

CARBON DIOXIDE AND METHANE PRODUCTION POTENTIALS OF PEATS FROM NATURAL, HARVESTED AND RESTORED SITES, EASTERN QUÉBEC, CANADA

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Abstract: Drainage, vegetation removal and harvesting, and vegetation restoration have a profound effect on carbon cycling in peatlands. Through laboratory incubations of 114 peat samples collected from the surface layer and just above and just below the water table at 13 sites, we examined the potential for carbon dioxide (CO₂) production under aerobic and anaerobic conditions and methane (CH₄) production under anaerobic conditions. CO₂ production rates ranged from 0.04 to 1.05 mg g⁻¹ d⁻¹ under aerobic conditions and 0.01 to 0.29 mg g⁻¹ d⁻¹ under anaerobic conditions. Rates of CO₂ production were generally smallest in the lower parts of the profiles and at the recently restored sites where deep peat was exposed at the surface; they were largest in the freshly-formed surface peat at the undisturbed bog and older restoration sites where a strong cover of vegetation had developed. The CO₂ production potentials were negatively correlated with the Von Post Index of decomposition, and aerobic:anaerobic production ratios averaged 4.3:1. Largest rates of anaerobic CH₄ production occurred in samples close to the soil surface with fresh peat accumulation and a high water table, and smallest rates were in samples from the subsurface of sites with a low water table. Anaerobic CH₄ production was significantly positively correlated with aerobic and anaerobic CO₂ production. These production potentials show that drainage, harvesting, and restoration change the ability of the peat profile to produce and emit CO₂ and CH₄.

Key Words: carbon dioxide, decomposition, incubation, methane, peatland, restoration

INTRODUCTION

In Canada, 150 km² of peatland have been affected by drainage, vegetation removal, and harvesting of peat moss (Cleary 2003). Peat moss extraction amounted to 1.3 million tonnes in 2000 (Jasinski 1999). Early peat extraction techniques involved block cutting, which produced a distinctive topography of ridges and trenches (Robert et al. 1999), but most of the current production arises from vacuum harvesting, which leaves large areas of peat devoid of vegetation. Natural restoration of vegetation (Robert et al. 1999) is slow, and techniques have been developed to speed restoration through blocking of the drainage ditches, adding plant material containing *Sphagnum* diaspores that was removed from another site where harvesting was beginning, and by adding straw mulch (Ferland and Rochefort 1997). As a result of these changes in land use, there have been changes in carbon (C) cy-

cling, particularly the exchange of carbon dioxide (CO₂) and methane (CH₄) with the atmosphere (e.g., Tuittila et al. 1999, 2000, Sundh et al. 2000, Waddington et al. 2001, Waddington and Warner 2001, Waddington et al. 2002).

Harvesting exposes deep peat at the surface, and successful restoration involves the deposition of plant material containing *Sphagnum* diaspores onto an old surface. The exchange of CO₂ and CH₄ between the peatland surface and the atmosphere depends on the rates of production, consumption, and transport of these gases within the peat profile. This, in turn, is dependent on water-table position, which influences the development of aerobic and anaerobic conditions, and temperature, which affects microbial activities and the potential of the peat substrate to produce or consume these gases. At one natural bog and two cut-over peatlands near Lac Saint-Jean, Québec, Waddington et al. (2001) determined the CO₂ production potentials of

samples from three profiles under aerobic and anaerobic conditions and the influence of temperature and moisture content on these potentials. Croft et al. (2001) showed that peat mining decreased total bacteria and microbial biomass, but they increased under restored conditions. Knowledge of CO₂ and CH₄ production potentials of peat at a wide range of natural, harvested, and restored sites is lacking.

Our objective in this study was to determine the variation in production potentials of CO₂ and CH₄ of peat collected from a natural bog, a vacuum-harvested site, proactively restored vacuum-harvested sites, a site that was harvested and abandoned, and naturally revegetated block-cut sites. At each site, we collected samples from the surface layer (0–10 cm) and from the 10 cm segments above and below the water-table position. We incubated samples in the laboratory under aerobic and anaerobic conditions to determine CO₂ production and under anaerobic conditions to determine CH₄ production.

