

Greenhouse Gas Emissions from Canadian Peat Extraction, 1990–2000: A Life-cycle Analysis

This study uses life-cycle analysis to examine the net greenhouse gas (GHG) emissions from the Canadian peat industry for the period 1990–2000. GHG exchange is estimated for land-use change, peat extraction and processing, transport to market, and the *in situ* decomposition of extracted peat. The estimates, based on an additive GHG accounting model, show that the peat extraction life cycle emitted 0.54×10^6 t of GHG in 1990, increasing to 0.89×10^6 t in 2000 (expressed as CO₂ equivalents using a 100-y time horizon). Peat decomposition associated with end use was the largest source of GHGs, comprising 71% of total emissions during this 11-y period. Land use change resulted in a switch of the peatlands from a GHG sink to a source and contributed an additional 15%. Peat transportation was responsible for 10% of total GHG emissions, and extraction and processing contributed 4%. It would take approximately 2000 y to restore the carbon pool to its original size if peatland restoration is successful and the cutover peatland once again becomes a net carbon sink.

INTRODUCTION

Northern peatlands cover approximately 3.5×10^{12} m², store between 220 and 460 Gt carbon (C), and currently accumulate C and emit methane (CH₄) to the atmosphere (1, 2). By clearing vegetation, draining bogs, and extracting peat, the Canadian peat industry has substantially altered the character of more than 100 km² of peatland. *Sphagnum* peat moss, prized for its high porosity and water retention capacity, is processed, packaged, and shipped to markets throughout the world. Although Canadian peat is used for a wide variety of nonfuel purposes, its most common use is in horticulture. Peat extraction, which generates greenhouse gas (GHG) emissions from land use, fossil fuel combustion, and peat decomposition, contributes to Canada's net atmospheric burden and, therefore, climate change. The objective of this study was to quantify this contribution. To prepare a peatland for harvesting, it is drained, cleared of vegetation, and leveled (3–5). This alters net GHG emissions from the peatlands in two ways. First, the drainage of the site increases the rate of *in situ* decomposition through greater diffusion of oxygen, increasing CO₂ emissions and reducing CH₄ emissions (6–8). Second, by removing the living biomass from the peatland surface, the gross ecosystem production falls to zero (9).

The Canadian peat industry also emits GHGs by using vehicles and equipment powered by fossil fuels to extract, process, and “add value” to its product, as well as to transport the peat to market. Finally, the extracted peat decomposes where it is used through bacterial and fungal activity. Decomposition rates for extracted peat, which vary with temperature, C:N ratio, pH, and water availability (10, 11), are significantly greater than those observed in natural peatlands. The decomposition process generates CO₂ under aerobic conditions and both CO₂ and CH₄ under anaerobic conditions. In this paper, we apply a life-cycle analysis to estimate the GHG

emissions from the Canadian peat extraction industry for the period 1990–2000. This life-cycle analysis takes into account raw material acquisition, manufacturing, use, and disposition (12, 13). GHG emissions, comprising carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), are estimated for each of the following four components of the peat extraction life cycle: land-use change, extraction and processing, transport to market, and decomposition of extracted peat.

MATERIALS AND METHODS

The methods used to calculate the GHG emissions generated during each stage of the peat extraction life cycle vary with the type of data available. We assumed that extracted peat has a 45% moisture content on a wet basis (14, 15) and that 50% of the dry biomass is C (10). Global warming potentials (GWPs), which estimate the relative potential of GHGs to absorb infrared radiation, are used to convert non-CO₂ GHGs to CO₂ equivalents over a given time period. A 100-y time horizon has been adopted to calculate GWP because this period is used for GHG accounting under the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Over this time horizon, the GWP of CH₄ is 23 and N₂O is 296 on a mass basis (16). We used both published and unpublished results on GHG fluxes from peatlands and the decomposition rate of peat, as well as government and industry data relating to the extraction and transportation of the product. Data on land use and the extraction, processing, and transportation of peat were gathered using a questionnaire (17) that was sent to all of Canada's peat extraction establishments. The response rate represented 69% of total peat production in 2000.

RESULTS

Land-use Change

The characteristics of the various peatland types we use are *i*) undisturbed peatland, naturally high water table and full vegetation cover; *ii*) peatland under extraction, low water table, no vegetation cover, peat near the surface has a higher degree of decomposition than that in undisturbed sites; *iii*) abandoned cutover peatland, low water table, little or no vegetation cover; and *iv*) cutover peatland under restoration, high water table, increasing vegetation cover, mulch (e.g. straw) on surface. The net annual GHG emissions from land use change (GHG_{LUC}) are given by:

$$GHG_{LUC} = A_{PUE} F_{PUE} + A_{ACP} F_{ACP} + A_{CPR} F_{CPR} - (A_{PUE} + A_{ACP} + A_{CPR}) F_{UDP}$$

where A_{PUE} , A_{ACP} , and A_{CPR} represent the areas of peatland under extraction, abandoned cutover peatland, and cutover peatland under restoration, respectively. F_{PUE} , F_{ACP} , F_{CPR} , and F_{UDP} represent the average annual per unit area GHG flux from peatland under extraction, abandoned cutover peatland, cutover peatland under restoration, and undisturbed peatland, respectively.

