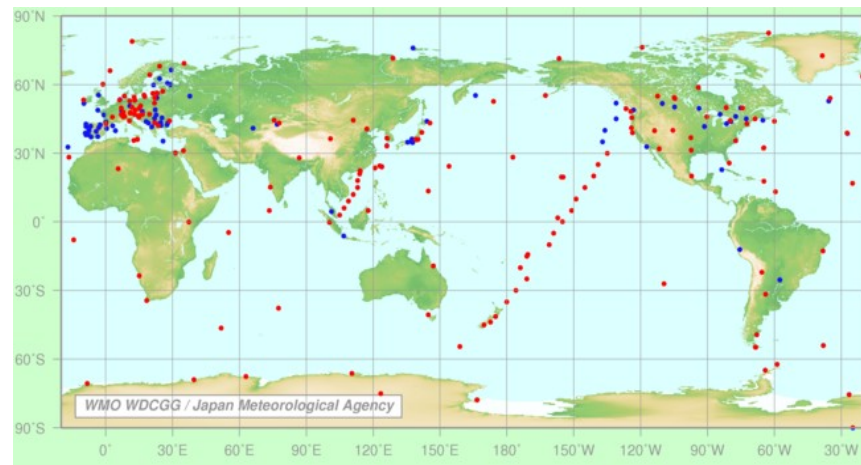
## Global Stations Carbon Dioxide Concentration Trends

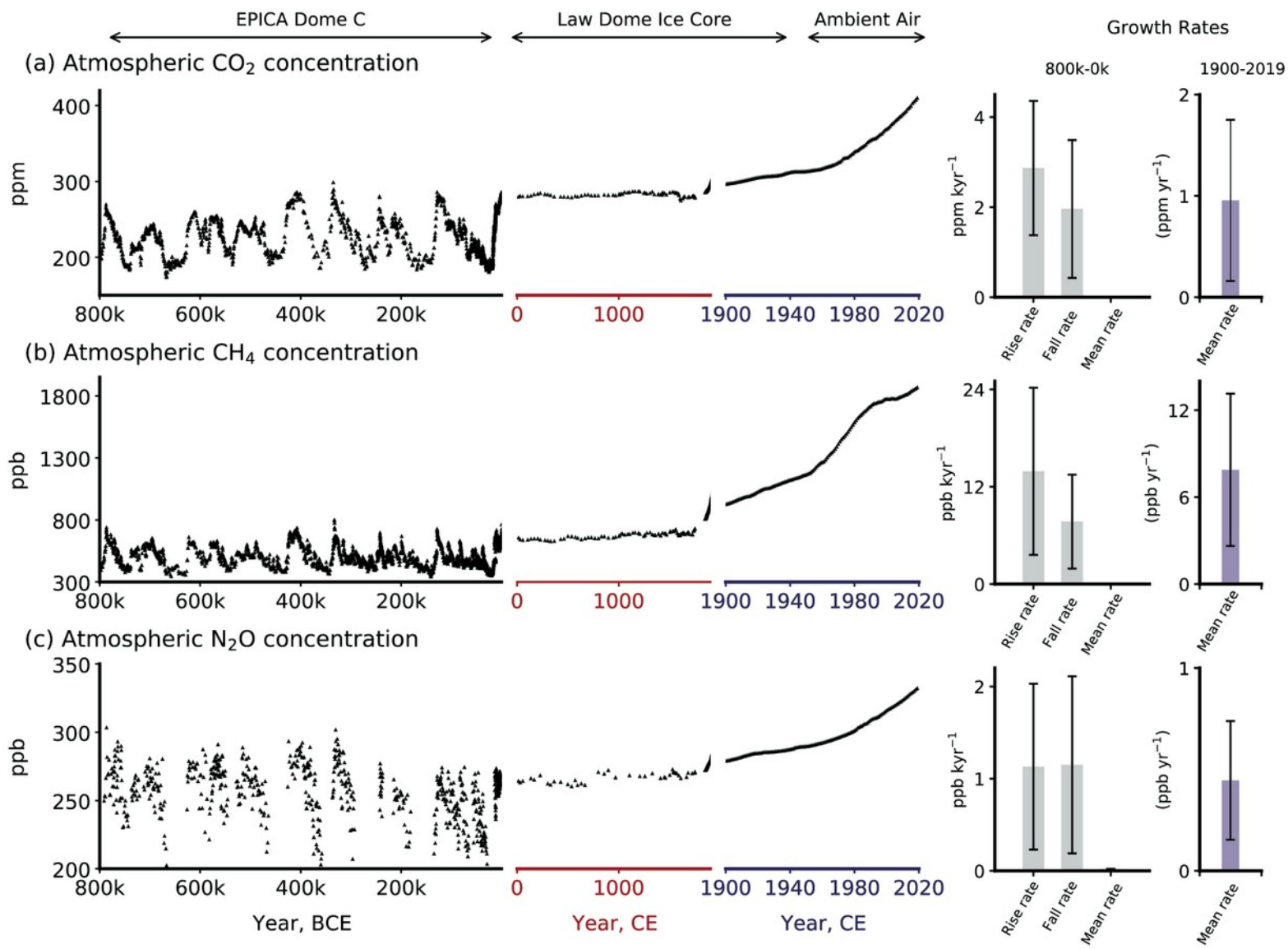
Data from Scripps CO<sub>2</sub> Program Last updated February 2020



Regularne pomiary CO<sub>2</sub> i innych gazów atmosferycznych są zbierane w WMO World Data Centre for Greenhouse Gases (WDCGG)

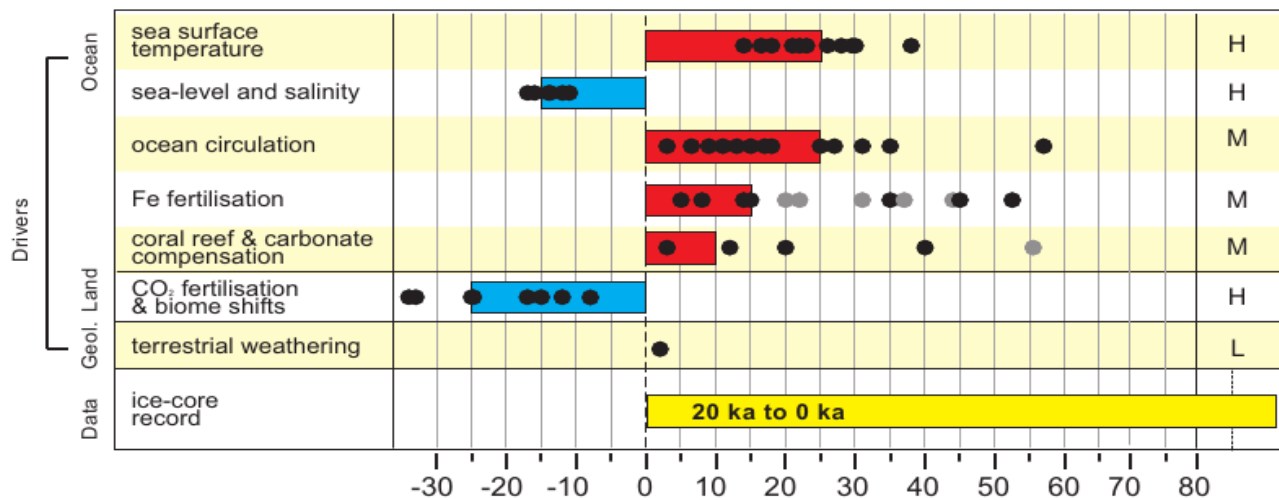
<http://ds.data.jma.go.jp/gmd/wdogg/>



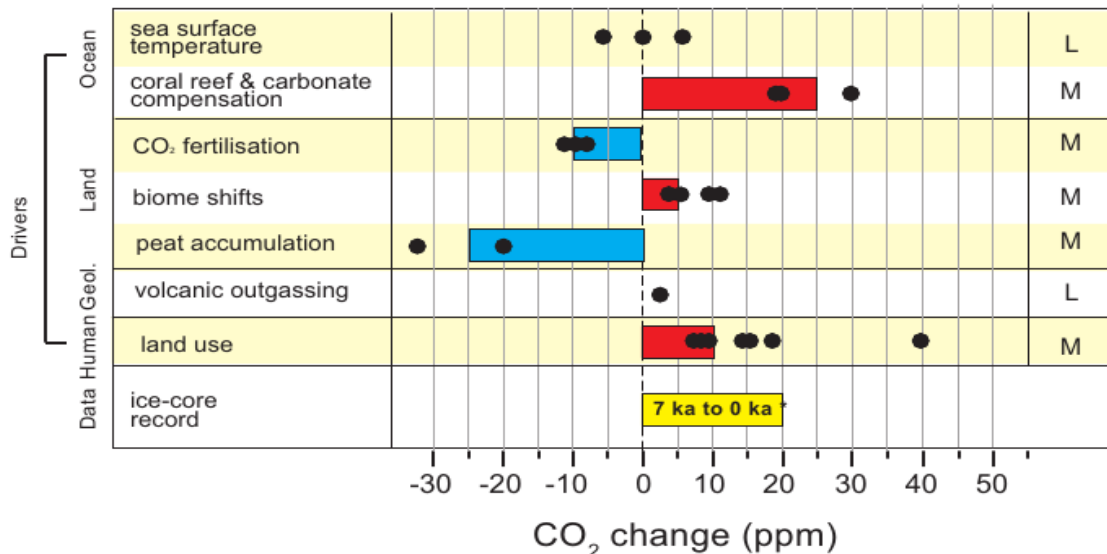


Zmiany w koncentracji atmosferycznych CO<sub>2</sub>, CH<sub>4</sub> i N<sub>2</sub>O .

## Glacial to Interglacial



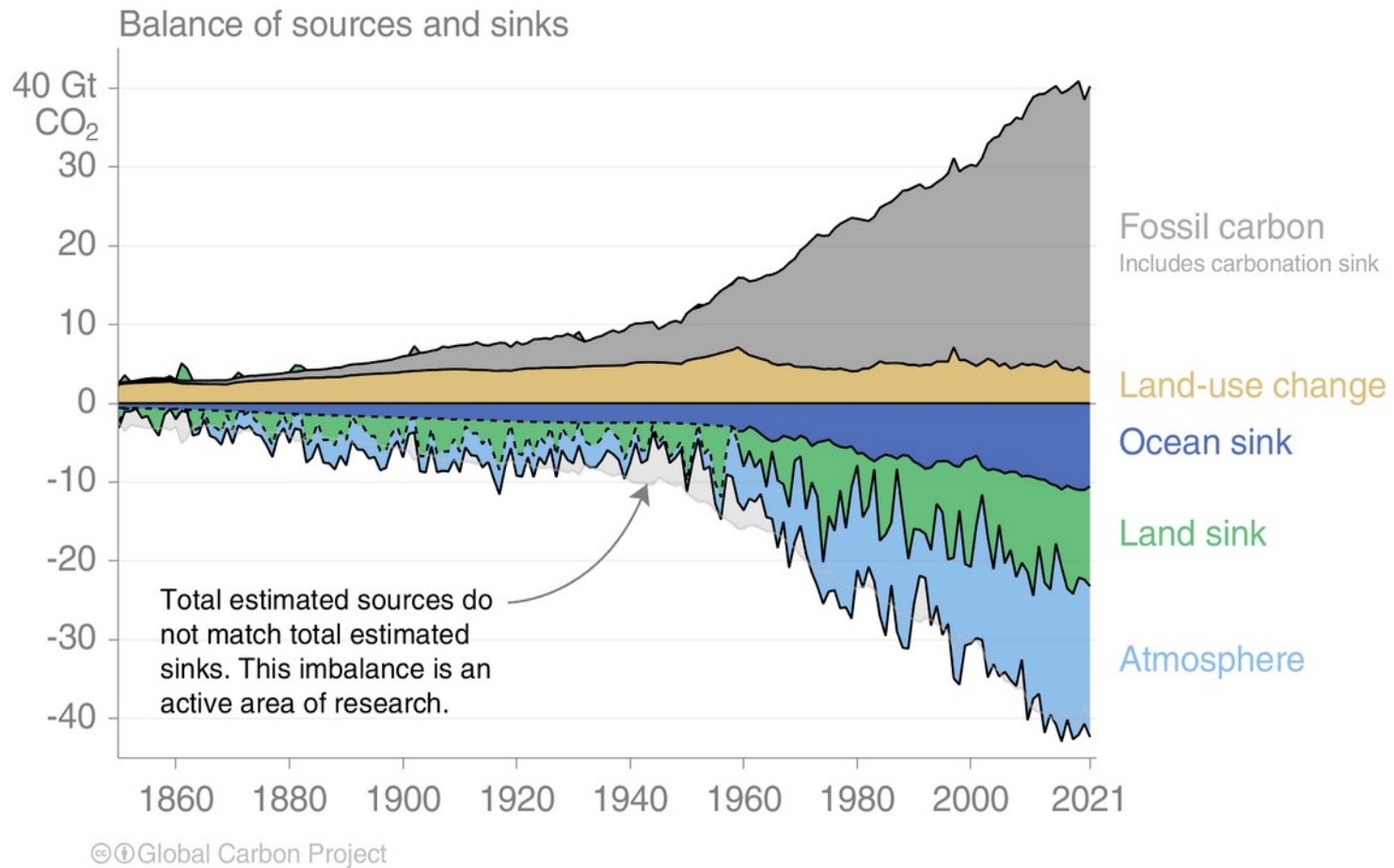
## Holocene



Czynniki odpowiedzialne za naturalne zmiany koncentracji CO<sub>2</sub> w atmosferze:  
 górny panel – od poprzedniego maksimum lodowego do Holocenu  
 dolny panel: w Holocenie.

# Global carbon budget

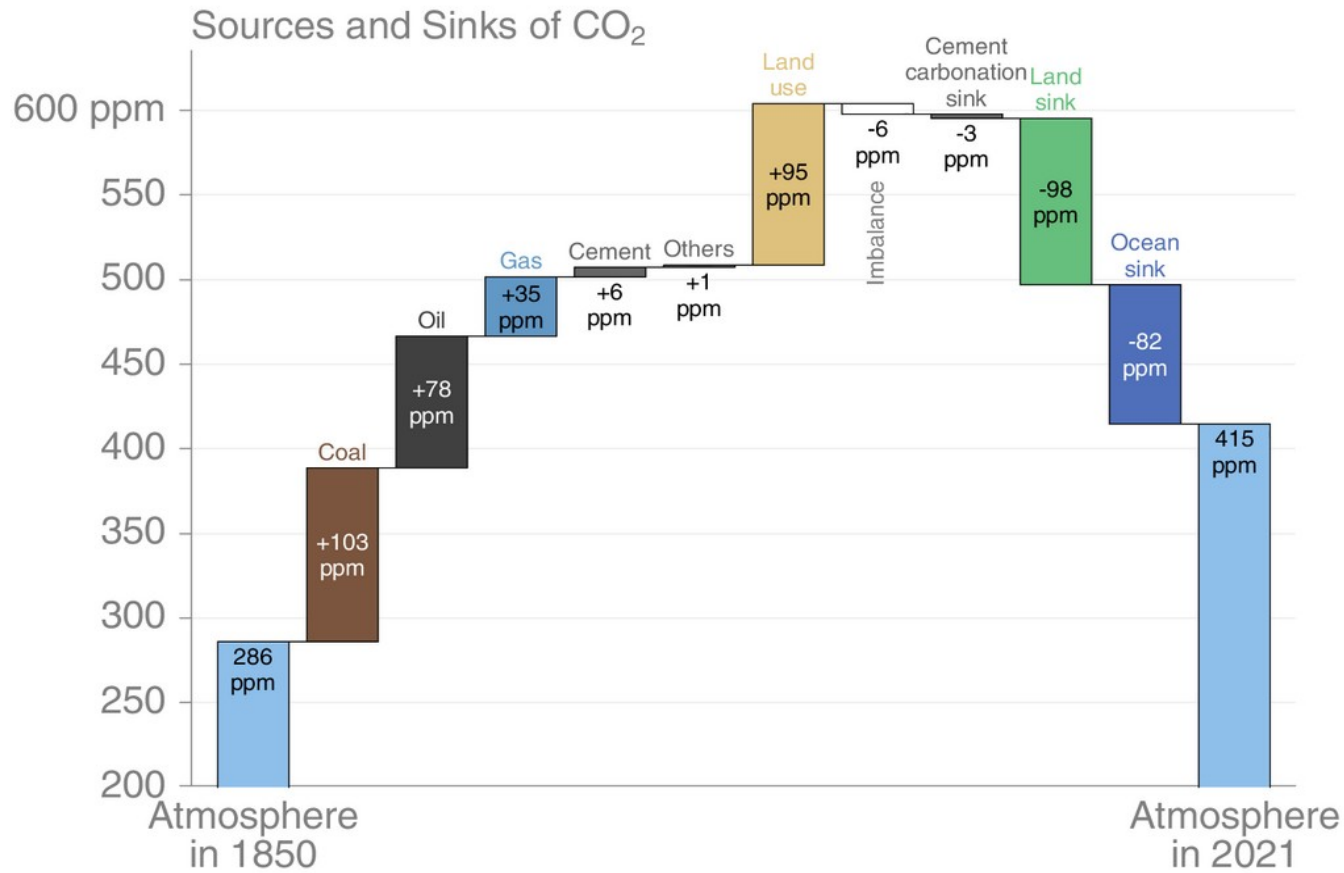
Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean  
 The “imbalance” between total emissions and total sinks is an active area of research





