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Current disturbance and the diminishing peatland carbon sink

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[1] Cumulative impacts of disturbances on peatland carbon must be understood to predict future soil carbon stocks, yet the vulnerability and response of peatlands to disturbance have been neglected. We provide the first regional-scale assessment of peatland carbon storage across 1.7 million km^2 of western boreal land. We estimate that disturbances, mainly fire, release approximately 6460 ± 930 GgCyr^{-1} to the atmosphere. Concurrently, disturbances reduce carbon uptake in continental peatlands by 85% compared to a no-disturbance scenario. A 17% increase in the area of peatland burned annually and the intensity of organic matter combustion would convert these peatlands into a regional net source of carbon to the atmosphere. Peatlands widely are considered to represent a northern carbon sink, however, we suggest reevaluation of this paradigm for continental boreal regions. *INDEX TERMS:* 1615 Global Change: Biogeochemical processes (4805); 1803 Hydrology: Anthropogenic effects; 1620 Global Change: Climate dynamics (3309)

1. Introduction

[2] The Intergovernmental Panel on Climate Change maintains that global carbon (C) sinks and reservoirs must be enhanced and maintained [*Watson et al.*, 2000]. Disturbances such as fire and insect outbreaks cause declining ecosystem C storage in boreal uplands [*Kurz and Apps*, 1999], but have not been evaluated adequately for peat-accumulating lowlands, despite the importance of peatlands to soil C storage [*Moore et al.*, 1998]. In fact, peatland C budgets typically are constructed for small areas of pristine wetland without consideration for past and ongoing disturbances such as fire, flooding, permafrost melt, and peat extraction. Spatial information on wetland area and land-use is needed, particularly over regional or national scales, to understand current C storage in northern and tropical wetlands [*Watson et al.*, 2000].

[3] Here, we use detailed inventories of peat C stocks across the western Canadian provinces of Alberta, Saskatchewan, and Manitoba produced by extensive mapping and field surveys of peatlands [*Vitt et al.*, 2000a]. Peatlands in this region cover 365,160 ± 14,606 km^2, or 21% of the landbase, and store 48 ± 5 Pg (=10^{15} g) of C as peat (42 Pg) and living biomass (6 Pg) [*Vitt et al.*, 2000a]. This C stock represents about 2.1% of the world's terrestrial C stored on 0.3% of the world's land surface. These detailed peatland inventories allowed us to estimate the areal extent of ongoing disturbances affecting boreal peatlands of western Canada and to calculate potential impacts on peatland C balance. When possible, we estimate and propagate uncertainties surrounding disturbance parameters, assuming Gaussian distributions.

1.1. Carbon Losses from Historical Fires

[4] Long-term peat accumulation rates based on radiocarbon dating average 19.4 ± 2.1 g C m^{-2} yr^{-1}, or 7080 ± 779 Gg (=10^9 g) C yr^{-1} across the entire region [*Vitt et al.*, 2000a]. As charcoal layers have been identified in peat deposits [*Zoltai et al.*, 1998], we note that C losses due to historical fire activity are incorporated into this long-term accumulation rate. Radiocarbon-based accumulation rates, therefore, underestimate long-term net peatland C accumulation.

[5] In continental boreal regions, dry, wooded peatlands burn more readily than wet open or shrub-dominated peatlands. Charcoal frequencies in long-term peat stratigraphies suggest that 0.25% of continental peatlands in North America have burned annually [*Zoltai et al.*, 1998]. We multiplied 0.25% by the total aerial extent of wooded peatlands in the study area (235,460 ± 9,418 km^2) [*Vitt et al.*, 2000a] to calculate that 580 ± 23 km^2 of wooded peatland area burned historically each year. Published estimates of C losses due to peatland fires average 3.2 ± 0.4 kg C m^{-2} per fire event (n = 6 studies; ranging from 2.1 to 4.9 kg C m^{-2} with a median value of 2.7 kg C m^{-2}) [*Turetsky and Wieder*, 2001]. The historical burned area (580 ± 23 km^2) was multiplied by 3.2 ± 0.4 kg C m^{-2} to calculate a regional historical combustion rate of 1860 ± 242 Gg C yr^{-1}. We added 1860 ± 242 Gg C yr^{-1} to the long-term regional accumulation rate based on radiocarbon dating (7080 ± 779 Gg C yr^{-1}) to calculate C accumulation under no disturbance (Table 1). We estimate long-term C accumulation in the absence of fire of 8940 ± 816 Gg C yr^{-1} (Table 1), 26% higher than previous estimates. Thus, following the practice of using long-trends to estimate current C accumulation rates, peatlands across continental, western Canada today are accumulating 24.5 ± 2.4 g C m^{-2} yr^{-1}.