Area Subject to Land Use by the Peat Industry

Canadian peatlands cover approximately $1.2 \times 10^{12} \text{ m}^2$, storing an estimated 155 Gt C (18). The current area of peatland under extraction, 125 km² [G. Hood, Canadian Sphagnum Peat Moss Association (CSPMA), pers. comm.], represents 0.01% of peatlands in Canada. Nonfuel peat extraction statistics for the years 1941–2000 were used to estimate the areas of land affected by peat extraction from 1990 to 2000 (17). The percentage of peat extracted by the vacuum method was assumed negligible before 1960, 60% in 1970, 90% in 1980, 95% in 1990, and 97.1% in 2000 (linear increases assumed), based on results from the questionnaire (17) and estimates from the CSPMA (G. Hood pers. comm.). The average annual yield of vacuum-harvested peatlands was estimated to be $10 \times 10^3 \text{ t km}^{-2} \text{ y}^{-1}$ in 2000. It is assumed that, once entered into production, peatlands under extraction cannot be removed from production until all of the commercially viable peat is extracted. Vacuum-harvested peatlands were assumed to have a life span of between 20 and 50 y, with an average of 35 y, consistent with observations by Nyronen and Oy (14) and the CSPMA (G. Hood pers. comm.). Applying the average annual peat yield over 35 y, $350 \times 10^3 \text{ t km}^{-2}$ of peat would be extracted, equivalent to a depth of about 2.3 m in a typical bog (19). The vast majority of non-vacuum-harvested peatlands were assumed to be block-cut, with an average annual yield of $175 \times 10^3 \text{ t km}^{-2}$ (cutover area only) (R. Mecking, Heveco Ltd., pers. comm.). The block-cut areas entering into and removed from production were estimated, but the estimates possess significant uncertainty because many block-cut sites were converted to the vacuum method of extraction in the 1960s (R. Mecking, pers. comm.). It is also characteristic of the block-cut method to shift production to another location before all of the peat remaining in the area under extraction is removed (G. Hood pers. comm.). The time taken until the lower layers of peat are block-cut is dependent on the size of the site. The estimate of 2 y for an area to be removed from production is based on the assumption that one 1.15-m-deep harvest occurs each year from one trench. Therefore, 2 y may be considered the minimum length of time required for a site to be removed from production. Our estimate of 124 km² of peatland under extraction (Table 1) is consistent with the results of the questionnaire (131 km² in 2000) and the industry estimate (125 km², G. Hood pers. comm.), but less than the 170 km² estimated by Daigle and Gautreau-Daigle (5). The modeled estimate of the area of vacuum-harvested peatlands removed from production by the year 2000 (12.5 km²) is also consistent with the findings extrapolated from the responses to the questionnaire (12.7 km²).

Greenhouse Gas Fluxes Per Unit Area

GHG fluxes from undisturbed peatlands in Canada suitable for peat extraction are estimated at $4 \text{ g CH}_4\text{-C m}^{-2} \text{ y}^{-1}$ emitted to the atmosphere, with an uptake of $27 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$, based on Gorham (1). These flux figures fall within the typical range of long-term apparent rates of net C accumulation in Canadian peatlands of $10\text{--}35 \text{ g C m}^{-2} \text{ y}^{-1}$ (20). Although CH₄ emissions are highly variable depending on peatland type, peat extraction in Canada is focused on bogs (5), which tend to emit less CH₄ than peatlands with higher water tables, such as fens (21).

Growing season net fluxes of CO₂ and CH₄ from bogs affected by peat extraction were measured in Rivière-du-Loup (Québec) in 1999 and 2000 and in Shippagan (New Brunswick) in 2001 (T. Moore unpub. data). We converted these estimates to an annual flux by assuming that the winter GHG flux was 15.5% of the annual emission, based on the observation by Mast, Wickland, Striegl and Clow (22) that average winter CO₂ fluxes varied from 8% to 23% of the gross annual fluxes from a subalpine wetland. Malkki and Frilander (15), Uppenberg, Zetterberg, and Ahman (23), and Crill, Hargreaves, and Korhola (24) reported fluxes of 250, 273, and 289 g CO₂-C m⁻² y⁻¹ and 1.4, 1.6, and 5.0 g CH₄-C m⁻² y⁻¹ for peatlands under extraction, respectively. These values are similar to those used in Table 1. Although cutover peatlands under restoration may eventually sequester C, they show a net loss during the early stages of restoration (Table 1) (T. Moore unpub. data). Waddington and Price (25) similarly observed that a block-cut peatland under restoration lost both CO₂ ($170 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$) and CH₄ ($0.3 \text{ g CH}_4\text{-C m}^{-2} \text{ y}^{-1}$). On the other hand, Uppenberg, Zetterberg, and Ahman (23) estimated an uptake between 37 and 160 g CO₂-C m⁻² y⁻¹, whereas Malkki and Frilander (15) estimated $64 \text{ g CO}_2\text{-C m}^{-2} \text{ y}^{-1}$. The CO₂ release from eastern Canadian peatlands under restoration may be explained, in part, by the decomposition of the straw that is added to the surface during the initial stage of restoration. The additional GHG emissions from the decomposition of straw were not included in the estimates by Uppenberg, Zetterberg and Ahman (23) and Malkki and Frilander (15). The GHG fluxes from the abandoned cutover peatland (Table 1) are similar to those found in other studies. Waddington, Warner, and Kennedy (8) observed emissions at abandoned cutover peatlands (2–8 years since abandonment) varying from 88 to 397 g CO₂-C m⁻² from early May to late August. At the same sites, Waddington and Price (25) observed CH₄ emissions ranging from 0.3 to 1.2 g CH₄-C m⁻² during a summer described by Waddington, Warner and Kennedy (8) as relatively dry. We assumed that there were no net GHG

Table 1. Land-use area for peat extraction in Canada (km²) and GHG fluxes (10³ t CO₂ eq) from land use and land-use change, 1990–2000.