# Global carbon budget

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

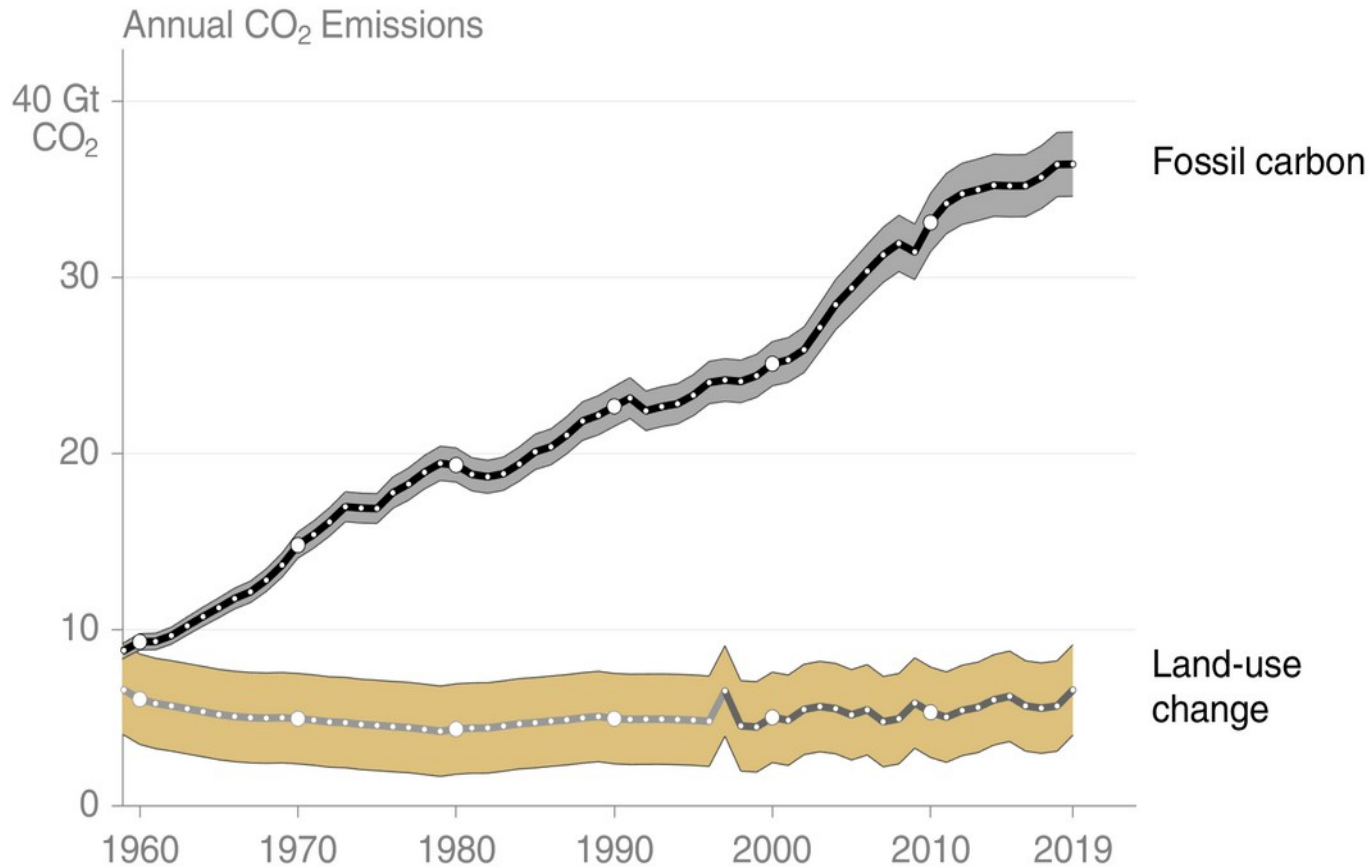


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# Total global emissions

Total global emissions:  $43.0 \pm 3.3$  GtCO<sub>2</sub> in 2019, 56% over 1990

Percentage land-use change: 39% in 1960, 14% averaged 2010–2019



Fossil carbon



Land-use change

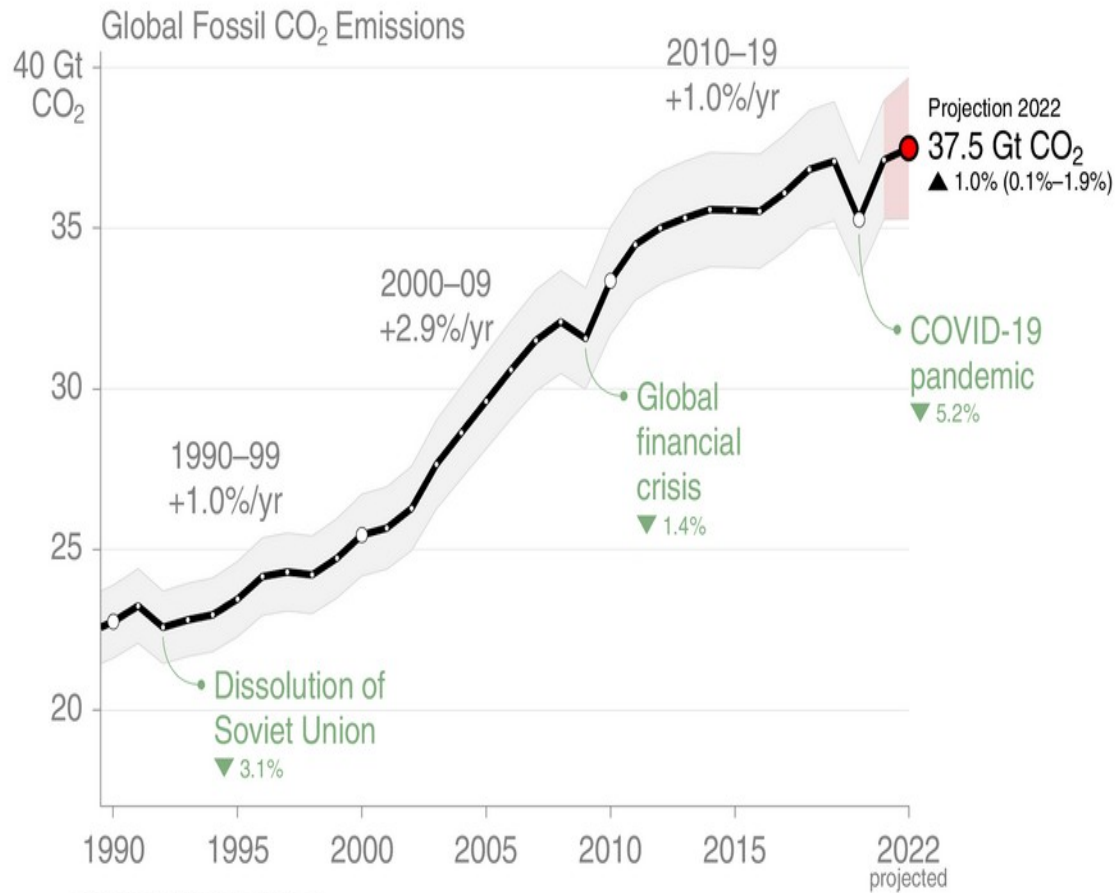
© Global Carbon Project • Data: CDIAC/UNFCCC/BP/USGS/GCP

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 CO<sub>2</sub> Emissions

Global fossil CO<sub>2</sub> emissions: 37.1 ± 2 GtCO<sub>2</sub> in 2021, 63% over 1990  
 Projection for 2022: 37.5 ± 2 GtCO<sub>2</sub>, 1.0% [0.1% to +1.9%] higher than 2021



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

36.6 ± 2 GtCO<sub>2</sub>

When includir

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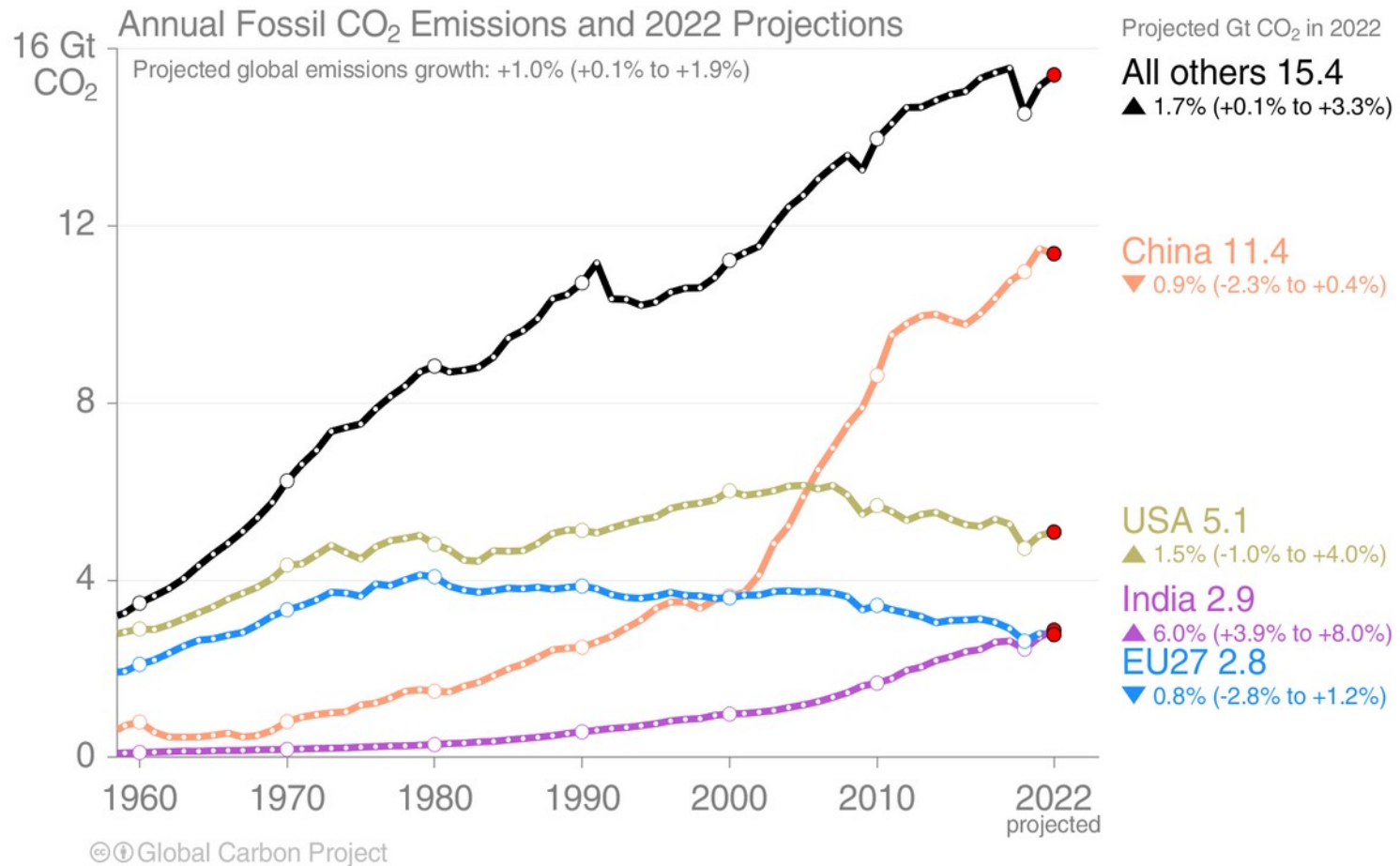
respectively

The 2022 projection is based on preliminary data and modelling.

Source: [Friedlingstein et al 2022](#); [Global Carbon Project 2022](#)

# Emissions Projections for 2022

Global fossil CO<sub>2</sub> emissions are projected to increase by 1.0% [0.1% to 1.9%] in 2022

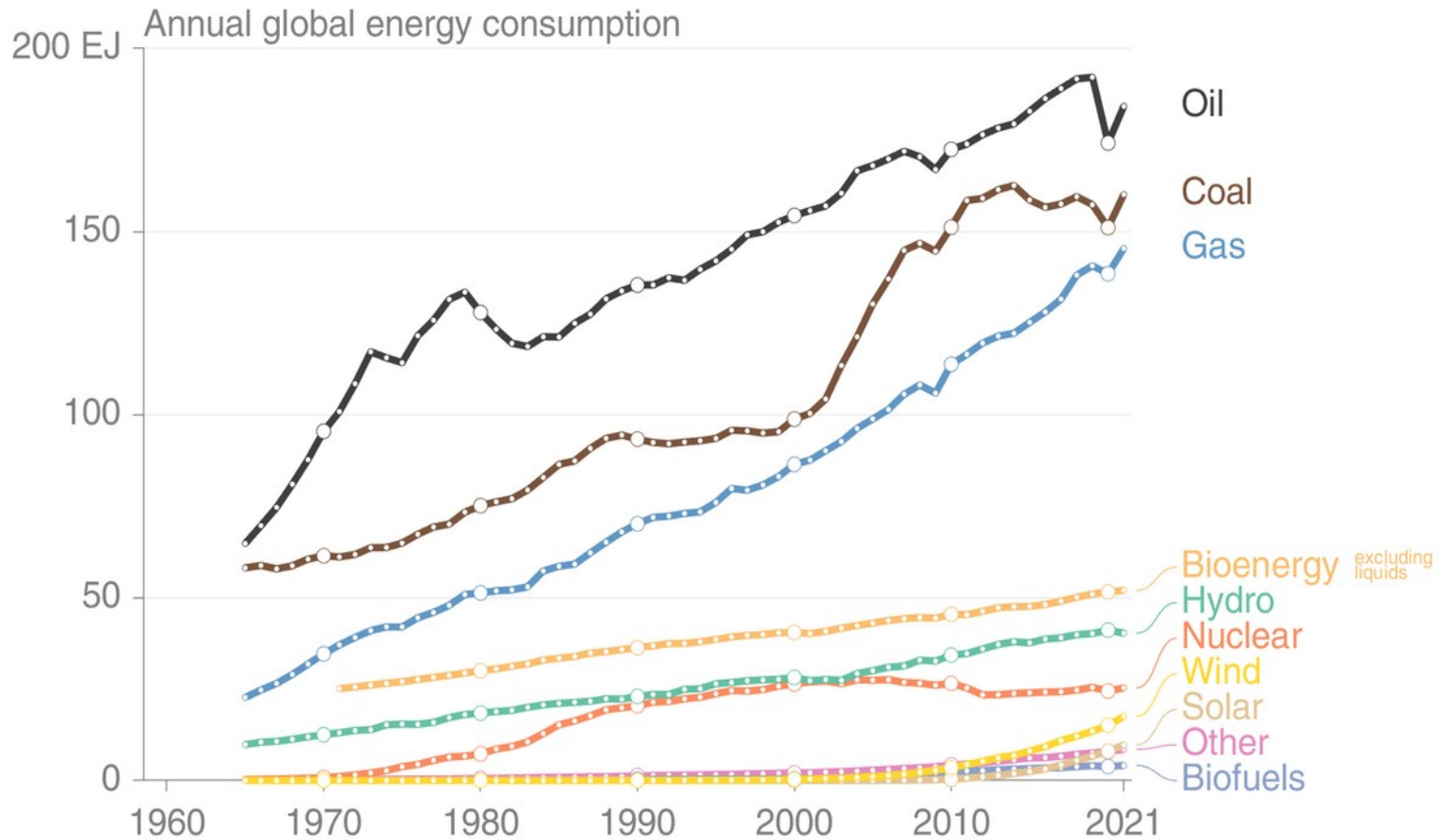


The 2022 projections are based on preliminary data and modelling.

Source: [Friedlingstein et al 2022](#); [Global Carbon Project 2022](#)

# 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.



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

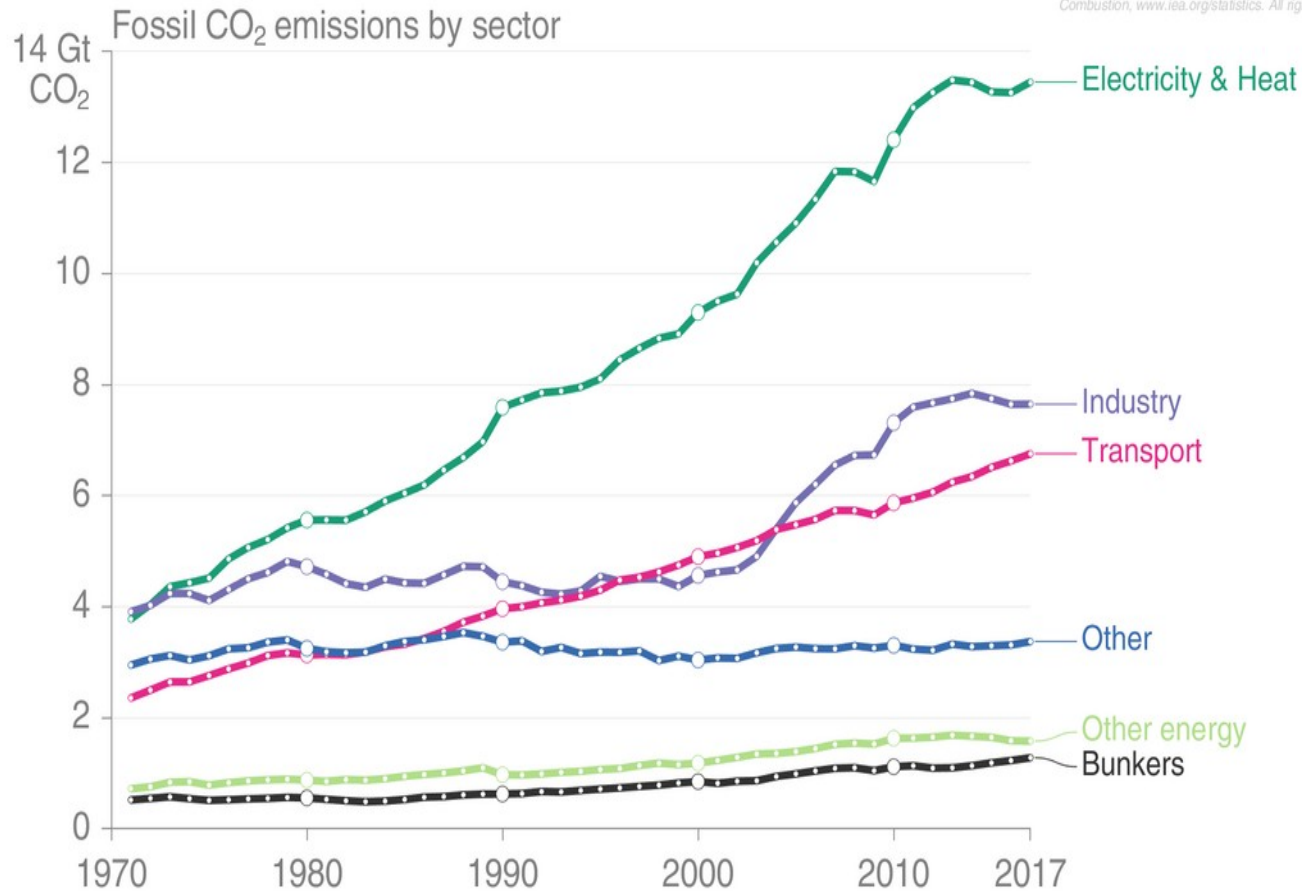
This figure shows “primary energy” using the BP substitution method (non-fossil sources are scaled up by an assumed fossil efficiency of approximately 0.38)

Source: [BP 2022](#); [Global Carbon Project 2022](#)

# Fossil CO<sub>2</sub> Emissions by Sector

Global fossil CO<sub>2</sub> emissions are dominated by electricity, heat, & energy (45%), industry (23%), & national transport (19%). International aviation and marine bunkers are 3.5% & remaining sectors 10%.

