Fonte du pergélisol et décomposition microbienne: quels impacts sur le cycle du carbone ?

Rémi Gaillard et Bertrand Guenet

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Permafrost is a huge carbon reservoir

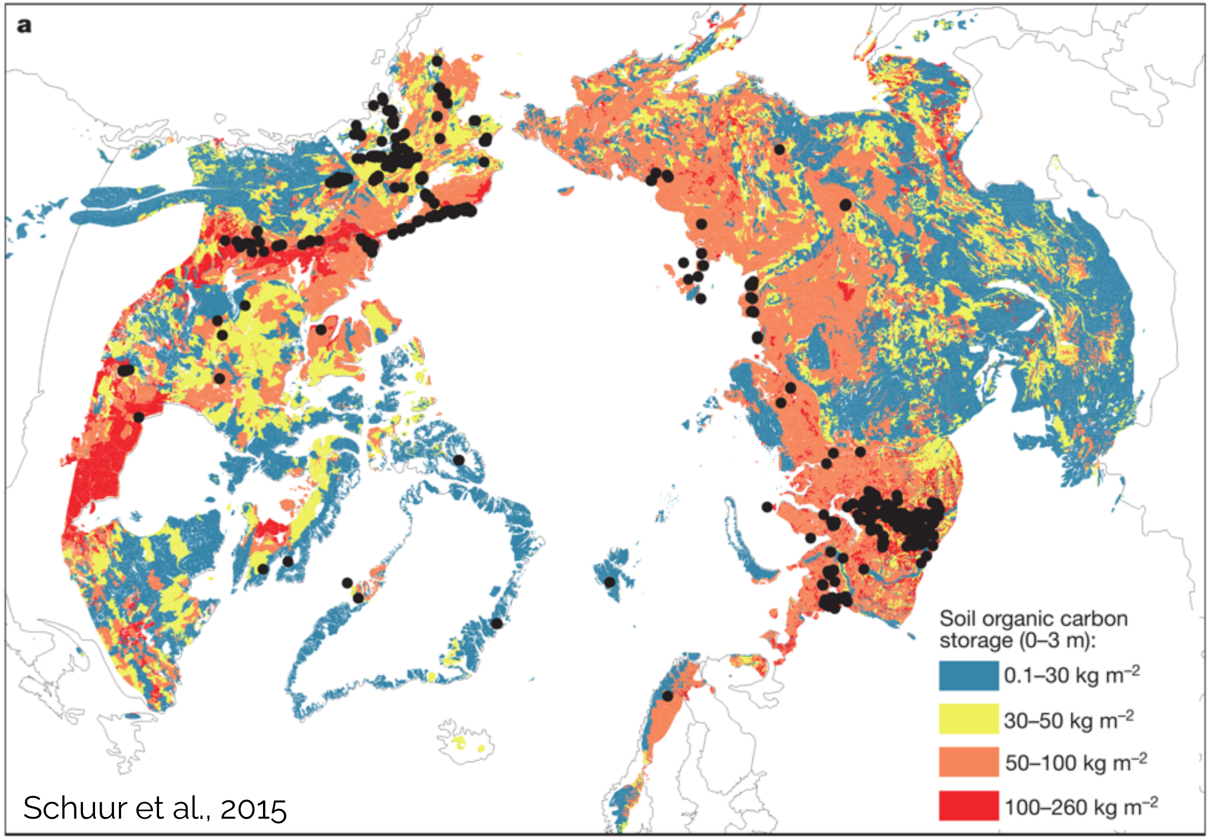
Permafrost covers ~15 million km²

→ 11% of continental surfaces

Permafrost soils contain ~1500 PgC

→ 2 times the atmospheric carbon content

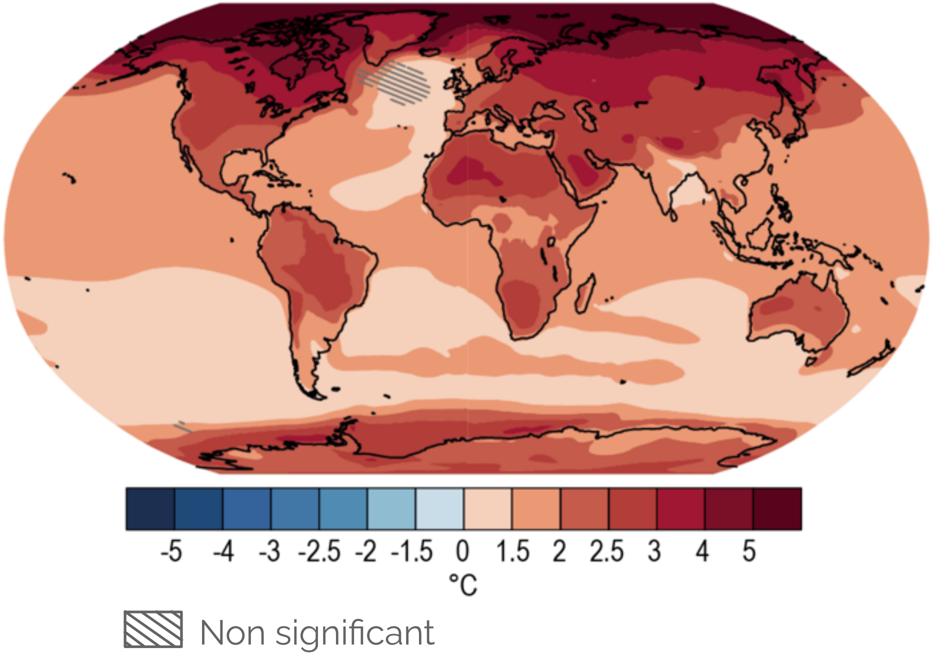
→ 60% of the world's soil carbon



Schuur et al., 2015

The Arctic is warming faster than the rest of the globe

Surface air temperature change at +2˚C global warming
(model projection)



IPCC AR6 WGI Chap.2, 2021

The Arctic is warming faster than the rest of the globe, resulting in permafrost warming

Surface air temperature change at +2˚C global warming
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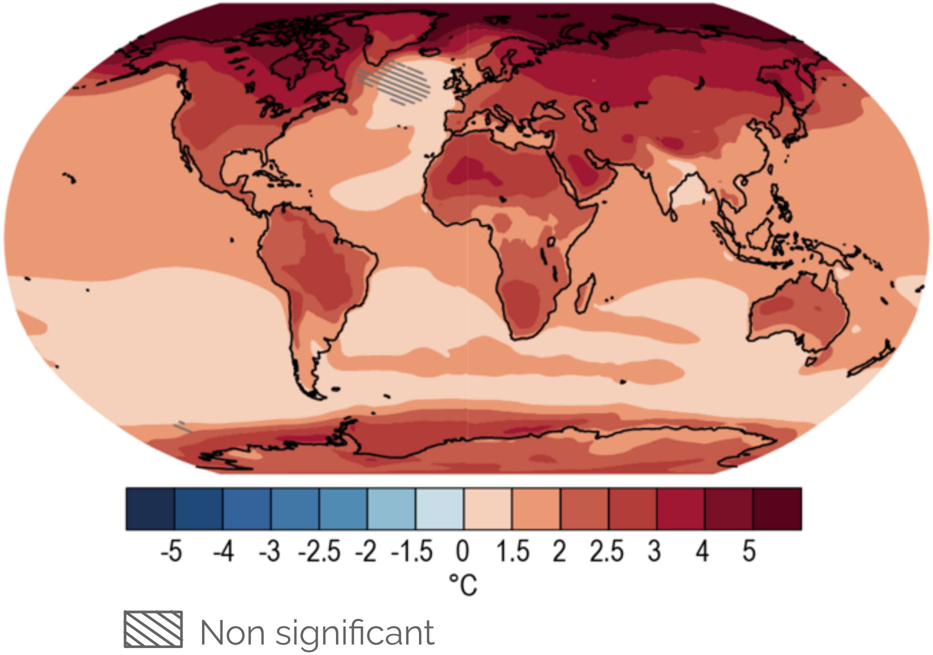
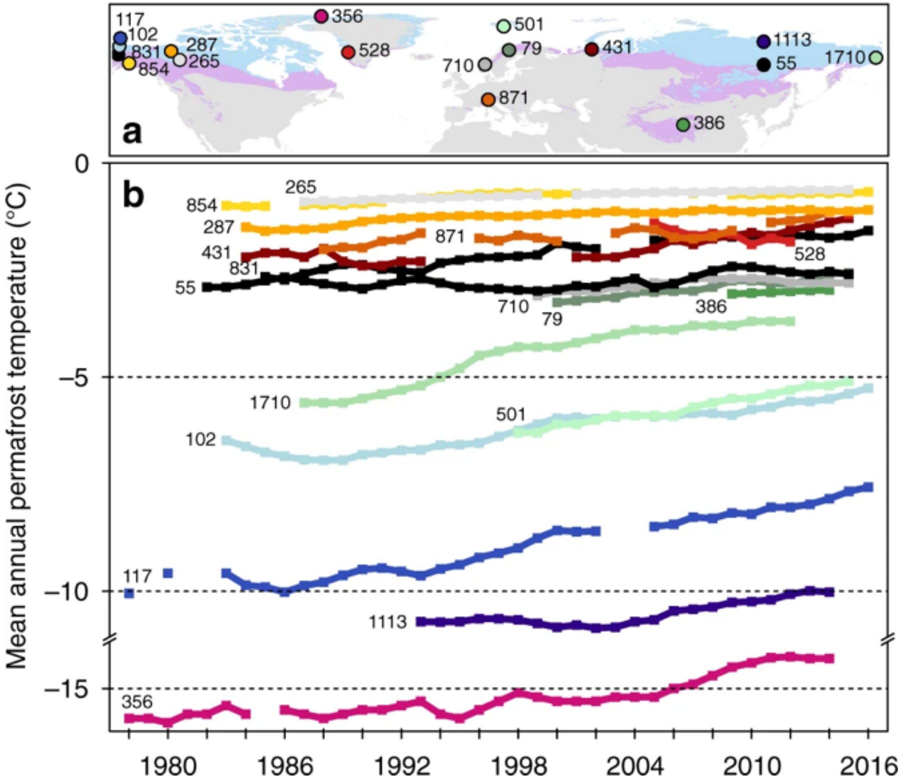
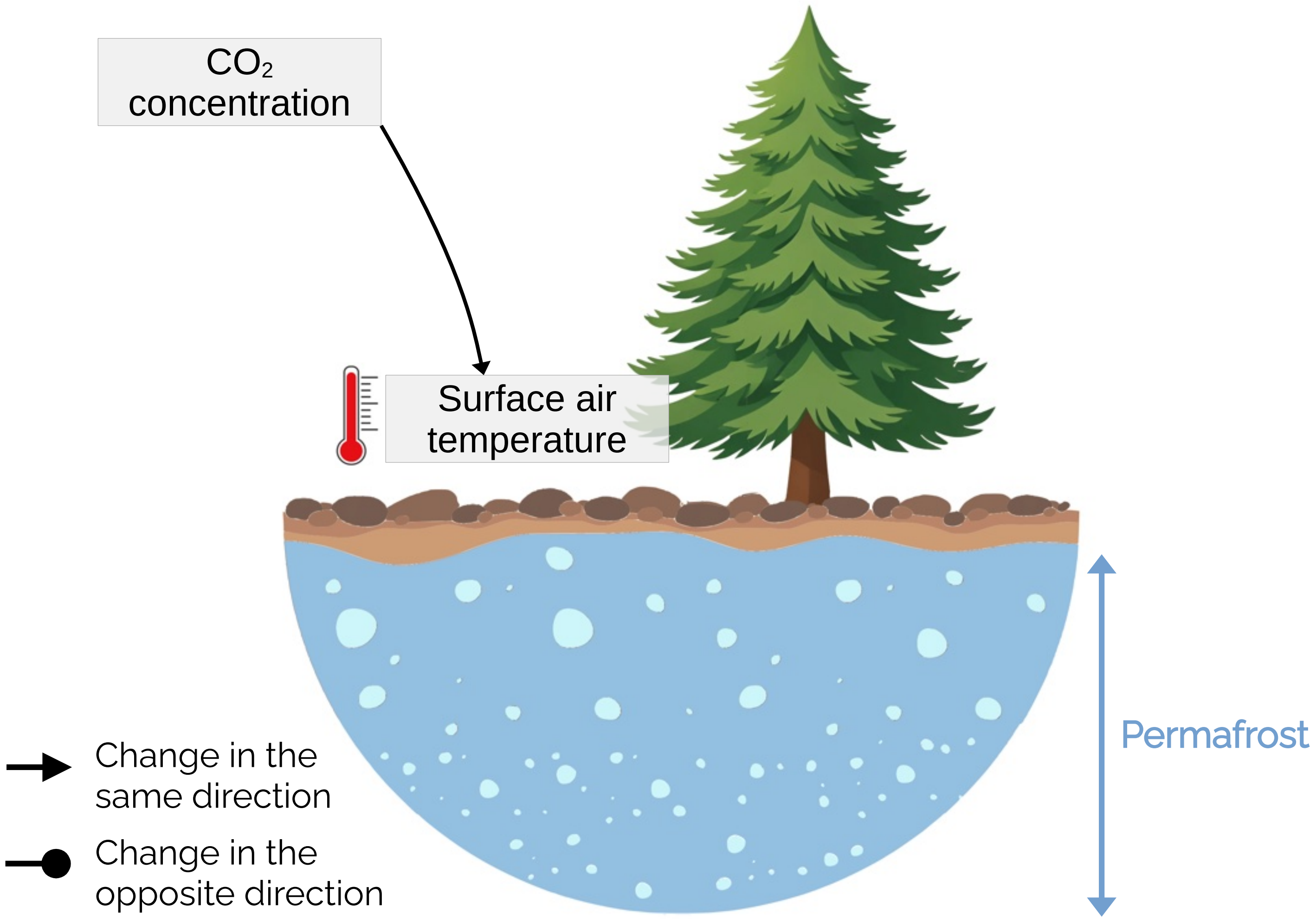




