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Significant climate risks are associated with a positive carbon–temperature feedback in northern latitude carbon-rich ecosystems, making an accurate analysis of human impacts on the net greenhouse gas balance of wetlands a priority. Here, we provide a coherent assessment of the climate footprint of a network of wetland sites based on simultaneous and quasi-continuous ecosystem observations of CO_2 and CH_4 fluxes. Experimental areas are located both in natural and in managed wetlands and cover a wide range of climatic regions, ecosystem types, and management practices. Based on direct observations we predict that sustained CH_4 emissions in natural ecosystems are in the long term (i.e., several centuries) typically offset by CO_2 uptake, although with large spatiotemporal variability. Using a space-for-time analogy across ecological and climatic gradients, we represent the chronosequence from natural to managed conditions to quantify the "cost" of CH_4 emissions for the benefit of net carbon sequestration. With a sustained pulse–response radiative forcing model, we found a significant increase in atmospheric forcing due to land management, in particular for wetland converted to cropland. Our results quantify the role of human activities on the climate footprint of northern wetlands and call for development of active mitigation strategies for managed wetlands and new guidelines of the Intergovernmental Panel on Climate Change (IPCC) accounting for both sustained CH_4 emissions and cumulative CO_2 exchange.

wetland conversion | methane | radiative forcing | carbon dioxide

For their ability to simultaneously sequester CO_2 and emit CH_4, wetlands are unique ecosystems that may potentially generate large negative climate feedbacks over centuries to millennia (1) and positive feedbacks over years to several centuries (2). Wetlands are among the major biogenic sources of CH_4, contributing to about 30% of the global CH_4 total emissions (3), and are presumed to be a primary driver of interannual variations in the atmospheric CH_4 growth rate (4, 5). Meanwhile, peatlands, the main subclass of wetland ecosystems, cover 3% of the Earth's surface and are known to store large quantities of carbon (about 500 ± 100 Gt C) (6, 7).

The controversial climate footprint of wetlands is due to the difference in atmospheric lifetimes and the generally opposite directions of CO_2 and CH_4 exchanges, which leads to an uncertain sign of the net radiative budget. Wetlands in fact have a great

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Significance

Wetlands are unique ecosystems because they are in general sinks for carbon dioxide and sources of methane. Their climate footprint therefore depends on the relative sign and magnitude of the land–atmosphere exchange of these two major greenhouse gases. This work presents a synthesis of simultaneous measurements of carbon dioxide and methane fluxes to assess the radiative forcing of natural wetlands converted to agricultural or forested land. The net climate impact of wetlands is strongly dependent on whether they are natural or managed. Here we show that the conversion of natural wetlands produces a significant increase of the atmospheric radiative forcing. The findings suggest that management plans for these complex ecosystems should carefully account for the potential biogeochemical effects on climate.

potential to preserve the carbon sequestration capacity because near water-logged conditions reduce or inhibit microbial respiration, promoting meanwhile CH_4 production that may partially or completely counteract carbon uptake. Potential variations of the CO_2/CH_4 stoichiometry in wetlands exposed to climate and land-use change require the development of mitigation-oriented management strategies to avoid large climatic impacts.

The current and future contribution of wetlands to the global greenhouse gas (GHG) budget is still uncertain because of our limited knowledge of the combined and synergistic response of CH_4 and CO_2 land–atmosphere exchange to environmental variability (8, 9) and land-use change (e.g., wetland restoration, drainage for forestry, agriculture, or peat mining) (9, 10). Fluxes of CH_4 and CO_2 from natural wetlands show large spatiotemporal variations (11, 12), arising from environmental interactions controlling the production, transport, consumption, and release of CH_4 (13, 14) as well as the dynamic balance between photosynthetic and respiratory processes that regulate the net accumulation of carbon in biomass and soil. Environmental factors such as variations in air and soil temperature, water table, and substrate availability for methanogenesis lead to a high spatial and temporal variation of CH_4 emissions (15–17). The magnitude of emissions is also controlled by the balance between CH_4 production and oxidation rates and by transport pathways: diffusion (18), ebullition (19), and aerenchyma transport (20).

Climate change influences the GHG balance of wetlands through thawing of the near-surface permafrost (21, 22) and thaw lakes (23), increased nitrogen availability due to accelerated decomposition of organic matter (24), and modification of the water tables with consequent shifts in CH_4 emissions (1, 25). A review of carbon budgets of global peatlands concluded that these ecosystems may remain a small but persistent sink that builds a large C pool, reducing the atmospheric CO_2 burden, whereas the stimulation of CH_4 emissions induced by climate warming may be locally tempered or enhanced by drying or wetting (26). The climate footprint of wetlands can also be affected by anthropogenic activities such as the conversion of natural ecosystems to agricultural or forested land (10, 27). Draining peatlands for forestry may lead to a C loss and reduced CH_4 emissions (10, 26), whereas land use for agriculture typically reduces the CH_4 emissions and increases N_2O emissions (26).

Several studies have analyzed the impact of northern peatlands on the Earth's radiative budget either by computing the radiative forcing (RF) of sustained CH_4 and CO_2 fluxes (2) or by multiplying the annual ecosystem exchange of CO_2 and CH_4 with the global warming potentials of the two gases (28–30). However, although this latter approach is useful for comparison, its appropriateness in computing the actual RF has been questioned (31–33). An alternative approach for assessing the impact of peatland draining/drying on the RF has been applied by driving an atmospheric composition and RF model with pre- and post-drainage measured fluxes of CO_2, CH_4, and N_2O (34).

Here, we ask, what is the climate cost of CH_4 emissions compared with the benefit of net carbon sequestration? We assessed this question, using data from a network of wetland observational sites where direct and quasi-continuous CO_2 and CH_4 chamber and eddy covariance measurements are performed. Using the space for time analogy, flux observations at sites with contrasting land cover are combined with a sustained pulse–response model to predict the potential future RF of natural wetlands converted to agricultural or forested land.

Results and Discussion

As the land–atmosphere fluxes of CH_4 and CO_2 in wetlands can be opposite in sign and very different in magnitude, their net impact on the climate system is difficult to assess and predict. In particular, CH_4 emissions from wetlands are continuous and thus add a positive term to the radiative balance (31) that can be partially or totally offset by a sustained carbon sequestration (35). The availability of consistent and simultaneous measurements of ecosystem CO_2 and CH_4 fluxes provides an opportunity to address these issues, using direct observations collected at 29 both natural and managed wetlands located in the Northern Hemisphere (Fig. 1*A*). Details on site locations, climate, vegetation type, measurement techniques, and yearly/seasonal GHG budgets are reported in *SI Text*, *Site Analysis* and *SI Text*, *Measurement Techniques and Gap-Filling Methods* (Tables S1–S5).

The trade-off between CH_4 net emission and CO_2 net sequestration in wetlands is evident in Fig. 1*B*, where most sites are sources of CH_4 (positive ecosystem fluxes) and CO_2 sinks (negative values of net ecosystem exchange, NEE). Given that CH_4 has a relatively short lifetime in the atmosphere (~10 y) compared to CO_2, the radiative balance of these two gases depends on the timeframe of the analysis. As an example of this dependence, the two red–blue equilibrium lines in Fig. 1*B* represent the ratio of sustained CO_2 and CH_4 fluxes that would result in a zero net cumulative radiative balance over 20 y and 100 y. The lines were simulated with a sustained pulse–response model (27) and used in this study also to calculate the RF of management options. The model generates the following flux ratios: −31.3 g and −19.2 g $CO_2\text{-}C \cdot m^{-2} \cdot y^{-1}$ per gram $CH_4\text{-}C \cdot m^{-2} \cdot y^{-1}$ for 20 y and 100 y, respectively. This implies that a continuous emission of 1 g $CH_4\text{-}C \cdot m^{-2} \cdot y^{-1}$ and uptake of 31.3 g $CO_2\text{-}C \cdot m^{-2} \cdot y^{-1}$ would have a positive cumulative RF (warming) for the first 20 y and a negative cumulative RF (cooling) after that. Sites that fall on the right side of the equilibrium lines have a positive radiative budget and those on the left side have a negative radiative budget for the specified 20-y or 100-y timeframe (Fig. 1*B*). Under the current climate, 59% of arctic and boreal sites' and 60% of temperate sites' observations have a positive radiative balance compared with both 20-y and 100-y equilibrium lines. All but one of the forested wetlands [arctic/boreal (AB)5, AB7, temperate (T)9, and T11] currently have a negative net radiative balance owing to their considerable CO_2 uptake and relatively low CH_4 emissions (Fig. 1*B* and Fig. S1). Sites located between the two lines have a positive or negative radiative budget, depending on the time span of the analysis (e.g., AB9, AB4, and T8, Fig. 1*B*).

Changes in the water level in wetlands substantially alter the ratio of CH_4 and CO_2 fluxes. Recent warming and drying in the Arctic has led to increased CO_2 losses from the soil, in some cases switching arctic regions from a long-term carbon sink to a carbon source (36). In other cases, the drying of arctic and boreal wetlands reduces CH_4 emission without generating larger CO_2 emissions, owing to the compensation between accelerated decomposition of organic matter and an increase in net primary productivity (NPP) (37–39). As an example of management impacts, data show that the CO_2 and CH_4 emissions of the site AB3a dropped toward a near zero net radiative budget one year

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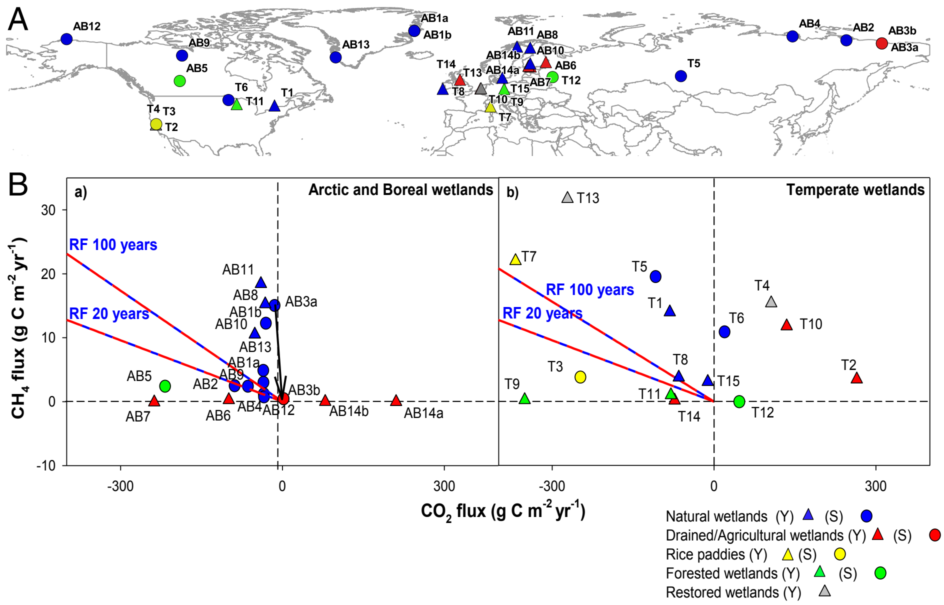

Fig. 1. (*A*) Global distribution of the 29 measurement sites involved in the present analysis. Triangles represent sites with annual budgets (Y) and circles represent sites with growing season budgets (S). Site IDs and description are reported in *SI Text, Site Analysis* and Tables S1 and S2. (*B*) CH_4 vs. CO_2 flux (in grams $C{\cdot}m^{-2}{\cdot}y^{-1}$) for arctic/boreal and temperate wetlands relative to the modeled RF equilibrium lines. The two blue–red equilibrium lines represent the ratio of sustained CO_2 and CH_4 fluxes (grams CO_2-$C{\cdot}m^{-2}{\cdot}y^{-1}$ per gram CH_4-$C{\cdot}m^{-2}{\cdot}y^{-1}$) that would result in a zero cumulative RF over the period indicated for the line (20 y and 100 y). The slope of the line depends on the constant CO_2 uptake rate that would be needed for compensating the positive RF of a unit CH_4 emission at a fixed changing time. The arrow pointing down (AB3a to AB3b) indicates the carbon flux change at the specific site after a drainage experiment.

after drainage, whereas sites that were drained a long time ago, such as AB6 and AB7, have large carbon uptake rates (Fig. 1).