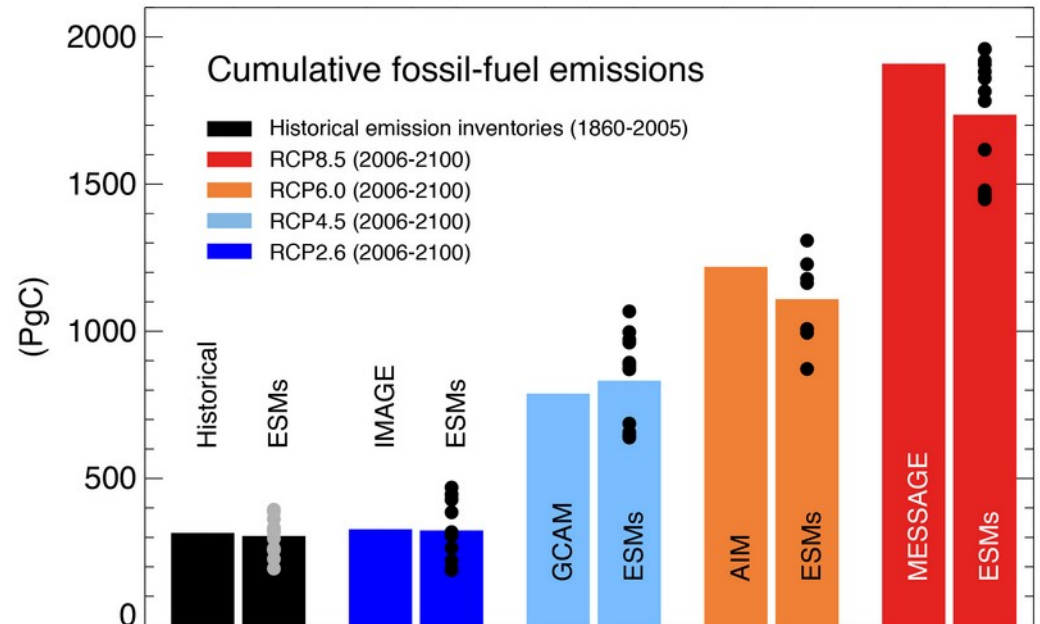
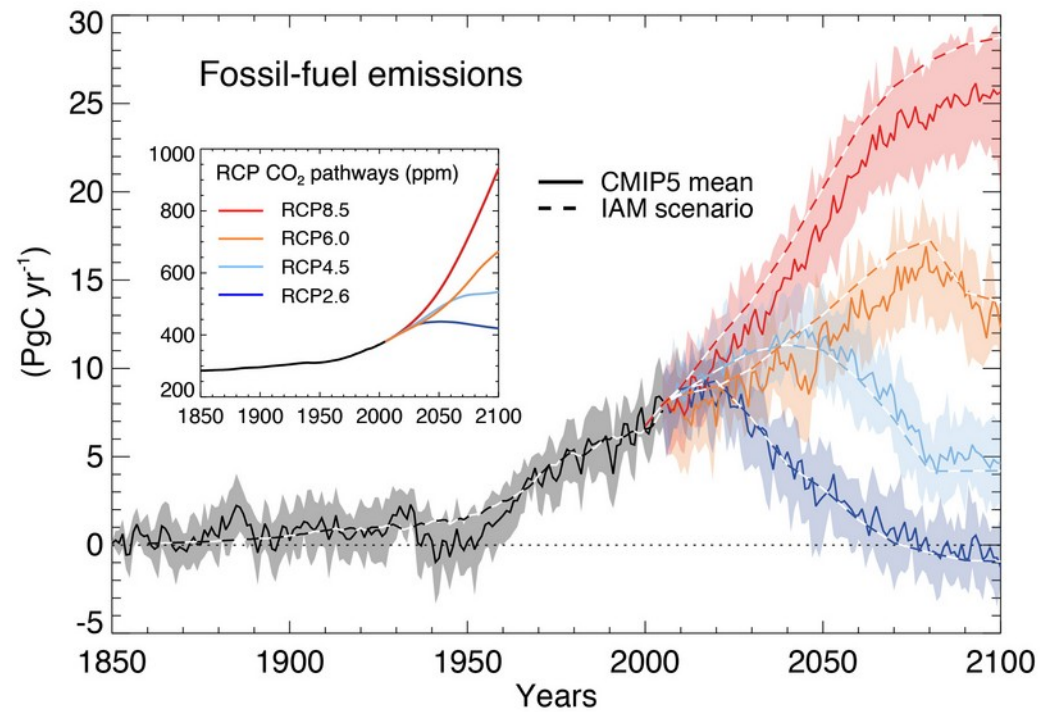
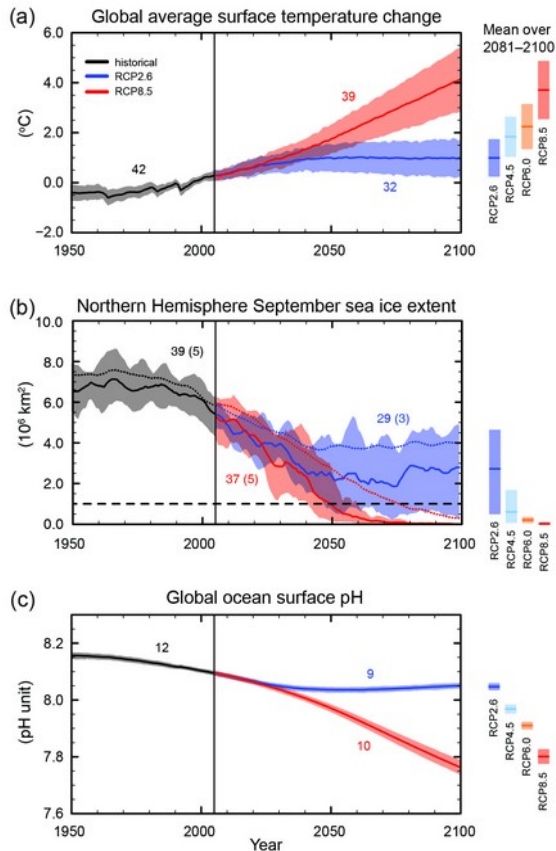
Based on IEA data from the IEA (2019) CO<sub>2</sub> Emissions from Fuel Combustion, www.iea.org/statistics. All rights reserved.



© 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.

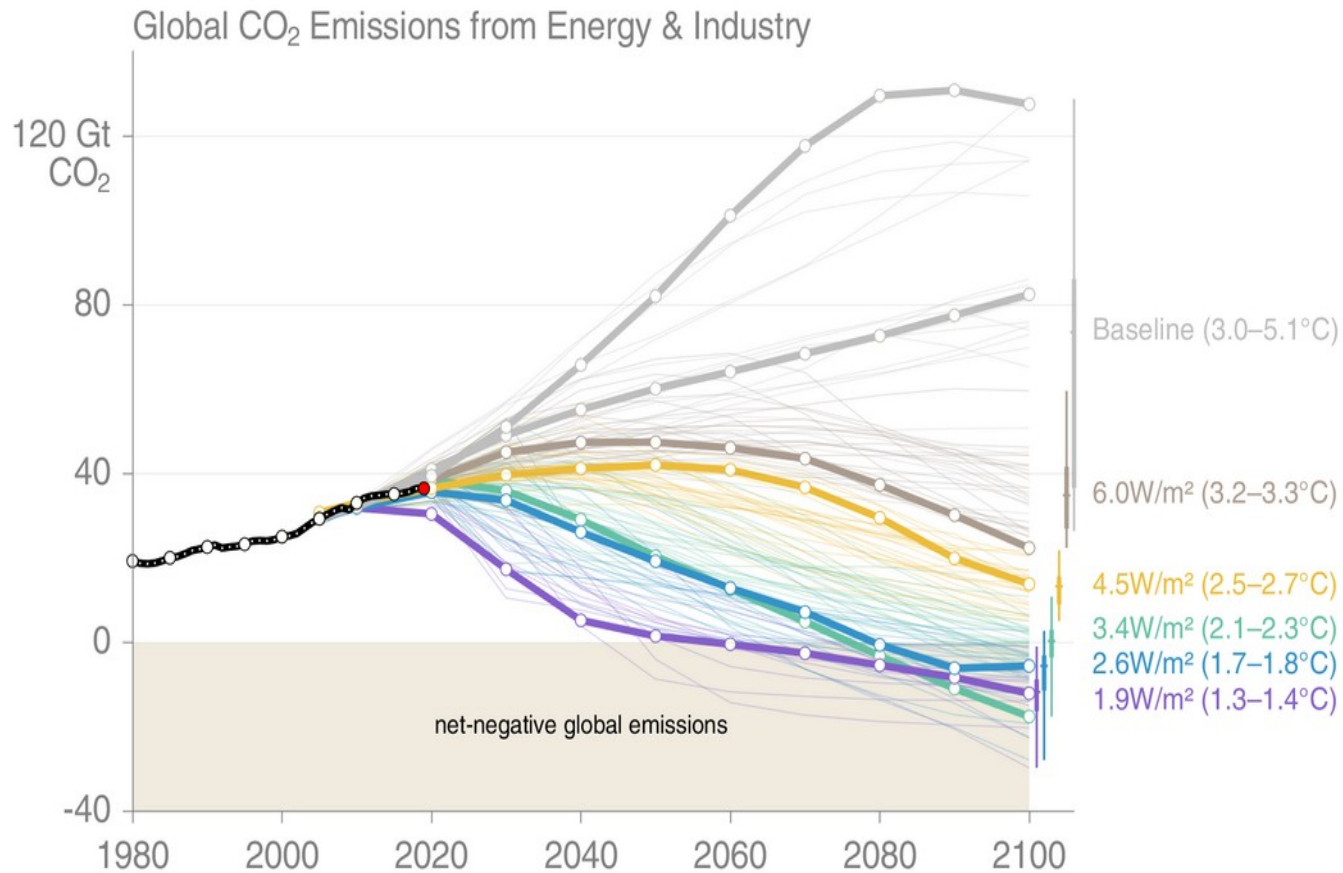
## RCP – Representative Concentration Pathways



# 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)

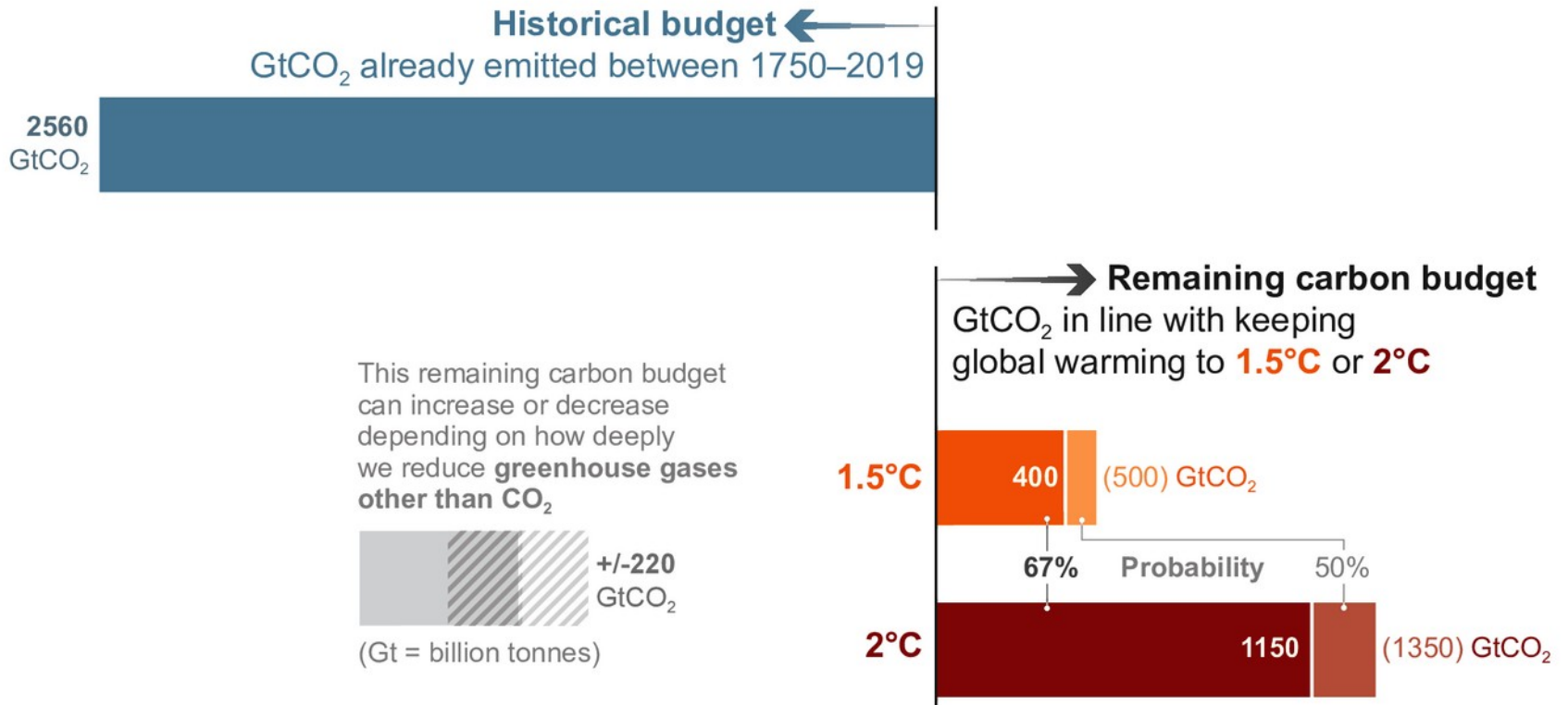
This set of quantified SSPs are based on the output of six Integrated Assessment Models (AIM/CGE, GCAM, IMAGE, MESSAGE, REMIND, WITCH). Net emissions include those from land-use change and bioenergy with CCS.

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



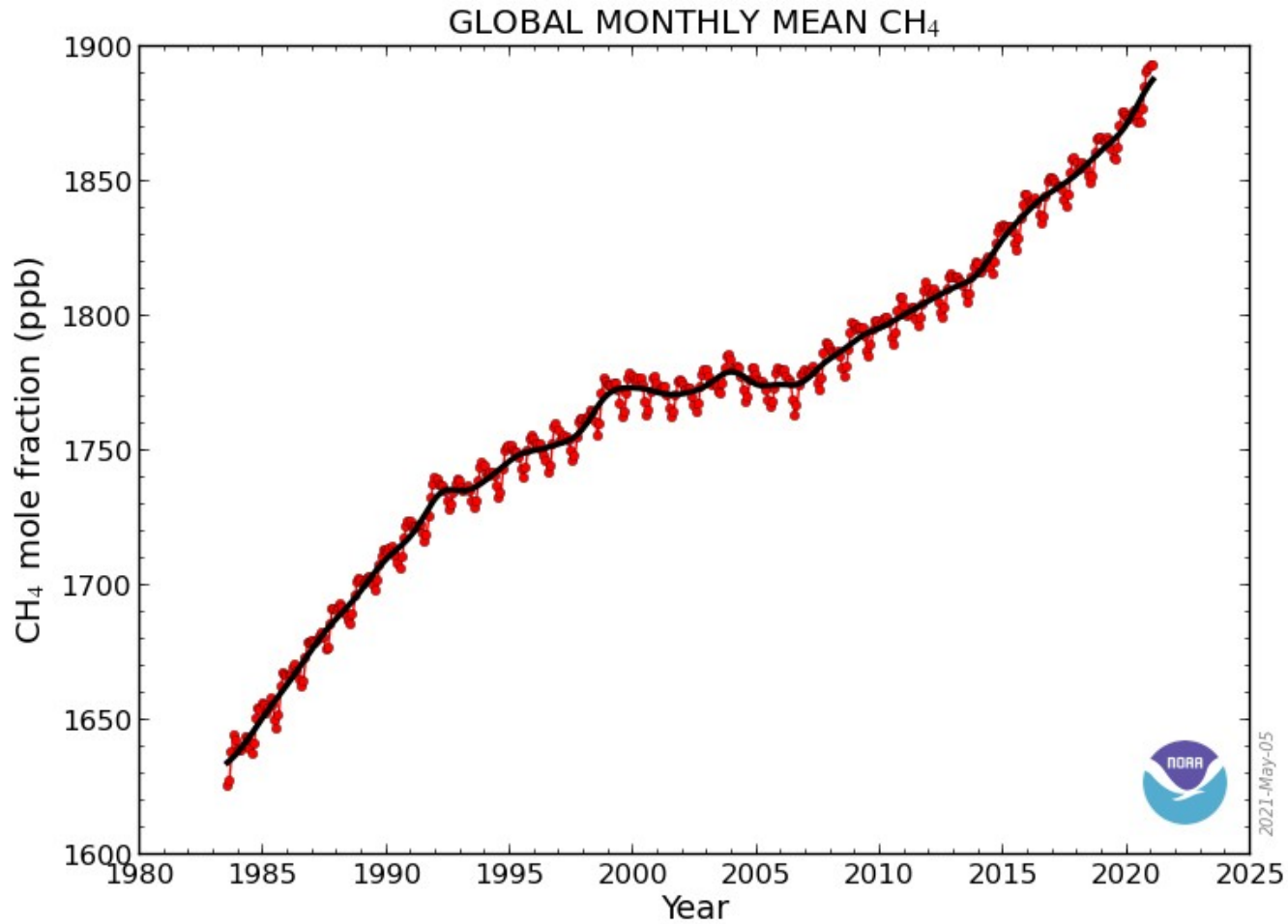
## FAQ 5.4: What are Carbon Budgets?

