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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.

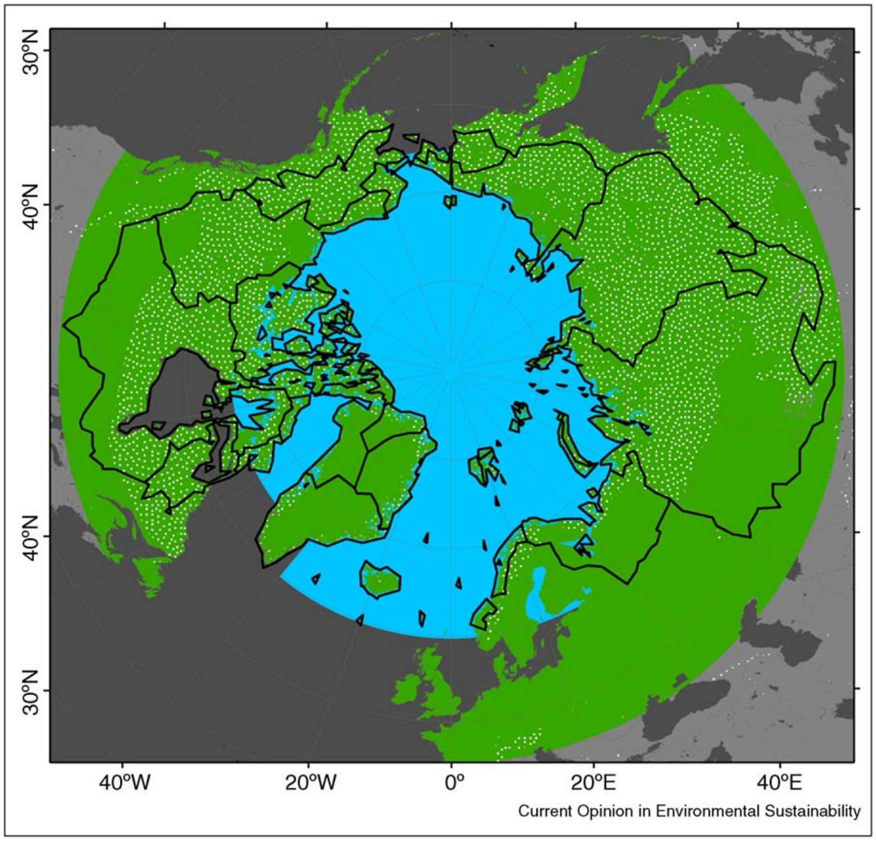
Contemporary carbon stocks and fluxes of the northern cryosphere