Different responses of CH_4 and CO_2 budgets at drained temperate wetlands compared with boreal or arctic wetlands mainly occur due to management activities. At these sites draining for agricultural use suppresses CH_4 emissions and enhances CO_2 efflux owing to accelerated peat degradation, exploitation through grazing, and carbon export (T2, T10, and T14). Conversely, rewetted former agricultural areas or restored wetlands typically emit CH_4 (T13) at a rate that in the short term is not offset by the CO_2 sink (T4). Although most of the studied temperate wetlands have a positive radiative budget, natural forested wetlands show significant carbon uptake driven by high rates of photosynthesis that offsets ecosystem respiration (T9 and T11). The long-term CH_4 and CO_2 balance of these ecosystems thus ultimately depends on the fate of the carbon stored in the trees.

At temperate latitudes, it is interesting to note that the two rice paddies (T3 and T7) that in general are known as major contributors to atmospheric CH_4 (5% of the total emissions and about 10% of the anthropogenic emissions) (3) are also characterized by large CO_2 uptake. However, the net GHG budget of this crop is further complicated by significant carbon imports (fertilization) and exports (harvest and dissolved organic carbon). Based on site observations, carbon losses due to harvest account for 67% and 70% of net ecosystem exchange at T3 (40) and T7, respectively, so that the net GHG balance from these ecosystems is strongly influenced by the carbon exports.

To quantify the effect of ecosystem management on the net climate impact of multiple GHG fluxes, we applied an analytical approach based on the concept of radiative forcing. RF is a widely used metric in climate change research to quantify the magnitude of an externally imposed perturbation to the incoming long-wave radiative component of the Earth's atmospheric energy budget (41). Two types of human perturbations were considered: the conversion of natural wetlands to agricultural land and the conversion of natural forested wetlands to managed forested wetlands. Natural wetlands with full annual GHG budget were used as reference and paired in all possible combinations to managed sites (*SI Text, Radiative Forcing Calculations* and Table S6). Based on the difference between natural and perturbed ecosystems, we calculated the net RF due to CO_2 and CH_4 fluxes for 100 y, using a sustained pulse–response model (27) (*SI Text, Radiative Forcing Calculations*). The contribution of N_2O fluxes to the RF was accounted for only in agricultural sites (AB6, AB14a,b, T10, and T14) where significant emissions of this GHG can be observed (3).

Losses of carbon due to harvest and natural disturbances (e.g., mainly fires, wind throw, and pests) were also taken into account in the RF calculation, either in the form of annual harvest (for agricultural land) or after each rotation for wood harvest, and assumed every 100 y for natural disturbances in forested wetlands (42–44). It was assumed that all of the removed biomass was emitted into the atmosphere as CO_2 during the same year. The results of the RF simulations (Fig. 2) are thus dependent on the ecosystem and management type. Results show that at all timescales the net effect of GHG emissions in arctic and boreal natural wetlands converted into agricultural sites (Fig. 2*A*) is a large positive RF, whereas the conversion of drained wetlands into energy crops (AB6) results in a minor negative RF for the 100-y simulations. The temperate wetlands (Fig. 2*B*) that were converted into agriculture sites showed, in general, a positive RF with a large spread among sites induced by management intensity [e.g., intensive (T10) vs. extensive (T14) grazing]. Given that the carbon balance of forest ecosystems largely depends on the fraction of harvested biomass, we carried out an uncertainty analysis by perturbing the harvest rate of the accumulated NPP according to two Gaussian distributions for natural (50 ± 10%, observed harvest rate at AB7) and managed (67 ± 10%) (45) sites, respectively (*SI Text, Radiative Forcing Calculations*). To evaluate the uncertainty generated by our assumptions, NPP was estimated with two alternative methodologies: (*i*) applying average ratios of NPP/gross primary productivity derived from the partitioning of the observed NEE (46), based on a recent meta-analysis (NPP/GPP = 0.39 and 0.49 for boreal and temperate forests, respectively) (47), and (*ii*) summing the observed NEE to the soil respiration rates

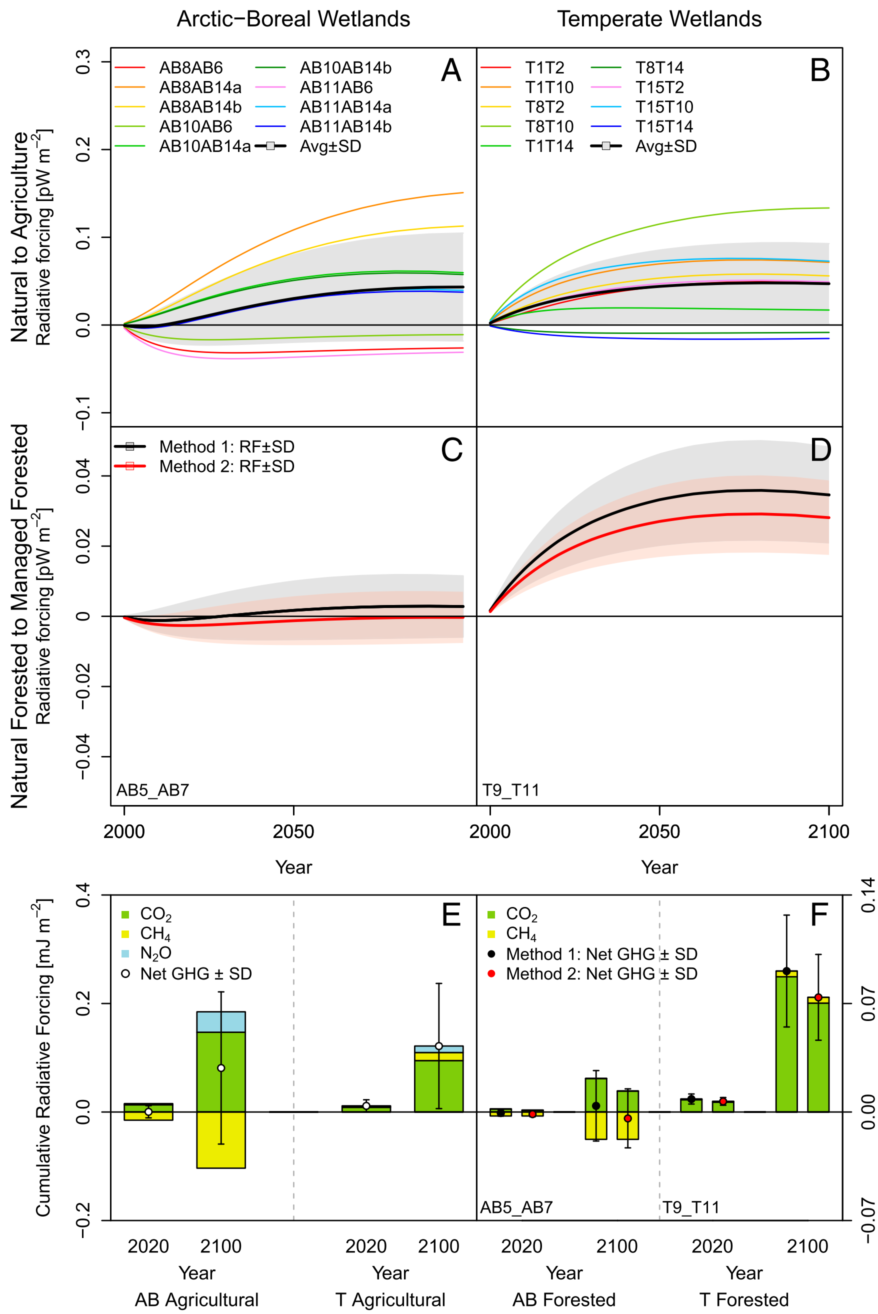

Fig. 2. Trends of radiative forcing (RF, period 2000–2100) for paired sites and ecosystem types. (*A* and *B*) Net RF for CO_2, CH_4, and N_2O in natural wetlands converted to agricultural land. (*C* and *D*) Net RF for the conversion of natural forested wetland to managed forests (AB5→AB7 and T9→T11). For each of the two pairs an uncertainty analysis on the effect of the harvest rate is presented. (*E* and *F*) Cumulative RF of individual gases at 20 y and 100 y for all site pairs, with their net RF (circles ± SD). The forcing units refer to the mean global impact of 1 m^2 of wetland area (*SI Text, Radiative Forcing Calculations*). Site IDs can be found in *SI Text, Site Analysis* and Tables S1 and S2.

reported in the *IPCC Wetland Supplement* for natural and managed wetlands (48).

Results for the boreal site pair (AB5→AB7) show that the confidence intervals cross the *x* axis and therefore the ultimate sign of the RF depends on the harvest rate. In addition, with both methods used for the calculation of NPP, at average harvest rates the RF is not statistically different from zero (Fig. 2*C*). In contrast, for the temperate site pair (T9→T11) RF is positive, independently of the management intensity and of the applied methodology (Fig. 2*D*). Our analysis demonstrates that, to assess the RF of wetland management, both CH_4 fluxes and the concomitant changes in CO_2 emissions have to be accounted for. This is especially true at the decadal timescales for boreal wetlands converted to forest or agricultural land (Fig. 2 *E* and *F*).

Conclusions

The recent availability of simultaneous and continuous ecosystem observations of CH_4 and CO_2 fluxes in wetlands provides fundamental insights into the climate footprint of these ecosystems to support the development of sustainable mitigation strategies based on ecosystem management. Careful accounting of both CO_2 and CH_4 fluxes (and N_2O fluxes where significant) is essential for an

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accurate calculation of the climate impact of wetlands. We also stress the importance of direct and quasi-continuous chamber or eddy covariance flux measurements over annual timescales for the observation of ecosystem responses to environmental drivers and management (e.g., flooding, drainage, and land use change) that may be missed with intermittent manual chamber measurements.

The net GHG budget of these ecosystems is spatially and temporally variable in sign and magnitude due to the generally opposite direction of CH_4 (emission) and CO_2 (uptake) exchange and, therefore, can be easily altered by both natural and anthropogenic perturbations (*SI Text, Site Analysis* and Table S3). Management and land use conversions in particular play a critical role in determining the future GHG balance of these ecosystems. Our results prove that management intensity strongly influences the net climate footprint of wetlands and in particular the conversion of natural ecosystems to agricultural land ultimately leads to strong positive RF. These considerations suggest that future releases of GHG inventories based on IPCC guidelines for wetlands should indeed address the relationship between the fluxes of CH_4 and CO_2, the management intensity, and the land use/land cover change on the net GHG balance as well as on the RF of these complex ecosystems.

Materials and Methods

This study is based on measurements of net ecosystem exchange of CO_2 and CH_4 trace gas exchange performed with eddy covariance and/or chamber methods (*SI Text, Site Analysis* and Tables S1 and S2). Most of the included study sites are part of FLUXNET, an international network of sites where energy and GHG fluxes are continuously monitored with a standardized methodology (49). The RF due to wetlands management was calculated for CO_2, CH_4, and, where significant (agricultural sites AB6, AB14a,b, T10, and T14), N_2O fluxes, using a sustained pulse–response model (27). Annual concentration pulses were derived from the flux differences between pristine wetlands, taken as reference, and wetlands converted to either cropland or forests.

Natural-managed site pairs were defined for all possible combinations of similar ecosystem types with available annual CO_2 and CH_4 budgets within each climatic or management-related category (arctic/boreal or temperate regions, cropland or forest; *SI Text, Radiative Forcing Calculations* and Table S6). These site pairs were selected to represent plausible and representative wetland conversions, and thus part of the sites were excluded from this analysis (e.g., rice fields). In the simple pulse–response RF model used here the perturbations to the tropospheric concentrations of CO_2, CH_4, and N_2O were derived by integrating the effect of a series of consecutive annual mass pulses that correspond to the mean annual balances of these gases (27) (*SI Text, Radiative Forcing Calculations*). Different radiative efficiencies and atmospheric residence times of CO_2, CH_4, and N_2O were taken into account, as well as the annual variation of their background concentrations. RF was calculated for a 100-y period starting from 2000, assuming that the background concentrations increase as in the A2 scenario of the Special Report on Emissions Scenarios (SRES). The RF methodology is described in detail in *SI Text, Radiative Forcing Calculations*. The data reported in this paper are tabulated in *SI Text* and part is archived in the FLUXNET database and/or published in peer-review articles as shown in *SI Text* references.