The term carbon budget is used in several ways. Most often the term refers to the total net amount of carbon dioxide (CO<sub>2</sub>) that can still be emitted by human activities while limiting global warming to a specified level.



Nie tylko CO<sub>2</sub>:

Wzrost koncentracji metanu w atmosferze



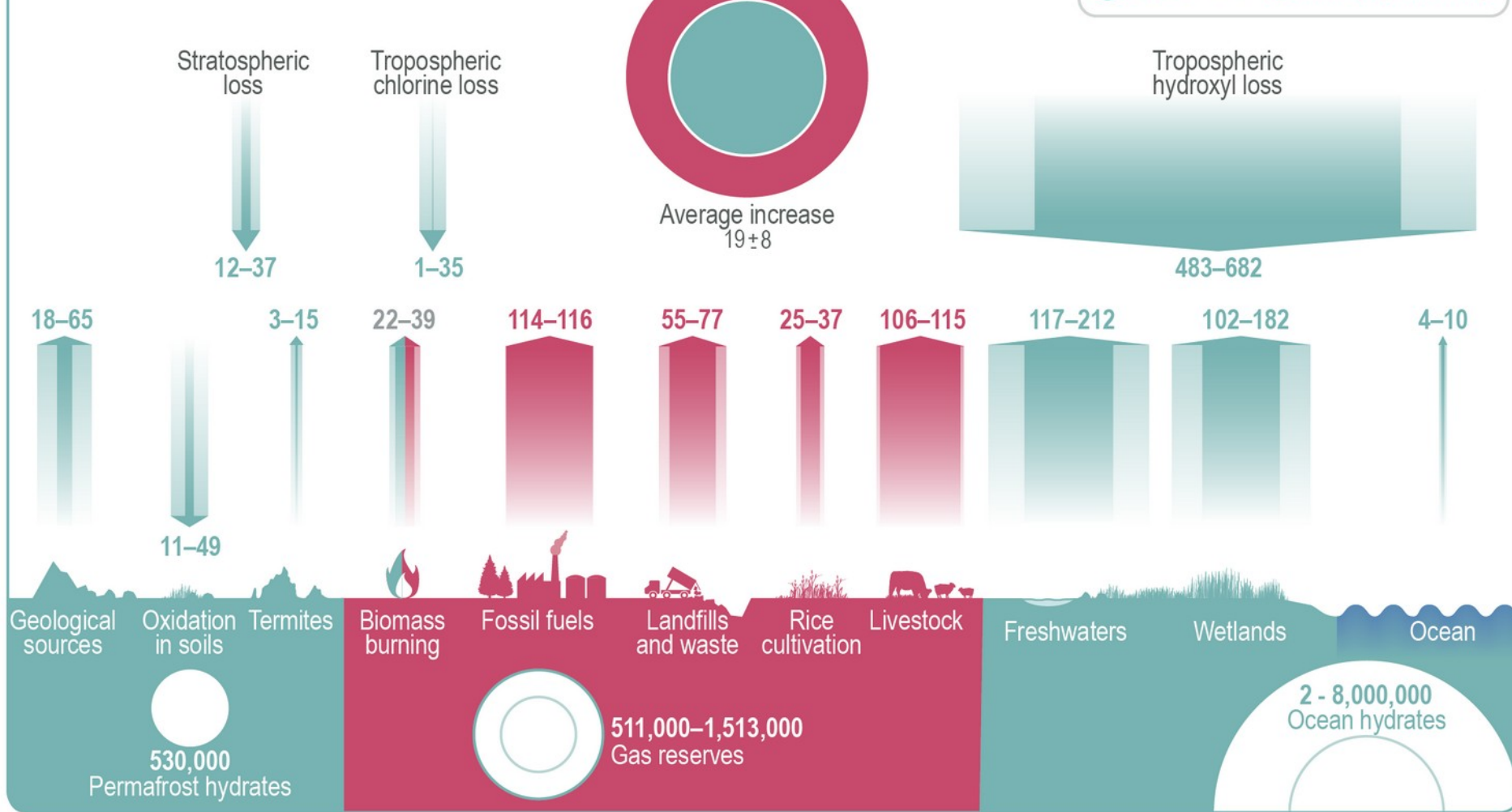
# Methane (CH<sub>4</sub>) Budget

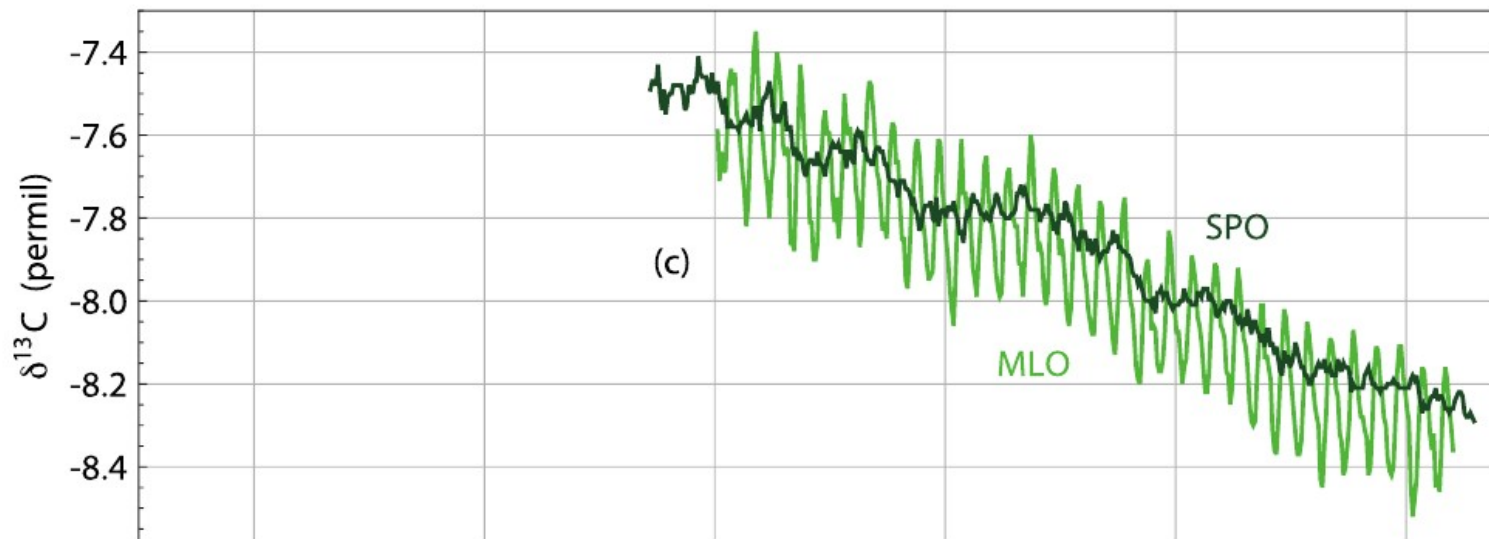
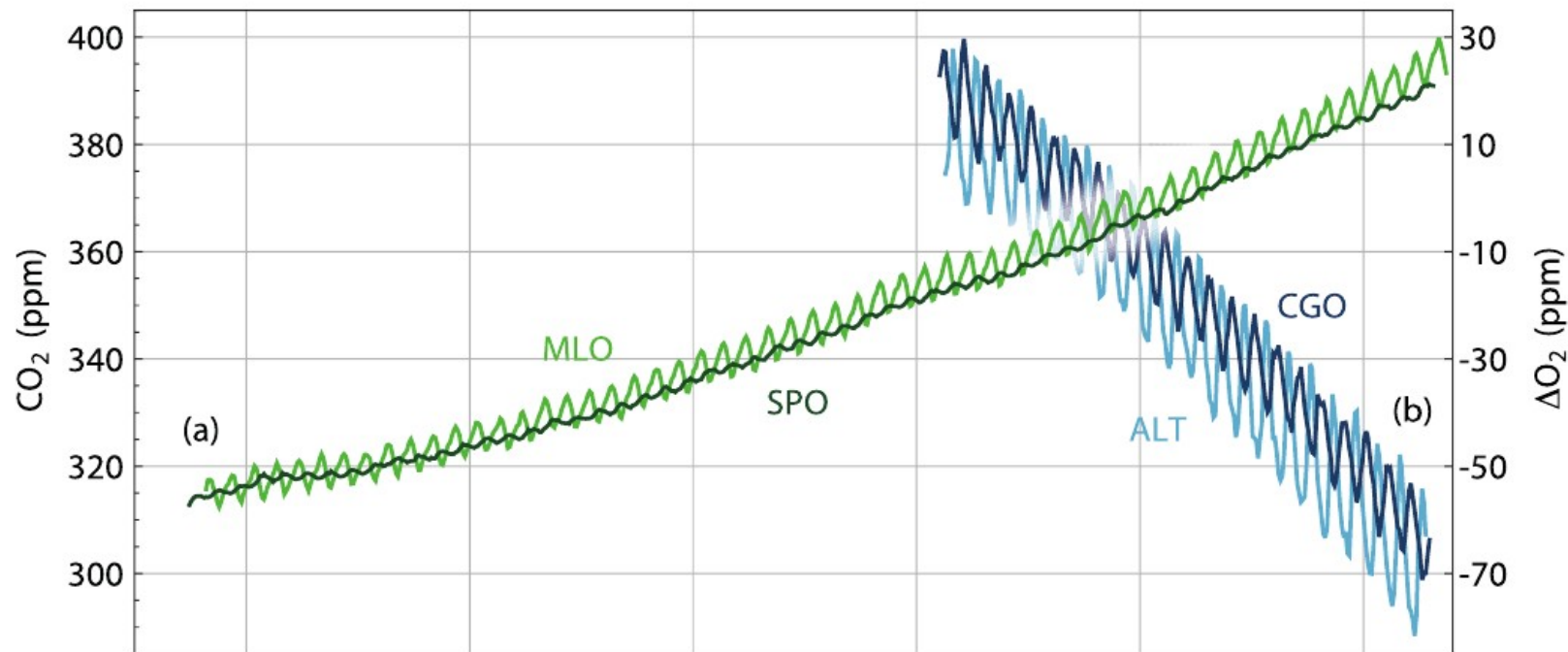
Flux: Million tonnes of CH<sub>4</sub> per year (Tg CH<sub>4</sub>/yr)

▮ Natural 
 ▮ Anthropogenic 
 ▮ Both

Stocks: Million tonnes of Methane (CH<sub>4</sub>)

○ Stocks (range) 
 ● Anthropogenic change



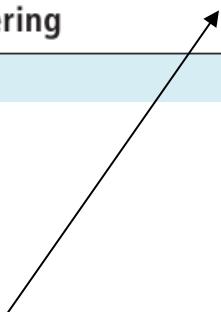


Inne dowody (poza bilansem węgla) na to że wzrost koncentracji CO<sub>2</sub> w atmosferze pochodzi ze spalania paliw kopalnych

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 CO<sub>2</sub> consecutive to a large emission pulse to the atmosphere, their atmospheric CO<sub>2</sub> adjustment time scales, and main (bio)chemical reactions involved.

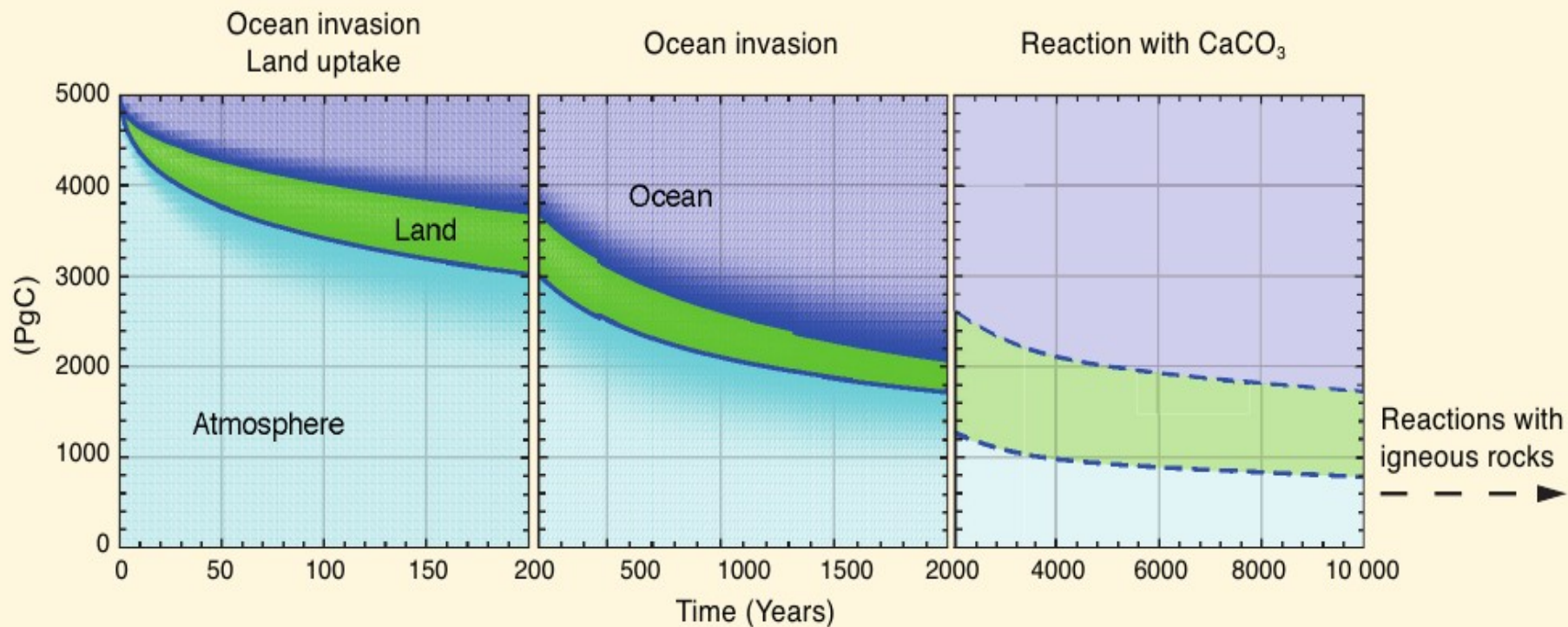
Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	1–10 <sup>2</sup>	$6\text{CO}_2 + 6\text{H}_2\text{O} + \text{photons} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$ $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}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



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

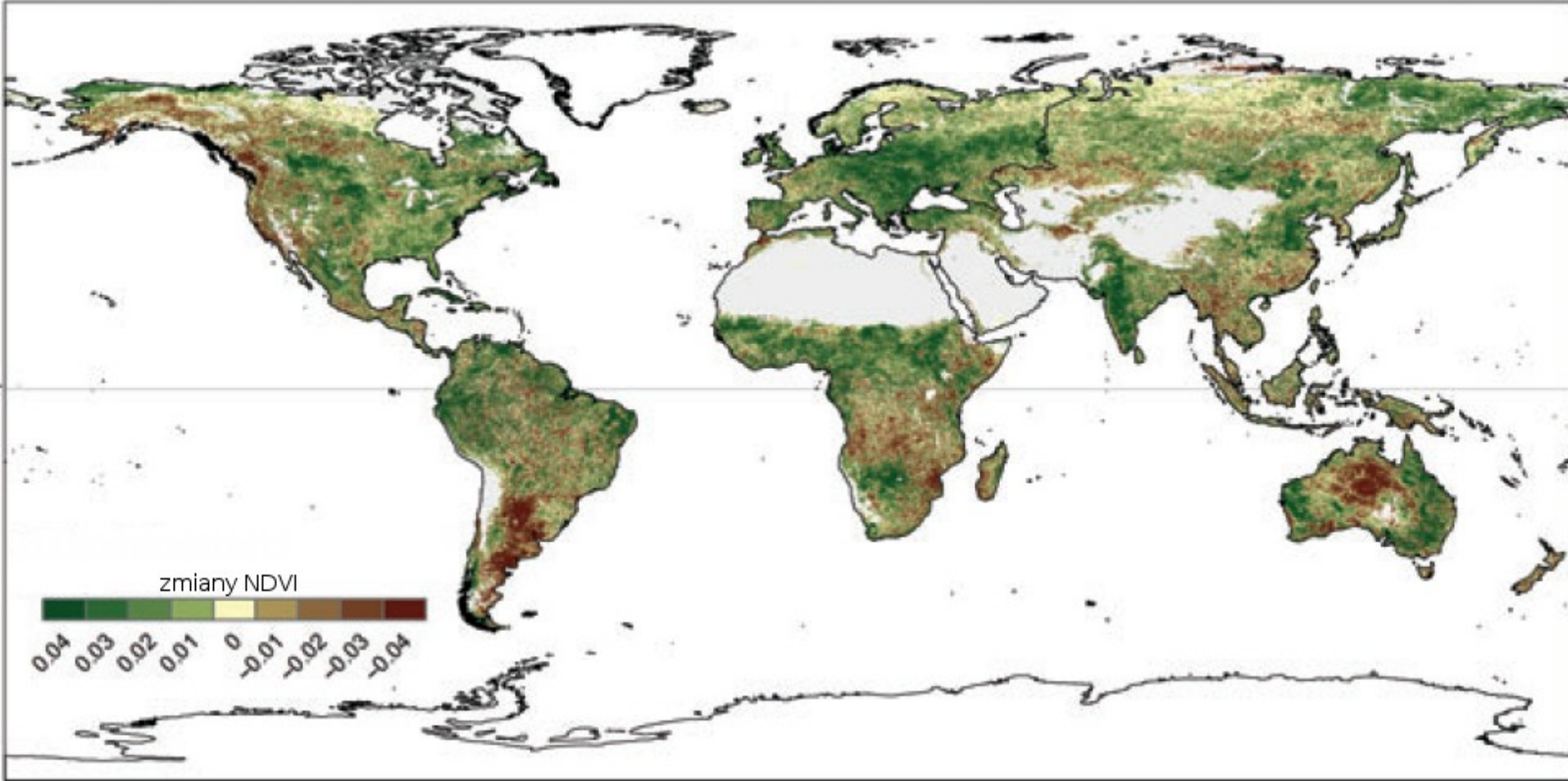
Tempo (skale czasu) usuwania dwutlenku węgla z atmosfery.

