ITS4.1/NP8.9 | Hall X4 | EGU26-9438
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Irreversible Land Carbon Losses under Idealized Overshoot Experiments

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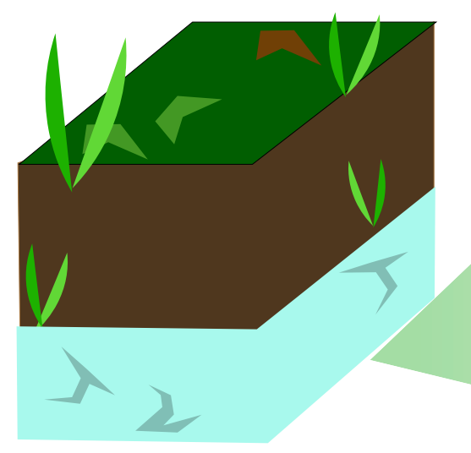

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- How does terrestrial carbon respond to 2-4°C overshoots and recovery?
- How does warming-induced CO₂ fertilization effect compete with climate change effect?
- What controls the magnitude and reversibility of land carbon losses under warming?

GFDL **TIPMIP**-ESM and **LPX** model

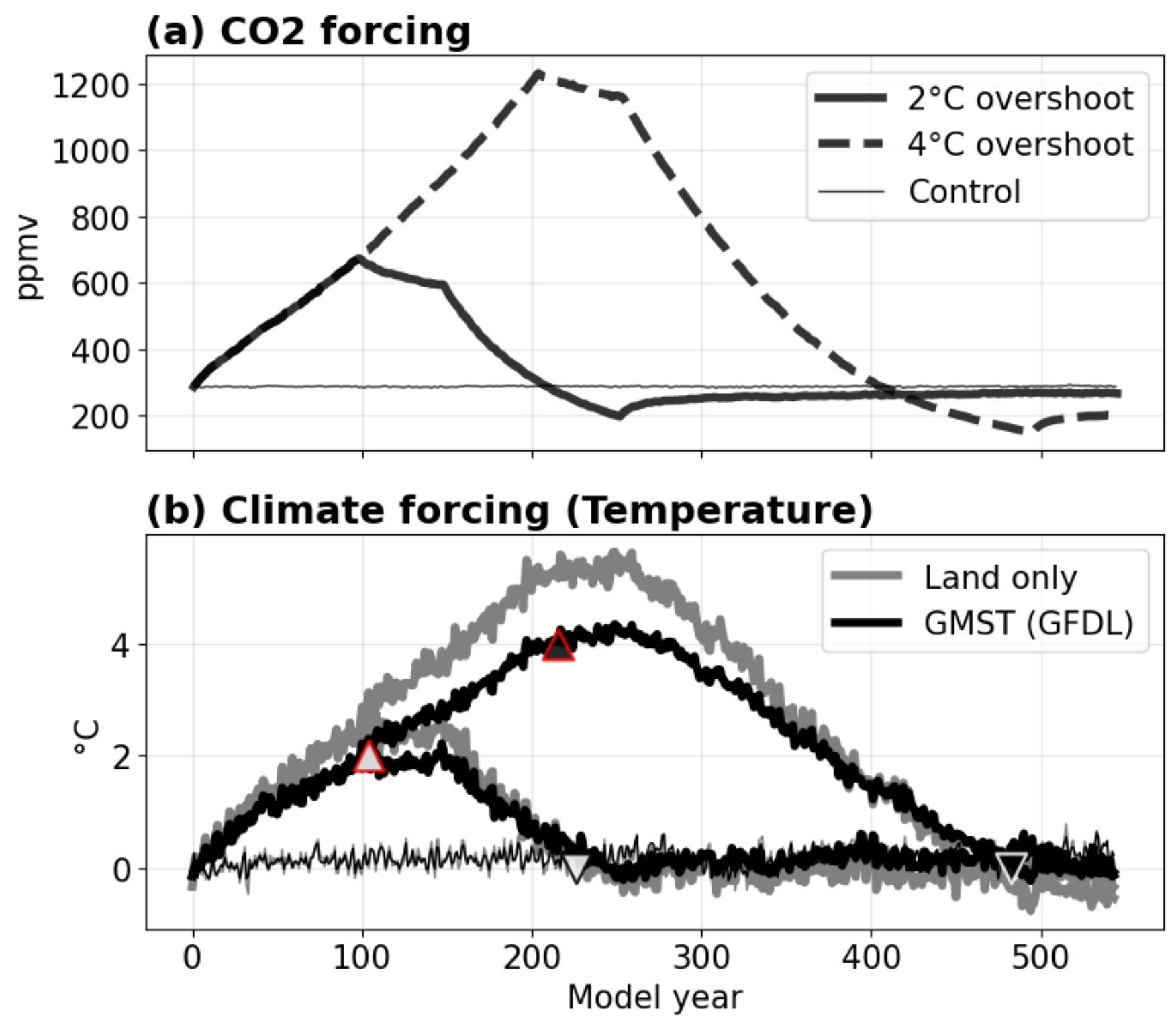
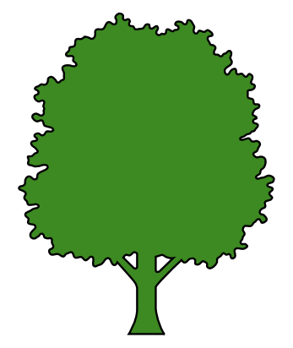