	Peatland under extraction		Abandoned cutover peatland (vacuum method)		Cutover peatland under restoration (vacuum method)		Cutover peatland (nonvacuum methods)		Baseline GHG flux	Gross GHG flux	Net GHG flux
GHG flux per unit area											
(t CO ₂ -C km ⁻² yr ⁻¹)	278		302		336		0				
(t CH ₄ -C km ⁻² yr ⁻¹)	1.4		1.3		1.9		0				
(t CO ₂ -eq. km ⁻² yr ⁻¹)	1061		1145		1288		0				
Year	Area	GHG	Area	GHG	Area	GHG	Area	GHG			
1990	68.2	72.4	2.8	3.2	0	0	13.8	0	1.9	75.6	73.7
1991	81.8	86.8	3.4	4.0	0	0	13.9	0	2.3	90.7	88.5
1992	70.8	75.1	4.2	4.8	0	0	14.0	0	2.0	79.9	77.9
1993	83.7	88.8	4.9	5.6	0	0	14.2	0	2.4	94.4	92.1
1994	92.9	98.6	5.7	6.6	0	0	14.2	0	2.6	105.2	102.6
1995	84.4	89.6	6.6	7.6	0	0	14.4	0	2.4	97.2	94.8
1996	86.9	92.3	7.6	8.7	0	0	14.5	0	2.5	101.0	98.5
1997	101.9	108.1	8.6	9.9	0	0	14.6	0	2.9	118.0	115.2
1998	109.0	115.7	9.8	11.2	0	0	14.7	0	3.1	126.9	123.8
1999	114.5	121.6	10.1	11.6	1.0	1.3	14.9	0	3.2	134.5	131.3
2000	124.2	131.8	9.5	10.9	3.0	3.9	14.9	0	3.5	146.6	143.1

Note: Numbers may not add up because of rounding.

emissions from cutover peatlands extracted through nonvacuum, primarily block-cut methods, most of which were abandoned before 1970. This assumption is based on several factors. The current land use of these cutover peatlands is uncertain. Whereas some of these sites are growing *Sphagnum*, others are forests, agricultural fields, or are used otherwise (G. Hood pers. comm.). Many sites are no longer part of the current holdings of peat companies in Canada because numerous operations no longer exist. In addition, the responses to the questionnaire indicated that almost all (> 99%) of the cutover sites in the holdings of the peat industry were from companies that extracted peat using the vacuum method. We have not included emissions of nitrous oxide (N₂O) in our calculations because there are so few estimates from peatlands (6, 24). Although peatland drainage tends to increase N₂O emissions, this increase seems to take place in nutrient-rich fens more than in ombrotrophic bogs (6). Other studies have considered these emissions from peatlands under extraction to be negligible (15, 26).

Sustainability of Peat Extraction

Models of peatland growth may be used to estimate changes in C accumulation through time and thus predict the number of years it would take to restore the extracted peat. Clymo (27) and Hilbert, Roulet, and Moore (28) indicated that a younger ombrotrophic peatland with a smaller catotelm (anoxic layer) has a faster rate of peat accumulation than a bog with a thicker catotelm. When peat is extracted, it is analogous to resetting the peatland clock. Using this assumption, the C accumulation for three peatland disturbance scenarios were estimated to establish *i*) the time it takes to sequester the C emitted because of land use and *ii*) the time it takes to sequester the C extracted and emitted from land use. The scenarios include: a restored vacuum-harvested or block-cut site (scenario A); an abandoned block-cut site (scenario B); and an abandoned vacuum-harvested site (scenario C). For scenario A, it is assumed that a peatland emits 300 g C m⁻² y⁻¹ (T. Moore unpub. data) (8) for the first 50 y from the time it enters into production and takes another 50 y to reach a net sink of 90 g C m⁻² y⁻¹. This accumulation rate is derived from an estimate for a 1-m-deep peatland (28), the

depth of peat remaining after extraction, assuming an annual depth of precipitation of 900 mm, which is a fairly representative value in eastern Canada. The change in flux is assumed to be linear with time. For scenario B, the same 50-y initial flux of 300 g C m⁻² y⁻¹ is assumed, taking an additional 100 y to reach a net sink of 90 g C m⁻² y⁻¹. In scenario C, the flux of 300 g C m⁻² y⁻¹ is sustained for 100 y, taking an additional 100 y to reach an uptake of 90 g C m⁻² y⁻¹. The results from the three scenarios show that between 21 and 42 kg C m⁻² (equivalent to 76 and 150 × 10³ t peat km⁻²) are lost from the peatlands as CO₂ and CH₄ emissions due to the disturbance caused by peat extraction (Table 2). This decomposition is equivalent to 22%–44% of the C extracted as commercial peat, assuming that 96 kg C m⁻² g C m⁻² (equivalent to 350 × 10³ t peat km⁻²) are taken out of the average peatland under extraction. Therefore, a substantial amount of additional peat could be extracted per unit area if the harvest and restoration period is reduced, because there would be less time for the peat to decompose *in situ*. Alternately, fewer areas would need to be drained to extract peat.

Extraction and Processing

The second component of this study addressed the GHG emissions from the use of fossil fuels during the extraction and processing of peat (Table 3). Data on fuel consumption and GHG emissions by fuel type were obtained from the annual *Census of Manufacturers* (29, 30) and *Canada's Emissions Outlook: An Update* (31), respectively. The fuel purchased by an establishment for transportation purposes is included in Statistics Canada fuel consumption data (32). However, very few peat establishments own the trucks that are used to ship their peat to market (17). Most establishments hire shipping firms to do so and thus do not directly purchase the fuel used to operate the vehicles (33). The questionnaire results indicated that there are approximately 20 trucks owned by peat establishments, each of which traveled an average of 43 000 km y⁻¹. Therefore, although there may be some double counting of GHG emissions from transportation, the effect is small, amounting to less than 1 × 10³ t CO₂ eq y⁻¹. The proportion of total GHGs emitted during extraction and processing

Table 2. Estimated C emissions from a peatland under restoration, an abandoned block-cut peatland, and an abandoned vacuum-harvested peatland, and years to sequester the emitted C.