Sposób oszacowania: stała czasowa spadku CO<sub>2</sub> po nagłym wzroście koncentracji tego gazu w atmosferze.

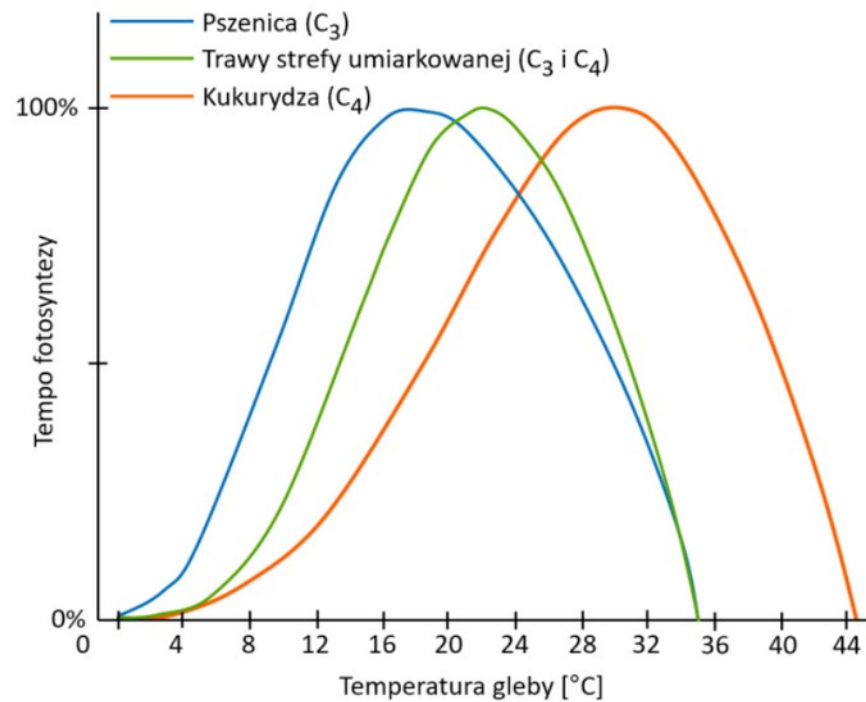
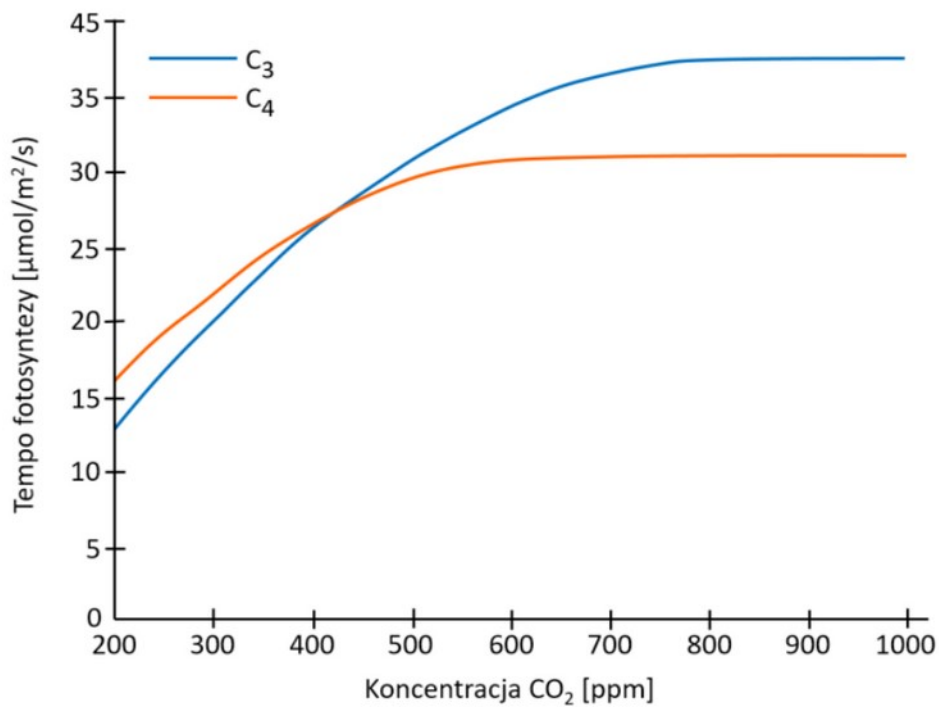


**FAQ 6.2, Figure 2 |** Decay of a CO<sub>2</sub> excess amount of 5000 PgC emitted at time zero into the atmosphere, and its subsequent redistribution into land and ocean as a function of time, computed by coupled carbon-cycle climate models. The sizes of the colour bands indicate the carbon uptake 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 CO<sub>2</sub> w atmosferze oznacza większą produkcję roślinną?



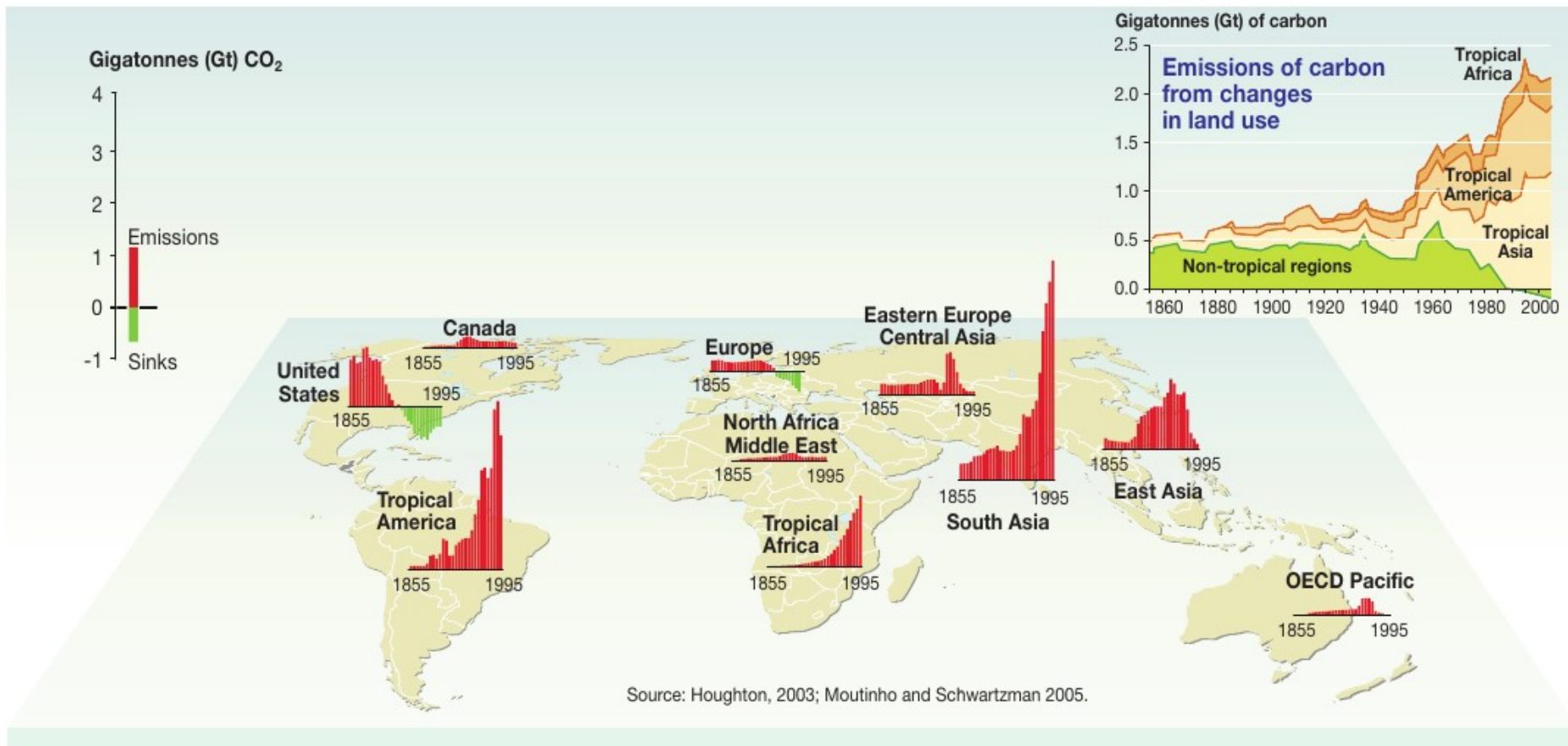
Zmiany wskaźnika NDVI (Normalized Difference Vegetation Index) w okresie 1982-2008. Globalne ocieplenie zmniejsza produktywność roślin. W miarę jak przybywa dwutlenku węgla, na półkuli północnej rosną wartości wskaźnika NDVI (obszary oznaczone na mapie kolorem zielonym), co oznacza zdrową i rozwijającą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



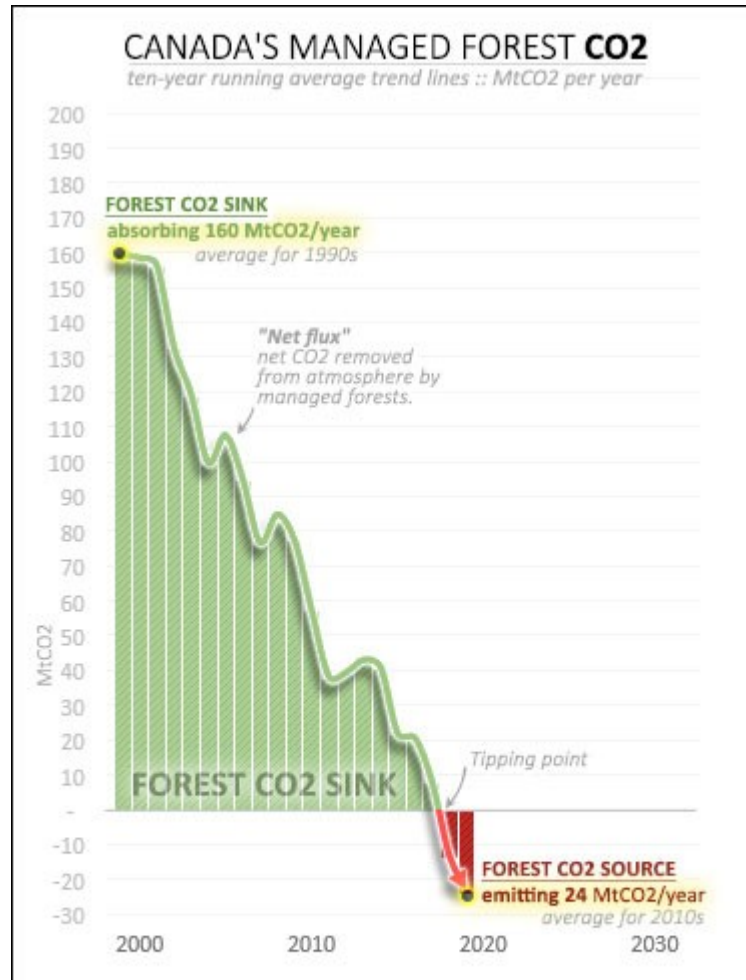
Ilustracja 2.17.11. Po lewej: Poglądowo przedstawiona zależność tempa fotosyntezy od koncentracji  $\text{CO}_2$  dla różnych typów fotosyntezy. Po prawej: Zależność tempa fotosyntezy dla różnych roślin od temperatury powierzchniowej warstwy gleby.



## Historical forest carbon balance, 1855-1995



Rola lasów w bilansie węgla



CANADA MANAGED FOREST & LOGGING CO<sub>2</sub> – Data from Canada's National Inventory Reports. All lines are 10-year running averages. Green line & area is net CO<sub>2</sub> 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 CO<sub>2</sub> ("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 CO<sub>2</sub> 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

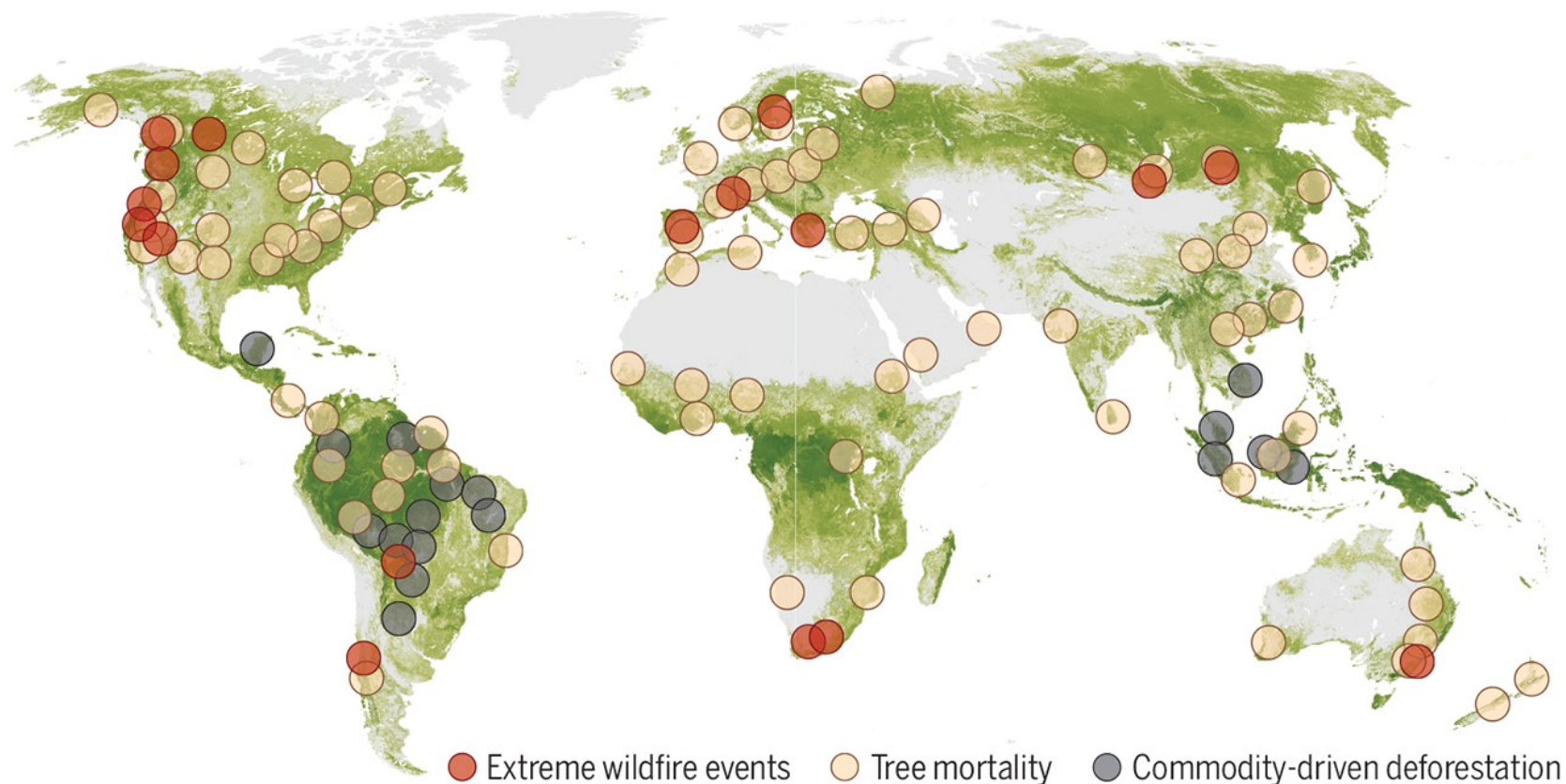
Jonathan T. Overpeck<sup>1</sup>, David D. Breshears<sup>2</sup>