IPCC AR6 WGI Chap.2, 2021

Biskaborn et al., 2019

The permafrost carbon-climate feedback could amplify global warming



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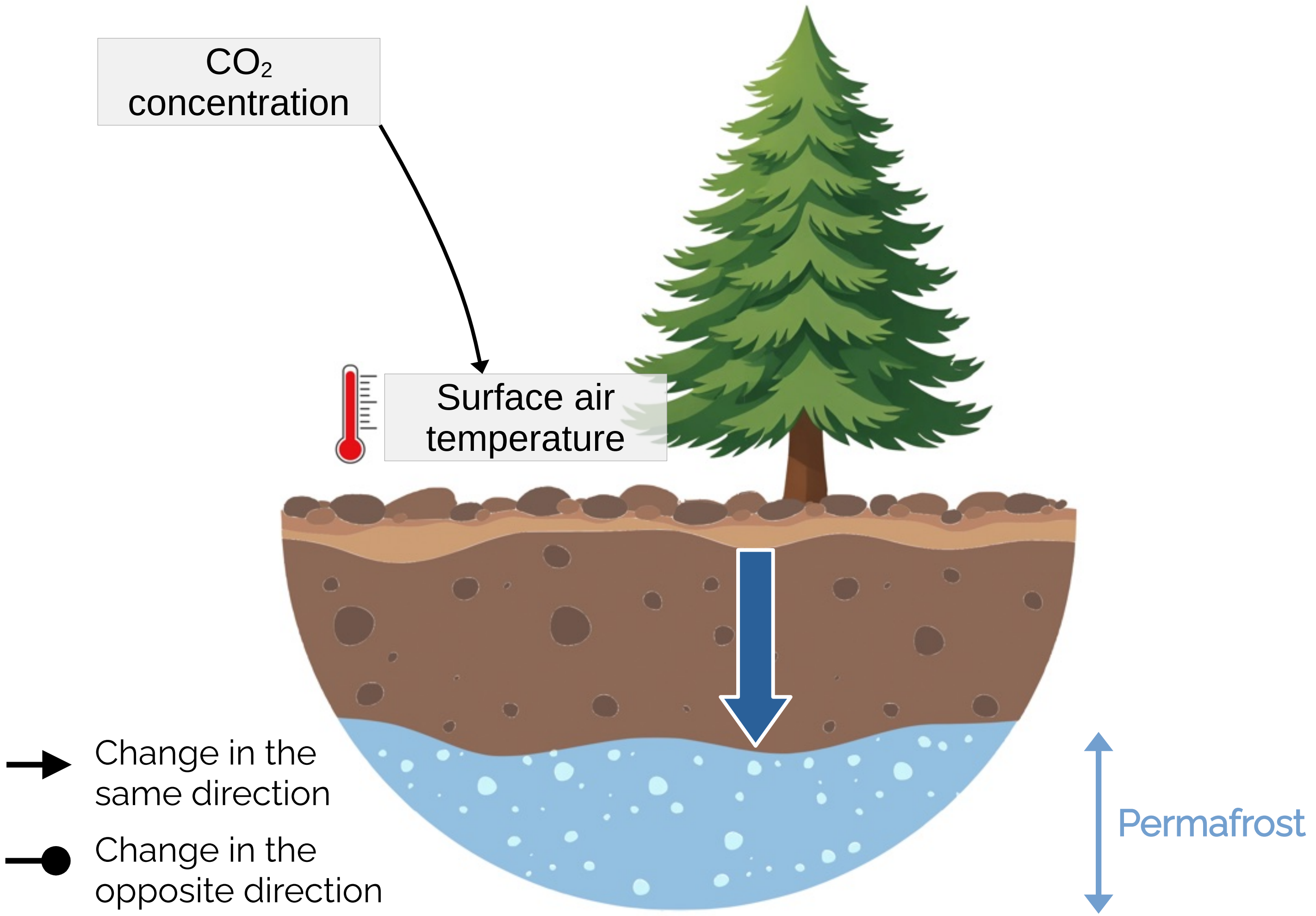

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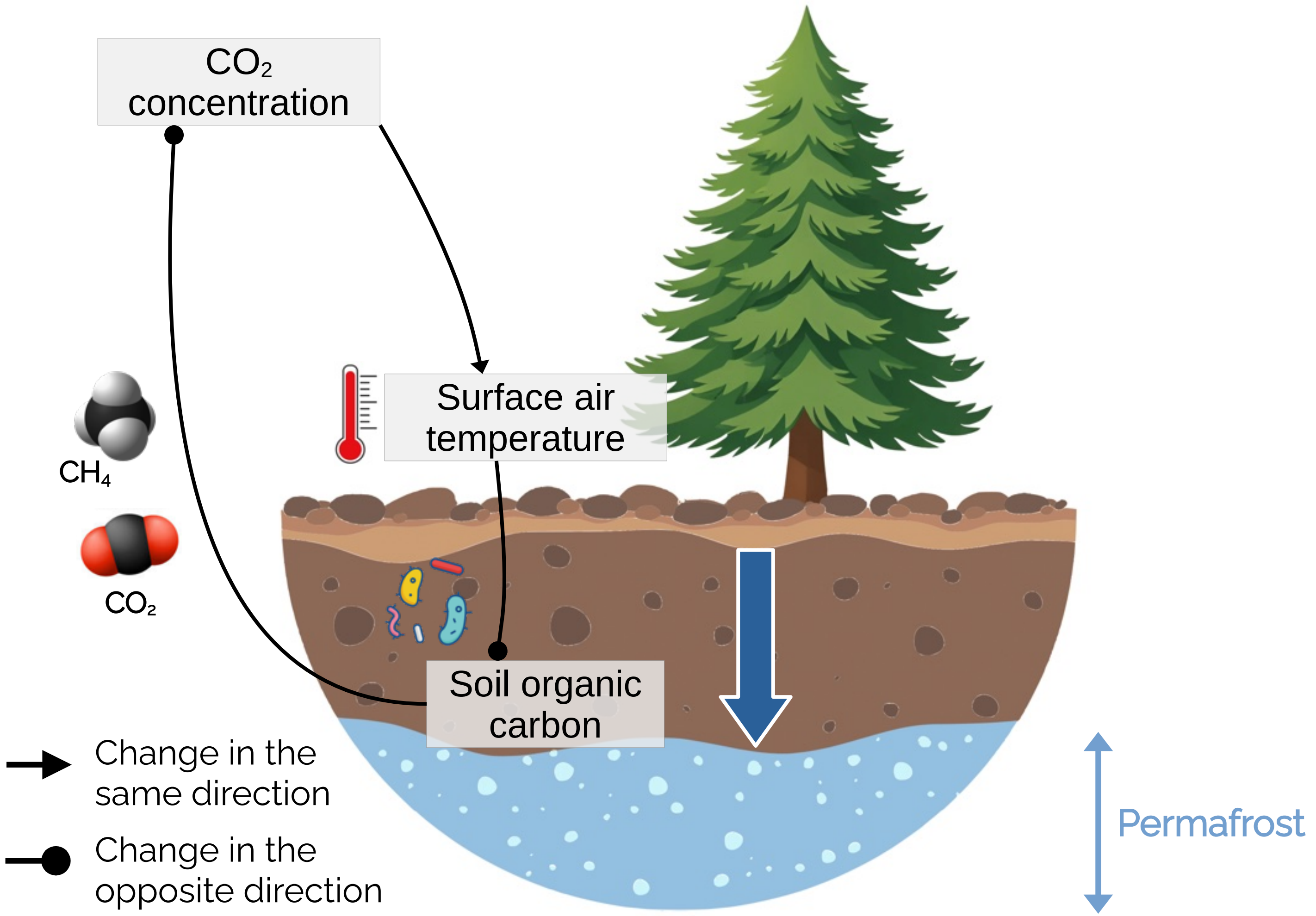

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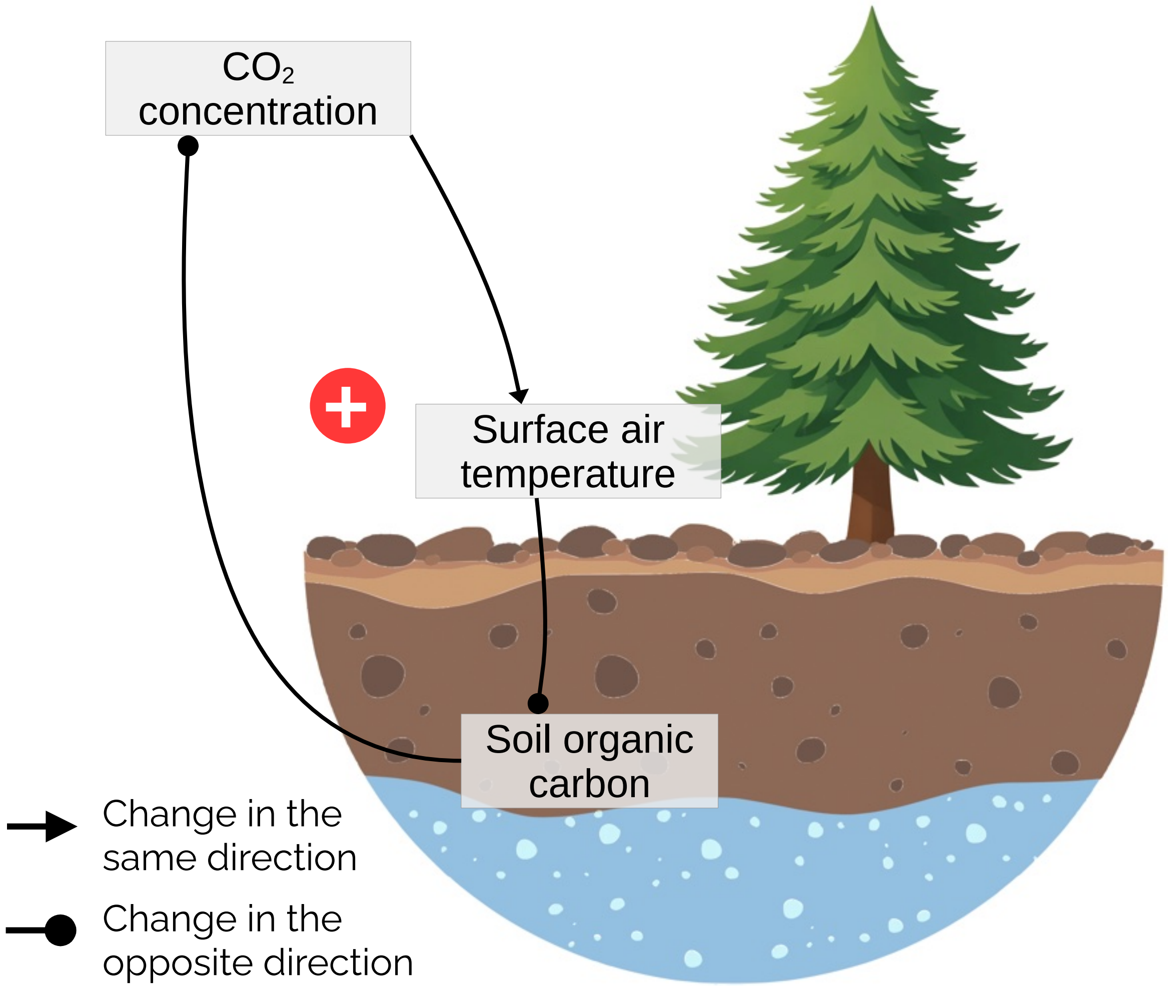

