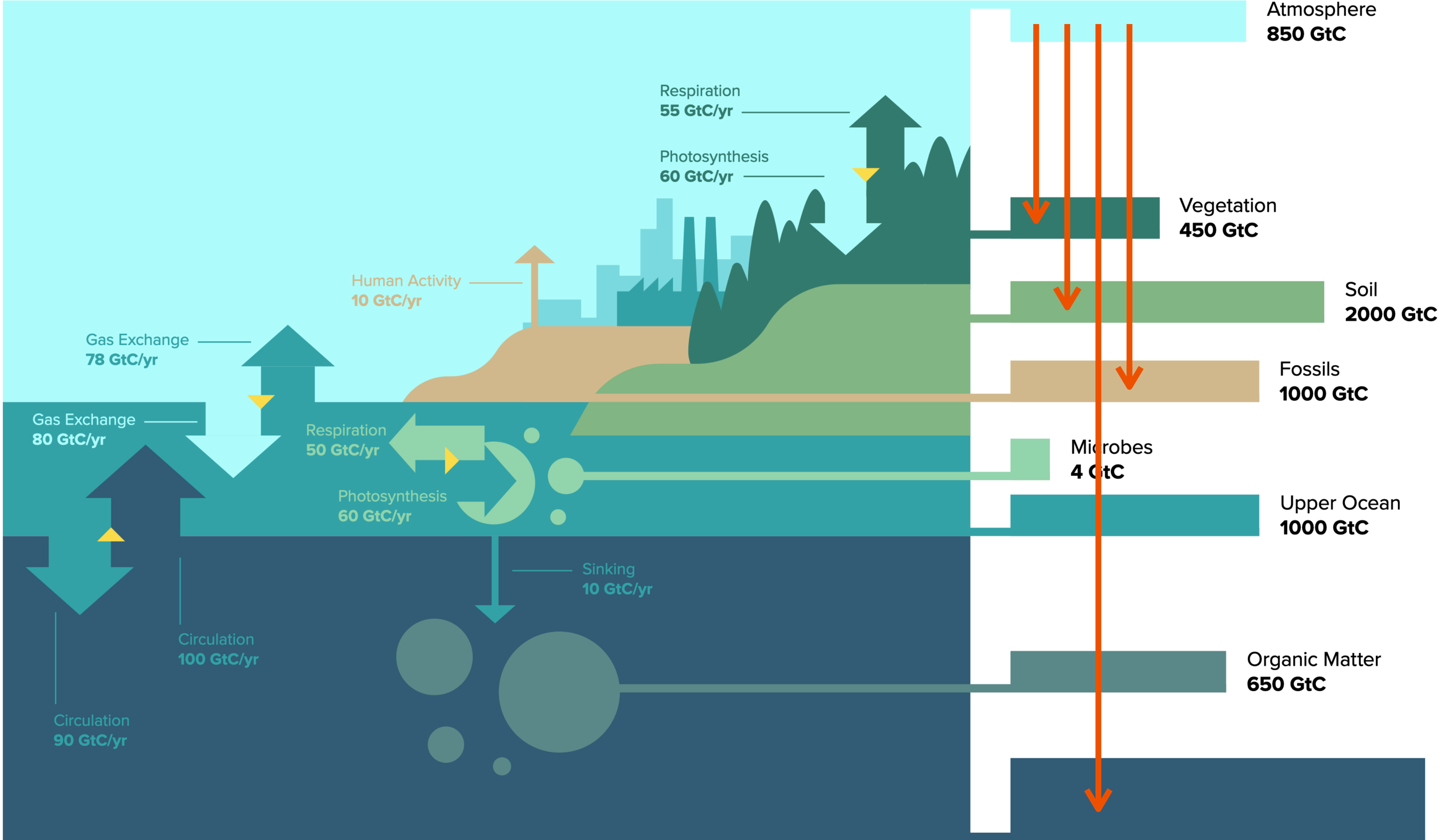


Removing CO₂ from the atmosphere

B B Cael
25 Oct 25

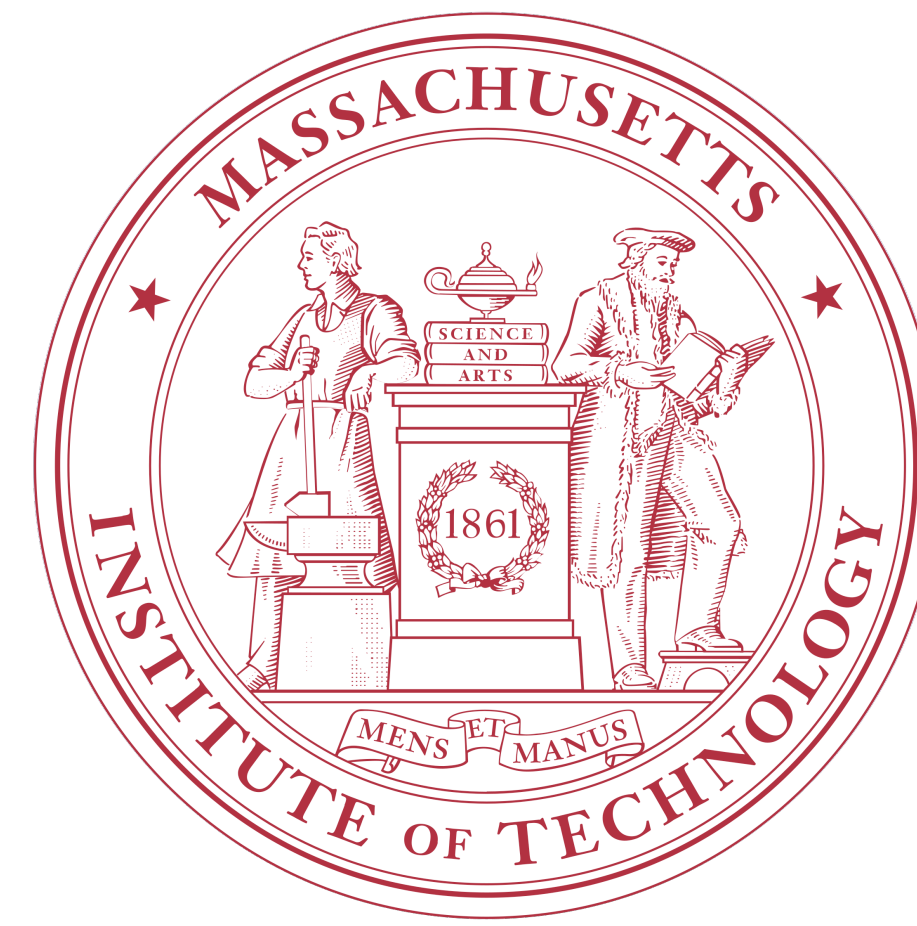


	Speakers	Topics
Oct 4	Keith	Introductions. Climate in 4 Dimensions. Emissions are peaking. Adaptation. Climate in Context.
Oct 11	Archer	Carbon cycle and natural geochemical processes as basis to understand carbon removal.
Oct 18	Shaw	Scientific basis for predicting climate changes in response to emissions of greenhouse gases and aerosol pollution.
Oct 25	Cael	Carbon removal, including ocean alkalinity enhancement, land-based methods, bioenergy with carbon capture, and direct air capture with storage.
Nov 1	Keith	Sunlight Reflection Methods (SRM) Part 1: How to Reflect Sunlight, the history of SRM, and why stratospheric sulfur aerosols are most plausible now.
Nov 8	MacAyeal & Keith	MacAyeal on science of glaciers and interventions to prevent glacial melt. Keith on developing DAC technologies at Carbon Engineering, and lessons for cleantech.
Nov 15	Shaw & Keith	The climate responses to SRM, potential side effects, and what can be learned from past aerosol pollution, highlighting the limits and uncertainties of experiments.
Nov 22	Keith	The future of climate systems engineering, and climate engineering in context.

