Gaia and global greening

What does Gaia state?

Three (at least) propositions of the Gaia hypothesis(Kirchner 2002)

1. Biologically mediated feedbacks contribute to environmental **homeostasis**

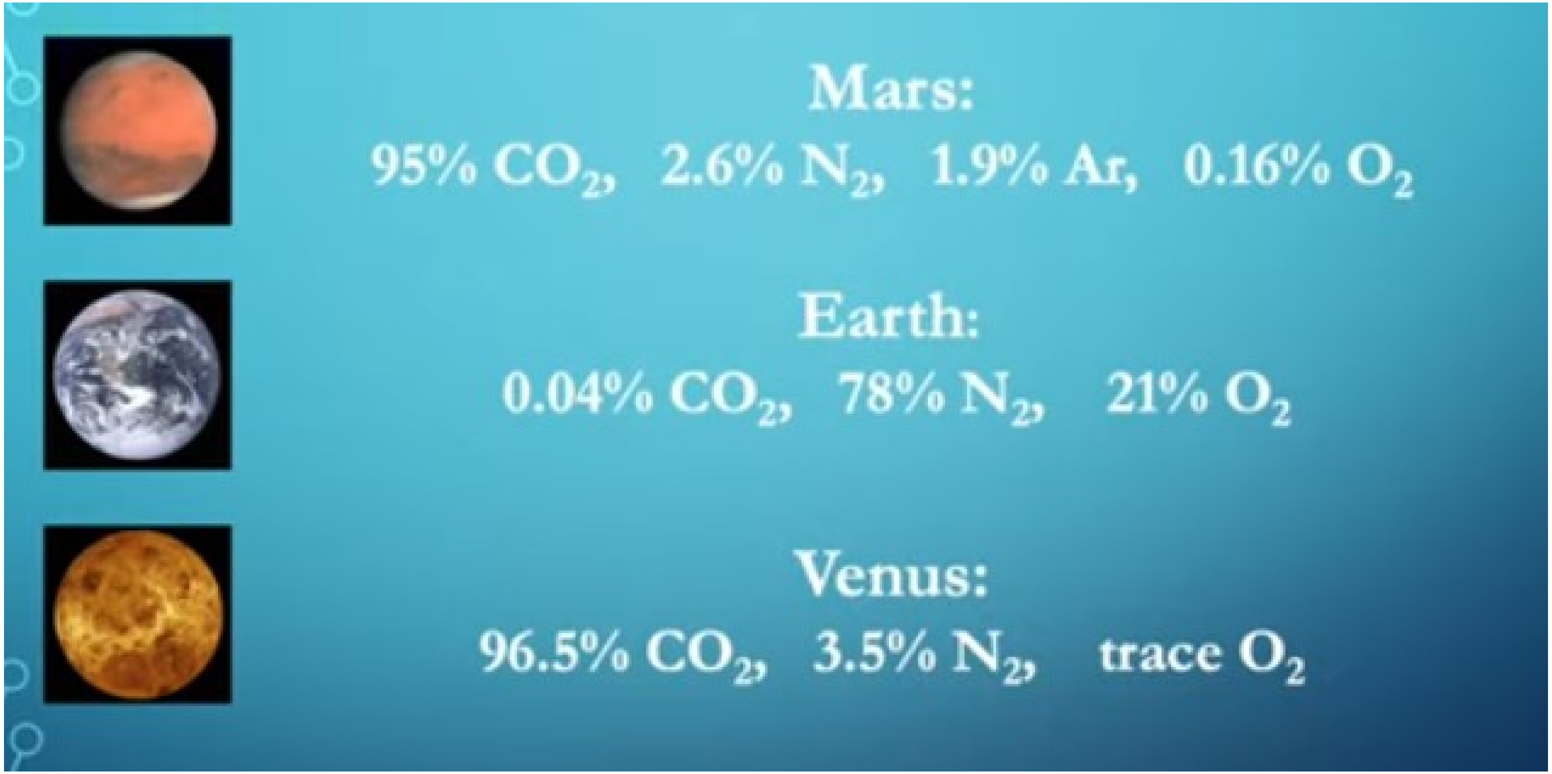
2. These make the environment **more suitable for life**

3. Feedbacks should arise by Darwinian natural selection

Implications

- The concept that life (the biota) mediates physical processes (e.g. climate) is uncontroversial.
- However: Do biotic mediated feedbacks really lead to **homeostasis**?

Earth atmosphere vs Venus and Mars



Gaia and anthropogenic forcing

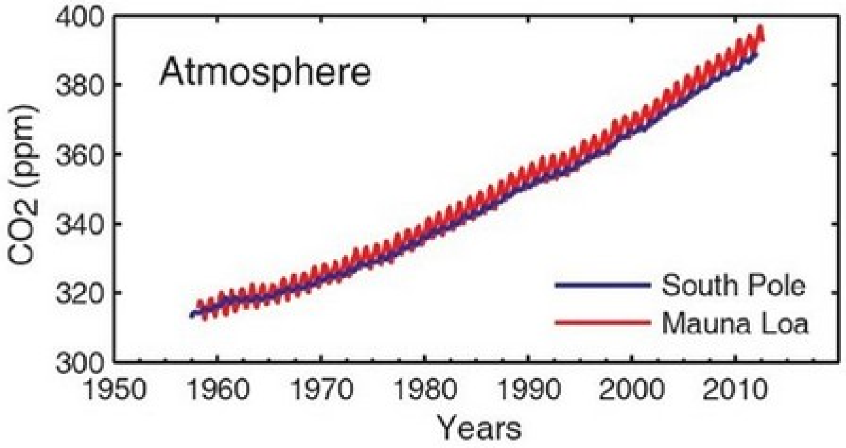
- The gaia hypothesis may explain why the earth is not like venus
- Ancient life converted $C0_2$ into oxygen
- How relevant are biotic feedbacks with respect to current climate change?