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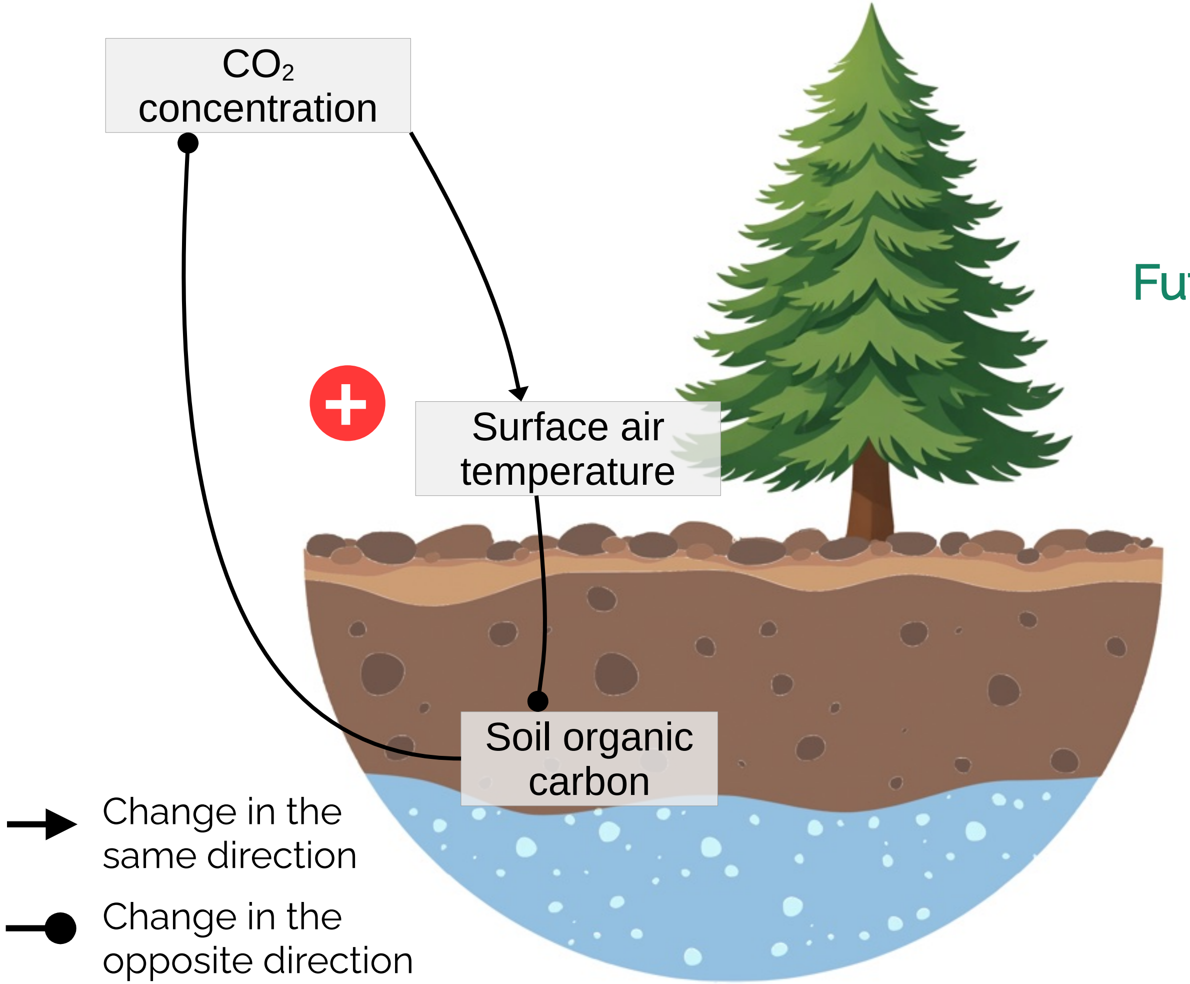
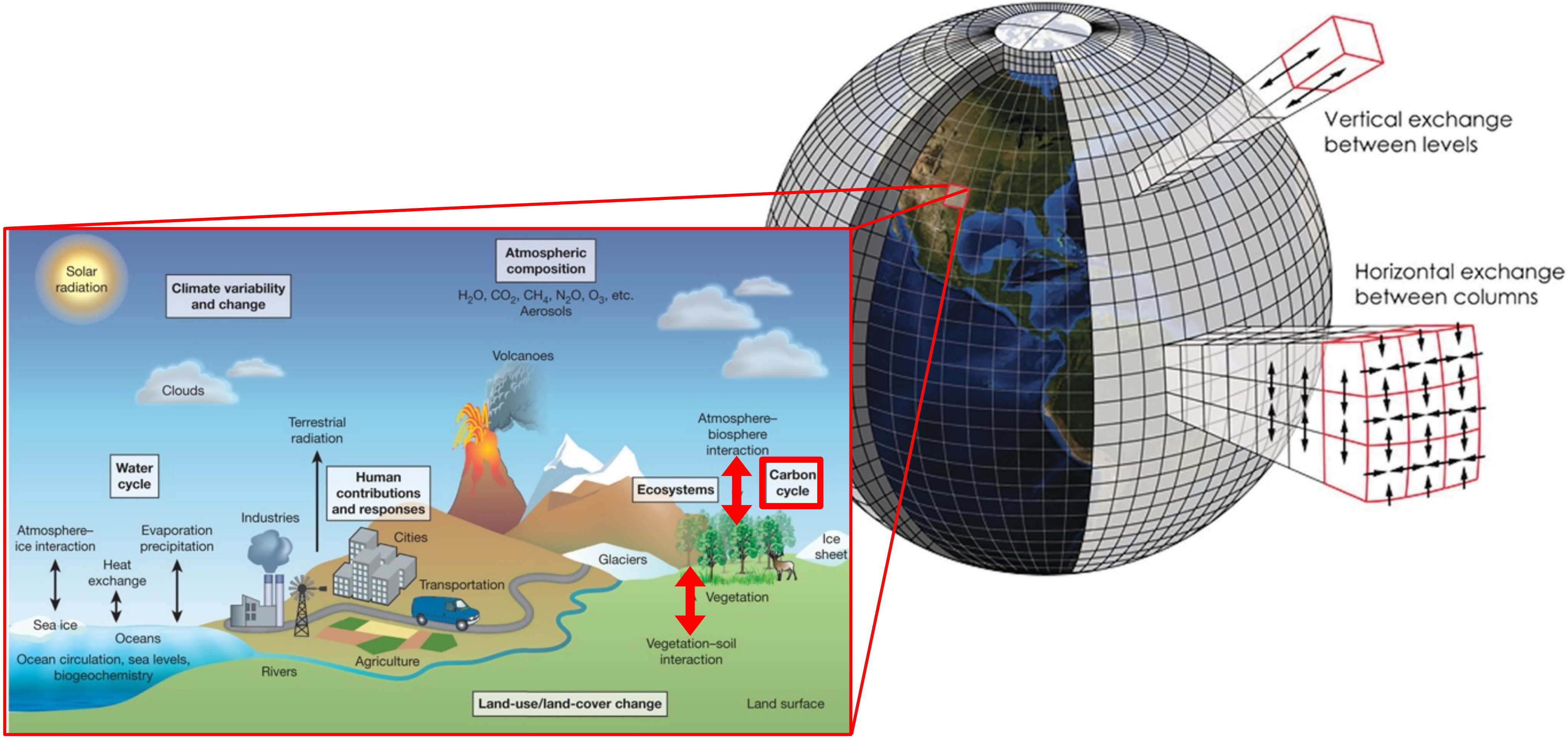


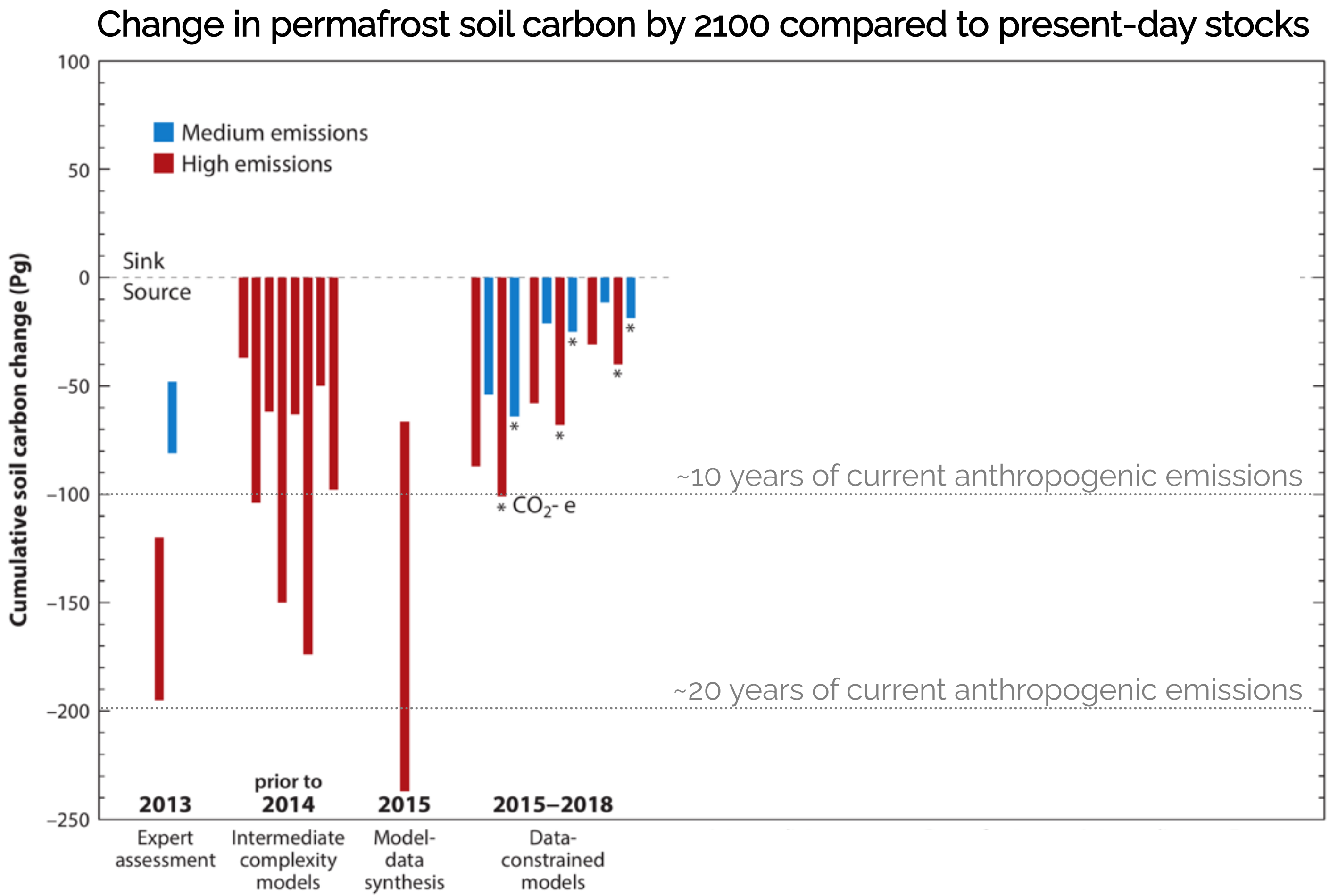
Future strength of this feedback ?

Earth system models (ESMs) or land surface models (LSMs)



Adapted from Moss et al., 2010 and Kotamarthi et al., 2021

Historically, permafrost has been seen as a potential carbon source...

