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Organic matter accumulation in a restored peatland: Evaluating restoration success

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ABSTRACT

Recent advances in peatland restoration techniques have succeeded in establishing *Sphagnum* moss on the remnant cutover peat surface following peat extraction; however, evaluating restoration success remains a key issue. We argue that a *Sphagnum*-dominated peatland can only be considered functionally 'restored' once organic matter accumulation has achieved a thickness where the mean water table position in a drought year does not extend into the underlying formerly cutover peat surface. Here we monitor the spatio-temporal development of organic matter accumulation in a new peat layer for the first 8 years following the restoration of a Québec peatland and couple a simple acrotelm carbon accumulation model and ecohydrological model to assess peatland restoration success.

We determined that organic matter accumulation increased from 2.3 ± 1.7 cm 4 years post-restoration to 13.6 ± 6.5 cm 8 years post-restoration. For comparison, at an adjacent non-restored section of the peatland organic matter accumulation was significantly lower ($p < 0.001$ for all years), with mean thicknesses of 0.2 ± 0.6 and 0.8 ± 1.2 cm for 24 and 28 years post-extraction, respectively. Given the mean summer water deficit at the site (−64 mm), our ecohydrological modeling results suggest that a 19-cm-thick moss layer would be required to offset the water table decrease induced by the summer water deficit. Given the current rate of organic matter accumulation, net primary productivity and the new peat layer decomposition rates determined using litter bags, we estimate it will take 17 years post-restoration to accumulate a 19-cm moss layer. Consequently, we argue that successful peatland restoration may be achieved in the medium-term and that our simple modeling approach can be useful in assessing the long-term impact of restoration on atmospheric carbon dioxide sequestration.

1. Introduction

Northern peatlands store approximately one-third of the world's soil carbon through the long-term accumulation of atmospheric carbon dioxide (CO_2) as peat (Gorham, 1991). In both Canada and Europe, peatlands are extracted for fuel peat and horticultural peat and this has an impact on the vegetation (Poulin et al., 2005), hydrological conditions (Van Seters and Price, 2001) and carbon balance (Waddington and Price, 2000) of these ecosystems. Following drainage and extraction, these cutover peatlands become a large and persistent source of atmospheric CO_2 due to increased soil decomposition and reduced vegetation productivity (Waddington et al., in press; Petrone et al., 2001). Recent advances in peatland restoration techniques (e.g., Price et al., 1998; Sottocornola et al., 2007) have succeeded in establishing *Sphagnum* moss on previously cutover surfaces (Rochefort and Lode, 2006), leading to enhanced productivity and increased carbon storage (Waddington et al., in press). Restoration techniques (e.g., blocking drainage ditches) improve the hydrological conditions necessary for moss establishment at cutover sites mainly by increasing moisture content and water table position (Waddington et al., in press; Shantz and Price, 2006). However, the hydrophysical characteristics of the old exposed peat on the cutover surface often present a problem in maintaining constant water levels (Price and Whitehead, 2001). McNeil and Waddington (2003) suggested that water table fluctuations would likely remain problematic for restoration efforts until a suitably thick organic matter had developed, that is, until accumulated organic matter reaches a thickness where the water table position in a drought year does not extend into the underlying formerly cutover peat surface and by definition becomes an 'acrotelm'. Indeed, determining and/or modeling the time required to develop a new acrotelm would be valuable

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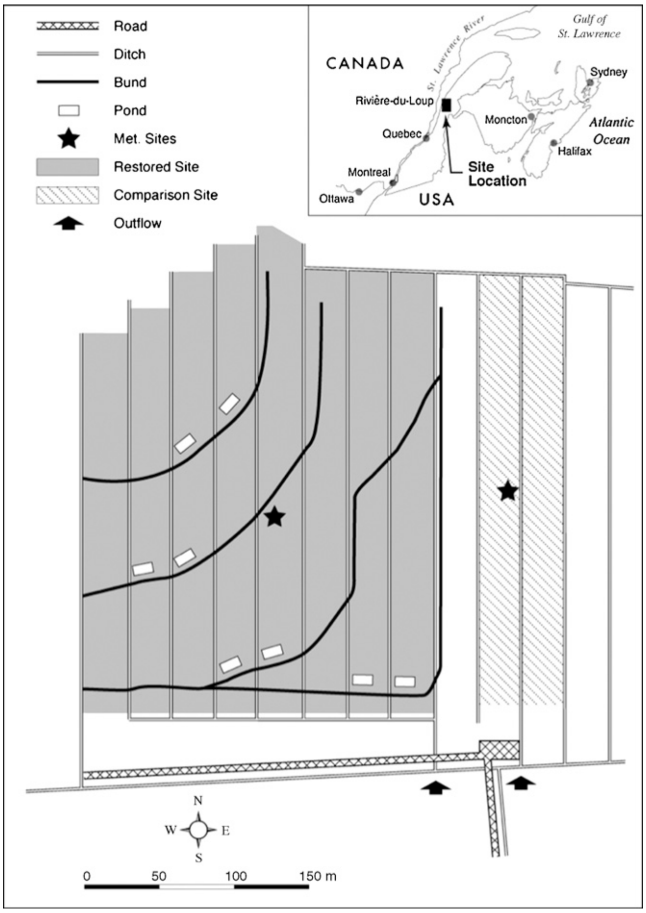

