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Reducing the Carbon Footprint of Canadian Peat Extraction and Restoration

The Canadian horticultural peat industry generates carbon emissions through various methods of peat extraction, processing, and land-use changes. This study provides a carbon emissions analysis comparing the traditional vacuum harvest (VH) and block-cut (BC) extraction techniques to a new acrotelm transplant (AT) method that restores natural peatland function by preserving and replacing the surface layer vegetation as part of the extraction process. The relative global warming potential for each extraction method was determined by estimating carbon dioxide (CO_2) and methane exchange for each phase of peat extraction, including emissions from land-use change and machinery fuel consumption. Preliminary findings, based on 1 y of measurements, indicate that the AT technique has the lowest annual carbon emissions compared to the VH and BC methods. Projected total carbon emissions from a 75-ha peatland after 50 y of extraction using the AT technique produced a sink of approximately 3300 t CO_2 equivalents (CO_2-e). This represents a marked reduction in total carbon emissions estimated for the VH (19 000 t CO_2-e) and BC (29 000 t CO_2-e) extraction techniques. This analysis suggests that the AT method reestablishes peat accumulation and peatland carbon storage function more effectively than the VH and BC methods, which are associated with delayed restoration efforts. Consequently, the AT technique has the potential to greatly reduce the carbon footprint of the Canadian horticultural peat industry.

INTRODUCTION

Natural peatlands represent an important component of the global carbon cycle, storing approximately one-third of the world's total soil carbon and representing a net sink of atmospheric carbon dioxide (CO_2) (1, 2). Traditional peat extraction techniques, such as the block-cut (BC) and vacuum harvest (VH) methods convert these ecosystems to persistent sources of atmospheric CO_2 (3, 4). Cleary et al. (5) estimated that carbon emissions for the different phases of Canadian horticultural peat extraction increased from 0.54 to 0.89 Mt CO_2 equivalents (CO_2-e) between the years 1990 and 2000. The largest source of greenhouse gas (GHG) emissions was *in situ* peat decomposition (71%) followed by peatland land-use conversion (15%), transportation to market (10%), and extraction/processing (4%). Cleary et al. (5) suggest that it would take approximately 2000 y to restore the carbon lost during horticultural peat production, assuming that restoration efforts were successful in returning the peatland to a net carbon sink (6).

Given that peatlands are long-term stores of carbon, it is important to minimize GHG impact during peatland extraction. Reducing carbon emissions at various stages of peat extraction and processing could potentially decrease the overall carbon footprint of the horticultural peat industry. The aim of this research is to analyze carbon emissions generated by traditional VH and BC horticultural peat production methods compared to a recently developed Canadian peat extraction technique in terms of peatland land-use conversion, extraction, and processing. Similar GHG assessments for the utilization of peat as fuel have been carried out in Europe (7–9).

Four phases of peat extraction were analyzed in this study: *i)* natural peatland reserves, *ii)* peatland preparation, *iii)* extraction and processing, and *iv)* restoration/after-treatment. Specific components of the peatland extraction life cycle process were compared without undertaking a full life cycle analysis (LCA) (5). We assumed that carbon emissions from *in situ* decomposition and transport to market (5) would be the same for all methods.

Carbon dioxide and methane (CH_4) emissions generated during each phase of the component analysis were calculated using a combination of field and laboratory measurements, responses to a questionnaire, and literature values. The global warming potential (GWP) of each method of peat extraction was calculated based on the net CO_2 and CH_4 exchange rates generated by the four-phase component analysis.

Natural Peatland Reserves: Emissions and Sinks

To determine the relative GWP impact of different peat extraction methods, it is necessary to evaluate CO_2 and CH_4 exchange rates in natural peatland reserves. Atmospheric CO_2 is taken up by natural peatland vegetation and released primarily by aerobic microbial decomposition, whereas CH_4 emissions are generated by the metabolism of anaerobic methanogenic bacteria and CH_4 oxidation. The balance of these emissions and sinks within natural reserves determines the baseline GHG exchange of peatland ecosystems. The baseline levels are then used to compare with carbon emissions generated from land-use changes by the peat industry due to peatland drainage, extraction, and restoration.

Peatland Preparation: Ditching and Trenching

The first stage of peat land-use conversion involves the initial drainage of the peatland. Backhoes and bulldozers cut drainage ditches to lower the water table in the peatland, thereby supporting the heavy extraction machinery. The resulting, predominantly oxic, conditions enhance CO_2 emissions due to increased aerobic microbial decomposition of organic matter and CH_4 oxidation (10–12). Waddington and Warner (10) demonstrated that microbial respiration in drained peatlands can increase CO_2 emissions by 100% to 400%. Moreover, emissions can remain high up to 2 decades postextraction (13). Drainage ditches are often large sources of CH_4 as a result of their saturated conditions, warm temperatures, and supply of labile carbon (12, 14). Conversely, CH_4 emissions in the adjacent drained peat fields are generally negligible (12).