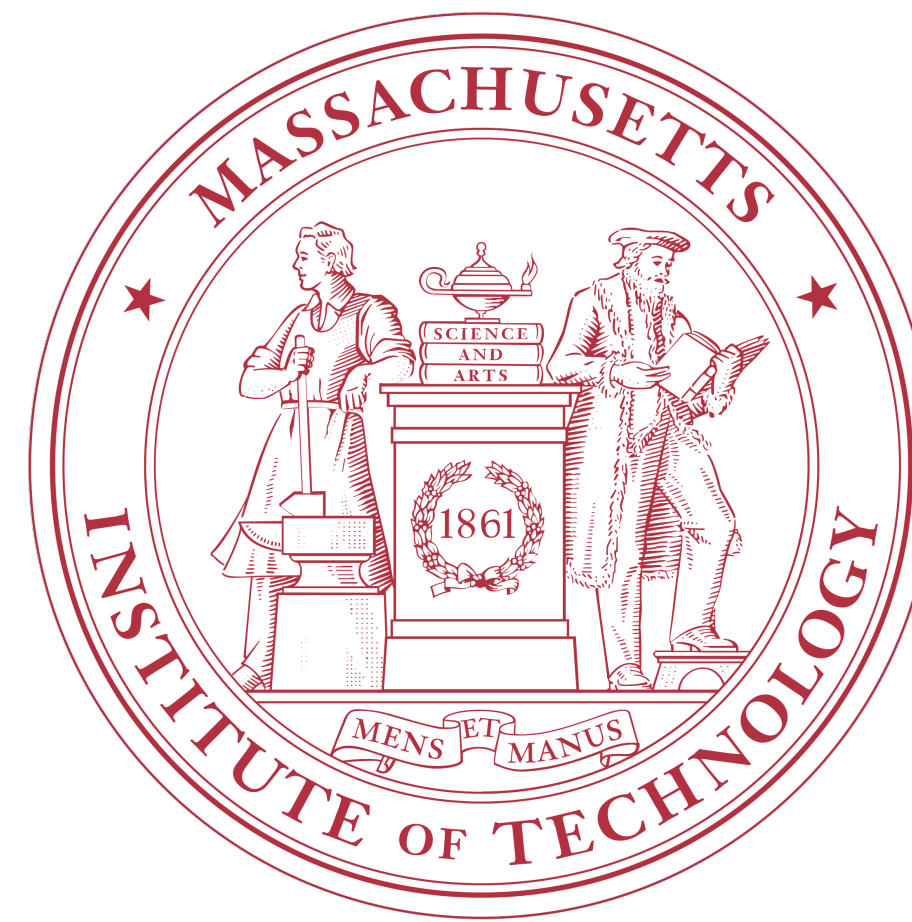




PhD (2018): Ocean C & circulation



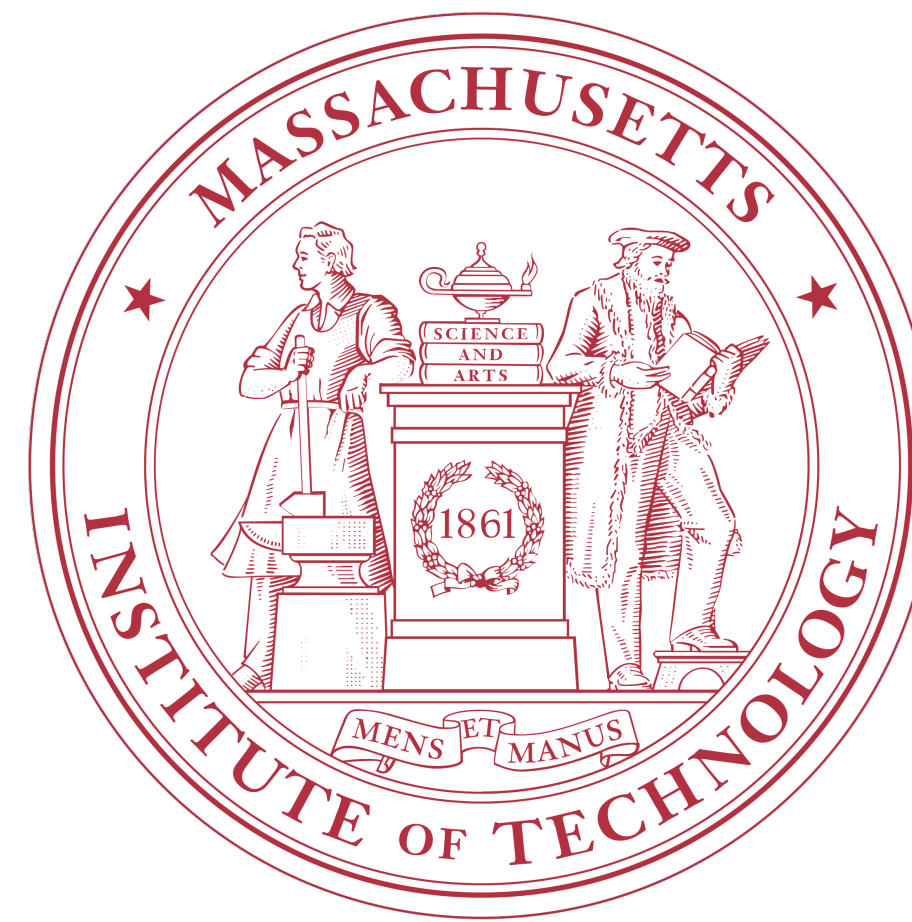
PhD (2018): Ocean C & circulation



Res. Sci. ('19-'24): +Climate, +CDR



PhD (2018): Ocean C & circulation

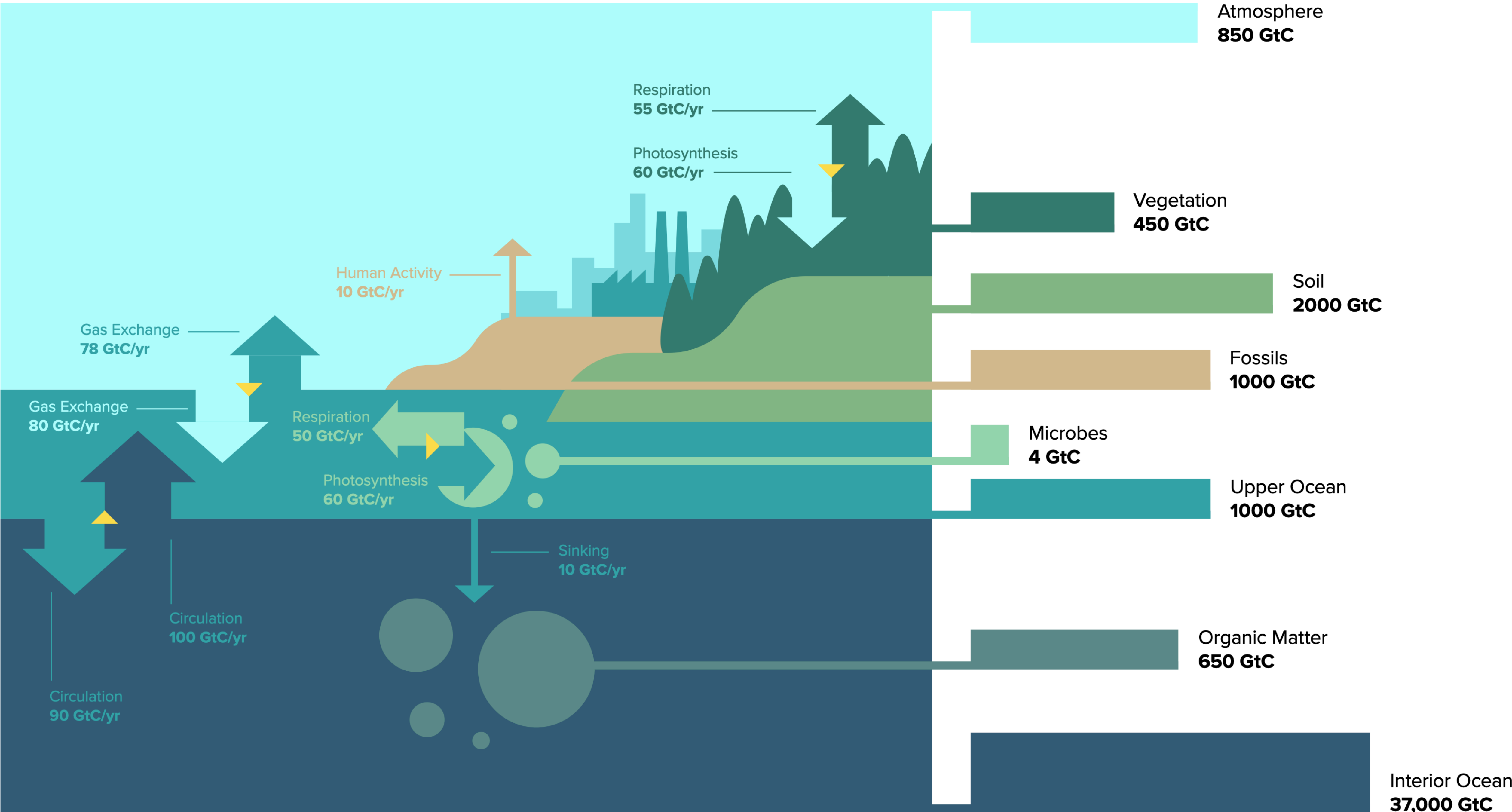


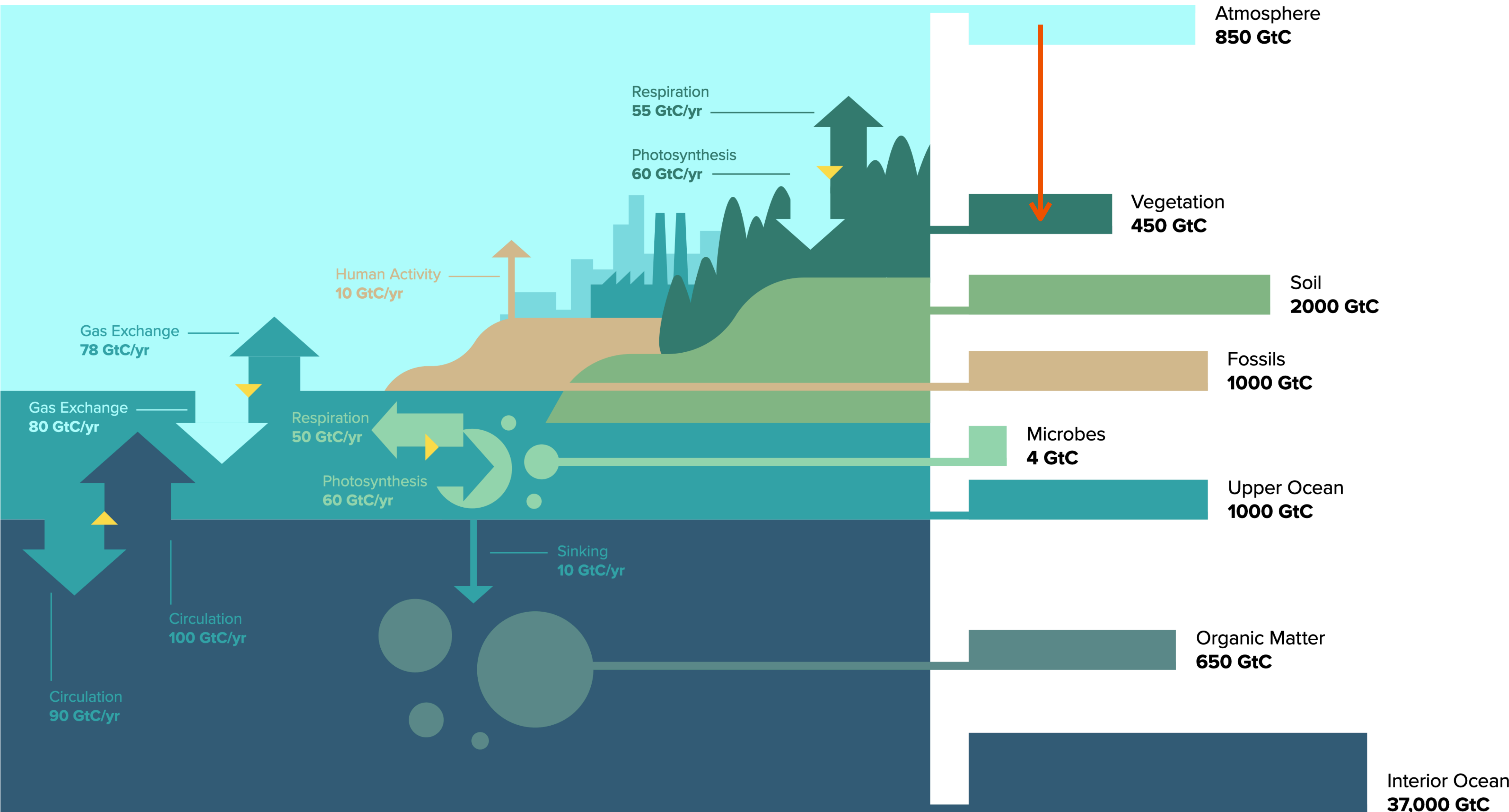
Res. Sci. ('19–'24): +Climate, +CDR

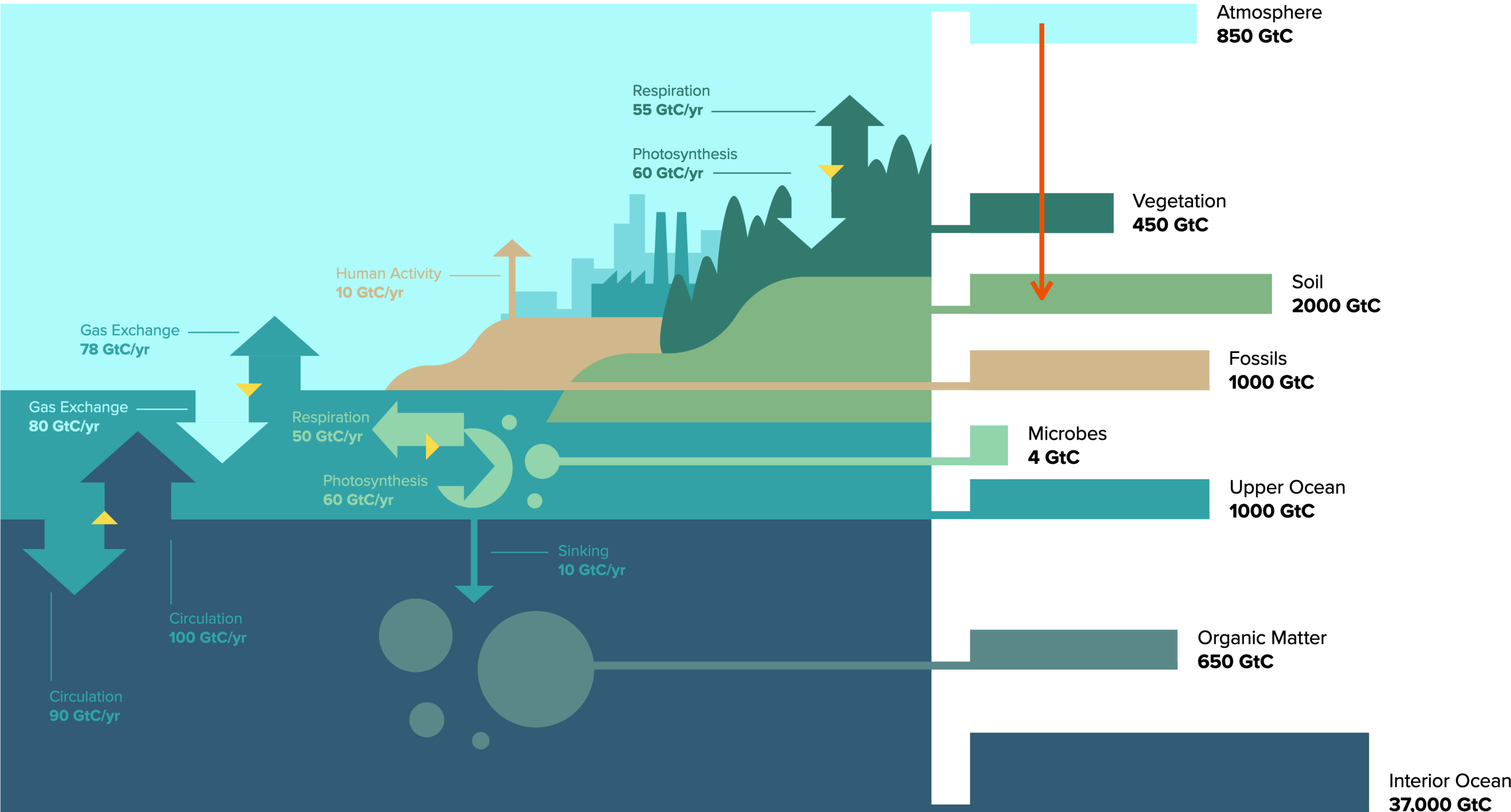


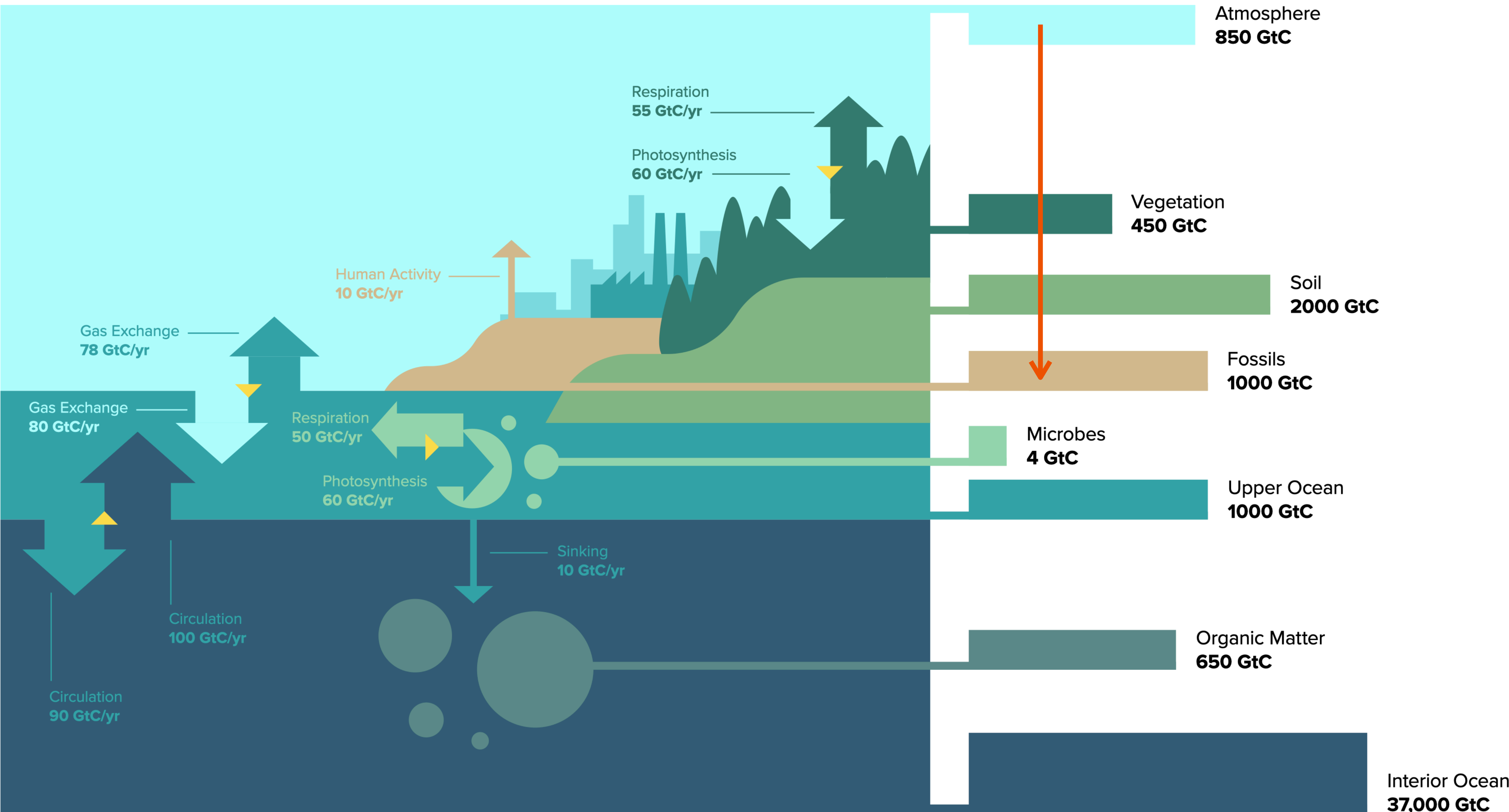
Asst. Prof. ('25–): +SRM, +Paleoclimate

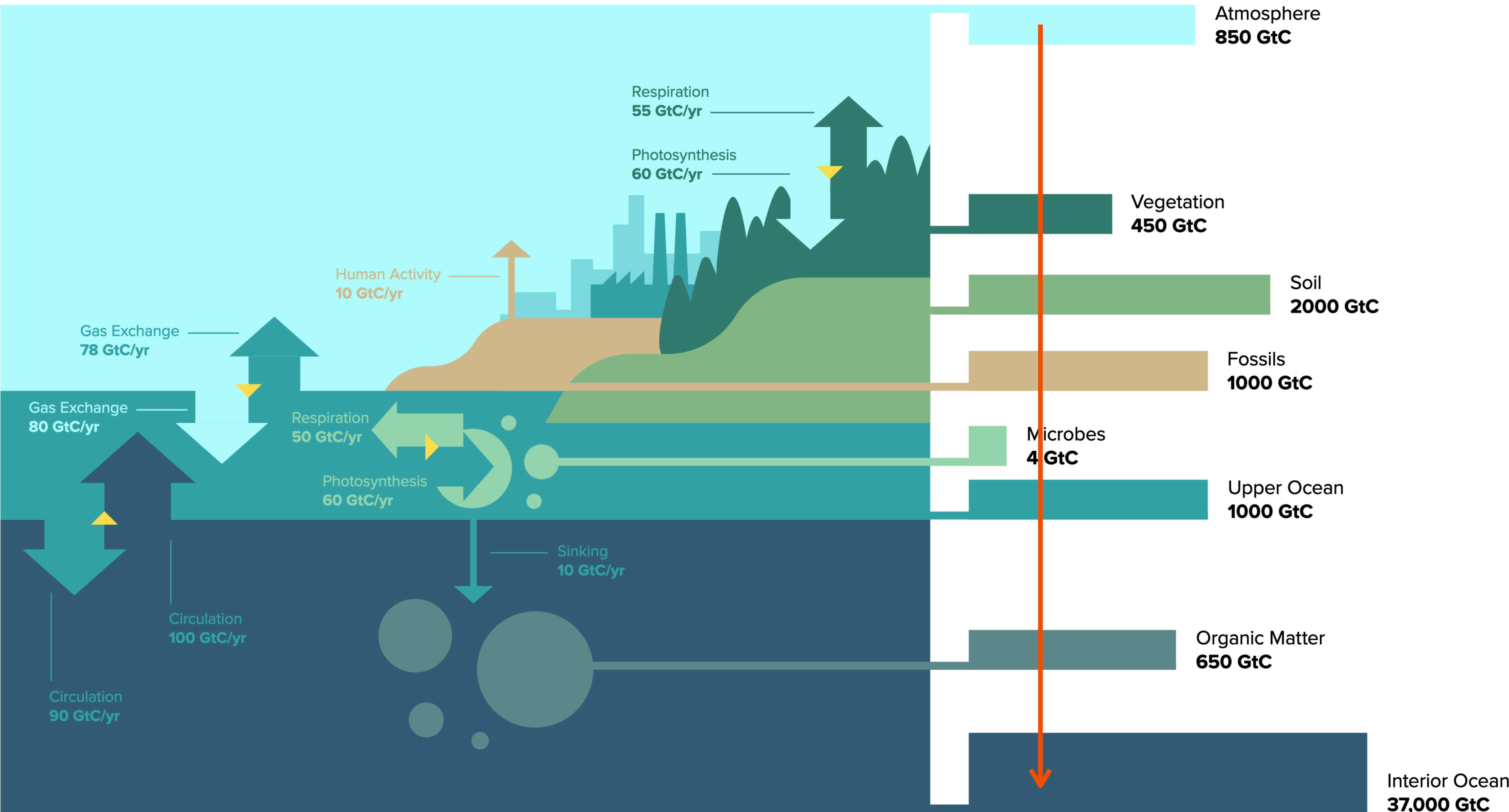










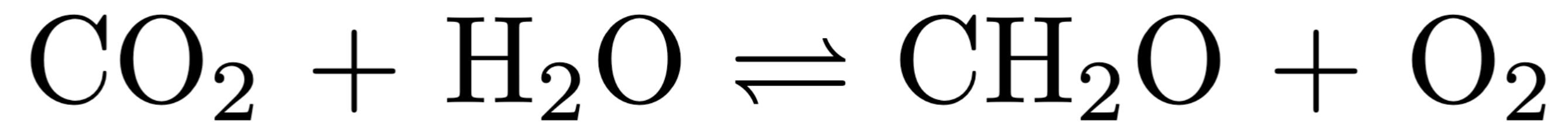


[illegible]

Further-out or bucket-drop ideas:

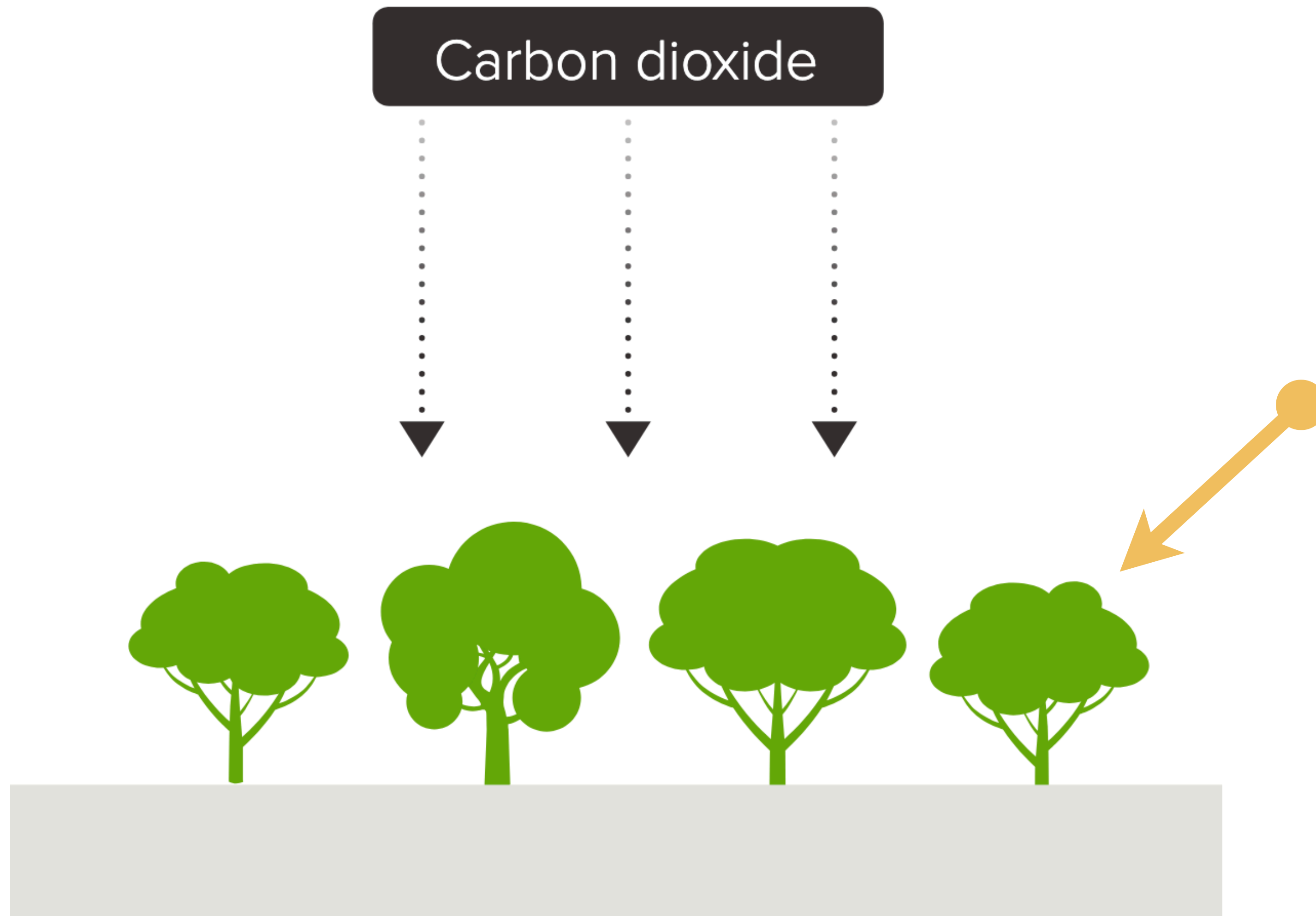
- Antarctic condensation
- Ocean upwelling
- Kelp forestry
- Wetland or coastal recovery
- Building materials
- ...

