Preface

This report is the result of a master thesis as part of the Energy and Environmental Science Master program at the University of Groningen, the Netherlands. I would like to acknowledge my supervisors Dr. A. J. Schilstra and Prof. Dr. A.P. Grootjans and my parents for suggestions, comments, and inputs that significantly contributed to the improvement of this thesis. I would also like to thank my husband - without his help I would have not found the time to finish.
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Summary

Peatlands cover about three percent of earth’s land surface in primarily the northern hemisphere and store an estimated 550 Gigatons of carbon. Peat is the substance formed when organic matter cannot completely decompose due to waterlogged and anoxic conditions. Under these circumstances, peatlands have sequestered carbon for thousands of years. The construction of ditches to drain mires causes hydrological changes resulting in the drying of the peat which can then be harvested. The drying and removal of peat layers destroys habitat and disables vegetation growth and thus peat accumulation. Furthermore, carbon sequestration function is destroyed.

Large scale restoration efforts have not been achieved and long-term restoration successes cannot yet be evaluated. Additionally there has not been an evaluation of the collective impact of mire restoration measures. This study aims to determine whether peatland restoration projects meet their goal setting and contribute to re-establish peatland ecosystems and their function in the global carbon cycle and in contribution to biodiversity, by assessing factors that contribute to successes and failures. Therefore, literature research is undertaken to investigate (1) what the restoration techniques are, (2) what successes and failures of restoration can be distinguished, and (3) if efforts meet the goals of restoration of restoration projects undertaken in Canada and Ireland.

The evaluation of measures taken at the Canadian and Irish restoration sites were found to take a whole ecosystem approach, focusing on all aspects of a mire ecosystem-hydrology, vegetation, peat accumulation, carbon flux, and biodiversity which is why they were chosen. One project in each country was chosen due to time constraints and the limited number of evaluation studies available. The main measure taken to restore mires is the blocking of drainage ditches which should aid in returning hydrological conditions necessary for vegetation establishment and peat accumulation. To investigate if the measures taken reach the goal of restoration, changes to hydrology, biodiversity, and carbon flux of two restoration projects were investigated. At the Bois-des-Bel Bog in eastern Canada restoration measures were carried out, including blocking of drainage ditches, construction of embankments, plant fragment spreading, fertilization, and straw mulch application. At Camderry Bog in central Ireland restoration measures included clear felling and embankment of the area and blocking of drainage ditches using peat dams. The goal of restoring Bois-des-Bel Bog is the re-establishment of a self-regulating peat accumulating ecosystem. Camderry bog is restored with the goal to restore threatened raised bog habitats to a favourable status. The pre-restoration conditions of the sites differed in terms of naturally established vegetation. While Bois-des-Bel was nearly void of vegetation, Camderry Bog showed some Sphagnum coverage, indicating favourable conditions for mire-typical vegetation establishment. At both sites water table level and vegetation coverage were monitored. At Bois-des-Bel monitoring was more comprehensive compared to Camderry Bog. At both sites the restoration measures taken resulted in a raised water table level but increased seasonal fluctuations. Vegetation coverage had significantly increased; however, non-typical mire vegetation is competing with mire-typical vegetation. Amphibian and bird diversity and abundance had increased at Bois-des-Bel bog where artificial pools created habitat and breeding grounds. Although some fungal activity was observed there appears to be a lag time between vegetation establishment and microorganism recovery. The carbon sequestration function was not restored. It was concluded that although the individual objectives of restoration such as raising the water table and establishing vegetation coverage were achieved, the overall goal was not. Restoration measures did not lead to a self-regulating peat accumulating ecosystem at Bois-des-Bel. The goal for Camderry Bog is too ambiguous to determine whether it was met and clarification of “favourable status” is needed. Although these results may not be representative for all bog restoration efforts, they may have implications for future use of pristine bogs; their conservation may be the more feasible option in terms of preserving biodiversity and their role in the global carbon cycle.
**Geography and Status of Mires**

Although the exact global coverage of peatlands is unknown, they are the most widespread of all wetland types covering about 3 percent of earth’s land surface, primarily in the northern hemisphere (Joosten, 2004) (Figure 1).