MATERIALS AND METHODS

Study Sites

Thirteen sites were located in peatlands near Rivière-du-Loup, Québec, Canada, one of the largest peat-harvesting regions in Québec. Robert et al. (1999) have portrayed the region, peat extraction methods used, and the resulting post-harvest landscapes.

Two sites (*Bog hummock* and *Bog hollow*) were located in a small peatland surrounded by harvested peatlands. There was a dense cover of shrubs (e.g., *Chamaedaphne calyculata* (L.) Moench and *Ledum groenlandicum* Oeder.) and *Sphagnum* mosses (e.g., *Sphagnum angustifolium* Warnst. and *Sphagnum rusowii* Warnst.) and a shallow accumulation of peat. Although 200 m from the drained peatland, it is suspected that the profile had become drier from the lowering of the adjacent water table. Two sites were actively vacuum-harvested (*Harvested middle*, *Harvested edge*) and devoid of vegetation. Three sites were restored from vacuum-harvested sites by raising the water table and applying plant material containing *Sphagnum* diaspores and mulch four years (*Restored'95 bare*, *Restored'95 vegetated*) and two years (*Restored'97 bare*) prior to peat sampling; these sites did not have an accumulation of fresh peat and were sparsely vegetated with cotton-grass (*Eriophorum vaginatum* L. var. *Spissum* Fern.) and shrubs and mosses. Two sites were harvested with block-cutting techniques and then abandoned ~30 years prior to sampling (*Abandoned upper* and *Abandoned lower*), the former with a sparse cover of birch trees (*Betula cordifolia* Regel) and ericaceous shrubs and the latter with

widely-spaced, large patches of cotton-grass (*Eriophorum angustifolium* Honckeney). Three sites were located in an area that was harvested with block-cutting techniques ~30 years prior to sampling, after which the drains were blocked and became naturally vegetated. The ridge (*Block-cut ridge*) had a cover of small trees, shrubs, and lichen, but no mosses, and the trench contained the *Block-cut centre* and *Block-cut trench* sites with a dense cover of mosses, sedges, and shrubs (described in Robert et al. 1999) and a 32- to 35-cm thick recent accumulation of *Sphagnum*-dominated peat. At one site (*Block-cut flooded*), the water table was raised close to the ridge surface, resulting in a dense, floating mat of mosses (e.g., *Sphagnum fallax* H. Klinggr.) and shrubs (e.g., *C. calyculata*).

Peat Sample Collection and Preparation

In September 1999, triplicate cores from each site were collected down to either 1 m or at least 10 cm below the water table. At the *Restored'97 bare* and *Bog hollow* sites, mineral substrate was found at < 1 m. Surface vegetation was removed when present, and samples were divided into 10 cm depth segments, except to ensure that peat immediately from above and below the water table were sampled separately. We stored the sample in two heavy-gauge, self-sealing plastic bags that were transported on ice in tightly sealed plastic coolers in order to minimize oxygen exposure for the samples collected from beneath the water table. Samples chosen for laboratory incubations were from the top 10 cm or just below living vegetation and from the 10 cm immediately above and below the water. In sites where the water table was at or near the surface, we incubated peat from the top three 10-cm depth segments. Roots were removed, and samples were homogenized by hand.

Laboratory Analyses. We assessed the degree of decomposition using the von Post measure (AG Boden 1994), where a value of 1 indicates no decomposition and a value of 10 indicates complete humification (i.e., no plant structures present and paste-like texture).