Fig. 1. Bois-des-Bel peatland study area.

for *Sphagnum* peatland restoration management. However, we are unaware of any research that has determined organic matter accumulation rates and estimated what thickness of accumulated organic matter is needed to stabilize water table fluctuations in restored peatlands. Here we examine the accumulation of organic matter in a new peat layer (hereafter referred to as 'accumulated organic matter') in a cutover peatland following restoration and use Clymo's (1984) acrotelm growth model as well as a simple ecohydrological model to estimate the thickness (and time) required to develop a self-regulating acrotelm.

2. Methodology

2.1. Study area

This study was conducted at the Bois-des-Bel peatland in the Bas-Saint-Laurent region of Québec, on the south shore of the St. Lawrence River, 210 km north-east of Québec City (47°53′N, 69°27′W). The 30-year normal (1971–2000) annual temperature for the region (St. Arsène, 5 km south) is 3.2 °C, with mean January and July temperatures of −12.6 and 17.8 °C, respectively. The mean annual precipitation is 963 mm, with 29% falling as snow (Environment Canada, 2008).

Bois-des-Bel (BDB) is a 189-ha forested bog of which an 11.5 ha section of the peatland was drained in 1972. The peatland was divided into 11 fields (30 m × 300 m each), and separated by drainage ditches running parallel (north-south) to the fields (Fig. 1). From 1973 to 1980 the upper 80 cm of peat was extracted from this site using the vacuum harvest approach. The site was then abandoned for 20 years. In the autumn of 1999, ecosystem-scale restoration commenced using the *Sphagnum* moss layer transfer restoration technique (see Rochefort et al., 2003 for details) and was completed in fall 2000 (Fig. 1). The cutover peatland was separated into two sections: a 8.4-ha restored section and a 2.0-ha non-restored section with a buffer strip left between the two sections (Fig. 1). Thus, newly accumulated organic matter after restoration will be compared to organic matter accumulated since the cessation of peat extracting activities (20 years + the number of years post-restoration). The restored section of the Bois-des-Bel peatland was dyked along topographical contour lines (Fig. 1) to better redistribute water during the rewetting process. The average residual peat depths of the cutover peatland was 1.5 m, and the peatland is underlain by a layer of marine clay that hinders vertical flow through the base of the peat deposit. The dominant species found at Bois-des-Bel 6 years post-restoration include: a complete moss carpet composed of *Sphagnum rubellum* (70%), *Sphagnum magellanicum* (15%); 13 other species of *Sphagnum* (10%) and *Polytrichum strictum* (5%), along with ericaceous shrubs and *Eriophorum vaginatum* tussocks. The non-restored site harbored young trees of *Picea mariana* and *Betula* spp. but the cover of non-vascular plants is very scarce except for some patches of *P. strictum*. The natural section of the peatland is located adjacent to the restored section (Lavoie et al., 2001).

2.1.1. Organic matter accumulation survey—post-restoration

During the 2003, 2005 and 2007 field seasons, the thickness of organic matter above the abandoned cutover peat surface was measured by inserting a metal rod into the peat until the older, highly decomposed and compacted cutover peat layer was reached. This measurement was completed at 755 point locations which marked the center of each grid cell (7 m × 20 m) in our Geographic Information System (GIS) database (Fig. 2). This transition between the older cutover surface and accumulated organic matter was easy to identify due to the distinctly different physical properties between the older catotelmic peat and the newer fibrous organic matter.