Carbon dioxide



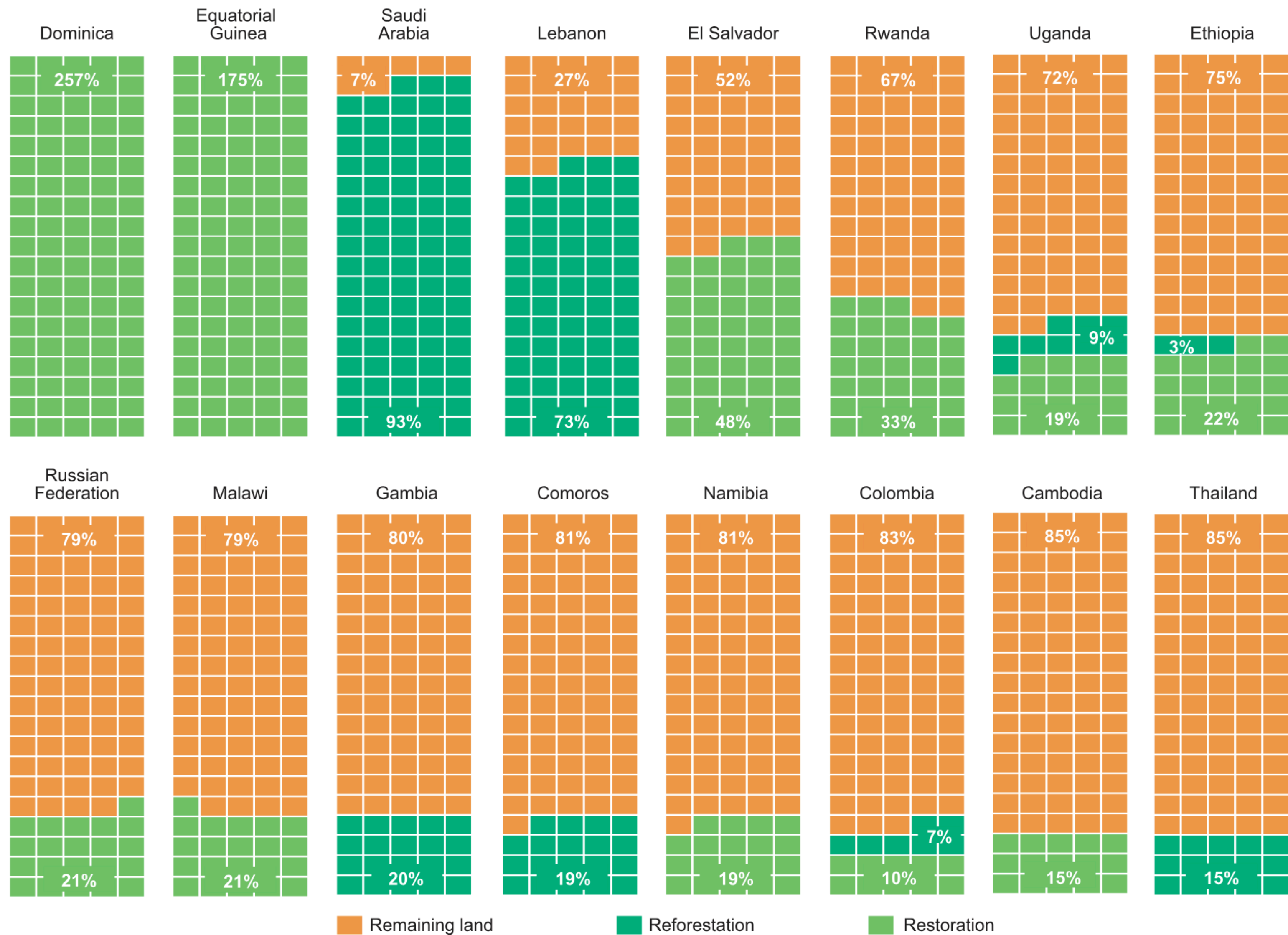
does it
work?

how
well?

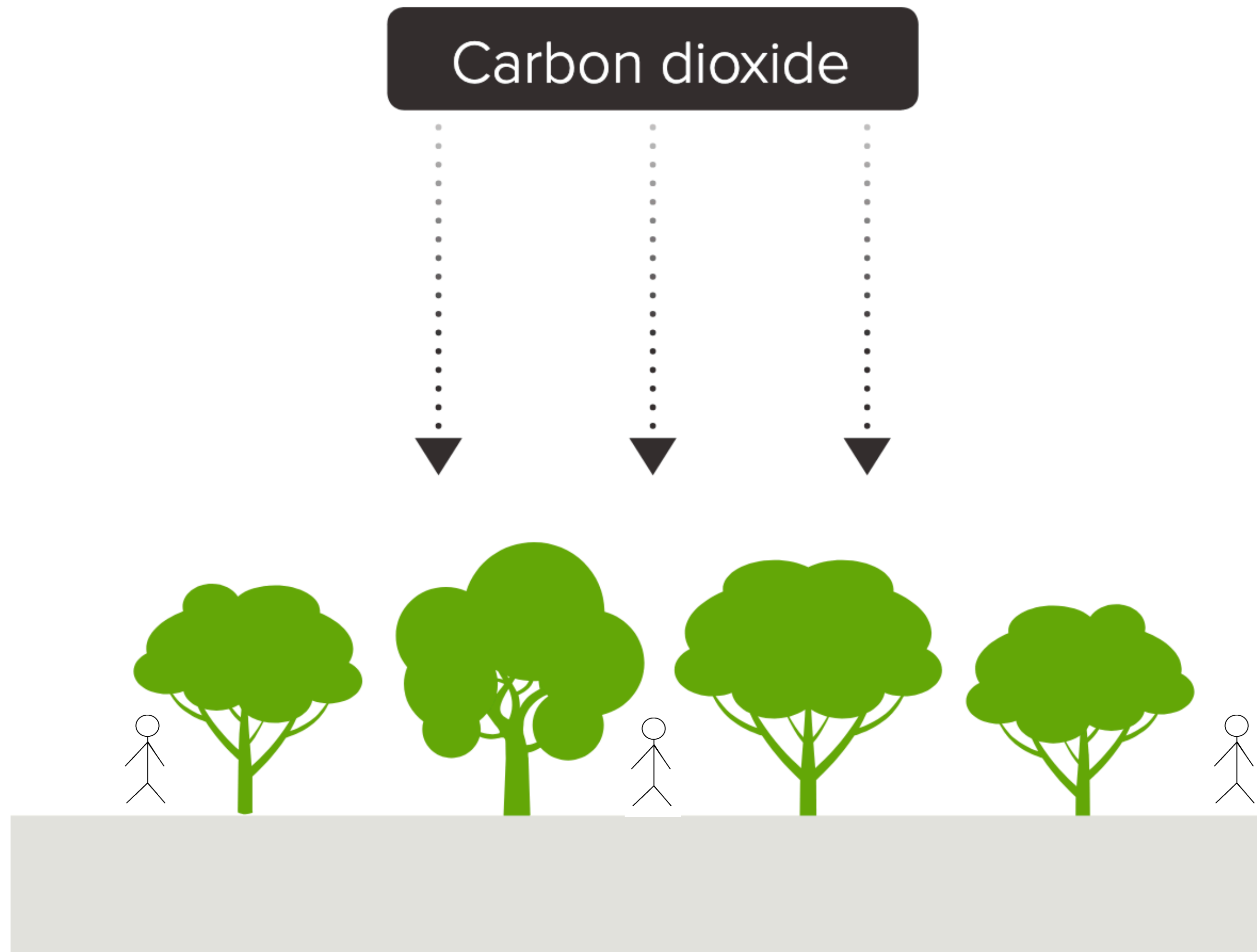


is it safe?

what
drawbacks?



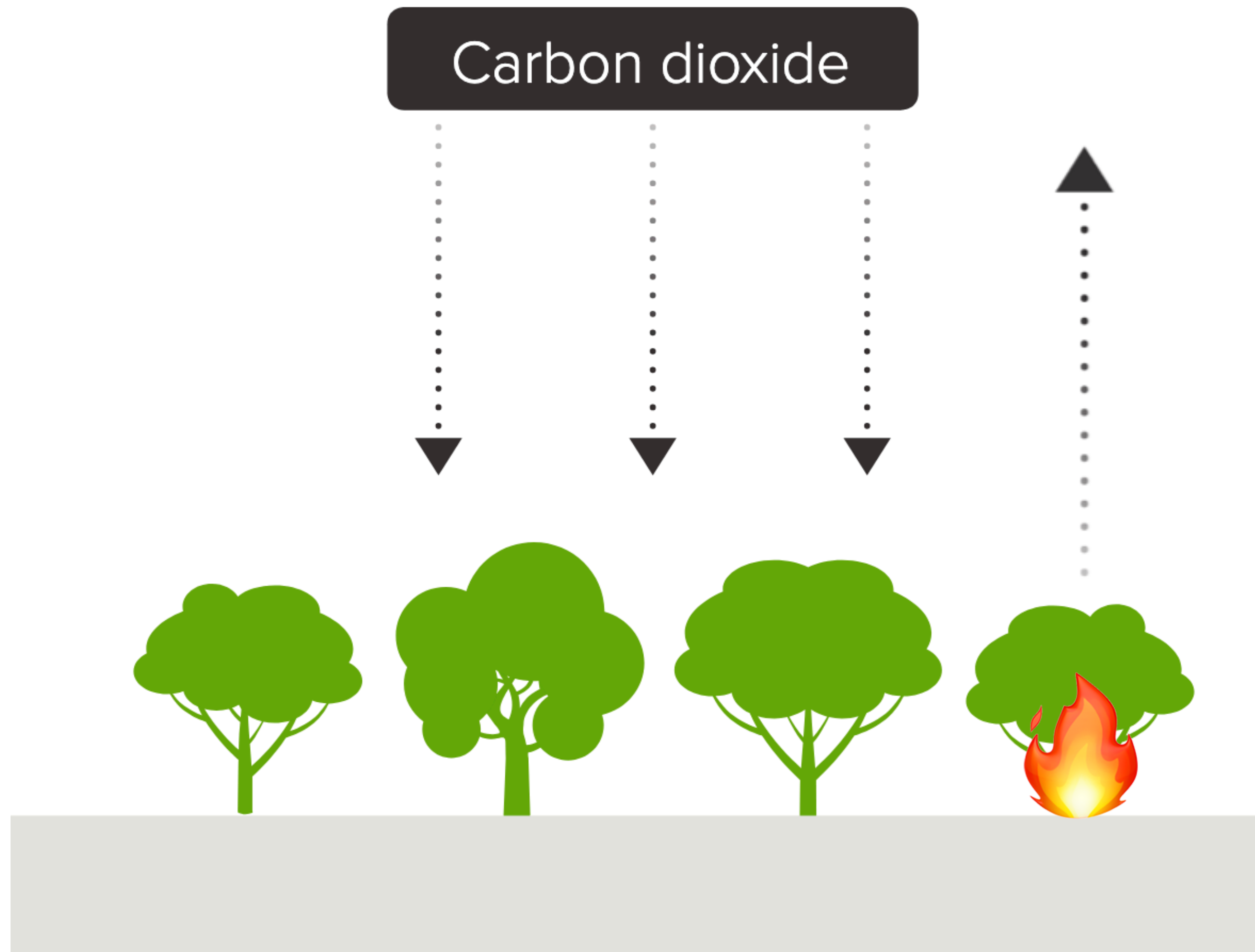
how much
can we do?



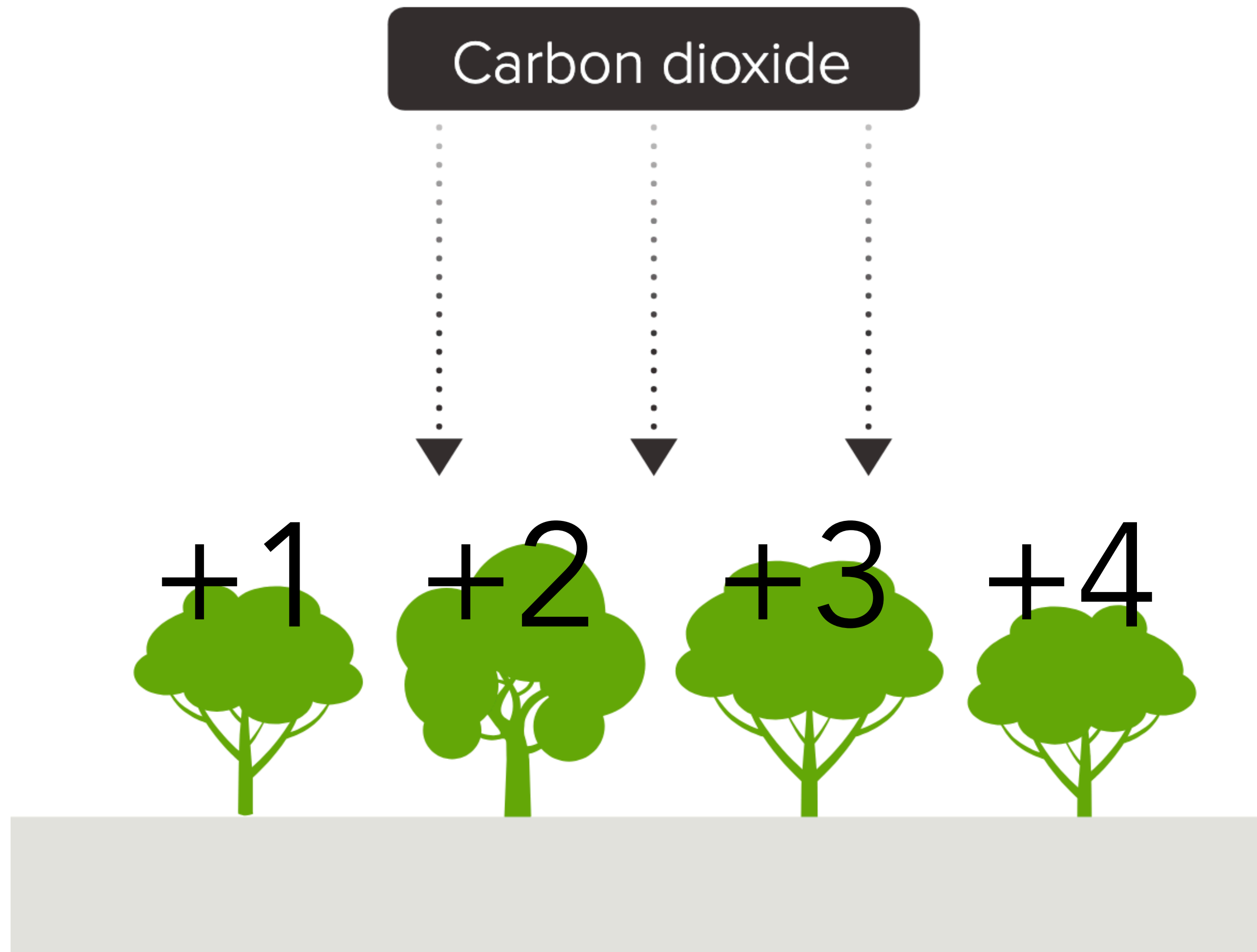
what does
it cost?



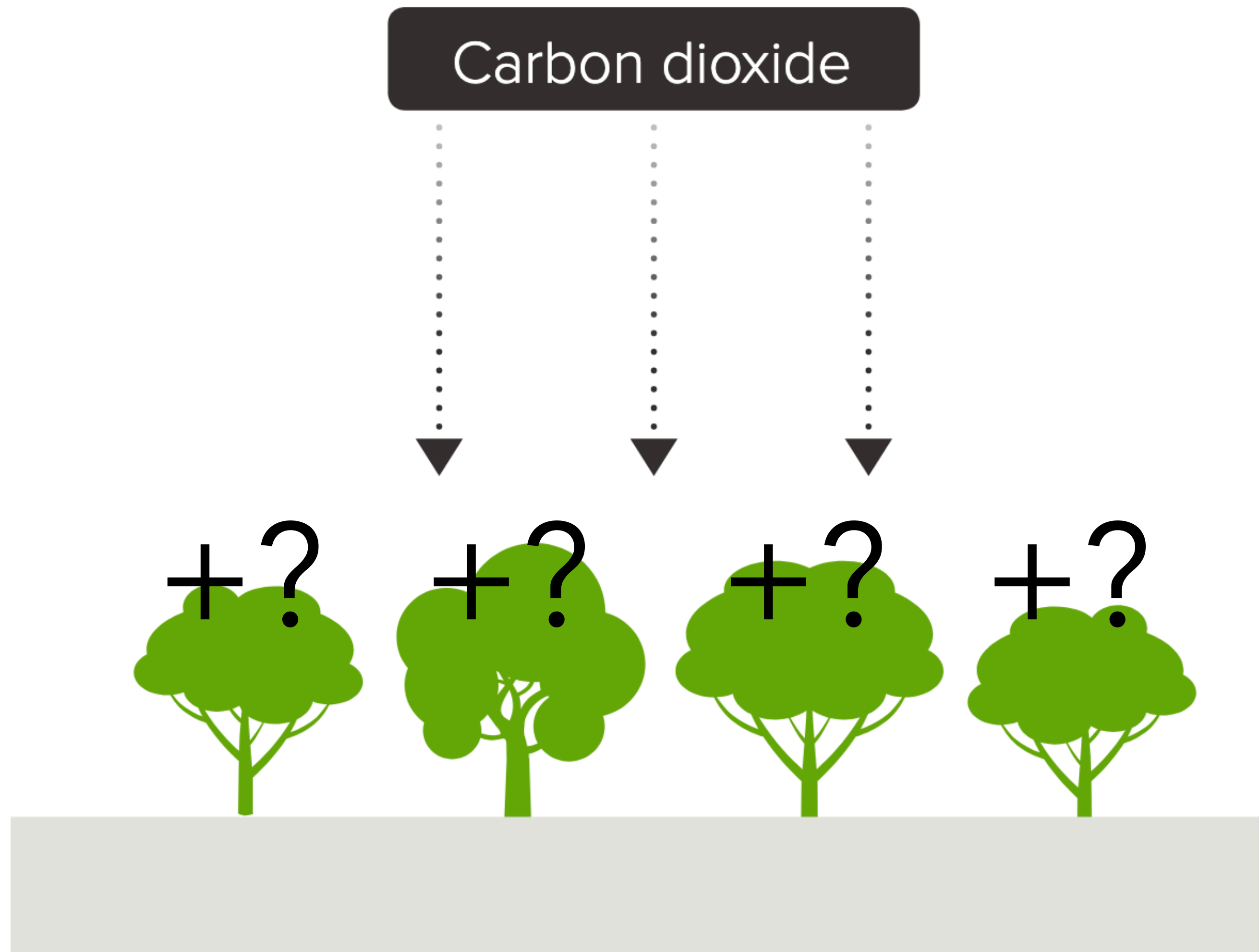
what else
is needed?



how long
is it stored?