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1. Gorham E (1991) Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecol Appl* 1(2):182–195.
2. Frolking S, Roulet NT (2007) Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. *Glob Change Biol* 13:1079–1088.
3. Ciais P, et al. (2013) Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Stocker TF, et al. (Cambridge Univ Press, Cambridge, UK), pp 505–510.
4. Bousquet P, et al. (2006) Contribution of anthropogenic and natural sources to atmospheric methane variability. *Nature* 443(7110):439–443.
5. Nisbet EG, Dlugokencky EJ, Bousquet P (2014) Atmospheric science. Methane on the rise—again. *Science* 343(6170):493–495.
6. Limpens J, et al. (2008) Peatlands and the carbon cycle: From local processes to global implications – a synthesis. *Biogeosciences* 5:1475–1491.
7. Yu ZC (2012) Northern peatland carbon stocks and dynamics: A review. *Biogeosciences* 9:4071–4085.
8. Sturtevant C, Oechel WC (2013) Spatial variation in landscape-level CO_2 and CH_4 fluxes from arctic coastal tundra: Influence from vegetation, wetness, and the thaw lake cycle. *Glob Change Biol* 19(9):2853–2866.
9. Zona D, et al. (2009) Methane fluxes during the initiation of a large-scale water table manipulation experiment in the Alaskan arctic tundra. *Global Biogeochem Cycles* 23(2):GB2013.
10. Minkkinen K, Korhonen R, Savolainen I, Laine J (2002) Carbon balance and radiative forcing of Finnish peatlands 1900-2100 – the impact of forestry drainage. *Glob Change Biol* 8:785–799.
11. Drösler M, Freibauer A, Christensen TR, Friborg T (2008) Observation and status of peatland greenhouse gas emission in Europe. *The Continental-Scale Greenhouse Gas Balance of Europe*, *Ecological Studies*, eds Dolman H, Valentini R, Freibauer A (Springer, New York), Vol 203, pp 237–255.
12. Harazono Y, et al. (2006) Temporal and spatial differences of methane flux at arctic tundra in Alaska. *Memoirs of National Institute of Polar Research* 59(Special Issue): 79–95.
13. Matthews E (2000) Wetlands. *Atmospheric Methane: Its Role in the Global Environment*, ed Khalil MAK (Springer, Berlin), pp 202–233.
14. Vourlitis GL, Oechel WC (1997) The role of northern ecosystems in the global methane budget. *Global Change and Arctic Terrestrial Ecosystem*, Ecological Studies, eds Oechel WC, et al. (Springer, New York), Vol 124, pp 266–289.
15. Moore TR, Knowles R (1990) CH_4 emissions from fen, bog and swamp peatlands in Quebec. *Biogeochemistry* 11:45–61.
16. Whalen SC, Reeburgh WS (1992) Interannual variations in tundra CH_4 emissions: A four-year time series at fixed sites. *Global Biogeochem Cycles* 6(2):139–159.
17. Dise NB (1993) Methane emissions from Minnesota peatlands: Spatial and seasonal variability. *Global Biogeochem Cycles* 7(1):123–142.
18. Kip N, et al. (2010) Global prevalence of methane oxidation by symbiotic bacteria in peat-moss ecosystems. *Nat Geosci* 3:617–621.
19. Kellner E, Waddington JM, Price JC (2005) Dynamics of biogenic gas bubbles in peat: Potential effects on water storage and peat deformation. *Water Resour Res* 41:W08417.
20. Öquist MG, Svensson BH (2001) Vascular plants as regulators of CH_4 emissions from subarctic mire ecosystem. *J Geophys Res* 107(D21):4580.
21. Lawrence DM, Slater A, Romanovsky VE, Nicolsky DJ (2008) Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. *J Geophys Res Earth Surface* 113(F2):000883.
22. Lupascu M, et al. (2014) High Arctic wetting reduces permafrost carbon feedbacks to climate warming. *Nature Climate Change* 4:51–55.
23. Anthony KM, et al. (2014) A shift of thermokarst lakes from carbon sources to sinks during the Holocene epoch. *Nature* 511(7510):452–456.
24. Keuper F, et al. (2012) A frozen feast: Thawing permafrost increases plant-available nitrogen in subarctic peatlands. *Glob Change Biol* 18:1998–2007.
25. Nykänen H, Alm J, Silvola J, Tolonen JK, Martikainen PJ (1998) Methane fluxes on boreal peatlands of different fertility and the effect of long term experimental lowering of the water table on flux rates. *Global Biogeochem Cycles* 12(1):53–69.
26. Frolking S, et al. (2011) Peatlands in the Earth's 21^{st} century climate system. *Environ Rev* 19:371–396.
27. Lohila A, et al. (2010) Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *J Geophys Res* 115:G04011.
28. Roulet NT (2000) Peatlands, carbon storage, greenhouse gases, and the Kyoto protocol: Prospects and significance for Canada. *Wetlands* 20(4):605–615.

29. Whiting GJ, Chanton JP (2001) Greenhouse carbon balance of wetlands: Methane emission versus carbon sequestration. *Tellus* 53B:521–528.
30. Friborg T, et al. (2003) Siberian wetlands: Where a sink is a source. *Geophys Res Lett* 30(21):2129–2132.
31. Frolking S, Roulet NT, Fuglestvedt J (2006) How northern peatlands influence the Earth's radiative budget: Sustained methane emission versus sustained carbon sequestration. *J Geophys Res* 111:G01008.
32. Neubauer SC (2014) On the challenges of modeling the net radiative forcing of wetlands: Reconsidering Mitsch et al. (2013). *Landscape Ecol.* 29:571–577.
33. Bridgham S, Moore T, Richardson C, Roulet NT (2014) Errors in greenhouse forcing and soil carbon sequestration estimates in freshwater wetlands: A comment on Mitsch et al. (2013). *Landscape Ecol* 29(6):1–5.
34. Laine J, Minkkinen K (1996) Effect of forest drainage on the carbon balance of a mire: A case study. *Scand J For Res* 11:307–312.
35. Tarnocai C, et al. (2009) Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochem Cycles* 23(2):GB2023.
36. Oechel WC, et al. (1993) Recent change of arctic tundra ecosystems from a net carbon sink to a source. *Nature* 361:520–526.
37. Sulman BN, Desai AR, Cook BD, Saliendra N, Mackay DS (2009) Contrasting carbon dioxide fluxes between a drying shrub wetland in Northern Wisconsin, USA, and nearby forests. *Biogeosciences* 6:1115–1126.
38. Flanagan LB, Syed KH (2011) Stimulation of both photosynthesis and respiration in response to warmer and drier conditions in a boreal peatland ecosystem. *Glob Change Biol* 17:2271–2287.
39. Merbold L, et al. (2009) Artificial drainage and associated carbon fluxes (CO_2/CH_4) in a tundra ecosystem. *Glob Change Biol* 15:2599–2614.
40. Hatala JA, et al. (2012) Greenhouse gas (CO_2, CH_4, H_2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. *Agric Ecosyst Environ* 150:1–18.
41. Ramaswamy V, et al. (2001) Radiative forcing of climate change. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, eds Houghton JT, et al. (Cambridge Univ Press, Cambridge, UK), pp 349–416.
42. Vanderwel MC, Coomes DA, Purves DW (2013) Quantifying variation in forest disturbance, and its effects on aboveground biomass dynamics, across the eastern United States. *Glob Change Biol* 19(5):1504–1517.
43. Peters BE, Wythers KR, Bradford JB, Reich PB (2013) Influence of disturbance on temperate forest productivity. *Ecosystems* 16(1):95–110.
44. Krankina ON, et al. (2005) Effects of climate, disturbance and species on forest biomass across Russia. *Can J For Res* 35:2281–2293.
45. Callesen I, Østergaard H (2008) Energy efficiency of biomass production in managed versus natural temperate forest and grassland ecosystems. *16th IFOAM Organic World Congress, Modena, Italy, June 16–20*. Available at orgprints.org/view/projects/conference.html.
46. Reichstein M, et al. (2005) On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algo- rithm. *Glob Change Biol* 11:1424–1439.
47. Tang J, et al. (2014) Steeper declines in forest photosynthesis than respiration explain age-driven decreases in forest growth. *Proc Natl Acad Sci USA* 111(24):8856–8860.
48. IPCC (2014) *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, eds Hiraishi T, et al. (IPCC, Geneva, Switzerland).
49. Baldocchi DD, et al. (2001b) FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bull Am Meteorol Soc* 82:2415–2434.

Supporting Information

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SI Text

Site Analysis

This study is based on measurements of CO_2 (NEE) and CH_4 (plus N_2O for agricultural sites where significant emissions can be observed) (1) trace gas exchange performed with eddy covariance and/or chamber methods. Most of the included study sites are part of FLUXNET, an international network of sites where energy and greenhouse gas fluxes are continuously monitored with a standardized methodology (2). Fig. S1 presents the CO_2 and CH_4 fluxes, expressed in C units for each of the sites, whose main characteristics are summarized in Tables S1 and S2 and divided into ecosystem types [i.e., arctic/boreal (AB) and temperate (T) wetlands]. Here, negative values indicate carbon uptake, whereas positive values indicate carbon release by the system. The average CH_4 and CO_2 flux values shown in Table S1 are annual/seasonal (growing season) cumulative sums; existing gaps (hourly to daily, mainly for AB sites) were filled by the different techniques detailed in Tables S4 and S5 to estimate the cumulative seasonal totals.

Combined eddy covariance measurements of CO_2 and CH_4 ecosystem exchange have become more common during the past 5 y. This study represents to our knowledge the first large-scale synthesis of these observations in wetlands. Due to the harsh winter, measurements in the arctic and boreal regions mainly refer to the growing season whereas for temperate regions annual measurements are mostly available. For northern wetlands most of the CH_4 emissions occur during the growing season and are mainly explained by water table level variability (3–5). In a southern boreal Finnish fen, growing season CH_4 emissions accounted for ~91% of the total annual emissions (6, 7) whereas other studies (8) estimated that winter CH_4 emissions account for 10–22% of the total annual emissions, depending on the ecosystem type (bog and fen, respectively). It was also observed that CH_4 emissions during winter are attributed to physical processes during soil freezing rather than microbial activity (9). Because winter CO_2 emissions can be substantial (10, 11), they cannot be ignored in the GHG budget of a site. Therefore, we use only sites reporting annual budgets for both CO_2 and CH_4 in the RF analysis. Sites reporting growing season fluxes are shown in Fig. 1 *A* and *B* with different symbols (Tables S1–S3).

Measurement Techniques and Gap-Filling Methods

Tables S4 and S5 show site-specific measurement techniques and instrumentation for CO_2 and CH_4 fluxes and site-specific gap-filling methods, respectively.

Radiative Forcing Calculations

The radiative forcing (RF) was calculated for CO_2, CH_4, and, where significant (sites AB6, AB14a,b, T10, and T14), N_2O fluxes, using a sustained pulse–response model (12). Annual concentration pulses were derived from the flux differences between natural wetlands, taken as reference, and wetlands converted to either agriculture or forestry. Natural-managed site pairs were defined for all possible combinations of similar ecosystem types with available annual CO_2 and CH_4 budgets within each climatic or management-related category (arctic/boreal or temperate regions; agriculture or forestry). These site pairs were selected to represent plausible and representative wetland conversions, and thus parts of the sites were excluded from this analysis (e.g., rice fields).

For each agricultural site, we first determined the annual net ecosystem carbon balance (NECB), as follows:

$$\begin{aligned}\mathrm{NECB} = &-\text{net ecosystem exchange(NEE)}\\ &+\text{manure}-CO_2(CH_4\ \text{oxid.})\\ &-\text{dissolved organic carbon(DOC)}-\text{harvest}.\end{aligned}$$

$CO_2(CH_4$ oxid.) represents the CO_2 flux produced from the oxidation of CH_4 in the atmosphere. The carbon removal by harvest was taken into account for all sites by assuming that all of the removed biomass is emitted into the atmosphere as CO_2 during the same year. The carbon import with manure was included for one site (T10). Management-related changes in the DOC fluxes could not be estimated, because DOC data are not available for most of the sites. In general, direct measurements of the DOC loss after peatland drainage are scarce. In the recent IPCC guidelines for greenhouse gas inventories (13), values of ~10 g and 30 g $C \cdot m^{-2} \cdot y^{-1}$ for boreal and temperate peatlands, respectively, are recommended for the DOC loss due to drainage. Thus, it seems clear that, on average, the DOC loss following from peatland drainage and management is much smaller than the carbon released directly to the atmosphere as CO_2 (on average 400 g $C \cdot m^{-2} \cdot y^{-1}$, Table S6). Hence we assumed that DOC change equals zero. This conservative assumption leads to a slight underestimation of the management-induced RF. For the reference scenarios, we used data from three arctic/boreal sites (AB8, AB10, and AB11) and three temperate sites (T1, T8, and T15). The annual gas balance of these sites was subtracted from the corresponding balances of the managed site (AB6, AB14a, AB14b, T2, T10, and T14). The RF effect of management was estimated separately for CO_2 (NECB), CH_4, and N_2O. For N_2O we used reported fluxes where significant (AB8→AB6, AB8→AB14a, AB8→AB14b, T1→T14, and T15→T14) and, in addition, assumed the N_2O flux in the natural T8 site to equal zero (in the T8→T10 and T8→T14 site pairs).