At the end of the each growing season starting in 2000 and continuing until 2005, samples of post-restored accumulated organic matter were removed from 74 quadrats (25 cm × 25 cm) by clipping all above-ground vegetation and litter present over the residual cutover peat substrate surface. Samples were obtained along 10 transects, which corresponded to each of the restored former peat fields and the two non-restored peat fields (Fig. 1). In the non-restored zone, when a *Polytrichum* moss carpet was present, above-ground biomass was harvested above the level where the moss colour changed. Samples were frozen and returned to the laboratory for analysis. In the laboratory, sample material was sorted into *Sphagnum*, *Polytrichum* and other mosses, Ericaceae, and other vascular vegetation categories. For *Polytrichum* mosses; brown, red or yellow mosses were considered green biomass. For herbaceous species, any leaf that was more than 50% dead (denoted by dark or brown colour) was placed in the litter category, otherwise it was included as green biomass. For ericaceous plants, the whole leaf was kept in the green biomass category unless it was 100% dead. Plant tissues were dried at 70 °C until constant dry weight (2–4 days) and weighed. Biomass was converted to g m^{-2}. We calculated net primary productivity (NPP) by the difference in accumulated organic matter biomass between each year of study and also as the annual average accumulated between the first and final few years of study.

Sphagnum decomposition rates were determined over two growing seasons using the litter bag technique (e.g., Moore, 1984). Materials from the newly formed *Sphagnum* fibers, comprising over 90% *S. rubellum*, from 2 to 3 cm below the capitula were placed in litter bags made of fine nylon netting with small opening sizes

Fig. 2. Thickness of the accumulated organic matter layer at the restored section of Bois-des-Bel in 2003 (4 years post-restoration) compared to 24 years in the non-restored section since peat extracting activity ceased. Grid cell = 7 m × 20 m.

(~0.5 mm). Litter bags were weighed, filled with plant material, dried at 60 °C for 24 h, and then weighed again in order to record the amount of dry material present. Twenty litter bags were placed in the peatland on October 16, 2006 in the upper 5 cm in each of three surface types (*Sphagnum*, *Polytrichum*, and *Sphagnum* with ericaceous shrubs). Half of the litter bags were removed after one full year of incubation (October 11, 2007) and the remaining half after 2 years (September 30, 2008). Following removal, litter bags were cleaned of roots and fine particles coming from outside of the bags. The remaining plant material within the litter bag was dried at 60 °C for 24 h. Mass loss was calculated as the difference between the initial dry mass and final dry mass, in proportion to the initial dry mass. Values that showed negative loss (mass gain due to the growth of roots into the bags) over the 1-year period were discarded from the dataset, which resulted in loss of ~10% of the total dataset.

2.2. Organic matter and peat physical properties

Samples of accumulated organic matter and underlying peat were collected for the determination of physical properties. Bulk density was determined by cutting a sample of known volume and drying at 70 °C until constant dry weight (2–4 days) and weighed. Specific yield was determined by allowing free drainage of saturated soil samples and determining the ratio of water loss (see Price et al., 1998 for details).

2.3. Ecohydrological model for acrotelm development

The thickness of the accumulated organic matter was entered into a GIS database for analysis. ArcGIS 9.2 GIS and mapping software (ESRI) was used for analysis of data and production of maps. Point values for the thickness survey were spatially referenced and converted into a shape file based on a standard grid cell shape file developed for the site. Data was compiled into a main shape file that contained thickness values measured in 2003, 2005 and 2007 for the 755 grid cells.

The concepts of Clymo's (1984) model for acrotelm growth were used and the model parameterized for the Bois-des-Bel peatland to predict the growth of the accumulated organic matter and to compare model predictions to actual field measurements. The model provides a representation of biomass accumulation per unit area over time and takes into consideration productivity as an input and rate of loss to decay as an output. A modification to the decay component of the original model (Clymo, 1984) was made by Clymo (1992); allowing decay to decrease with the proportion of original mass remaining and this was used in the acrotelm growth model below:

$$\frac{dM}{dt} = p_a - \alpha_a \frac{m_t}{m_o} \times M \tag{1}$$

where M represents cumulative mass of organic matter (kg m^{-2}), t represents time in years, m_o represents original mass, m_t represents mass after time t, p_a is the annual input of dry biomass (kg m^{-2} yr^{-1}) and α_a is a ratio representing the mass lost by decay. In order to obtain the annual thickness of the accumulated layer, biomass accumulation values were converted to linear growth by incorporating the bulk density of the accumulated organic matter layer into Eq. (1).

A simple ecohydrological model was developed to estimate when the accumulated organic matter layer will be thick enough to contain all water table fluctuations and become a functional acrotelm. The model takes into account overall site water storage, represented by the difference of precipitation and evapotranspiration, storage properties of the layer (characterized by specific yield) and changes in water table position. Assuming the system re-saturates itself every year during snowmelt, we can infer that the net water table drop over the growing season will be a result of the water deficit in the summer, or the difference between water input through precipitation and output through evapotranspiration (since runoff is considered negligible in the summer months) and the relative ability of the layer to offset this deficit and store water. This can be represented by the following equation:

$$\Delta h = \frac{P - E}{S_y} \tag{2}$$

where h is the depth to the water table below the surface, P is the precipitation (mm), E is the evapotranspiration (mm) and S_y is the mean specific yield for the new peat layer.