Figure 1: Global mire distribution (IPS, 2008)

Most peatland are located in sub-arctic and boreal regions. More than 87 percent of known peatlands are found in North America, Europe, and Russia. Historically, humans have used peatlands, especially mires for its peat and up to 90 percent of Europe’s mires have been drained (Joosten & Clarke, 2002) and more than 50 percent of Europe’s pristine mire area is reported lost.

Table 1: Canadian and Irish peatland (and mire) status. Numerical estimates may vary depending on source because of regional definition of peatland and mires. From Rydin et al. (2006) and Irish Peatland Conservation Council (2001).

<table>
<thead>
<tr>
<th>Country</th>
<th>Territory covered by peatland (%)</th>
<th>Area of peatland loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>&gt;11(1)</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Ireland</td>
<td>16(2)</td>
<td>&gt;80</td>
</tr>
</tbody>
</table>

Joosten & Clarke (2002) report northern mire loss of 16 percent based on the current and former extent of mires. This loss is detrimental for biodiversity and the global carbon cycle because ecosystems are lost along with their carbon sequestration function; harvested mire can no longer accumulate carbon via photosynthesis and drainage causes an increased layer of aerobic activity. This is especially significant when considering current climate change caused by increased concentrations of greenhouse gases in the atmosphere. Greenhouse gases, most of which are carbon compounds trap heat radiating from the earth into the atmosphere and thus increase global temperatures. This warming effect impacts every ecosystem, including mires as climatic conditions change. The continuing ero-
sion due to climate change and anthropogenic activities further aggravate the change of mires from carbon sinks to carbon sources.
Introduction

Peat Formation and Development

Peat is the substance formed when organic matter cannot decompose completely due to water saturation and thus anoxic environment. (i.e. Joosten & Clarke, 2002; IPS, 2008).

Formation

Even though undisturbed mires vary in shape, size, age, and other characteristics they all are di-plotelmic, meaning they consist of two layers: the acrotelm and catotelm. The acrotelm is the layer where peat grows and accumulates and is situated on top of the catotelm. The acrotelm is comprised of living, dead, and partly decomposed vegetation debris. In this top layer the water table can fluctuate causing both aerobic and anaerobic conditions. This determines the vegetation type and the rate of its decomposition. The acrotelm can store and release large quantities of water which dampens water table fluctuations and variations (Rochefort & Quinty, 2003). The catotelm layer contains primarily decomposed and compacted peat and is thus subject to peat harvest. Anaerobic conditions prevail at the catotelm layer due to its prolonged location below the water table. This is cause for a very slow microbial activity (hence peat decomposition) as well as the catotelm being a large water reservoir. The hydrological properties and characteristics of mires are vital to it and are the main subject of restoration.

Development

Principally there are two processes that lead to peat formation: Paludification and terrestrialization. Paludification is peatland development on mineral ground. Paludification theory proposes that the initial land was drier and may have been forest-covered. A progression from forest to swamp forest and wooded fen and finally mire ecosystem is believed to have formed most of present global mires (Rydin et al., 2006). Another way of paludification is due to a rise in water level. The vertical growth of mires raises the water level whereby adjacent upland is slowly waterlogged and conditions for peat formation established. Progression leading to mires is most likely encouraged by climate shifts and/or local changes to hydrology and thus could also be human induced.