Production Phase: Peat Extraction and Processing

Currently, the two traditional methods of horticultural peat extraction in Canada are BC and VH. The BC method relies on human labor or machinery to remove blocks of peat from large trenches, usually 200 m long and 10 m wide. The peat blocks are left in piles to dry before they are removed from the peatland (6). The VH technique is the contemporary and more common

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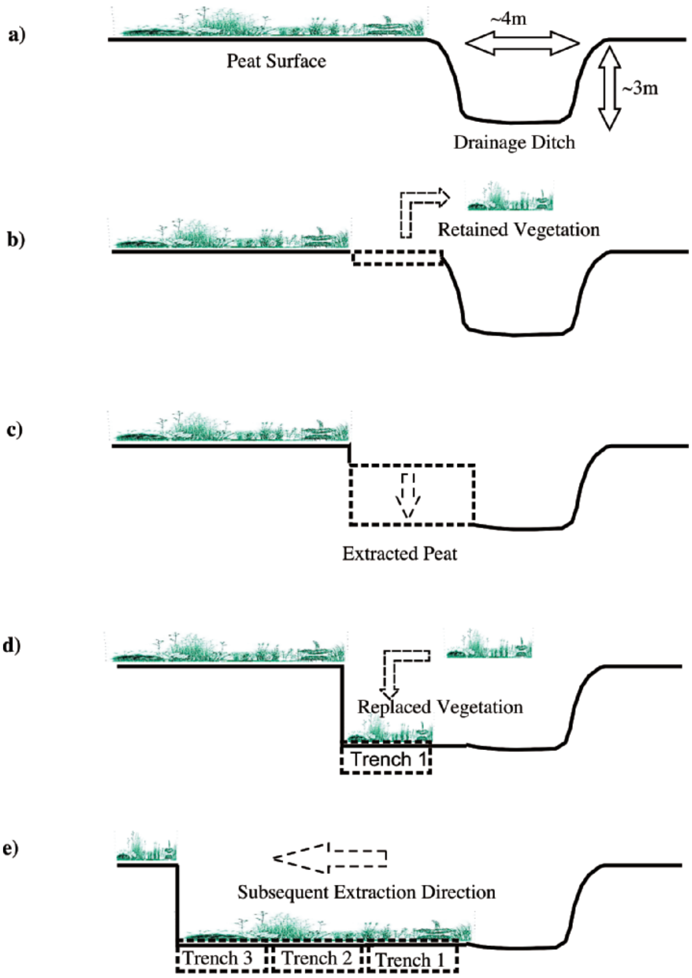

Figure 1. The AT technique. a) A natural peatland prior to extraction adjacent to a large drainage ditch. b) Approximately 20–30 cm of surface vegetation-acrotelm is removed and retained. c) Extracted peat. d) Retained vegetation-acrotelm replaced on cutover surface. e) Extraction-restoration continues parallel and away from the ditch and moves into the peatland as subsequent trenches are created.

method of peat extraction in Canada. Following peatland drainage, the surface vegetation is removed and the upper layers of peat are milled to enhance drying to a moisture content of approximately 45% (wet basis) (5). Large vacuum extraction vehicles then drive over the surface to collect the peat fragments. Once harvested, the peat is left in stockpiles for an average of 5 to 6 mo (average = 5.6 mo [5]) prior to being processed and bagged in the factory. During this period, the peat decomposes, releasing significant amounts of CO_2. Peat decomposition rates in stockpiles depend on temperature, oxygen availability, and moisture conditions. If conditions are favorable, peat stockpiles may emit as much as 3 g CO_2 m^{-2} hr^{-1} (15). Stockpiles of peat are then transported to factories for processing. Machinery and equipment are used to screen, compact, and bag the peat before it is transported to market.

Cutover peatlands are usually exhausted after 20 to 30 y of management once it is no longer economically profitable to continue extraction operations. Exhausted BC peatlands usually do not recover their original ecological function, but naturally revegetate much faster than VH sites (16). Exhausted VH peatlands usually cannot return to functional peatland ecosystems because the viable seed bank has been removed during the extraction process (17). In both cases, Price (18) found that cutover peatlands lose the physical and hydrological conditions that are necessary for carbon sequestration and the regeneration of *Sphagnum* moss, the dominant peat-forming species.