3. Results

3.1. Accumulated organic matter thickness

Three years post-restoration, the thickness of the accumulated organic matter was greater in the western portion of zone 3 and the mean thickness of the new layer was 2.3 ± 1.7 cm, with a maximum thickness of 11.4 cm (Fig. 2). Six years post-restoration, thickness was greater in the northern and southern portions of zones 3 and 4 and the mean thickness for the whole restored section increased to 5.3 ± 4.6 cm in 2005, with a maximum thickness of 20.0 cm (data not shown). Mean thickness, was 13.6 ± 6.5 cm 8 years post-restoration, with a maximum thickness of 34 cm (Fig. 3). The minimum thickness was 0 cm for all years. Mean accumulated organic matter thickness at the non-restored section were significantly lower than the mean values for the restored section for

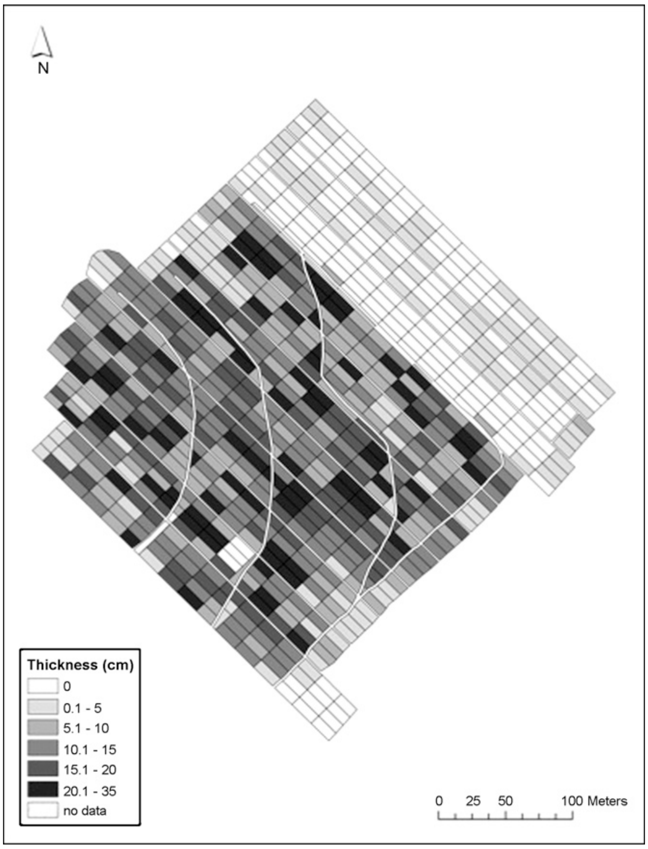

Fig. 3. Accumulated organic matter thickness at the restored section of Bois-des-Bel in 2007 (8 years post-restoration) compared to 28 years in the non-restored section since peat extracting activity ceased. Grid cell = 7 m × 20 m.

each year compared (t-test, $p < 0.001$ for all years), with 0.2 ± 0.7 cm thickness 24 years post-extraction and 0 cm and 0.8 ± 1.2 cm thickness 28 years post-extraction.

3.2. *Organic matter accumulation, net primary productivity, and decomposition*

Accumulated organic matter at the restored site increased over the 6 years post-restoration (Fig. 4), ranging from $47 \pm 43\,\mathrm{g\,m^{-2}}$ in 2000 to $1692 \pm 932\,\mathrm{g\,m^{-2}}$ in 2005. Total biomass was relatively evenly distributed among the four functional types, with *Sphagnum*, other mosses, ericaceous shrubs and other vascular plants accounting for 27%, 34%, 10% and 29% of the total accumulated biomass respectively. NPP ranged from $79\,\mathrm{g\,m^{-2}\,yr^{-1}}$ (2002–2003) to $680\,\mathrm{g\,m^{-2}\,yr^{-1}}$ (2004–2005), with a mean value over the last 4 years of $379 \pm 225\,\mathrm{g\,m^{-2}\,yr^{-1}}$. Overall NPP generally increased over time, except in 2003 when the value decreased relative to the previous year. NPP 6 years post-restoration ranged from $66 \pm 184\,\mathrm{g\,m^{-2}\,yr^{-1}}$ for ericaceous to $332 \pm 694\,\mathrm{g\,m^{-2}\,yr^{-1}}$ for other vascular vegetation. Average *Sphagnum* NPP over the first 6 years post-restoration was $179 \pm 515\,\mathrm{g\,m^{-2}\,yr^{-1}}$.