For the forest-covered sites (AB5, AB7, T9, and T11), the average annual NECB was estimated from the NEE dynamics over a rotation cycle. As only a few years of measurements for a middle-aged forest are available at each site, it was necessary to prescribe a generic shape for the NEE dynamics that is applied for all sites. The actual NEE profile at a certain site was scaled from this generic function according to the measured NEE. In addition to NEE, heterotrophic soil respiration (R_{soil}) was estimated as described below.

The NEE dynamics were assumed to start from NEE = R_{soil} and decrease linearly for 15 y, after which the maximum (absolute) NEE (NEE_{max}) is reached (14, 15). The NEE_{max} level is maintained for 60 y, after which the net primary production (NPP = –NEE + R_{soil}) is assumed to decrease (14–16) with a time constant of 300 y (16, 17). For managed sites losses due to harvest were set to 67 ± 10% of the accumulated NPP (18), after each rotation period of 70 y and 80 y at T11 and AB7, respectively. Disturbances (fire, windthrow, pest outbreaks, diseases) were simulated at the natural sites AB5 and T9 every 100 y by removing 50 ± 10% of the accumulated NPP (19–21). After the harvest, NEE returned to the R_{soil} value, whereas after natural disturbance NPP was assumed to decrease by 50% and NEE changed accordingly. In each case, the amount of carbon removed by harvest or disturbance was assumed to be instantaneously released into the atmosphere.

The R_{soil} of forest-covered sites was estimated with two alternative methods: (*i*) calculated from the carbon budget of each site and (*ii*) based on the *IPCC Wetland Supplement* (13). In the former method, NPP was assumed to be 39% and 49% of GPP (derived from the partitioning of NEE) at the boreal and temperate sites, respectively (16, 17), and the heterotrophic respiration is calculated as R_{soil} = NPP + NEE. In the second method, R_{soil} for the temperate sites was fixed at 950 g $CO_2 \cdot m^{-2} \cdot y^{-1}$, whereas the average of the nutrient-poor (91.5 g $CO_2 \cdot m^{-2} \cdot y^{-1}$) and nutrient-rich (340.4 g $CO_2 \cdot m^{-2} \cdot y^{-1}$) sites was used for the boreal sites (215 g $CO_2 \cdot m^{-2} \cdot y^{-1}$) (13). With both methods, R_{soil} was assumed to remain constant during the whole rotation.

The mean NECB was finally calculated by averaging the resulting C balance over the full rotation of the forest. The mean NECB of the natural sites was subtracted from that of the corresponding managed sites and this difference was then assumed to be fixed from/released to the atmosphere each year. To assess the uncertainty related to our assumptions on the harvest rate, we calculated the RF due to management, using a Gaussian distribution for the fraction of harvested NPP (67 ± 10% and 50 ± 10% for the managed and natural forested sites, respectively). From this distribution, the RF of 20 randomly sampled values was calculated for both site pairs and ensemble statistics are shown in Fig. 2 *C* and *D*.

In the simple pulse–response RF model used here the perturbations to the tropospheric concentrations of CO_2, CH_4, and N_2O were derived by integrating the effect of a series of consecutive annual mass pulses that correspond to the times series of annual balances of these gases (22). Different radiative efficiencies and atmospheric residence times of CO_2, CH_4, and N_2O were taken into account, as well as the annual variation of their background concentrations. RF was calculated for a 100-y period starting from 2000, assuming that the background concentrations increase as in the SRES A2 scenario. The RF calculations are based on data of measured mass flux densities ($g \cdot m^{-2} \cdot s^{-1}$) and thus represent the effect of the sustained emission/uptake per square meter of peatland. The resulting RF ($W \cdot m^{-2} = J \cdot m^{-2} \cdot s^{-1}$) is expressed as the globally averaged energy flux density and thus equals the energy flux per square meter of the Earth's surface. Positive (negative) RF indicates a warming (cooling) impact on climate.

1. Ciais P, et al. (2013) Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Stocker TF, et al. (Cambridge Univ Press, Cambridge, UK), pp 505–510.
2. Baldocchi DD, et al. (2001b) FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bull Am Meteorol Soc* 82:2415–2434.
3. Pelletier L, Moore TR, Roulet NT, Garneau M, Beaulieu-Audy V (2007) Methane fluxes from three peatlands in the La Grande Rivière watershed, James Bay lowland, Canada. *J Geophys Res* 112:G01018.
4. Walter BP, Heimann M (2000) A process-based, climate-sensitive model to derive methane emissions from natural wetlands: Application to five wetland sites, sensitivity to model parameters, and climate. *Global Biogeochem Cycles* 14:745–765.
5. Petrescu AMR, et al. (2010) Modeling regional to global CH_4 emissions of boreal and arctic wetlands. *Global Biogeochem Cycles* 24:GB4009.
6. Rinne J, et al. (2007) Annual cycle of methane emission from a boreal fen measured by the eddy Covariance technique. *Tellus B Chem Phys Meterol* 59:449–457.
7. Melloh RA, Crill PM (1995) Winter methane dynamics beneath ice and in snow in a temperate poor fen. *Hydrol Processes* 9:947–956.
8. Saarnio S, Silvola J (1999) Effects of increased CO_2 and N on CH_4 efflux from a boreal mire: A growth chamber experiment. *Oecologia* 119:349–356.
9. Whalen SC, Reeburgh WS (1992) Interannual variations I tundra CH_4 emissions: A four-year time series at fixed sites. *Global Biogeochem Cycles* 6(2):139–159.
10. Belshe EF, Schuur EA, Bolker BM (2013) Tundra ecosystems observed to be CO_2 sources due to differential amplification of the carbon cycle. *Ecol Lett* 16(10):1307–1315.
11. Oechel WC, et al. (2000) Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming. *Nature* 406(6799):978–981.
12. Lohila A, et al. (2010) Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *J Geophys Res* 115:G04011.
13. IPCC 2014, *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories:* Wetlands, eds Hiraishi T, et al. (IPCC, Geneva, Switzerland).
14. Goulden ML, et al. (2011) Patterns of NPP, GPP, respiration, and NEP during boreal forest succession. *Glob Change Biol* 17:855–871.
15. Amiro BD, et al. (2010) Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *J Geophys Res Biogeosci* 115:G00K02.
16. Tang J, et al. (2014) Steeper declines in forest photosynthesis than respiration explain age-driven decreases in forest growth. *Proc Natl Acad Sci USA* 111(24):8856–8860.
17. Luyssaert S, et al. (2008) Old-growth forests as global carbon sinks. *Nature* 455(7210): 213–215.
18. Callesen I, Østergaard H (2008) Energy efficiency of biomass production in managed versus natural temperate forest and grassland ecosystems. *16th IFOAM Organic World Congress, Modena, Italy, June 16–20*. Available at orgprints.org/view/projects/conference.html.
19. Vanderwel MC, Coomes DA, Purves DW (2013) Quantifying variation in forest disturbance, and its effects on aboveground biomass dynamics, across the eastern United States. *Glob Change Biol* 19(5):1504–1517.
20. Peters BE, Wythers KR, Bradford JB, Reich PB (2013) Influence of disturbance on temperate forest productivity. *Ecosystems* 16(1):95–110.
21. Krankina ON, et al. (2005) Effects of climate, disturbance and species on forest biomass across Russia. *Can J For Res* 35:2281–2293.
22. Frolking S, Roulet NT, Fuglestvedt J (2006) How northern peatlands influence the Earth's radiative budget: Sustained methane emission versus sustained carbon sequestration. *J Geophys Res* 111:G01008.

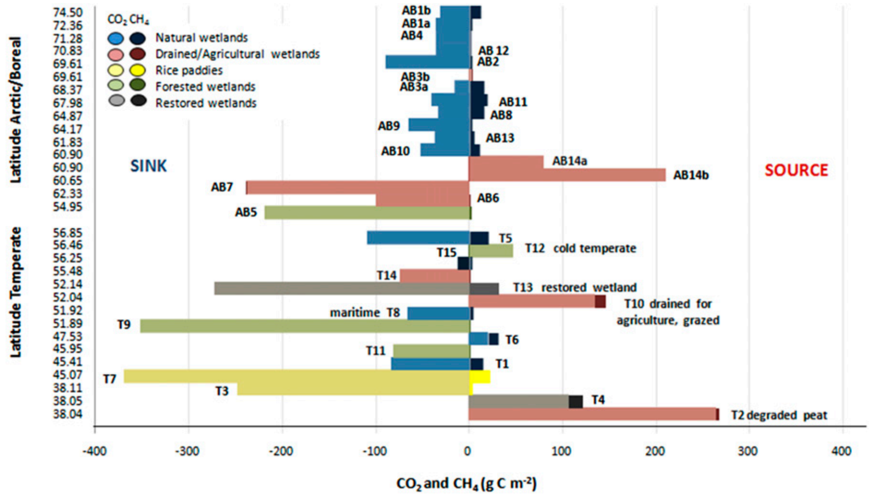

Fig. S1. CO_2 (light colors) and CH_4 (dark colors) fluxes in grams $C{\cdot}m^{-2}$ for each study site. Site IDs can be found in Tables S1 and S2.

Table S1. Main characteristics of the study sites for arctic/boreal (AB) wetlands