Aerobic and anaerobic incubations for determining production and oxidation potentials were conducted similarly to Moore and Dalva (1993, 1997). Approximately 3 g (wet weight) of peat and 20 mL distilled H₂O were placed in 50 mL Erlenmeyer flasks sealed with silicon-filled rubber Suba seals (William Freeman Ltd, Barnsley, UK). Aerobic incubations used room air in the flask headspace. Aerobic flasks were shaken on a rotary shaker to ensure that no anaerobic micro-sites developed. The headspace of the aerobic incubations was sampled daily with 1 mL syringes, and 1 mL of room air was added to maintain pressure. Sampling of

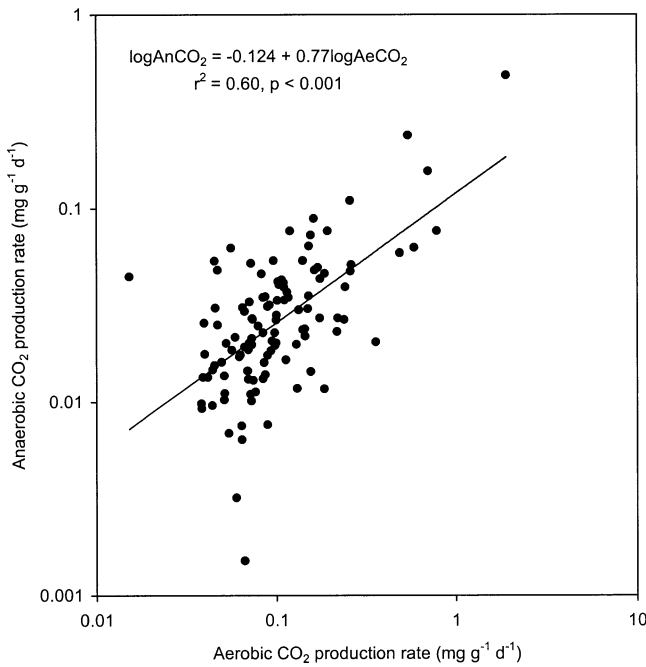


Figure 2. Relationship between aerobic and anaerobic CO₂ production among the samples.

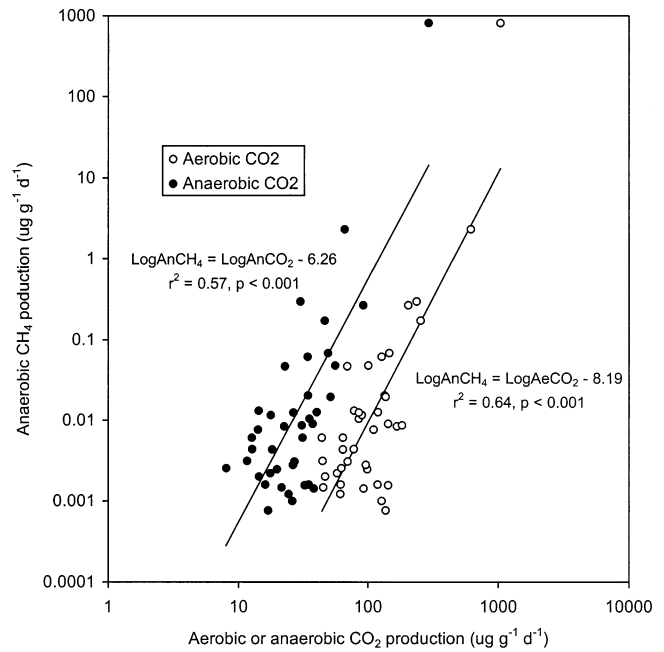


Figure 4. Relationship between anaerobic CH₄ production rate and aerobic and anaerobic CO₂ production rates among the samples.

0.00 to 816 $\mu\text{g g}^{-1} \text{d}^{-1}$, with a mean of $21\mu\text{g g}^{-1} \text{d}^{-1}$ (Figure 3). The smallest rates of production were found in the subsurface layers of the *Bog*, *Harvested*, *Abandoned* and *Restored* sites, and the largest rates were found in the surface layers of the *Bog* and *Inundated* sites and particularly in the trench at the *Block-cut* site, where the water table was very close to the peat surface during the year. Across sites, there was no consistent pattern of higher CH₄ production in

peat from beneath the water table relative to peat from above the water table. There was a strong correlation between anaerobic CH₄ production and aerobic and anaerobic CO₂ production ($r^2 = 0.63$ and 0.58 , respectively, when log-transformed, Figure 4). The Von Post Index of degree of decomposition showed a significant negative relationship with aerobic and anaerobic CO₂ production and anaerobic CH₄ production (Figure 5).