Peatland disturbance scenario	C emissions (kg m ⁻²)*	Time to accumulate emitted C from land-use change (y)	Time to accumulate emitted C from extraction and land-use change (y)
A: Peatland under restoration	20.9	602	2012
B: Abandoned block-cut peatland	26.7	794	2258
C: Abandoned vacuum-harvested peatland	41.7	1251	2911

* The C emissions resulting from land use do not include the C sequestration that would be forgone.

Table 3. Fuel use (10³ L) by Canadian peat industry and their GHG emissions (10³ t CO₂ eq), 1990–2000.

	Natural gas		Gasoline		Kerosene		Diesel		Light fuel oil		Heavy fuel oil		LPG		
	Use	GHG	Use	GHG	Use	GHG	Use	GHG	Use	GHG	Use	GHG	Use	GHG	
GHG factor (t CO ₂ eq. per 10 ³ L)	1.99		2.47		2.57		2.91		2.85		3.15		1.44		
Year	Use	GHG	Use	GHG	Use	GHG	Use	GHG	Use	GHG	Use	GHG	Use	GHG	Total GHG
1990	8	0	1842	4.6	2	0	4502	13.1	55	0.2	105	0.3	2464	3.5	21.7
1991	10	0	1762	4.4	6	0	5559	16.2	31	0.1	111	0.4	2472	3.5	24.6
1992	3	0	1442	3.6	0	0	4654	13.5	72	0.2	202	0.6	3272	4.7	22.7
1993	3	0	1257	3.1	0	0	5121	14.9	543	1.5	172	0.5	3078	4.4	24.5
1994	4	0	1294	3.2	0	0	6898	20.1	306	0.9	302	1.0	3697	5.3	30.4
1995	4	0	2113	5.2	0	0	7326	21.3	376	1.1	348	1.1	6180	8.9	37.6
1996	4	0	1381	3.4	0	0	6968	20.3	147	0.4	0	0	6517	9.4	33.5
1997	6	0	1541	3.8	0	0	6947	20.2	9	0	0	0	5441	7.8	31.9
1998	4	0	1455	3.6	0	0	8625	25.1	155	0.4	0	0	5111	7.3	36.5
1999	7	0	1540	3.8	0	0	8746	25.4	29	0.1	0	0	4779	6.9	36.2
2000	6	0	1281	3.2	0	0	8806	25.6	36	0.1	0	0	5362	7.7	36.6

Note: Numbers may not add up because of rounding.

operations from the combustion of diesel fuel increased by approximately 10% from 1990 to 2000, replacing gasoline. Diesel emits 18% more GHG (in CO₂ equivalents) than gasoline when burned, so the substitution of diesel for gasoline further increases GHG emissions (31).

Transport of Peat to Market

To calculate GHG emissions resulting from the transport of peat to market on an annual basis, we used the size, origin, and market destination of peat shipments, the proportion of shipments using each mode of transport (truck, train, and ship), and the fuel efficiency of each mode of transport (Table 4). Estimates are based on 17.4 t or 450 bales of peat per truckload (34, G. Hood pers. comm.), diesel fuel consumption by truck (0.39 L km⁻¹) (35), and the diesel fuel consumed to ship one ton of goods one km by rail and ship (135 and 311 t km L⁻¹) (35). Fuel use was converted into CO₂, CH₄, and N₂O emissions (tons of GHG per liter of fuel) by rail and marine transport and by heavy-duty road vehicles with moderate pollution control (36). For each overseas shipment, it is assumed that the peat travels 250 km by land from the location of extraction to the shipping port and another 250 km from the overseas port of arrival to the final market destination. The most recent data on the primary domestic destinations for peat deliveries from major producing regions within Canada (Western, Central, and Atlantic Canada) are from 1987 and 1988 (37). We assumed that there had been no change in the ratio of peat extracted to peat consumed in Western, Central, and Atlantic Canada. Annual domestic export data from Statistics Canada (38) were used for peat shipped to the United States and overseas. For exports to the United States, this export data specified the province of origin and American state to which the peat was destined, although this may not be the location of consumption (39) and may result in an underestimate of GHG emissions. Distances traveled to the domestic and American markets were adapted from the methodology used by Brown and Anderson (40). For overseas shipments, the distances were generated from World-Ports Distances software, assuming that peat was shipped from the port of Halifax (17). We estimated that 87% of North American shipments of Canadian peat (measured in t km) were sent by truck in 1990, declining to 78% by 2000, and that the remainder of the peat was shipped by rail (G. Hood pers. comm.).

Decomposition

Canadian peat, typically used in horticulture, landscaping, and mushroom farming, decomposes in a well-aerated environment, thus generating CO₂ emissions. There are few empirical studies of peat decomposition that last more than 1 y. Aerobic decomposition rates of peat in the first year range from 0% to 6% for moderately to well-humidified peat (41–46). A few studies have shown rates greater than 10% in the first year, and

Table 4. GHG emissions (10³ t CO₂ eq) from the transport of peat to domestic, U.S., and non-U.S. foreign markets, 1990–2000.

Year	Domestic	United States	Non-U.S. foreign	Total
1990	4.0	41.0	8.1	53.1
1991	7.5	41.7	8.2	57.3
1992	0.9	50.5	9.0	60.4
1993	5.4	54.9	9.9	70.2
1994	8.1	58.6	10.4	77.0
1995	4.0	58.6	11.6	74.2
1996	5.1	58.3	11.0	74.4
1997	8.8	62.4	7.9	79.0
1998	10.4	62.8	8.9	82.1
1999	12.5	60.5	9.2	82.2
2000	12.3	64.8	17.9	95.0

Note: Numbers may not add up because of rounding.