Arctic/ boreal	Site name, location	Coordinates	Climate	Ecosystem type/characteristics	Vegetation type	Measurement period	WTD, cm	Mean T, °C	Mean P, mm	Avg. CO_2 flux, g $CO_2 \cdot m^{-2}$	Avg. CH_4 flux, g $CH_4 \cdot m^{-2}$	Avg. CH_4 flux, g $CO_2eq \cdot m^{-2}$, 100 y
AB1a*	Zackenberg, Greenland	74° 30′ N, 21° 00′ W	High arctic	Natural wetland (fen)	E, SA, O	June 2–August 26, 1997 (growing season)	−0.9	3.4	56	−129 (S)	4.0 (S)	100
AB1b*	Zackenberg, Greenland	74° 30′ N, 21° 00′ W	High arctic	Natural wetland (fen)	E, SA, O	June 23–August 25, 2008 and July31–October 13, 2009 (growing season)	−6	3.6	62	−112 (S)	16.3 (S)	407.5
AB2*	Kytalyk, Russia	70° 49′ N, 147° 29′ E	High arctic	Natural wetland (tundra)	E, S, C, B, O	Average 2007–2009 (growing season)	2.3	6.3	92	−324 (S)	3.3 (S)	82.5
AB3a[†]	Cherskii, Russia	69° 36′ N, 161° 20′ E	High arctic	Natural wetland (tundra)	C, E, B, O	July–October 2002–2004	7.4	−7.8	200	−53 (S)	20 (S)	500
AB3b[†]	Cherskii, Russia			Drained wetland experiment drained in late 2004		July–October 2005	−9.5	−7.8	200	8 (S)	0.6 (S)	15
AB4	Lena Delta, Russia	72° 22′ N, 126° 30′ E	High arctic	Natural wetland (tundra polygons)	C, SA, O	June 11–September 3, 2006	4	−14.7	137	−126 (S)	1.6 (S)	40.3
AB5	Western peatland of FLUXNET–Canada Research Network, Canada	54° 57′ N, 112° 28′ W	Boreal continental	Treed wetland (moderately rich treed fen)	T, S, O	Y, average 2004–2009	−65	2.1	504	−693 (Y)	3.2 (S)	80
						S, late May–late September 2007				−796 (S)		
AB6	Linnansuo, Finland	62° 19′ N, 30° 17′ E	Boreal	Drained wetland (cutaway peatland, drained in 1981)	Reed canary grass	Average 2004–2007	−65	2.1	669	−364 (Y)	0.4 (Y)	9.3
AB7	Kalevansuo, Finland	60° 39′ N, 24° 21′ E	Boreal	Drained treed wetland (dwarf-shrub pine bog, drained in 1969)	T, E, S, B	2005	−40	5	658	−870 (Y)	−0.1 (Y)	−3
AB8	Lompolojänkkä, Finland	68° 00′ N, 24° 13′ E	Boreal	Natural wetland (mire/sedge fen)	S, SA, O	2006–2008	2	−0.1	569	−117 (Y)	20.3 (Y)	507.5
AB9*	Daring Lake, Canada	64° 52′ N, 111° 34′ W	Low arctic	Natural wetland (sedge fen tundra)	E,S	July–August 2008	−5	12	142	−234 (S)	3.2 (S)	80
AB10	Siikaneva, Finland	61° 50′ N, 24° 12′ E	Boreal	Natural wetland (fen)	E, C, S, O	March 2005–February 2006 (CH_4) and 2005 CO_2	−15	3.3	713	−188 (Y)	12.6 (S) 14 (Y)	350
AB11	Stordalen, Sweden	68° 22′ N, 19° 03′ E	High arctic	Natural wetland (mire)	C, S, E, O	2006–2007	−12	−0.7	300	−146 (Y)	24.5 (Y)	612.5
AB12*	Barrow, AK	71° 17′ N, 156° 35′ W	High arctic	Natural wetland	C, E, O	June 12–August 31, 2007	4.3	5.4	14	−125 (S)	1.0 (S)	24.5
AB13*	Nuuk, Greenland	64° 07′ N 51° 23′ W	High arctic	Natural wetland (fen)	S, E, O	May 14–October 11, 2010	5.8	8.8	397	−130 (S)	6.5 (S)	162.5
AB14a	Jokioinen, Finland	60° 54′ N, 23° 31′ E	Boreal	Drained peatland	Spring barley	October 2000–September 2001	−80	5.9	719	771 (Y)	−0.05 (Y)	−1.3
AB14b	Jokioinen, Finland	60° 54′ N, 23° 31′ E	Boreal	Drained peatland	Forage grass	October 2001–September 2002	−80	5.8	502	290 (Y)	−0.03 (Y)	−0.8

P, precipitation; S, seasonal estimates; T, air temperature; WTD, water table depth; Y, yearly estimates. B, *Betula* spp.; C, *Carex* spp.; E, *Eriophorum* spp.; S, *Sphagnum* spp.; SA, *Salix* spp.; T, trees spp., *Picea mariana* and *Larix laricina* (AB5) and *Pinus sylvestris* (AB6). O, others: *Dupontia psilosantha* (AB1a,b); Sedges (AB2); *Potentilla palustris*, *Calamagrostis* sp. (AB3); *Drepanocladus revolvens, Meesia triquetra*,

Aulacomnium turgidum, *Dryas octopetala*, *Astragalus frigidus*, *Hylocomium splendens*, *Timmia austriaca* (AB4); (shrub) *Betula pumila*; (herbs) *Carex* spp., *Menyanthes trifoliate*, *Triglochin maritime*; (mosses) *Aulocomium palustre*, *Drepanocladus aduncus*, *Pleurozium schreberi*, *Sphagnum* spp. (AB5) *Ledum palustre*, *Vaccinium uliginosum*, *V. vitis-idaea*, *V. myrtillus*, *Empetrum nigrum*, *Calluna vulgaris*, *Rubus chamaemorus*, *Pleurozium schreberi*, *Dicranum polysetum*, *Aulacomnium palustre*, and *Polytrichum strictum* (AB7); vascular plants, *aerenchymatous* species (AB8); *Eriophorum* spp. (75%), *Sphagnum* (100% ground cover) (AB9); *Russow ex C.E.O. Jensen*, *S. majus* (*Russow*), *C. limosa L.* (AB10); woody herbaceous (AB11); *dupontia* (AB13); *Calluna vulgaris*, *Erica tetralix* (AB14).
*Seasonal mean T and mean P for the measured period only. If not mentioned otherwise, T, P, and WTD are values referring to the mean seasonal or yearly measurements.
†Thirty-year long-term mean for temperature records. Negative values refer to water table below surface and positive values refer to above surface.

Table S2. Main characteristics of the study sites for temperate (T) wetlands

Temperate	Site name, location	Coordinates	Climate	Ecosystem type	Vegetation type	Measurement period	WTD, cm	Mean T, °C	Mean P, mm	Avg. CO_2 flux, g $CO_2 \cdot m^{-2}$	Avg. CH_4 flux, g $CH_4 \cdot m^{-2}$	Avg. CH_4 flux, g $CO_2eq \cdot m^{-2}$, 100 y
T1	Mer Bleue, Canada	45° 24′ N, 75° 31′ W	Temperate continental	Natural wetland (ombrotrophic bog)	S, E, O	Average 2009–2010	−35	6.4	758	−301 (Y)	10.5 (Y)	350
T2	Sherman Island, CA	38° 2′ N, 121° 45′ W	Temperate	Drained wetland (peatland pasture-grazed peat, top layer degraded)	O	April 5–end 2007 Average 2007–2009 and 2010 for CO_2 and January 1–September 25, 2010 for CH_4	−53.5	15.3	282	968 (Y)	4.7 (S)	112.5
T3	Twitchell Island, CA	38° 6′ N, 121° 39′ W	Temperate	Rice paddy	*Oryza sativa*	April 4–end 2010	−12.2	15.2	394	−906 (S)	5.1 (S)	127.5
T4	Mayberry Slough, CA	38° 2′ N, 121° 45′ W	Temperate	Restored wetland (at the end of 2010)	O	October 14, 2010–October 14, 2011	50.9	14.8	394	388 (Y)	21 (Y)	525
T5	Plotnikovo, Russia	56° 51′ N, 82° 58′ E	Temperate	Natural wetland	C, E, O	May 10–September 16, 1999 (growing season)	−0.2	14.5	105	−396 (S)	26 (S)	650
T6	Bog Lake peatland, United States	47° 32′ N, 93° 28′ W	Temperate continental	Natural wetland (open ombrotrophic bog)	C, S	May 20–October 12, 1991, 1992 for CO_2 1991 and 1992 for CH_4	−1.5	13.6	553	72 (S)	14.5 (Y)	362.5
T7	Castellaro, Italy	45° 04′ N, 8° 4′′ E	Temperate	Rice paddy	*O. sativa*	2009–2010 for CO_2 April 9, 2009–end 2010 for CH_4	8.6	12.6	847	−1,346 (Y)	29 (Y)	725
T8	Glencar, Ireland	51° 55′ N, 9° 55′ W	Temperate maritime	(Relatively) Natural wetland (Atlantic blanket bog)	S, O	Average 2003–2005 and 2008	−3.5	10.4	2,541	−239 (Y)	5.1 (Y)	113
T9	Spreewald, Germany	51°53′ N, 14°02′ E	Suboceanic/ Subcontinental/ Temperate	Treed wetland	T	Average 2010–2013 for CO_2, April 8–May 23, 2011 for CH_4	−0.1	11.1	481	−1,285 (Y)	0.3 (S)	6.8
T10	Oukoop, The Netherlands	52° 02′ N, 4° 46′ E	Temperate	Drained wetland (peat meadow, drained for agriculture, grazed)	O	2005, CO_2 Average 2006–2008, CH_4	−42.5	10.9	863	493 (Y)	15.7 (Y)	392.5
T11	Park Falls, WI, WLEF–United States	45° 57′ N, 90° 16′ W	Mixed temperate/ boreal	Mixed forest/wetland landscape	T, O	Average 2011–2012	N/A	5.7	245	−292 (Y)	1.04 (Y)	24.3
T12	Fyodorovskoye (Ru-Fyo), Russia	56° 27′ N, 32° 55′ E	Temperate continental	Natural forest wetland (spruce forest)	T, S	April 11–October 15, 2009 March 27–October 27, 2010 April 30–December 24, 2011	−19.1	5.1	898	172 (S)	−0.02 (S)	−0.5
T13	Horstermeer, The Netherlands	52° 8′ N, 5° 2′ E	Temperate	Restored wetland (peat meadow)	O	2005–2006	−2	9.8	797	−994 (Y)	42.2 (Y)	1,055

Table S2. Cont.

Temperate	Site name, location	Coordinates	Climate	Ecosystem type	Vegetation type	Measurement period	WTD, cm	Mean T, °C	Mean P, mm	Avg. CO_2 flux, g $CO_2{\cdot}m^{-2}$	Avg. CH_4 flux, g $CH_4{\cdot}m^{-2}$	Avg. CH_4 flux, g $CO_2eq{\cdot}m^{-2}$, 100 y
T14	Auchencorth Moss, Scotland	55° 47′ N, 03° 14′ W	Temperate	Acid moorland (drained 100 y ago)	S, E, O	Average 2007–2010	−12.7	7.4	1,100	−267 (Y)	0.3 (Y)	6.7
T15	Fäjemyr, Sweden	56° 15′ N 13° 33′ E	Temperate	Natural wetland (ombrotrophic bog)	S, E, O	Average 2007–2009	0	8.5	692	−42 (Y)	4.1 (Y)	77

T, P, and water table depth (WTD) are values referring to the mean seasonal or yearly measurements. S, seasonal estimates; Y, yearly estimates. Negative values refer to water table below surface whereas positive values refer to above surface. B, *Betula* spp.; C, *Carex* spp.; E, *Eriophorum* spp.; S, *Sphagnum* spp.; SA, *Salix* spp.; T, trees spp., *Alnus glutinosa* (T9), sugar maple, aspen (T11), spruce (T12). O, Others: *Maianthemum trifolium*/*Ledum groenlandicum*, *Chamaedaphne calyculata*, *Kalmia angustifolia*, *Vaccinium myrtilloides* (T1); *Lepidium latifolium*, *Hordeum murinum* (T2); *Schoenoplectus acutus*, *Typha latifolia* (T4); *Menyanthes trifoliate*, horse-tail *Equisetum fluviatile* (T5); *Molinia caerulea*, Ericaceae, sedges, brown mosses (T8); *Lolium perenne*, *Poa trivialis* (T10); alder-willow shrub, ericaceous bogs, and sedge fens (T11); *Vaccinium myrtillus* and *V. vitis idaea* (T12); *Holcus lanatus*, *Phalaris arundinacea*, *Glyceria fluitanus*, *Equisetum palustre*, *fluviatile*, *Phragmites australis*, *Typha latifolia* (T13); Juncacea, Cyperaceae, *Calluna vulgaris* (T14); *C. vulgaris*, *Erica tetralix* (T15). Note that the sites were classified into AB and T wetlands following the expert judgment of each site primary investigator.