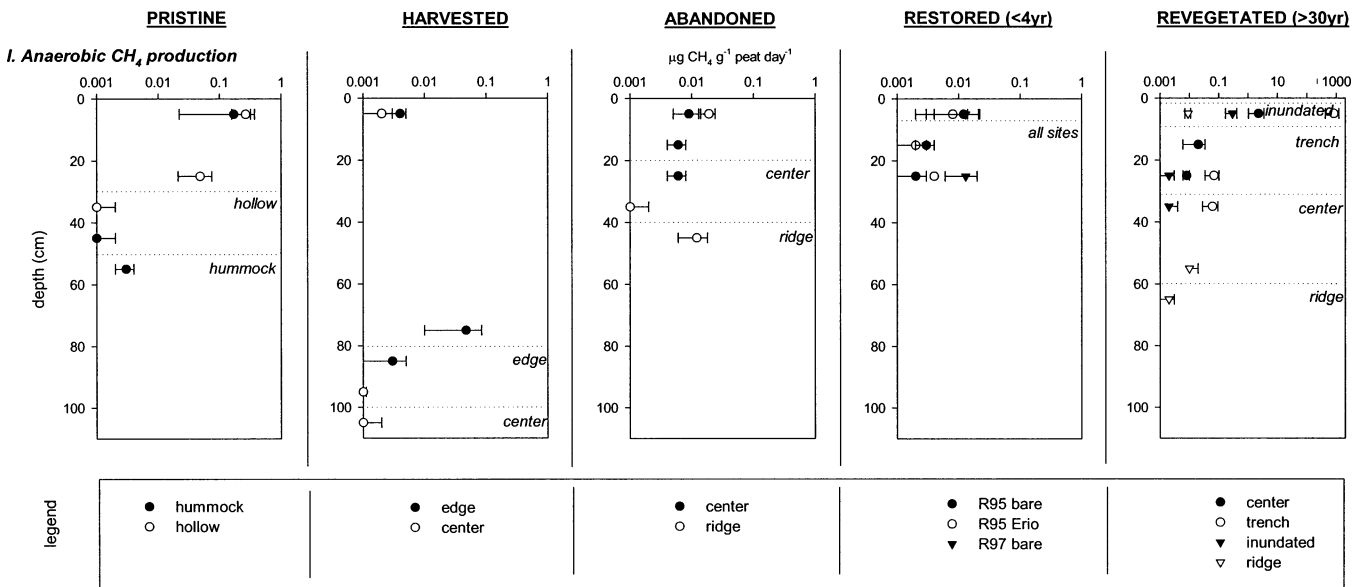


Figure 3. Anaerobic CH₄ production rates the peat samples by site. Horizontal bars represent the standard error of the triplicate samples collected from each depth at each site. The horizontal lines represent the position of the water table at sampling.