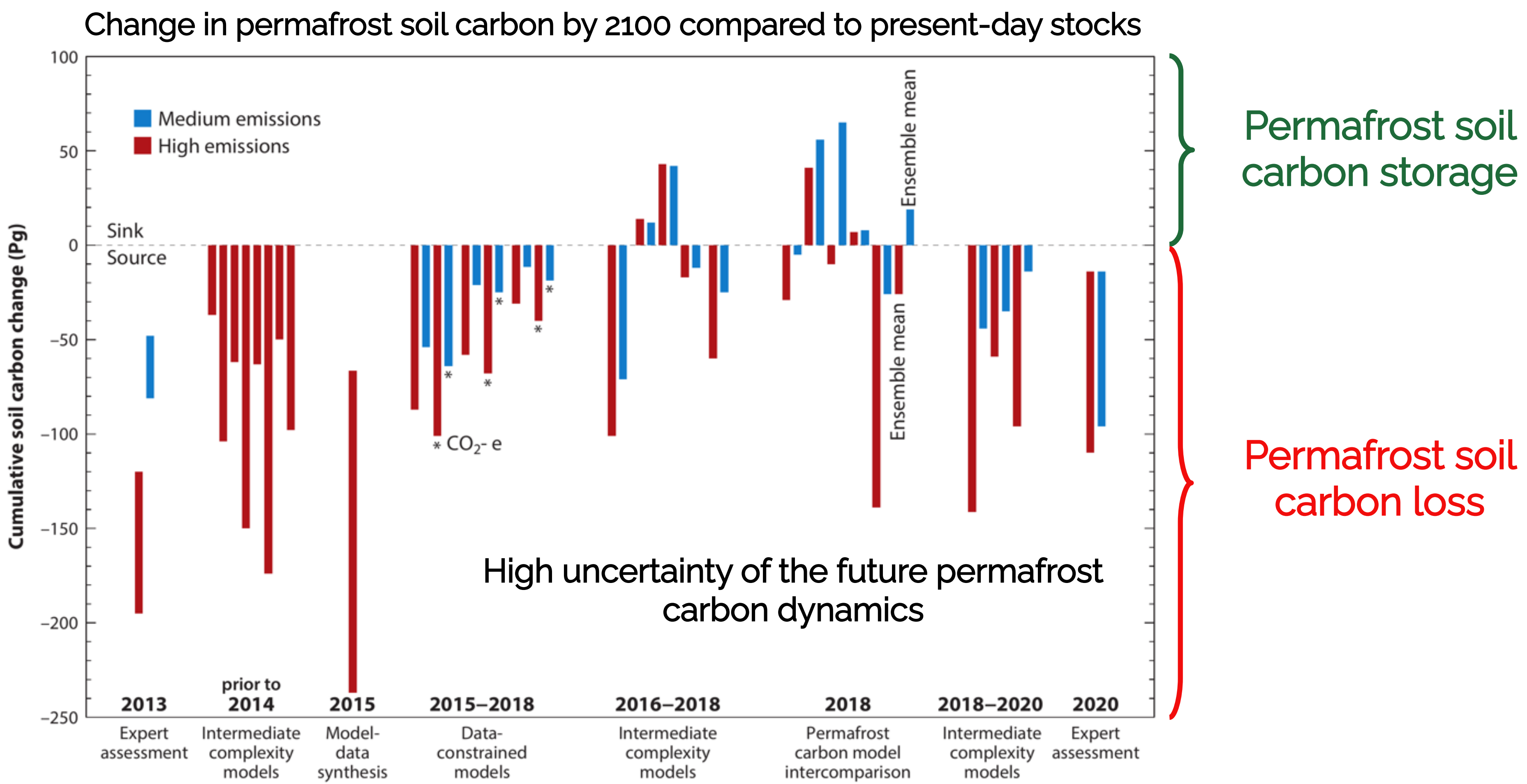


Permafrost soil carbon storage

Permafrost soil carbon loss

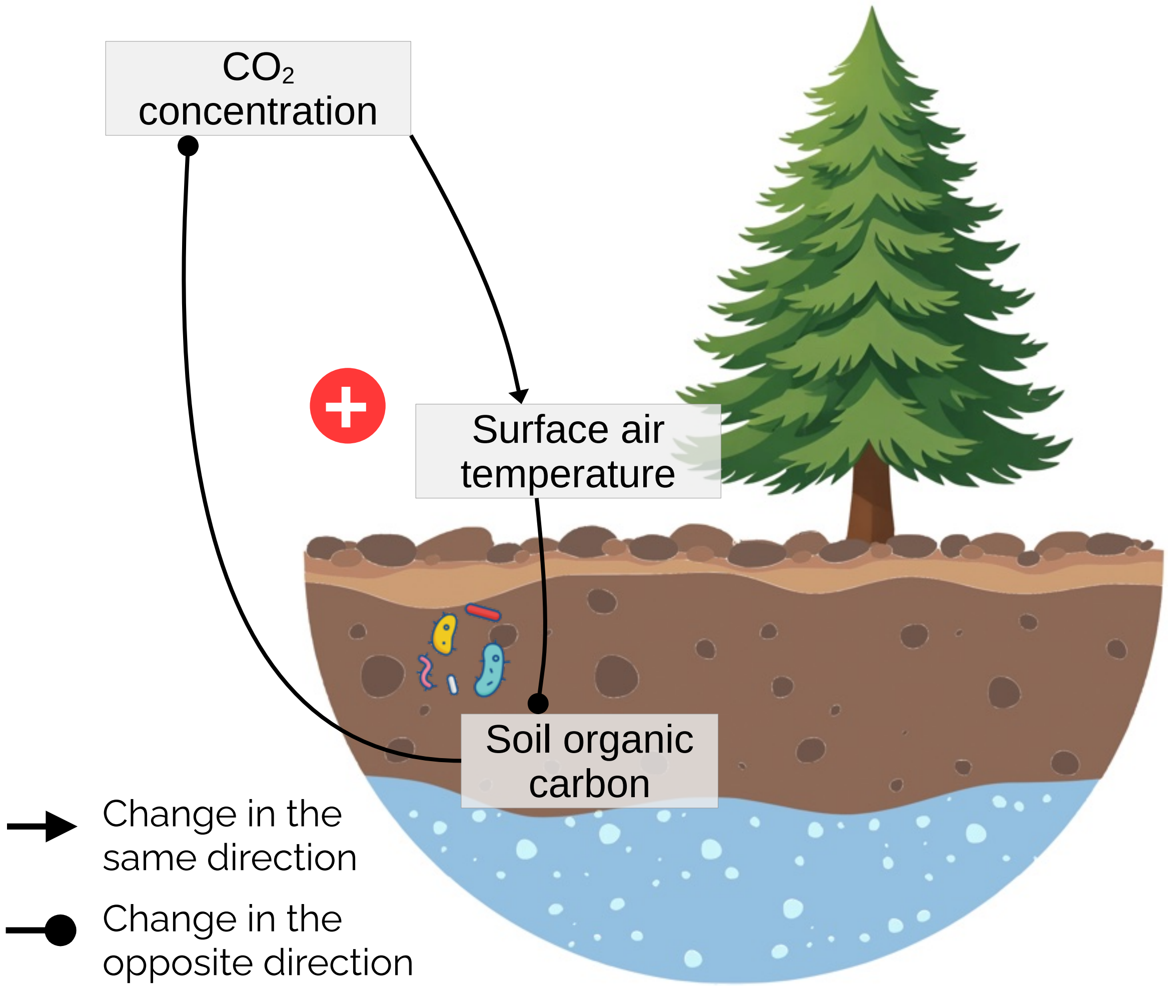
Schuur et al., 2022

...but the story gets more complicated as models become more complex



Schuur et al., 2022

The permafrost carbon-climate feedback depends on the parameterization of soil respiration



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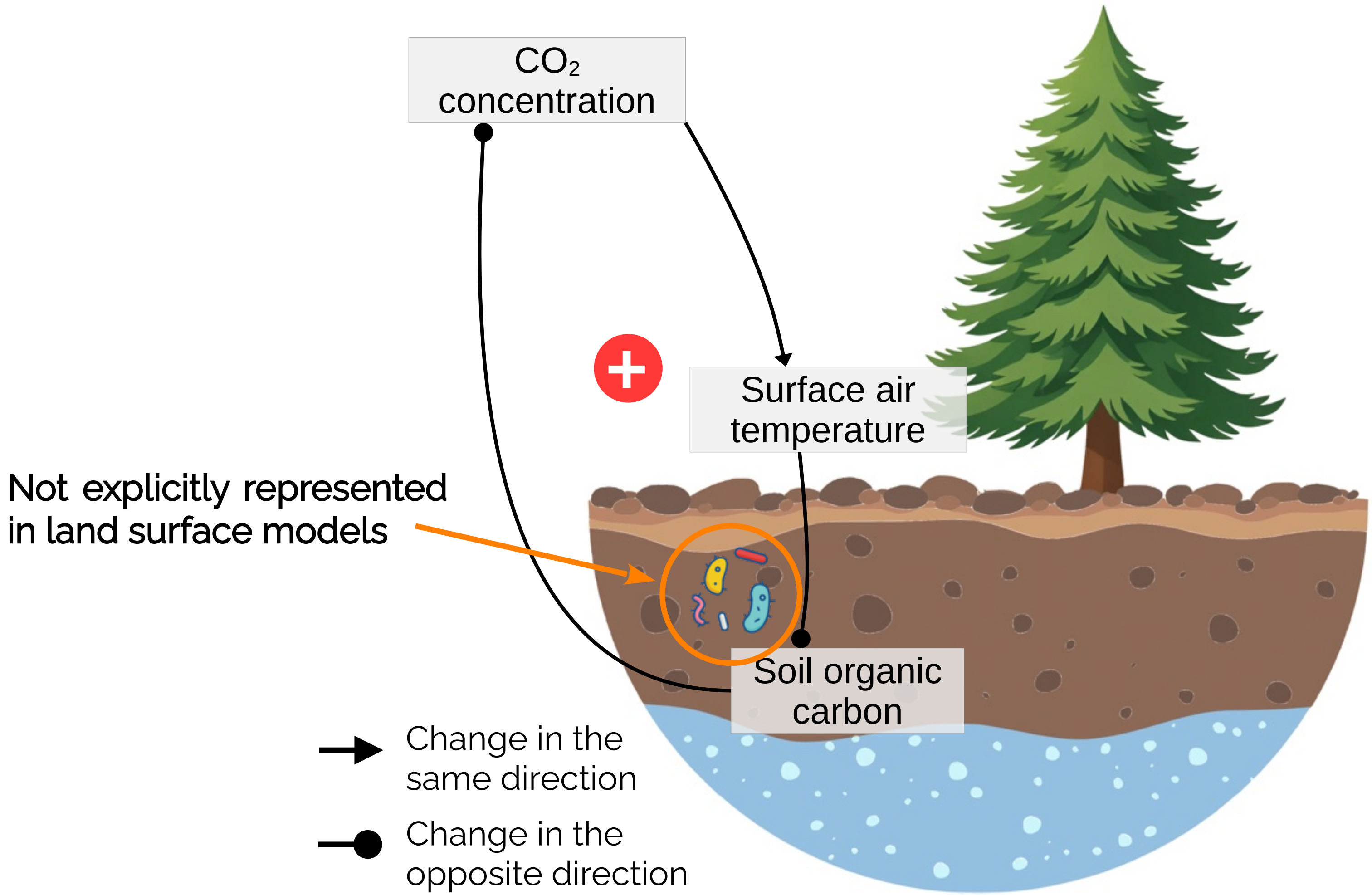

Parameterization of soil respiration in LSMs and ESMs

→ Soil organic carbon dynamics follows a simple equation :

$$\frac{\partial SOC}{\partial t} = I - \underbrace{k \times SOC \times \theta \times \tau}_{\text{Soil respiration}}$$

SOC = soil organic carbon concentration ($kgC.m^{-3}$)
I = SOC inputs ($kgC.m^{-3}.s^{-1}$)
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Arrhenius equation or Van't Hoff laws

$$\tau = A \times e^{-Ea/RT}$$

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Models are highly sensitive to Q_{10}

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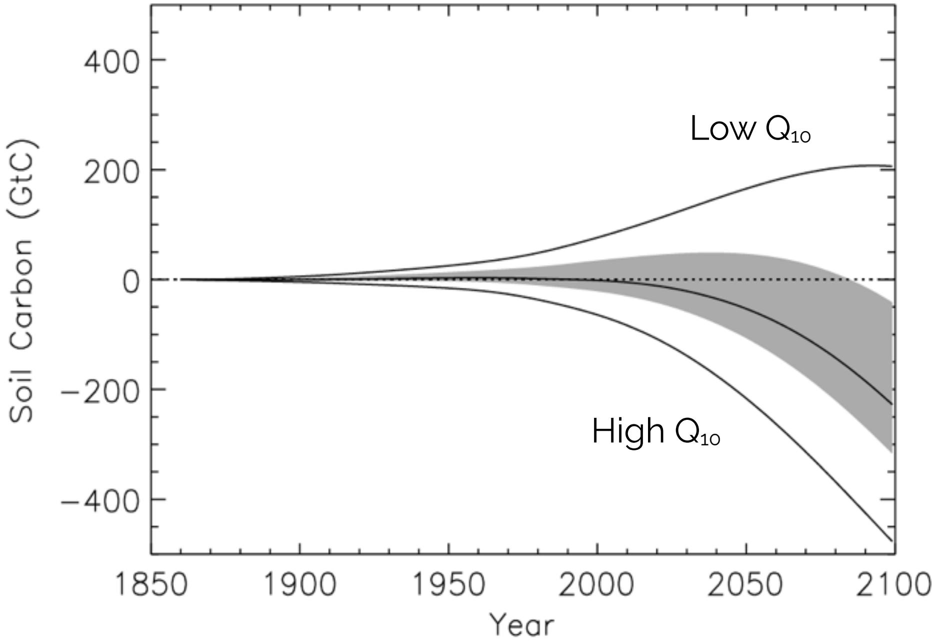
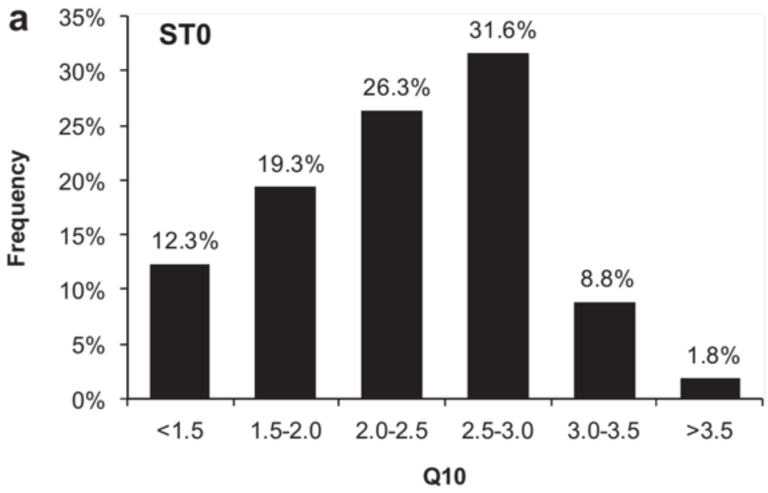