1.2. Carbon Losses from Current Fires

[6] The Large Fire Database [*Stocks et al.*, in press] compiles provincial data recording fires over 200 ha in size, which represent more than 95% of the total area burned in western Canada. We overlaid mean proportions of land burned in 1° latitude × 1° longitude grids from 1980 to 1995 [*Stocks et al.*, in press] on digitized peatland distributions [*Vitt et al.*, 2000a] to calculate a current burned area of peatlands across the study region of 1470 ± 59 km^2 yr^{-1}. It seems likely that fires in our study area will impact upland forest to a greater extent than peatlands; therefore, we assumed that open peatlands, representing about 40% of the total peatland area in our region, do not burn and excluded them from our analysis. We multiplied 1470 ± 59 km^2 by average combustion rates (3.2 ± 0.4 kg C m^{-2}) [*Turetsky and Wieder*, 2001], to calculate a regional combustion rate of 4704 ± 618 Gg C yr^{-1} (Table 1).

[7] Because fires remove vegetation and stimulate decay, peatlands function as net sources of atmospheric C post-fire. The strength of the regional post-fire C source depends on the area of peatland burned annually, the magnitude of immediate C losses after fire, the time to recovery to pre-fire net primary production levels, and the shape of the recovery trajectory (Figure 1). We know of no data on post-fire C fluxes from burned peatlands. However, based on an empirical modeling approach, decomposition in the upper 30 cm of peat, where most organic matter mineralization probably occurs, was estimated at 183–243 g organic matter m^{-2} yr^{-1} (mean of 209 g m^{-2} yr^{-1}) for three

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Table 1. Peatland Carbon Fluxes Across Western Canada Under Current Disturbance Regimes

Disturbance	Total Extent km^2	Annual Disturbance km^2 yr^{-1}	Mechanism of C Flux	C flux g C m^{-2} yr^{-1}	C flux (Gg C yr^{-1})[a]
No disturbance	365,160 ± 14,606		Production > decay	24.5 ± 2.4[b]	+ 8940 ± 816[c]
Current fire	44,100 ± 1764[d]	1470 ± 59	Combustion	3200 ± 400	− 4704 ± 618
			Mineralization		− 1578 ± 696
Permafrost melt	2630 ± 105	26.3 ± 1.1	Enhanced plant production	38 ± 9	+ 100 ± 12
Peat extracting	37[e]	1.1[e]	Direct harvest	3649[e]	− 135
			Mineralization	470 ± 108	− 17 ± 4
Reservoirs	780 ± 3.1	9.6 ± 0.04	Mineralization	102 ± 24	− 80 ± 19
Oil sands mining	16 ± 0.6	0.3 ± 0.01	Direct removal	2400 ± 168	− 48 ± 3
Total disturbance	47,563 ± 1767	1507 ± 60	Total disturbance losses	9883 ± 478	− 6462 ± 931
Undisturbed area	317,580 ± 14,713		Production > decay	24.5 ± 2.4[d]	+ 7781 ± 843[f]
C balance	365,160 ± 14,606		Production > decay + disturbance losses		+ 1319 ± 1256

[a] Positive C fluxes represent net sinks of atmospheric C while negative fluxes represent net sources of atmospheric C.

[b] Rates of C accumulation accounting for historical fires: (8940 ± 816 Gg C) ÷ (365,160 ± 14,606 km^2).

[c] 7080 ± 779 Gg C yr^{-1} [*Vitt et al.*, 2000a] + 1860 ± 242 Gg C yr^{-1} (accounting for C loss through historical fires).

[d] 1470 km^2 × 30 yr average peatland recovery time (Figure 1).

[e] Error estimates not available.

[f] Total peatland area minus disturbed peatland area, accumulating at 24.5 ± 2.4 g C m^{-2} yr^{-1}.

sites in Alberta (assuming that peat is 47% C, equivalent to 100 g m^{-2} yr^{-1} of CO_2-C loss) [*Wieder*, 2001]. Using this value for initial post-fire mineralization, and peatland recovery times and trajectories outlined in Figure 1, we estimate a regional enhanced post-fire peatland mineralization rate of 1578 ± 696 Gg C yr^{-1}. The combined direct and indirect effects of peatland fire amounts to a source of C to the atmosphere of 6282 ± 931 Gg C yr^{-1} (Table 1).