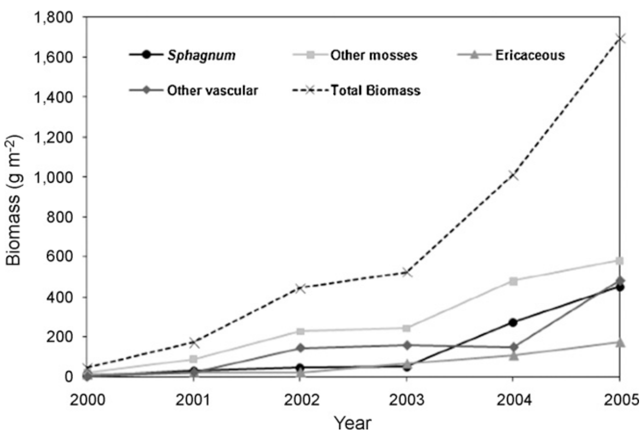

Fig. 4. Accumulated organic matter for each year post-restoration for *Sphagnum* moss, other mosses, ericaceous shrubs and other vascular plants. The dotted line represents total accumulation.

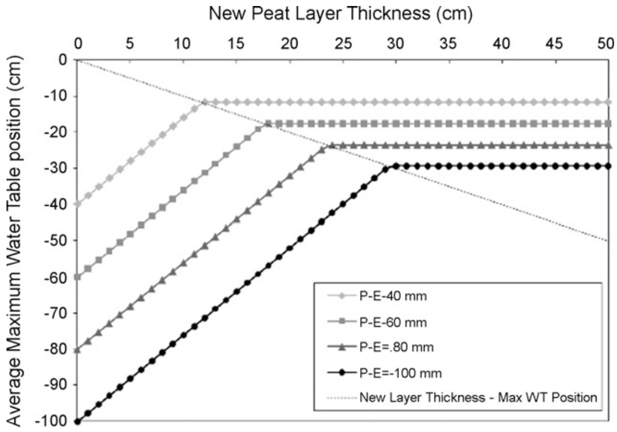

Fig. 5. Lowest summer water table position at BDB as the moss layer grows. Dotted line represents the point at which lowest water table position equals accumulated organic matter thickness, an estimation of the thickness required for the layer to be considered restored.

In contrast, the non-restored portion of Bois-des-Bel had a higher accumulated organic matter for ericaceous vegetation (mean $280 \pm 310\,\mathrm{g\,m^{-2}}$ in comparison to $175 \pm 167\,\mathrm{g\,m^{-2}}$ at the restored section), but lower accumulated organic matter for other mosses ($72 \pm 171\,\mathrm{g\,m^{-2}}$), other vascular plants ($8 \pm 18\,\mathrm{g\,m^{-2}}$), and almost no *Sphagnum* accumulation, except at one location ($154\,\mathrm{g\,m^{-2}}$) out of 16 locations sampled at the non-restored portion of the peatland, which provides a mean of $10\,\mathrm{g\,m^{-2}}$ for *Sphagnum*. This represents a *Sphagnum* NPP value of $0.4\,\mathrm{g\,m^{-2}\,yr^{-1}}$ (assuming a 26-year accumulation period since peatland abandonment).

Mean percent loss after 1 year for litter bags placed in *Sphagnum*, *Polytrichum*, and *Sphagnum* with ericaceous shrubs surfaces was 9.1 ± 2.7%, 4.0 ± 3.3%, and 8.1 ± 2.6%, respectively. After 2 years, mean percent loss was 13.9 ± 4.0%, 11.5 ± 6.6%, and 10.8 ± 3.6%, in *Sphagnum*, *Polytrichum*, and *Sphagnum* with ericaceous shrub covered surfaces, respectively.

3.3. *Ecohydrological modeling*

Mean accumulated organic matter specific yield, S_y, was 0.34 ± 0.04 and for the lower catotelm layer was 0.10 ± 0.02. Using these values we ran the ecohydrological model for hypothetical mean summer water deficits of 40, 60, 80 and 100 mm and varied the thickness of the accumulated organic matter from 0 to 50 cm (Fig. 5). The inflection point in Fig. 5 represents the thickness required for the water table position to be contained within the accumulated organic matter for each of the summer water deficit scenarios. For example, for a summer water deficit of −100 mm, initially the cutover site would have a water table position of −100 cm as there is no accumulated organic matter to moderate the water table drop into the catotelmic peat ($S_y = 0.1$) (Fig. 5). However, once the accumulated organic matter has achieved a thickness of 34 cm, the water table remains at this depth. By incorporating the values

