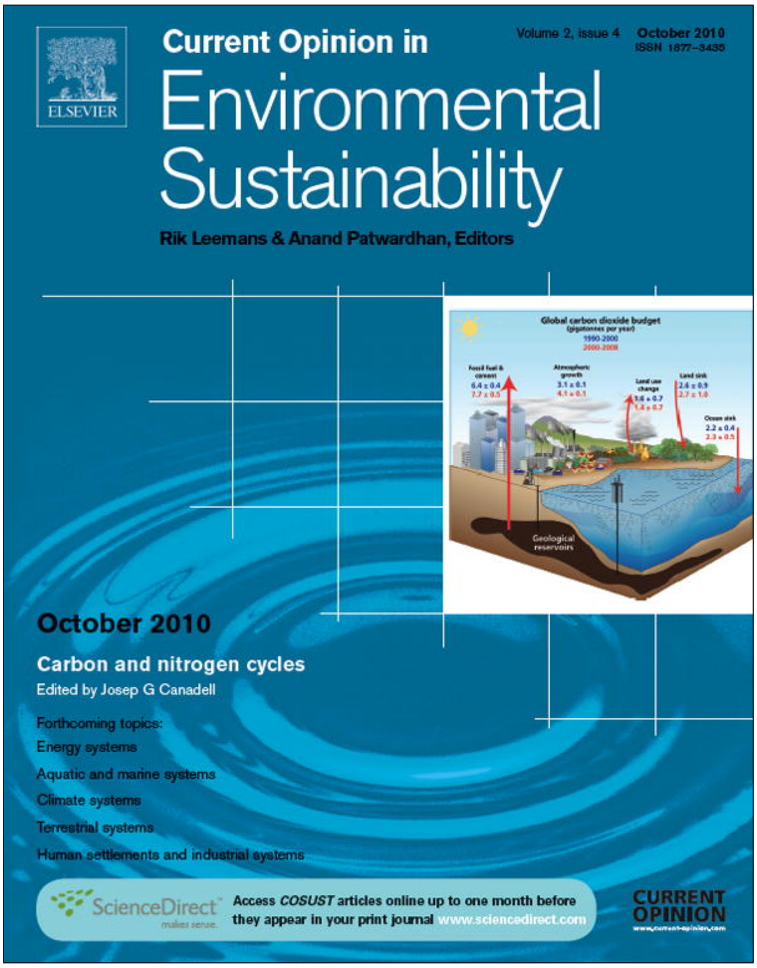
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The carbon budget of the northern cryosphere region

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The northern cryosphere is undergoing substantial warming of permafrost and loss of sea ice. Release of stored carbon to the atmosphere in response to this change has the potential to affect the global climate system. Studies indicate that the northern cryosphere has been not only a substantial sink for atmospheric CO_2 in recent decades, but also an important source of CH_4 because of emissions from wetlands and lakes. Analyses suggest that the sensitivity of the carbon cycle of the region over the 21st Century is potentially large, but highly uncertain because numerous pathways of response will be affected by warming. Further research should focus on sensitive elements of the carbon cycle such as the consequences of increased fire disturbance, permafrost degradation, and sea ice loss in the northern cryosphere region.

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Introduction

The northern cryosphere region extends from the North Pole to the southern limits of permafrost on land and sea ice in the Arctic Ocean and adjacent seas (Figure 1) [1••,2]. The land component, which extends southward to approximately 45°N in Asia and 50°N in North America, largely drains into the Arctic Ocean. Vast amounts of organic carbon are stored within permafrost [3•,4•] and in methane hydrates beneath both subterranean and submerged permafrost [5•]. Air temperatures have already increased dramatically within the Arctic [6] accompanied by consequential warming of permafrost [7], and loss of sea ice mass [8] and cover [9]. Continued warming has the potential to affect the storage of the carbon contained in the region in ways that could cause substantial changes in the global climate system [1••]. Here we provide a contemporary carbon budget for the northern cryosphere region and discuss its vulnerability to projected climate change. We end this review with recommendations for future research on the fate of carbon in the northern cryosphere.