Acrotelm Transplant Extraction Technique

Premier Horticultural Ltd., a Canadian peat horticultural company, has developed a new extraction technique referred to as the acrotelm transplant (AT) approach. This technique incorporates the reapplication of ~30 cm of surface vegetation resembling closely the thickness of the natural acrotelm during the extraction process (see details below and Cagampan and Waddington [19, 20]). Extraction of the peat is performed mechanically with a backhoe by creating extraction trenches parallel to a drainage ditch ~4 m wide and ~3 m deep (Fig. 1a). Initially an approximately 30-cm thick section of the surface vegetation (mosses, shrubs, and surface peat) within an approximately 5 × 5 m plot is removed and placed beside the extraction zone (Fig. 1b). Peat is mechanically removed to the depth of interest (approximately 2 m), which contains the viable peat for horticultural purposes (Fig. 1c). The extracted peat is transported to a nearby processing facility. Once extraction is complete, the surface vegetation that was retained is transplanted over the older and more decomposed peat (catotelm) in the cutover peatland (Fig. 1d). This creates a trench topography in which the surrounding natural peatland is higher than the extraction zone. The process is repeated along a transect, thereby expanding the trench. Subsequent trenches are created parallel to the initial trench, decreasing the overall elevation of the peatland over time (Fig. 1e). The transplanting of the acrotelm onto the cutover peatland within the trench is considered the *restoration*, or rehabilitation, process since the acrotelm structure is retained (19, 20).

Peatland Restoration/After-treatment

In some cases, BC peatlands recover spontaneously over time with the regrowth of natural peatland vegetation and return to a natural net carbon sink (17). However, in most cases, active restoration is required following peat extraction before the carbon sequestration function is recovered. Active restoration methods attempt to rehabilitate peatlands by rewetting (21). Drainage ditches are blocked to raise the water table position and straw mulch is applied on cutover peat to reduce evaporation (18). A combination of these techniques provides the highest soil moisture conditions and encourages the regrowth of local vegetation, including *Sphagnum* moss (13). Waddington and Warner (10) found that rewetting a cutover peatland increased CO_2 storage within 2 y postrestoration due to decreased respiration and increased ecosystem productivity as vegetation reestablished. In addition, the seasonal average ditch respiration at a restored peatland also decreased with time postrestoration. Waddington and Day (12) determined that CH_4 fluxes in the peatland increased with each year postrestoration due to an increase in the water table position and the reemergence of vascular vegetation.

We hypothesize that the AT peat extraction method will produce lower overall carbon emissions than traditional extraction methods. Reduced respiration rates are hypothesized to occur due to wetter conditions and the removal of the high-quality peat in the lower acrotelm and upper catotelm. Given that the surface vegetation in the AT method is retained and replaced immediately after peat extraction, this method may further reduce emissions through carbon uptake.

METHODOLOGY

Global Warming Potentials

In order to assess carbon emissions, the GWP methodology (22) was used to compare the emissions between the different peat extraction methods. The GWP index integrates climatic forcing

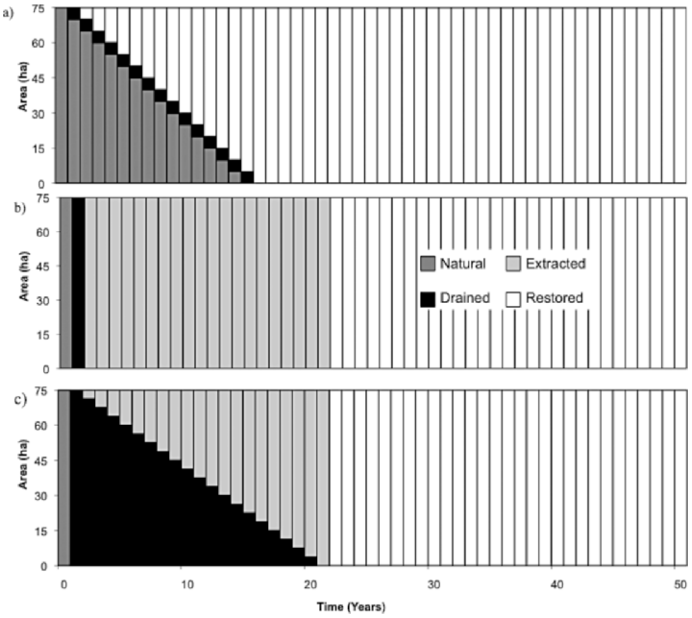

Figure 2. Land-use change for a 75-ha peatland over a 50-y period for a) AT, b) VH, and c) BC techniques.

over a period of time (e.g., 20, 100, or 500 y) of different GHGs and compares it to the relative warming potential of CO_2. In this analysis, carbon emissions are expressed as CO_2-e, with CH_4 having 23 times the GWP over the 100-y time horizon currently used in the GHG accounting under the Kyoto Protocol to the United Nations Framework Convention on Climate Change (22). A positive flux indicates a net warming GWP, whereas a negative flux indicates a net cooling GWP.