Figure 1. Time series of (a) atmospheric CO$_2$ used to constrain 2°C and 4°C ramp-up and ramp-down scenarios in GFDL TIPMIP-ESM experiments[1], and the corresponding time series of **(b) global mean surface temperature** (black) and global mean land surface temperature (grey).

- **LPX (Dynamic Global Vegetation Model):** includes peatland (wetland)[2], permafrost, and fire processes, coupled N-C cycling, dynamic vegetation, and methane; N deposition, N fertilization, harvest, and land use land cover change fixed at year 1901.
- **Spin-up:** 15,000 years under PI-control climate fields and 280 ppm CO₂ to generate realistic peatland (~490 PgC)[3] and permafrost (~300 PgC) carbon stocks. Computational speed is approximately 1,000 model years per hour on the HPC of the University of Bern.
- **LPX-Forcing:** Annually varying atmospheric CO₂ and monthly climate fields (surface temperature, precipitation, cloud cover) derived from **GFDL-ESM2M TIPMIP-ESM** overshoot scenarios[1] and PI control simulations (Fig 1; Table 1)

Table 1. Experimental design showing target warming levels (ΔGMST), and whether CO$_2$ and climate fields are prescribed as PI-control or transient

#	ΔGMST (°C)	CO2 forcing	Climate forcing	
1		PI (280 ppm)	PI	
2	2	Transient	PI	β-effect: 0.6 PgC ppm^{-1}
3	4	Transient	PI	
4	2	PI	Transient	γ-effect: -29~-57 PgC K^{-1}
5	4	PI	Transient	
6	2	Transient	Transient	Net effect
7	4	Transient	Transient	



Takeaways

- Land carbon responds nonlinearly to warming due to **climate-induced C-loss**.
- Peatland and permafrost carbon losses at +4°C (~x3 Vs. +2°C) strongly reduce net carbon uptake.
- Permafrost thaw causes long-lasting, only partially reversible carbon loss.