→ Simple climate-carbon cycle model under a high-emission scenario

→ From +200 PgC gain to -475 PgC loss in soil carbon in 2100

Jones et al., 2003

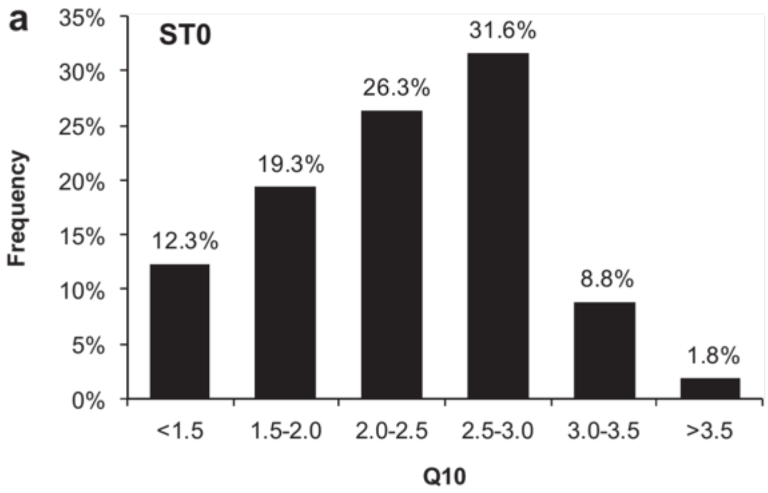
But observations show that Q_{10} depends on time

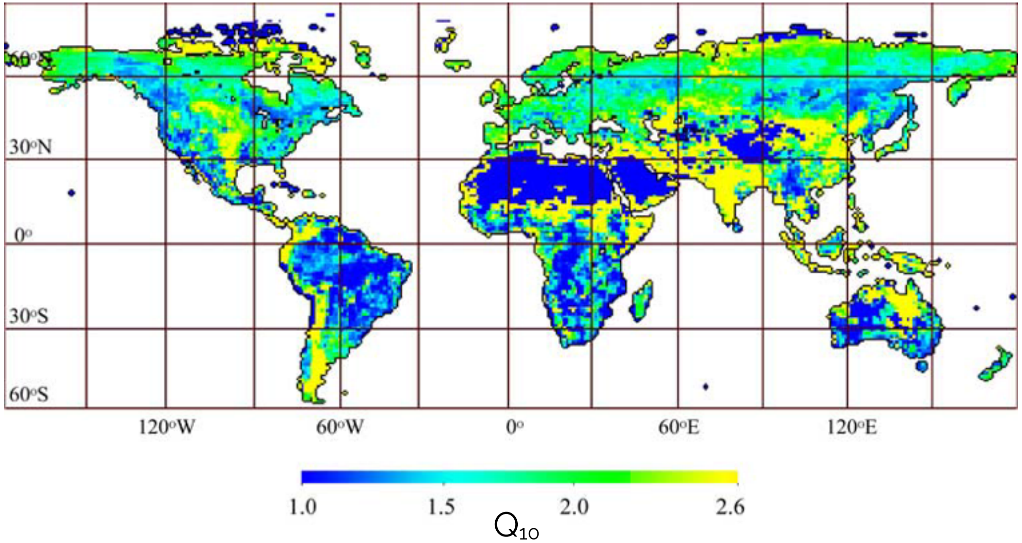


→ Seasonal variations of Q_{10} from soil field measurements

Wang et al., 2010

But observations show that Q_{10} depends on time and space





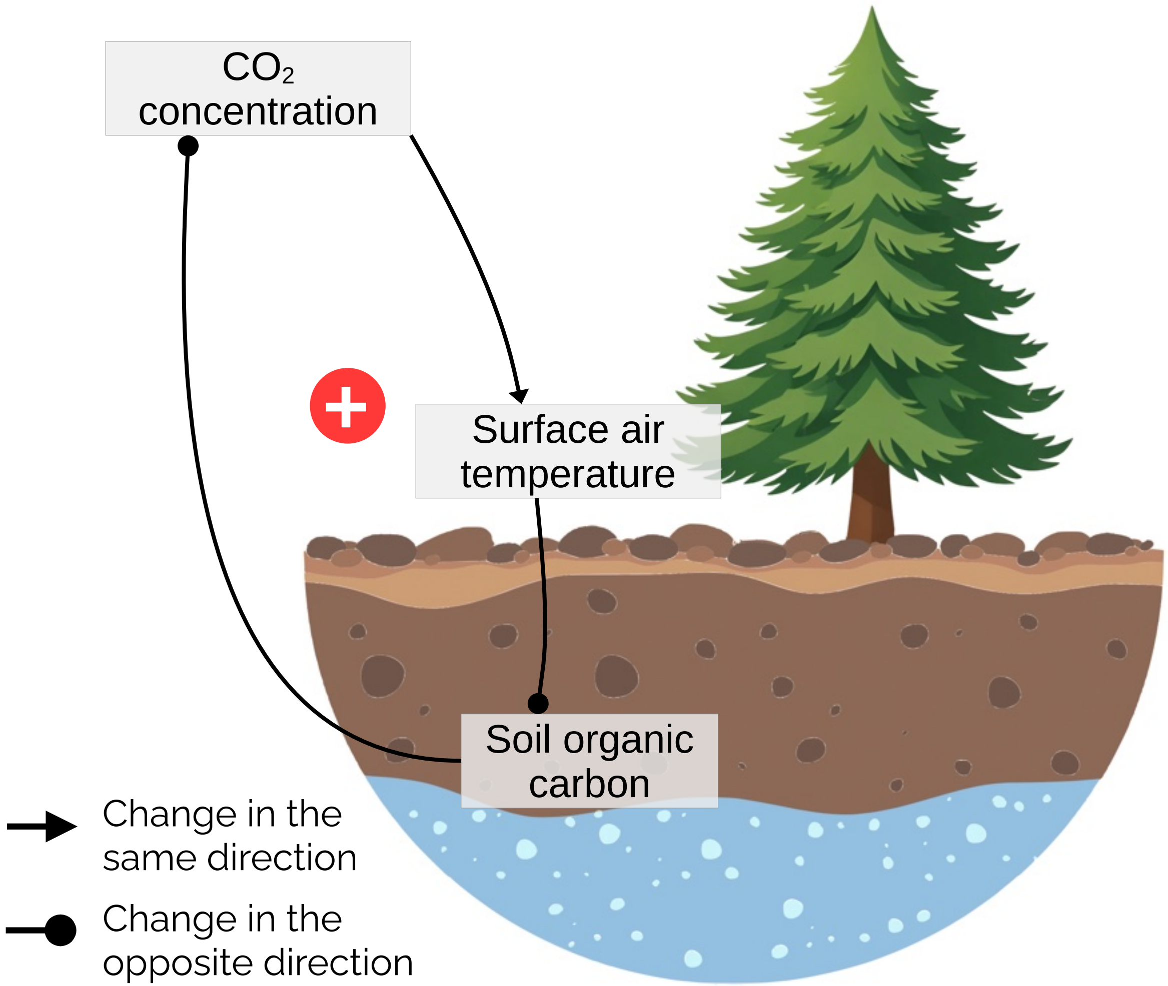
→ Seasonal variations of Q_{10} from soil field measurements

→ Spatial variations of Q_{10} from inverse modeling

Wang et al., 2010

Zhou et al., 2009

Another source of uncertainty comes from the response of vegetation to warming and CO_2



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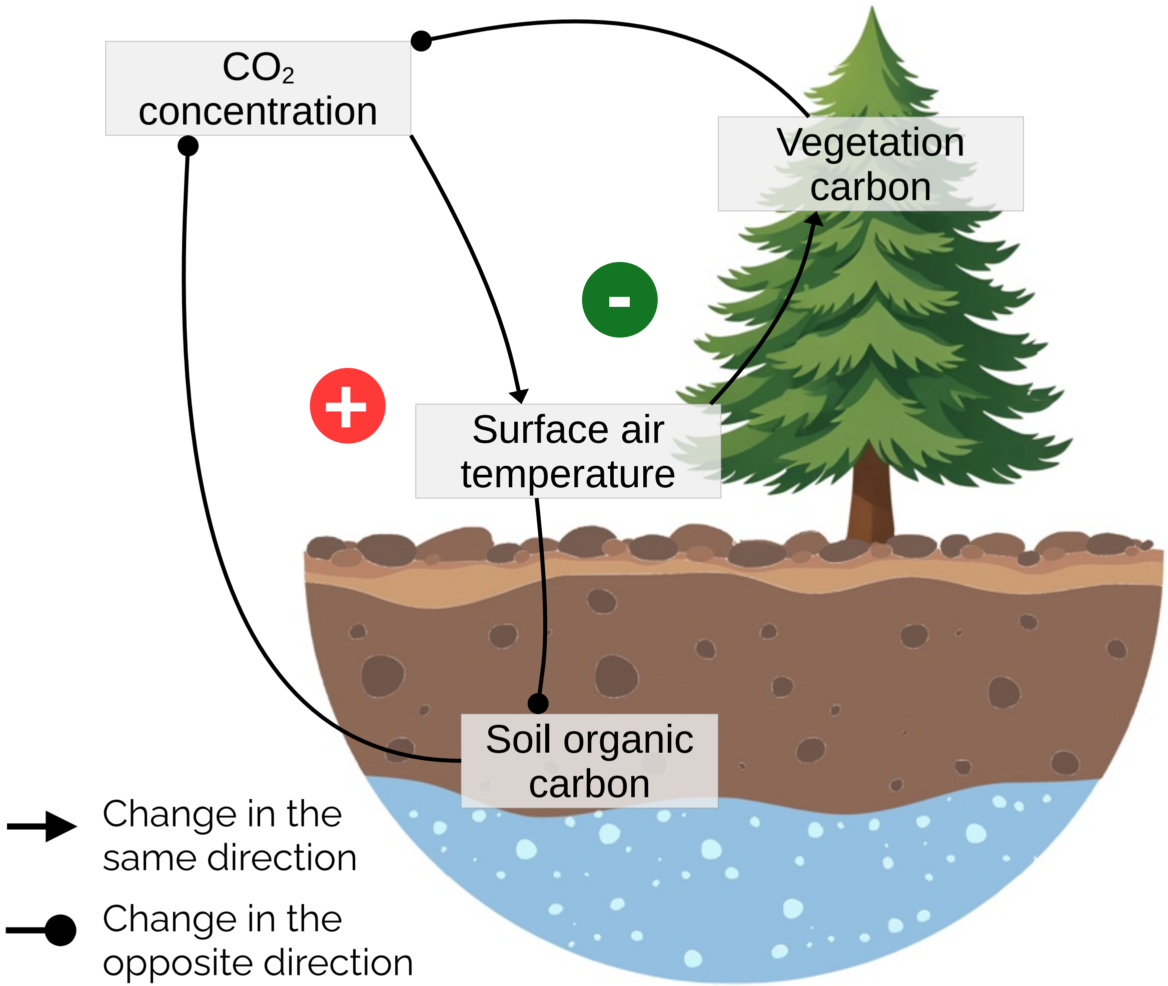