Table S3. Annual CO_2 and CH_4 fluxes for the AB and T sites with available data from multiple years

Site ID	Site name, location	Coordinates	Period	g $CO_2 \cdot m^{-2} \cdot y^{-1}$	g $CH_4 \cdot m^{-2} \cdot y^{-1}$	Refs.
Arctic/boreal						
AB2	Kytalyk, Russia	70° 49′ N,	2007	−300.12 ± 100.65*	6.30*	(1)
		147° 29′ E	2008	−324.27*	4.00*	
			2009	−347.33*	2.90*	
AB3a*	Cherskii, Russia	69° 36′ N,	2002	−193.98*	26.6 ± 19.95*	(2)
		161° 20′ E,	2003	54.90*	26.6 ± 14.63*	
			2004	14.64/−40.26*	31.92 ± 25.27*	
			2005	29.28*	0.79 ± 1.59*	
AB5	Western peatland of FLUXNET–Canada	54° 57′ N,	2004	−535		(3)
	Research Network, Canada	112° 28′ W	2005	−986		(4)
			2006	−64		
			2007	−620 (−796*)	3.20*	
			2008	−814		
			2009	−561		
AB6	Linnansuo, Finland	62° 19′ N,	2004	−773.72	0.58 ± 0.28	(5)
		30° 17′ E	2005	−31.84	0.62 ± 0.25	
			2006	−188.49	0.16 ± 0.30	
			2007	−463.35	0.14 ± 0.29	
AB8	Lompolojänkkä, Finland	68° 00′ N,	2006	−12	17	(6)
		24° 13′ E	2007	−123	23	
			2008	−216	21	
AB11	Stordalen, Sweden	68° 22′ N,	2006	−146	24.50	(7)
		19° 03′ E	2007		29.50	
Temperate						
T1	Mer Bleue, Canada	45° 24′ N,	2009	−399	11.60	(8)
		75° 31′ W	2010	−201	9.40	(9)
T2	Sherman Island, CA	38° 2′ N,	2007	644.16*	4.90*	(10)
		121° 45′ W	2008	592.92	2.70	
			2009	1,588.44	2.80	
			2010	1,046.76	3.90	
T7	Castellaro, Italy	45° 04′ N,	2009	−1,316.77	37.14	(11)
		8° 43′ E	2010	−1,374.47	21.03	(12)
T8	Glencar, Ireland	51° 55′ N,	2003	−244.48 ± 19.03	5.05 ± 2.12	(13)
		9° 55′ W	2004	−245.95 ± 10.98	4.78 ± 2.12	
			2005	−307.44 ± 17.56	5.98 ± 2.52	
			2008	−156.28 ± 17.2	4.78 ± 2.12	
T9	Spreewald, Germany	51° 53′ N,	2010	−1,324.92		(14)
		14° 02′ E	2011	−1,555.50		
			2012	−1,291.98	0.30*	
			2013	−966.24		
T10	Oukoop, The Netherlands	52° 02′ N,	2005	493		(15)
		4° 46′ E	2006		19.40	(16)
			2007		14.00	
			2008		13.80	
T11	Park Falls, WI, WLEF–United States	45° 57′ N,	1997	22.2688		(17)
		90° 16′ W	1998	53.0031		(18)
			1999	81.4158		
			2000	70.1942		
			2001	137.487		
			2002	71.9335		
			2003	59.6953		
			2004	79.5593		
			2005	5.04275		
			2006	−98.7249		
			2007	−94.578		
			2008	−109.696		
			2009	−44.0794		
			2010	41.596		
			2011	−58.3582	1.215	
			2012	−101.423	0.879	
			2013	19.589		
T12	Fyodorovskoye (Ru-Fyo), Russia	56° 27′ N,	2009	−92	−0.01	(19)
		32° 55′ E	2010	436	−0.02	
			2011	172	−0.02	

Table S3. Cont.

Site ID	Site name, location	Coordinates	Period	g $CO_2 \cdot m^{-2} \cdot y^{-1}$	g $CH_4 \cdot m^{-2} \cdot y^{-1}$	Refs.
T13	Horstermeer, The Netherlands	52° 8′ N,	2005	−1,138.26 (±212.28)	41.58 (±27.13)	(20)
		5° 2′ E	2006	−849.12 (±212.28)	42.91 (±28.03)	
T14	Auchencorth Moss, Scotland	55° 47′ N,	2007	−498	0.37	(21)
		03° 14′ W	2008	−300	0.43	
			2009	−145	0.27	
			2010	−125	−0.02	
T15	Fäjemyr, Sweden	56° 15′ N,	2007	−107.7 ± 28.1	5.45	(22)
		13° 33′ E	2008	86.4 ± 29.1	3.05	
			2009	−106.1 ± 16.3	3.85	

*The values are for the growing season only.

1. Parmentier FJW, et al. (2011) Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra. *J Geophys Res* 116:G04013.
2. Merbold L, et al. (2009) Artificial drainage and associated carbon fluxes (CO_2/CH_4) in a tundra ecosystem. *Glob Change Biol* 15:2599–2614.
3. Flanagan LB, Syed KH (2011) Stimulation of both photosynthesis and respiration in response to warmer and drier conditions in a boreal peatland ecosystem. *Glob Change Biol* 17(7):2271–2287.
4. Long KD, Flanagan LB, Cai T (2010) Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy covariance. *Glob Change Biol* 16(9):2420–2435.
5. Shurpali NJ, et al. (2009) Cultivation of a perennial grass for bioenergy on a boreal organic soil - carbon sink or source? *GCB Bioenergy* 1(1):35–50.
6. Aurela M, et al. (2009) Carbon dioxide exchange on a northern boreal fen. *Boreal Environ Res* 14:699–710.
7. Jackowicz-Korczynski M, et al. (2010) Annual cycle of methane emission from a subarctic peatland. *J Geophys Res* 115:G02009.
8. Lai DYF, Roulet NT, Humphreys ER, Moore TR, Dalva M (2012) The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland. *Biogeosciences* 9(8):3305–3322.
9. Lai DYF, Moore TR, Roulet NT (2014) Spatial and temporal variations of methane flux measured by autochambers in a temperate ombrotrophic peatland. *J Geophys Res Biogeosci* 119: 864–880.
10. Hatala JA, et al. (2012) Greenhouse gas (CO_2, CH_4, H_2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. *Agric Ecosyst Environ* 150:1–18.
11. Meijide A, et al. (2011) Seasonal trends and environmental controls of methane emissions in a rice paddy field in Northern Italy. *Biogeosciences* 8:3809–3821.
12. Meijide A, et al. (2011) Greenhouse gas budget from a Mediterranean rice paddy field. *Nitrogen and Global Change: Key-Findings - Future-Challenges Conference Proceedings, Session S11, April 11–15, 2011* (Edinburgh, Scotland). Available at www.nitrogen2011.org/abstracts.html. Accessed March 11, 2015.
13. Koehler A-K, Sottocornola M, Kiely G (2011) How strong is the current carbon sequestration of an Atlantic blanket bog? *Glob Change Biol* 17(1):309–319.
14. Tiemeyer B, et al. (2013) Klimarelevanz von Mooren und Anmooren in Deutschland: Ergebnisse aus dem Verbundprojekt "Organische Böden in der Emissionsberichterstattung" [Climate impact of peatlands and bogs in Germany: Results from the joint project "Organic soils in emissions reporting"], Thünen Working Paper 15 (Johann Heinrich von Thünen-Institut, Braunschweig, Germany). German.
15. Veenendaal EM, et al. (2007) CO_2 exchange and carbon balance in two grassland sites on eutrophic drained peat soils. *Biogeosciences* 4:1027–1040.
16. Kroon PS, Vesala T, Grace J (2010) Flux measurements of CH_4 and N_2O exchanges. *Agric For Meteorol* 150:745–747.
17. Desai AR (2014) Influence and predictive capacity of climate anomalies on daily to decadal extremes in canopy photosynthesis. *Photosynth Res* 119(1–2):31–47.
18. Desai AR, et al. (2015) Landscape-level terrestrial methane flux observed from a very tall tower. *Agric For Meteorol* 201:61–75.
19. Kurbatova J, et al. (2013) Partitioning of ecosystem respiration in a paludified shallow-peat spruce forest in the southern taiga of European Russia. *Environ Res Lett* 8:045028.
20. Hendriks DMD, van Huissteden J, Dolman AJ, van der Molen MK (2007) The full greenhouse gas balance of an abandoned peat meadow. *Biogeosciences* 4:411–424.
21. Skiba U, et al. (2013) Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate. *Biogeosciences* 10:1231–1241.
22. Lund M, Christensen TR, Lindroth A, Schubert P (2012) Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland. *Environ Res Lett* 7:045704.

Table S4. **Site-specific measurement techniques and instrumentation for CO_2 and CH_4 fluxes**

Site ID	Site name	Measurement technique, CO_2 fluxes	Measurement technique, CH_4 fluxes	Refs.
AB1a	Zackenberg	Eddy covariance (LICOR 6262)	Eddy covariance (TDL)	(1)
AB1b	Zackenberg	Autochambers (PP systems SBA-4)	Autochambers (LGR FMA)	(2)
AB2	Kytalyk	Eddy covariance (LICOR 7500)	Eddy covariance (DLT-100 CH_4 analyzer)	(3)
			Flux chambers (INNOVA 1412)	(4)
AB3	Cherskii	Eddy covariance (LICOR 6262, LICOR 7500)	Static soil chambers	(5)
				(6)
AB4	Samoylov, Lena River Delta	Eddy covariance (LICOR 7000)	Eddy covariance (Campbell TDL)	(7)
		Closed dynamic chambers (INNOVA 1412 Photoacoustic IR Gas Spectrometer)	Closed dynamic chambers (INNOVA 1412 Photoacoustic IR gas spectrometer)	(8)
				(9)
				(10)
AB5	Western peatland of Fluxnet–Canada Research Network	Eddy covariance (LICOR 7000)	Eddy covariance (Campbell Tunable Diode laser spectrometer; TGA100A)	(11)
				(12)
				(13)
				(14)
				(15)
				(16)
AB6	Linnansuo	Eddy covariance (LICOR 7500)	Static chambers	(17)
				(18)
				(19)
AB7	Kalevansuo	Eddy covariance (LICOR 7000)	Static manual chambers and laboratory gas chromatograph	(20)
AB8	Lompolojänkkä	Eddy covariance (LICOR 7000)	Eddy covariance (LGR CH_4)	(21)
AB9	Daring Lake	Eddy covariance (LICOR 7500)	Static Chambers (manual)	(22)
AB10	Siikaneva	Eddy covariance (LICOR 7000)	Eddy covariance (TDL, TGA-100; Campbell Scientific)	(23)
				(24)
AB11	Stordalen	Eddy covariance (LICOR 7500)	Eddy covariance (TDL Aerodyne Res).	(25)
AB12	Barrow	Eddy covariance (LICOR 7500)	Eddy covariance (DLT-100 CH_4 analyzer; Los Gatos)	(26)
AB13	Nuuk	Autochambers (PP systems SBA-4)	Autochambers (LGR FMA)	(2)
AB14a	Jokioinen	Eddy covariance (LICOR 6262)	Static manual chambers (laboratory gas chromatograph)	(27)
				(28)
				(29)
AB14b	Jokioinen	Eddy covariance (LICOR 6262)	Static manual chambers (laboratory gas chromatograph)	(27–29)
T1	Mer Bleue	Eddy covariance (LICOR 7000)	Autochambers	(30)
				(31)
T2	Sherman Island	Eddy covariance (LICOR 7500)	LGR TDL (DLT-100 FMA)	(32)
T3	Twitchell Island	Eddy covariance (LICOR 7500)	LGR TDL spectrometer (DLT-100 FMA)	(32)
T4	Mayberry Slough	Eddy covariance (LICOR 7500)	Eddy covariance (LICOR 7700)	(32)
T5	Plotnikovo	Eddy covariance (LICOR 6262)	Eddy covariance (TDL)	(33)
T6	Bog Lake peatland, United States	Eddy covariance (TDLS and LICOR 6251)	Eddy covariance (TDLS and LICOR 6251)	(34)
				(35)
T7	Castellaro	Eddy covariance (LICOR 6262)	Static chambers and eddy covariance	(36)
T8	Glencar	Eddy covariance (LICOR 7500)	Static chambers and laboratory gas chromatograph	(37–47)
T9	Spreewald	Eddy covariance (LICOR 7000)	Eddy covariance (Los Gatos FGGA)	—
T10	Oukoop	Eddy covariance (LICOR 7500)	Static chambers	(48)
			Eddy covariance (QCL TILDAS_76 aerodyne Instrumental)	(49)

Table S4. Cont.