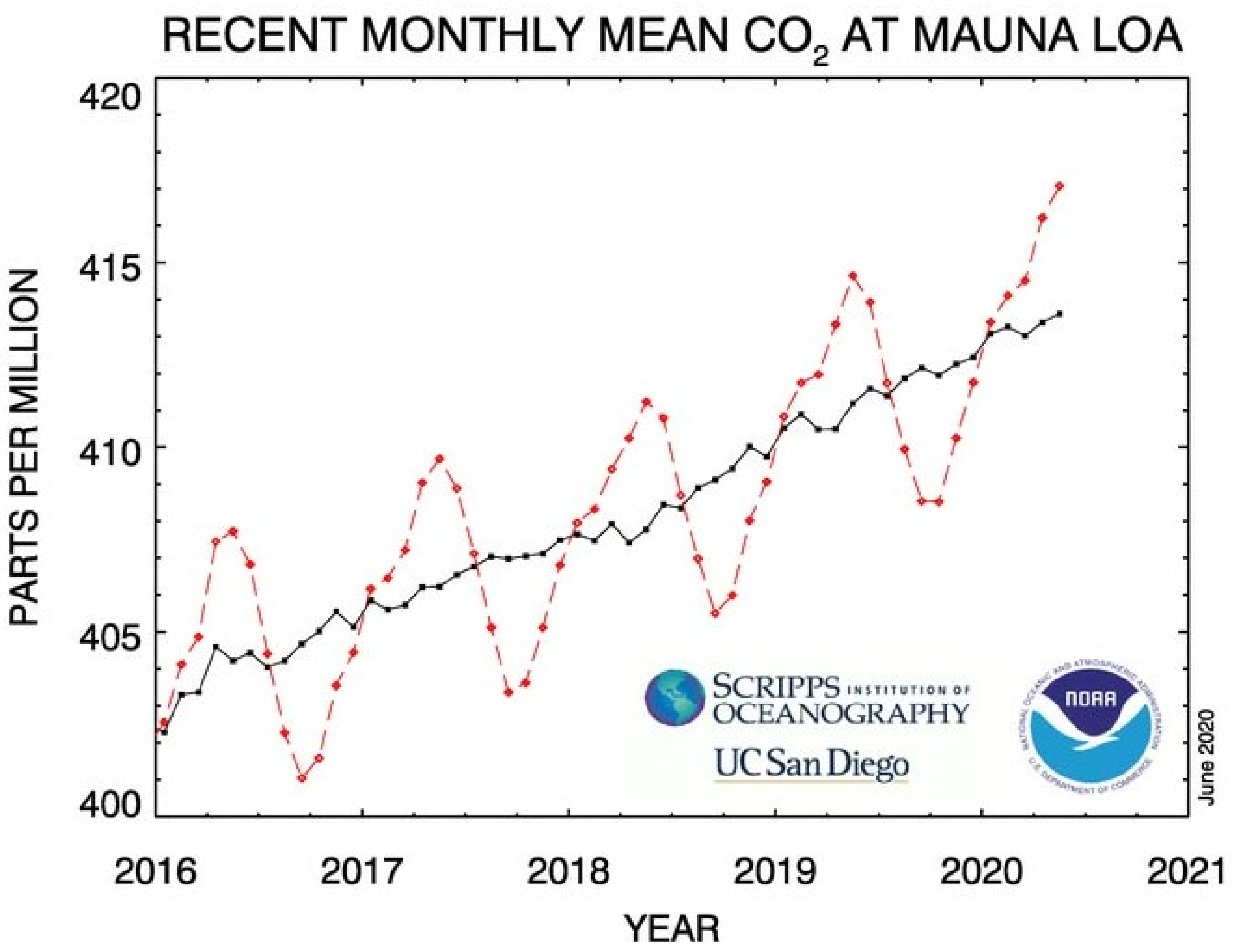
Complexity

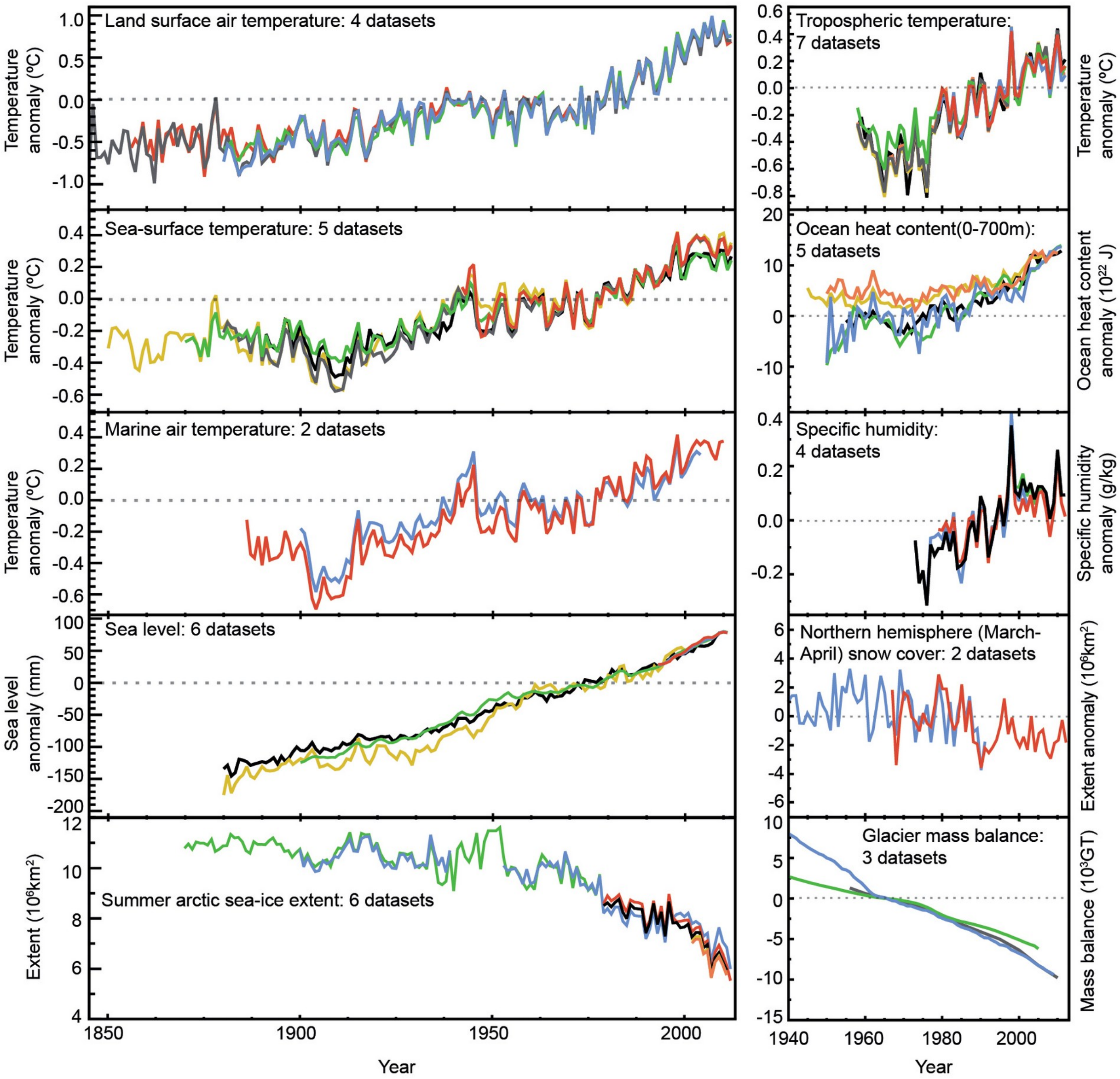
- A **complicated** system can be described in full (e.g an internal combustion engine is a complicated system)
- Complicated systems have a design: Each part has a function.
- A **complex** system can never be fully understood and predicted.
- Complex system are not designed.
- Each part may have numerous roles and functions Some interactions within a complex system can be understood.
- However the whole system is inherently unpredictable. Complex systems show emergent properties that occur as the result of diverse interactions

Anthropogenic climate forcing

- CO_2 levels in the atmosphere have increased from 277 ppm to >400 ppm
- Would a “homeostatic Gaia” tend to return the concentration to pre-industrial levels?

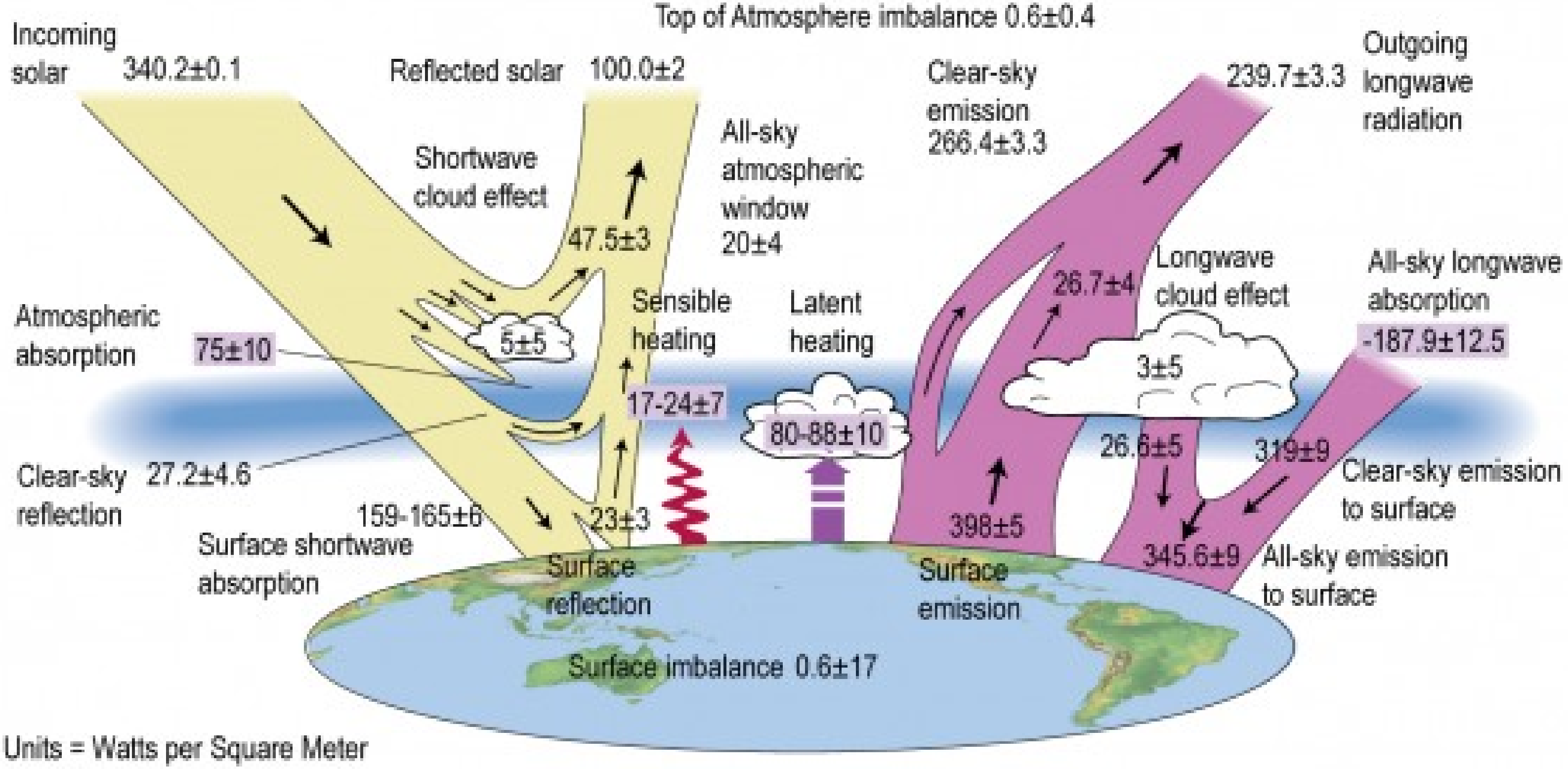



RECENT MONTHLY MEAN CO_2 AT MAUNA LOA
PARTS PER MILLION
420
415
410
405
400
2016
2017
2018
2019
2020
2021
YEAR
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego
NOAA
June 2020