However, it must be noted that the GWP methodology has underlying assumptions that may not be appropriate when addressing ecosystem exchanges. While it provides a mechanism for evaluating climate impacts of different gases, it does not assess the impact of sustained or variable GHG emissions on radiative forcing and climate systems at any given time (23). The time-integrated impacts of CO_2 and CH_4 are treated as isolated, instantaneous, single-year flux emissions. However, ecosystem exchanges are continuous, variable, and compounded over time (i.e., they are not steady-state systems). The application of GWP to undisturbed peatlands over short-term time periods (e.g., 20-y time horizons) has shown that they are net sources of GHGs (24). However, Frolking et al. (23) have shown that peatlands, over thousands of years of development, are large net sinks for GHGs. The ratio between the uptake of CO_2 and the release of CH_4 (i.e., the offset potential) varies over the development of a peatland; therefore, this must be taken into consideration when choosing a time period for GHG management strategies.

Study Sites

The AT method was assessed in the Pointe-Lebel peatland in eastern Québec (PLB) (49°07′59″ N, 68°12′26″ W). PLB is an ombrotrophic (nutrient-poor) bog that lies 22 m above sea level. The main drainage ditch was excavated during the 2003–2004 winter period. The VH site (Bois-des-Bel) is located in the Bas-Saint-Laurent region of eastern Québec, ~14 km east of Rivière-du-Loup on the south shore of the St. Lawrence River (42°58′ N, 69°25′ W). Bois-des-Bel is an approximately 200-ha treed bog, of which an 11.5-ha section of the peatland was drained in 1972 and subsequently vacuum extracted from 1973 to 1980. The site was left abandoned until 1999, when it was restored using traditional restoration techniques (described above). The BC-extracted site (Cacouna) is also in the Bas-Saint-Laurent region (47°53′ N, 69°27′ W). This ombrotrophic bog covers an area of 126 ha. Harvesting began in 1942 and was progressively ceased between 1968 and 1972.

Table 1. Summary of annual CO_2, CH_4, and CO_2-e emissions of production reserves (pristine bogs) where negative values denote uptake and positive values denote flux of carbon.

Emissions	Gorham (25)	Roulet et al. (24)	Cagampan and Waddington (20)
	($t\ 75\ ha^{-1}\ y^{-1}$)		
CO_2	−129	−110.6	14.2
CH_4	3.9	3.7	0.5
CO_2-e	−37.6	−25.5	25.9

Extraction Process Data Standardization

Each extraction process utilizes a different land-use change strategy in terms of the area and duration over which the peatland is left in different states (i.e., natural, drained, extracted, and restored). The areas assigned to each peatland phase in a given year were multiplied by CO_2 and CH_4 emissions factors from field measurements and literature values (see below for details). Emissions were standardized by assuming a hypothetical 75-ha peatland (the approximate area to be harvested using AT at PLB) to be extracted over a 50-y period using the VH, BC, and AT techniques (Fig. 2).

Natural Peatland Reserves: Emissions and Sinks

CO_2 and CH_4 emissions rates for natural peatland reserves were taken from the literature and from field measurements from three separate studies: *i)* estimates for northern peatlands (25), *ii)* multiyear average fluxes from the Mer Bleue peatland near Ottawa (24), and *iii)* field measurements from the natural site at PLB during the summer of 2005 (20) (Table 1).

Peatland Preparation: Peatland Ditching/Trenching

Emissions from trenching machinery for the AT method were estimated by calculating the typical fuel consumption of the machinery during trench construction. Trenching machinery emissions were determined by multiplying fuel consumption by a GHG emissions factor. Fuel consumption was determined using data (machinery distance traveled and average speed) obtained from a questionnaire sent to Premier Horticultural Ltd. in March 2006. The GHG emissions factor was 2.73 t ML^{-1} CO_2 and 0.10 kg ML^{-1} CH_4 according to the official Intergovernmental Panel on Climate Change (22) values for diesel combustion. Ditching machinery emissions for VH and BC techniques were similarly calculated. Fuel consumption rate and machinery speed for VH and BC ditch construction machinery was assumed to be the same as the AT technique. Distance traveled for ditch construction was based on the VH site at Bois-des-Bel and the BC site at Cacouna.

Daily carbon emissions from the drainage ditches were calculated by multiplying CO_2 and CH_4 fluxes by the drainage ditch area and accounting for the differences in GWP between the gases. Annual ditch emissions were calculated by multiplying the daily ditch emissions by 164.25 d as flux measurements take place during approximately 45% of the year (26). In addition, values were multiplied by 1.155 to account for a 15.5% average winter flux observed by Mast et al. (27).