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

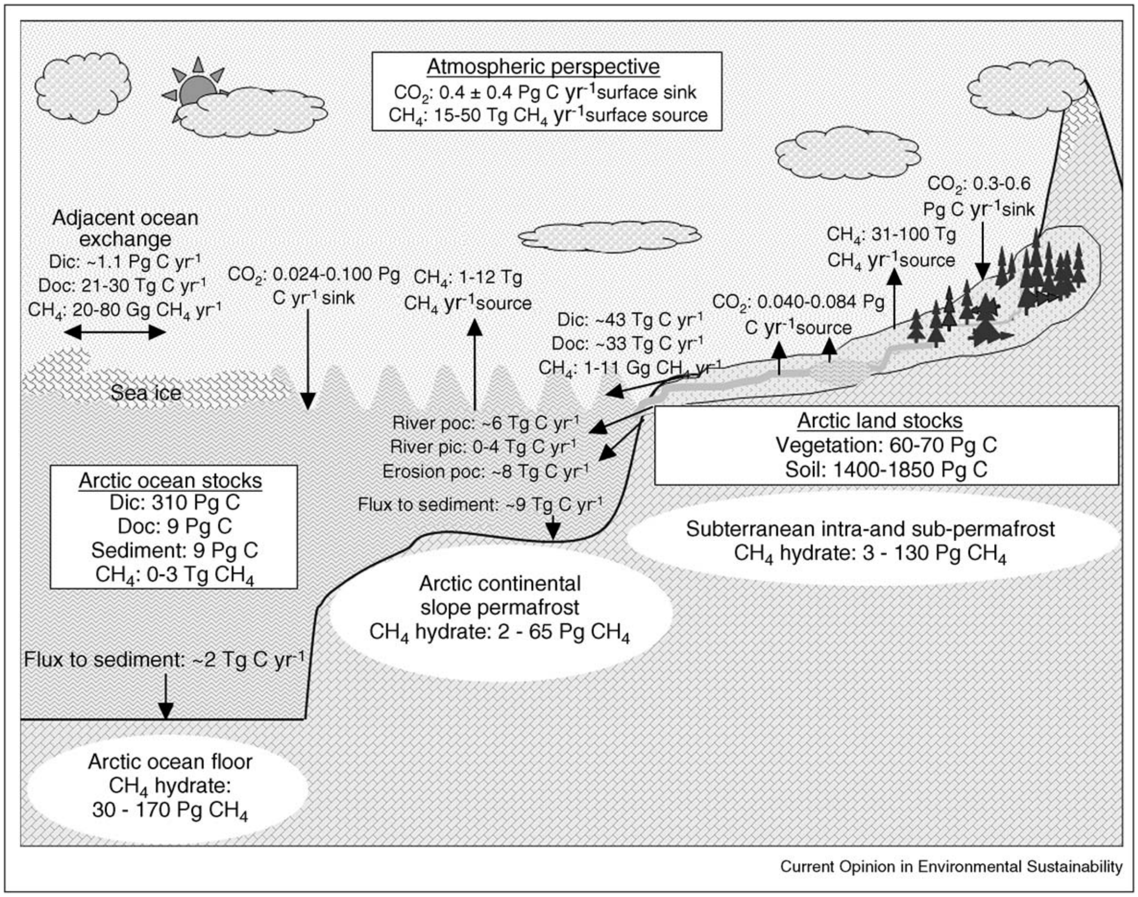
Estimates of carbon stocks in the northern cryosphere region[a]

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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References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. •• McGuire AD, Anderson LG, Christensen TR, Dallimore S, Guo L, Hayes DJ, Heimann M, Lorenson TD, Macdonald RW, Roulet N: **Sensitivity of the carbon cycle in the Arctic to climate change**. *Ecological Monographs* 2009, **79**:523-555.

This is a comprehensive synthesis of the understanding of the contemporary carbon cycle of the Arctic.

2. Macdonald RW, Anderson LG, Christensen JP, Miller LA, Semiletov IP, Stein R: **The Arctic Ocean: budgets and fluxes**. In *Carbon and Nutrient Fluxes in Continental Margins: a Global Synthesis.* Edited by Liu KK, Atkinson L, Quinones R, Talaue-McManus L. Springer; 2009:290-303.

3. • Tarnocai C, Canadell JG, Mazhitova G, Schuur EAG, Kuhry P, Zimov S: **Soil organic carbon pools in the northern circumpolar permafrost region**. *Global Biogeochemical Cycles* 2009, **23**:GB2023 doi: 10.1029/2008GB003327.

This is the most up to date estimate of carbon stocks in northern permafrost soils.

4. • Ping CL, Michaelson GJ, Jorgenson MT, Kimble JM, Epstein H, Romanovsky VE, Walker DA: **High stocks of soil organic carbon in the North American Arctic region**. *Nature Geoscience* 2008, **1**:615-619.

This study highlights the importance of cryoturbation in the sustantial storage of organic carbon in permafrost soils of the North American Arctic.

5. • Corell RW, Hassol SJ, Melillo JM, Archer D, Euskirchen E, Chapin FS, McGuire AD, Christensen TR, Fichelet VP, Walter K *et al.*: **Methane from the Arctic: global warming wildcard**. In *UNEP Year Book 2008.* Edited by Harrison P. United Nations Environment Programme; 2008:37-48.

The report reviews the vulnerability of the global climate system to the various pathways of methane release to warming in the Arctic.

6. Overland JE, Wang M, Salo S: **The recent Arctic warm period**. *Tellus* 2008, **60A**:589-597.

7. Hinzman LD, Bettez ND, Bolton WR, Chapin FS, Dyurgerov MB, Fastie CL, Griffith B, Hollister RD, Hope A, Huntington HP *et al.*: **Evidence and implications of recent climate change in northern Alaska and other Arctic regions**. *Climatic Change* 2005, **72**:251-298.