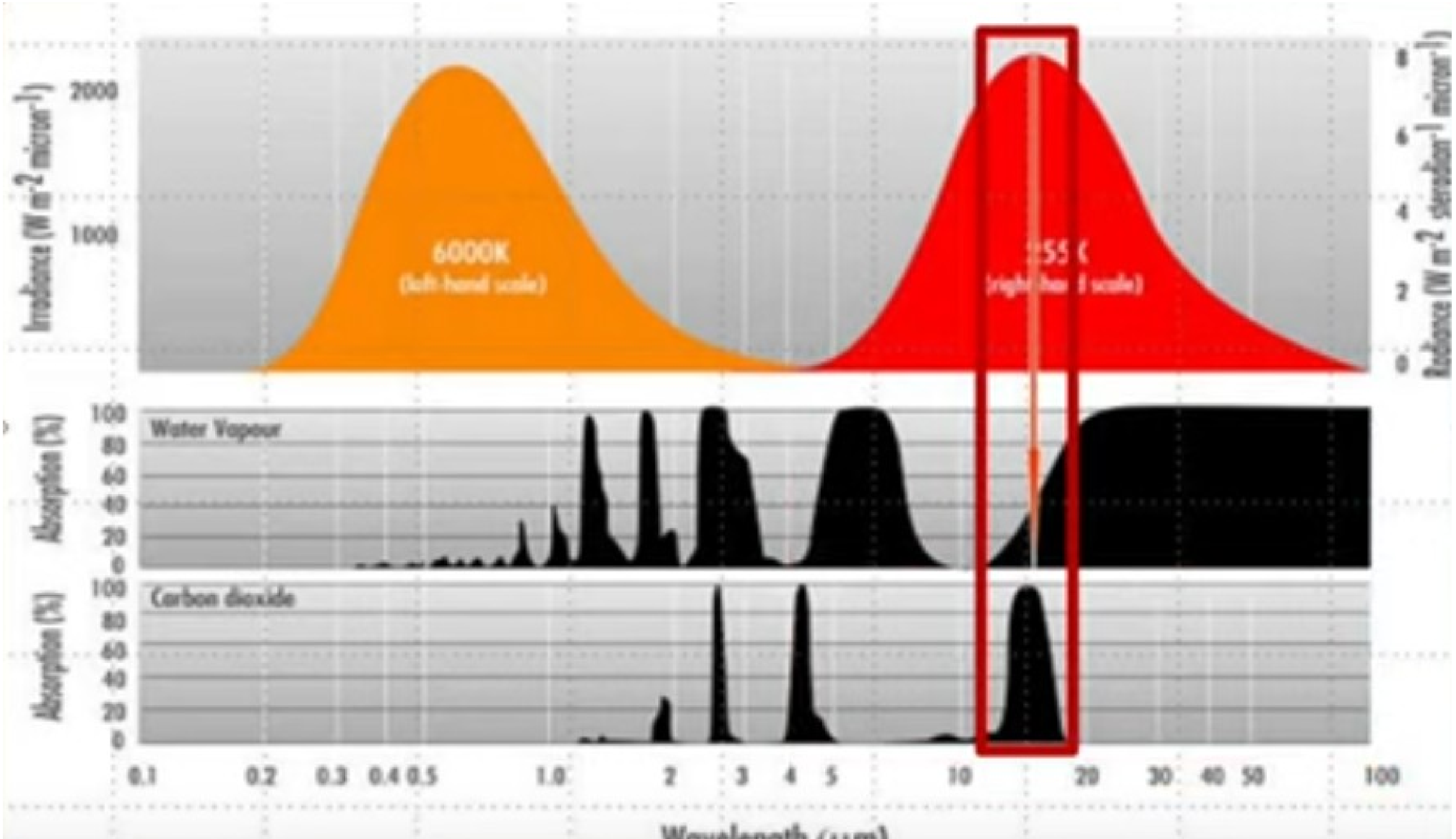
Land surface air temperature: 4 datasets
Temperature anomaly (ºC)
Sea-surface temperature: 5 datasets
Temperature anomaly (ºC)
Marine air temperature: 2 datasets
Temperature anomaly (ºC)
Sea level: 6 datasets
Sea level anomaly (mm)
Summer arctic sea-ice extent: 6 datasets
Extent ($10^6 km^2$)
Year
Tropospheric temperature: 7 datasets
Temperature anomaly (ºC)
Ocean heat content(0-700m): 5 datasets
Ocean heat content anomaly (10^{22} J)
Specific humidity: 4 datasets
Specific humidity anomaly (g/kg)
Northern hemisphere (March-April) snow cover: 2 datasets
Extent anomaly ($10^6 km^2$)
Glacier mass balance: 3 datasets
Mass balance (10^3GT)
Year

Earth's Energy Balance



CO_2 and gaseous H_20 are greenhouse gases

- Clouds have complex effects both reflecting incoming radiation and trapping outgoing radiation
- Water vapour (invisible) can absorb some outgoing radiation from the earth
- CO_2 plugs a “hole” in the spectrum



Irradiance (W m⁻² micron⁻¹)
2000
1000
6000K
(left-hand scale)
255 K
(right-hand scale)
Radiance (W m⁻² steradian⁻¹ micron⁻¹)
8
6
4
2
0
Absorption (%)
Water Vapour
Carbon dioxide
100
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
1.0
2
3
4
5
10
20
30
40
50
100

Physical processes are worked on by physicists

Dependence of Earth's Thermal Radiation on Five Most Abundant Greenhouse Gases

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The calculations are very complex!

Using (72) in (59) for each of the 400 altitude samples z above the tropopause would give 400 linear equations in the five unknowns, $\Delta\theta_1, \Delta\theta_2, \ldots \Delta\theta_5$. This grossly overdetermines the $\Delta\theta_\lambda$. However, we can find values of $\Delta\theta_\lambda$ that give the best approximate solution to (59) by minimizing

$$Q = \sum_{i=1}^{500} W_i(\delta Z_i)^2. \quad (76)$$

where $\delta Z_i = \delta Z(z_i)$. The adjustments $\Delta\theta_\lambda$ are not very sensitive to the weights W_i, and we used

$$W_i = \begin{cases} \Delta z_i & \text{if } z_i \geq \zeta_1, \\ 0 & \text{if } z_i < \zeta_1. \end{cases} \quad (77)$$

The altitude interval size is $\Delta z_i = z_{i+1} - z_i$.

The temperature adjustments $\Delta\theta_\lambda$, that minimize (76) are the simultaneous solutions of the five linear equations $(\lambda = 1, 2, 3, 4, 5)$

$$\frac{\partial Q}{\partial \Delta\theta_\lambda} = 2\sum_i V_{\lambda i} W_i \, \delta Z_i = 0, \quad (78)$$

where $V_{\lambda i} = V_\lambda(z_i)$ was defined by (73) and (74). We can write (75) as the 5×5 matrix equation

$$\sum_\lambda A_{\kappa\lambda}\Delta\theta_\lambda = \Delta S_\kappa. \quad (79)$$

The adjustment matrix of (79) is

Temperature adjustments but no water-vapor adjustment.

$$\Delta\theta = \begin{bmatrix} 1.4 \\ 1.4 \\ -2.0 \\ -7.2 \\ -7.9 \\ -2.0 \end{bmatrix} \text{K}, \quad \text{and} \quad \Delta\zeta = \begin{bmatrix} 0 \\ 0.06 \\ 0.05 \\ -0.19 \\ -0.65 \\ -1.10 \end{bmatrix} \text{km}, \quad \text{for } \Delta C_w = 0. \quad (85)$$

The breakpoint temperature and altitude adjustments show the lower atmosphere warms and expands slightly after doubling the CO_2 concentration while the upper atmosphere cools and contracts.

Both temperature and constant relative humidity water-vapor adjustments.

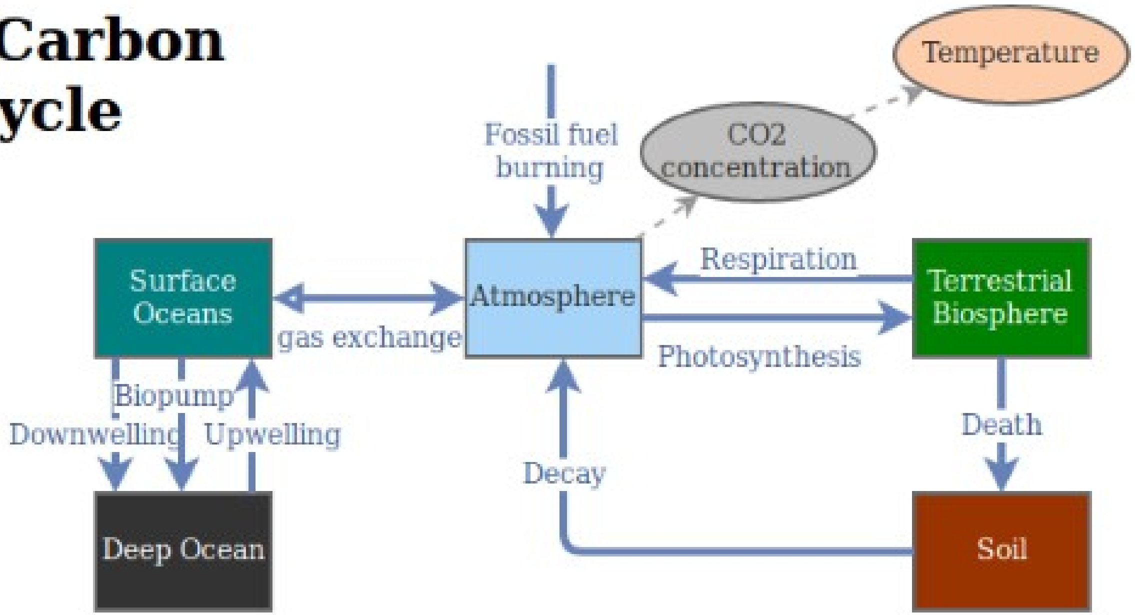
$$\Delta\theta = \begin{bmatrix} 2.3 \\ 2.3 \\ -2.8 \\ -7.0 \\ -8.6 \\ 3.8 \end{bmatrix} \text{K}, \quad \text{and} \quad \Delta\zeta = \begin{bmatrix} 0 \\ 0.10 \\ 0.09 \\ -0.17 \\ -0.64 \\ -0.98 \end{bmatrix} \text{km}. \quad (86)$$

CO_2 concentration 400 -> 800 ppm

Model Configuration	Manabe et al [35] [39]	Hunt et al [40]	Kluft et al [42]	This Work
Fixed absolute humidity, constant lapse rate (6.5 K km^{-1})	1.4 (1.4)		1.3	1.4
Fixed relative humidity, constant lapse rate (6.5 K km^{-1})	2.9 (2.2)	2.2	2.7	2.3
Fixed relative humidity, pseudoadiabatic lapse rate	2.0	1.8	2.1	2.2

Table 5: Climate sensitivity in Kelvins for different model configurations. The bracketed numbers next to the results found by Manabe and Wetherald [35] are the results of our calculation using their relative humidity profile given by ([87]). Our result for the case of

The Carbon Cycle



Ocean and terrestrial sinks

- Only around 50% of all anthropogenic carbon emissions remain in the atmosphere
- Ocean and terrestrial sinks have taken up the rest (approximately equal share)
- The terrestrial sink is extremely complex: Consists of many different ecosystems

Carbon emissions and sinks since 1750

Where our carbon emissions have come from: carbon emission sources 1750-2012 (Gt CO_2)

Where our carbon emissions have gone: carbon emission sinks 1750-2012 (Gt CO_2)

Notes: Both emissions and sinks sum to 1,997 Gt CO2. Land, ocean and atmospheric sinks represent the increased carbon dioxide absorption due to human emissions between 1750 and 2012. *Coal emissions are mostly coal but also include signficant biomass emissions. Gas emissions include a small volume of flaring emissions. Land use change emissions are the net change in carbon stocks resulting from human-induced land use, land use change and forestry activities.