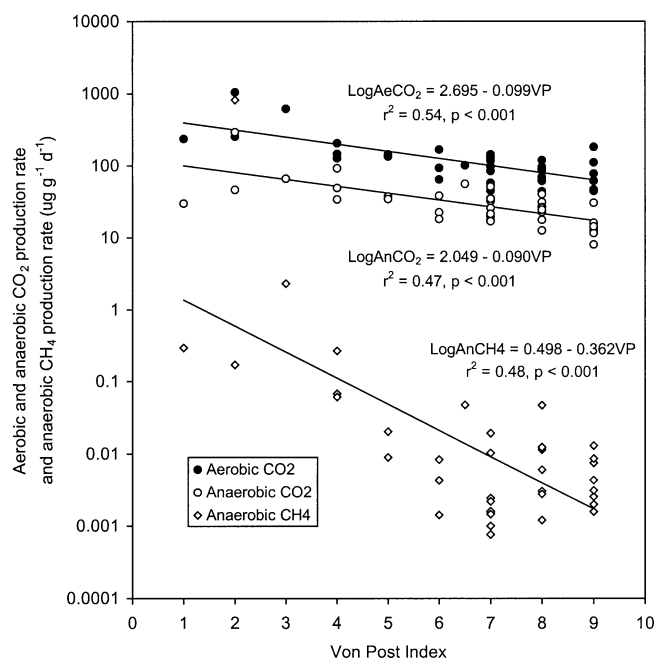


Figure 5. Relationship between aerobic and anaerobic CO₂ and anaerobic CH₄ production rates and Von Post Index of decomposition.

DISCUSSION

Samples used in this work were disturbed before and during incubation and incubated over a short period at a higher temperature than the soils in the field. Therefore, results represent only potential rates of gas production rather than values that can be compared to field fluxes, although Moore and Dalva (1997) suggested that integrated potential rates and fluxes may be similar. The aerobic and anaerobic CO₂ production rates that we found are similar to those reported by others for similar peaty materials (e.g., Hogg *et al.* 1992, Glenn *et al.* 1993, Updegraff *et al.* 1995, Moore and Dalva 1997, Yavitt *et al.* 1997, Bergman *et al.* 1999, van de Pol-van Dasselaar and Oenema 1999, Scanlon and Moore 2000) and from other natural and cutover peatlands in Québec (Waddington *et al.* 2001).

The aerobic-to-anaerobic C quotients are also within the range reported previously (e.g., Bridgman and Richardson 1992, Glenn *et al.* 1993, Moore and Dalva 1993, Updegraff *et al.* 1995, Moore and Dalva 1997, Bridgman *et al.* 1998, van de Pol-van Dasselaar and Oenema 1999, Scanlon and Moore 2000, Waddington *et al.* 2001), but it is important to note that anaerobic and aerobic rates were calculated at different times over the incubation period due to earlier rapid rates in the aerobic samples. The strong correlation between aerobic and anaerobic CO₂ production rates suggests the importance of peat composition.

Our data suggest that the degree of humification

may be an important control of aerobic and anaerobic CO₂ and CH₄ production, being strongly correlated with the Von Post humification index. Contrary to our findings from bog peat, Moore and Dalva (1997) were not able to relate aerobic CO₂ production to the degree of decomposition of 140 peat samples from northern Canada, but this might have been due to their diverse botanical origin.

It is likely that the microbial biomass and the composition of the microbial community differ among natural, harvested, and restored sites. Croft *et al.* (2001) found lower populations of hemicellulolytic microorganisms, cellulolytic microorganisms, fungi, and bacteria in harvested peatlands compared to natural peatlands. Bacterial populations decreased in the order: natural, restored, and harvested. The studies of Croft *et al.* (2001) corroborate earlier findings by Dooley and Dickinson (1970), who detected no increase in microflora species in peatlands that had been harvested and abandoned for ten years. This suggests that harvesting may reduce C substrate and nutrient availability for heterotrophic microorganisms and creates a harsher physical environment, which in turn decreases total biomass and induces an apparent functional shift in the communities. Abandonment does not restore microbial communities, although active restoration including re-colonization of a post-harvest surface with *Sphagnum* mosses can restore the bacterial community to conditions similar to those before disturbance. Although we did not characterize microbial biomass or the microbial communities in our sites, we observed a similar pattern in decomposer activity whereby harvesting led to decreased aerobic and anaerobic CO₂ production rates, presumably due to decreased microbial biomass resulting from changes in substrate and nutrient availability and a harsher physical environment. Restoration brought back rapid rates of decomposition, and in the case of the surface of the *Block-cut trench* and *center* sites, rates were higher than in pristine sites, indicating that newly formed peat was more bio-available or less stable than pristine peat.