![Figure 2: Terrestrialization process, also frequently referred to as infilling. The development of a fen into a bog does not always occur. The infilling process causes a shift in vegetation species (even within *Sphagnum*) and changes in hydrology and chemical characteristics of the ecosystem. From Rochefort & Quinty (2003).](image)

Terrestrialization takes place near or in aquatic environment where vegetation roots, rhizomes, and leafs facilitate peat formation. As vegetation becomes denser, formation of peat mats occurs, and
organic matter increases causing less wet conditions. A slow shift from an aquatic to a semi-aquatic habitat to a fen which can evolve into a bog (Rochefort & Quinty, 2003) occurs (Figure 2). This terrestrialization process contributes to an increasing thickness of the peat layer and thus the formation of various shapes and properties that are characteristic for the particular type of mire (i.e. Schumann & Joosten, 2008; Vasander, H., 1996). Depending on the stage of mire development, certain species of fauna and flora can be found.

Biodiversity

A mire is an unique ecosystem that can be compared to a “living organism because it grows, matures, and may even die.” (Joosten & Clarke, 2002). Its livelihood depends on the interdependent relationship of water, plants, and peat and is thus highly susceptible to disturbances. This relationship and its proper functioning determine the type of biodiversity. Another factor contributing to biodiversity is the presence and abundance of pools (Rochefort & Quinty, 2003). Mires with pools are usually more species rich as they are sanctuary, migratory halt and breeding ground for many birds as well as habitat for a variety of aquatic organisms. Additionally, amphibians and arthropods can be found in and around pools.

Unlike most ecosystems, the transfer of energy from one trophic level to a higher one occurs only partially; nothing forages on Sphagnum and the majority of energy accumulates as peat, thus limiting the species population sizes (and diversity) mires can sustain (Parish et al., 2008). While species richness is low compared to other ecosystems, species exhibit remarkable adaptations to the rather hostile environment of mires. Often these well-adapted species are found nowhere else and their conservation is important to maintain biodiversity. The presence of certain species may give an indication of the status, i.e. health, development, etc. of mire. One of the restoration aims is to restore biodiversity (Schumann & Joosten, 2008). The return of mire associated fauna species is a criteria for successful restoration (Gorham & Rochefort, 2003) because without fauna and flora of mires, peat would not accumulate and the overall goal of restoration, namely the “[re-establishment of] self-regulatory mechanisms that will lead back to functional peat accumulating ecosystems” (Rochefort & Quinty, 2003), cannot be achieved.

Flora

Flora diversity of mires depends on nutrient, mineral, and water availability. Graminoids, herbs, shrubs, trees, and aquatic vascular plants exhibit a limited diversity in Sphagnum-dominated mires (i.e. Crown, 2004; Daigle (2008). The most abundant and important plants in mires are bryophytes, commonly known as mosses and particularly the genus Sphagnum as it is directly involved in peat formation. There are about 250 species of Sphagnum that inhabit acidic, nutrient poor, and water-
logged environments in primarily the temperate environments but also the tropics and subtropics. *Sphagnum* mosses are well adapted to their environment. For instance, *Sphagna* lack both roots and stomata and thus depend on a capillary network formed by spaces within the moss and a great water storage capacity to ensure water supply (Rydin et al., 2006). Thus, *Sphagna* not only depend on water levels near the surface but also contribute to a waterlogged environment by retaining water - its content accounting for as much as 20 times the dry mass of the moss. Dependent on the position relative to the water table *Sphagna* form habitats of hummocks and hollows. Hollows or lawns are habitats that form depressions where the water table is close to the surface. *Sphagnum* mosses in lawns are not as well adapted to retain water, meaning their capillary network is less efficient, and so they form loose colonies in this habitat. Hummocks on the other hand are large plateaus or small mounds that exhibit drier conditions because it is located 40 to 80 cm higher than hollows. Due to the drier conditions, dense water retaining colonies of *Sphagnum* can be found here. Usually, a mixed habitat of hummocks and hollows can be found in mires.