Sources: IPCC (2007) WG1, Global Carbon Project, CDIAC, NOAA.

The “missing terrestrial sink”

- There appears to be a paradox when the global carbon stocks are estimated.
- Although land use change (mainly forest loss) accounts for large emissions, terrestrial ecosystems continue to take up carbon produced through fossil fuel burning

Feedbacks

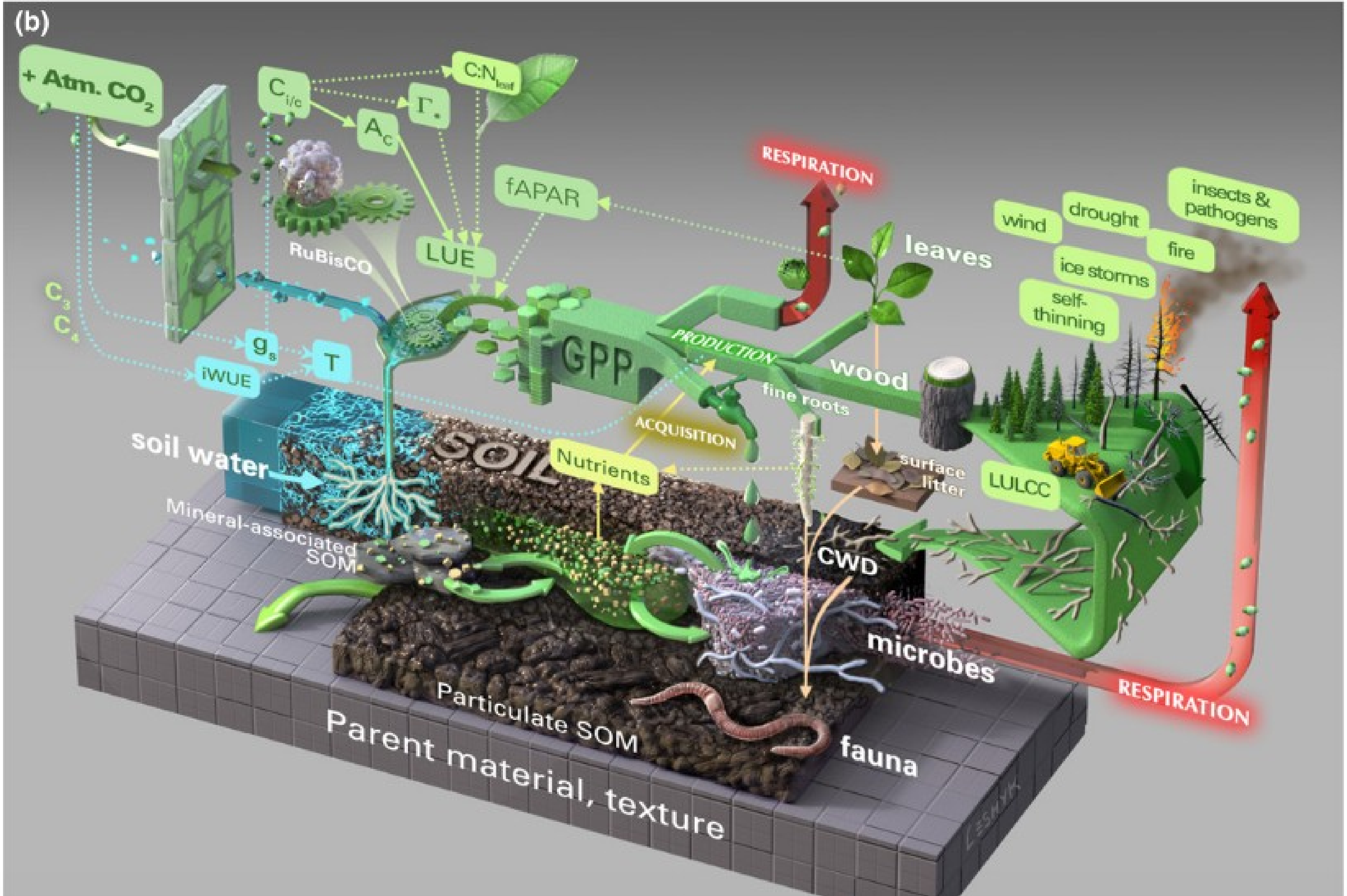
- Positive feedbacks accelerate warming
- Negative feedbacks lead to homeostasis
- Complexity: There are many negative feedbacks and many positive feedbacks
- The relative strengths of each can be measured in part, but the system as a whole is not well understood

Positive feedbacks

- Warmer temperatures increase soil respiration rates, releasing organic carbon stored in soils
- Warmer temperatures increase fire frequency, leading to net replacement of older, larger trees with younger, smaller ones, resulting in net release of carbon from forest biomass
- Higher atmospheric CO2 concentrations may increase drought tolerance in plants, potentially leading to expansion of shrublands into deserts,thus reducing planetary albedo and atmospheric dust concentrations
- Warming leads to replacement of tundra by boreal forest, decreasing planetary albedo
- Warming of soils accelerates methane production more than methane consumption
- Warming of soils accelerates N20 production rates

Negative feedback

- One important process could lead to a substantial negative feedback
- C02 is used for photosynthesis (both terrestrial and aquatic)
- Terrestrial photosynthesis is controlled by stomata

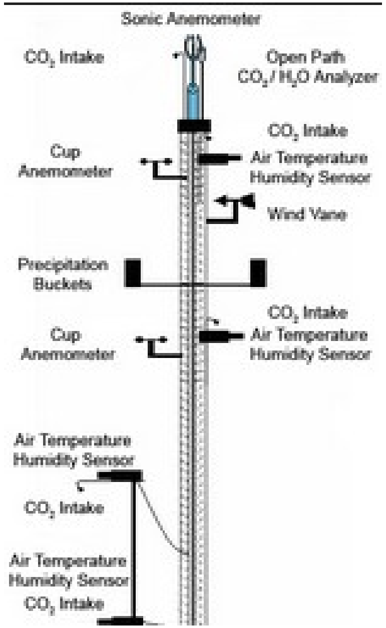


(b)
+ Atm. CO2
Ci/c
C:Nleaf
Γ.
Ac
RuBisCO
LUE
fAPAR
RESPIRATION
leaves
wind
drought
insects & pathogens
fire
ice storms
self-thinning
C3
C4
gs
T
iWUE
GPP
PRODUCTION
wood
fine roots
ACQUISITION
soil water
SOIL
Nutrients
surface litter
LULCC
Mineral-associated SOM
CWD
microbes
RESPIRATION
Particulate SOM
fauna
Parent material, texture

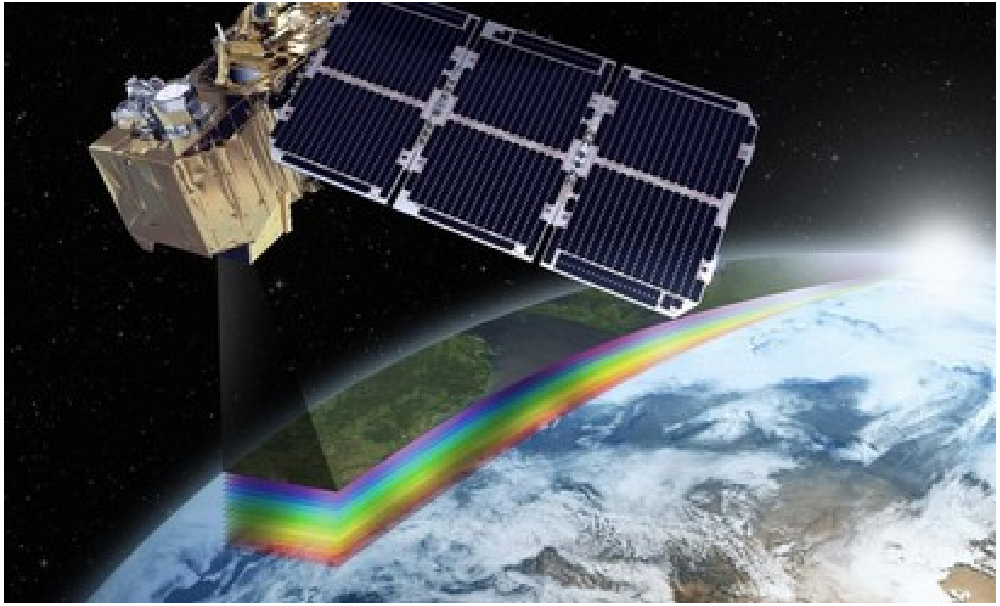
Enrichment in greenhouses

Free air carbon enrichment

Eddy flux covariance



Satellite monitoring



Results

- Important meta-analysis published in 2021
- Walker, A. P. et al. (2021) ‘Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO2’, New Phytologist, 229(5), pp. 2413–2445. doi: 10.1111/nph.16866.