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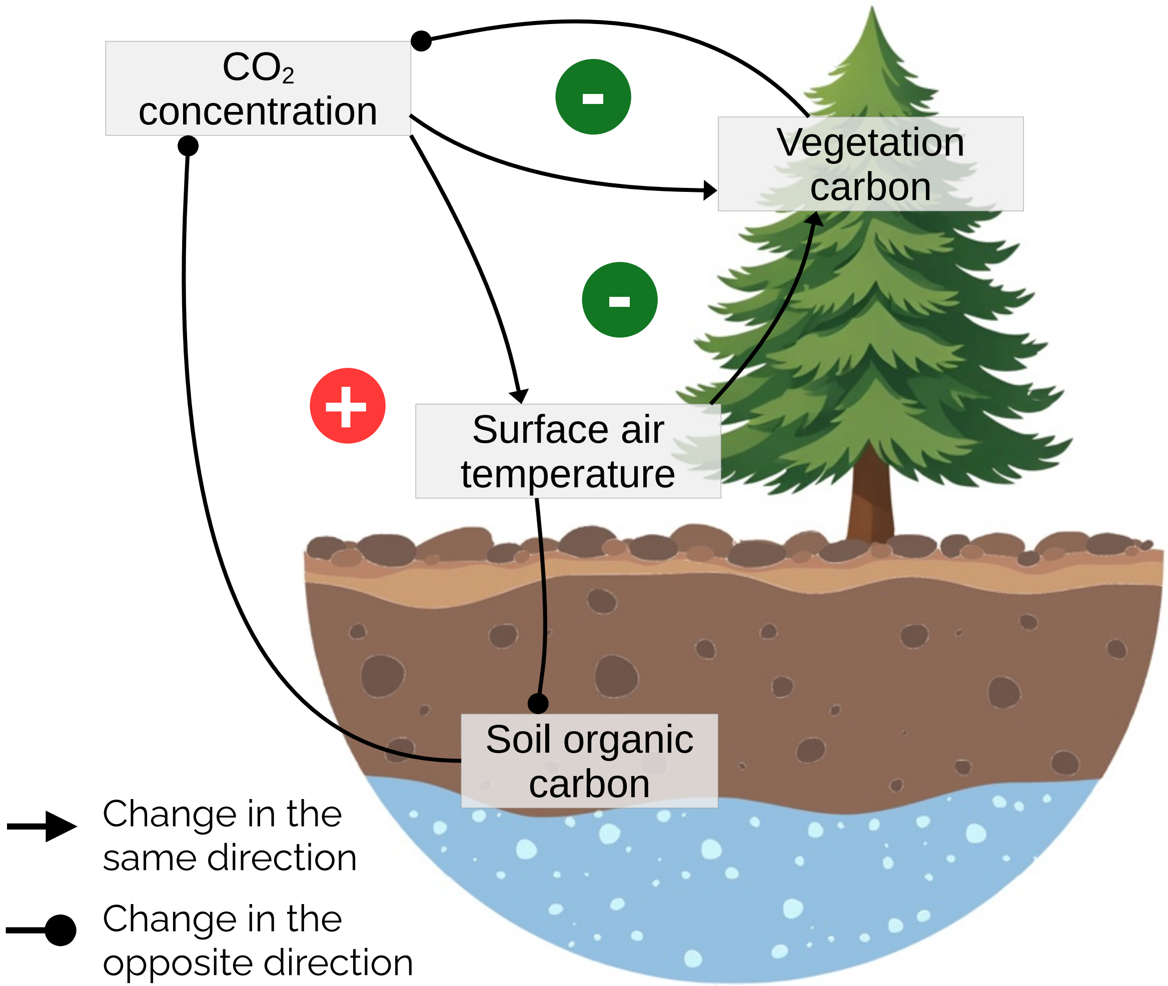
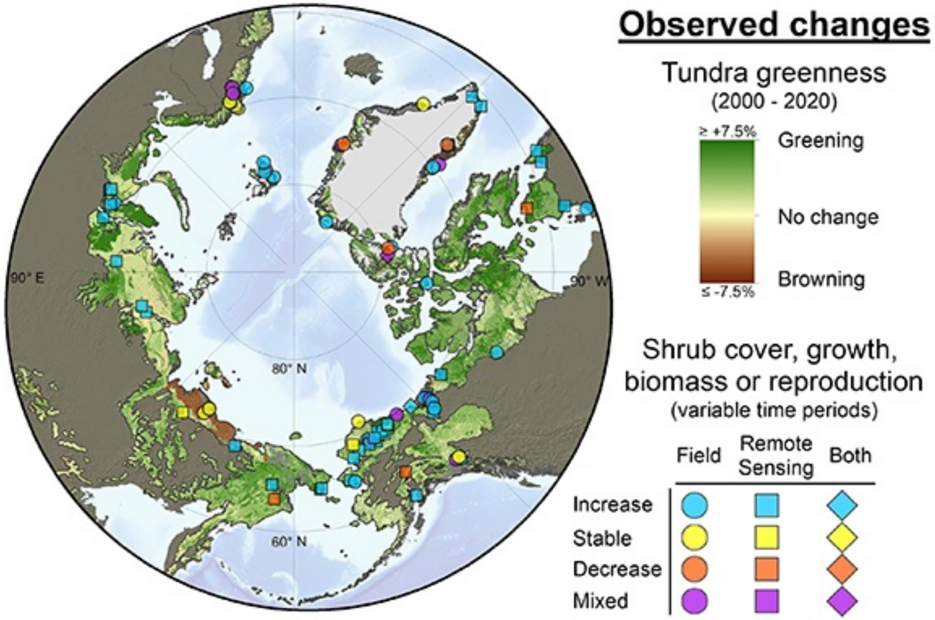


Arctic borealisation and shrubification

→ Increase in shrub biomass, growth and reproduction in the Arctic tundra.



Mekonnen et al., 2021

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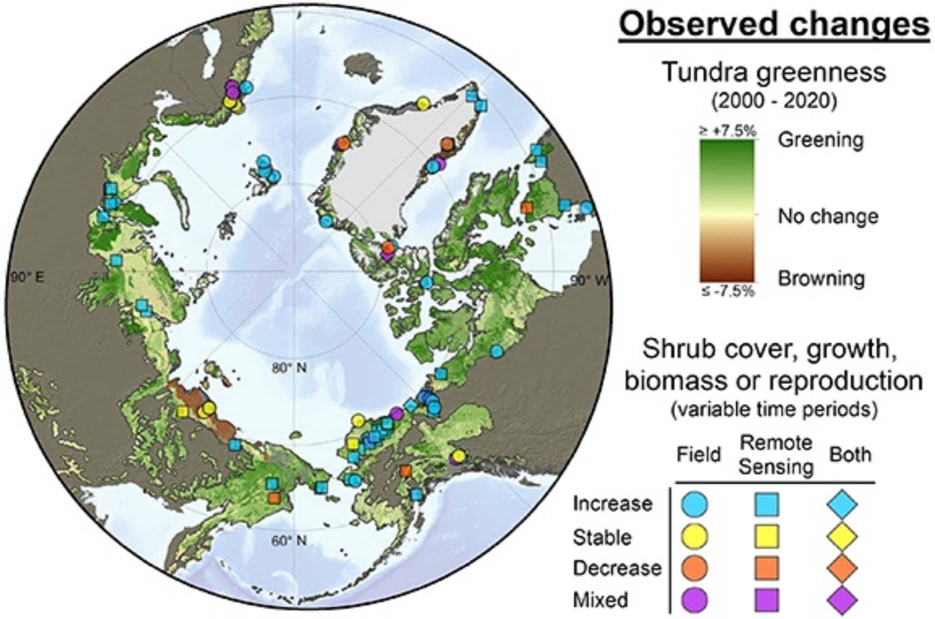

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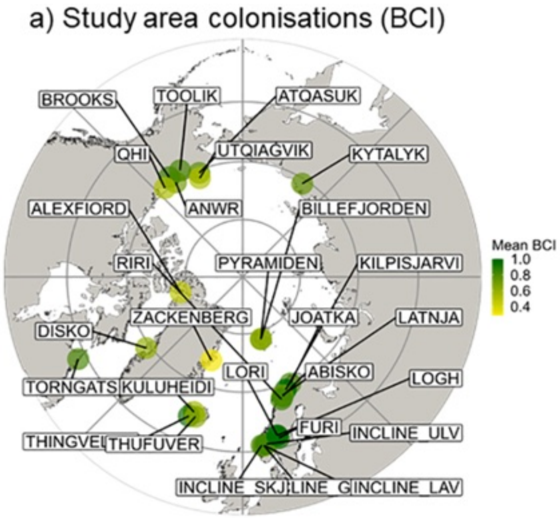

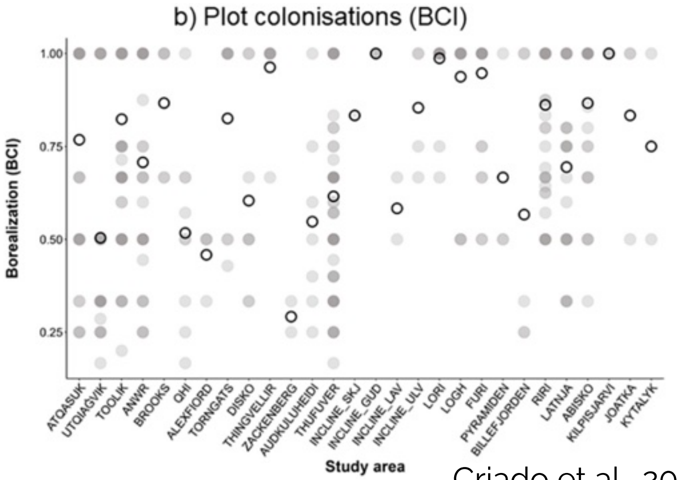

Criado et al., 2025

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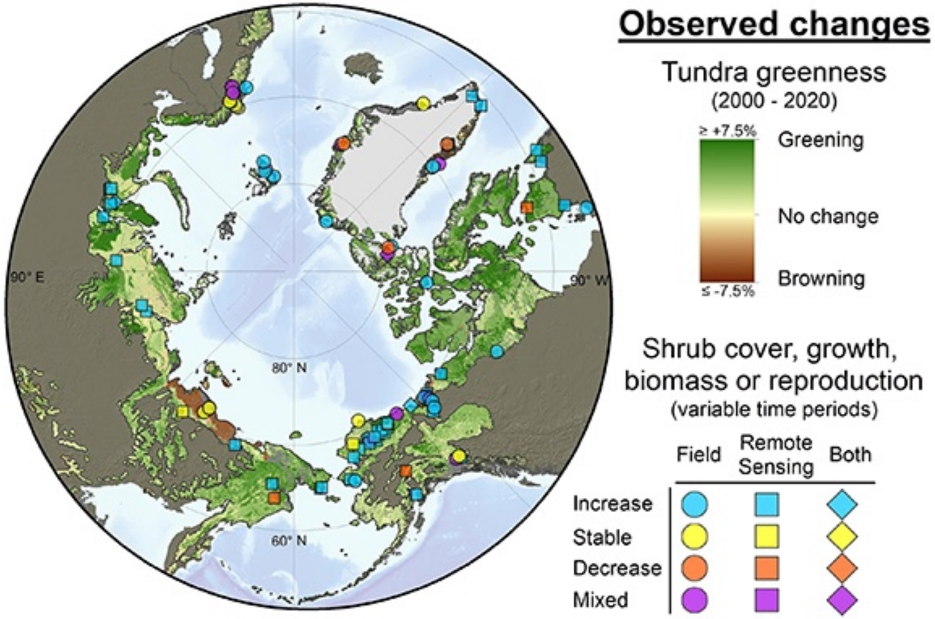
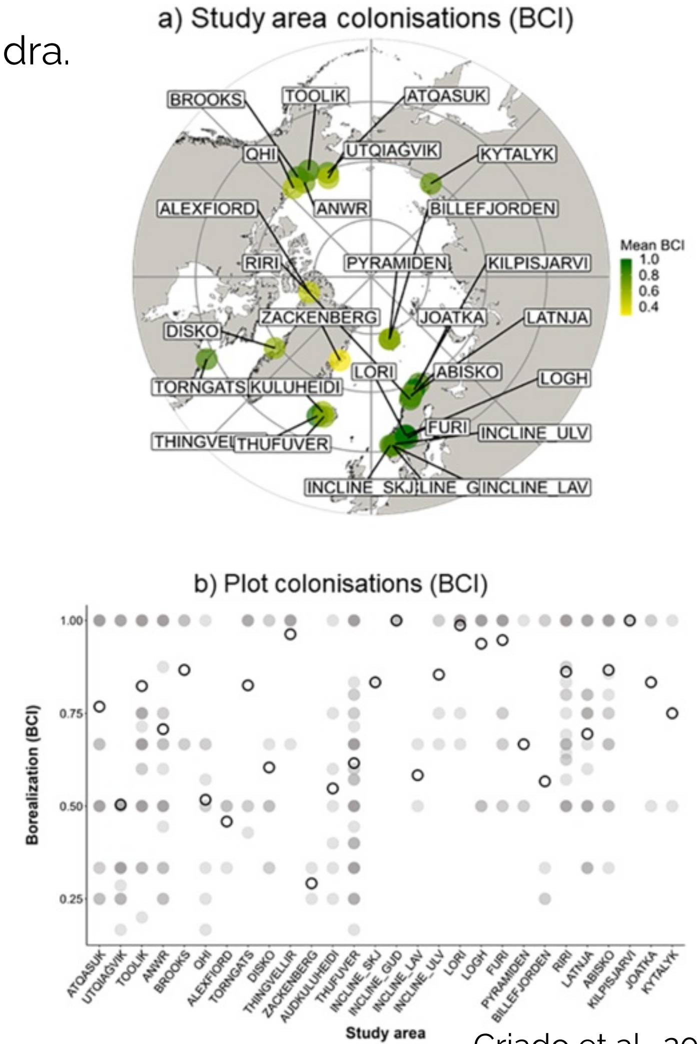
→ What impact on the permafrost carbon cycle ?