1.3. Permafrost Melt

[8] Approximately 2630 ± 105 km^2 of permafrost in peatlands has melted over the past ~100 yr in western Canada; permafrost degradation continues today [*Vitt et al.*, 1994]. Assuming constant degradation rates (2630 ± 105 km^2/100 y), we estimate that 26.3 ± 1.1 km^2 of permafrost in peatlands melts annually. Permafrost melt in peatlands converts permafrost mounds to wet depressions called internal lawns. Net C accumulation is greater in internal lawns than in permafrost mounds by 38 ± 4.5 g C m^{-2} yr^{-1}, for at least a century after initial melt [*Turetsky et al.*, 2000; Turetsky, unpublished data]. Therefore, we multiplied 2630 ± 105 km^2 of regional melt by 38 ± 4.5 g C m^{-2} yr^{-1} to estimate a regional enhanced C sink associated with the conversion of permafrost mounds to internal lawns of 100 ± 12 Gg C yr^{-1} (Table 1).

1.4. Peat Extraction

[9] In 1997, 78 Gg C (assuming peat is 47% C) was harvested as peat from three peat mines in Saskatchewan and Manitoba, and two mines in Nova Scotia [*Statistics Canada*, 1997]. These provincial data are not reported separately, therefore, we assumed 83% of this harvest (65 Gg) occurred in western Canada [*Statistics Canada*, 1997; G. Hood, Canadian *Sphagnum* Peat Moss Association, personal communication, 2001]. 70 Gg C also was harvested in Alberta [*Statistics Canada*, 1997] for a total regional export of 135 Gg C across western continental Canada. Approximately 23% of the 160 km^2 of peatland harvested across Canada is located in the prairie provinces (37 km^2). After harvest of the upper peat layers, an abandoned peat mine is a source of atmospheric C, as ongoing decomposition in the residual peat exceeds the negligible net secondary production at the denuded peat surface. We multiplied mineralization rates from harvested peatlands in eastern Canada and Europe (470 ± 108 g C m^{-2} yr^{-1}) [*Waddington and Price*, 2000; *Sundh et al.*, 2000] by 37 km^2 to estimate a regional enhanced mineralization rate of 17.4 ± 4.0 Gg C yr^{-1} (Table 1). Peat mines have average lifetimes of 32.5 yr [*Keyes*, 1993], suggesting that 1.1 km^2 of pristine peatland is developed annually.

1.5. Hydroelectric Reservoirs

[10] Manitoba has used hydroelectric generation as an energy source for nearly 80 years. Peatland inventories [*Vitt et al.*, 2000a]

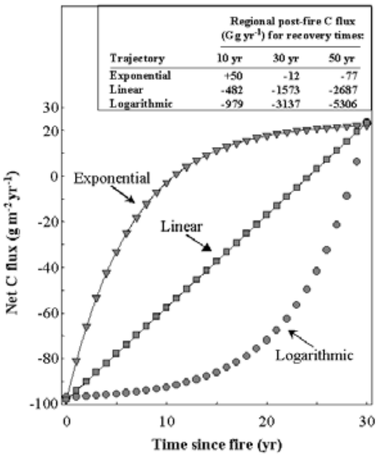

Figure 1. Recovery of peatland carbon accumulation following fire. Diminished primary production and enhanced mineralization occur post-fire in peatlands. Although peatland vegetation typically reestablishes within 20 yr [*Zoltai et al.*, 1998], no data are available regarding the length of recovery to pre-fire net C accumulation (24.5 ± 2.4 g C m^{-2} yr^{-1}; Table 1) following fire or the trajectory of recovery. Here we assumed an initial peat respiration after fire of 100 g C m^{-2} yr^{-1} [cf. *Wieder*, 2001], and used a cohort model in which the regional area of peatland currently burned annually (1470 ± 59 km^2) was divided into 9 categories following one of three recovery trajectories and one of three recovery times. Possible post-fire trajectories of peatland recovery are plotted for a 30-yr recovery time, while the inset shows C fluxes (Gg yr^{-1}) for each cohort. Long recovery times and logarithmic trajectories may be more characteristic of large fires in relatively cool and dry subarctic or high boreal peatlands, while short recovery times and exponential trajectories may be more characteristic of smaller fires in relatively warm and moist low boreal peatlands.

near Manitoba's hydroelectric generating stations suggest that 780 ± 3 km^2 of peatland has been flooded, corresponding to an average of 9.6 ± 0.04 km^2 of annual flooding over 80 years. Carbon emissions from peatland reservoirs in western Ontario and Finland, ranging from 2 to 28 years in age post-flooding, average 102 ± 24 g C m^{-2} yr^{-1} [*Kelly et al.*, 1997; *Hellsten et al.*, 1996]. We multiplied 780 km^2 by mean reservoir C emission rates (102 ± 24 g C m^{-2} yr^{-1}) to estimate a regional enhanced mineralization rate associated with peatland conversion to reservoirs of 80 ± 19 Gg C yr^{-1} (Table 1).

