Permafrost-carbon complexities

To the Editor — The thawing and decomposition of carbon stored in permafrost generates greenhouse gases that could further intensify global warming. Currently, most of the thawed carbon is assumed to be converted to greenhouse gases, such as carbon dioxide and methane, and carbon decomposition is thought to only occur at the site of the thaw. We argue that lateral transport of thawed permafrost carbon from land to ocean will translocate greenhouse gas release away from the thaw site, and that storage and burial of thawed carbon in long- and short-term reservoirs will attenuate greenhouse gas emissions.

Permafrost thawing is one of only a few processes that can move significant quantities of land carbon into the atmosphere in response to a changing climate on short timescales, thus providing a fast positive feedback loop of global warming[1,2]. Global stores of terrestrial permafrost are thought to hold 1,672 Pg (petagrams, 10^{15} grams) of carbon[3]. Model predictions suggest that permafrost regions could transition from a net sink to a net source of atmospheric carbon over the coming decades[4–7]. However, the latest report from the Intergovernmental Panel on Climate Change does not account for positive permafrost-carbon feedback[8].

The estimated magnitude of the terrestrial permafrost-carbon feedback[4,7,9] suggests carbon release in the range of 7 to 508 Pg by the year 2100. However, most models are overly simplistic and one-dimensional. They assume that carbon is only released from the active layer of permafrost, the layer that thaws in summer and freezes in winter (Fig. 1a). These models exclude localized but abrupt releases of carbon — generated, for example, by erosion, fires or thermokarst — and do not consider frozen submarine sediments or methane hydrates. Discontinuous and isolated permafrost regions are also excluded from most permafrost-carbon feedback estimates, yet these regions cover about 30% of the pan-Arctic watershed and are expected to thaw first[10]. It is also generally assumed that virtually all of the carbon released from permafrost will be completely converted into carbon dioxide or methane within a few hundred years[2,5,7]. Physical, chemical and biological attenuation processes, such as burial, selective preservation and microbial uptake, are disregarded.

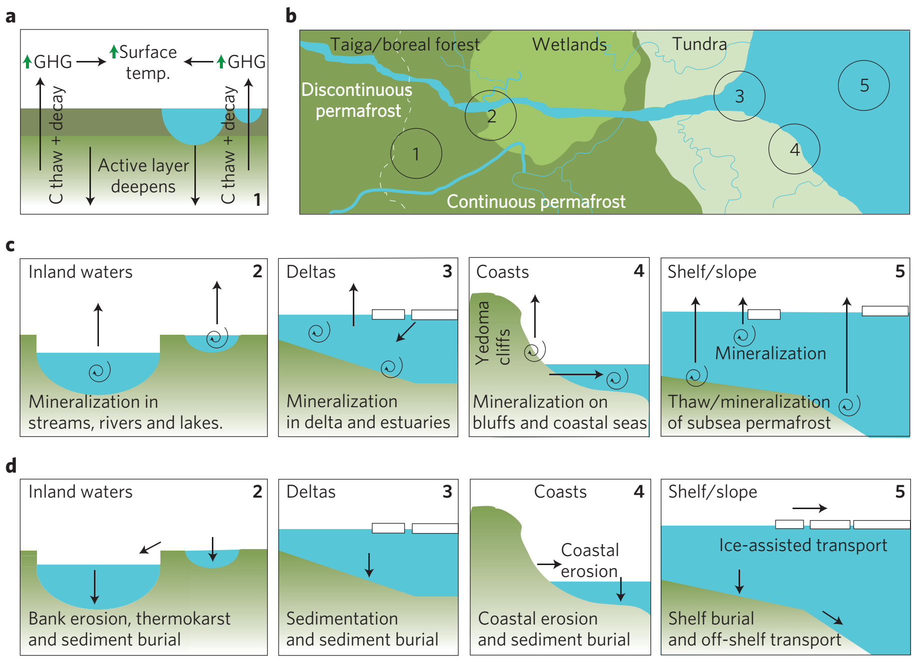

Figure 1 | Translocation and attenuation of permafrost carbon. **a**, The traditional permafrost-carbon feedback loop[2,6,7,10] assumes that permafrost carbon decays at the site of active layer thaw, generating greenhouse gases (GHG) and strengthening climate warming. **b–d**, However, spatial and temporal hysteresis associated with the reactive land-to-ocean transport system (**b**) will displace greenhouse gas generation away from the source (spatial hysteresis; **c**) and can delay or prevent greenhouse gas emission through storage and sequestration (temporal hysteresis; **d**). Mineralization (swirl shapes) in **c** refers to water and sediments. The circles in **b** correspond to the numbered boxes in **a**,**c**,**d**.

However, we argue that the processes surrounding permafrost thaw are not that simple, and that greenhouse gas emissions are both spatially relocated and temporally attenuated (Fig. 1b–d). The key driver of this twofold hysteresis is the coupling between the carbon cycle and the hydrological cycle along the land-to-ocean conduit. This transport system is increasingly seen as reactive[11,12], yet rarely considered in the impact of thawing permafrost on global climate. Carbon entering the aquatic system will continue to degrade during transport, sometimes over thousands of kilometres from the original source. This matters, because a redistribution of thawed carbon in rivers can affect its propensity to convert to a greenhouse gas. The carbon may also become buried in sediments, and thus re-sequestered in short- and long-term sinks, attenuating the release of greenhouse gases.

Thawed carbon from permafrost can, for example, be released into standing water, ponds and lakes, and mobilized in streams to move through tributaries and larger rivers towards the Arctic coastal waters and shelf seas. Aquatic conduits are active microbial reactors of the organic matter they receive[11,12], where carbon is processed and readily converted to greenhouses gases. On reaching a delta or estuary, the fresh waters converge with sea water, where organic matter coagulates to more accessible forms and remineralization — the transfer of organic carbon back into carbon dioxide or methane — may increase.

Permafrost is also exposed along coastal bluffs in large parts of the Siberian and Alaskan Arctic, and these bluffs are rapidly eroding[13,14]. The thawed organic matter can be remineralized in the coastal bluffs and further processed after coastal release into shelf waters[15].

Deltas and estuaries, however, can also be important sinks for terrestrial organic carbon. Sorption, mineral association and sedimentation processes remove significant amounts of both the dissolved and suspended organic matter[16,17], some of it permanently. Coastal collapse and retreat also delivers large volumes of sediments to Arctic shelf seas, and a substantial amount of carbon is estimated to be buried or transported off-shelf to isolated deeper-water strata. The outward transport of sediment-laden ice relocates coastal organic matter to the shelf or slope.

There are multiple other processes in addition to re-burial that also attenuate the release of carbon from thawing permafrost, such as biosphere uptake of carbon when growing seasons lengthen, re-vegetation after slumping and recovery of ecosystems after degradation, carbon dioxide fertilization and increasing net-carbon uptake following liberation of nutrients from thawing permafrost[2,6,7].

We must move on from the simple one-dimensional view of the permafrost-carbon feedback, towards a more multi-dimensional perspective. Coupling between the carbon cycle and the hydrological cycle, as well as more landscape components, must be considered to fully understand the magnitude of this important feedback mechanism. ❐

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