CO_2 fertilisation hypothesis

- The stimulation of photosynthesis byCO2 has been called **‘CO2 fertilisation**’ (Ciais et al., 2014),
- ‘Fertilisation’ is a value-laden, agricultural term that means the addition of nutrients to increase crop yield.
- Plant responses to increasing atmospheric [CO2] lead to increasing terrestrial- ecosystem carbon storage, causing **negative feedback** on atmospheric [CO2] growth.

Will $C0_2$ fertilisation “save the planet”?

- Negative feedbacks can be offset by positive feedbacks
- The strength of the effect is insufficient to offset fossil fuel emissions
- “Gaia” does not care about us!
- However: The effect is not negligible

Where is the effect apparent?

- Many, but not all, terrestrial ecosystems may be showing increased net primary productivity
- Forests, tundra, shrubland, salt marshes, grassland and cropland
- May alter ecosystem function through changes to carbon:nitrogen ratios

Stomatal control

- Trade offs: E.g. Henry, C. et al. (2019) ‘A stomatal safety-efficiency trade-off constrains responses to leaf dehydration’, Nature Communications. Springer US, 10(1), pp. 1–9. doi: 10.1038/s41467-019-11006-1.

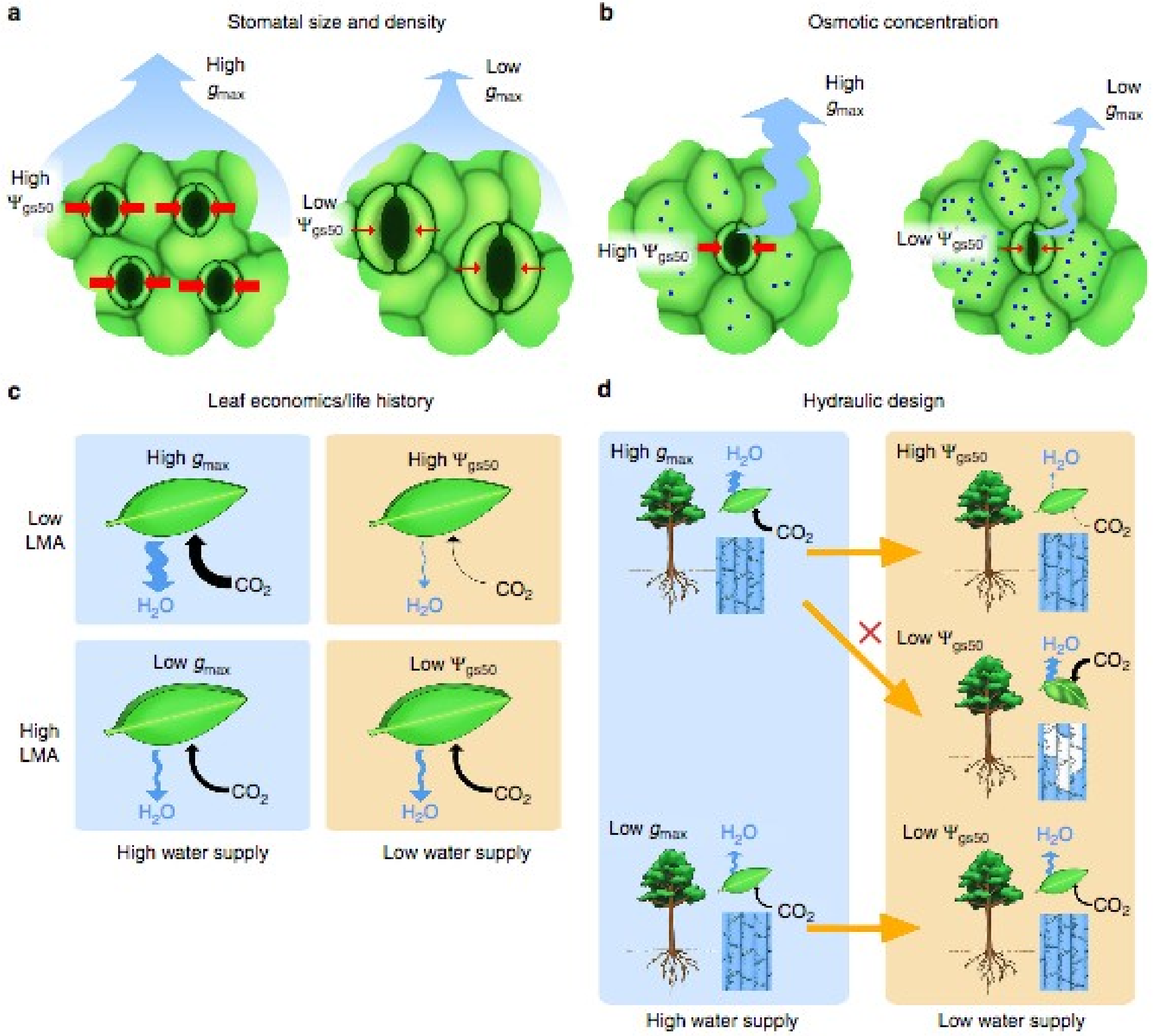
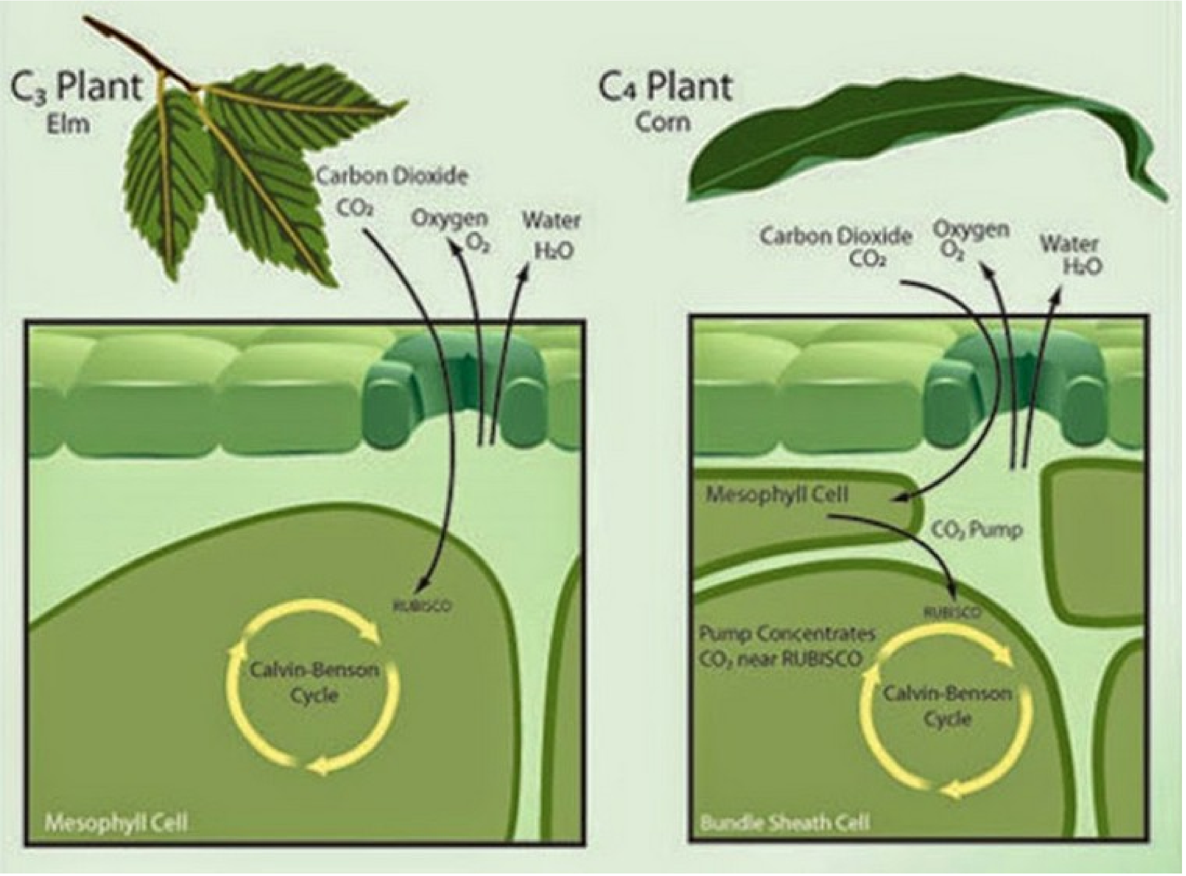


Fig. 1 Hypothesized rationales for a stomatal safety-efficiency trade-off. **a** Stomatal size and density: leaves with smaller, denser stomata (left) have higher maximum stomatal conductance (g_{max}), and stomata more sensitive to closure during drought (i.e., higher Ψ_{gs50}, indicated by thicker red lines) than leaves

C3 vs C4 photosynthesis



Some details

- Photosynthesis involves tradeoffs
- Open stomata increase uptake of C02 but also increase to water loss
- C4 (and CAM) plants are more water efficient and lose less energy through photorespiration