+ See all authors and affiliations

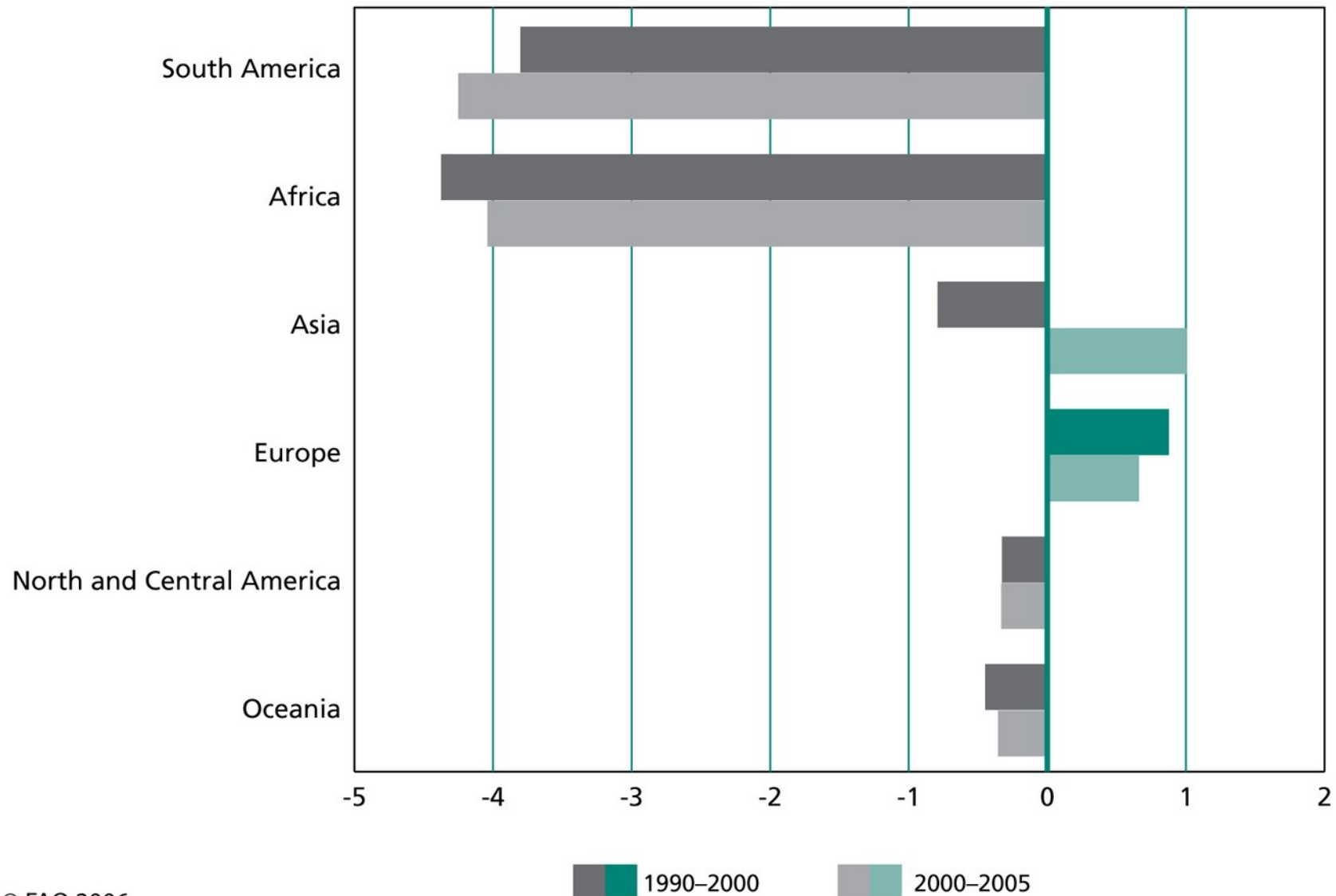
Science 21 May 2021:  
Vol. 372, Issue 6544, pp. 786-787  
DOI: 10.1126/science.abb9902

## Rapid tree loss around the world

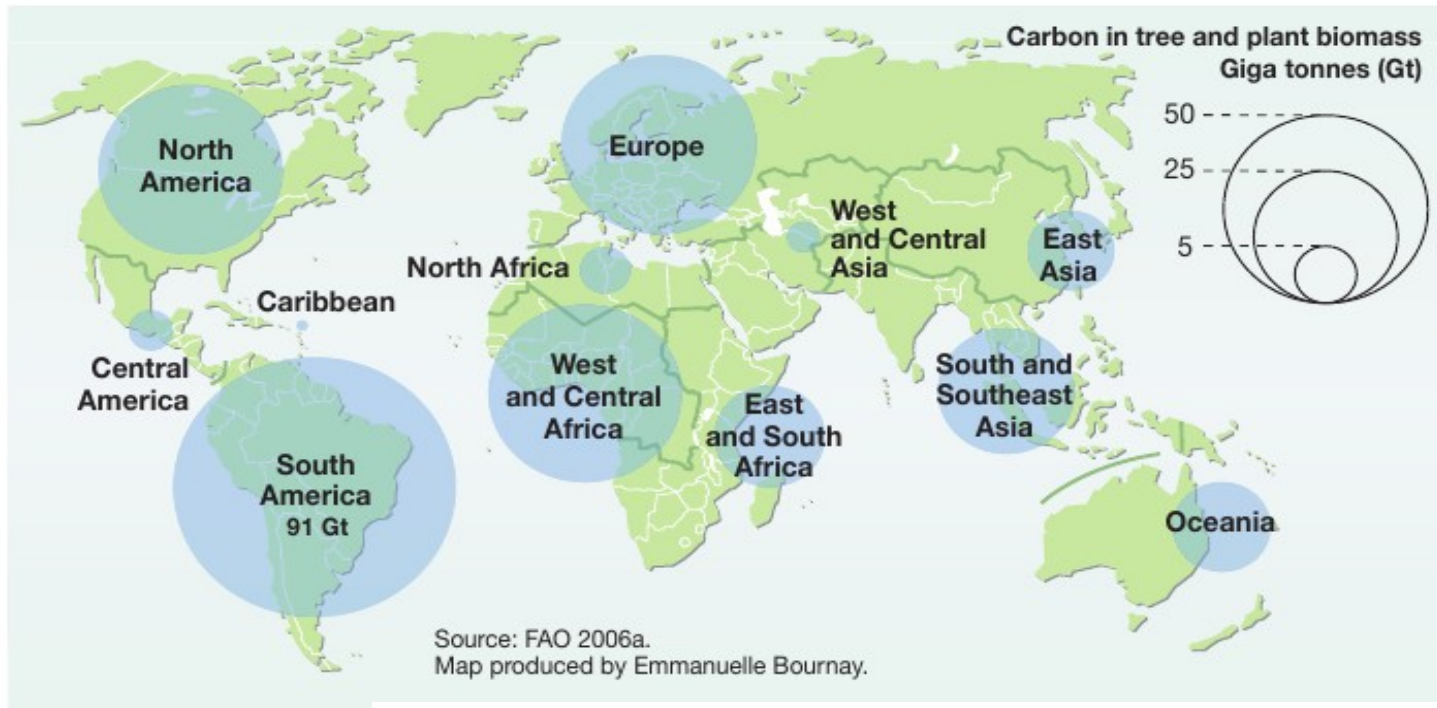
Global tree decline is attributed to commodity-driven deforestation (9), loss by wildfire (1), and drought- and heat-related mortality (often associated with pests and pathogens). The latter two are affected by increasing atmospheric moisture demand that drives forest stress. Forested areas are shown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



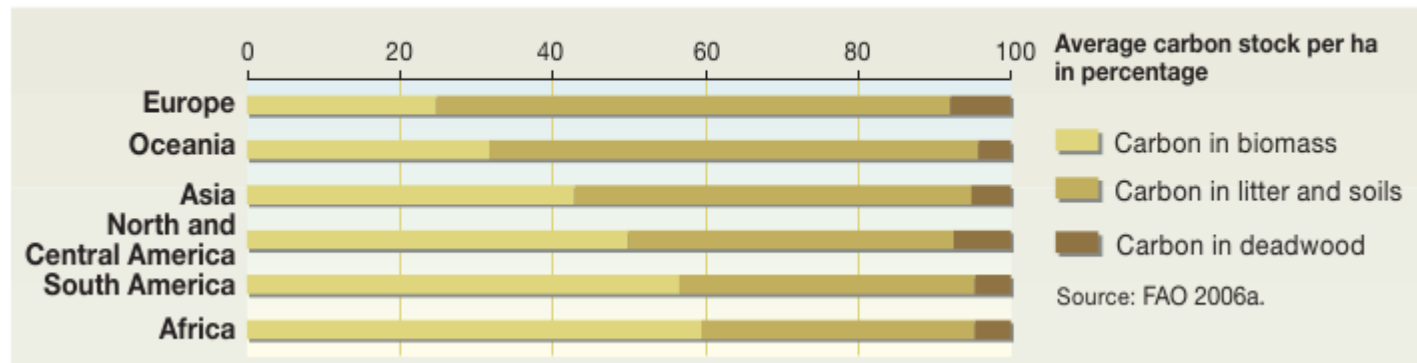
# Annual net change in forest area by region 1990–2005 (million ha per year)



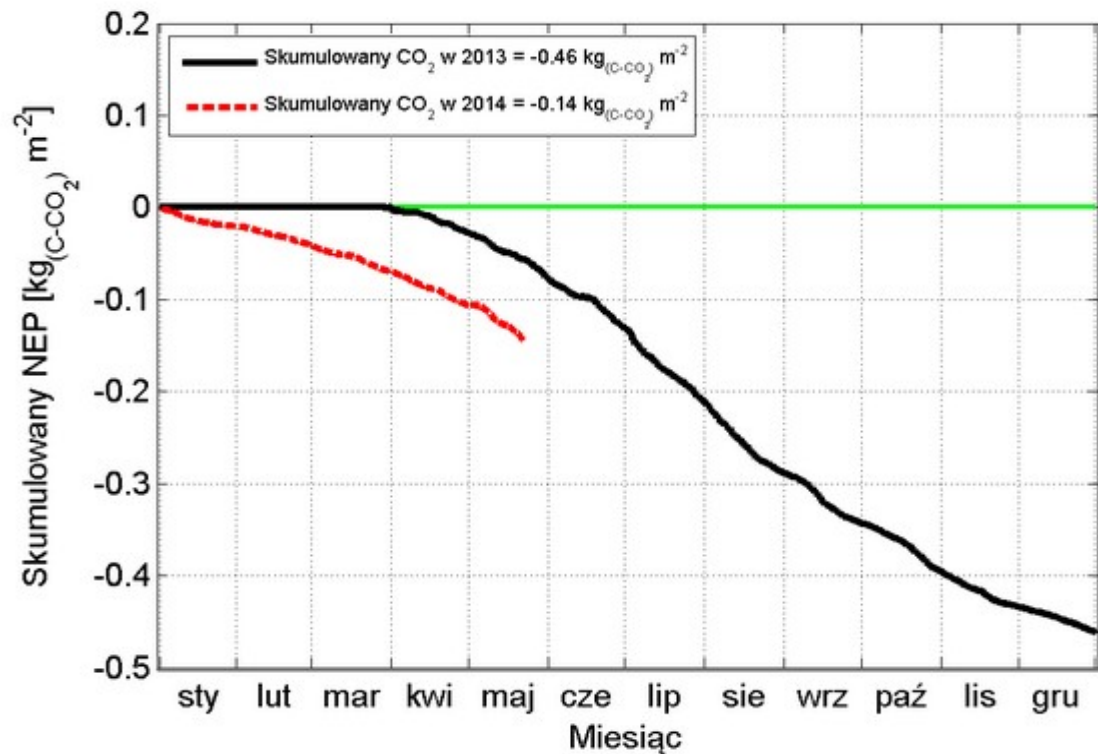
## Forest carbon stock per region



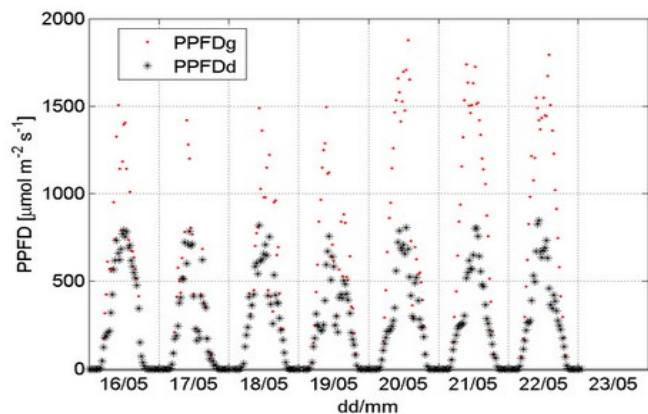
## Breakdown of carbon storage by region



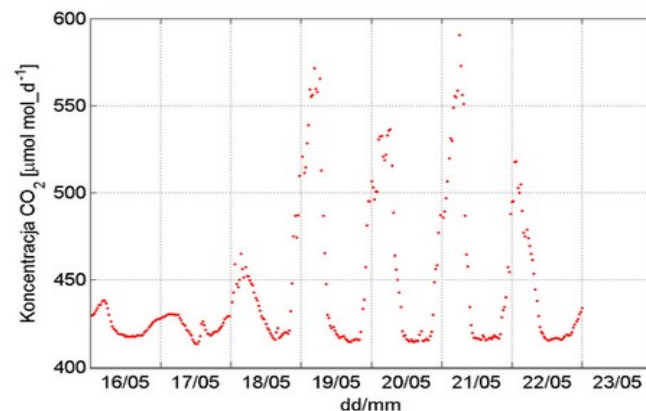
# Stacja badawcza Tleń- las iglasty po przejściu tornado (od 29 Marca 2013r.)



Cummulation of CO<sub>2</sub> estimated by EC



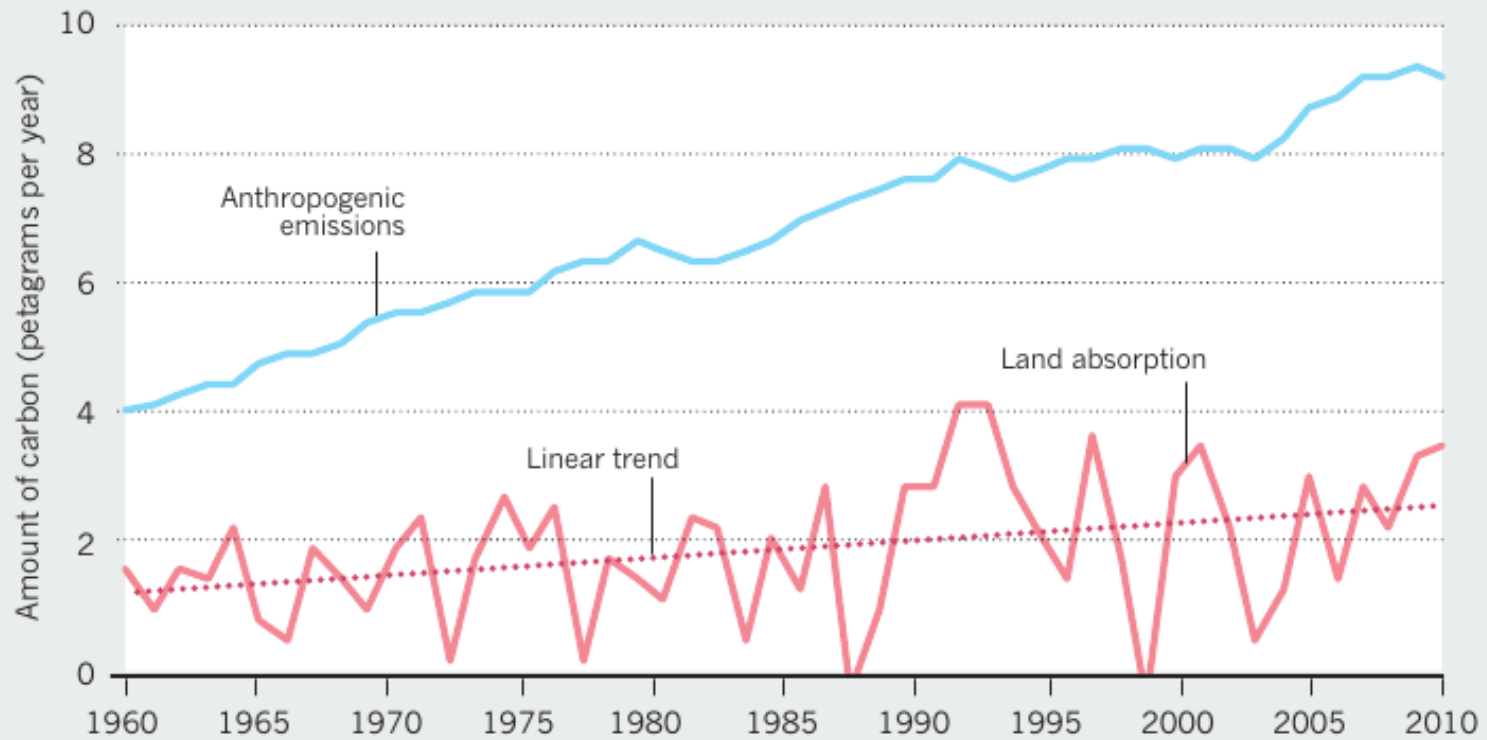
Photosynthetic Photon Flux Density (data from BF5), in last 7 days