**Fauna and other life forms**

A variety of fungi and bacteria are in symbiosis with vegetation and are thus well adapted and vital to mires. The diversity and abundance of below-ground microorganisms play an important role in mire functions, including nutrient cycling, carbon release and storage, peat accumulation and decomposition, and plant productivity. The type of peat, the availability and quality of organic matter (Rydin et al., 2006), and the availability of oxygen largely determine the diversity of fungi and microorganisms. Two important groups of mire microorganisms are methanogenic archaea and methanotrophic bacteria. Both are contributors to the mire’s role in the global carbon cycle as the methanogenic archaea produce methane (CH\textsubscript{4}) and methanotrophic bacteria oxidise CH\textsubscript{4} to carbon dioxide (CO\textsubscript{2}). Protozoans, algae, and lichens in large variety and often quantity can also be found in mires. Animals, such as arthropods, crustaceans, flatworms, and amphibians and reptiles make up the bottom of an intricate food web that attracts birds. Due to the limited variety of vegetation available to herbivores as well as the aquatic nature of mires, the presence of mammals is usually opportunistic and temporary (Crown, 2004).

Drainage of mires and harvest of peat not only threatens life above ground but also below ground. Peat harvest interferes with these functions because the upper mire layer, where most microorganisms are found, is removed. When a site is subject to peat harvest, microorganism populations decline, although not irreversibly (Croft, Rochefort, & Beauchamp, 2001). The presence, type, and level of abundance of microorganisms may be a potential indicator of mire rehabilitation status (Artz, Chapman, & Campbell, 2006; Laggoun-Défarge et al., 2008). However, it is not clear whether the diversity of microbe communities correlates with vegetation diversity (Andersen, Rochefort, & Grasset, 2008); e.g. a certain group of microbes is associated with *Sphagnum* while other groups of microbes are associated with other vegetation types. Therefore, although below-ground diversity may give indication of the mire health, it currently does not seem feasible to determine below-ground microbial status by investigating above-ground vegetation status. Additionally, it appears, that nutrient availability and composition determines microbial biomass (Andersen, Francez, & Rochefort, 2006).

**Effects of water table level changes**

As mentioned before mires exhibit an interdependent relationship of plant growth, peat accumulation, and the presence of water. Mire vegetation depends on water for growth and because it so heavily depends on water it is also directly involved in keeping water close to the surface (Rochefort & Quinty, 2003). As peat thickness increases the acrotelm rises above the surrounding landscape, eventually creating its own water table via capillary action. This attraction of water molecules to soil particles and pore spaces within the acrotelm is the force responsible for retaining water at the site. This force or “suction by which water is held to peat particles” is called water tension (Rochefort & Quinty, 2003). This tension must not be too high in order for mire mosses to access water through their capillary network. Drainage and peat extraction result in changes to the water balance of the ecosystem. These changes to the ecosystem along with the removal of the acrotelm create unfavourable conditions for (spontaneous) *Sphagnum* re-establishment and growth, thus inhibiting further peat accumulation (i.e. Price, 1997; Van-Seters & Price, 2001; Price, Heathwaite, & Baird, 2003). When drainage ditches are constructed, ground water seeps out of the peat, thus lowering the water table and
subsidence of the area (Joosten & Clarke, 2002). The chemical and physical characteristics of peat water change as pH, nutrient concentration and peat bulk density (BD) increase (Prevost, Plamondon, & Belleau, 1999 cited in Price, 2000). Changes to storage capacity and increased water tension follow. Evaporative forces further increase water tension as moisture is drawn from the bare peat surface to the atmosphere. Increased peat bulk density indicates a higher ratio of solid peat particles to the total volume. So, the more peat within a given volume the less pore space in which water can be retained. Increased BD of the peat and smaller pore space (Price, 1997) hamper the capillary processes within the moss because the water present adheres to peat particles and is thus unavailable for Sphagna. Relying on a capillary network formed by the spaces between the plants’ stem, branch, and leafs, Sphagna will desiccate because the force with which water is held to peat particles is too high for Sphagna to overcome. Therefore, the more compacted and less water saturated peat soil is, the more difficult it is for Sphagna to establish. Factors causing these circumstances are drainage of the area and peat extraction, by which the acrotelm is lost and the more decomposed, compacted peat (and thus higher peat BD) of the catotelm is left behind. Moreover, water availability and drying and wetting cycles limit Sphagnum productivity and growth (McNeil & Waddington, 2003). To restore an entire ecosystem successfully, restoration of mire hydrology is an important aspect. Shantz & Price (2006b) summarized three restoration aims for the Bois-des-Bel peatland restoration that attempt to restore hydrological conditions vital for the establishment of Sphagnum vegetation: a stable water table close to the surface and soil moisture above 50 percent; these hydrological conditions were observed in areas where Sphagnum had re-colonized (Price & Whitehead, 2001).