Site ID	Site name	Measurement technique, CO_2 fluxes	Measurement technique, CH_4 fluxes	Refs.
				(50)
T11	Park Falls, WI, WLEF	Eddy covariance (LICOR 6262)	Eddy covariance	(51)
T12	Fyodorovskoye (Ru-Fyo)	Eddy covariance (LICOR 6262)	Static chambers and laboratory gas chromatograph	(52)
T13	Horstermeer	Eddy covariance (LICOR 7500)	Flux chambers (Photo Acoustic Field Gas Monitor INNOVA 1312)	(53)
T14	Auchencorth Moss	Eddy covariance (LICOR 7000)	Static chambers	(54)
T15	Fäjemyr	Eddy covariance (LICOR 6262)	Autochambers (LGR FMA)	(55) (2)

1. Friborg T, Christensen TR, Hansen BU, Nordstroem C, Soegaard H (2000) Trace gas exchange in a high-arctic valley: 2. Landscape CH_4 fluxes measured and modeled using eddy correlation data. *Global Biogeochem Cycles* 14(3):715–723.
2. Mastepanov M, et al. (2008) Large tundra methane burst during onset of freezing. *Nature* 456(7222):628–630.
3. Parmentier FJW, et al. (2011) Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra. *J Geophys Res* 116:G04013.
4. Van Huissteden J, Maximov TC, Dolman AJ (2005) High methane flux from an arctic floodplain (Indigirka lowlands, eastern Siberia). *J Geophys Res* 110:G02002.
5. Corradi C, Kolle O, Walter K, Zimov SA, Schulze E-D (2005) Carbon dioxide and methane exchange of a north-east Siberian tussock tundra. *Glob Change Biol* 11(11):1910–1925.
6. Merbold L, et al. (2009) Artificial drainage and associated carbon fluxes (CO_2/CH_4) in a tundra ecosystem. *Glob Change Biol* 15:2599–2614.
7. Sachs T, Wille C, Boike J, Kutzbach L (2008) Environmental controls on ecosystem-scale CH_4 emission from polygonal tundra in the Lena River Delta, Siberia. *J Geophys Res Biogeosci* 113(G3):000505.
8. Sachs T, Giebels M, Boike J, Kutzbach L (2010) Environmental controls on CH_4 emission from polygonal tundra on the microsite scale in the Lena river delta, Siberia. *Glob Change Biol* 16(11):3096–3110.
9. Zhang Y, et al. (2012) Retrieval of methane profiles from spaceborne hyperspectral infrared observations. *J Remote Sens* 16(2):232–247.
10. Runkle BRK, Sachs T, Wille C, Pfeiffer E-M, Kutzbach L (2013) Bulk partitioning the growing season net ecosystem exchange of CO_2 in Siberian tundra reveals the seasonality of its carbon sequestration strength. *Biogeosciences* 10:1337–1349.
11. Flanagan LB, Syed KH (2011) Stimulation of both photosynthesis and respiration in response to warmer and drier conditions in a boreal peatland ecosystem. *Glob Change Biol* 17:2271–2287.
12. Long KD, Flanagan LB, Cai T (2010) Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy Covariance. *Glob Change Biol* 16:2420–2435.
13. Baldocchi DD, Hicks BB, Meyers TP (1988) Measuring biosphere atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology* 69:1331–1340.
14. Baldocchi DD (2003) Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future. *Glob Change Biol* 9:479–492.
15. Moncrieff JB, et al. (1997) A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide. *J Hydrol (Amst)* 188–189:589–611.
16. Aubinet M, et al. (2000) Estimates of the annual net carbon and water exchange of European forests: The EUROFLUX methodology. *Adv Ecol Res* 30:113–175.
17. Shurpali NJ, et al. (2009) Cultivation of a perennial grass for bioenergy on a boreal organic soil - Carbon sink or source? *GCB Bioenergy* 1(1):35–50.
18. Hyvönen NP, et al. (2009) Fluxes of nitrous oxide and methane on an abandoned peat extraction site: Effect of reed canary grass cultivation. *Bioresour Technol* 100(20):4723–4730.
19. Nykänen H, Alm J, Lang K, Silvola J, Martikainen PJ (1995) Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland. *J Biogeogr* 22:351–357.
20. Lohila A, et al. (2011) Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink. *Biogeosciences* 8:3203–3218.
21. Aurela M, et al. (2009) Carbon dioxide exchange on a northern boreal fen. *Boreal Environ Res* 14:699–710.
22. Humphreys ER, Lafleur PM (2011) Does earlier snowmelt lead to greater CO_2 sequestration in two low arctic tundra ecosystems? *Geophys Res Lett* 38(9):L09703.
23. Rinne J, et al. (2007) Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. *Tellus B Chem Phys Meterol* 59:449–457.
24. Aurela M, et al. (2007) CO_2 balance of a sedge fen in southern Finland – The influence of a drought period. *Tellus* 59B:826–837.
25. Jackowicz-Korczynski M, et al. (2010) Annual cycle of methane emission from a subarctic peatland. *J Geophys Res* 115:G02009.
26. Zona D, et al. (2009) Methane fluxes during the initiation of a large-scale water table manipulation experiment in the Alaskan arctic tundra. *Global Biogeochem Cycles* 23(2):GB2013.
27. Lohila A, Aurela M, Tuovinen J-P, Laurila T (2004) Annual CO_2 exchange of a peat field growing spring barley or perennial forage grass. *J Geophys Res* 109:D18116.
28. Regina K, Syväsalo E, Hannukkala A, Esala M (2004) Fluxes of N_2O from farmed peat soils in Finland. *Eur J Soil Sci* 55:591–599.
29. Regina K, Pihlatie M, Esala M, Alakukku L (2007) Methane fluxes on boreal arable soils. *Agric Ecosyst Environ* 119(3–4):346–352.
30. Lai DYF, Roulet NT, Humphreys ER, Moore TR, Dalva M (2012) The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland. *Biogeosciences* 9(8):3305–3322.
31. Lai DYF, Moore TR, Roulet NT (2014) Spatial and temporal variations of methane flux measured by autochambers in a temperate ombrotrophic peatland. *J Geophys Res Biogeosci* 119:864–880.
32. Baldocchi DD, et al. (2012) The challenges of measuring methane fluxes and concentrations over a peatland pasture. *Agric For Meteorol* 153:177–187.
33. Friborg T, Soegaard H, Christensen TR, Lloyd CR, Panikov NS (2003) Siberian wetlands: Where a sink is a source. *Geophys Res Lett* 30(21):2129.
34. Shurpali NJ, Verma SB, Clement RJ, Billesbach DP (1993) Seasonal distribution of methane flux in a Minnesota peatland measured by eddy correlation. *J Geophys Res* 98:20649–20655.
35. Shurpali NJ, Verma SB, Kim J, Arkebauer TJ (1995) Carbon dioxide exchange in a peatland ecosystem. *J Geophys Res* 100(D7):14319–14326.
36. Meijide A, et al. (2011) Seasonal trends and environmental controls of methane emissions in a rice paddy field in Northern Italy. *Biogeosciences* 8:3809–3821.
37. Koehler A-K, Murphy K, Kiely G, Sottocornola M (2009) Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South Western Ireland. *Biogeochemistry* 95:231–242.
38. Koehler A-K, Sottocornola M, Kiely G (2011) How strong is the current carbon sequestration of an Atlantic blanket bog? *Glob Change Biol* 17(1):309–319.
39. Sottocornola M, Kiely G (2005) An Atlantic blanket bog is a modest CO_2 sink. *Geophys Res Lett* 32(23):L23804.
40. Sottocornola M, Laine A, Kiely G, Byrne KA, Tuittila E-S (2009) Vegetation and environmental variation in an Atlantic blanket bog in South-western Ireland. *Plant Ecol* 203(1):69–81.
41. Sottocornola M, Kiely G (2010a) Energy fluxes and evaporation mechanisms in an Atlantic bog in south west Ireland. *Water Resour Res* 46:W11524.
42. Sottocornola M, Kiely G (2010b) Hydrometeorological controls on the CO_2 exchange variation in an Irish blanket bog. *Agric For Meteorol* 150(2):287–297.
43. Laine AM, et al. (2006) Estimating net ecosystem exchange in a patterned ecosystem: Example from a blanket bog. *Agric For Meteorol* 138:231–243.
44. Laine AM, Byrne KA, Kiely G, Tuittila E-S (2007a) Patterns in vegetation and CO_2 dynamics of a lowland blanket bog along a water level gradient. *Ecosystems* 10(5):890–905.
45. Laine AM, Wilson D, Kiely G, Byrne KA (2007b) Methane flux dynamics in an Irish lowland blanket bog. *Plant Soil* 299(1–2):181–193.
46. Laine AM, Byrne KA, Kiely G, Tuittila E-S (2009) The short term effect of altered water level on carbon dioxide and methane fluxes in a blanket bog. *Suoseura* 60(3–4):65–83.
47. McVeigh P, Sottocornola M, Foley N, Leahy P, Kiely G (2014) Meteorological and functional response partitioning to explain interannual variability of CO_2 exchange at an Irish Atlantic blanket bog. *Agric For Meteorol* 194:8–19.
48. Veenendaal EM, et al. (2007) CO_2 exchange and carbon balance in two grassland sites on eutrophic drained peat soils. *Biogeosciences* 4:1027–1040.
49. Hensen A, Groot TT, Van den Bulk WCM (2006) Dairy farm emissions, from one square meter to the full farm scale. *Agric Ecosyst Environ* 112(2-3):146–152.
50. Kroon PS, Vesala T, Grace J (2010) Flux measurements of CH_4 and N_2O exchanges. *Agric For Meteorol* 150:745–747.
51. Davis KJ, et al. (2003) The annual cycles of CO_2 and H_2O exchange over a northern mixed forest as observed from a very tall tower. *Glob Change Biol* 9:1278–1293.
52. Kurbatova J, Li C, Varlagin A, Xiao X, Vygodskaya N (2008) Modeling carbon dynamics in two adjacent spruce forests with different soil conditions in Russia. *Biogeosciences* 5:969–980.
53. Hendriks DMD, van Huissteden J, Dolman AJ, van der Molen MK (2007) The full greenhouse gas balance of an abandoned peat meadow. *Biogeosciences* 4:411–424.
54. Skiba U, et al. (2013) Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate. *Biogeosciences* 10:1231–1241.
55. Lund M, Lindroth A, Christensen TR, Stroem L (2007) Annual CO_2 balance of a temperate bog. *Tellus B Chem Phys Meterol* 59:804–811.

Table S5. Site-specific gap-filling methods

Site ID	Site name	Gap-filling CO_2	Gap-filling CH_4	Refs.
AB1a	Zackenberg	Collatz model and Q_{10} function for Rs	Q_{10} and water table	(1) (2)
AB1b	Zackenberg	Linear interpolation	Linear interpolation	—
AB2	Kytalyk	As per Reichstein et al. (4)	—	(3)
AB3a,b	Cherskii	Temperature response (Reco) and light response (GPP)	Mean seasonal averaging	(4) (5)
AB4	Samoylov, Lena River Delta	Light response and temperature response as per Runkle et al. (8)	Daily averages, no gap filling	(6) (7) (8)
AB5	Western peatland of FLUXNET–Canada Research Network	—	FCRN standard procedure	(9) (10)
AB6	Linnansuo	As per Reichstein et al. (4)	Linear interpolation	(11) (12) (4)
AB7	Kalevansuo	Temperature response, radiation response	Interpolation between each chamber measurement	(13)
AB8	Lompolojänkkä	Temperature response, radiation response, averaging in winter	Temperature response, averaging	(14)
AB9	Daring Lake	Linear interpolation and empirical modeling	Average, no gap filling	(15) (16)
AB10	Siikaneva	Empirical modeling	Linear interpolation, temperature regression	(17) (18)
AB11	Stordalen	Air temperature and light response	Temperature response	(19) (20) (21)
AB12	Barrow	Linear interpolation	—	(22) (21)
AB13	Nuuk	Linear interpolation	Linear interpolation	—
AB14a	Jokioinen	Temperature plus radiation response for the EC data	Linear interpolation for the chamber data	(23) (24)
AB14b	Jokioinen	Temperature plus radiation response for the EC data	Linear interpolation for the chamber data	(23) (24)
T1	Mer Bleue	Nonlinear regression with seasonal adjustment	Linear regression of log10 flux	(25) (26)
T2	Sherman Island	Neural networks	Neural networks	(27)
T3	Twitchell Island	Neural networks	Neural networks	(27)
T4	Mayberry Slough	Neural networks	Neural networks	(27)
T5	Plotnikovo	Linear regression	Linear regression	(28)
T6	Bog Lake peatland, United States	See refs. for procedure	Linear integration	(29) (30)
T7	Castellaro	Yes, Look-up tables	Yes, Look-up tables	(31)
T8	Glencar	Temperature response, radiation response	Nonlinear regression	(32–42)
T9	Spreewald	Temperature response, radiation response	—	(4)
T10	Oukoop	Dual-modeling approach	Empirical multivariate regression model	(43) (44) (45) (21)
T11	Park Falls, WI, WLEF	Nighttime moving-window regression	Simple exponential temperature model and linear interpolation to daily NEE	(46)

Table S5. Cont.