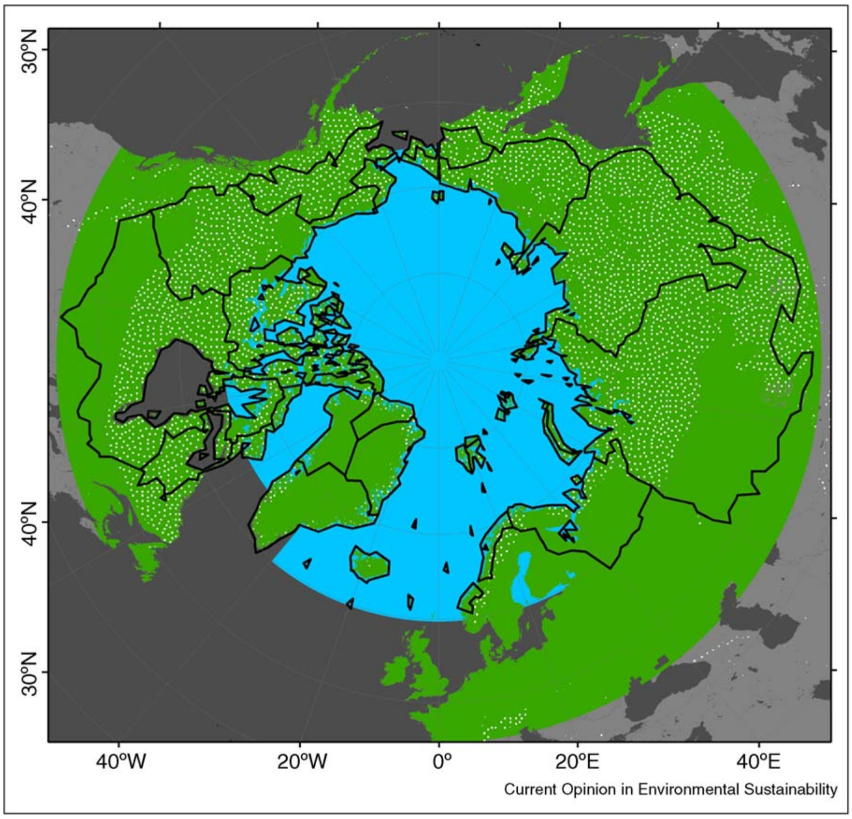
Contemporary carbon stocks and fluxes of the northern cryosphere

Between 1400 and 1850 Pg C of organic carbon are stored in surface (0–3 m) and deeper soils (up to ~25–50 m in some areas) of the northern cryosphere (Table 1) [1••]. The recent estimate of 1672 Pg C in permafrost soils of the northern circumpolar region [3•] falls within this range. Much of this soil organic carbon has accumulated because of wet and cold conditions that limit decomposition of soil organic matter, soil organic horizons that are too deep or wet for combustion, and the incorporation of organic carbon in permafrost. Between 60 and 70 Pg C is stored in vegetation of the region [1••], which is between 10% and 20% of the world's vegetation carbon; most of this storage is in tree biomass of the boreal forests in the region.

The Arctic Ocean and its shelf seas store inorganic carbon (DIC) stocks of 310 Pg C; approximately 1% of this storage has derived from fossil fuel emissions via the atmosphere [10]. It is speculated that there are substantial stocks of CH_4 stored as gas hydrate beneath the ocean floor and beneath both subterranean and submerged permafrost of the Arctic [5•]. Rough estimates reveal a large uncertainty in the storage, between 35 and 365 Pg CH_4 [1••], and the location of this stored carbon in warming shallow Arctic environments places it at risk of release [5•]. A slow steady release of CH_4 from the ocean hydrate reservoir is considered to be a slow but irreversible tipping point in the global carbon cycle [11•].