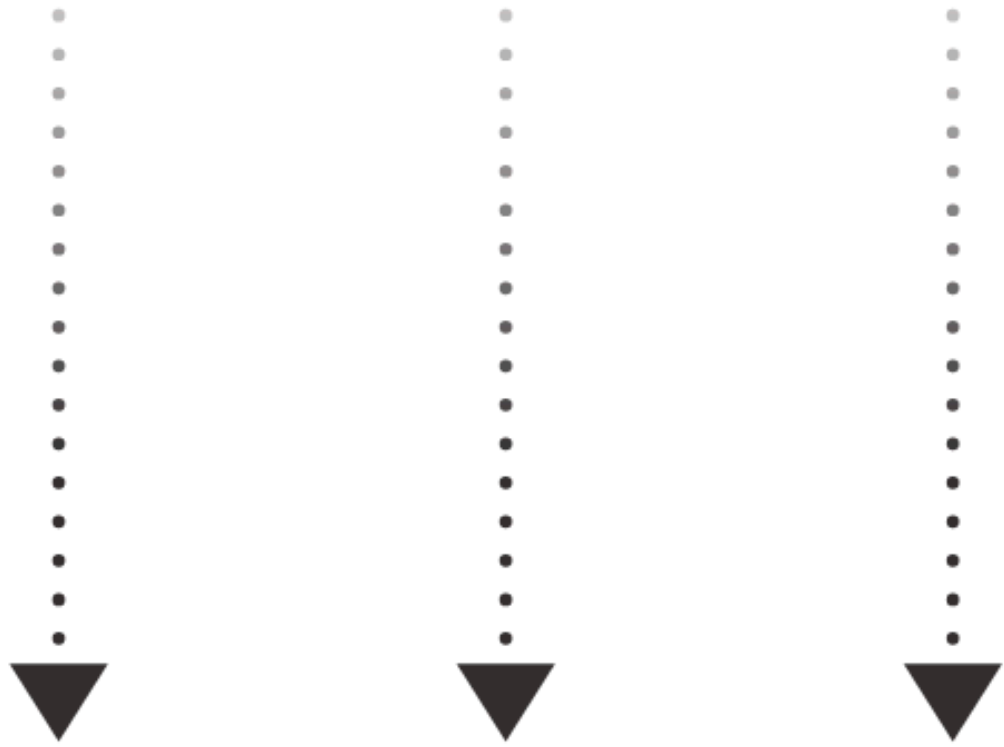


can we
verify?

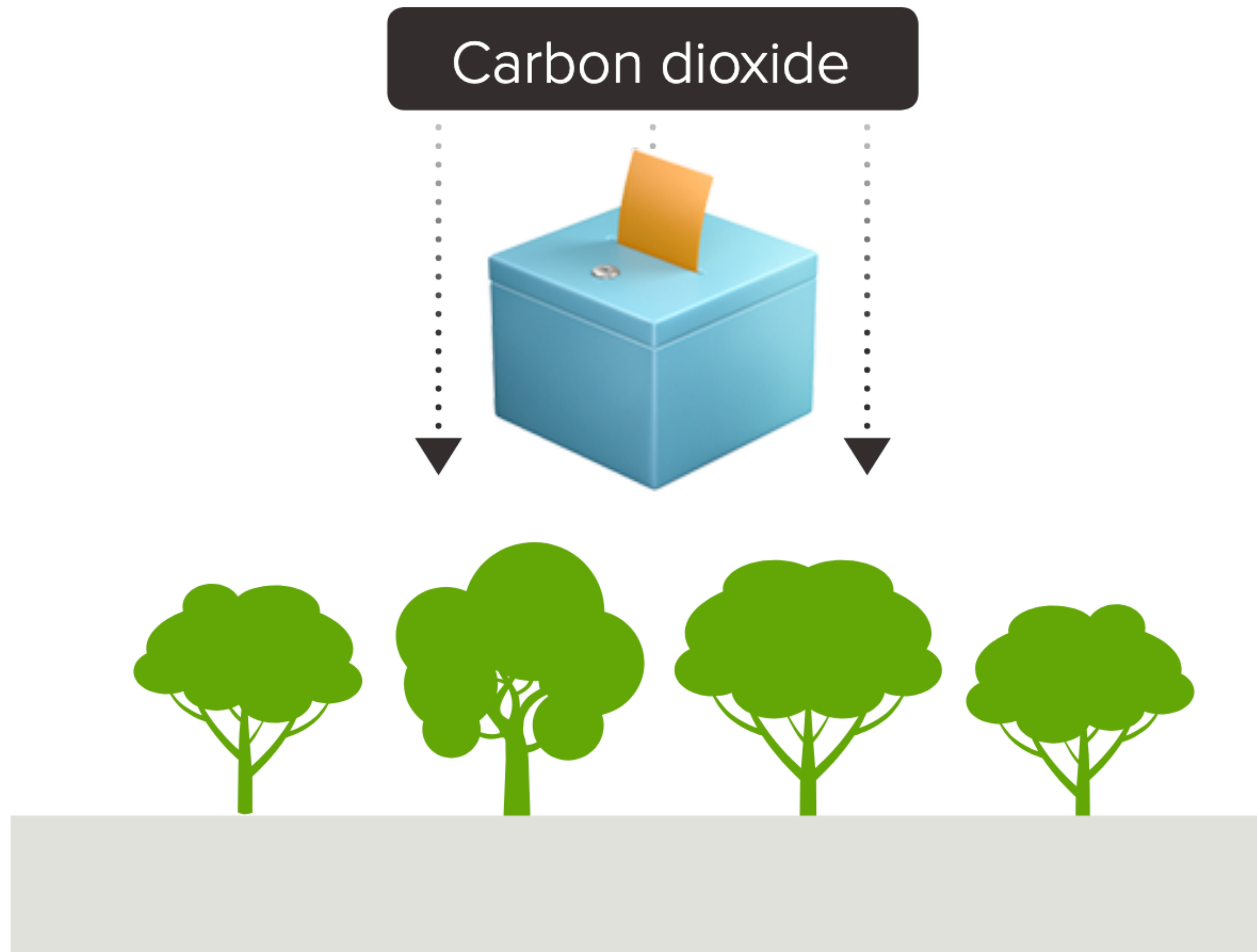


is storage
added?

Carbon dioxide



any
upsides?

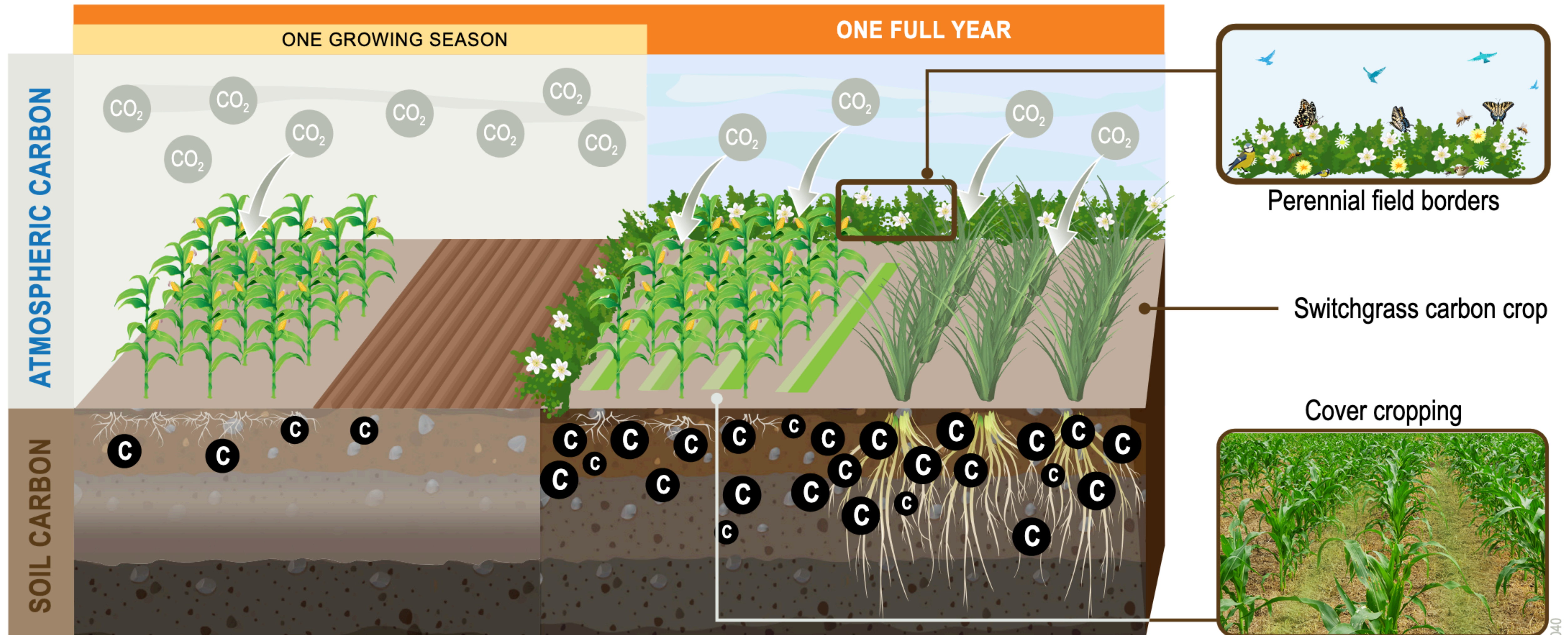


do people
like it?

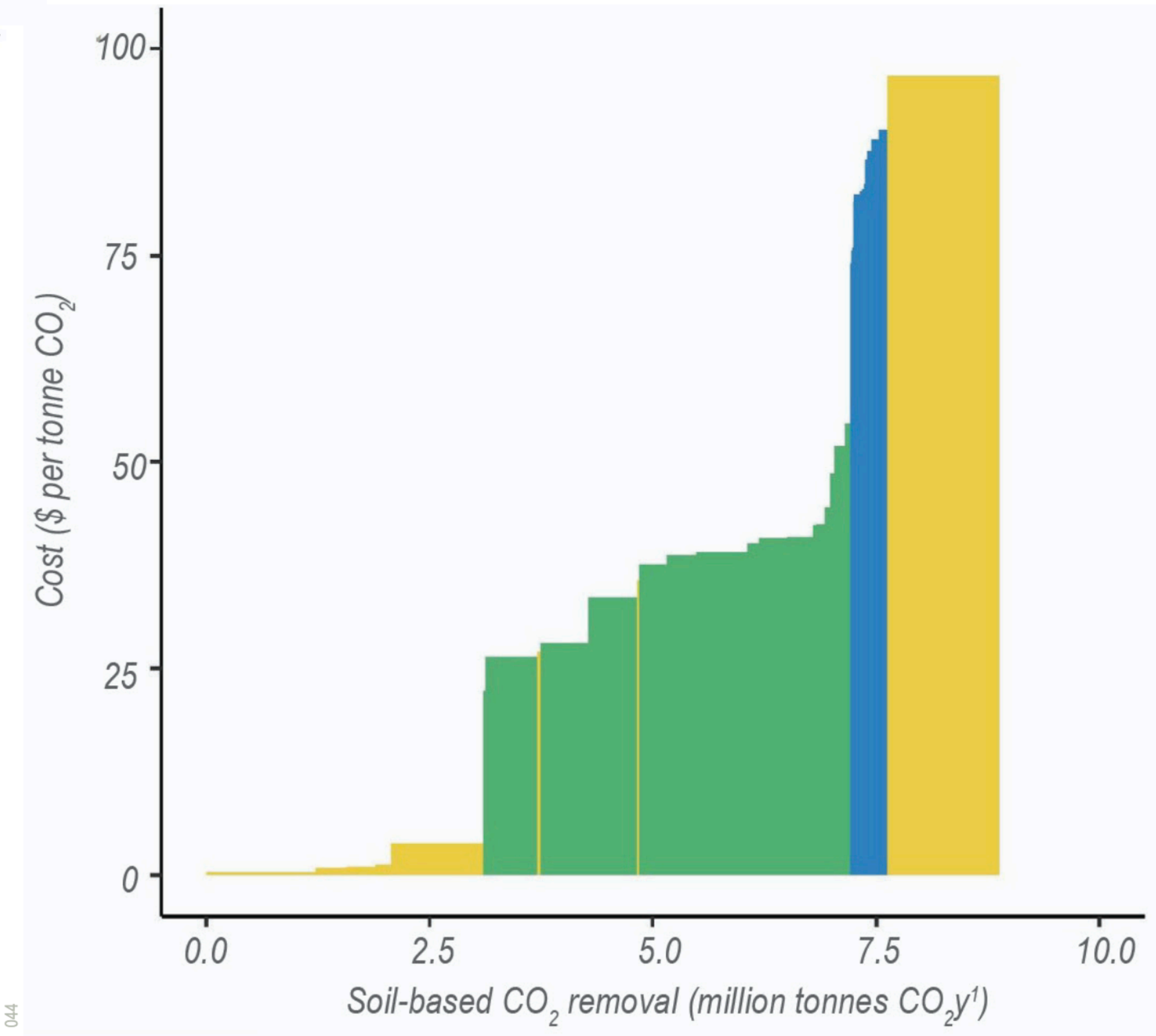
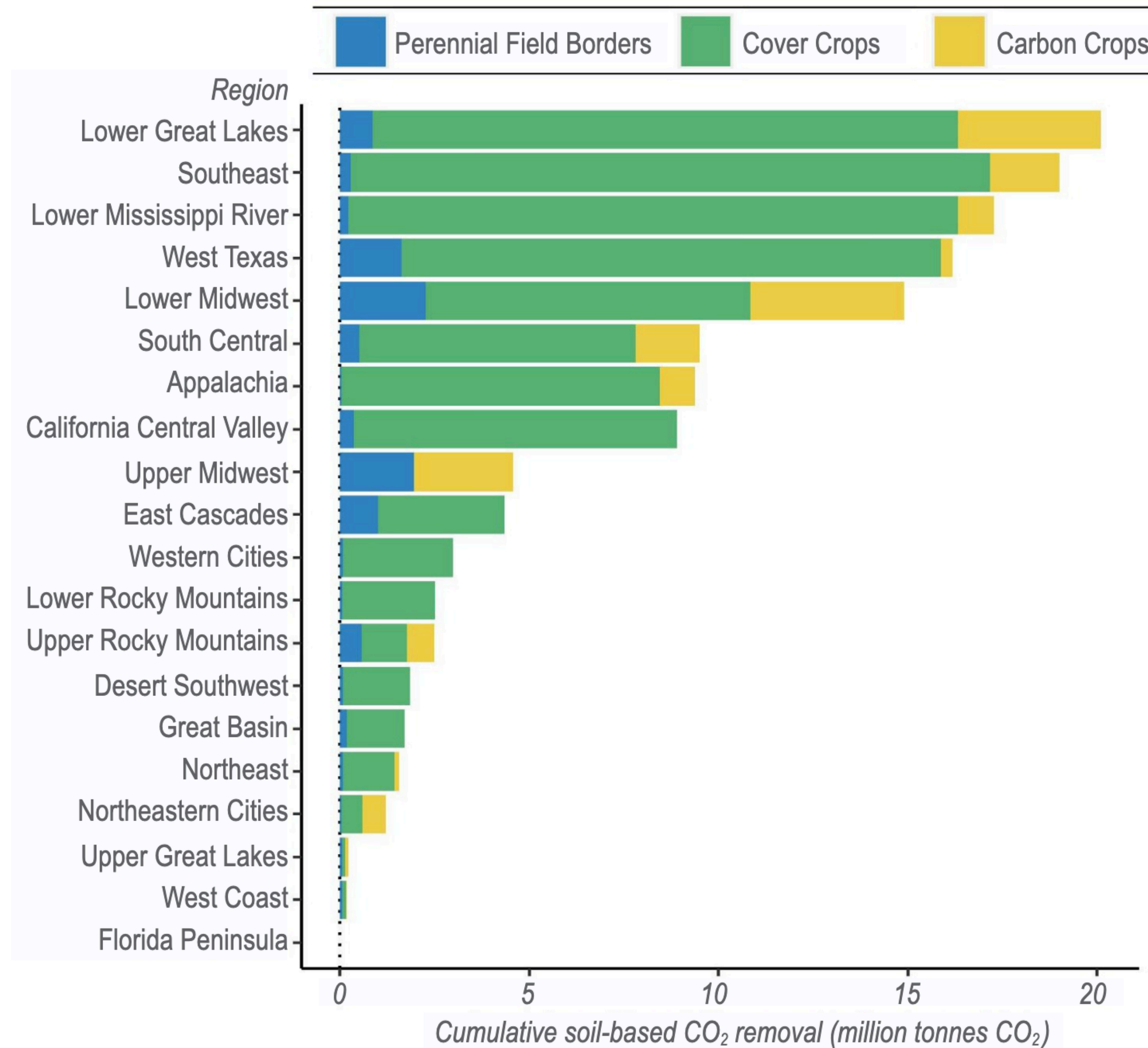
is it legal?