CO<sub>2</sub> mixing ratio runs in last 7 days

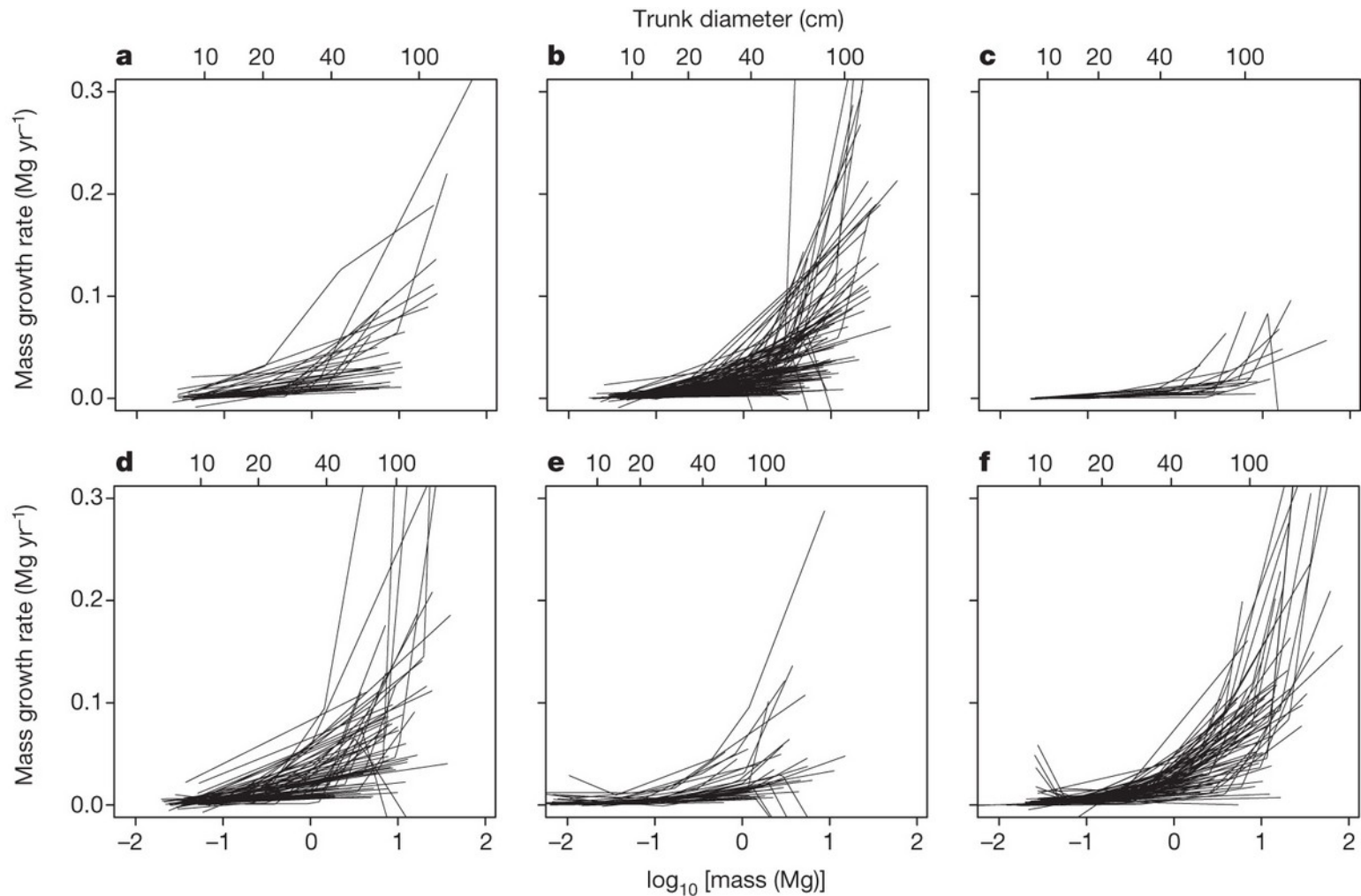
## GLOBAL LAND SINK

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.

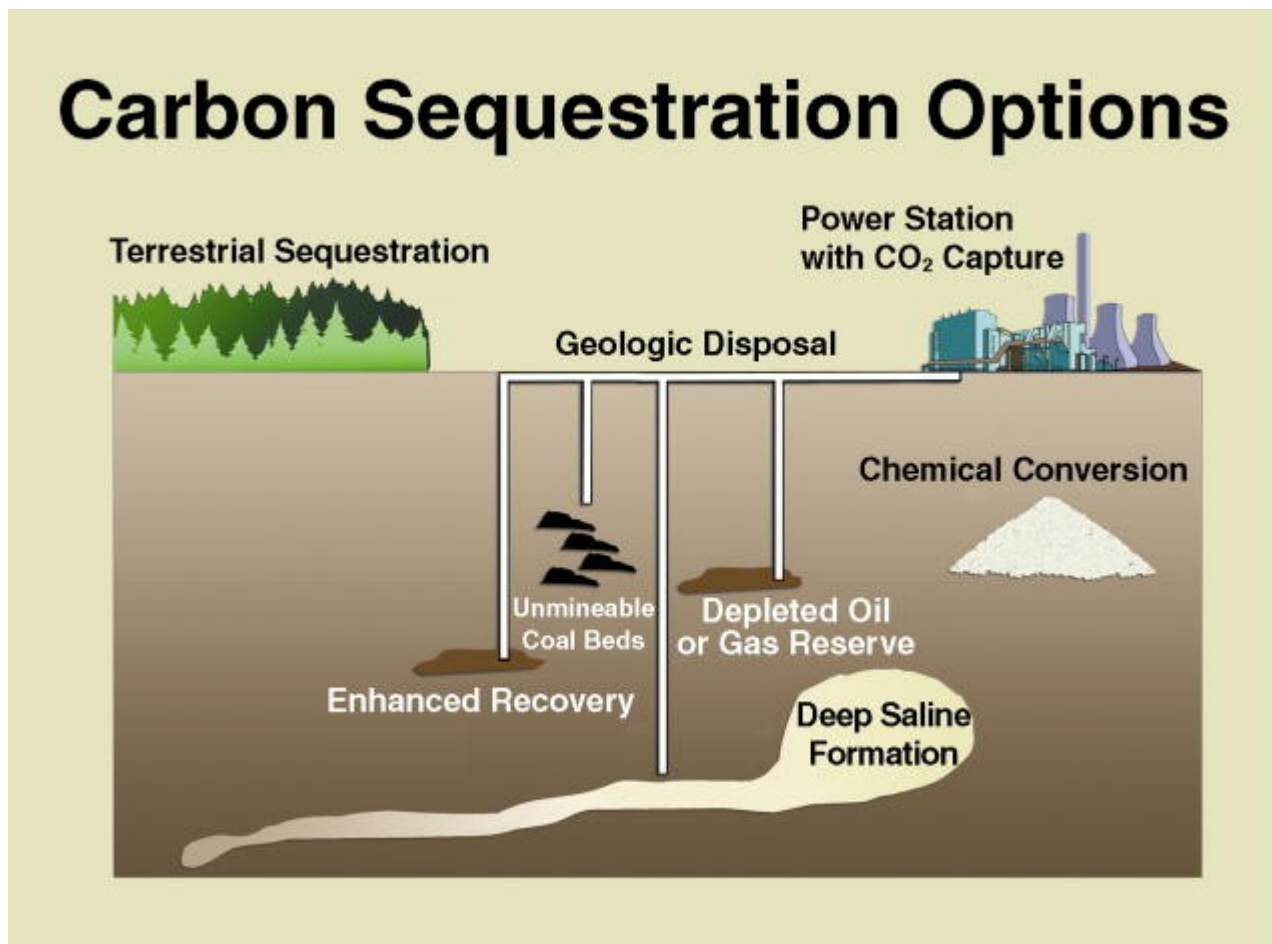


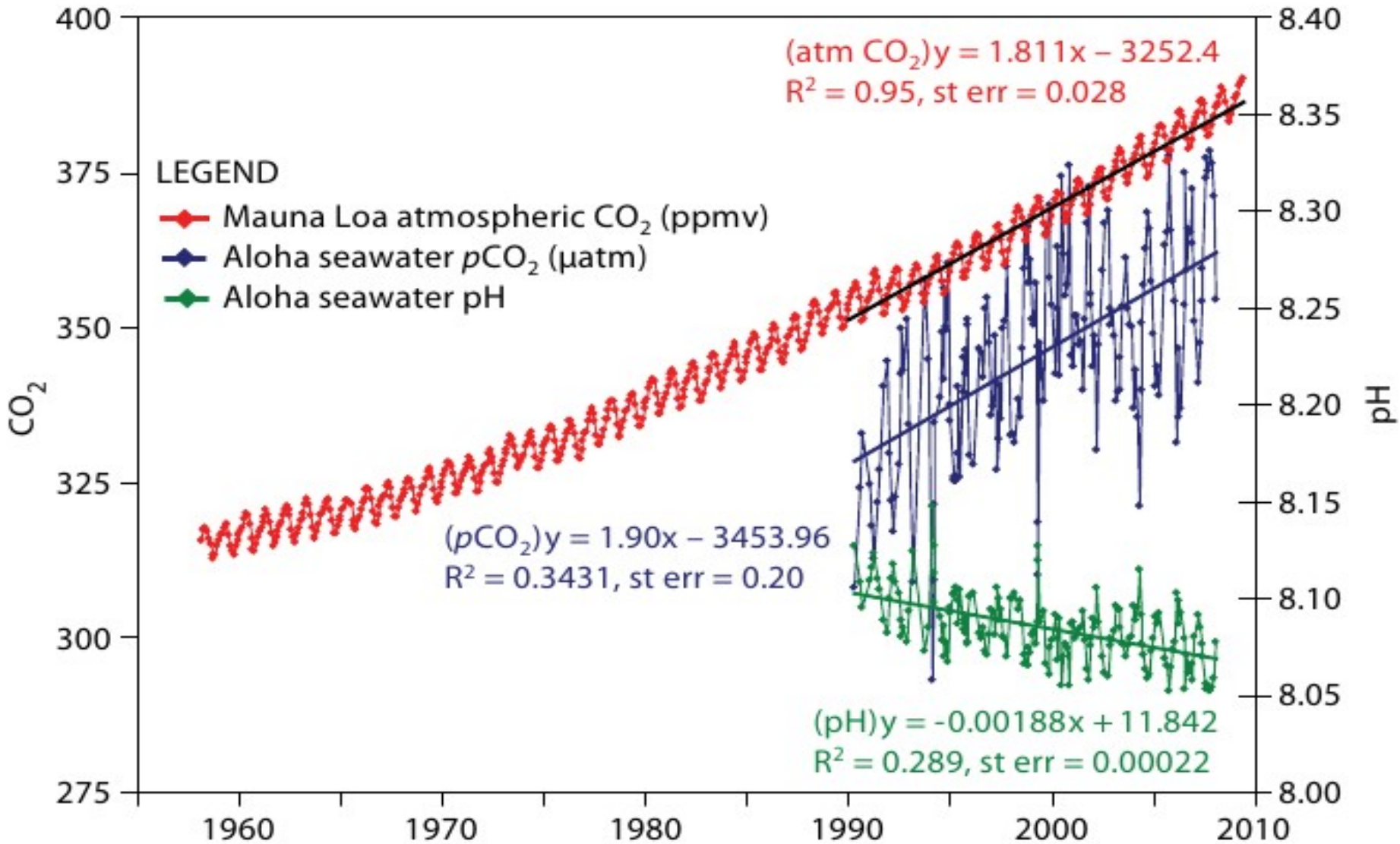
NL Stephenson *et al.* *Nature* **000**, 1-4 (2014) doi:10.1038/nature12914

**nature**



Nie tylko lasy – opcje sekwestracji węgla.



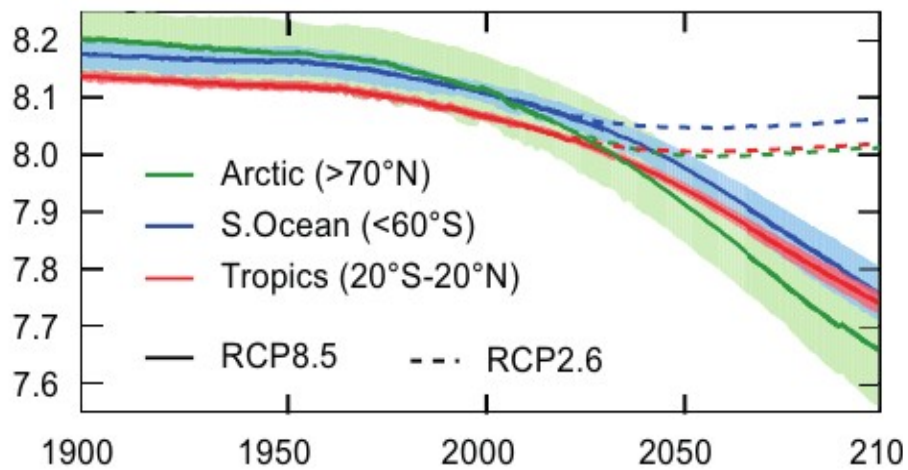


## Ocean zmienia odczyn na bardziej kwaśny

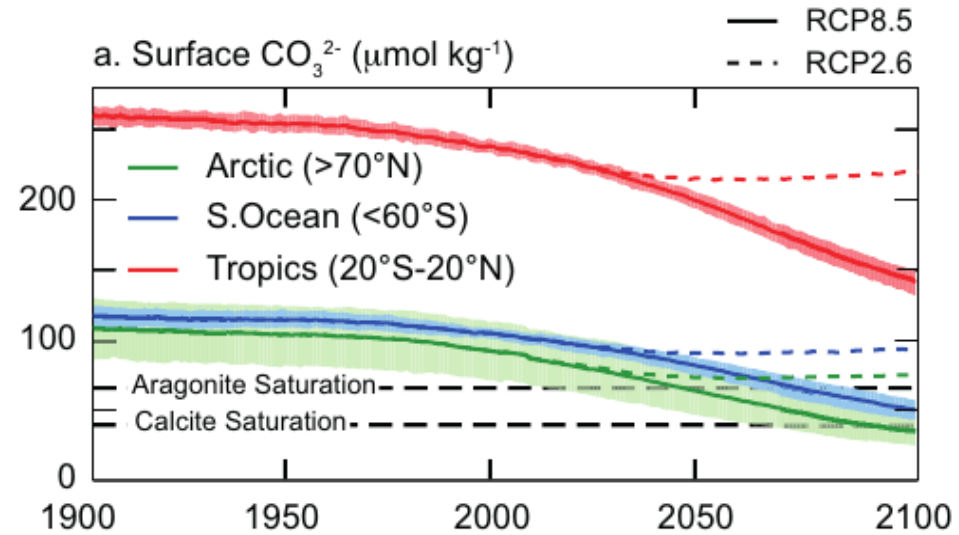
Feely, R.A., S.C. Doney, and S.R. Cooley. 2009. Ocean acidification: Present conditions and future changes in a high-CO<sub>2</sub> world. *Oceanography* 22(4):36–47, <http://dx.doi.org/10.5670/oceanog.2009.95>.