Role of Mires and Peat

Values of ecosystems have been gaining recognition in the scientific community (Gren, Folke, Turner, & Batemen, 1994; Costanza et al., 1997) as ecosystem functions and services become increasingly known. One such ecosystem, mires and their peat have provided humans with a variety of services and have thus been exploited by humans. However, as their ecological function and role on a global scale is increasingly investigated, mires and peat become increasingly valuable; their preservation, conservation, and restoration are of increasing interest not only within the scientific community but also among the public.

Values of Peat

The values of peat and mires are thoroughly discussed in Wise Use of Mires and Peatlands (2002) and only few will be mentioned here. Mires provide habitats for few but highly specialized plant species, many of which are used for medicinal purposes. Mires further store and filter water and act as a buffer for heavy rainwater, thereby reducing possible flooding. Nevertheless, the function of mires is not only to provide habitats, water, food, etc, or a paleo-ecological archive but also raw material for energy use because peat can be used as a source of fuel once it is dry.

Role in Carbon Cycle

The process of terrestrialization and peat formation contributes to a positive carbon balance (Joosten & Clarke, 2002) because over thousands of years organic matter has been accumulating and storing atmospheric carbon. There are various estimates as to how much carbon is stored in peatlands. The IPS report Peatlands and Climate Change (2008) estimates that peatlands store between 10-30 percent of the global terrestrial carbon. Others estimate that peatlands store about one-third of soil carbon (Gorham, 1991; Crow & Wieder, 2005) or the equivalent of twice as much carbon as the global forest biomass (Parish, Sirin, Joosten, Minaeva, & Silvius, 2008) or 75 percent of atmospheric carbon or all terrestrial biomass (Kaat & Joosten, 2008). Overall, although estimates vary, it appears that peatlands are a major contributor and regulator of the global carbon cycle and that a significant amount of carbon is stored within them. The underlying mechanism of carbon storage is through photosynthesis of mire vegetation and its average greater primary productivity than decomposition. The primary productivity is frequently measured as the change in biomass over time. Biomass is the weight per area of vegetation that has been dried before weighing. Annually, about five to ten percent of the produced biomass is converted to peat (Joosten & Clarke, 2002) where about half of all organic matter is comprised of carbon and consequently stored in the peat as decomposition is retarded or even halted; with increasing peat depth decomposers decline in diversity and actual numbers.
Current estimates of long-term rate of carbon accumulation of the last 10,000 years range from 16.5 – 20 g m$^{-2}$ y$^{-1}$ for the boreal region (Joosten & Clarke, 2002). Although carbon accumulation rate highly depends on primary productivity and can vary greatly throughout time and space, at this rate the accumulation of 550 Gigatons ($= 550 \times 10^{15}$ g) of carbon in peat takes thousands of years. Keeping in mind that peat grows about 0.5 – 1 mm per year (Rochefort & Quinty, 2003), harvesting several centimetres per year for decades can release hundreds or thousands of years of accumulated carbon.