8. Kwok R, Rothrock DA: **Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008**. *Geophysical Research Letters* 2009, **36**:L15501.

9. Stroeve J, Serreze M, Drobot S, Gearheard S, Holland M, Maslanik J, Meier W, Scambos T: **Arctic sea ice extent plummets in 2007**. *Eos* 2008, **89**:13-14.

10. Anderson LG, Chierici M, Fransson A, Olsson K, Jones EP: **Anthropogenic carbon dioxide in the Arctic Ocean: inventory and sinks**. *Journal of Geophysical Research* 1998, **103**:27707-27716.

11. • Archer D, Buffet B, Brovkin V: **Ocean hydrates as a slow tipping point in the global carbon cycle**. In *Proceedings of the National Academy of Sciences of the United States of America* 2009, **106**:20596-20601.

This is a very nice analysis of the role of ocean hydrates in the climate system.

12. Bousquet P, Peylin P, Ciais P, Le Quéré C, Friedlingstein P, Tans PP: **Regional changes in carbon dioxide fluxes of land and oceans since 1980**. *Science* 2000, **290**:1342-1346.

13. Rödenbeck C, Houweling S, Gloor M, Heimann M: **CO_2 flux history 1982–2001 inferred from atmospheric data using a global inversion of atmospheric transport**. *Atmospheric Chemistry and Physics* 2003, **3**:1919-1964.

14. Baker DF, Law RM, Gurney KR, Rayner P, Peylin P, Denning AS, Bousquet P, Bruhwiler L, Chen YH, Ciais P *et al.*: **TransCom 3 inversion intercomparison: impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988–2003**. *Global Biogeochemical Cycles* 2006, **20**:GB1002 doi: 10.1029/2004GB002439.

15. •• Denman KL, Brasseur G, Chidthaisong A, Ciais P, Cox PM, Dickinson RE, Hauglustaine D, Heinze C, Holland E, Jacob D *et al.*: **Couplings between changes in the climate system and biogeochemistry**. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Edited by Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery KB, Tignor M, Miller HL. Cambridge University Press; 2007:499-587.

This is most recent update by the IPCC about our understanding of the role of biogeochemistry in the climate system.

16. Liski J, Perruchoud D, Karjalainen T: **Increasing carbon stocks in the forest soils of Western Europe**. *Forest Ecology and Management* 2002, **169**:163-179.

17. Liski J, Korotkov AV, Prins CFL, Karjalainen T, Victor DG, Kauppi PE: **Increased carbon sink in temperate and boreal forests**. *Climatic Change* 2003, **61**:89-99.

18. Shvidenko A, Nilsson S: **A synthesis of the impact of Russian forests on the global carbon budget for 1961–1998**. *Tellus* 2003, **55B**:391-415.

19. Myneni RB, Dong J, Tucker CJ, Kaufmann RK, Kauppi PE, Liski J, Zhou L, Alexeyev V, Hughes MK: **A large carbon sink in the woody biomass of northern forests**. In *Proceedings of the National Academy of Sciences of the United States of America* 2001, **98**:14784-14789.

20. Kurz WA, Apps MJ: **A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector**. *Ecological Applications* 1999, **9**:526-547.

21. • Bates NR, Mathis JT: **The Arctic Ocean marine carbon cycle: evaluation of air–sea CO_2 exchanges, ocean acidification impacts and potential feedbacks**. *Biogeosciences* 2009, **6**:6695-6747.

This is the most up to date analysis of how CO_2 exchange of the Arctic Ocean is changing in response to changes in sea ice loss and ocean acidification.

22. Mikaloff Fletcher SEM, Tans PP, Bruhwiler LM, Miller JB, Heimann M: **CH_4 sources estimated from atmospheric observations of CH_4 and its C-13/C-12 isotopic ratios: 1. Inverse modeling of source processes**. *Global Biogeochemical Cycles* 2004, **18**:GB4004 doi: 10.1029/2004GB002223.

23. Mikaloff Fletcher SEM, Tans PP, Bruhwiler LM, Miller JB, Heimann M: **CH_4 sources estimated from atmospheric observations of CH_4 and its C-13/C-12 isotopic ratios: 2. Inverse modeling of CH_4 fluxes from geographical regions**. *Global Biogeochemical Cycles* 2004, **18**:GB4005 doi: 10.1029/2004GB002224.