Ditch emissions were measured by Greenwood (28) at Bois-des Bel using the static chamber technique described in Waddington et al. (4). These emissions values were assumed to be the same for BC ditches. Trench emissions from the AT method were obtained using the static chamber technique at the PLB site by Cagampan and Waddington (20). Drainage ditch areas for the VH and BC methods were obtained from Bois-des-Bel (28) and Cacouna (16), respectively, and were subsequently standardized for a 75-ha peatland.

Drained peatland emissions were measured using the static chamber technique at the PLB site by Luchesse (29) and were assumed to be the same for VH and BC peatlands. Emissions were multiplied by the area of peatland drained in each method and were standardized to a 75-ha peatland.

Production Phase: Peat Extraction and Processing

Annual emissions for the AT method peat extraction machinery (digger) and vehicles (field train and truck transport to the building) were based on the fuel consumption data collected from the questionnaire sent to Premier Horticultural Ltd. and from GHG emissions factors for diesel fuel. Extraction emissions for the VH and BC extraction machinery were estimated by multiplying the area of peatland extracted per year by the tonnes of peat per hectare and the tonnes of CO_2-e emitted per tonne of peat extracted. Fuel consumption data for VH and BC peat extraction machinery were obtained from Cleary (26).

Peat stockpile characteristics (moisture content and stockpile time) were collected from the Premier Horticultural Ltd. questionnaire. Stockpile emissions were estimated from a laboratory experiment in which peat samples from the depth of peat extraction (~23 cm) were collected from PLB and incubated at anticipated stockpile temperatures (4, 9, and 20°C) and volumetric water contents (94, 81, 63, and 52%). Carbon dioxide flux values obtained from Cleary (26) were used to estimate annual stockpiling emissions for the VH and BC methods.

The AT method is unique in that the extracted peat is dried within a factory by machinery powered by hydroelectricity, using 35 kW m^{-3} of horticultural bagged peat. The Canadian GHG inventory for Québec was used to indicate that no GHG emissions are associated with hydroelectricity (30); therefore, no additional emissions were assigned to the peat-drying machinery.

Peatland Restoration/After-treatment

Peatland restoration emissions were assumed to decrease linearly through time for each year postharvest. A 5-y restoration period best-case scenario was assumed. Initial restored peat emissions for the AT technique were sampled using the static chamber technique by Cagampan and Waddington (20) from the experimental restored site at PLB. Similarly, initial restored emissions for the VH method were obtained from Cagampan and Waddington (20). Emissions from a BC peatland under restoration for <2 y and 2 to 4 y were obtained from Cleary (26). Restored peatland emissions for all methods were assumed to reach –267 g CO_2 m^{-2} season^{-1} (28) and 5.3 g CH_4 m^{-2} season^{-1} (1) at year 5 of the restoration period and remain constant for the remaining study period.

RESULTS

Natural Peatland Reserves: Emissions and Sinks

The PLB natural site was a net source of carbon, emitting 25.9 t CO_2-e 75 ha^{-1} y^{-1} to the atmosphere (20). In contrast, Roulet et al. (24) and Gorham (1) reported natural peatlands as net sinks of carbon (Table 1). Therefore, in the absence harvesting disturbances, we used a natural peatland variability ranging from –37.6 to 25.5 t CO_2-e 75 ha^{-1} y^{-1}.

Table 2. Summary of annual carbon emissions and peat yields of BC, VH, and AT extraction methods.

	BC	**VH**	**AT**
Emissions	**(t CO_2-e 75 ha^{-1} y^{-1})**		
Trench construction			
CO_2	4.4E-02	2.2E-02	6.5E-04
CH_4	1.6E-06	7.9E-02	5.5E-07
Total	**4.4E-02**	**2.2E-02**	**6.7E-04**
Ditch emissions			
CO_2	93	36	3
CH_4	33	13	1
Total	**854**	**337**	**26**
Extracted peatland emissions			
CO_2	765	185	—
CH_4	31	−0.2	—
Total	**796**	**185**	**0**
Stockpile			
CO_2	—	—	—
CH_4	—	—	—
Total	**10**	**196**	**15**
Processing			
CO_2	—	—	—
CH_4	—	—	—
Total	**11**	**225**	**2.2E-01**
Annual peat yield	**1750 t ha^{-1}** (Cleary et al. [5])	**100 t ha^{-1}** (Cleary et al. [5])	**3.6×10^6 ft^3 y^{-1}** (Questionnaire)

Peatland Preparation: Peatland Ditching/Trenching

Total emissions from the ditching/trenching machinery were 4.4 × 10^{-2} and 2.0 × 10^{-2} t CO_2-e for the BC and VH methods respectively. The AT method (6.6 × 10^{-4} t CO_2-e) produced only 1.5% of the total emissions of the BC and 3.3% of VH ditching machinery due to the minimal distance traveled during trenching construction. Trench emissions were a net source of carbon to the atmosphere for all techniques, with BC having the highest emissions (18 000 t CO_2-e) due to the extensive ditching involved in this method. The AT technique had the lowest trench emissions, ~37% less than the BC method. Emissions from drained peat were 1 t CO_2-e ha^{-1} y^{-1}. Total drainage emissions were the highest for BC peatlands (722 t CO_2-e) after the projected 50-y study period.