Site ID	Site name	Gap-filling CO_2	Gap-filling CH_4	Refs.
				(47)
				(48)
T12	Fyodorovskoye (Ru-FYO)	Yes	—	(49)
T13	Horstermeer	Yes	—	(50) (21)
T14	Auchencorth Moss	Yes	—	(51)
T15	Fäjemyr	Neural networks	—	(52)

1. Friborg T, Christensen TR, Hansen BU, Nordstroem C, Soegaard H (2000) Trace gas exchange in a high-arctic valley: 2. Landscape CH_4 fluxes measured and modeled using eddy correlation data. *Global Biogeochem Cycles* 14(3):715–723.
2. Soegaard H, et al. (2000) Trace gas exchange in a high-arctic valley. 3. Integrating and scaling CO_2 luxes from canopy to landscape using lux data, footprint modelling and remote sensing. *Global Biogeochem Cycles* 14:725–744.
3. Parmentier FJW, et al. (2011) Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra. *J Geophys Res* 116:G04013.
4. Reichstein M, et al. (2005) On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algorithm. *Glob Change Biol* 11:1424–1439.
5. Merbold L, et al. (2009) Artificial drainage and associated carbon fluxes (CO_2/CH_4) in a tundra ecosystem. *Glob Change Biol* 15:2599–2614.
6. Sachs T, Wille C, Boike J, Kutzbach L (2008) Environmental controls on ecosystem-scale CH_4 emission from polygonal tundra in the Lena River Delta, Siberia. *J Geophys Res Biogeosci* 113(G3):000505.
7. Sachs T, Giebels M, Boike J, Kutzbach L (2010) Environmental controls on CH_4 emission from polygonal tundra on the microsite scale in the Lena river delta, Siberia. *Glob Change Biol* 16(11):3096–3110.
8. Runkle BRK, Sachs T, Wille C, Pfeiffer E-M, Kutzbach L (2013) Bulk partitioning the growing season net ecosystem exchange of CO_2 in Siberian tundra reveals the seasonality of its carbon sequestration strength. *Biogeosciences* 10:1337–1349.
9. Flanagan LB, Syed KH (2011) Stimulation of both photosynthesis and respiration in response to warmer and drier conditions in a boreal peatland ecosystem. *Glob Change Biol* 17:2271–2287.
10. Long KD, Flanagan LB, Cai T (2010) Diurnal and seasonal variation in methane emissions in a northern Canadian peatland measured by eddy covariance. *Glob Change Biol* 16:2420–2435.
11. Shurpali NJ, et al. (2009) Cultivation of a perennial grass for bioenergy on a boreal organic soil - Carbon sink or source? *GCB Bioenergy* 1:35–50.
12. Hyvönen NP, et al. (2009) Fluxes of nitrous oxide and methane on an abandoned peat extraction site: Effect of reed canary grass cultivation. *Bioresour Technol* 100(20):4723–4730.
13. Lohila A, et al. (2011) Greenhouse gas flux measurements in a forestry-drained peatland indicate a large carbon sink. *Biogeosciences* 8:3203–3218.
14. Aurela M, et al. (2009) Carbon dioxide exchange on a northern boreal fen. *Boreal Environ Res* 14:699–710.
15. Lafleur PM, Humphreys ER (2008) Spring warming and carbon dioxide exchange over low arctic tundra in central Canada. *Glob Change Biol* 14:740–756.
16. Humphreys ER, Lafleur PM (2011) Does earlier snowmelt lead to greater CO_2 sequestration in two low arctic tundra ecosystems? *Geophys Res Lett* 38:L09703.
17. Rinne J, et al. (2007) Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. *Tellus B Chem Phys Meterol* 59:449–457.
18. Aurela M, et al. (2007) CO_2 balance of a sedge fen in southern Finland – The influence of a drought period. *Tellus* 59B:826–837.
19. Jackowicz-Korczynski M, et al. (2010) Annual cycle of methane emission from a subarctic peatland. *J Geophys Res* 115:G02009.
20. Christensen TR, et al. (2012) Monitoring the multi-year carbon balance of a subarctic palsa mire with micrometeorological techniques. *Ambio* 41(Suppl 3):207–217.
21. Falge E, et al. (2001) Gap filling strategies for long term energy flux data sets. *Agric For Meteorol* 107(1):71–77.
22. Zona D, et al. (2009) Methane fluxes during the initiation of a large-scale water table manipulation experiment in the Alaskan arctic tundra. *Global Biogeochem Cycles* 23:GB2013.
23. Lohila A, Aurela M, Tuovinen J-P, Laurila T (2004) Annual CO_2 exchange of a peat field growing spring barley or perennial forage grass. *J Geophys Res* 109:D18116.
24. Regina K, Pihlatie M, Esala M, Alakukku L (2007) Methane fluxes on boreal arable soils. *Agric Ecosyst Environ* 119(3–4):346–352.
25. Lai DYF, Roulet NT, Humphreys ER, Moore TR, Dalva M (2012) The effect of atmospheric turbulence and chamber deployment period on autochamber CO_2 and CH_4 flux measurements in an ombrotrophic peatland. *Biogeosciences* 9(8):3305–3322.
26. Roulet NT, et al. (2007) Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Glob Change Biol* 13:397–411.
27. Hatala JA, et al. (2012) Greenhouse gas (CO_2, CH_4, H_2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. *Agric Ecosyst Environ* 150:1–18.
28. Friborg T, Soegaard H, Christensen TR, Lloyd CR, Panikov NS (2003) Siberian wetlands: Where a sink is a source. *Geophys Res Lett* 30:2129.
29. Shurpali NJ, Verma SB, Clement RJ, Billesbach DP (1993) Seasonal distribution of methane flux in a Minnesota peatland measured by eddy correlation. *J Geophys Res* 98:20649–20655.
30. Shurpali NJ, Verma SB, Kim J, Arkebauer TJ (1995) Carbon dioxide exchange in a peatland ecosystem. *J Geophys Res* 100:14319–14326.
31. Meijide A, et al. (2011) Seasonal trends and environmental controls of methane emissions in a rice paddy field in Northern Italy. *Biogeosciences* 8:3809–3821.
32. Koehler A-K, Murphy K, Kiely G, Sottocornola M (2009) Seasonal variation of DOC concentration and annual loss of DOC from an Atlantic blanket bog in South Western Ireland. *Biogeochemistry* 95:231–242.
33. Koehler A-K, Sottocornola M, Kiely G (2011) How strong is the current carbon sequestration of an Atlantic blanket bog? *Glob Change Biol* 17(1):309–319.
34. Sottocornola M, Kiely G (2005) An Atlantic blanket bog is a modest CO_2 sink. *Geophys Res Lett* 32:L23804.
35. Sottocornola M, Laine A, Kiely G, Byrne KA, Tuittila E-S (2009) Vegetation and environmental variation in an Atlantic blanket bog in South-western Ireland. *Plant Ecol* 203(1):69–81.
36. Sottocornola M, Kiely G (2010a) Energy fluxes and evaporation mechanisms in an Atlantic bog in south west Ireland. *Water Resour Res* 46:W11524.
37. Sottocornola M, Kiely G (2010b) Hydrometeorological controls on the CO_2 exchange variation in an Irish blanket bog. *Agric For Meteorol* 150(2):287–297.
38. Laine AM, et al. (2006) Estimating net ecosystem exchange in a patterned ecosystem: Example from a blanket bog. *Agric For Meteorol* 138:231–243.
39. Laine AM, Byrne KA, Kiely G, Tuittila E-S (2007a) Patterns in vegetation and CO_2 dynamics of a lowland blanket bog along a water level gradient. *Ecosystems* 10(5):890–905.
40. Laine AM, Wilson D, Kiely G, Byrne KA (2007b) Methane flux dynamics in an Irish lowland blanket bog. *Plant Soil* 299(1–2):181–193.
41. Laine AM, Byrne KA, Kiely G, Tuittila E-S (2009) The short term effect of altered water level on carbon dioxide and methane fluxes in a blanket bog. *Suoseura* 60(3–4):65–83.
42. McVeigh P, Sottocornola M, Foley N, Leahy P, Kiely G (2014) Meteorological and functional response partitioning to explain interannual variability of CO_2 exchange at an Irish Atlantic blanket bog. *Agric For Meteorol* 194:8–19.
43. Veenendaal EM, et al. (2007) CO_2 exchange and carbon balance in two grassland sites on eutrophic drained peat soils. *Biogeosciences* 4:1027–1040.
44. Hensen A, Groot TT, Van den Bulk WCM (2006) Dairy farm emissions, from one square meter to the full farm scale. *Agric Ecosyst Environ* 11:146–152.
45. Kroon PS, Vesala T, Grace J (2010) Flux measurements of CH_4 and N_2O exchanges. *Agric For Meteorol* 150:745–747.
46. Desai AR, Bolstad PV, Cook BD, Davis KJ, Carey EV (2005) Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA. *Agric For Meteorol* 128(1–2):33–55.
47. Desai AR, et al. (2015) Landscape-level terrestrial methane flux observed from a very tall tower. *Agric For Meteorol* 201:61–75.
48. Davis KJ, et al. (2003) The annual cycles of CO_2 and H_2O exchange over a northern mixed forest as observed from a very tall tower. *Glob Change Biol* 9:1278–1293.
49. Kurbatova J, Li C, Varlagin A, Xiao X, Vygodskaya N (2008) Modeling carbon dynamics in two adjacent spruce forests with different soil conditions in Russia. *Biogeosciences* 5:969–980.
50. Hendriks DMD, van Huissteden J, Dolman AJ, van der Molen MK (2007) The full greenhouse gas balance of an abandoned peat meadow. *Biogeosciences* 4:411–424.
51. Skiba U, et al. (2013) Comparison of soil greenhouse gas fluxes from extensive and intensive grazing in a temperate maritime climate. *Biogeosciences* 10:1231–1241.
52. Lund M, Lindroth A, Christensen TR, Stroem L (2007) Annual CO_2 balance of a temperate bog. *Tellus B Chem Phys Meterol* 59:804–811.

Table S6. Multiple paired sites for radiative forcing calculations

RF runs (1)	Reference site	Site type	Managed site	Site type	ΔNECB, M–R	ΔCH_4, M–R	ΔN_2O, M–R
Natural to agriculture, AB							
1	AB8	Natural fen →	AB6	Energy crop	214	−19.9	−0.06
2	AB8	Natural fen →	AB14a	Barley	2,066	−20.4	4.6
3	AB8	Natural fen →	AB14b	Grass	2,010	−20.3	3.0
4	AB10	Natural fen →	AB6	Energy crop	300	−13.6	—
5	AB10	Natural fen →	AB14a	Barley	2,152	−14.1	—
6	AB10	Natural fen →	AB14b	Grass	2,096	−14.0	—
7	AB11	Natural mire →	AB6	Energy crop	229	−24.1	—
8	AB11	Natural mire →	AB14a	Barley	2,081	−24.5	—
9	AB11	Natural mire →	AB14b	Grass	2,026	−24.5	—
Natural to agriculture, T							
1	T1	Natural bog →	T2	Pasture	1,490	−9.8	—
2	T1	Natural bog →	T10	Peat meadow	1,631	5.2	—
3	T1	Natural bog →	T14	Acid moorland	5	10.2	
4	T8	(Relatively) Natural bog →	T2	Pasture	1,446	−3.8	—
5	T8	(Relatively) Natural bog →	T10	Peat meadow	1,556	11.2	2.4
6	T8	(Relatively) Natural bog →	T14	Acid moorland	−40	−4.2	0.003
7	T15	Natural bog →	T2	Pasture	1,250	−3.4	—
8	T15	Natural bog →	T10	Peat meadow	1,390	11.6	—
9	T15	Natural bog →	T14	Acid moorland	−235	−3.8	
Natural forested to managed forested, AB and T							
1	AB5	Treed fen →	AB7	Drained wetland pine bog	217* 150†	−3.3	—
2	T9	Treed wetland →	T11	Mixed forest/wetland landscape	881* 713†	0.7	—

The difference in fluxes ΔNECB, ΔCH_4, and ΔN_2O between managed (M) and reference (R) sites has been expressed as grams CO_2, CH_4, or $N_2O \cdot m^{-2} \cdot y^{-1}$, respectively.

*R_{soil} calculated with method *i* (carbon budget at sites).

†R_{soil} calculated with method *ii* [*IPCC Wetland Supplement* values (2)].

1. Lohila A, et al. (2010) Forestation of boreal peatlands: Impacts of changing albedo and greenhouse gas fluxes on radiative forcing. *J Geophys Res* 115:G04011.

2. IPCC 2014, *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*, eds Hiraishi T, et al. (IPCC, Geneva, Switzerland).