24. Bergamaschi P, Krol M, Dentener F, Vermeulen A, Meinhardt F, Graul R, Peters W, Dlugokencky EJ: **Inverse modelling of national and European CH_4 emissions using the atmospheric zoom model TM5**. *Atmospheric Chemistry and Physics Discussions* 2005, **5**:1007-1066.

25. Bergamaschi P, Frankenberg C, Meirink JF, Krol M, Dentener F, Wagner T, Platt U, Kaplan JO, Korner S, Heimann M *et al.*: **Satellite chartography of atmospheric methane from SCIAMACHYon board ENVISAT: 2. Evaluation based on inverse model simulations**. *Journal of Geophysical Research* 2007, **112**:D02304 doi: 10.1029/2006JD007268.

26. Chen YH, Prinn RG: **Estimation of atmospheric methane emissions between 1996 and 2001 using a three-dimensional global chemical transport model**. *Journal of Geophysical Research* 2006, **111**:D10307 doi: 10.1029/2005JD006058.

27. • Walter KM, Zimov SA, Chanton JP, Verbyla D, Chapin FS: **Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming**. *Nature* 2006, **443**:71-75.

An important analysis of the role of thermokarst lakes of Siberia in the exchange of methane with atmosphere.

28. • Shakhova NE, Semiletov I, Salyuk A, Yusupov V, Kosmach D, Gustafsson O: **Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic shelf**. *Science* 2010, **327**:1246-1250.

An important analysis of the exchange of methane with the atmosphere from the East Siberian Arctic shelf.

29. Lammers RB, Shiklomanov AI, Vörösmarty CJ, Fekete BM, Peterson BJ: **Assessment of contemporary Arctic river runoff based on observational discharge records**. *Journal of Geophysical Research* 2001, **10**:63321-63334.

30. Sarmiento JL, Gruber N: *Ocean Biogeochemical Dynamics*. Princeton University Press; 2006.

31. Stein R, Macdonald RW: **Arctic Ocean organic carbon accumulation and its global significance**. In *The Organic Carbon Cycle in the Arctic Ocean.* Edited by Stein R, Macdonald RW. Springer; 2004:315-322.

32. Kasischke ES, Turetsky MR: **Recent changes in the fire regime across the North American boreal region**. *Geophysical Research Letters* 2006, **33**:L09703 doi: 10.1029/2006GL025677.

33. Soja AJ, Tchebakova NM, French NHF, Flannigan MD, Shugart HH, Stocks BJ, Sukhinin AI, Parfenova EI, Chapin FS, Stackhouse PW: **Climate-induced boreal forest change: predictions versus current observations**. *Global Planetary Change* 2007, **56**:274-296.

34. Kurz WA, Dymond CC, Stinson G, Rampley GJ, Neilson ET,
• Carroll A, Ebata T, Safranyik L: **Mountain pine beetle and forest carbon feedback to climate change**. *Nature* 2008, **452**:987-990.

This study is an important analysis of how insect disturbance may cause a region to become a substantial source of CO_2 to the atmosphere.

35. Hayes DJ, McGuire AD, Kicklighter DW, Burnside TJ, Melillo JM: **The effects of land cover and land use change on the contemporary carbon balance of terrestrial ecosystems in the Eurasian Arctic**. In *Arctic Land Cover and Land Use in a Changing Climate*. Edited by Gutman G, Groisman P, Reissell A. Springer; 2010, In Press.

36. Balshi MS, McGuire AD, Duffy P, Flannigan M, Walsh J, Melillo J: **Assessing the response of area burned in western boreal North America using a multivariate adaptive regression splines (MARS) approach**. *Global Change Biology* 2009, **15**:578-600.

37. Flannigan MD, Bergeron Y, Engelmark O, Wotton BM: **Future wildfire in circumboreal forests in relation to global warming**. *Journal of Vegetation Science* 1998, **9**:469-476.

38. Euskirchen ES, McGuire AD, Kicklighter DW, Zhuang Q, Clein JS, Dargaville RJ, Dye DG, Kimball JS, McDonald KC, Melillo JM *et al.*: **Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems**. *Global Change Biology* 2006, **12**:731-750.

39. Lawrence DM, Slater AG: **Incorporating organic soil into a global climate model**. *Climate Dynamics* 2008, **30**:145-160.