① Warmer climate, less efficient land carbon sink

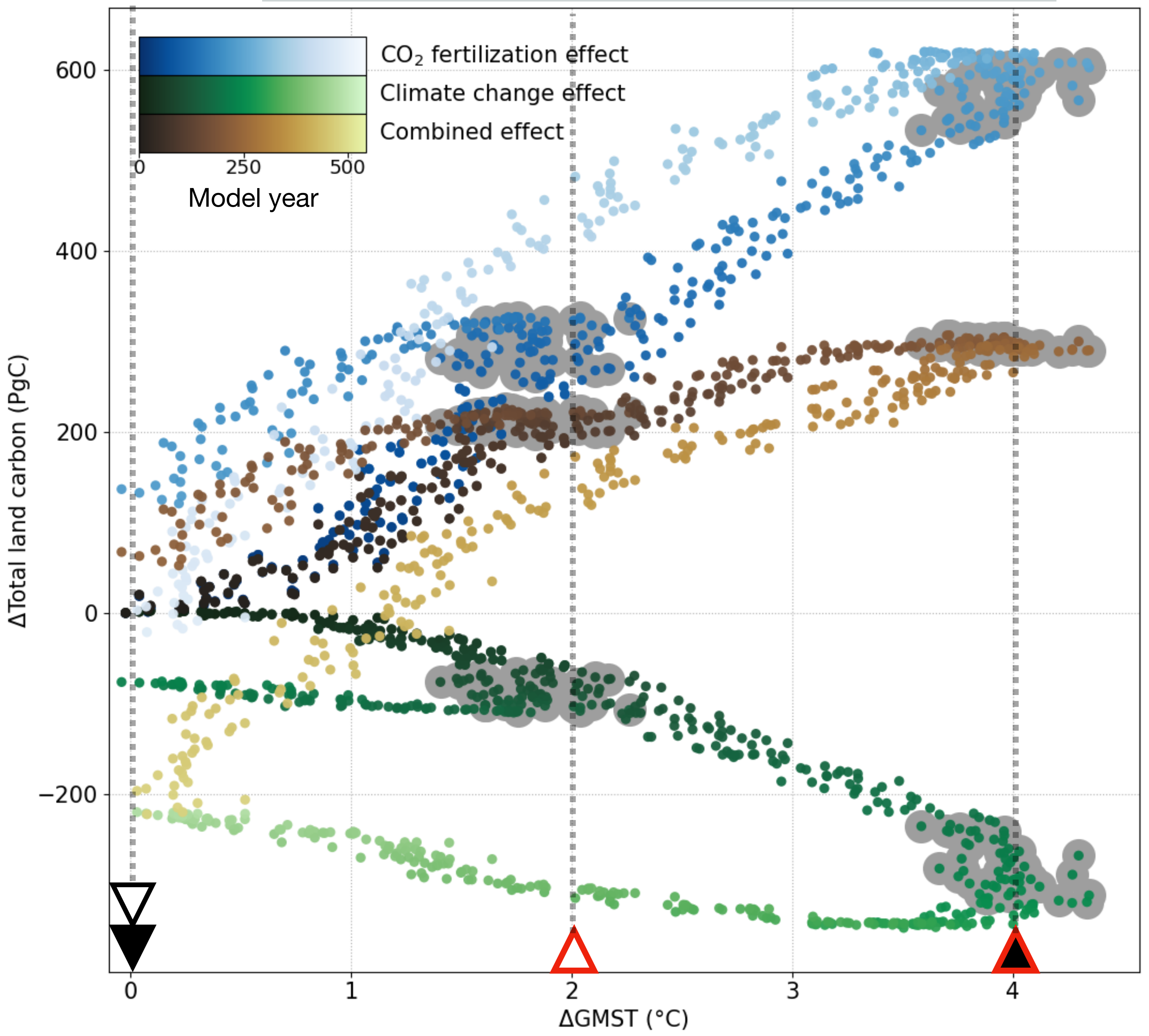


Figure 2. Simulated annual-mean anomalies of total land carbon for ramp-up and ramp-down pathways. Trajectories are separated into CO₂-fertilization-only (blue), climate-change-only (green), and combined-effect (brown) simulations for ΔGMST+2°C and +4°C. Grey shading indicates the stabilizing phase at ΔGMST+2°C and ΔGMST+4°C, extending into the recovery phase, which is marked by lighter colors over time.