[illegible]

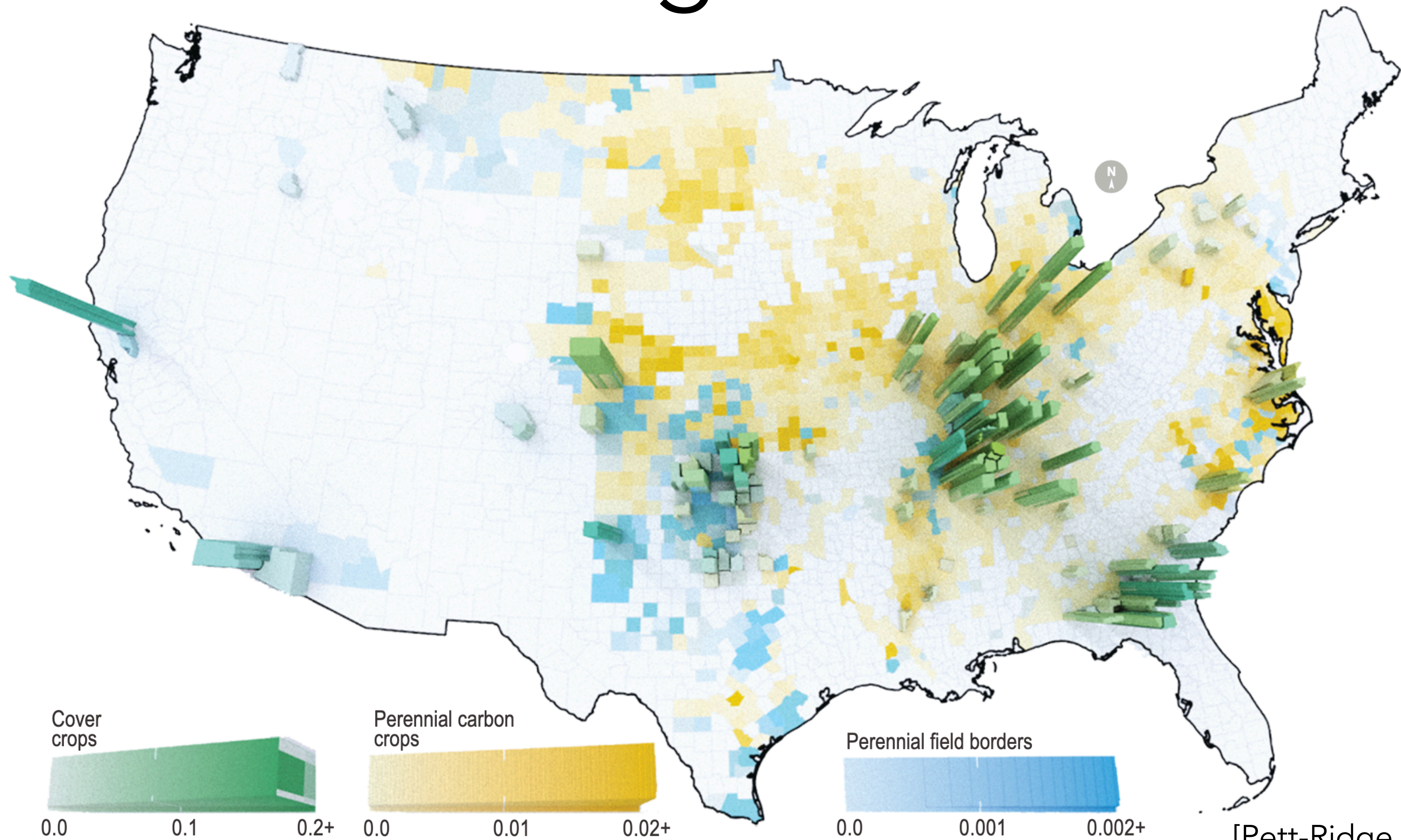
Soil carbon storage



Soil carbon storage



Soil carbon storage



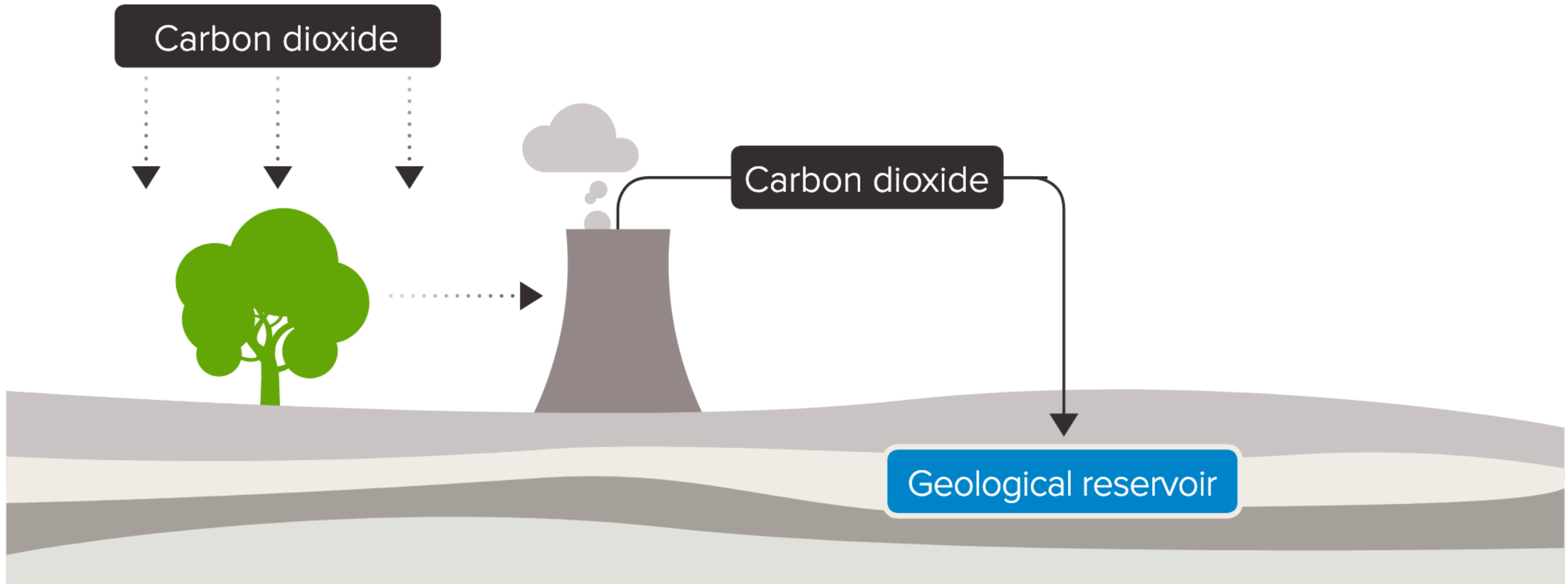
[Pett-Ridge et al. 2023]

Soil carbon storage

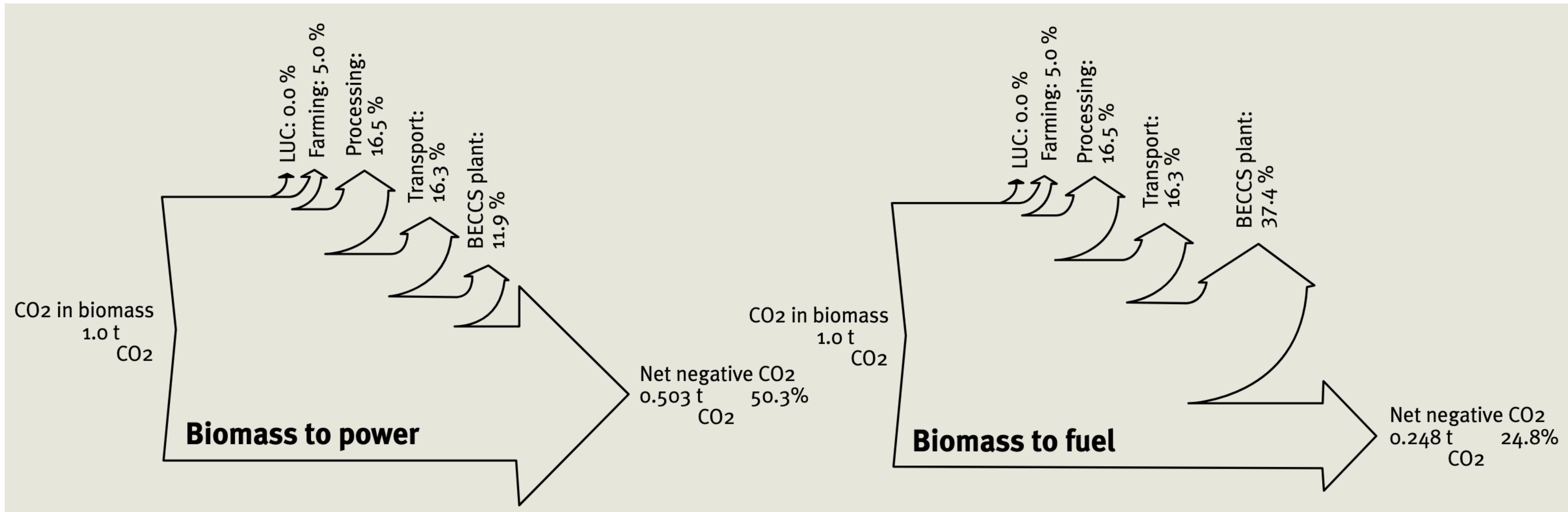


[illegible]

Bioenergy with carbon capture and storage

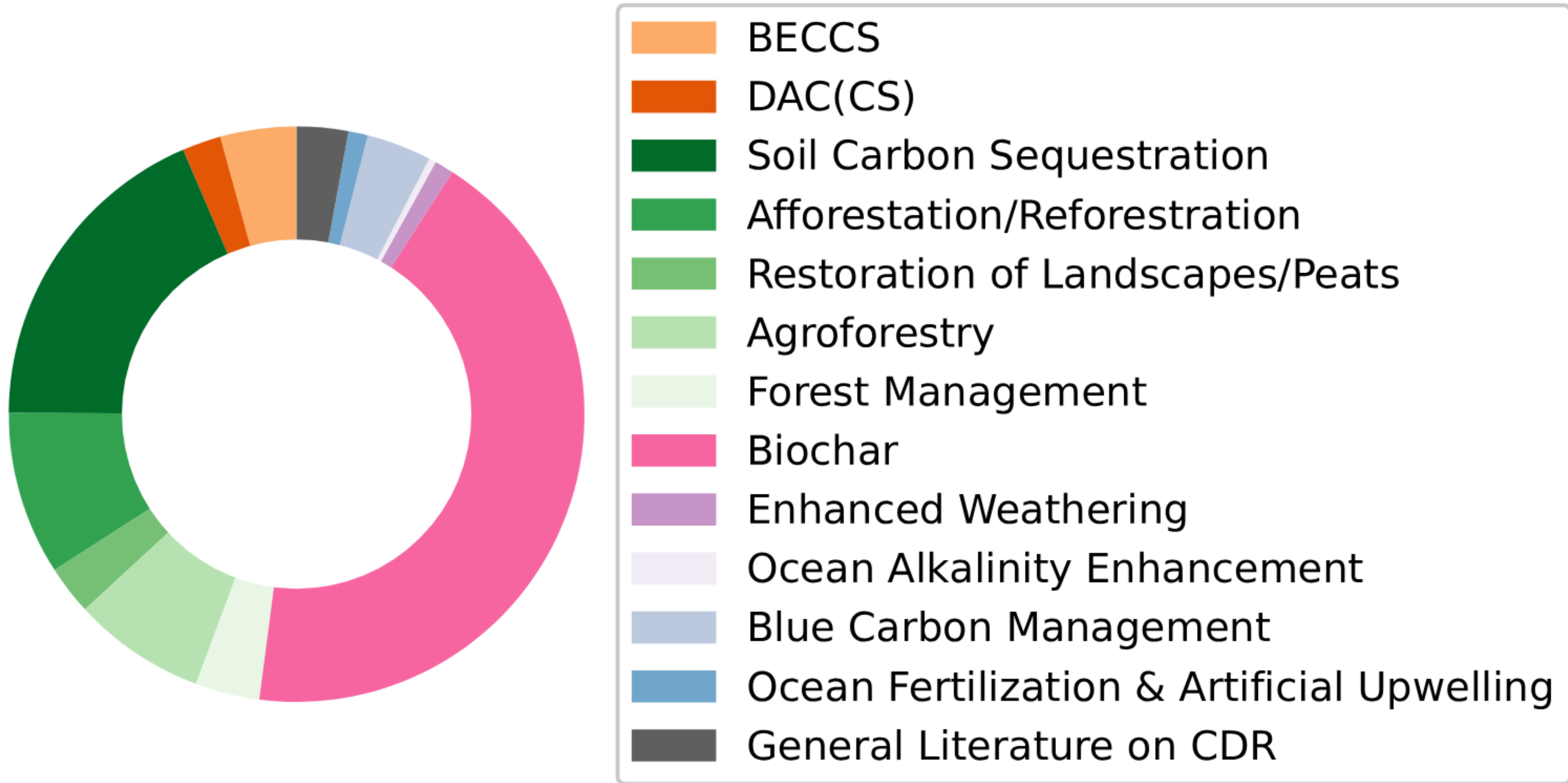


Bioenergy with carbon capture and storage

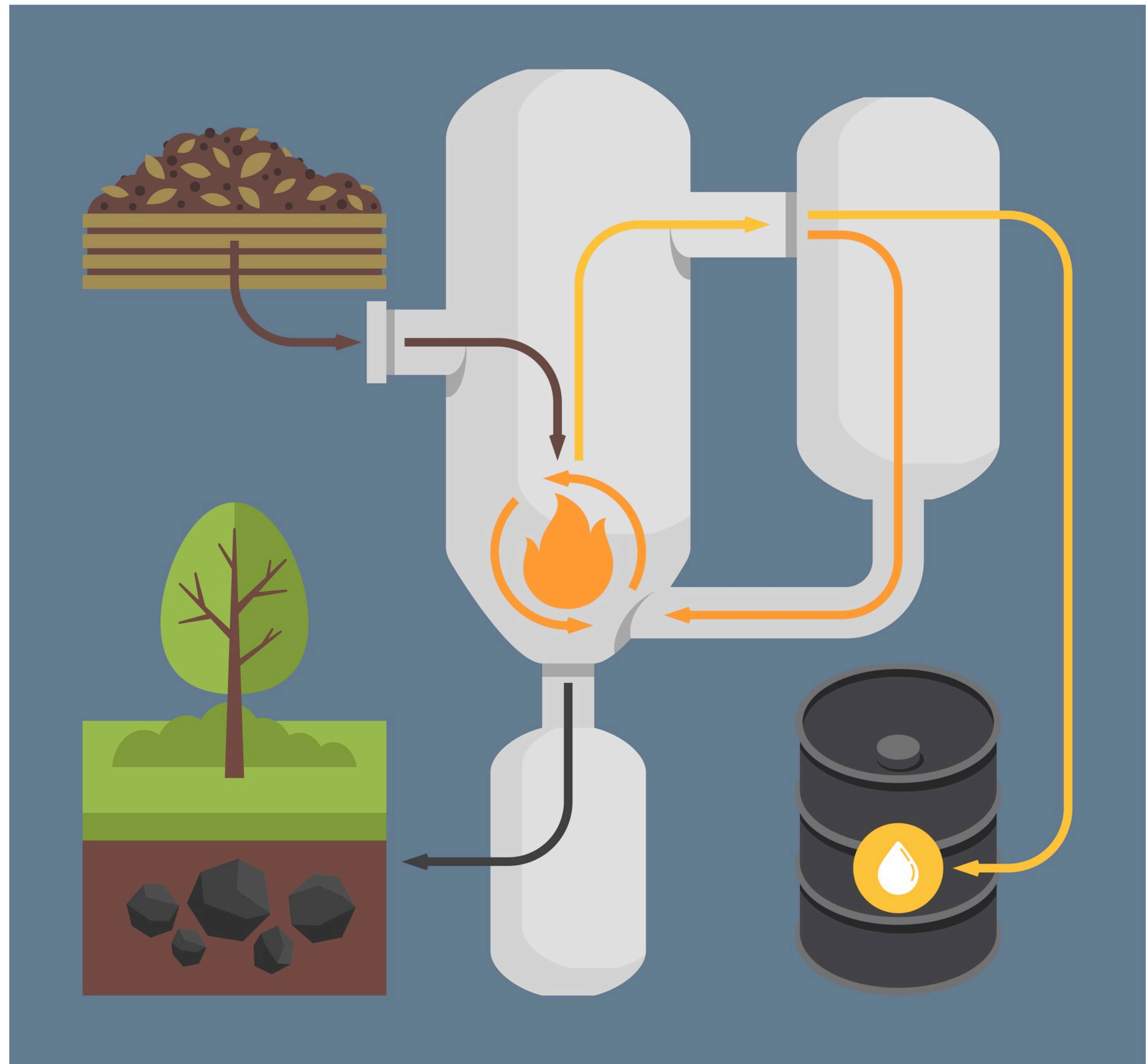


[illegible]