Estimates of carbon storage and emissions reveal that in ombrotrophic mires annually more than three times as much CO$_2$-carbons are stored than CH$_4$-carbons emitted (Saarnio et al., 2007). The delicate balance of CO$_2$ uptake and CH$_4$ release is in jeopardy as mires are being transformed. Compared to vegetation covered areas evapotranspiration rates are higher where vegetation coverage is low or absent (Waddington, Greenwood, Petrone, & Price, 2003). These increased evapotranspiration rates cause soil moisture to decrease. In combination with a lowered water table level, the zone of aerobic activities increases and peat oxidation is enhanced. Consequently, aerobic decomposition increases thereby releasing additional CO$_2$ from the soil. Furthermore, removal of the acrotelm during peat extraction disables further atmospheric CO$_2$ sequestration because there is no vegetation to accumulate carbon via photosynthesis. The inability to take up CO$_2$ from the atmosphere and the increased release of CO$_2$ from the soil to the atmosphere causes mires to shift from sinks to sources with ecosystem respiration rates up to 290 percent higher than natural sites (Waddington, Warner, & Kennedy, 2002). Measuring net ecosystem CO$_2$ exchange (NEE) provides a way to determine uptake of CO$_2$ by vegetation and release by soil and vegetation respiration. Generally, water table stabilization and establishment of vegetation should lower evapotranspiration, respiration, and net ecosystem CO$_2$ exchange towards the atmosphere. Because mires have the unique ability to store vast amounts of carbon for a long time (that is if they are not subject to natural or anthropological disturbance) a successful restoration of today’s cut-over mires may present an opportunity for future carbon sequestration.

Mire Restoration

Site preparation for modern peat harvest usually involves the construction of ditches to lower the water table. Once lowered, the acrotelm and consequently the catotelm become dry and the peat can be harvested. This also means that the conditions for typical mire vegetation growth are destroyed and consequently peat no longer accumulates. This further results in the loss of the mire’s function as a carbon sink. In order to restore cut-over mires to functional, peat-accumulating ecosystems, the “right” conditions must be (re-)created. Functional mires depend primarily on the hydrological situation. As mentioned above, peat accumulation depends on the composition of the mire vegetation which depends on the position of the water table and vice versa. Thus, re-establishing the hydrological pre-disturbance condition (if known) is one of the key components of restoration and part of any restoration (Rochefort & Quinty, 2003; Schumann & Joosten, 2008; Coillte, 2008).

Mire restoration is a relatively new scientific field and approaches often depend on site specific circumstances. Yet, over the years restoration approaches have become more similar and measures are overlapping as some short-term, small scale restoration successes can be claimed (e.g. Magner, 2007). However, large scale restoration efforts have not been achieved (Shantz & Price, 2006b) and long-term successes cannot yet be evaluated. Additionally, according to Shantz & Price (2006b) there has not been an evaluation of the collective impact of mire restoration measures.

Therefore, this research focuses on short-term results of restoration efforts and the successes and failures of accomplishing set goals of restoration of Sphagnum-dominated bogs in Canada and Ireland. While much research is done in Europe focusing on the mechanisms for failure and successes of mire restorations, none was found to focus on evaluating how restoration measures affect the entire ecosystem. Available literature focuses on individual aspects of restorations, such as hydrology, biodiversity, vegetation, etc. Additionally, available literature on European bog restoration is geographically very scattered and evaluation of all aspects of restoration of one location was not possible in a timely manner. Finally, due to time constraints one restoration project in Canada and Ireland each was selected due to their different pre-restoration conditions, similarity of the approaches to restoration,
and whole ecosystem restoration approach. At the two sites both vegetation establishment and hydrological conditions are monitored following restoration efforts. Unlike many other projects where research concentrates on single aspects of bog restoration such as hydrology, vegetation, biodiversity, and carbon fluxes, these two sites are evaluated as a whole ecosystem; the evaluation of practical restoration projects includes hydrology, vegetation establishment, biodiversity, and carbon flux. Historically, the Irish site may have been subject to manual peat cutting in earlier centuries but was definitely subject to afforestation in the 20th century. The Canadian site was vacuum harvested for less than a decade followed by abandonment of the site for nearly 20 years. Despite the short timeframe, vacuum harvest has left the Canadian site nearly void of vegetation. The Irish site showed some Sphagnum vegetation coverage prior to restoration. At both sites the taken measures included clearing the area of undesirable vegetation, blocking drainage ditches and construction of embankments. The Canadian site involved many more measures and is still subject to elaborate monitoring owing to the whole ecosystem approach of restoration. This approach of restoration was also the reason for using Bois-des-Bel bog as example of Canadian restoration. Here, all aspects of restoration are monitored and restoration focuses on all aspects of peatland – hydrology, vegetation establishment and growth, peat accumulation, carbon flux, and biodiversity. As for the Irish site, Camderry Bog represents restoration efforts undertaken under the Raised Bog Restoration Project. It was chosen for its location within a cluster of sites under restoration (which were also researched) and determined to be representative for other nearby restoration sites.