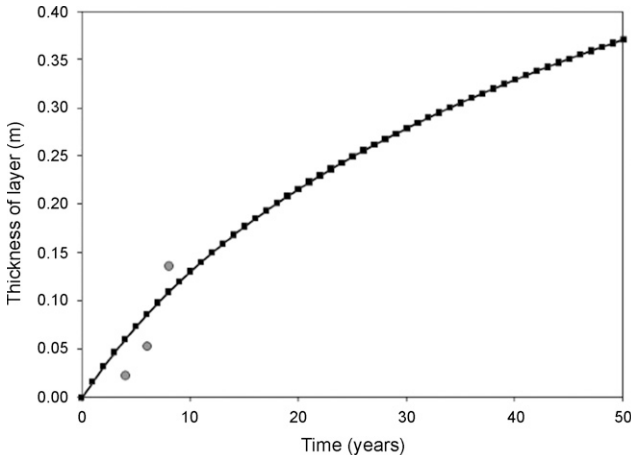

Fig. 6. Estimated accumulated organic matter thickness at the restored site over time using Clymo's (1984) model. Grey dots represent actual mean thickness 4, 6 and 8 years (2003, 2005 and 2007) post-restoration.

obtained for BDB into the summer water deficit model, the model predicts that an accumulated organic matter thickness of 19 cm layer would be required to offset the summer water deficit induced water table decline at the site. Moreover, using the maximum and minimum *P*–*E* values based on one standard deviation around the calculated mean for Bois-des-Bel restored peatland, the required thickness would range from 33 to 4 cm, respectively. By applying the same logic to the storativity of the accumulated organic matter and varying it one standard deviation above and below the mean S_y value of 0.34, a range in thickness from 21 to 17 cm is obtained. Consequently, it appears that larger inter-annual variability associated with environmental conditions is likely to have a more significant impact in determining the thickness required to offset summer deficit induced water table drop.

3.4. *Model for organic matter accumulation and acrotelm development*

Clymo's (1984) model for organic matter accumulation and acrotelm growth was used and the model adapted and parameterized for the BDB restored peatland in order to estimate how long it would take to develop a 19-cm new peat layer at this site. Model parameters include average dry biomass production, which was calculated based on mean NPP over the period from 2002 to 2005 (p_a = 0.38 kg m^{-2} yr^{-1}), bulk density of the upper peat layer (average between the upper 0–4 and 4–8 cm layers, 22 kg m^{-3}), and the average annual decomposition rate for *Sphagnum* in the newly formed layer (7% yr^{-1}), assuming that *Sphagnum*, other mosses and ericaceous/other vascular plants constitute approximately the same proportion of the produced mass and taking into account the individual decay rate for each of these species). The acrotelm growth model predicts that initially, the mass of accumulated organic matter rapidly increases however this rate decreases with time (Fig. 6). The mean thickness of the acrotelm layer would reach the 19 cm acrotelm threshold, determined in the previous section, 17 years post-restoration (Fig. 6). When comparing model results to our observed mean accumulated organic matter thickness values for the years of 2003, 2005 and 2007, the model appears to overestimate organic matter accumulation in the initial years post-restoration (2003 and 2005), and underestimate it for the latter year (2007).

The model was also run for three scenarios of biomass production to examine the model sensitivity to this parameter, given its inter-annual variability over the initial 6 years post-restoration. The following scenarios were considered: (1) average NPP over the period of 2002–2005, p_a = 0.38 kg m^{-2} yr^{-1}, (2) average NPP over 6 years post-restoration, p_a = 0.28 kg m^{-2} yr^{-1} and (3) NPP for the last year of data available, p_a = 0.68 kg m^{-2} yr^{-1}. The model demonstrated a better fit to observed results for the p_a = 0.28 or 0.38 kg m^{-2} yr^{-1} production values, as the p_a = 0.68 kg m^{-2} yr^{-1} scenario greatly overestimated accumulated organic matter thickness. Using the 0.28 and 0.38 kg m^{-2} yr^{-1} p_a values, a mean decay rate of 7% yr^{-1} for the accumulated organic matter or 9% yr^{-1} for only the accumulated *Sphagnum*, and bulk density values of 19 kg m^{-3} (upper portion of accumulated organic matter), 22 kg m^{-3} (mean) or 24 kg m^{-3} (lower portion of accumulated organic matter), the time to form 19 cm of accumulated organic matter ranged from 14 to 37 years post-restoration.