Biochar

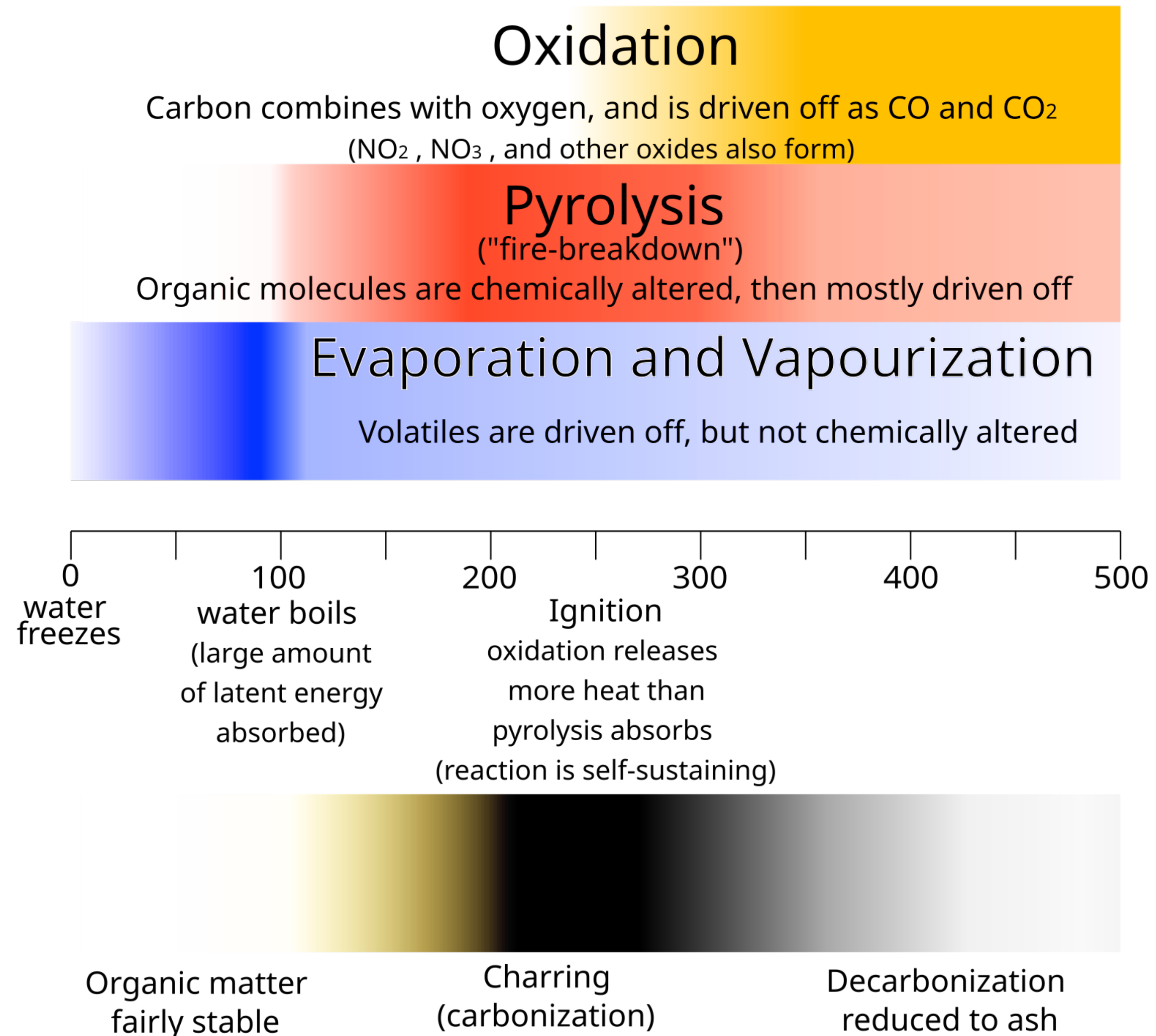


Biochar



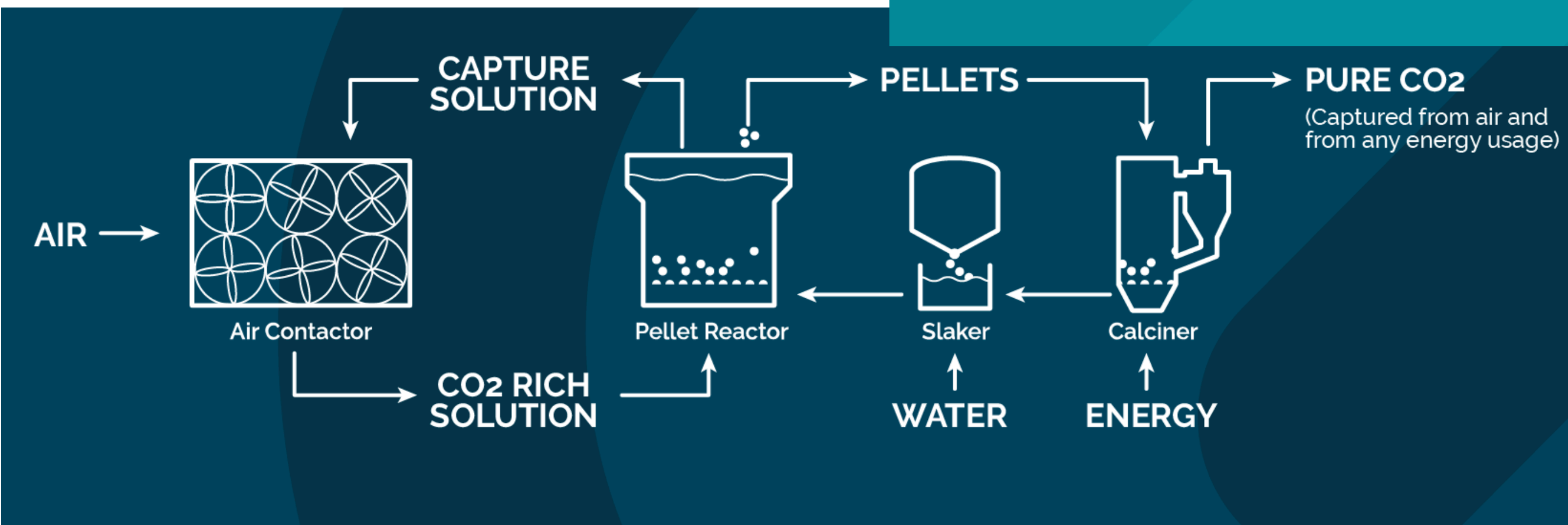
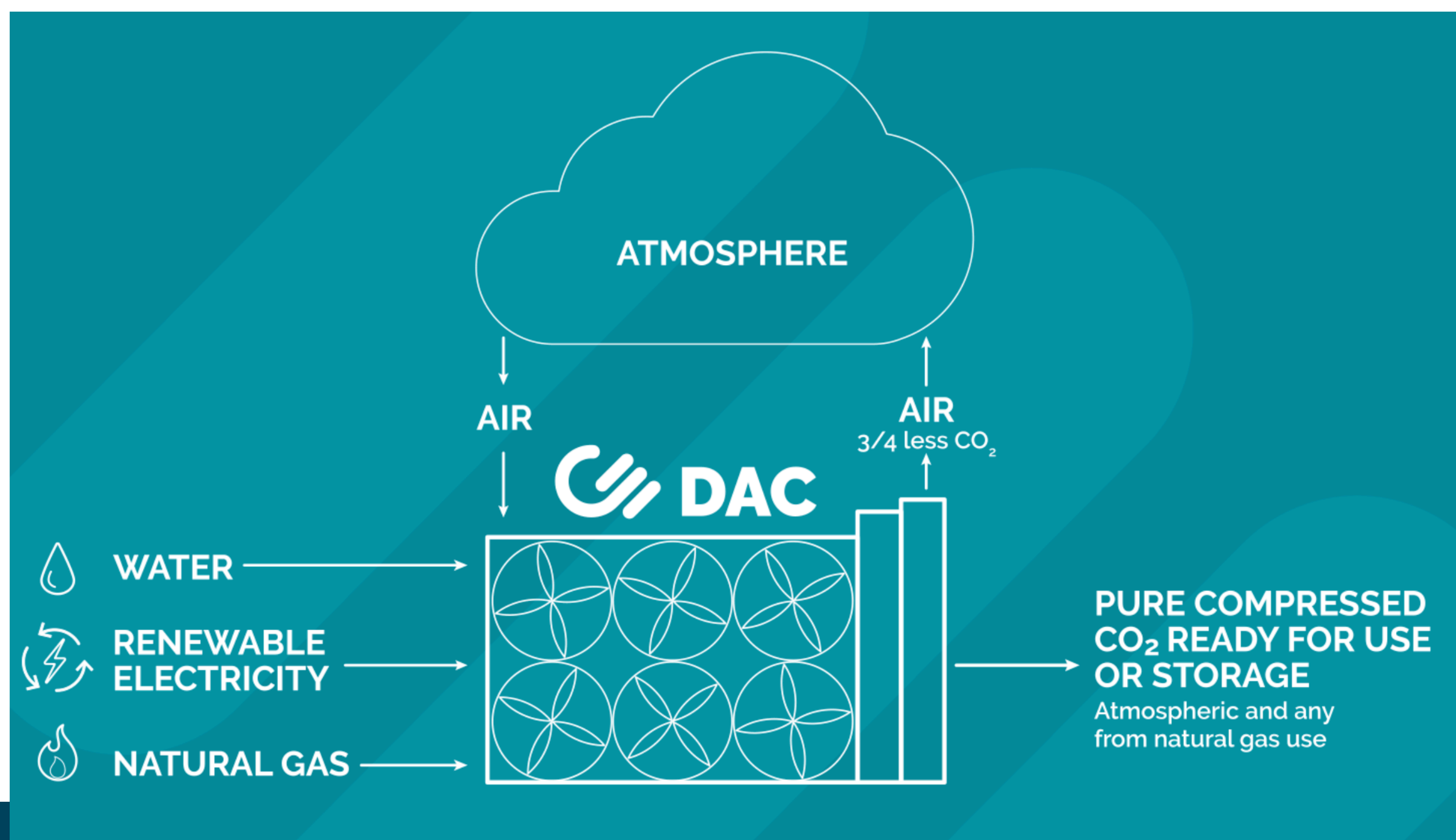
Biochar

Thermal decomposition of organic matter



[illegible]

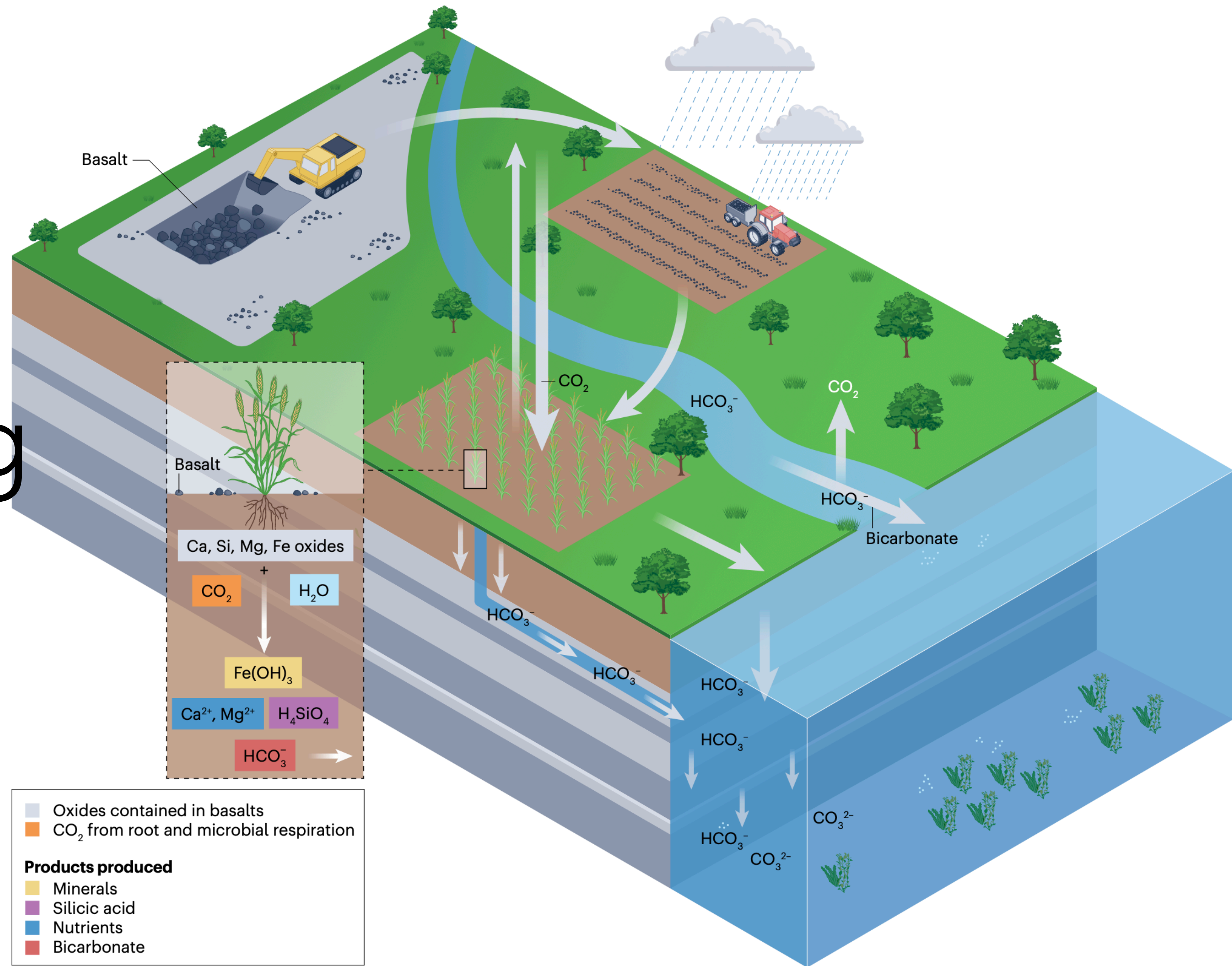
Direct Air Capture



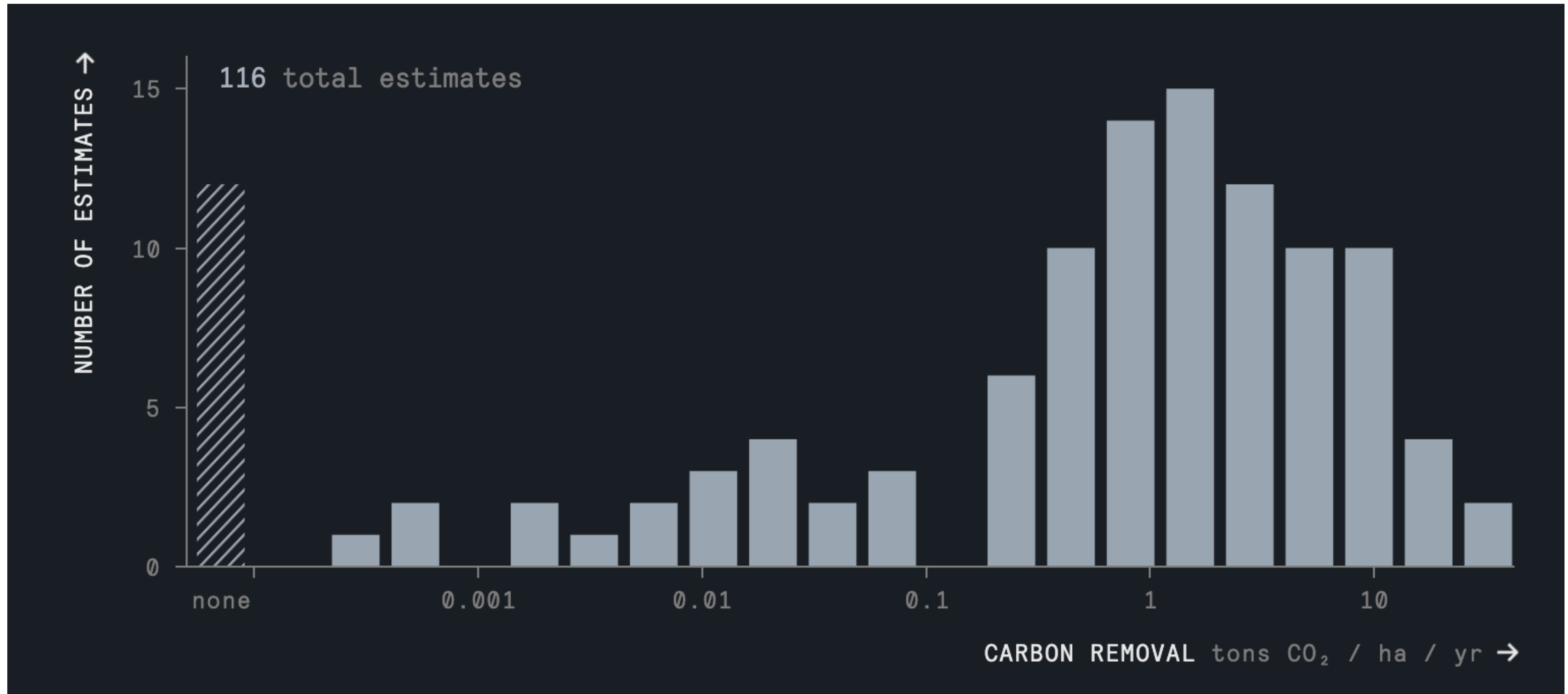
[Carbon Engineering]

[illegible]