1.6. Oil Sand Mining

[11] We estimate that 22% of current oil sands surface leases [*Oil Sands Mining Land Use Committee*, 1998] is covered by peatlands (15.5 ± 0.6 km^2) containing 2400 ± 168 Gg C [*Vitt et al.*, 2000a]. To our knowledge, current oil sands mining practice includes removal of peat overburden and stockpiling for potential reclamation use. Peat used in soil organic matter amendments eventually will decompose under aerobic conditions. We assumed a complete loss of extracted C over a 50 yr time interval to estimate a disturbance-related flux of 48 ± 3 Gg C yr^{-1} (Table 1).

1.7. Peatland Conversion to Agriculture or Forestry

[12] In some peat-rich regions, ongoing development results in the conversion of native peatlands to either agriculture or forestry land uses, both of which are likely to alter C balances. In western Canada, however, there is no present conversion of native peatland to cropland [*Dumanski et al.*, 1998]. There also is little interest today in draining or fertilizing peatlands for managed forestry uses, particularly in Saskatchewan and Manitoba [*Haavisto and Jeglum*, 1989].

2. Discussion

[13] Globally, peatlands represent a large C stock, estimated at 397–455 Pg C [*Zoltai and Martikainen*, 1996] or one-third of the world's soil C pool. Carbon sink/source relationships in peatlands can be estimated through measurements of both net primary production and decomposition rates in peatlands, with subsequent estimation of C storage capacity [*Thormann et al.*, 1999]. However, this approach largely is confounded by methodological limitations, as well as by large spatial and temporal process variability. Peatland C fluxes have been obtained via eddy covariance or chamber techniques in subarctic and boreal peatlands [cf. *Friborg et al.*, 1997; *Lafleur et al.*, 1997; *Suyker et al.*, 1997; *Goulden et al.*, 1998; *Waddington and Roulet*, 2000], yet these studies mainly have been conducted in eastern- or mid- North America where different moisture regimes and underlying substrates make application to western continental Canada imprudent. Constructing regional C budgets from net ecosystem flux requires temporally and spatially intensive measurements for larger-scale extrapolation. Alternatively, our approach capitalizes on the long-term records stored in vertically accumulating peat across western boreal Canada. We use current peat volumes on the landscape, obtained from detailed aerial photograph inventories and peat depth information from 818 sites, corrected for long-term catotelm decay [*Vitt et al.*, 2000a]. While C accumulation in the region has decreased since the mid-Holocene, we estimate current accumulation rates (accounting for historical fires) at 24.5 g m^{-2} yr^{-1}. This value is only slightly lower than model-derived estimates for current net C accumulation in the upper 30 cm of peat of 34–52 g C m^{-2} yr^{-1} for three sites in Alberta [*Wieder*, 2001], which do not include C losses from decomposition deeper in the peat profile.

[14] Climatic fluctuations clearly have influenced trends in peatland C storage across western Canada [*Vitt et al.*, 2000a], yet to date the various natural and anthropogenic disturbances affecting peatland C stocks have not been evaluated. We estimate that about 47,600 km^2 of peatland are affected by recent disturbance, or 13% of the regional peatland area (Table 1). New disturbances cumulatively affect about 1500 km^2, or 0.4%, of peatlands each year across western Canada (Table 1). Therefore, assuming an even distribution of disturbances over the landscape, a typical boreal peatland may experience disturbance in some form about every 250 years.

[15] Disturbance across the boreal forest is not spatially homogeneous, particularly in peatlands where permafrost patterning is important. The degradation of 2630 km^2 of permafrost in peatlands is a relatively recent phenomenon in the boreal forest, likely due to climatic warming over the past 100–150 years [*Vitt et al.*, 1994]. Ongoing permafrost melt accounts for only about 2% of new areal peatland disturbance (26.3 km^2 yr^{-1}; Table 1). However, permafrost thaw has long-term effects on peatland water tables and albedos, and results in distinct species composition compared to surrounding peatlands for at least a century [*Vitt et al.*, 2000b].