Mekonnen et al., 2021

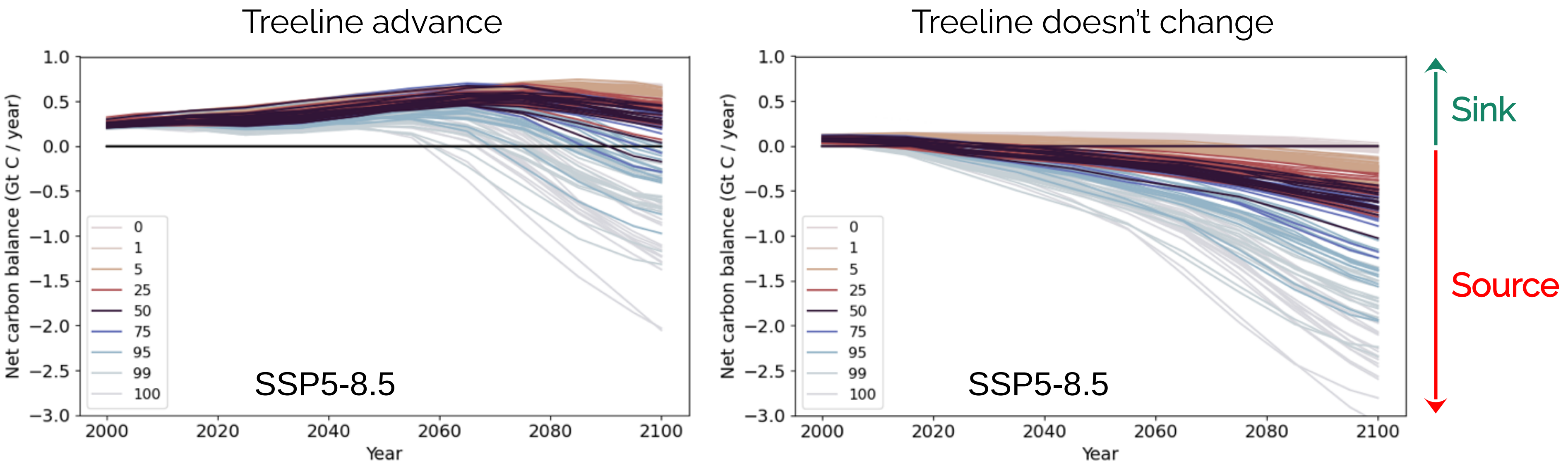


Criado et al., 2025

The dynamics of vegetation could have a great impact on future carbon uptake

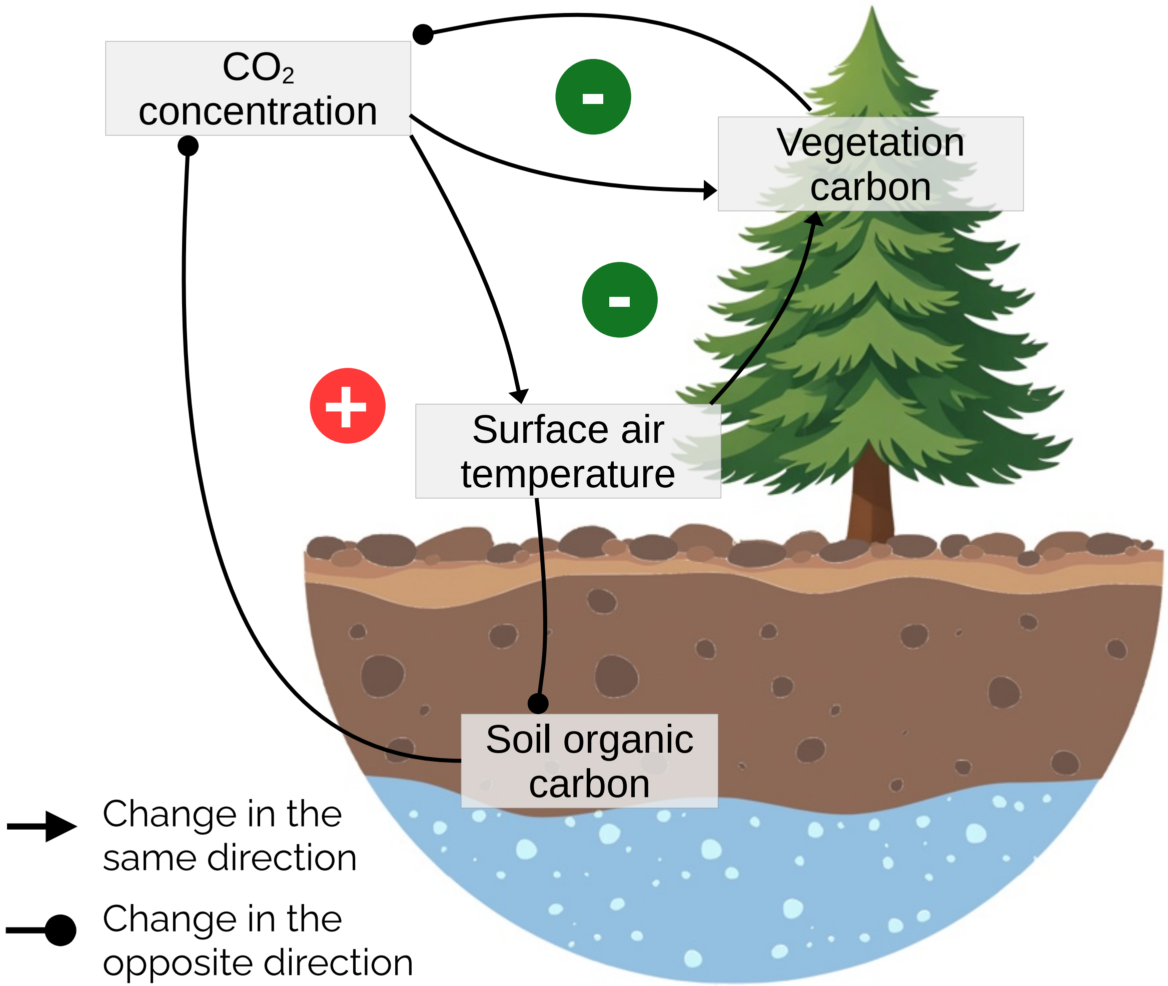
→ Land surface model (JULES) simulations show a sustained carbon uptake due to the advance of treeline in a high-warming scenario.

→ Partially offsets soil carbon losses from permafrost thaw and microbial decomposition.



Courtesy of E. Burke

Nitrogen release from permafrost thaw could also increase vegetation carbon uptake



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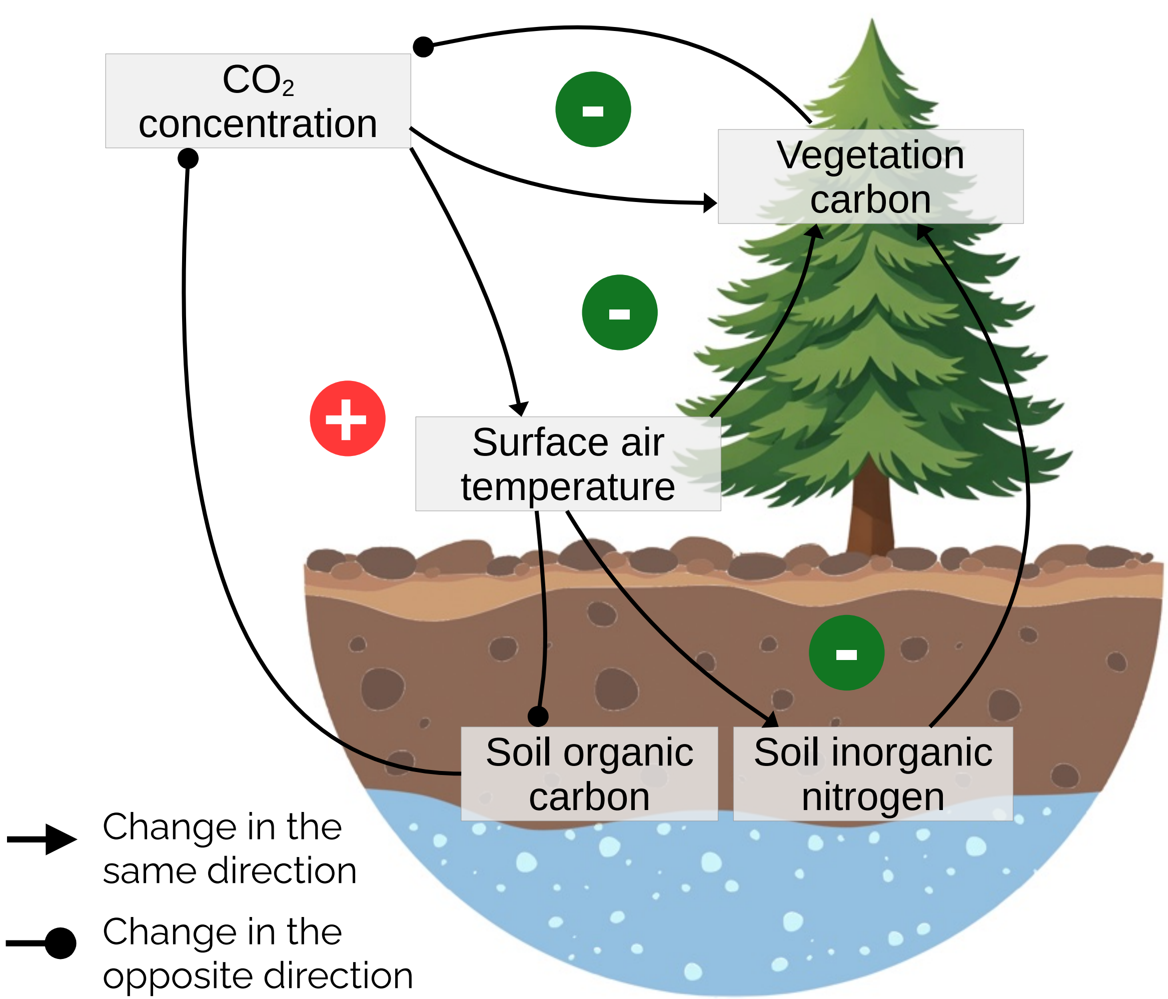
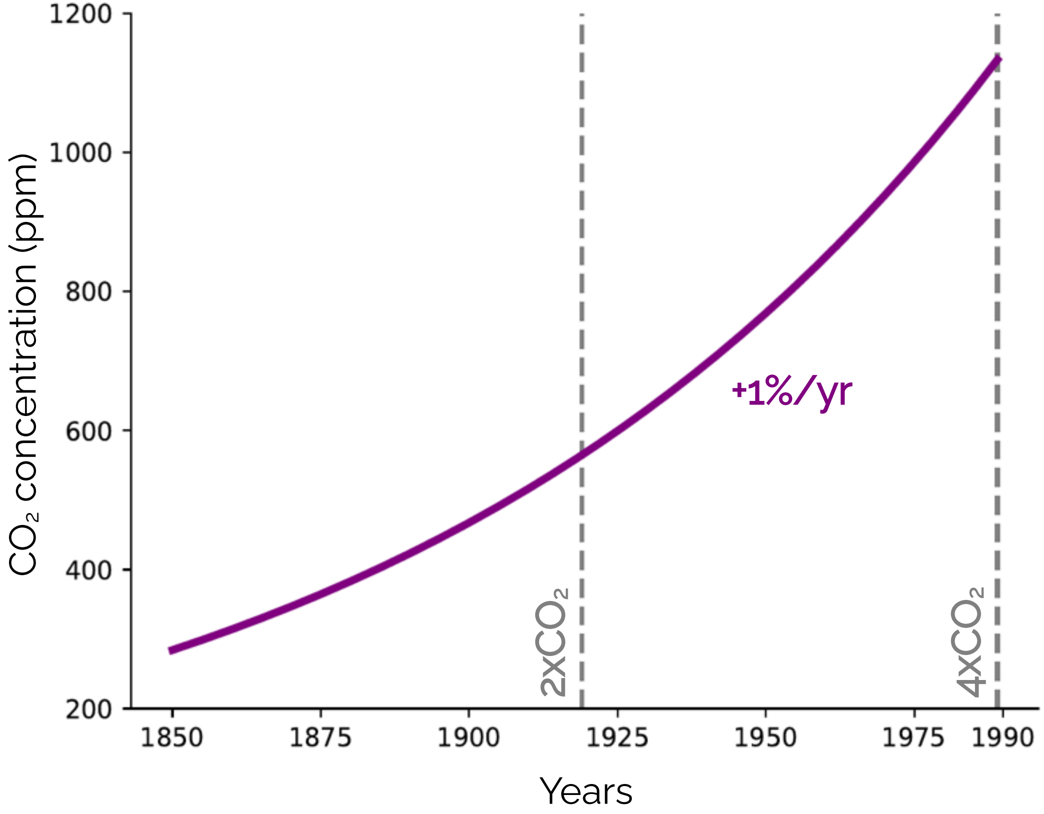


Idealised 1pctCO2 experiment from C_4MIP

→ CO_2 increases at 1%/yr



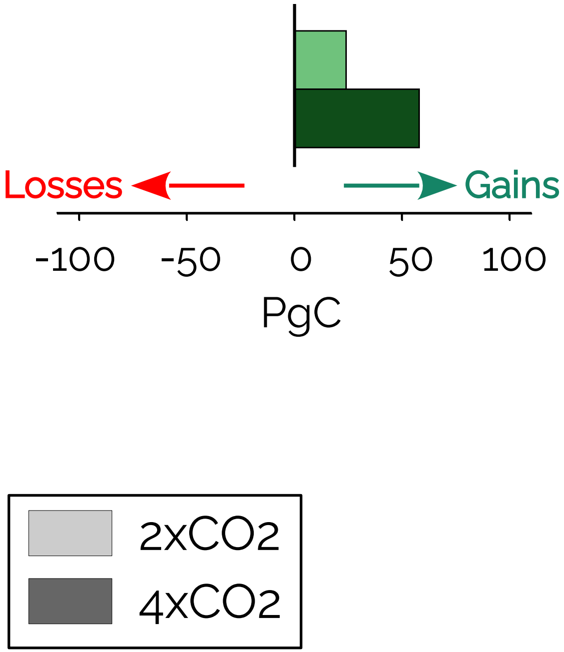
→ All other greenhouse gases at pre-industrial concentrations