The northern cryosphere plays an important role in the global dynamics of both CO_2 and CH_4. Top-down

Figure 1



The northern cryosphere region extends from the North Pole to the southern limits of discontinuous permafrost on land and of sea ice in the Arctic Ocean and adjacent seas. The distribution of land underlain by permafrost in the Northern Hemisphere over unglaciated regions is shown as the white mottled area. The green area depicts the circumpolar land area north of 45°N, and the land area of watersheds draining into the Arctic Ocean and its margin seas (the blue area) is identified by the thick black lines.Figure reprinted from Ref. [1••] with permission.

atmospheric analyses indicate that the region has been a sink for atmospheric CO_2 of up to 0.8 Pg C yr^{-1} in recent decades (Figure 2) [12–14], which is up to 25% of the net land/ocean sink of 3.2 Pg C yr^{-1} estimated for the 1990s by the Intergovernmental Panel on Climate Change 4th Assessment Report (AR4) [15••]. Inventory-based analyses indicate that the land sink of the northern cryosphere region has been between 0.3 and 0.6 Pg C yr^{-1} [16–20], which is 30–60% of the 1.0 Pg C yr^{-1} global net land sink estimate for the 1990s [15••]. Much of this storage is due to growth of trees in Russian forests [18]. The Arctic Ocean is estimated to have a net uptake of CO_2 from the atmosphere between 24 and 100 Tg C yr^{-1} [1••], which is 1–5% of the 2.2 Pg C yr^{-1} net ocean CO_2 sink estimated globally by AR4 for the same time period [15••]. Similar recent estimates of 65–175 Tg C yr^{-1} net CO_2 uptake [21•] imply an even higher potential uptake by the Arctic Ocean.

Table 1

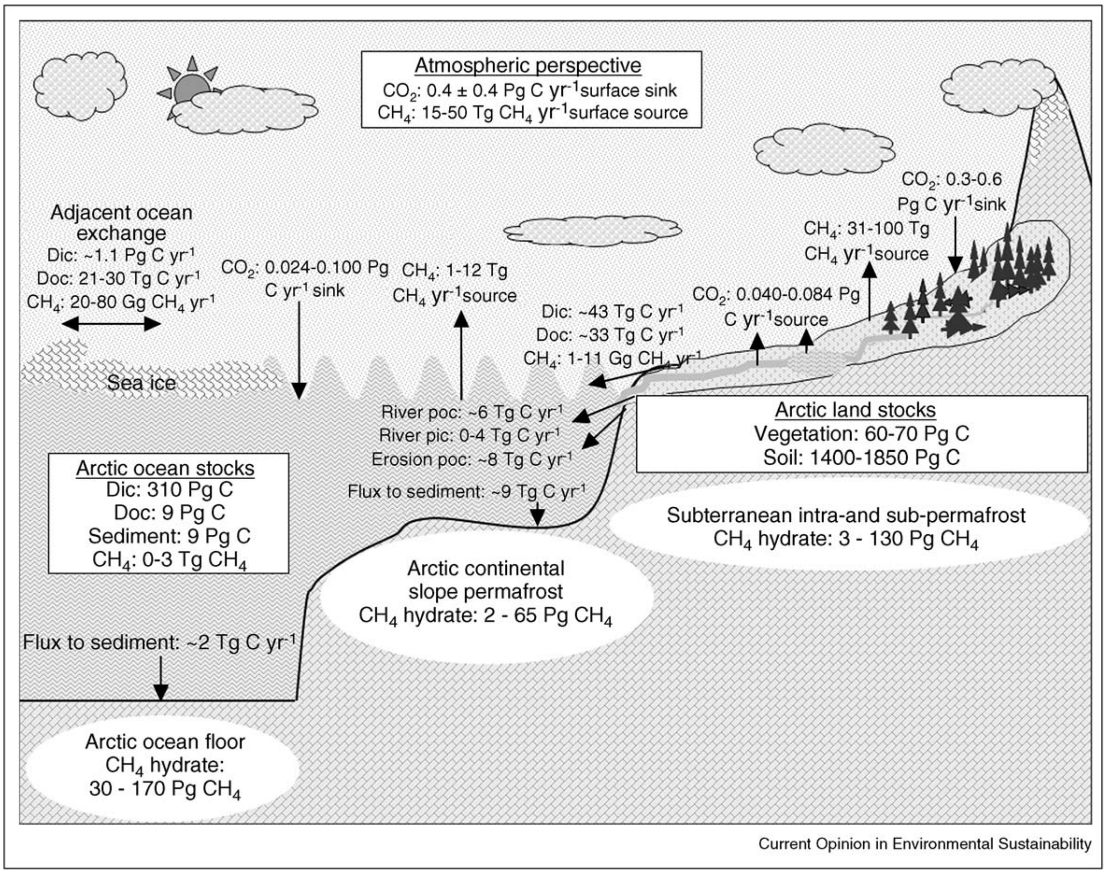
Estimates of carbon stocks in the northern cryosphere region[a]