[16] Lightning-initiated fires also are common in western Canada, representing 98% of the annual areal peatland disturbance (Table 1). Fires in the western boreal forest have increased since the 1980s [*Kurz and Apps*, 1999], but an increase in peatland fires in recent years previously has not been documented. Across our study region, we estimate that as much as 1470 km^2 of peatland burns currently each year, an area 2.5-fold greater than the historical estimate. This change in burn areas may be attributed to methodological differences and/or increasing fire regimes in recent years.

[17] Permafrost melt and fire have very different impacts on the storage of soil C. Melting permafrost increases peatland C accumulation in our study area [*Turetsky et al.*, 2000; Turetsky, unpublished data] by stimulating bryophyte primary production. The strength of this sink will be enhanced if rates of permafrost degradation increase under a warming climate. Fire, however, results in the immediate release of CO_2, CO and CH_4 to the atmosphere through combustion and increased post-fire decomposition through increased temperatures and increased nutrient supply from ash [*Hogg et al.*, 1992; *Wardle et al.*, 1998]. Our estimates suggest that the immediate impact of combustion releases about 4700 Gg of C to the atmosphere, about 3 times greater than emissions due to enhanced post-fire mineralization. Fire is the most important disturbance affecting peatland C emissions, accounting for 97% of total disturbance-related C losses (Table 1).

[18] Certain human activities remove large amounts of organic matter from peatlands that either are exported (e.g. peat extraction for horticultural products) or stockpiled (e.g. oil sand development), and subsequently oxidized under aerobic conditions. Hydroelectric reservoirs are large sources of greenhouse gases to the atmosphere, particularly those reservoirs inundating peatlands [*St. Louis et al.*, 2000; *Kelly et al.*, 1997]. We estimate that these anthropogenic disturbances contribute to 280 Gg of C losses through a combination of C removal from the landscape and changing mineralization rates on site (Table 1).

[19] In total, C emissions from disturbed peatlands across western Canada totaled 6462 ± 931 Gg C yr^{-1} and reduced regional C accumulation by 85% compared to our no-disturbance scenario (Table 1). Combustion during fire clearly leads to large C losses to the atmosphere, but also is associated with relatively large error estimates due mostly to error in combustion rates rather than current burn areas (Table 1). Additional studies focusing on combustion during peatland fires will help to determine whether uncertainties in our approach are attributed to measurement error or variability in fire intensity. Carbon fluxes associated with enhanced mineralization in burned peatlands also are large (Table 1), indicating a strong need for field measurements of post-fire C fluxes in peatlands. Our approach suggests that fire monitoring programs in the boreal forest should follow both fire frequencies and burn intensities to best assess total C loss from organic soils.

3. Conclusion

[20] We show that natural and anthropogenic disturbances have a substantial influence on soil C storage in the boreal forest that

only can be recognized at regional scales of study. Our approach relies upon all available information on peatland C stocks and current levels of disturbance and development across western Canada, and points to the need for more mechanistic understanding of lowland disturbances and peatland recovery. Our assessment of regional C stocks suggests that peatlands accumulate 24.5 g C m^{-2} yr^{-1} without disturbance (Table 1). However, these average C accumulation rates are reduced to a regional average 3.6 g C m^{-2} yr^{-1} under contemporary levels of disturbance and development across our study region in western boreal Canada.

[21] Consideration of changing disturbance regimes with near-future climate change also must be evaluated across broad scales. Fire is more important to organic soil C stocks than direct human activities such as flooding, peat extraction, and oil sands development. Global circulation models predict temperature increases of 1–5°C in boreal and subarctic regions with a doubling of atmospheric CO_2 [*Moore et al.*, 1998]. Both fire and permafrost melt largely are controlled by climate, and may become more important to peatland C balances in the future under these climate change scenarios [*Vitt et al.*, 2000b; *Stocks et al.*, 1998]. Permafrost melt in peatlands is not independent of fire in boreal landscapes, and will serve as a small buffer against future C losses. However, predicted increases in fire frequency and intensity under a warmer, drier climate in western boreal forest [*Stocks et al.*, 1998] will have large consequences for peatland C storage.

[22] We argue that a true understanding of C sinks at northern latitudes must account for disturbances in both upland and lowland systems. A similar ecosystem approach may reconcile C emission estimates from recent boreal forest models differing in organic soil and disturbance representation. According to our estimates, increases in both the area of peatland burned annually (km^2 yr^{-1}) and the intensity of organic matter combustion (g C m^{-2} $fire^{-1}$) of 17% would convert these northern peatlands to a net C source to the atmosphere.

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