Production Phase: Peat Extraction and Processing

Total emissions from land-use change of the extracted peatland were assumed to be 0 t CO_2-e for the AT technique (Table 2). Because the acrotelm is transplanted immediately after extraction, the peatland is never left in an extracted state. As a result, there are no associated extraction emissions for this method. The BC technique had the highest peatland extraction emissions (8300 t CO_2-e) followed by the VH method (3700 t CO_2-e). The VH method had the highest peat extraction/processing machinery emissions (4500 t CO_2-e) mainly due to the extensive use of tractors and vacuuming equipment during peat extraction. The BC and AT techniques had considerably less extraction/processing machine emissions, 225 and 3 t CO_2-e, respectively, since these are less machinery–intensive techniques. The AT method is considerably less due to the use of hydroelectricity to dry and process the peat.

Calculated annual stockpiling emissions for the AT technique (15 t CO_2 y^{-1}) were 8% of the BC and 5% of the VH method stockpiling emissions. The VH technique produces the

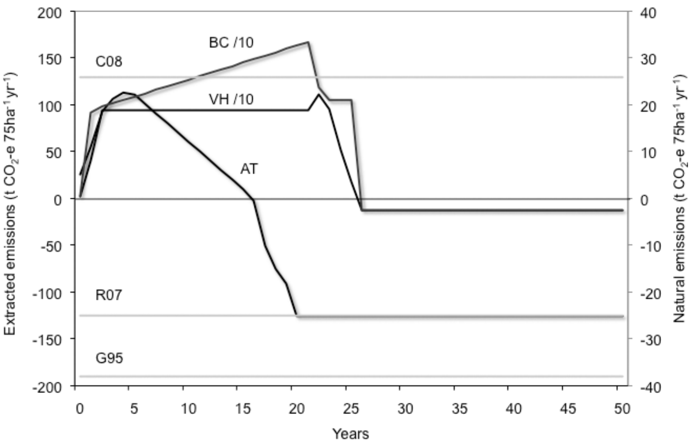

Figure 3. Annual emissions for the AT, VH, and BC methods for harvesting a 75-ha peatland over 50 y, assuming a 5-y restoration period.

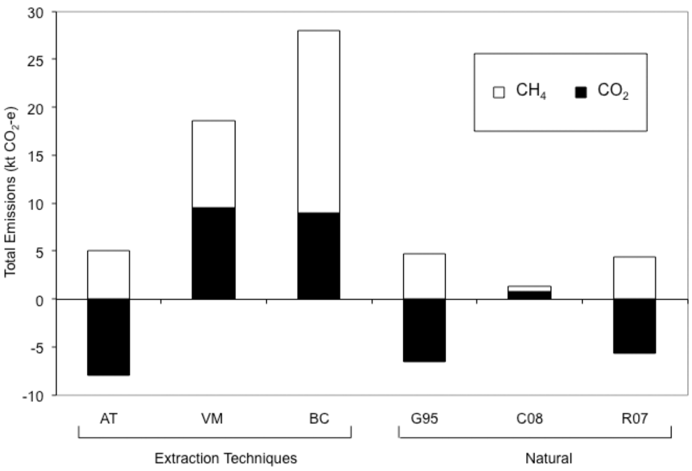

Figure 4. Total weighted CO_2 and CH_4 emissions for the AT, VH, and BC methods and natural (N) peatland values. Emissions represent a 75-ha peatland over a 50-y period of extraction.

largest volume of peat stockpiles, which results in the highest total peat stockpiling emissions (3900 t CO_2-e) of all three techniques.

Peatland Restoration/After-treatment

Assuming a best-case scenario of a 5-y period to restoration, total restored emissions after the 50 y were greatest for the BC (1200 t CO_2-e) method, followed by the VH (–400 t CO_2-e) and AT (–4000 t CO_2-e) techniques.

Total Extraction GHG Emissions

Harvesting a 75-ha peatland over a 50-y study period using the AT technique results in the lowest annual GHG emissions, followed by the VH method and BC method (Fig. 3). After the projected 50-y study period, the VH- (19 000 t CO_2-e) and BC- (29 000 t CO_2-e) extracted peatlands are net sources of carbon to the atmosphere, whereas the AT-extracted peatland (–3300 t CO_2-e) is a net sink. CH_4 contributes a large portion of the total emissions associated with each harvesting process (Fig. 4). In many cases, VH and BC peatlands are not restored following extraction as the restoration is not built into the extraction process. If VH- and BC-extracted peatlands are abandoned postextraction, emissions would continue to rise, reaching 44 000 and 52 000 t CO_2-e, respectively, at the end of 50 y (Fig. 5).