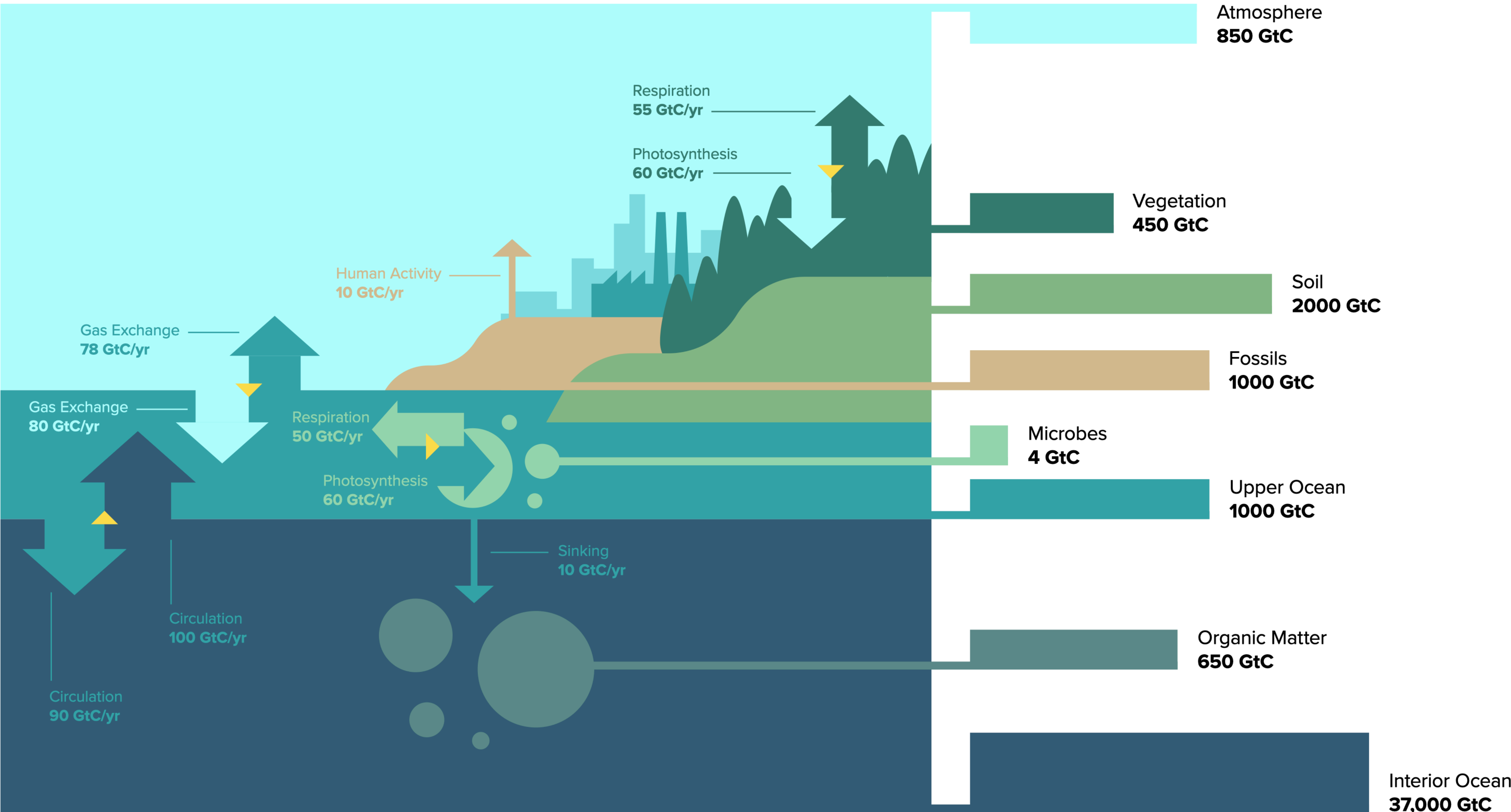
Enhanced Rock Weathering



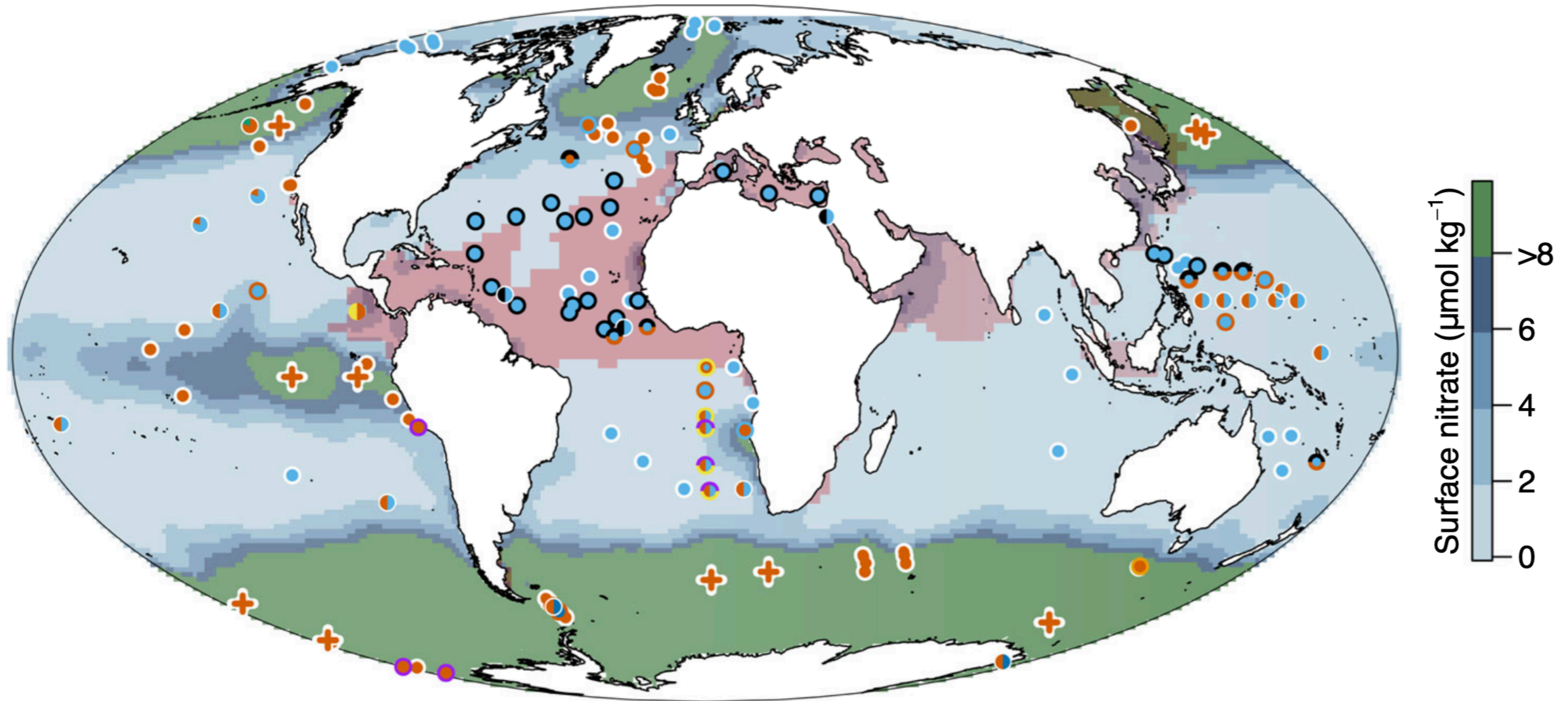
Enhanced Rock Weathering



[illegible]

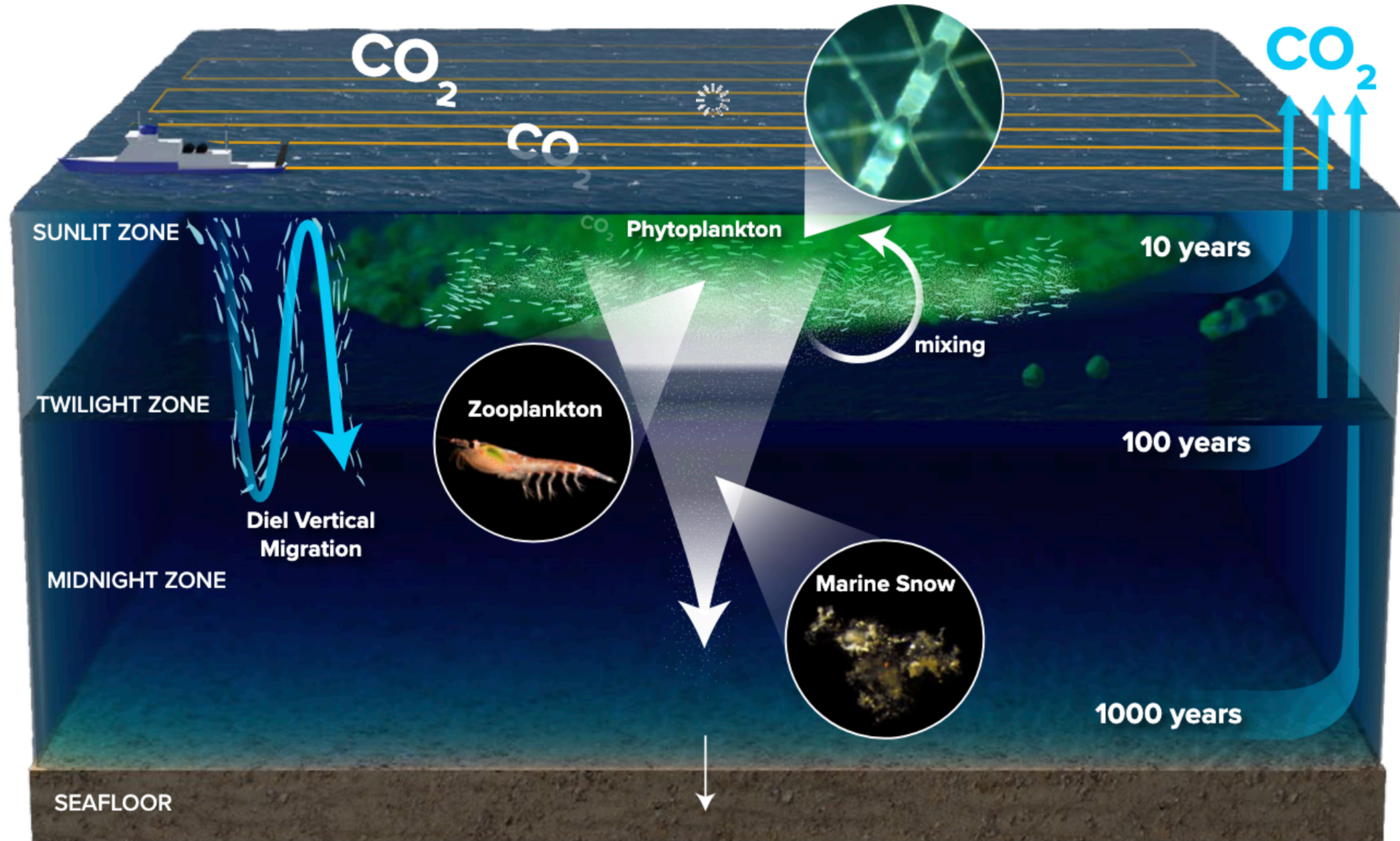


Iron fertilization

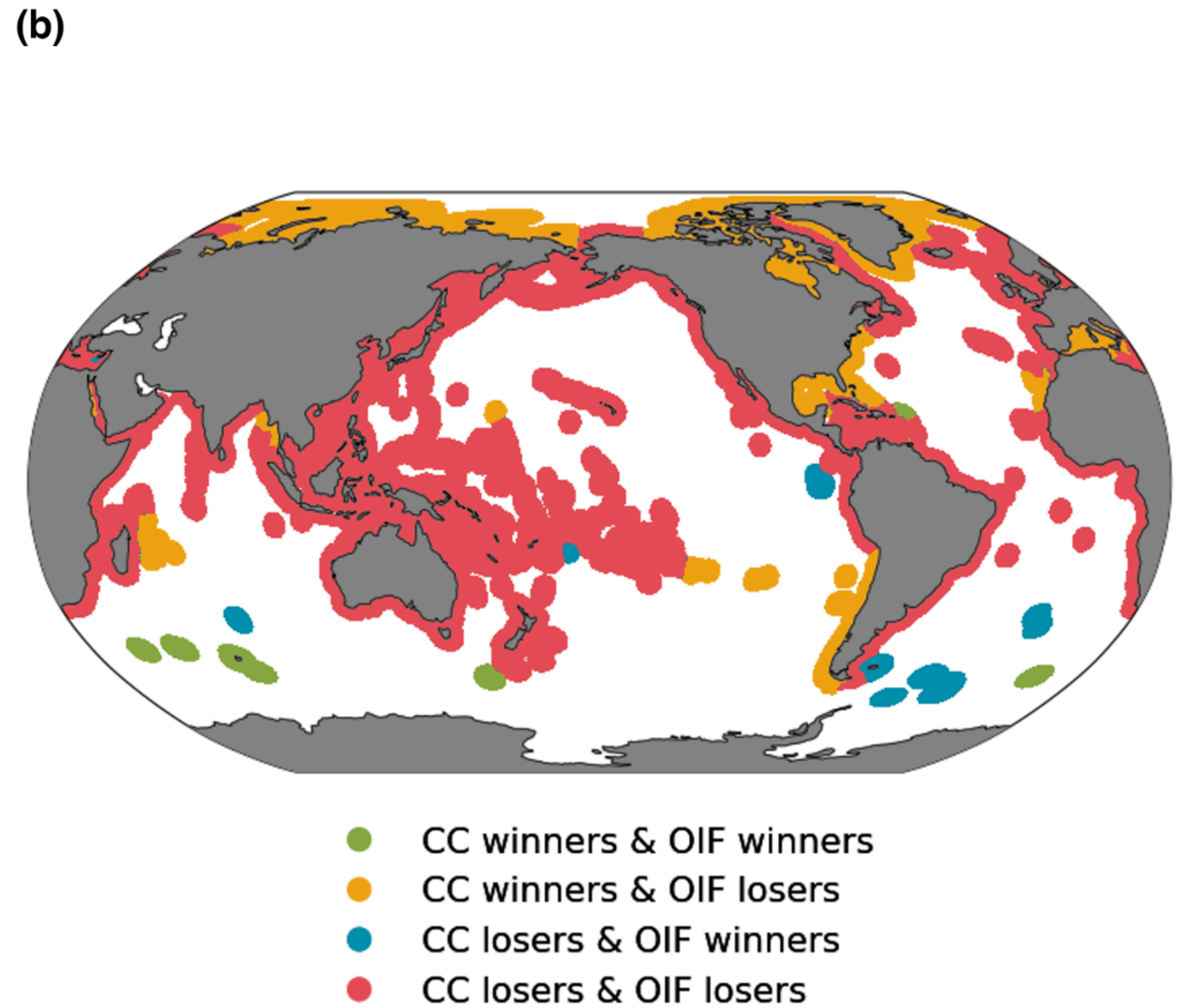
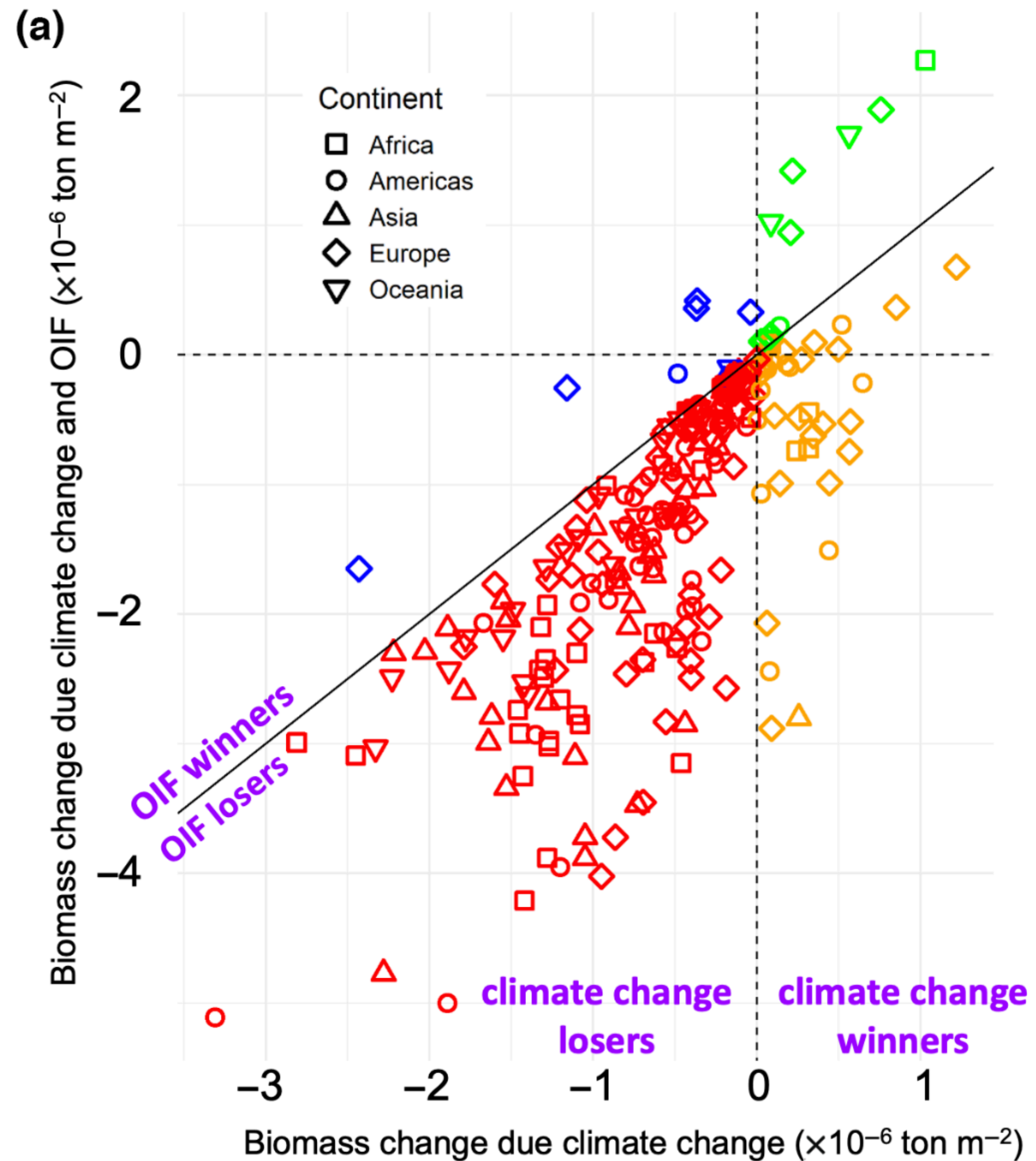


[Browning & Moore 2023]