② Land carbon responds nonlinearly to warming

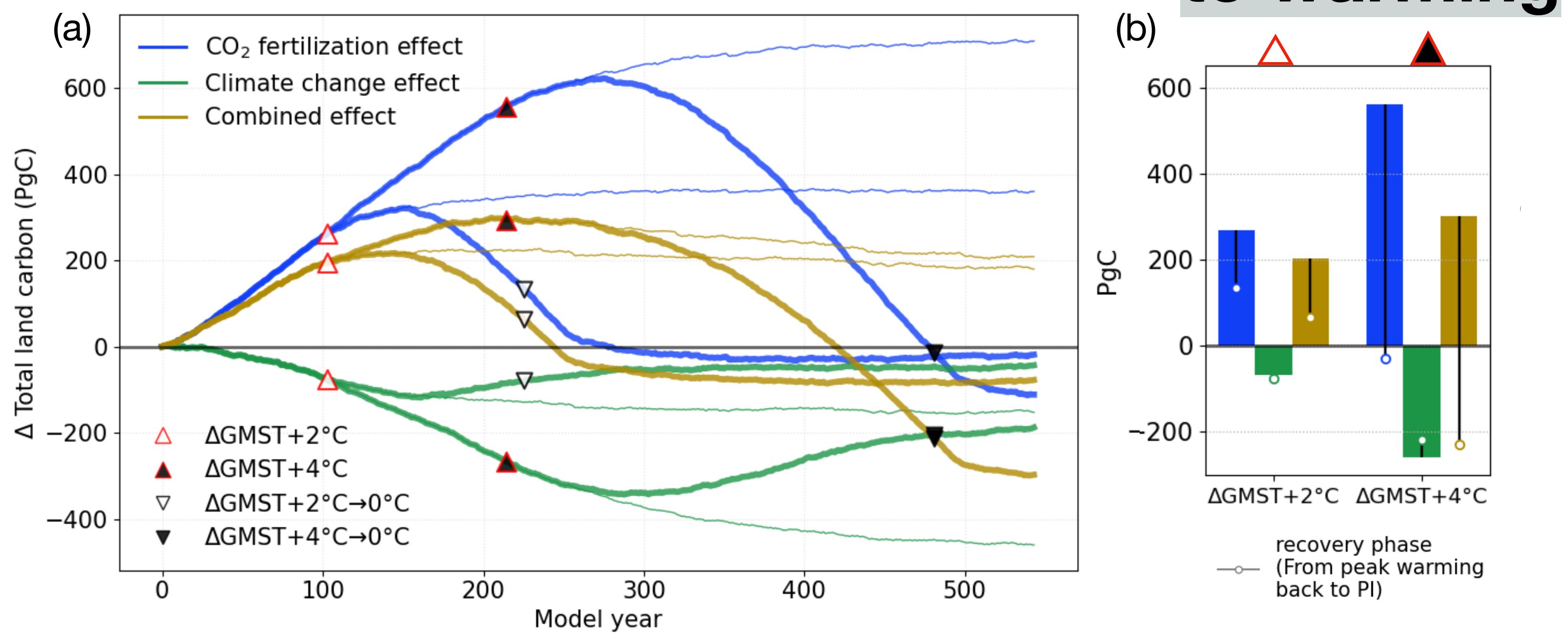


Figure 3. (a) Annual mean anomalies of total land carbon. △ indicates the time when the ΔGMST reaches +2°C, while ▲ indicates ΔGMST+4°C. Similarly, ▽ and ▼mark the recovery phase when ΔGMST returns to 0°C from +2°C and +4°C, respectively. (b) Changes in total land carbon under ΔGMST+2°C and ΔGMST+4°C. Black vertical lines with colored circles indicate changes during the ramp-down phase; values closer to **zero** indicate greater reversibility. Further details on reversibility for the case of ΔGMST+4°C are shown in the following figures.

③ Are these changes reversible?