4. Discussion

4.1. *Development of a new acrotelm*

Peatlands represent a large sink for atmospheric CO_2, with an estimated 455 Pg of carbon stored in peatland soils which represents almost one-third of the total global soil carbon (Gorham, 1991). This is a result of high and stable water levels, which enable the slow decay of plant matter and transfer for storage into the catotelm. A healthy acrotelm is what links together these eco-hydrological processes operating in natural *Sphagnum* dominated peatlands. It ensures that water table levels can be maintained high and above the catotelm even during periods of high water deficits such as those experienced in the summer months. In this manner, we argue that the successful restoration of a cutover peatland will be defined by the re-establishment of a functional acrotelm. In the short-term, the return of key moss species such as *Sphagnum* is the main goal of peatland restoration, and for this the hydrology of cutover sites must be manipulated to ensure adequate conditions are met for these non-vascular plants to grow (Gorham and Rochefort, 2003). In the longer term, it is necessary that the biodiversity, trophic organization of plants and animals, and the productivity, decomposition and biogeochemical cycles characteristic of these systems be re-established (Gorham and Rochefort, 2003).

Sphagnum moss has been successfully re-established at the restored portion of Bois-des-Bel due to active restoration. Estimates of biomass productivity for natural peatlands vary considerably, but organic matter accumulation rates from this study are comparable to findings from other studies on *Sphagnum* dominated bogs (Clymo and Reddaway, 1971; Moore et al., 2002; McNeil and Waddington, 2003). Also, our NPP values ranged from 79 to 680 g m^{-2} yr^{-1} and are comparable to values reported in studies for other restored peatlands (e.g., Waddington et al., 2003), and within the range reported for natural systems.

Accumulated organic matter was significantly higher for the restored section of the peatland in comparison to the non-restored section, demonstrating the importance of restoration in the re-establishment of a moss carpet. Moreover, it appears that despite some spatial variation in thickness observed throughout the site in the initial years post-restoration (likely due to the time required to restore the site), after 8 years there were no significant differences in accumulated organic matter thickness between the four zones at the restored section of the site. Our organic matter accumulation rates (1.7 cm yr^{-1} over 6 years post-restoration) were higher than values of Waddington et al. (2003) from a central Québec restored peatland (1.1–1.4 cm yr^{-1}). However, the plots studied by Waddington et al. (2003) were 100% *Sphagnum* fully established moss colonies, while in this study we examined ~600 locations throughout the entire site, ranging over a variety of conditions.

Our annual *Sphagnum* decomposition rates for the upper moss layer (7–9%) fall within the reported range for restored and natural peatlands. Waddington et al. (2003) found that mean loss over 2 years for *S. capillifolium* and *S. fuscum* was $17.1 \pm 1.1\%$ and $13.1 \pm 0.7\%$ respectively for a restored peatland. Rochefort et al. (1990) reported 16% loss over 2 years for *S. fuscum*. *S. capillifolium* annual mass loss was found to be 16% (Clymo, 1965). Mean seasonal decomposition for *S. capillifolium* was $9.1 \pm 6.2\%$ in the revegetated Cacouna Bog, Québec (McNeil and Waddington, 2003). An important factor to note is that decomposition of mosses is not generally linear with time (Johnston and Damman, 1993). Nevertheless, our mean annual losses were not significantly different between the first and second year.

4.2. Predicting the time for restoration success

Peat extraction leads to the removal of the upper living moss layer and exposure of the old catotelm peat, which greatly alters the ecohydrological properties and functions of these systems. As previously mentioned, the re-establishment of the diplotelmic structure of a peatland is essential for restoration. It is proposed here that it is not until a new acrotelm layer overlying the old catotelmic peat has developed that a *Sphagnum* dominated peatland can be considered functionally restored. In this manner, peatland restoration focuses on returning hydrological conditions more suitable for *Sphagnum* re-establishment. As *Sphagnum* vegetation grows and forms a new peat layer, its properties aid in further regulating the hydrological conditions of the site and possibly lead to the eventual restoration of a peatland once this layer is deep enough to moderate water table fluctuations (Price and Whitehead, 2001; Waddington et al., in press).

Our results indicate that 8 years post-restoration, the newly formed layer was not sufficiently thick (13.6 ± 6.5 cm in thickness) to contain water table fluctuations at the site (mean -12.4 ± 12.1 cm, minimum -42.6 cm in 2006), deeming it not truly restored from an ecohydrological perspective. While our water deficit model assumes that the system re-saturates itself post-snow melt and therefore does not take into account microtopography, the model is a simple and useful tool in predicting the accumulated organic matter thickness required to encompass water table fluctuations over the summer. The water deficit model also demonstrates that climate has a strong control on the re-establishment of an acrotelm. Inter-annual variability in precipitation and evapotranspiration is common, and therefore it would be valuable to obtain these measurements for a longer period in a restored peatland for a better estimate of how these would impact the predicted mean thickness value. Natural/undisturbed *Sphagnum* dominated peatlands have acrotelms that typically range between 10 and 50 cm thick (Clymo, 1984) and the estimated required minimum thickness of an acrotelm for Bois-des-Bel (19 cm) falls within this range for natural systems.