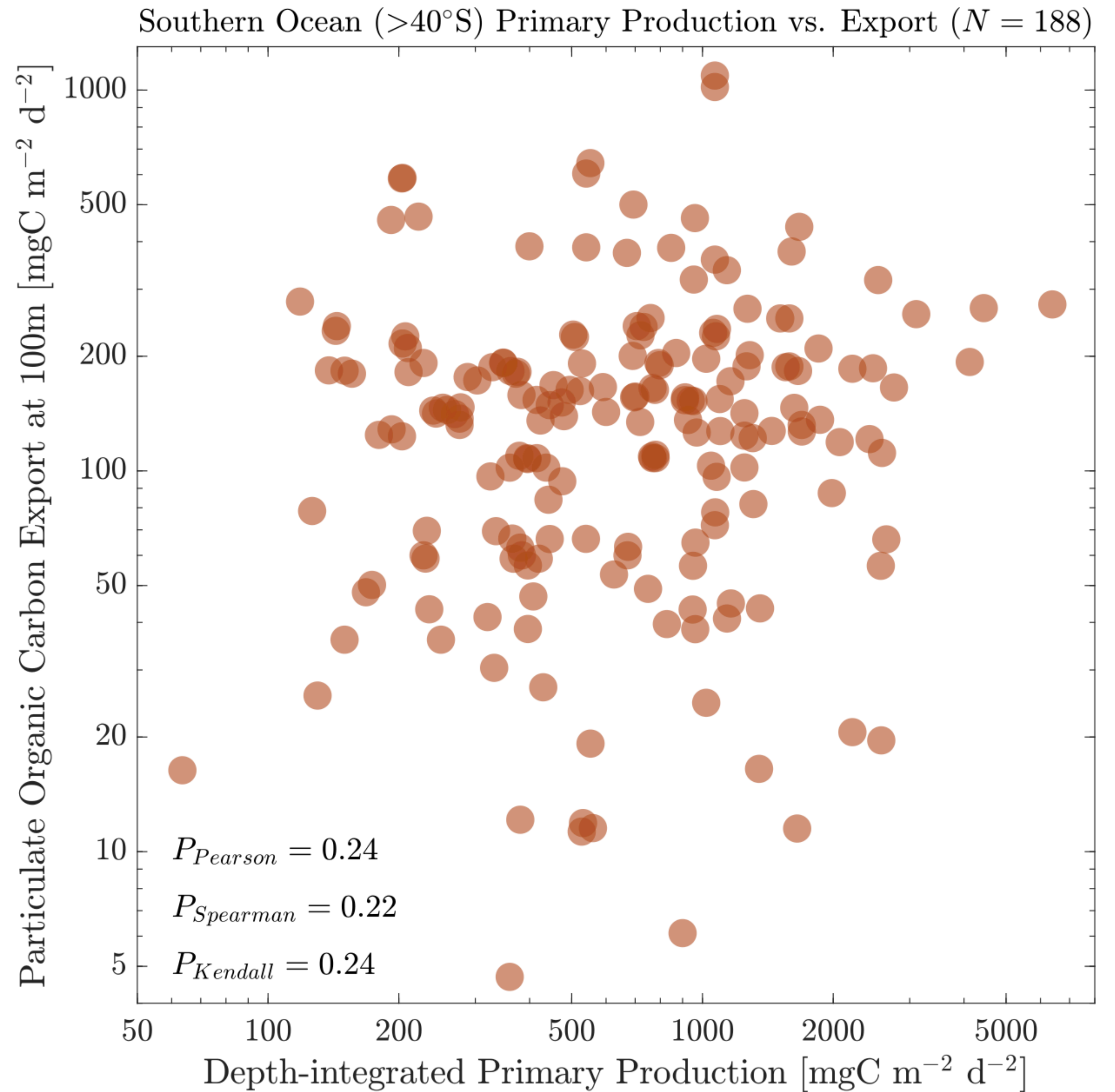
Iron fertilization



Iron fertilization



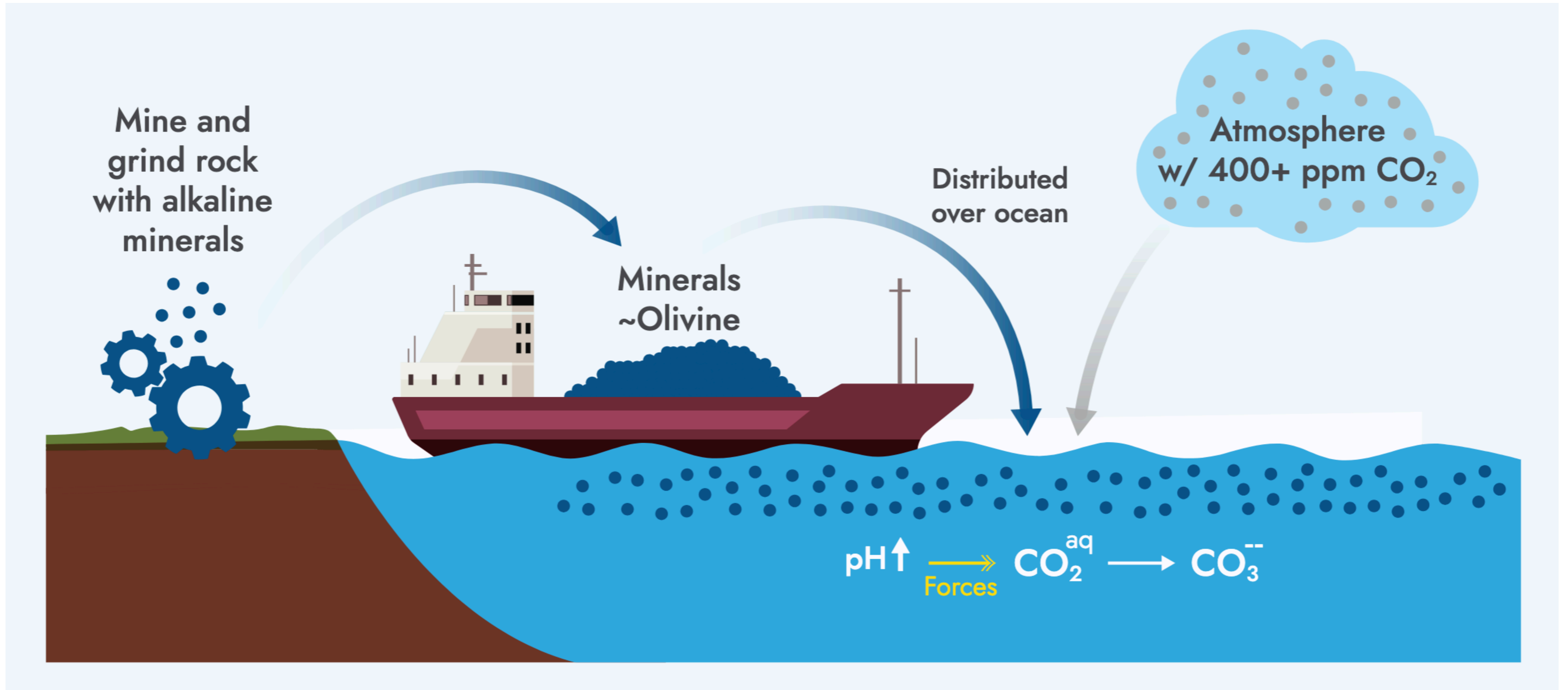
Iron fertilization



[Cael et al. in review]

[illegible]

Ocean Alkalinity Enhancement



What is alkalinity?

$$\begin{aligned} A_T \equiv & [\text{Na}^+] + 2[\text{Mg}^{2+}] + 2[\text{Ca}^{2+}] + [\text{K}^+] \\ & + 2[\text{Sr}^{2+}] - [\text{Cl}^-] - 2[\text{SO}_4^{2-}] - [\text{Br}^-] \\ & - [\text{F}^-] - [\text{NO}_3^-] + \dots = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] \\ & + [\text{B}(\text{OH})_4^-] + [\text{OH}^-] - [\text{H}^+] + \dots \end{aligned}$$

What is alkalinity?

$$\text{DIC} = [\text{CO}_2^*] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]$$

$$[\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] \lesssim A_T$$

What is alkalinity enhancement?

Add stuff → increase A_T



Sea CO_2 deficit vs. air

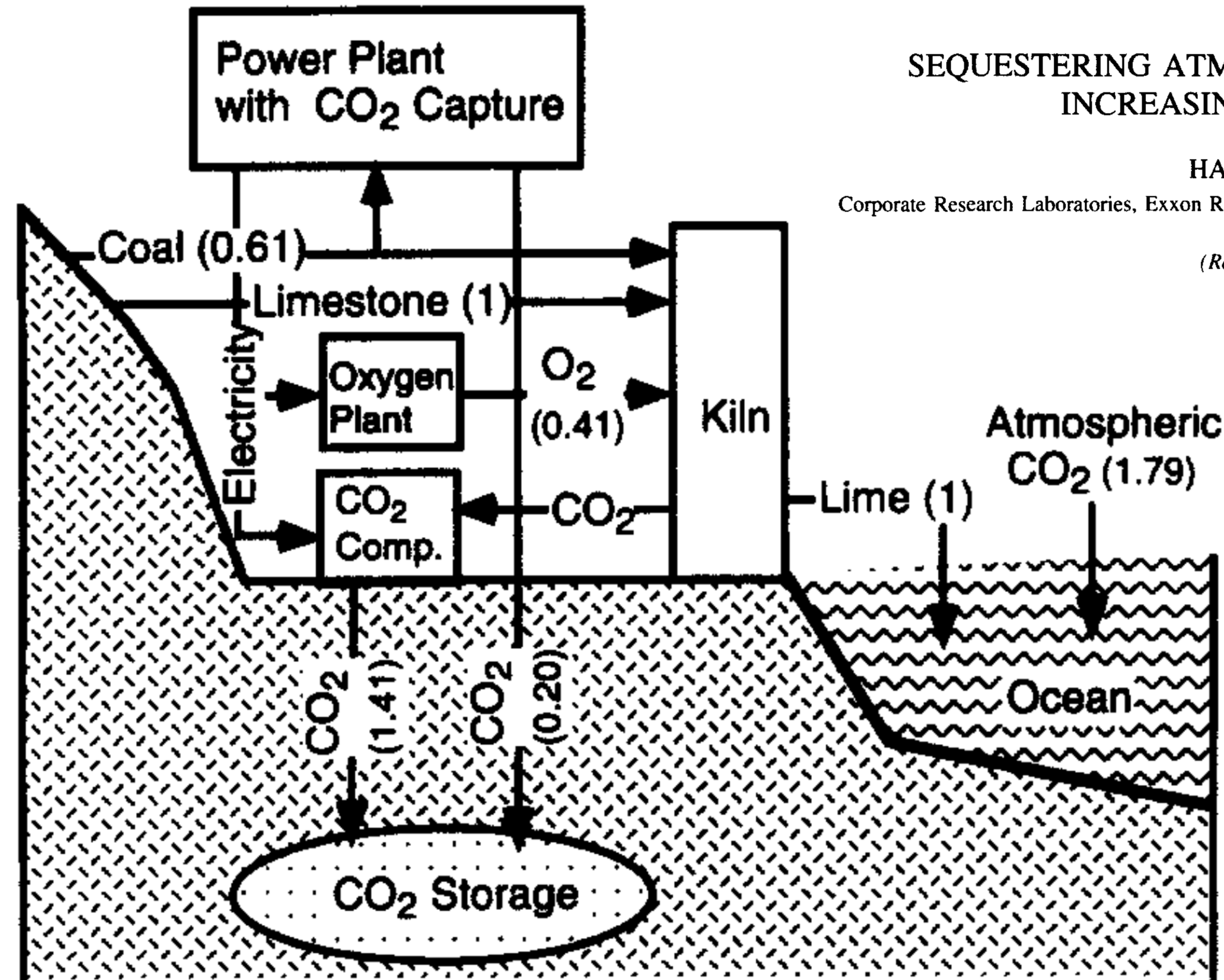
Air-to-Sea CO_2 flux

SEQUESTERING ATMOSPHERIC CARBON DIOXIDE BY INCREASING OCEAN ALKALINITY

HAROON S. KHESHGI

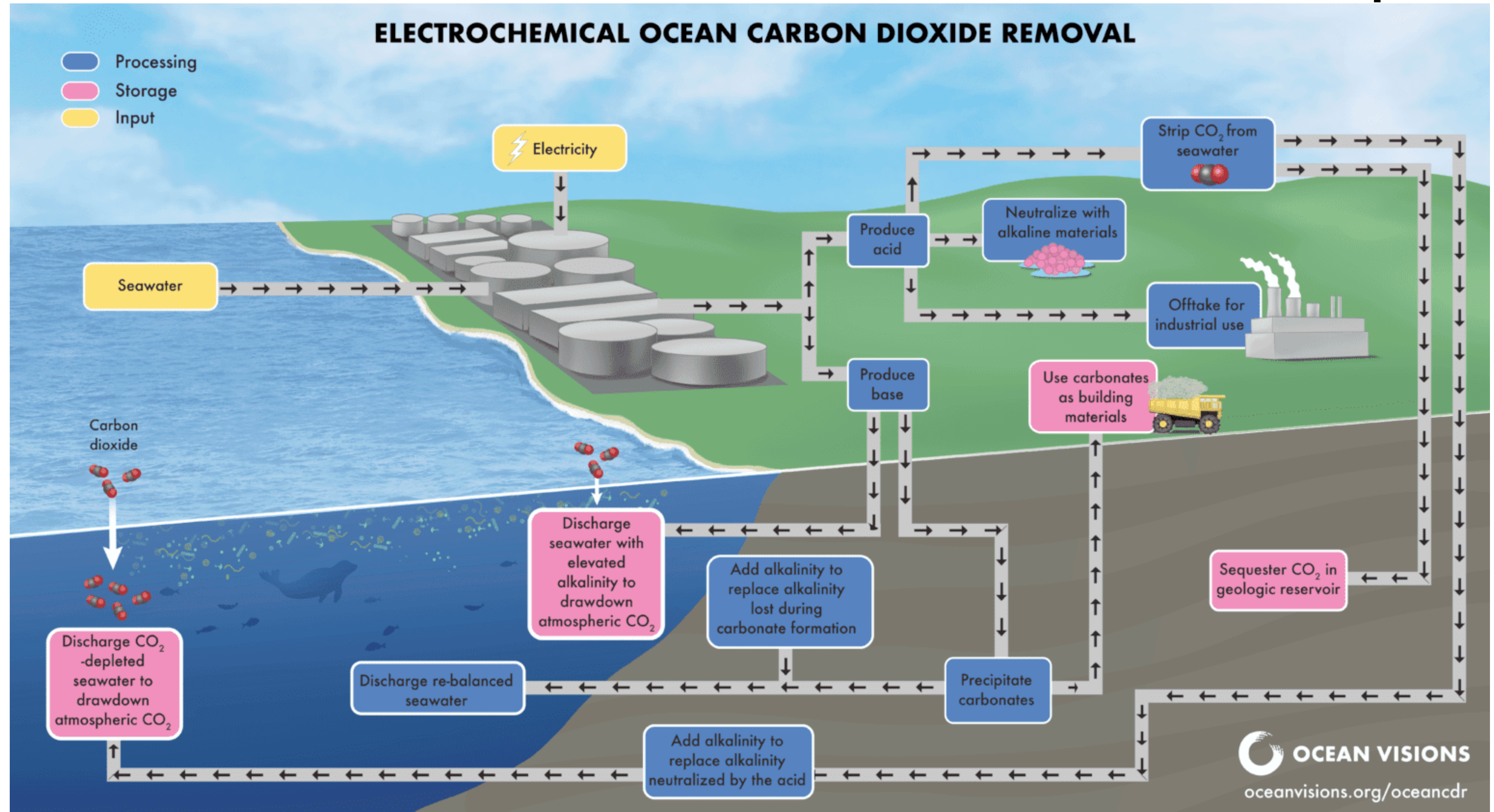
Corporate Research Laboratories, Exxon Research and Engineering Company, Annandale, NJ 08801, U.S.A.

(Received 14 October 1994)

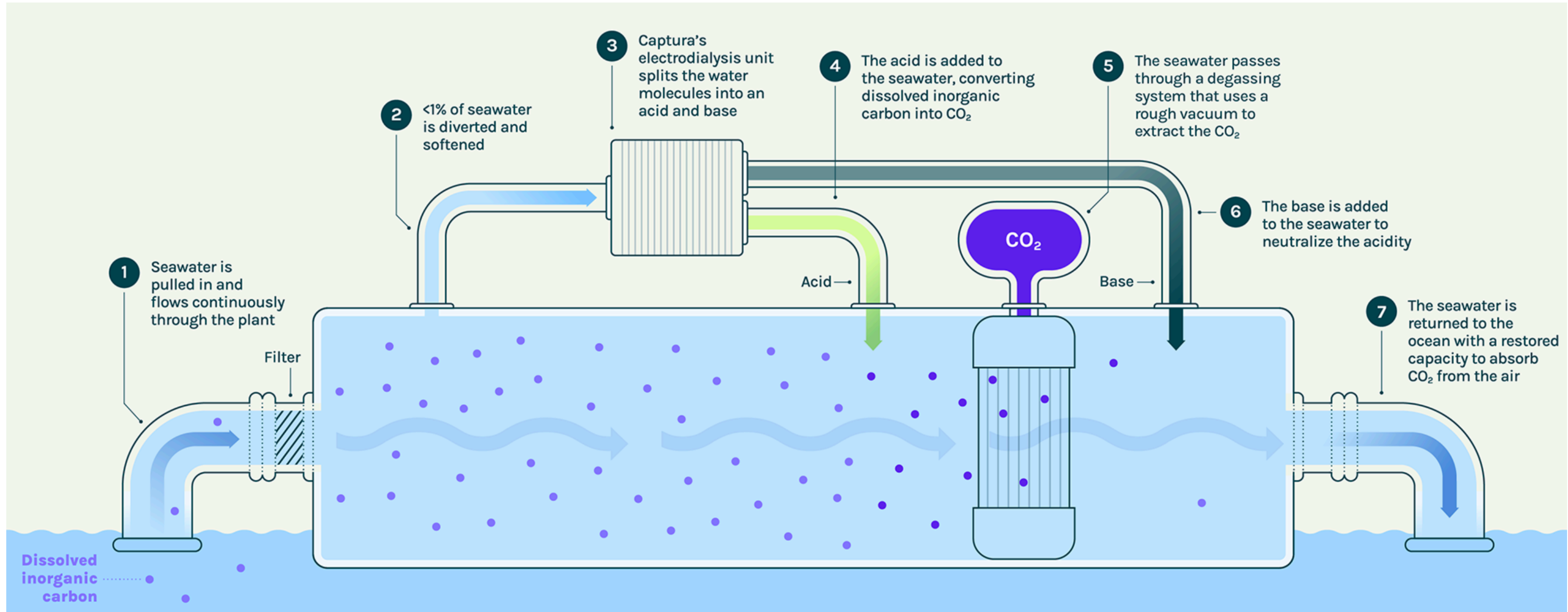


[illegible]

Electrochemical ocean carbon capture



Electrochemical ocean carbon capture



	Works?	Safe?	Scale?	Cost?	Reqs?	Time?	Know?	Added?	Upside?	Gov?
Trees	✓	✓	~	✓	X	X	✓	~	✓	✓
Soil	✓	✓	~	✓	✓	~	X	✓	✓	✓
BECCS	✓	✓	~	~	X	✓	✓	✓	~	✓
Biochar	✓	✓	~	~	X	~	~	✓	✓	✓
DAC	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
ERW	~	~	✓	~	✓	✓	X	✓	✓	✓
Fertilize	~	~	~	✓	✓	~	~	~	~	~
OAE	✓	~	✓	✓	~	✓	~	✓	✓	~
E-chem	✓	~	✓	X	✓	✓	✓	✓	✓	✓

	Works?	Safe?	Scale?	Cost?	Reqs?	Time?	Know?	Added?	Upside?	Gov?
Trees	✓	✓	~	✓	X	X	✓	~	✓	✓
Soil	✓	✓	~	✓	✓	~	X	✓	✓	✓
BECCS	✓	✓	~	~	X	✓	✓	✓	~	✓
Biochar	✓	✓	~	~	X	~	~	✓	✓	✓
DAC	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
ERW	~	~	✓	~	✓	✓	X	✓	✓	✓
Fertilize	~	~	~	✓	✓	~	~	~	~	~
OAE	✓	~	✓	✓	~	✓	~	✓	✓	~
E-chem	✓	~	✓	X	✓	✓	✓	✓	✓	✓

	Works?	Safe?	Scale?	Cost?	Reqs?	Time?	Know?	Added?	Upside?	Gov?
Trees	✓	✓	~	✓	X	X	✓	~	✓	✓
Soil	✓	✓	~	✓	✓	~	X	✓	✓	✓
BECCS	✓	✓	~	~	X	✓	✓	✓	~	✓
Biochar	✓	✓	~	~	X	~	~	✓	✓	✓
DAC	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
ERW	~	~	✓	~	✓	✓	X	✓	✓	✓
Fertilize	~	~	~	✓	✓	~	~	~	~	~
OAE	✓	~	✓	✓	~	✓	~	✓	✓	~
E-chem	✓	~	✓	X	✓	✓	✓	✓	✓	✓

	Works?	Safe?	Scale?	Cost?	Reqs?	Time?	Know?	Added?	Upside?	Gov?
Trees	✓	✓	~	✓	X	X	✓	~	✓	✓
Soil	✓	✓	~	✓	✓	~	X	✓	✓	✓
BECCS	✓	✓	~	~	X	✓	✓	✓	~	✓
Biochar	✓	✓	~	~	X	~	~	✓	✓	✓
DAC	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
ERW	~	~	✓	~	✓	✓	X	✓	✓	✓
Fertilize	~	~	~	✓	✓	~	~	~	~	~
OAE	✓	~	✓	✓	~	✓	~	✓	✓	~
E-chem	✓	~	✓	X	✓	✓	✓	✓	✓	✓

	Works?	Safe?	Scale?	Cost?	Reqs?	Time?	Know?	Added?	Upside?	Gov?
Trees	✓	✓	~	✓	X	X	✓	~	✓	✓
Soil	✓	✓	~	✓	✓	~	X	✓	✓	✓
BECCS	✓	✓	~	~	X	✓	✓	✓	~	✓
Biochar	✓	✓	~	~	X	~	~	✓	✓	✓
DAC	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd	tbd
ERW	~	~	✓	~	✓	✓	X	✓	✓	✓
Fertilize	~	~	~	✓	✓	~	~	~	~	~
OAE	✓	~	✓	✓	~	✓	~	✓	✓	~
E-chem	✓	~	✓	X	✓	✓	✓	✓	✓	✓



Opinionated Summary

- Lots of ideas out there, all have their problems
- e.g. at-scale OAE execution would be... not easy
- If there's a hail mary silver bullet, it's probably OAE
- Probably need a mix, & the more the merrier
- CDR vs. decarbonization: it's **and**, not **or**

Thanks! Questions?