Reservoir	Size of carbon stock ($Pg = 10^{15}$ g)
Northern cryosphere land	
Soil	1400–1850 Pg C
Vegetation	60–70 Pg C
Northern cryosphere ocean	
Dissolved inorganic carbon	310 Pg C
Dissolved organic carbon	9 Pg C
Surface sediments	9 Pg C
Methane hydrates	
Beneath northern cryosphere land	2–65 Pg CH_4 (2–49 Pg C)
Beneath northern cryosphere ocean	30–170 Pg CH_4 (23–128 Pg C)
Total	1813–2425 Pg C

[a] Based on estimates in Ref. [1••].

Atmospheric analyses indicate that the northern cryosphere is a source of CH_4 to the atmosphere of between 15 and 50 Tg CH_4 yr^{-1} (Figure 2) [22–26], which is between 3% and 9% of the net land/ocean source of 552 Tg CH_4 yr^{-1} estimated by AR4 [15••]. In comparison with the top-down analyses, bottom-up analyses have wider uncertainty bounds (32 and 112 Tg CH_4 yr^{-1}, respectively) for the net source of CH_4 from the surface

Figure 2



The contemporary state of the carbon budget of the northern cyrosphere region presented by McGuire *et al.* [1••]. Pg = 10^{15} g, Tg = 10^{12} g, and Gg = 10^{9} g.Figure reprinted with permission.

to the atmosphere in the northern cryosphere [1••]. The uncertainty bounds from the bottom-up analyses would be closer to that of the top-down analyses if the estimated 15–35 Tg CH_4 yr^{-1} from thermokarst lake systems of the region [27•] were neglected. An important research question is whether consideration of the estimated fluxes from thermokarst lake systems and from the Arctic continental shelf [28•] would influence the top-down estimates of CH_4 exchange for the northern cryosphere.

The drainage basin of the Arctic Ocean accounts for 11% of global river discharge of water from land to ocean [29]. Approximately 80 Tg C yr^{-1} is transferred from land to ocean via rivers in the northern cryosphere (Figure 2) [1••], which is approximately 10% of the estimated 0.8 Pg C yr^{-1} transferred globally by rivers [30]. Coastal and wind erosion contribute another 8 Tg C yr^{-1} to the Arctic Ocean, and ultimately approximately 11 Tg C yr^{-1}, including marine carbon, is buried in marine sediments (Figure 2) [31], which is about 5% of the estimated 0.2 Pg C yr^{-1} transferred to ocean floor sediments globally [30]. This is approximately proportional to the areal representation of the Arctic Ocean and its associated shelf seas in the global ocean system.

How vulnerable is carbon in the northern cryosphere to climate change?

Carbon storage in the land areas of the northern cryosphere is primarily vulnerable to increases in disturbance, permafrost thaw, and change in hydrology. The frequency of boreal forest fires [32,33] and insect outbreaks [34•] is increasing, which appears to contribute CO_2 to the atmosphere [34•,35]. In some regions of the North America boreal forest, fire frequency could increase 4–6 times depending on emission scenarios [36]. Fire increases are also predicted in Asia [37]. Similarly, near-surface permafrost area is projected to decrease by between 6 and 11×10^6 km^2 by 2100 [38,39]. Hydrology of the northern cryosphere is changing with increases in river discharge [40] and decreases in lake area [41•,42•]. Fires in the northern cryosphere, which initially release carbon largely through the combustion of organic soil carbon stocks [43•], can also trigger subsequent thaw of permafrost in a warming climate through removal of the thermally protective organic layer [44]. Thawing of permafrost occurs both gradually in ice-poor permafrost and abruptly in ice-rich permafrost, exposing organic C to microbial decomposition [45•]. Abrupt permafrost thaw results in subsidence and may lead to thermal erosion. This thermokarst disturbance interacts strongly with local hydrology and can lead to either well-drained or saturated conditions that, in turn, have a strong impact on the rate and form of C that will be lost from thawed permafrost [45•]. The response of carbon storage to fire or permafrost thaw depends on assumptions about CO_2 fertilization [46,47]. Under an assumption of no CO_2 fertilization in the boreal forest region, it is estimated that the northern cryosphere region could lose up to 50 Pg C (1000 g C m^{-2}) in the 21st Century in response to a doubling of area burned and the thawing of permafrost [46]. However, the response of carbon storage to permafrost thaw is highly uncertain, as current regional and global models typically only consider how the fate of carbon is affected by a deepening active layer and do not consider the complex interactions that cause thermokarst and more rapid permafrost thaw. For example, field measurements of thermokarst in tundra ecosystems showed that initial permafrost thaw resulted in a carbon sink as plant uptake was stimulated more than the release of carbon from permafrost [48•]. However, as permafrost thawed and thermokarst progressed over decades, increased decomposition of old permafrost carbon by microbes was greater than the increased plant uptake. Moreover, carbon density in permafrost far exceeds potential carbon density in biomass even under the most favorable assumptions about growth responses of biomass. Therefore, long-term carbon releases from permafrost will probably lead to net carbon loss from ecosystems affected by thermokarst.