→ All other forcings (land-use, nitrogen inputs…) pre-industrial

Land gains carbon throughout the simulation in the permafrost region

Changes in the **permafrost region** simulated by an **Earth system model** (IPSL-Perm-LandN)

ΔC_{land} = Change in total land carbon (vegetation + soils)



Gaillard et al. (in prep)

ΔC_{land} is driven by CO_2 fertilization

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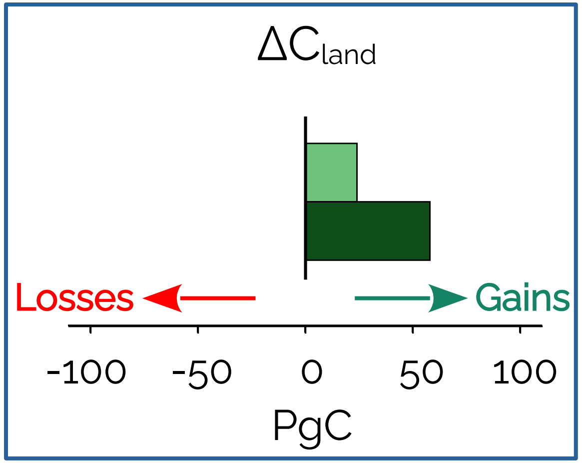

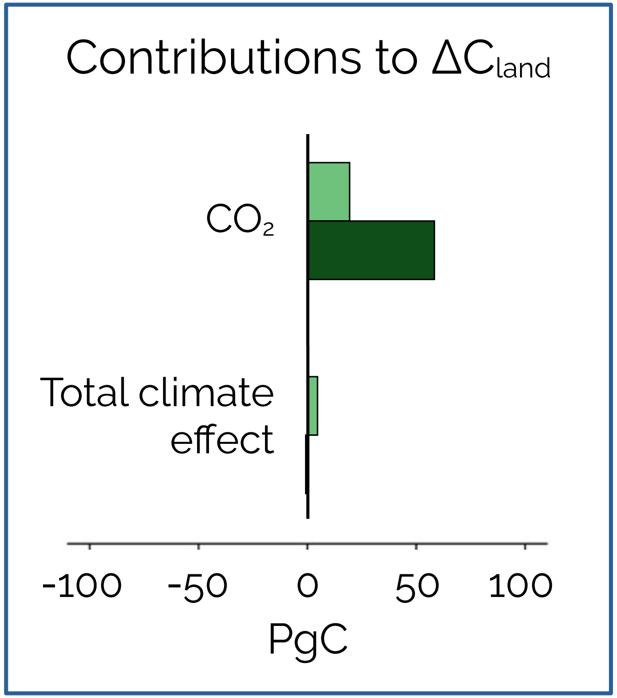

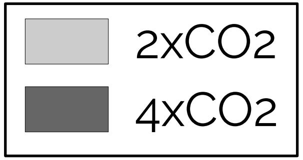

→ Total climate effect is negligible

Gaillard et al. (in prep)

Strong nitrogen effect compensates direct climate effect

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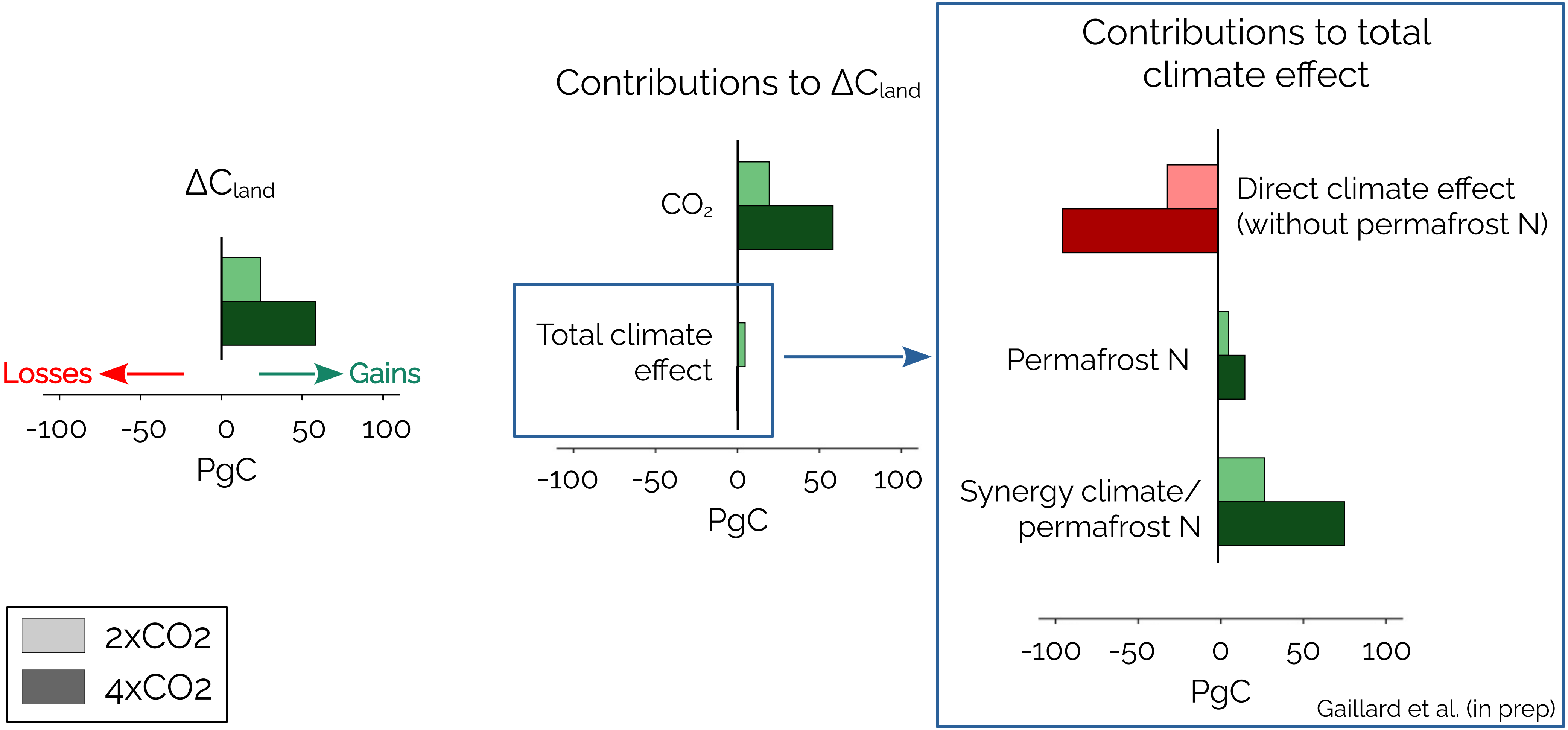


Strong nitrogen effect compensates direct climate effect

Changes in the **permafrost region** simulated by an **Earth system model** (IPSL-Perm-LandN)

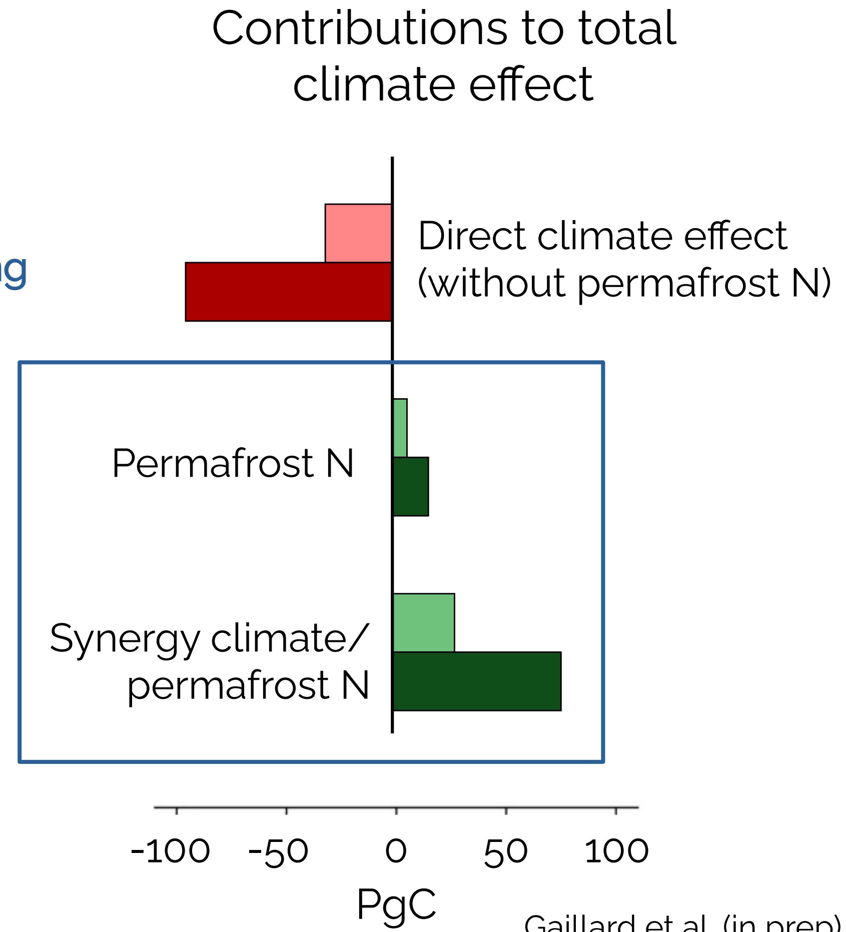
→ Nitrogen effect assessed in few modelling studies with **contrasting results**

+ Strong increase in vegetation carbon uptake due to increased nitrogen availability (Burke et al., 2022).

= Limited to no effect of nitrogen release on vegetation carbon uptake (Lacroix et al., 2022; Koven et al., 2015).

Supporting

Contrasting



(light)	2xCO2
(dark)	4xCO2

Gaillard et al. (in prep)

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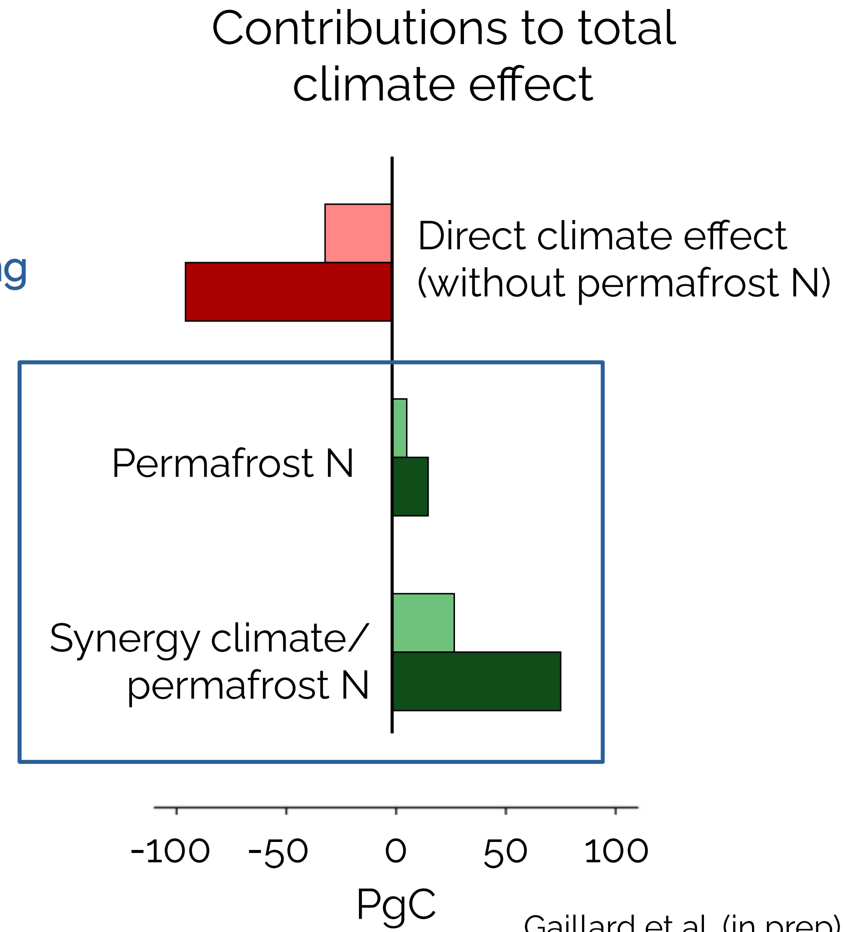

Gaillard et al. (in prep)

→ The representation of **nitrogen dynamics** after permafrost thaw is key for accurately predicting the **future permafrost net carbon balance**.

Conclusion

→ The future net carbon balance of the permafrost region remains **uncertain**.

→ As LSMs and ESMs become **more complex**, they start to integrate processes that could (partially?) compensate for warming-induced permafrost soil carbon losses.

→ A large part of the uncertainty originates from **biogeochemical processes**.

→ Improvements of the **physics** of models are also needed (snow dynamics, soil thermal properties and hydrology, small-scale heterogeneity, abrupt thaw processes…).