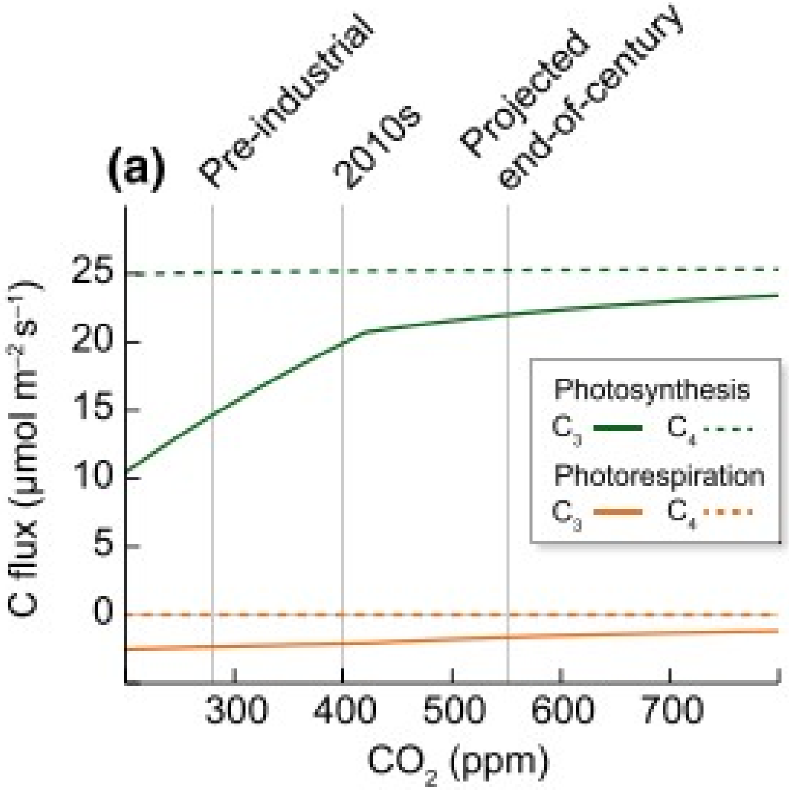
1. Direct plant physiological responses to CO_2

Photosynthesis is limited by CO_2 or light (Farquhar *et al.*, 1980). When CO_2 is limiting, theory predicts that eCO_2 increases leaf-scale net carbon assimilation (A_{net}) ($\beta_{dir,hist} = 0.86$, *c.* 280–400 ppm; Table S1). The enzyme that fixes CO_2 (RuBisCO) also catalyses an oxygenation reaction, which results in CO_2 loss (photorespiration; Farquhar *et al.*, 1980). eCO_2 also suppresses photorespiration (Fig. 2a). Given that photorespiration always occurs during C_3 photosynthesis, the suppression of photorespiration by eCO_2 increases A_{net} also when light is limiting, but with a lower response ($\beta_{dir,hist} = 0.31$). Canopy-scale A_{net} results from a mixture of CO_2 and light-limited photosynthesis, and thus has an intermediate eCO_2 response that depends on the fraction of light-saturated leaves in the canopy ($\beta_{dir,hist} = 0.60 \pm 0.3$; Fig. 2c). As [$CO_2$] increases, the fraction of light-saturated leaves in the canopy is expected to decrease, and therefore the historical eCO_2 response of GPP is expected to be higher than the future response ($\beta_{dir,fut} = 0.46 \pm 0.2$, *c.* 400–550 ppm; Fig 2c).

C_4 plants have evolved to concentrate carbon, thus saturating photosynthesis and suppressing photorespiration at low [CO_2] (Ehleringer & Björkman, 1977). Therefore A_{net} in C_4 plants is not directly influenced by [CO_2] above *c.* 200 ppm (Fig. 2a), although water savings from reduced stomatal conductance (g_s) may stimulate A_{net} indirectly (Leakey *et al.*, 2004).

Photosynthesis requires the acquisition of other resources and eCO_2 stimulation of A_{net} increases A_{net} per unit resource consumption, that is, increases resource use-efficiencies of water (WUE), light (LUE), and leaf nitrogen (Cowan, 1982; Drake *et al.*, 1997). Increased use efficiencies imply a shift in a plant's resource-use economy (Bloom *et al.*, 1985) which is commonly studied using optimization theory.

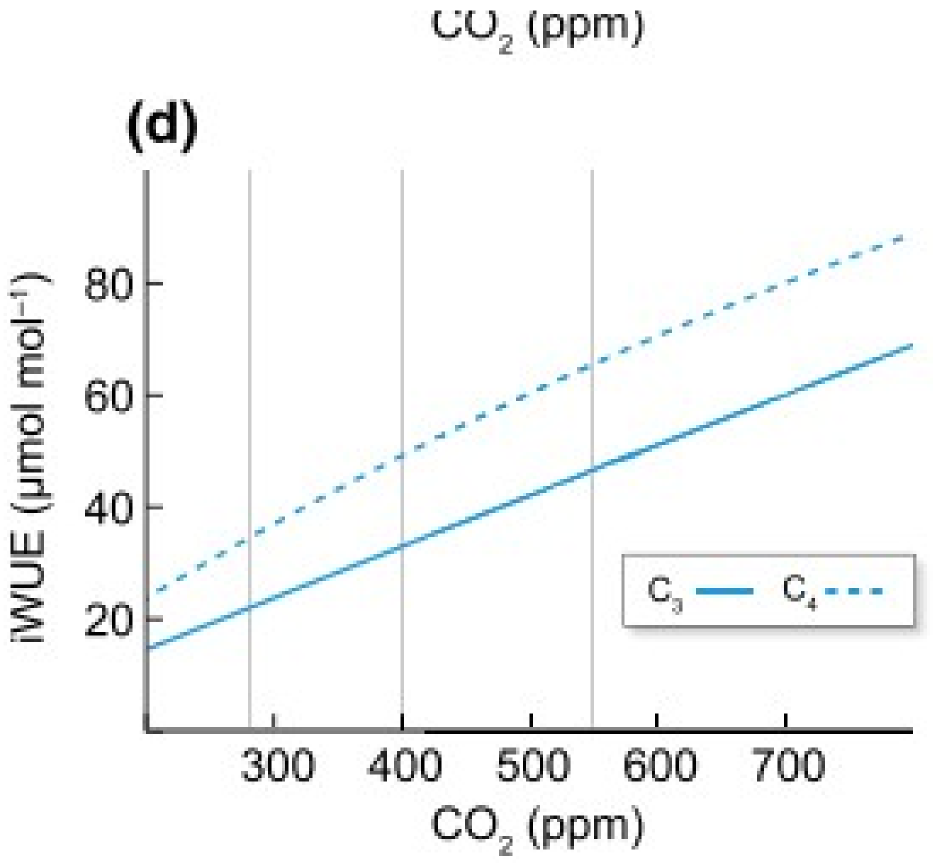
Increased [CO_2] has less direct effect on C4 photosynthesis



Implications

- Most temperate trees are C3
- Some tropical crops are C4 (sugarcane, maize, sorghum)
- Major crops (wheat, soya) are C3
- C4 plants can also benefit from enhanced C02 through effect on water use efficiency (WUE)