Clymo's (1984) acrotelm model adopts an ecological approach of acrotelm development based on input (production) and output (decay) rates. Production is assumed to be constant in the model, which as was shown in this study is not the case especially in the initial years post-restoration. Also, the initial rate of decay is assumed to remain constant with time, which is unlikely to hold true as the hydrological conditions of the site improve with time post-restoration. One of the main criticisms towards Clymo's Bog Growth Model view is that it does not consider the interactions between peat accumulation and hydrological conditions (Belyea and Baird, 2006). Despite its limitations, this model and Clymo's concepts have been widely used in the field and they provide a simplified approach to the interactions between the two main ecological processes taking place in the re-establishment of an acrotelm. Van der Schaaf (1999) used a similar approach to estimate acrotelm growth for a bog in Ireland. Van der Schaaf (1999) suggested that as an acrotelm is re-establishing, it is possible that development may speed up after a slow start, as conditions for accumulation change. For the different production scenarios for which we ran the acrotelm model, the most realistic scenario was the average of the last 4 years of data. It is apparent that for the initial years post-restoration production does not provide a appropriate representation of a longer term mean value, as the system recovers from harsh hydrological conditions imposed by peat extraction and abandonment. However, as mentioned earlier, restoration is indeed successful in returning the peatland productivity and organic matter accumulation to values which are comparable to those of natural systems only 8 years post-restoration.

In pristine peatlands microtopography plays a significant role in determining acrotelm thickness with hummocks characterized by thicker acrotelms than hollows simply due to the fact that the depth to the water table in hummock microforms is greater than water table depth in hollows. The organization of this microtopography also determines overall mean peatland specific yield. While the BDB peatland has only just started to develop minor microforms (R. Pouliot, unpublished data) some regions of the peatland have accumulated more new peat than others. In fact, only approximately 23% of the restored peatland was above the 19 cm threshold thickness in 2007. By coupling the 2007 thickness data in each cell of our GIS to the acrotelm growth model, we estimated that 17 years post-restoration ~57% of the site would have a thickness of, or higher than, 19 cm. We argue that future studies in restored peatlands should examine microform specific rates of production and decomposition in order to assess a more micro-site specific required acrotelm thickness. This would also aid in providing a better understanding in relating acrotelm formation to microform development in peatlands.

Nevertheless, despite its simplicity, the acrotelm model provides a reasonable estimate of accumulated organic matter thickness with time, as model results fall close to our field measured thicknesses at Bois-des-Bel. In addition, the predicted time (~20 years) it would take for ecosystem restoration at Bois-des-Bel falls close to values previously estimated. For example, Rochefort et al. (2003) stated that the return of a restored peatland to a peat accumulating system in 20–30 years would be acceptable but the authors were unsure if this time estimate was realistic. Rochefort et al. (2003) suggested that a number of significant characteristics of *Sphagnum* bogs can be re-established in 3–5 years, a stable and high water table in about a decade, and a functional ecosystem that accumulates peat in 30 years. Finally, our results suggest that without active restoration it is likely that disturbed cutover peatlands using the harvest technique would never re-establish as a functioning peatland ecosystem (Rochefort et al., 2003).

4.3. Conclusions and implications for restoration

Peatland restoration research has shown great developments in the past decade and currently we have a sufficient understanding of how to manipulate the hydrology and ecology of cutover peatlands (e.g., Rochefort et al., 2003), improving the conditions of these sites and consequently minimizing anthropogenic impacts with respect to carbon losses as CO_2, even returning sites to net sinks for CO_2 in the short-term (Waddington et al., in press). *Sphagnum* has been successfully re-introduced as a result of restoration, and it appears that some characteristic properties of these sites such as production and decay can be returned in the short-term. However, it is important for researchers to also focus on better understanding restoration from a peatland development perspective. Little is known about how the hydrological and physical properties of the growing moss layer change with time, and more importantly how this relates to acrotelm development. It is proposed here that restoration will not have reached its main objective until an acrotelm has developed, and currently little is known about the dynamics of the ecohydrological processes operating in the re-establishment of the diplotelmic nature of restored peatlands. The simple hydrological and peat formation models utilized in this study are optimistic and suggest that this may be achieved in the medium term, through the development of a thick accumulated organic matter layer able to offset water table fluctuations, restoring the ability for long-term accumulation of carbon as peat; however, this would greatly depend on site-specific peat hydrophysical properties as well as climatic controls.

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