Although the two sites are not directly compared, the similar restoration techniques offer an opportunity to investigate if despite different pre-restoration conditions the goal of establishing a self-regulating and peat accumulating ecosystem can be reached. By assessing factors that contribute to successes and failures, the aim of this study is to determine whether mire restoration projects can reestablish these ecosystems including biodiversity and their functions in the global carbon cycle. An investigation through literature research and analyses of two completed mire restoration projects is believed to determine (1) what the restoration techniques of selected Irish and Canadian restoration projects are, (2) what success and failure factors of bog restoration can be distinguished and (3) if restoration efforts meet their goals.

First, a detailed overview of two completed bog restoration projects will be given. Next, changes in hydrology, biodiversity and carbon flux will be reported and discussed. Finally, the results will be used to establish whether restorations have led to achieving the restoration goals and how this may affect future use of mires, especially bogs.
Methods

The literature review was carried out using online available scientific journal articles, subject specific websites and books. In general the RuG online library resources were used to search electronic journals and electronic databases on mire restoration literature.

An EBSCOhost COMPLETE and Fulltext Database search were done. The results were similar as with Google Scholar with literature primarily from Canada. The geographic region in this database was narrowed down to Europe in order to find European literature on mire restoration. Literature unavailable though RuG online library was ordered via Interlibrary Borrowing (Illiad). Additional literature relevant to the subject and a summary of the 13th International Peat Society’s proceedings was provided by Dr. A.J. Schilstra. All literature found relevant to the subject of this report was saved and citation was exported into Reference Manager 12 usually using the website’s Citation Export option. Citation tracking was done only from the primary found literature but not from the secondary literature (ie. the citations of the citation were not followed).

The main source of literature came from two entities working on mire restoration projects: Coillte in Ireland and Peatland Ecology Research Group in Canada. Their works and publications were main source of information for this report and research further focused on two individual projects in each country. Project specific publications were studied and used to determine the extent to which restorations are successful in reaching the goal of restoration at the two sites.
Results and Discussion

To investigate changes to hydrology, biodiversity and carbon flux, several ongoing and completed restoration projects in Canada and Ireland were researched. While the objectives of the projects were similar, the goals differed (Table 2). This report differentiates between goals and objectives to highlight the achievement of either or both and its contribution to the overall success. The objectives are used to achieve the goal; in other words, the objectives represent physical steps required to achieve the goal. It further follows that not achieving the objective will probably cause a failure in reaching the goal. However, achieving the objectives does not necessarily entail achieving the goal. Besides differences in goals, there were also differences in who is carrying out the restoration, the sources of funding and initial conditions of the area under restoration. These factors influenced restoration measures taken and the extent to which restoration effects were monitored.

Canadian restoration efforts are carried out by academic scientists collaborating within the Peatland Ecology Research Group (PERG). It also includes the Canadian peat moss industry as well as federal and provincial agencies. The latter two are also the main source of funding. Their common objective is the “integrated sustainable management of peatland” (Peatland Ecology Research Group, 2006).