The largest portion of production emissions is generated by the drainage ditches in all methods, BC (65%), AT (62%), and VH (37%) (Fig. 6). The next-largest source of emissions is generated during peatland land-use change from the BC and VH methods. Approximately 30% of the BC production emissions are associated with land-use change compared to 16% generated during the VH method. In contrast, land-use changes by the AT method are negligible. Stockpiling emissions were greatest for the VH method (~3900 t CO_2-e), more than 16 times the stockpiling emissions associated with the AT technique. In all cases, the AT process generated the lowest emissions during each step of peat processing and resulted in an overall net carbon sink after the 50-y study period.

DISCUSSION

Drainage ditches were the largest source of emissions as the often saturated and anoxic conditions in the ditches enhance methanogenic activity, thereby increasing CH_4 production. The BC method involves extensive ditch construction, which results in the highest CH_4 emissions of all investigated extraction methods and consequently the greatest GWP. In contrast, the AT technique involves the construction of a single ditch around the perimeter of the peatland, which contributes to a much lower GWP.

Another major contribution of GHG emissions is CO_2 generated by stockpiling peat. This is particularly evident in the

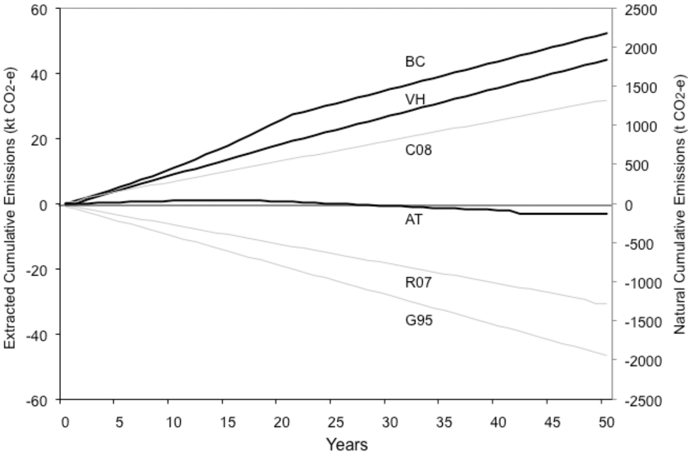

Figure 5. Cumulative emissions for the AT, VH, and BC methods for harvesting a 75-ha peatland over 50 y, assuming a 5-y restoration period.

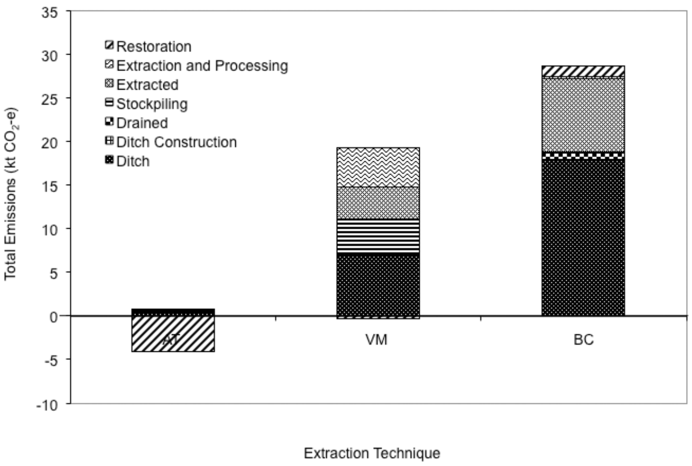

Figure 6. Summary of emissions for each stage of peat extraction and processing for the AT, VH, and BC methods.

VH method, in which large volumes of peat are stockpiled and are left to dry for several months at a time (26). In contrast, the AT technique stockpiles only a small volume of peat for only a few days between each step of drying in the factory. The power used for the drying machinery is hydroelectric, which is the major source of energy in the province of Québec. This is a major advantage since, according to the Canadian Inventory of Greenhouse Gases, carbon emissions from hydroelectric power in Québec is zero (30). It is important to note that if this technique were applied in Alberta or New Brunswick (the two other main peat extraction provinces in Canada), where fossil fuels are used to generate electricity, emissions from this phase of the AT technique would be greater. For example, there would be an extra 1.0 t CO_2-e y^{-1} if the technique were to be applied to Alberta and 0.5 t CO_2-e y^{-1} if applied in New Brunswick, where fossil fuels are used as an energy source.