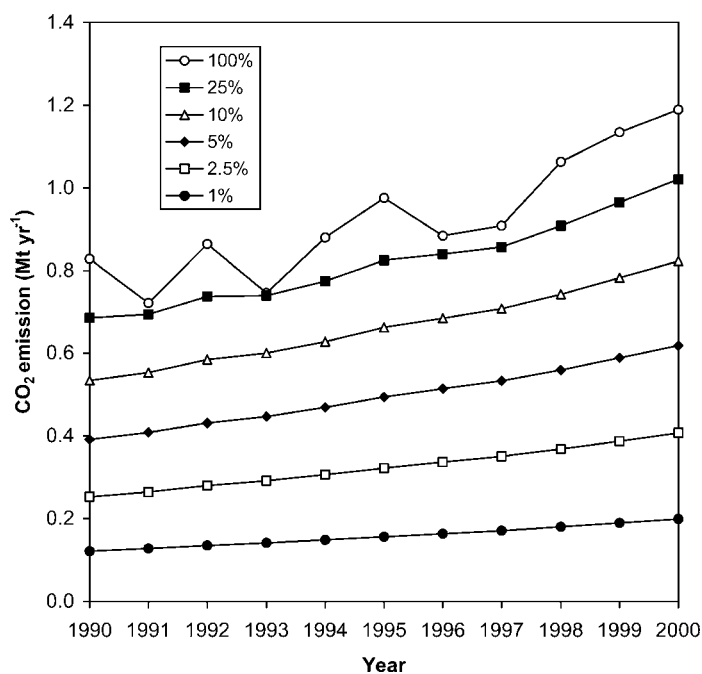


Figure 1. Annual CO₂ emission from peat decomposition at different rates of decay, 1990–2000.

these have generally examined the decomposition of peat mixed with other substances such as fertilizer and soil (42, 47). The vast majority of extracted peat is mixed with other substances when used in horticulture, increasing peat decomposition rates (42). Unfortunately, it is difficult to isolate the decomposition of peat from the decomposition of the substances with which it is mixed. We used an exponential model with an annual decay rate of 5% to estimate the emission of CO₂ from decomposing peat moss. To assess the uncertainty associated with decay rates, we also used annual rates of 1%, 2.5%, 10%, 25%, and 100% (Fig. 1). We applied a peat decomposition model to nonfuel peat extraction data for the years 1941–2000 to estimate annual GHG emissions. The year 1941 is used as the initial year of extraction because no more than a few thousand tons of peat were extracted per year in Canada before the 1940s (48, 49). Over this 60-y period, a total of 24.3×10^6 t of nonfuel peat was extracted, representing approximately 6.7×10^6 t C (Fig. 2).

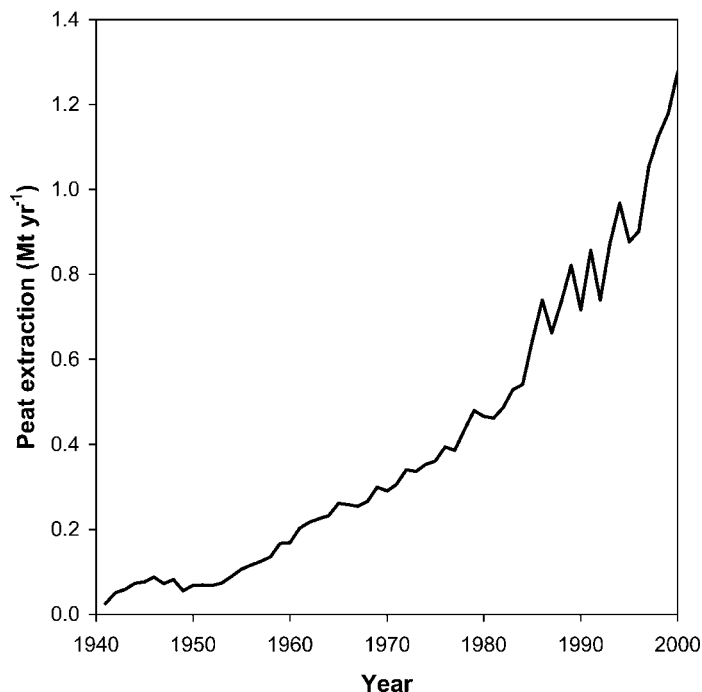


Figure 2. Nonfuel peat extraction in Canada, 1941–2000.

Table 5. GHG contributions (10^3 t CO₂ eq) from each component of the life cycle of peat extraction, 1990–2000.

Year	Land use change	Peat extraction and processing	Transport to market	Decomposition of extracted peat	Total
1990	73.7	21.7	53.1	392.1	540.6
1991	88.5	24.6	57.3	408.6	579.0
1992	77.9	22.7	60.4	431.4	592.3
1993	92.1	24.5	70.2	447.1	633.8
1994	102.6	30.4	77.0	468.7	678.8
1995	94.8	37.6	74.2	494.1	700.6
1996	98.5	33.5	74.4	513.6	720.0
1997	115.2	31.9	79.0	533.3	759.3
1998	123.8	36.5	82.1	559.8	802.2
1999	131.3	36.2	82.2	588.5	838.2
2000	143.1	36.6	95.0	618.6	893.3

Note: Numbers may not add up because of rounding.