Most of our anaerobic CH₄ production rates were within the range reported by others (e.g., Moore and Dalva 1993, Yavitt *et al.* 1997, Bergman *et al.* 1999). The very large production rate of 819 $\mu\text{g g}^{-1} \text{d}^{-1}$ in the *Block-cut trench* is more than an order of magnitude higher than all studies we are aware of, except that by van de Pol-van Dasselaar and Oenema (1999), who detected CH₄ production rates of up to 1200 $\mu\text{g g}^{-1} \text{d}^{-1}$ for fen peat particle size separates >2 mm, but not from whole peat.

Rapid methanogenesis in peat requires prolonged anaerobic conditions and an adequate supply of primarily microbial derived redox and carbon substrates that has been indirectly linked to peat carbon substrate

quality (e.g., Yavitt et al. 1997). Interestingly, the *Block-cut flooded* site, which had the highest water table, had a much smaller CH₄ production potential than the *Block-cut trench* site. The extraordinarily high CH₄ production rate of 819 μg g⁻¹ d⁻¹ could be due to good substrate availability, as Glatzel et al. (2003) detected DOC concentrations of up to 625 mg L⁻¹ and a low humification index of DOC at this very site in October 2000. Apart from these two locations with the high water table, the water table at the other sites was rather low; therefore, it is unlikely that a large population of methanogens could survive close to the surface. However, the fact that potential CH₄ production in the deep horizons was not larger than those closer to the surface suggests that the peat properties discussed above are more important than the presence or absence of methanogens, which must have been able to survive in the aerobic peat layer, possibly in anaerobic microsites. We incubated peat for one month under anaerobic conditions at 20° C and, in many samples, observed fastest rates of methane production after three weeks, which may have indicated that peat properties and not *insitu* moisture conditions influenced relative rates of production. However, very rapid rates of CH₄ production were found in newly formed peat taken from the flooded, or at least very wet, restored sites in contrast to newly formed peat from the drier and presumably more aerobic pristine site that produced much less CH₄. It is likely that our potential CH₄ production rates were controlled by both substrate availability and *insitu* moisture conditions, with rapid production occurring in peat from sites that were both at least partially flooded and had newly formed peat that was, based on aerobic and anaerobic CO₂ production, very biologically labile. Although we attempted to minimize sample exposure to air, it is possible that lags before rapid rates of CH₄ production were in part caused by oxygen damage to the methanogenic populations sustained during sampling and sample transport to the laboratory.

These CO₂ and CH₄ production rates have implications for gas exchange and carbon balance in harvested and restored peatlands. Harvested and abandoned sites have a slower CO₂ production potential, so emission rates to the atmosphere are small. The successful establishment of plant species and the creation of fresh peat through restoration increase the production rate of CO₂ under both aerobic and anaerobic conditions. Thus, although the plant cover takes up atmospheric CO₂ by photosynthesis, the high decomposability of the new peat material means that overall C sequestration is slow, which has been noted in field studies of CO₂ exchange (Petrone et al. 2001). Similarly, the anaerobic CH₄ production potential of the drained and harvested site peat is small, but raising of the water

table and the incorporation of plant material containing *Sphagnum* diaspores after restoration creates large production potentials, leading to substantial CH₄ emission rates (unpublished data). Thus, the peatland restoration process, through the changes in substrate and microbiological activities, increases the emission rates of CO₂ and CH₄ from the peat to the atmosphere, compared to harvested or abandoned sites. These results extend a pattern of CO₂ production noted by Waddington et al. (2001) at one natural and two cutover peatland sites.

ACKNOWLEDGMENTS

We thank M. Dalva for laboratory assistance and the peat producer Premier Horticulture for their logistic support at the sites. We gratefully acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada, the Canadian Sphagnum Peat Moss Association and the Deutsche Forschungsgemeinschaft.

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Manuscript received 8 September 2003; revisions received 5 January 2004; accepted 18 February 2004.