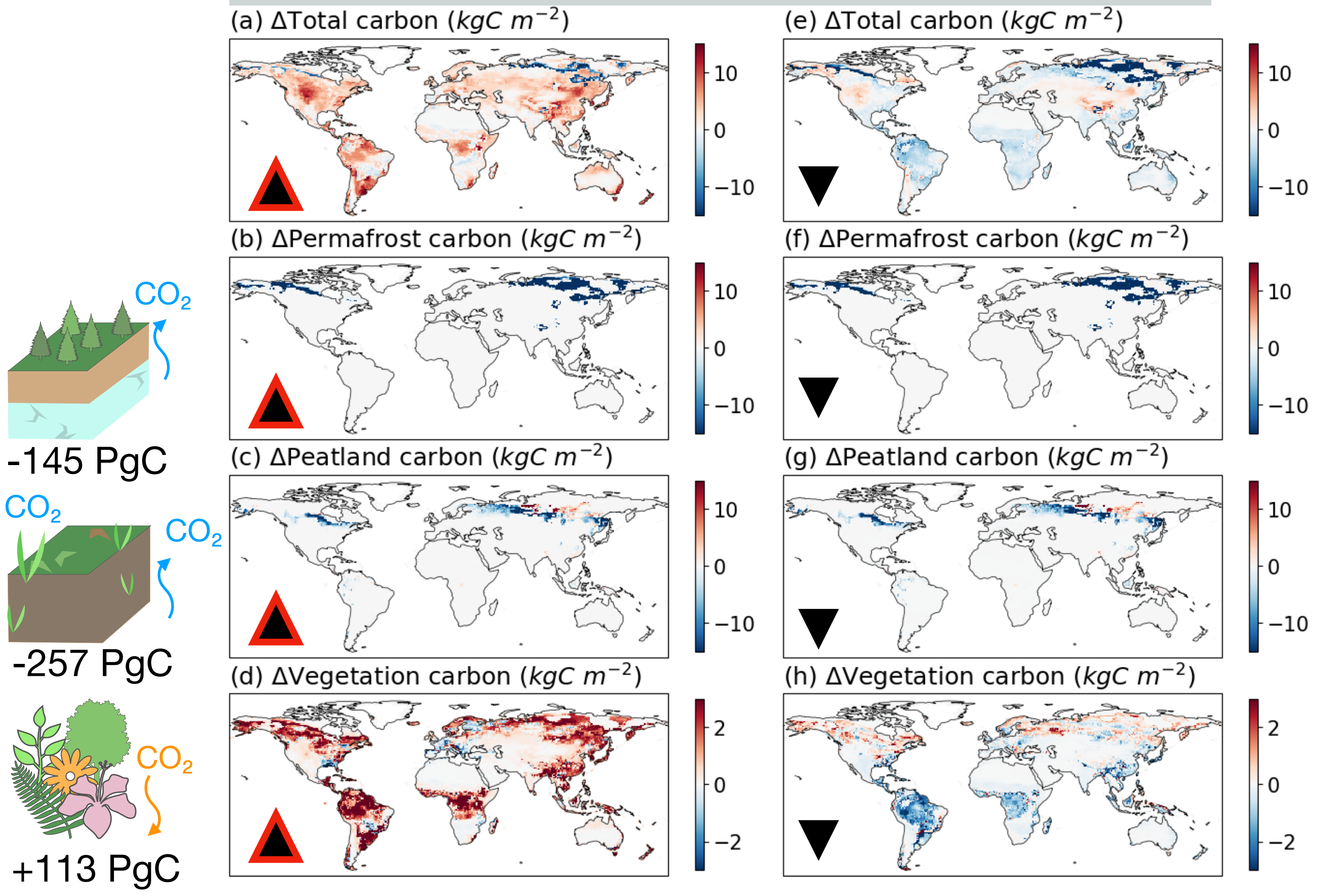


Figure 4. Mean changes in (a) total land carbon, (b) permafrost carbon, (c) peatland carbon, and (d) vegetation carbon (kg C m^{-2}) when ΔGMST reaches +4°C (▲: years 205-225). Right panels (e–h) show the same as (a-d) but when ΔGMST returns to +0°C (▼: years 472-492) representing reversibility in terrestrial carbon.