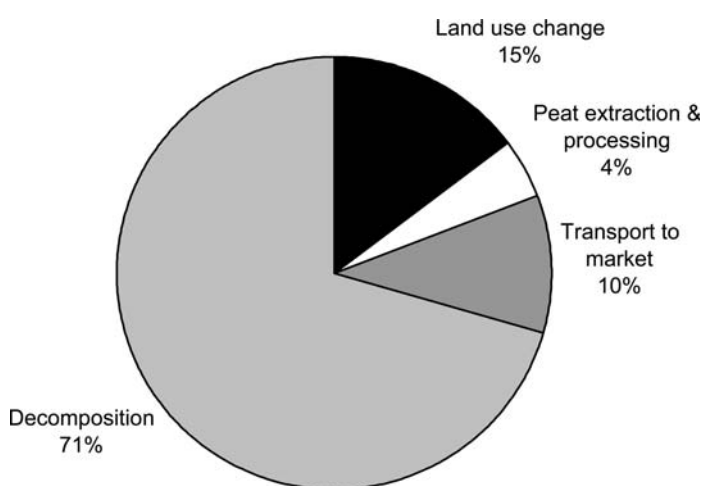


Figure 3. Contribution of land-use change, peat extraction and processing, transport to market, and decomposition of extracted peat to the life cycle of peat extraction from 1990 to 2000.

Summary of GHG Emissions

GHG emissions from the life cycle of peat extraction increased by 66% from 1990 to 2000 (Table 5). Decomposition, land use change, the transport of peat to market, and extraction and processing comprised 71%, 15%, 10%, and 4%, respectively (Fig. 3). There was little variation in these percentages over the 11-y period.

DISCUSSION

Kyoto Protocol and Peat Extraction

Canada committed, under the Kyoto Protocol, to reduce its annual GHG emissions by an average of 6% below the 1990 level between 2008 to 2012 (50). Peat extraction in 1990 was unusually small (0.75×10^6 t), a 6% decline from the previous year, partly because of unfavorable weather (51) and resulted in reduced GHG emissions. This could place an extraordinary burden on the peat industry regarding its baseline. Assuming a 5% annual increase in peat extraction from 2000 to 2010, the life-cycle GHG intensity of peat extraction would have to be reduced 63% by 2010 to meet the Kyoto target of 6% below the 1990 baseline. To date, peat extraction has not been selected specifically for reductions in emissions. The precise design of the framework to be used to account for unconventional GHG emissions under the Protocol has not been resolved (50). Presently, the only emissions from the peat industry that are included in Canada's GHG inventory are those from fossil fuel combustion in peat extraction machinery and for the transport of peat within Canada. These particular emissions increased by 83% from 1990 to 2000 and accounted for approximately 62×10^3 t CO₂ equivalents in 2000, or about 0.008% of total GHG emissions (726×10^6 t CO₂ equivalents) (17). In comparison, Canada's annual GHG emissions increased by 19.6% from 1990 to 2000 (50).

Potential for Greenhouse Gas Reduction

Canada produced approximately 1.3×10^6 t of peat in 2000 (30) and possessed the world's second largest peat resource, after Russia, at 510×10^9 t (52). Unlike many European countries, Canada's peat industry does not extract peat for use as fuel, but the gradual decomposition of extracted peat is responsible for the majority of GHG emissions from the peat extraction life cycle. However, this does not mean that GHG emissions from a product's use should be attributed to the producer because it is the consumer that purchases and uses the product. GHG emissions that may be attributed to the peat producer derive from land-use change and the fuel used during extraction, processing, and transport, less than one-third of the complete life-cycle emissions. Consumers may delay peat decomposition by storing the peat at low temperatures, by keeping it relatively dry, or by restricting its access to oxygen and nutrients. Unfortunately, many of the end uses of Canadian *Sphagnum* peat necessarily create conditions that speed peat decomposition. There are, however, instances where peat can also be used to help stabilize a methane-emitting substance, such as sludge or liquid manure (53).

Peat extraction alters the turnover time of the C pool in peatlands. Over the short-term, land use change from peat extraction is a net emitter of GHGs. However, cutover peatlands may achieve C neutrality over thousands of years, assuming that they can be successfully restored. GHG emissions can be reduced if peat extraction companies avoid lowering the water tables of sites adjacent to those under extraction. Mosses adjacent to peatlands under extraction and to cutover sites tend to become more prone to desiccation, and the decomposition rate of the peat substrate increases (26, 54). Nyström (54) estimated that the adjacent area affected may vary from 50% to 130% of the area under extraction, whereas Uppenberg, Zetterberg and Ahman (23) assumed 200%.

GHG emissions during extraction, processing, and transportation can be reduced by adopting more fuel-efficient equipment and peat extraction techniques and by substituting biodiesel and ethanol for conventional fossil fuels. Decreasing the time spent idling the vehicles used to extract, process, and transport peat is also environmentally and economically desirable. There is no discernible trend toward a decreased intensity of fuel consumption during extraction and processing from 1990 to 2000, based on fuel GHG emitted per mass of peat extracted. Over the 1990s, this GHG intensity ranged from 0.028 (1993) to 0.043 (1995) t GHG t⁻¹ of peat extracted. Cleary (17) found no evidence that fuel prices or size of the establishment affected the GHG intensity of peat extraction and processing. There is a substantial economic incentive to reduce the distance of shipping peat to market because peat is very price sensitive (55). GHG reductions may be achieved by exploiting production sites closer to the major locations of peat consumption. For example, peat extraction sites in Manitoba were expressly developed owing to their proximity to central and midwestern United States markets (55). Trucks are used more commonly than rail for the land-based movement of peat because of their greater route flexibility and lower shipping

costs (55). However, if 80% of land-based peat transport took place by rail, the annual GHG emissions from peat transport for 1990 to 2000 would have decreased by an average of 40%. The increasing availability of intermodal services could make trains more attractive for peat shipments in the future.

A number of products may be used as substitutes for peat, such as compost, barks, mulches, and coir dust (55, 56). These materials are not perfect substitutes because they may differ from *Sphagnum* peat in quality, use, and price. The GHG burden associated with the production of peat substitutes is not known.