40. Peterson BJ, Holmes RM, McClelland JW, Vorosmarty CJ, Shiklomanov IA, Shiklomanov AI, Lammers RB, Rahmstorf S: **Increasing river discharge to the Arctic Ocean**. *Science* 2002, **298**:2171-2173.

41. Smith LC, Sheng Y, MacDonald GM, Hinzman LD: **Disappearing**
• **Arctic lakes**. *Science* 2005, **308**:1429.

This analysis documented lakes are shrinking in area in the discontinuous permafrost zone of Eurasia.

42. Riordan B, Verbyla D, McGuire AD: **Shrinking ponds in subarctic**
• **Alaska based on 1950–2002 remotely sensed images**. *Journal of Geophysical Research* 2006, **111**:G04002 doi: 10.1029/2005JG000150.

This analysis documented that closed-basin ponds in the discontinuous permafrost zone of Alaska have been shrinking in area.

43. Boby LA, Schuur EAG, Mack MC, Verbyla D, Johnstone JF:
• **Quantifying fire severity, carbon, and nitrogen emissions in Alaska's boreal forest**. *Ecological Applications* 2010, In Press.

This study conducted a comprehensive analysis of the loss of carbon from black spruce ecosystems in Alaska, and identified that the composite burn index can be used to quantify emissions.

44. Yi S, McGuire AD, Harden J, Kasischke E, Manies K, Hinzman L, Liljedahl A, Randerson J, Liu H, Romanovsky V *et al.*: **Interactions between soil thermal and hydrological dynamics in the response of Alaska ecosystems to fire disturbance**. *Journal of Geophysical Research – Biogeosciences* 2009, **114**:G02015 doi: 10.1029/2008JG000841.

45. Schuur EAG, Bockheim J, Canadell JG, Euskirchen E, Field CB,
• Goryachkin SV, Hagemann S, Kuhry P, Lafleur PM, Lee H *et al.*: **Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle**. *BioScience* 2008, **58**:701-714.

This is a comprehensive synthesis of the various mechanisms through which permafrost responses to climate change may affect carbon storage in permafrost soils.

46. Zhuang Q, Melillo JM, Sarofin MC, Kicklighter DW, McGuire AD, Felzer BS, Sokolov A, Prinn RG, Steudler PA, Hu S: **CO_2 and CH_4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st Century**. *Geophysical Research Letters* 2006, **33**:L17403 doi: 10.1029/2006GL026972.

47. Balshi MS, McGuire AD, Duffy P, Kicklighter DW, Melillo J: **Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st Century**. *Global Change Biology* 2009, **15**:1491-1510.

48. Schuur EAG, Vogel JG, Crummer KG, Lee H, Sickman JO,
• Osterkamp TE: **The effect of permafrost thaw on old carbon release and net carbon exchange from tundra**. *Nature* 2009, **459**:556-559.

This study identified that carbon storage in tundra ecosystems initially increases after thermokarst formation, but that carbon is ultimately lost from ecosystems over time from the thawing and decomposition of older deep carbon.

49. Guinotte JM, Fabry VJ: **Ocean acidification and its potential effects on marine ecosystems**. *Annals of the New York Academy of Sciences* 2008, **1134**:320-334.

50. Bates NR, Moran SB, Hansell DA, Mathis JT: **An increasing CO_2 sink in the Arctic Ocean due to sea–ice loss**. *Geophysical Research Letters* 2006, **23**:L23609 doi: 10.1029/2006GL027028.

51. Zhuang Q, Melillo JM, McGuire AD, Kicklighter DW, Prinn RG, Steudler PA, Felzer BS, Hu S: **Net emissions of CH_4 and CO_2 in Alaska: implications for the region's greenhouse gas budget**. *Ecological Applications* 2007, **17**:203-212.

52. Gedney NP, Cox M, Huntingford C: **Climate feedback from wetland methane emissions**. *Geophysical Research Letters* 2004, **31**:L20503 doi: 10.1029/2004GL020919.

53. Archer DE: **Methane hydrate stability and anthropogenic climate change**. *Biogeosciences* 2007, **4**:993-1057.

54. Heimann M: **How stable is the methane cycle?** *Science* 2010,
• **327**:1211-1212.

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.