# Zakwaszenie oceanów

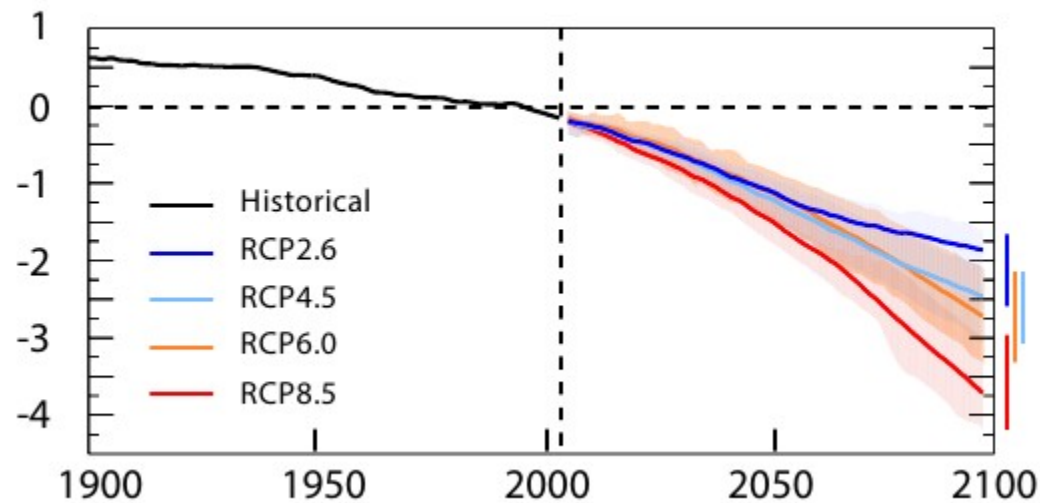
a. Surface pH

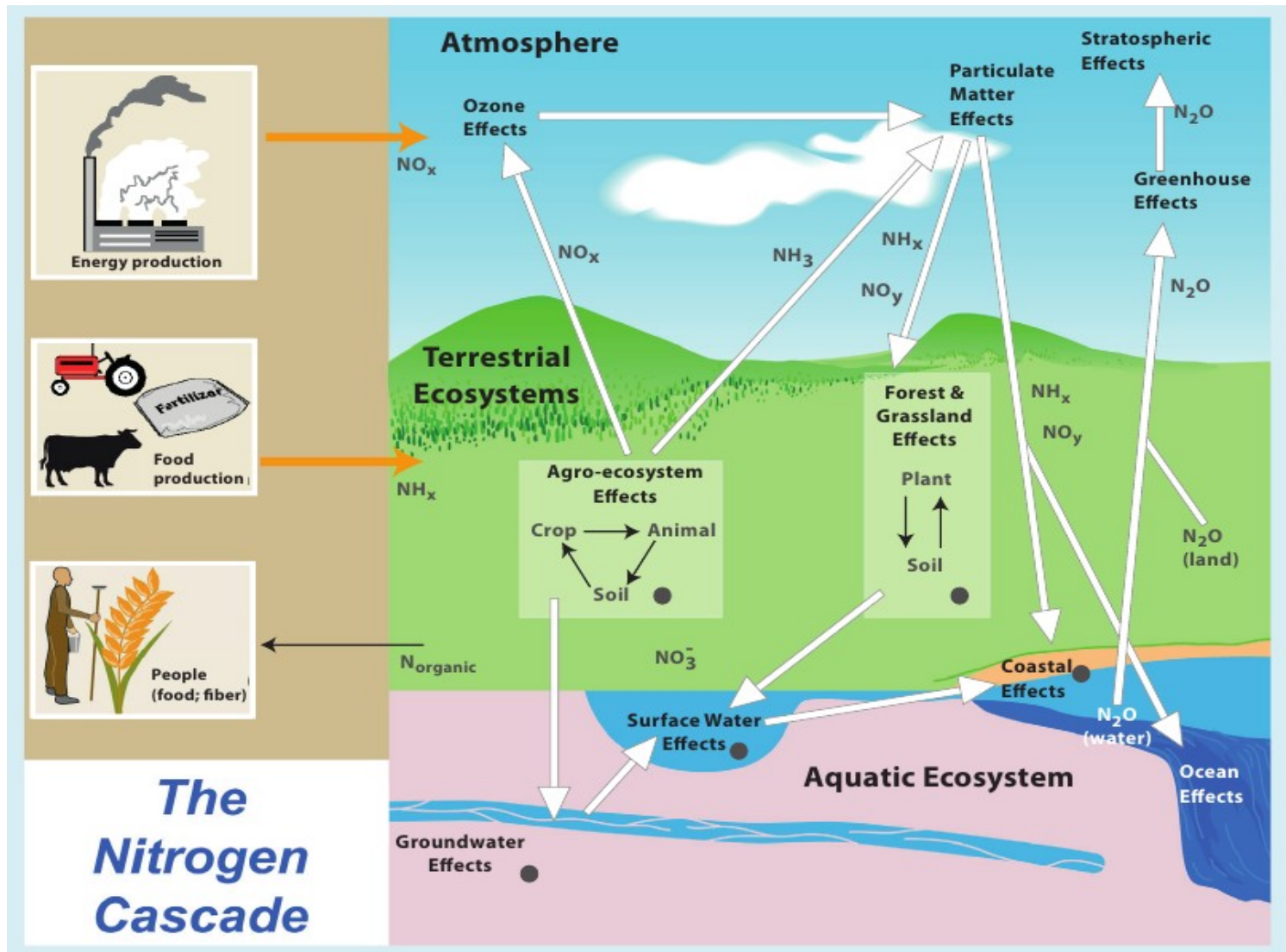


a. Surface  $\text{CO}_3^{2-}$  ( $\mu\text{mol kg}^{-1}$ )



a. Ocean oxygen content change (%)

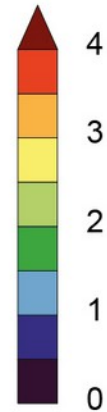
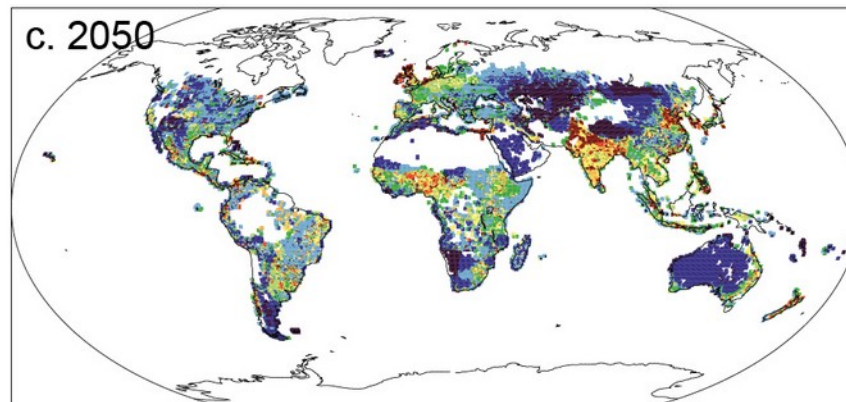
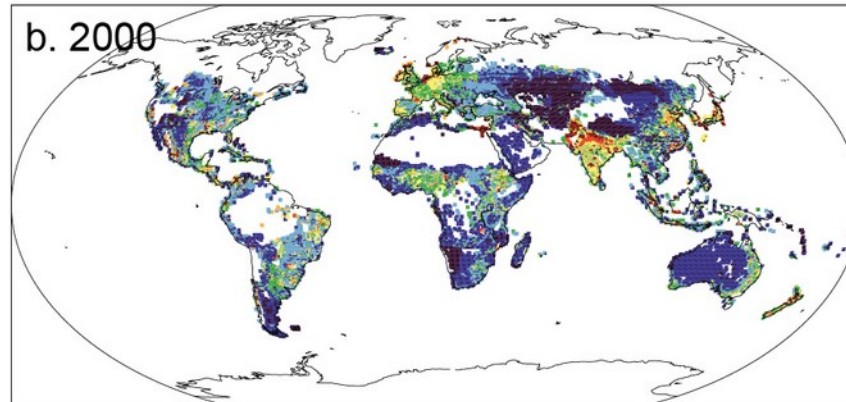
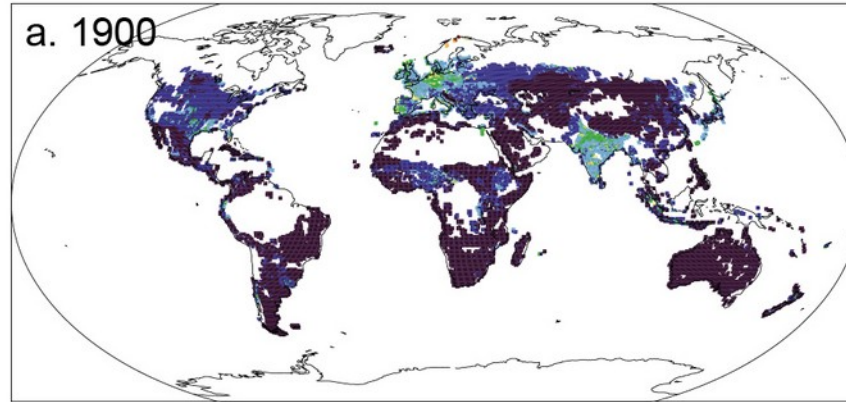




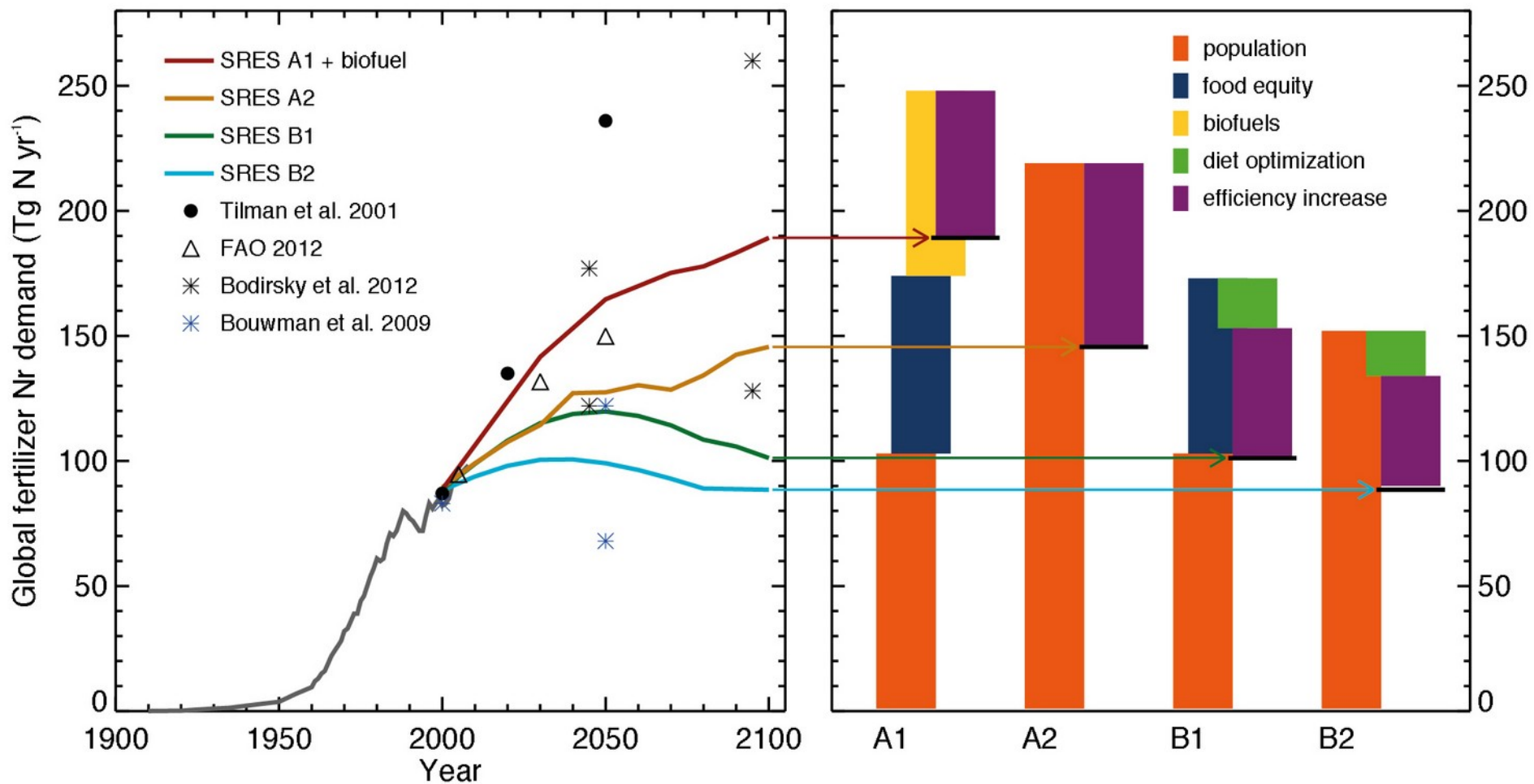
“Kaskada azotowa” - zmiany jakie powoduje w cyklu azotowym każdy atom przekształcony z nieaktywnej formy  $\text{N}_2$  do formy reaktywnej chemicznie – biorącej udział w procesach biologicznych i chemicznych w systemie klimatycznym

# N<sub>2</sub>O emissions (kgN km<sup>-2</sup> y<sup>-1</sup>)

Emisje podtlenku azotu – estymacje geograficzne.



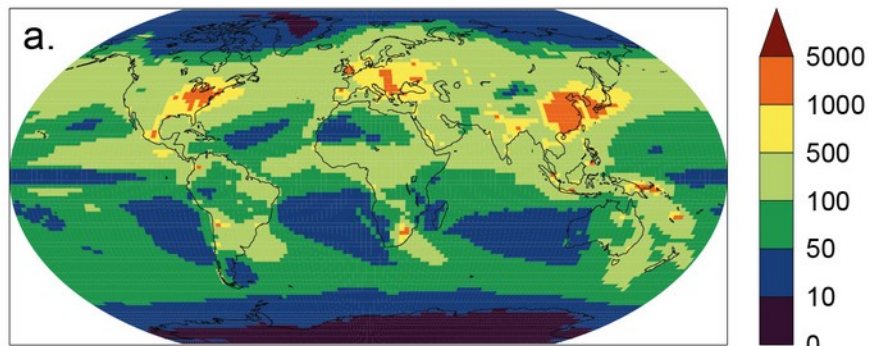
## Zaburzenia w cyklu azotowym wskutek działania rolnictwa – rozkład czasowy emisji i wartości skumulowane.



# Jak będzie się zmieniać depozycja związków siarki i azotu.

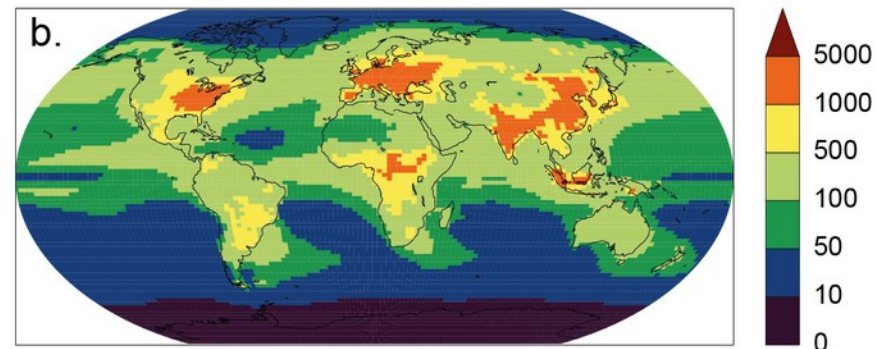
SO<sub>x</sub> deposition (kgS km<sup>-2</sup> y<sup>-1</sup>)

1990s

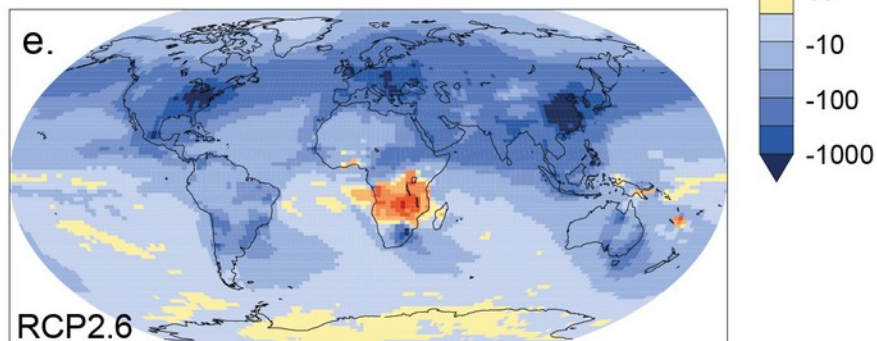
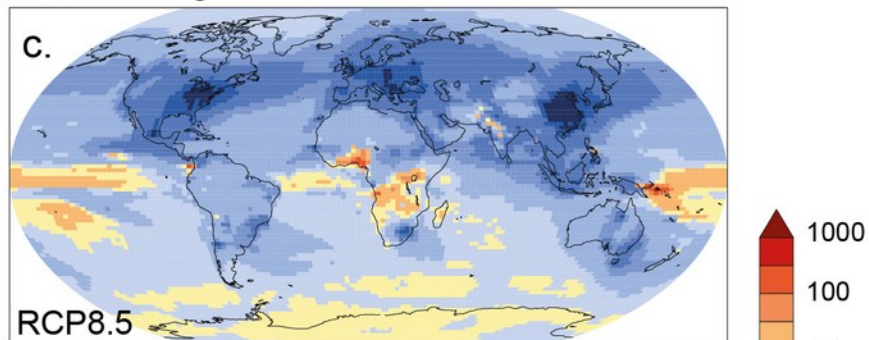


N deposition (kgN km<sup>-2</sup> y<sup>-1</sup>)

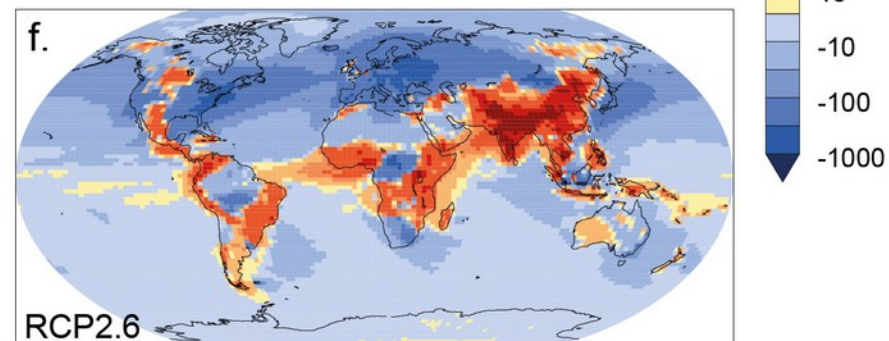
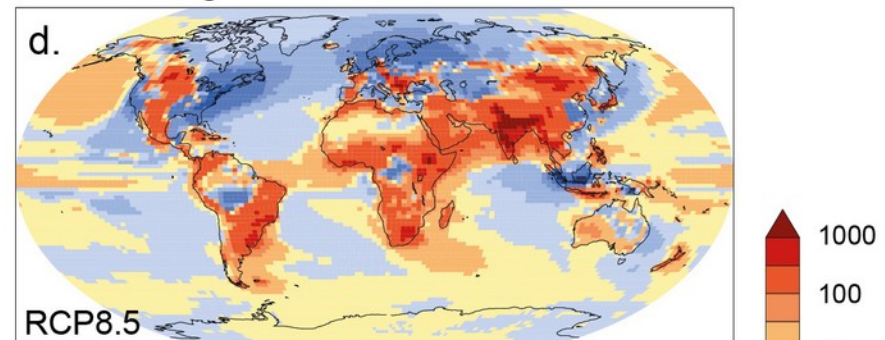
1990s



2090s, changes from 1990s



2090s, changes from 1990s



Podsumowanie:

Problem z węglem: CO<sub>2</sub> i CH<sub>4</sub> poważny.

Ale nie jedyny...