In summary, our study is the first life-cycle analysis of the GHG emissions from any nonfuel peat extraction industry. Other studies, including Malkki and Frilander (15), Crill, Hargreaves, and Korhola (24), and Uppenberg, Zetterberg, and Ahman (23), have accounted for the GHG emissions from industries that extract peat for energy production in Scandinavia. They tend to show higher end-use emissions caused by peat combustion instead of the slower decomposition of Canadian peat used in horticulture. The Scandinavian studies also show lower transportation emissions, because the locations of use tend to be closer to the peat extraction sites. The emission of GHGs from the Canadian peat industry is a very small, but growing, component of the overall GHG emissions for Canada. The net change in emissions from the loss of the carbon sink and the reduction of the methane source when peatlands are converted for peat extraction represents only 15% of the life-cycle emissions from the industry. However, the argument that peatlands are a renewable resource has little validity in the current climate change discussion and can only be considered over millennia. The fuels used in the extraction, processing, and transport of peat to market are significant contributors to the industry's emissions, especially because the vast majority of peat is extracted for nondomestic markets. The decomposition of extracted peat contributes, by far, the most GHGs to the atmosphere. Although this emission source is not attributed directly to the industry, the atmosphere receives this quantity of GHGs whether the industry or the consumer is responsible.

References and Notes

- Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climate warming. *Ecol. Appl.* 1, 182–195.
- Turunen, J., Tomppo, E., Tolonen, K. and Reinikainen, A. 2002. Estimating carbon accumulation rates of undrained mires in Finland—application to boreal and subarctic regions. *Holocene* 12, 69–80.
- Lavoie, M. and Rochefort, L. 1996. The natural revegetation of a harvested peatland in southern Québec: a spatial and dendroecological analysis. *Ecoscience* 3, 101–111.
- Robert, E.C., Rochefort, L. and Garneau, M. 1999. Natural revegetation of two block-cut mined peatlands in eastern Canada. *Can. J. Bot.* 77, 447–459.
- Daigle, J.-Y. and Gautreau-Daigle, H. 2001. *Canadian Peat Harvesting and the Environment*. (2nd ed.). Secretariat to the North American Wetlands Conservation Council Committee, Ottawa.
- Martikainen, P.J. 1996. The fluxes of greenhouse gases CO₂, CH₄ and N₂O in northern peatlands. In: *Global Peat Resources*. Lappalainen, E. (ed.). International Peat Society, Jyväskylä, pp. 29–36.
- Sundh, I., Nilsson, M., Mikela, C., Granberg, G. and Svensson, B.H. 2000. Fluxes of methane and carbon dioxide on peat-mining areas in Sweden. *Ambio* 29, 499–503.
- Waddington, J.M., Warner, K.D. and Kennedy, G.W. 2002. Cutover peatlands: a persistent source of atmospheric CO₂. *Global Biogeochem. Cycles* 16, 2–1.
- Waddington, J.M. and Warner, K.D. 2001. Atmospheric CO₂ sequestration in restored mined peatlands. *Ecoscience* 8, 359–368.
- Mathur, S.P. and Lévesque, M.P. 1980. Relationship between acid phosphatase activities and decomposition rates of 22 virgin peat materials. *Comm. Soil Sci. Plant Anal.* 11, 155–162.
- Belyea, L.R. 1996. Separating the effects of litter quality and microenvironment on decomposition rates in a patterned peatland. *Oikos* 77, 529–539.
- Curran, M.A. and Young, S. 1996. Report from the EPA conference on streamlining LCA. *Int. J. Life-Cycle Assess.* 1, 57–60.
- Graedel, T.E. 1998. *Streamlined Life-Cycle Assessment*. Prentice Hall, Upper Saddle River.
- Nyrenon, T. and Oy, V. 1996. Peat production. In: *Global Peat Resources*. Lappalainen, E. (ed.). International Peat Society, Jyväskylä, pp. 315–318.
- Malkki, H. and Frilander, P. 1997. *Life Cycle Assessment of Peat Utilisation in Finland*. VTT Publication 333. Technical Research Centre of Finland, Espoo.
- Intergovernmental Panel on Climatic Change. 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press, New York.
- Cleary, J. 2003. *Greenhouse Gas Emissions from Peat Extraction in Canada: A Life Cycle Perspective*. Report No. 2003-1. Centre for Climate and Global Change Research, McGill University, Montreal.
- Kettles, I.M. and Tarnocai, C. 1999. Development of a model for estimating the sensitivity of Canadian peatlands to climatic warming. *Geograph. Phys. Quat.* 53, 323–338.
- Frolking, S.E., Roulet, N.T., Moore, T.R., Richard, P.J.H., Lavoie, M. and Muller, S.D. 2001. Modelling northern peatland decomposition and peat accumulation. *Ecosystems* 4, 479–498.
- Ovenden, L. 1990. Peat accumulation in northern wetlands. *Quat. Res.* 33, 377–386.
- Nykanen, H., Silvola, J., Alm, J. and Martikainen, P.J. 1996. The effect of peatland forestry on fluxes of carbon dioxide, methane, and nitrous oxide. In: *Northern Forested Wetlands: Ecology and Management*. Trentin, C.C., Jurgensen, M.F., Grigal, D.F., Gale, M.R. and Jørgensen, J.K. (eds.). Lewis Publishers, Boca Raton, pp. 325–339.
- Mast, M.A., Wickland, K.P., Striegl, R.T. and Clow, D.W. 1998. Winter fluxes of CO₂ and CH₄ from subalpine soils in Rocky Mountain National Park, Colorado. *Global Biogeochem. Cycles* 12, 607–620.