Another large source of GHG emissions in this extraction component analysis resulted from harvesting machinery powered by fossil fuels, including diesel and natural gas. This was particularly evident in the VH method, which employs large harvesting machinery. In contrast, emissions from extraction machinery used in the AT technique did not contribute greatly to overall GHGs due to the less intensive nature of the mechanical process.

Uncertainty

This study lacks long-term CO_2 and CH_4 flux data from peatlands undergoing harvesting and restoration. It was necessary, therefore, to estimate these values. Estimates were based on a combination of field measurements and average literature values for each of the harvesting methods. The measured and reported literature data were used to complete the extraction component analysis for each extraction method. To address the sensitivity of the greenhouse impact of each phase, an uncertainty value was associated with each reported carbon emission (see Appendix). The greatest uncertainty was associated with emissions from extracted and restored peatlands (>100%) due to the limited number and wide range of reported flux values from these land uses. In general, the total uncertainty in the estimates of total GWP for each extraction technique is +/−100%.

Another limitation of this component analysis was that only 1 y of postrestoration field measurements were available for the AT technique. To evaluate the relative success of vegetation transplantation and its productivity over time, additional CO_2 and CH_4 measurements on an annual basis for several years postextraction would be necessary. If the vegetation regenerates successfully, it would confirm that the AT technique is more efficient at restoration than current harvesting and restoration methods. Further carbon cycling studies of natural, extracted, and restored peatlands are required in a wider variety of geographical regions to predict peatland emissions in various climatic conditions. Saarnio et al. (32) suggest that naturally high spatial and interannual variation in CO_2 fluxes can create a wide range of background values (from undisturbed peatlands) used in the LCA of peatlands, with potential implications in terms of management decisions. They also suggest that current gas fluxes for natural or drained peatlands cannot be reliably projected into the future and suggest that more long-term, *in situ* field measurements and dynamic CO_2 flux models, based on atmospheric scenarios, could improve life cycle calculations on peatlands.

CONCLUSIONS

The results of this extraction component analysis indicate that the AT technique has the lowest annual carbon emissions and lowest GWP of all three methods. The AT technique reduces land-use impact by incorporating restoration at the time of harvesting (19, 20). This eliminates the time during which the cutover peatland is unrestored, thus eliminating the associated extraction emissions. In contrast, the BC and VH methods extract the entire peatland before restoration can begin, resulting in high carbon emissions during the extraction phase. Moreover, drainage and extraction by the BC and VH methods removes the top layer of vegetation, which is critical for carbon uptake (10). Replacement of vegetation as part of extraction in the AT technique restores the carbon fixation function more readily. Assuming that this vegetation regenerates relatively quickly, it may potentially convert peatlands harvested by the AT technique to a net CO_2 sink sooner than the other two methods. Collectively, considering harvesting, stockpiling, processing machinery and preliminary findings of land-use change, the AT technique is a major improvement over the other extraction techniques from a global warming perspective. Moreover, the AT approach may provide a financial incentive to reduce the impact of peat harvesting on GHG emissions as carbon emissions exchange (i.e., trading of permits to emit CO_2 and other GHGs, calculated in t CO_2-e) allows countries to meet their obligations under the Kyoto Protocol. Consequently, the reduced GHG emissions of this new peat extraction technique enhances the capacity to achieve the goals of the Kyoto Protocol in Canada and in peat-extracting countries around the world.

References and Notes

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Appendix: Uncertainty Analysis

	Value Utilized ($g\ m^{-2}\ y^{-1}$)	Range ($g\ m^{-2}\ y^{-1}$)	Source
Natural peatlands			
CO_2	−172, −147,18	−172 to 18	20, 25, 25
CH_4	5.3, 4.9, 0.7	0.7 to 5.3	
Peatland preparation			
Ditch emissions			
CO_2	1556	266 to 2846	28
CH_4	569	0 to 1138	20
Production phase			
Drained peatland			
CO_2	436	133 to 816	29
CH_4	0	—	—
Extracted emissions			
AT *			
CO_2	—	—	—
CH_4	—	—	—
VH			
CO_2	247	†	—
CH_4	−0.01	−0.27 to 0.02	12
BC			
CO_2	1020	917 to 1060	6, 7, 26
CH_4	1.8	1.8 to 9.3	6, 7, 26
Peatland restoration			
Initial restoration <2 y			
AT			
CO_2	285	171 to 740	20
CH_4	9	0.3 to 29	20
BC			
CO_2	1312	1100 to 1833	26
CH_4	2.4	0.4 to 3.6	26
VH			
CO_2	1 429	1240 to 2172	28
CH_4	2.3	0.9 to 5.3	12, 31
Restoration $>$ 5 y			
CO_2	−267	−470 to −73	28, 31
CH_4	5.3	0 to 10.6	1, 31

* No values given since this assumes immediate restoration with no emissions.
† Assumes 100% error to the value utilized.

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