WUE continues to increase at high $[Co_2]$



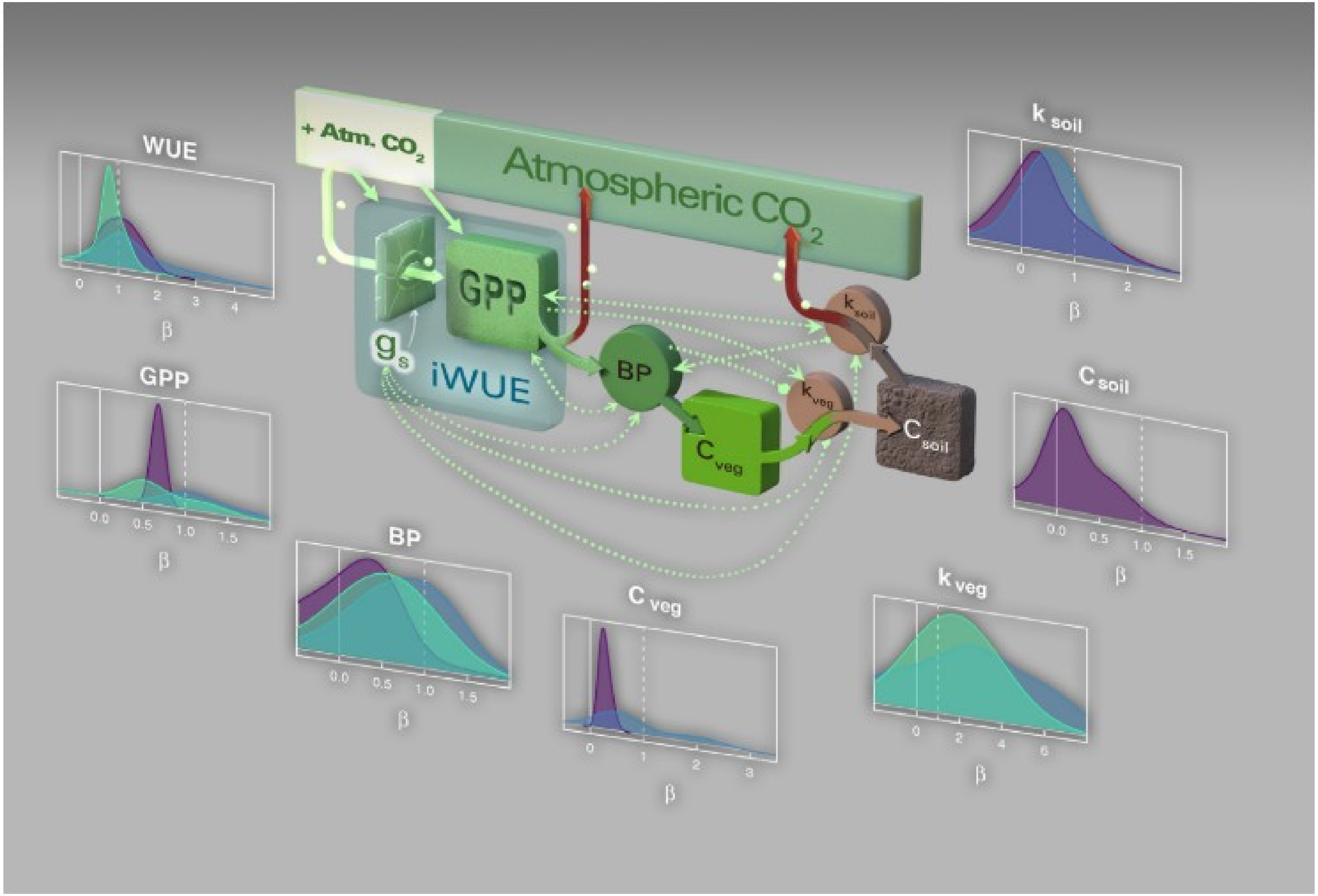
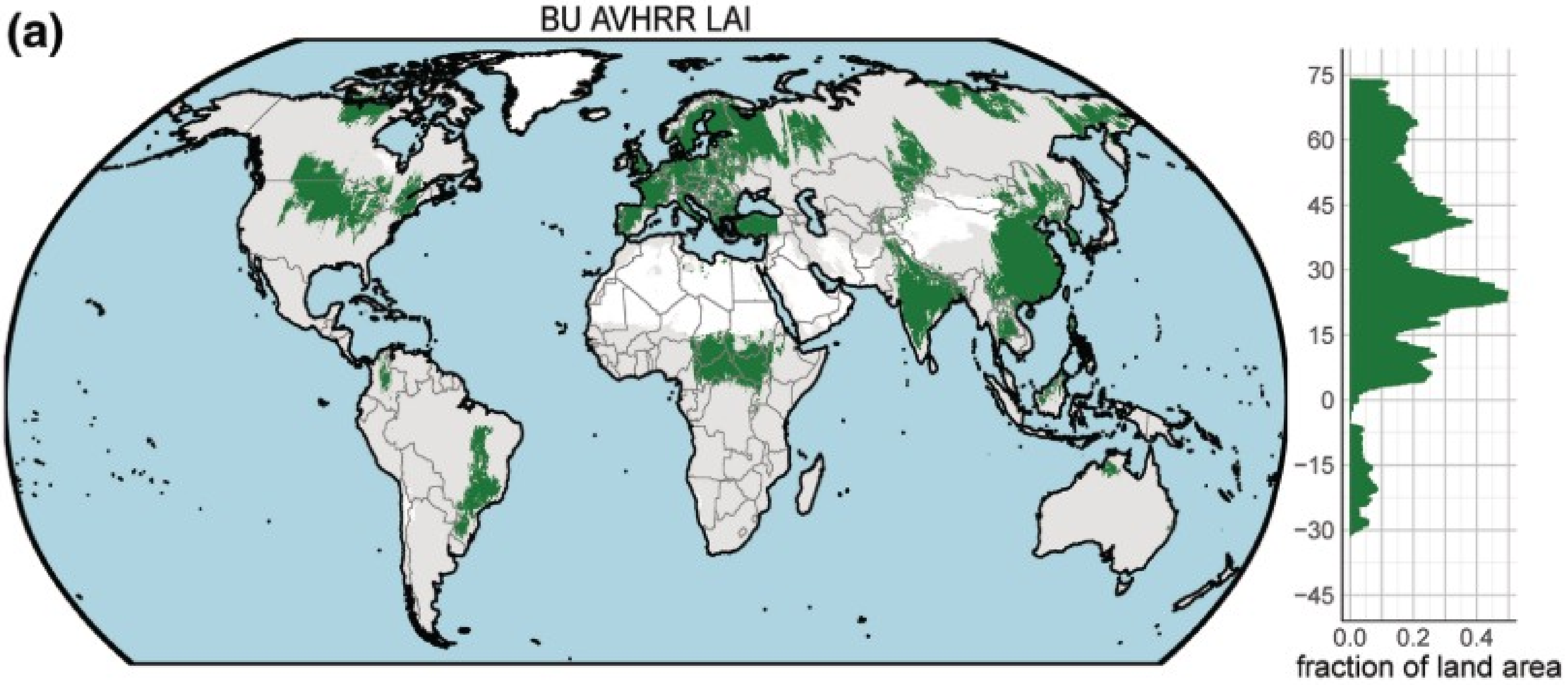


Fig. 3 *β* distributions based on data from Table 2 for water-use efficiency (WUE), gross primary production (GPP), biomass production (BP), turnover rate of vegetation (k_{veg}) and soil organic matter (k_{soil}), and plant (C_{veg}) and soil (C_{soil}) carbon. Data are organized by CO_2 response category – increasing [CO_2] (iCO_2, blue), attribution to iCO_2 (green), and elevated [CO_2] (eCO_2, purple). See Supporting Information Figs S2–S4 for further details.

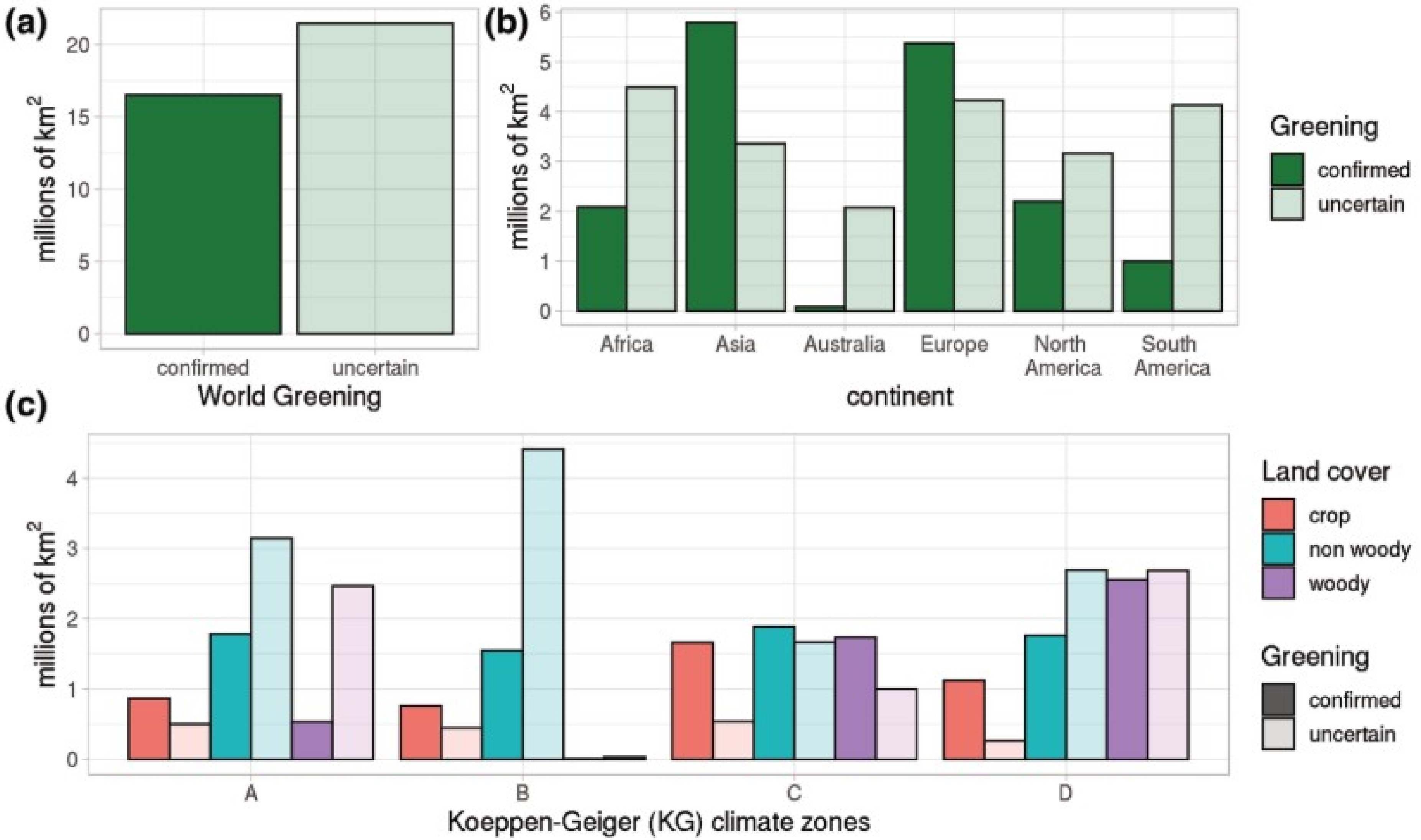
Greening trends

- Cortés, J. et al. (2021) ‘Where Are Global Vegetation Greening and Browning Trends Significant?’, Geophysical Research Letters, 48(6), pp. 1–9. doi: 10.1029/2020GL091496.
- Munier, S. et al. (2018) ‘Satellite Leaf Area Index: Global scale analysis of the tendencies per vegetation type over the last 17 years’, Remote Sensing, 10(3). doi: 10.3390/rs10030424.