In general, reduced sea ice will result in greater exchange of carbon from the Arctic Ocean to the atmosphere [1••]. More light will penetrate the surface water, wind mixing and upwelling will increase, all of which will stimulate plankton photosynthesis and enhance the uptake of CO_2. However, increased inflow from land together with a period of enhanced melting of sea ice will mean more freshwater in upper ocean layers, which can reduce biological activity in a more stable surface layer and result in less CO_2 being taken up by biota. Furthermore, as the ocean warms, and as its pH decreases owing to CO_2 accumulation, it can hold less DIC. Ocean acidification associated with increases in atmospheric CO_2 may further modify the uptake of CO_2 by the Arctic Ocean by affecting inorganic and biotic C dynamics in the ocean [49]. Warmer water may also lead to increased production of CO_2 and CH_4 through decomposition and other biological activity. While the balance of these competing exchanges and their overall effect on the uptake of CO_2 into the marine system is not clearly understood, it is argued that reduced sea ice will result in increased uptake of CO_2 from the atmosphere [50].

The discharge of water from land to sea increased in the northern cryosphere throughout the 20th Century [40], and is expected to continue to increase during the 21st Century. Increased water flow will probably mean increased carbon transport, though the relative proportions of different types of carbon are difficult to predict. One possibility is that carbon carried by rivers ends up stored in coastal sediments. Another possibility is that this carbon decomposes in the water column and is released as CO_2 and CH_4.

Modeling analyses indicate that climate change has the potential to substantially increase biogenic CH_4 emissions throughout the northern cryosphere during the 21st Century [46,51,52] because the sensitivity of methanogenesis to temperature dominates over water table sensitivity. However, the effects of thermokarst on biogenic CH_4 emissions have not been adequately considered in these models, and the release of CH_4 could be greater than projected. By contrast, the release of methane from gas hydrates currently locked in permafrost is likely to be a very slow process. Most hydrates are stored at considerable depth and methane release due to near-surface thawing is not expected in the short term [11•,53]. Nonetheless, the fate of gas hydrates remains largely uncertain in both the short and long term [5•].

Conclusions

The northern cryosphere contains several times the amount of carbon that is contained in the atmosphere. Our current understanding of the carbon cycle in the northern cryosphere is insufficient to rule out large releases of CO_2 and CH_4 to the atmosphere in a warming climate [1••,54•]. Such releases may be irreversible if they overwhelm efforts to sequester CO_2 in other sectors of the global C cycle. Integrated studies of regional carbon dynamics are needed to provide better information on key elements of the carbon cycle in the northern cryosphere. Such studies should link observations of carbon dynamics to the processes that influence those dynamics. The resulting information should be incorporated into modeling efforts that connect carbon dynamics and climate. The studies should focus on sensitive parts of the system, for example areas experiencing major changes or thresholds such as increased fire disturbance, permafrost degradation, and sea ice loss. Furthermore, the rapidity and extent of change occurring in the northern cryosphere demand an increased attention to collection of appropriate time-series data for the carbon cycle of this region.

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This comment very usefully evaluate reports of new methane sources in the Arctic (for example from references [27•] and [28•] in the context of the global methane cycle.