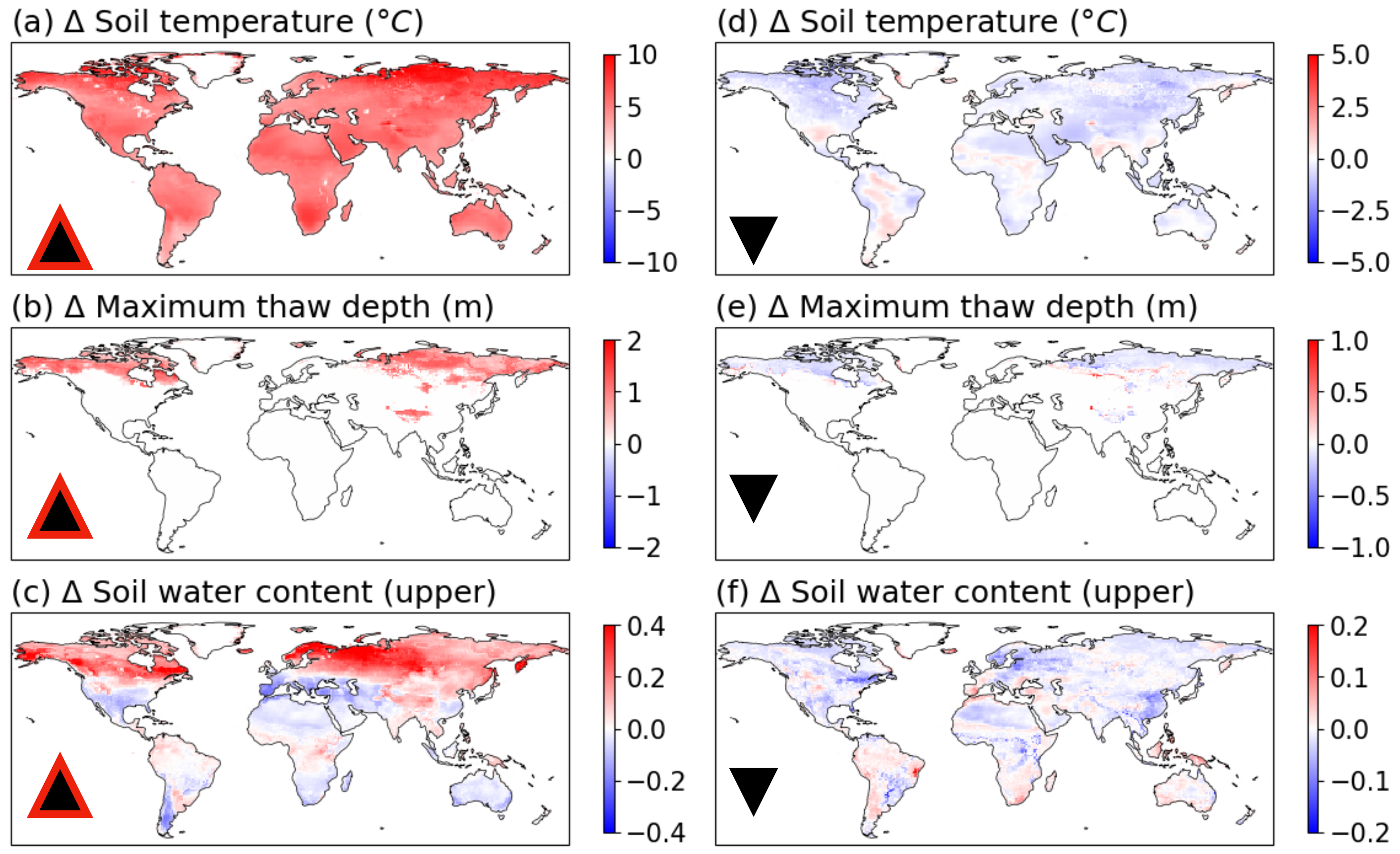


Figure 5. Mean anomalies of (a) soil temperature, (b) maximum thaw depth (m), and (c) upper soil water content from the ΔGMST+4°C run (▲: years 205-225). Right panels (d-f) show the same as (a-c) but when ΔGMST returns to +0°C (▼: years 472-492).

Table 2. Changes in land carbons (PgC), showing carbon–fertilization (blue), climate change (green), and net (brown) effects in ΔGMST+2°C and +4°C

	△ ΔGMST+2°C			▲ ΔGMST+4°C		
	β	γ	net	β	γ	net
Δ Total land carbon	321	-114	214	613	-328	287
Δ Permafrost	**24**	**-65**	**-57**	**25**	**-159**	**-145**
Δ Soil (Peatland)	**2**	**-98**	**-92**	**4**	**-277**	**-257**
Δ Vegetation	**85**	**-26**	**51**	**161**	**-51**	**113**
Δ Litter	60	-17	43	113	-36	69
Δ Soil	168	26	195	326	32	348

References

[1] Jones, C., Bossert, I., Dennis, D., Jeffery, H., Jones, C. D., Koenigk, T., ... & Ziehn, T. (2025). The TIPMIP Earth system model experiment protocol: phase 1. Geoscientific Model Development Discussions (GMDD).
[2] Stocker, B. D., Spahni, R., & Joos, F. (2014). DYPTOP: a cost-efficient TOPMODEL implementation to simulate sub-grid spatio-temporal dynamics of global wetlands and peatlands. *Geoscientific Model Development*, *7*(6), 3089-3110.
[3] Qiu, C., Zhu, D., Ciais, P., Guenet, B., & Peng, S. (2020). The role of northern peatlands in the global carbon cycle for the 21st century. Global Ecology and Biogeography, 29(5), 956-973.