- Uppenberg, S., Zetterberg, L. and Ahman, M. 2001. *Climate Impact from Peat Utilisation in Sweden*. IVL Swedish Environmental Research Institute, Stockholm.
- Crill, P., Hargreaves, K. and Korhola, A. 2000. *The Role of Peat in Finnish Greenhouse Gas Balances*. Ministry of Trade and Industry, Helsinki.
- Waddington, J.M. and Price, J.S. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Phys. Geograph.* 21, 433–451.
- Rodhe, H. and Svensson, B. 1995. Impact on the greenhouse effect of peat mining and combustion. *Ambio* 24, 221–225.
- Clymo, R.S. 1984. The limits to peat growth. *Phil. Trans. Roy. Soc. Lond. B* 303, 605–654.
- Hilbert, D.W., Roulet, N. and Moore, T. 2000. Modelling and analysis of peatlands as dynamical systems. *J. Ecol.* 88, 230–242.
- Statistics Canada. 1991–1999. *Non-metal Mines*. Statistics Canada, Ottawa.
- Statistics Canada. 2000–2002. *Non-metallic Mineral Mining and Quarrying*. Statistics Canada, Manufacturing, Construction and Energy Division, Ottawa.
- Analysis and Modelling Group. National Climate Change Process. 1999. *Canada's Emissions Outlook: An Update*. Analysis and Modelling Group, National Climate Change Process, Ottawa.
- Statistics Canada. 1984. *Concepts and Definitions of the Census of Manufacturers*. Statistics Canada, Ottawa.
- Fred Kennedy & Associates. 1997. *A Study of the Transportation Requirements of the New Brunswick Peat Industry*. Prepared for Jean-Yves Daigle, General Manager, Peat Research and Development Centre. Fred Kennedy & Associates, Moncton, New Brunswick.
- Three-D Geococonsultants 1992. *Bulk Transportation of Peat: Final Report*. Three-D Geococonsultants, Fredericton, New Brunswick.
- Transportation Table: National Climate Change Process. 1998. *Foundation Paper on Climate Change: Transportation Sector*. (http://www.tc.gc.ca/programs/environment/climate-change/english/climatechange/prog_reports/trans_upnote.pdf)
- Neitzert, F., Olsen, K. and Collas, P. 1999. *Canada's Greenhouse Gas Inventory: 1997 Emissions and Removals with Trends*. Greenhouse Gas Division, Air Pollution Prevention Directorate, Environment Canada, Ottawa.
- Energy, Mines and Resources Canada/Natural Resources Canada. 1991. 1990 Canadian Minerals Yearbook: Review and Outlook. Energy, Mines and Resources Canada/Natural Resources Canada, Ottawa.
- Statistics Canada. 2000. *1996 Trade Information and Retrieval System (CD-ROM)*. Statistics Canada, Ottawa.
- Brown, W.M. and Anderson, W.P. 1999. The influence of industrial and spatial structure on Canada-US regional trade. *Growth Change* 30, 23–47.
- Brown, W.M. and Anderson, W.P. 2002. Spatial markets and the potential for economic integration between Canadian and U.S. regions. *Papers Region. Sci.* 81, 99–120.
- Farrell, E.P. and McDonnell, J.G. 1996. Decomposition in man modified peat soils. *Int. Peat J.* 1, 99–111.
- Murayama, S., Asakawa, Y. and Ohno, Y. 1990. Chemical properties of subsurface peats and their decomposition kinetics under field conditions. *Soil Sci. Plant Nutr.* 36, 129–140.
- Hogg, E.H., Lieffers, V.J. and Wein, R.W. 1992. Potential carbon losses from peat profiles: effects of temperature, drought cycles and fire. *Ecol. Appl.* 2, 298–306.
- Hogg, E.H. 1993. Decay potential of hummock and hollow *Sphagnum* peats at different depths in a Swedish raised bog. *Oikos* 66, 269–278.
- Updegraff, K., Pastor, J., Bridgman, S.D. and Johnston, C.A. 1995. Environmental and substrate controls over carbon and nitrogen mineralization in northern wetlands. *Ecol. Appl.* 5, 151–163.
- Scanlon, D. and Moore, T. 2000. Carbon dioxide from peatland soil profiles: the influence of temperature, oxic/anoxic conditions and substrate. *Soil Sci.* 165, 153–160.
- Aendecker, T.G.L. 1997. Decomposition of peat substrates in relation to physical properties and growth of *chamaecyparis*. *Acta Horticult.* 450, 191–198.
- Swinerton, A.A. 1950. *The Peat Moss Industry in Canada*. Department of Mines and Technical Surveys, Ottawa.
- Warner, B.G. and Buteau, P. 2000. The early peat industry in Canada, 1864–1945. *Geosci. Can.* 27, 57–66.
- Olsen, K., Collas, P., Boileau, P., Blain, D., Ha, C., Henderson, L., Liang, C., McKibbin, S., et al. 2002. *Canada's Greenhouse Gas Inventory: 1990–2000*. Greenhouse Gas Division, Environment Canada, Ottawa.
- Prud'homme, M. 1991. Peat. *Canadian Minerals Yearbook, 1990*. Energy, Mines and Resources Canada, Ottawa.
- Jasinski, S.M. 2001. *Peat. Mineral Commodity Summaries, January 2001*. United States Department of the Interior, United States Geological Survey, Washington, DC.
- Mutka, K. 1996. Environmental use of peat. In: *Global Peat Resources*. Lappalainen, E. (ed.). International Peat Society, Jyväskylä, pp. 335–338.
- Nyström, K.L.E. 1992. Peat and the greenhouse effect. *Int. Peat Congress*, 2, 266–271.
- Physical Distribution Advisory Service. 1984. *Distribution Requirements of the New Brunswick Peat Industry*. Canada Department of Regional Industrial Expansion, Moncton, New Brunswick.
- Knight, D. 1991. Growing threats to peat. *New Scientist* 1780, 27–32.
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