(a)



BU AVHRR LAI
75
60
45
30
15
0
−15
−30
−45
0.0
0.2
0.4
fraction of land area

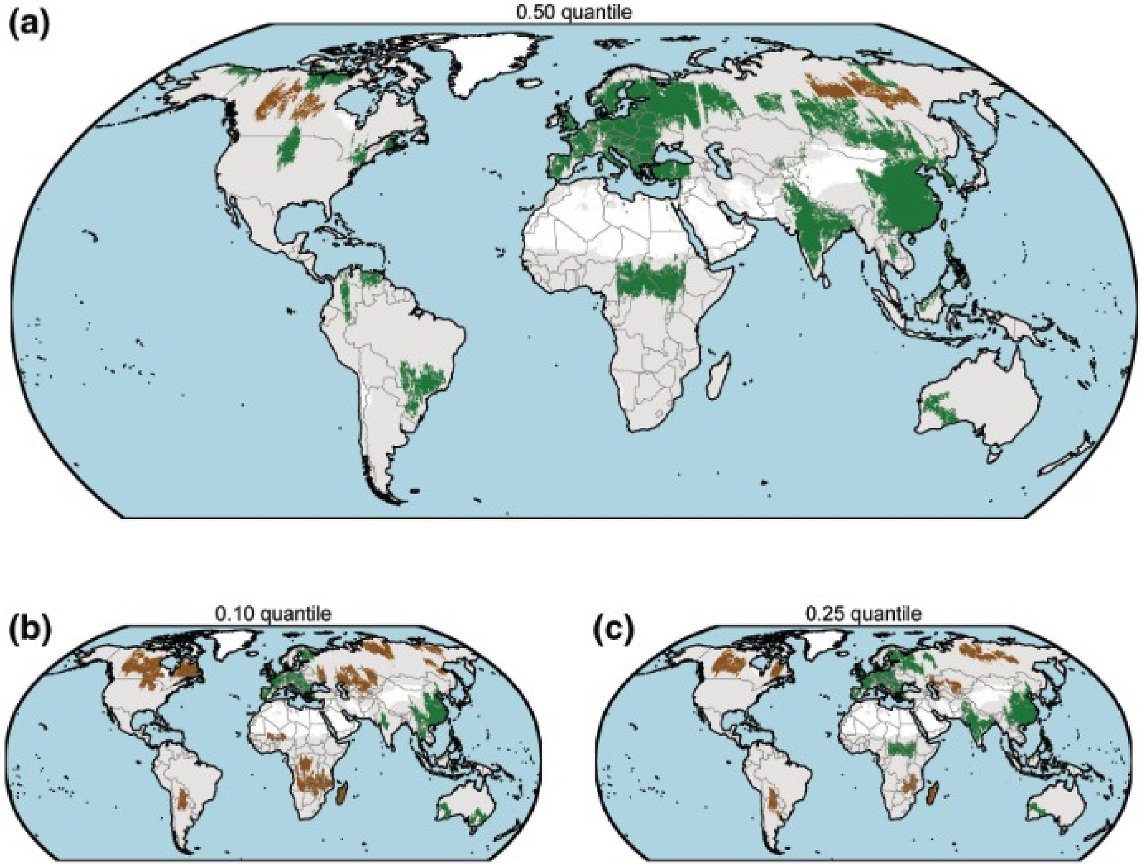


(a)
millions of km^2
0
5
10
15
20
confirmed
uncertain
World Greening
(b)
millions of km^2
0
1
2
3
4
5
6
Africa
Asia
Australia
Europe
North America
South America
continent
Greening
confirmed
uncertain
(c)
millions of km^2
0
1
2
3
4
A
B
C
D
Koeppen-Geiger (KG) climate zones
Land cover
crop
non woody
woody
Greening
confirmed
uncertain

Summary

- Detect greening in 15% of the terrestrial land surface, as opposed to 35% when applying no multiple testing correction.
- Greening detected in crop land is the most reliable. Browning is only detected when aggregating the yearly data using the median instead of the mean.
- Increase in the seasonal amplitude of LAI around the globe.

Browning (likely due to fire)



Impact on food production

- Extremely uncertain
- Climate change may have negative impacts on crops
- However, some modelling does suggest increases in crop yield through “CO_2 fertilisation”
- Degener, J. F. (2015) ‘Atmospheric CO 2 fertilization effects on biomass yields of 10 crops in northern Germany’, Frontiers in Environmental Science, 3(JUL), pp. 1–14. doi: 10.3389/fenvs.2015.00048.

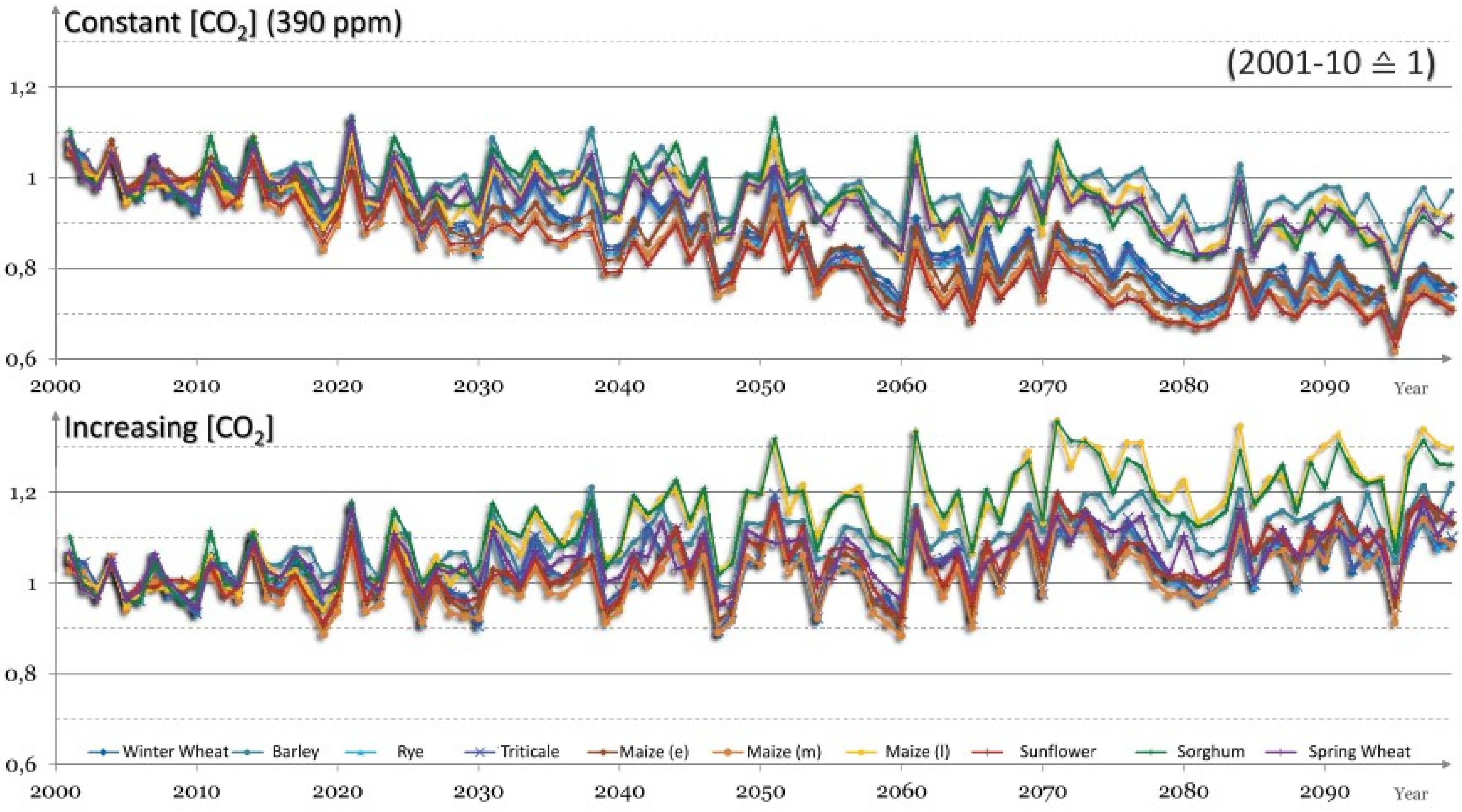


FIGURE 5 | Biomass development with constant and changing [CO_2]. Top: biomass development throughout the 21st century if [CO_2] is hold constantly at 390 ppm-Below: Same modeling approach as above, only [CO_2] is changed for each year according to SRES scenario A1B.

		2011–2030 $[CO_2]$		2031–2050 $[CO_2]$		2051–2099 $[CO_2]$	
		Constant	**Changing**	**Constant**	**Changing**	**Constant**	**Changing**
Winter	Wheat	0.96	1.01	0.91	1.03	0.80	1.04
	Barley	1.01	1.05	1.01	1.09	0.96	1.13
	Rye	0.95	1.00	0.90	1.03	0.78	1.05
	Triticale	0.96	1.00	0.90	1.04	0.80	1.05
Maize	Early	0.96	1.00	0.89	1.02	0.79	1.07
	Medium	0.92	0.97	0.85	1.00	0.75	1.04
	Late	0.97	1.03	0.97	1.13	0.92	1.22
Other	Sunflower	0.93	1.00	0.85	1.03	0.74	1.08
	Sorghum	0.99	1.04	1.00	1.14	0.91	1.21
	Spring wheat	0.99	1.03	0.97	1.06	0.91	1.08

Values >1 indicate rising future yields. Results are displayed for constant (390 ppm) and changing $[CO_2]$ concentrations according to SRES scenario A1B respectively.

Caveats

- Plants may acclimate to higher C02 by reducing stomatal density
- Higher carbon fixation may reduce nitrogen availability
- In agricultural systems weeds may benefit more than crops
- Negative impacts of climate change, particularly increased drought and floods may outweigh marginal increases in productivity
- The availability of fertiliser may decline, limiting crops yields
- Increase in the terrestrial sink is not a strong enough negative feedback to reverse climate change
- Drought may result in fires that wipe out any gains in forests