On the other hand Irish restoration is done by Coillte, a commercial company and owner of about seven percent of Ireland’s land cover (Coillte, 2007). The Raised Bog Restoration Projects undertaken by Coillte are funded by the European Union LIFE program as part of the Habitat Directive and NATURA 2000 (European Communities, 2009). The goal of Coillte’s efforts include restoring sites to “a favourable conservation status” (Coillte, 2008) along with others. Since “favourable” can be rather ambiguous, this report assumes restoration was done to re-establish a functional mire ecosystem and conserve remaining pristine mire because the title of Coillte’s project - Raised Bog Restoration Project - implies this.

Table 2: Goals and Objectives of the Bois-des-Bel restoration project in eastern Canada and Camderry Bog raised bog restoration in central Ireland (Peatland Ecological Research Group, 2007; Coillte, 2008a; Coillte, 2008b)

<table>
<thead>
<tr>
<th>Project</th>
<th>Goal</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bois-des-Bel</td>
<td>Reestablishment of self regulating ecosystem capable of peat accumulation</td>
<td>• Reestablishment of mire typical vegetation, including Sphagnum mosses</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rewetting of the site by raising and stabilizing the water table near the surface</td>
</tr>
<tr>
<td>Camderry Bog</td>
<td>Conservation and Restoration of threatened raised bog habitat to favourable conservation status</td>
<td>• Increased coverage of raised bog typical vegetation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Raising of water level within 10cm near the surface</td>
</tr>
</tbody>
</table>

The following detailed introduction to the two project sites aids in putting the restoration measures taken in context with goals and objectives. An analysis of successful accomplishment of the objectives is further provided and success and failures in re-establishment of mires’ hydrological conditions and biodiversity and carbon flux functions are explored in detail.

PERG Restoration projects and Bois-des-Bel Bog

The majority of mire restoration projects taking place in Eastern Canada (Figure 4, Figure 5) are carried out by PERG. While most projects are involved in long-term-monitoring to assess restoration successes, most sites assess specific ecological functions, such as hydrology, biodiversity, or the establishment of Sphagnum mosses.
St.-Charles-de-Bellechasse (site 3) investigates the effects of climate change on mires. On the other hand, ten sites are used to investigate the establishment of vegetation. Sites 2, 12, and 19 research berry plantation potential. Sites 8 and 13 are studied for Sphagnum growth while site 9 and 11 are used to study how invasive species affect mires. Site 5, 6, and 7 are abandoned mire where the establishment of spruce and larch are studied. Sites 6 and 11 are used to research amphibian movements and how to counter frost heaving respectively; sites 14 and 16 are being restored to fens. There are also experimental restoration projects of mires after various disturbances took place, such as sea water flooding (site 10) or block-cutting (site 15).

Figure 4: Sites of various experimental restoration projects focusing on long-term monitoring of restoration success, vegetation establishment, fertilization, climate change effects, and amphibian movements. Source: Peatland Ecology Research Group, 2006

Figure 5: Bois-des-Bel research site Quebec, Canada (47°59’N, 69°25’W); mined for seven years and abandoned in 1980. In 1999 restoration was initiated on 11.5 ha of which 8.4 ha (a) were restored, 2.4 ha (c) serve as reference, and 1 ha (b) as buffer zone. Source: Shantz & Price, 2006b

All these sites are used to investigate various aspects of restoration; however, PERG also recognized that it is very laborious to study restoration measure effects on small plots with specific indicators, such as hydrology or biodiversity. Investigating single indicators of restoration success may even be futile since mire functions depend on the interplay of hydrology, vegetation, and peat accumulation, as previously discussed. Therefore, Bois-des-Bel research station (Figure 4 site 17, and Figure 5) is used to study the restoration of a mire in its whole (Peatland Ecology Research Group, 2007).

Bois-des-Bel is located in Eastern Canada in the Province of Quebec (Figure 4). A weather station nearby measured a yearly temperature average of 3.2°C; from November – March temperatures are typically below 0°C and from April – October temperatures are above 0°C; total average precipitation of 962.9 cm, 277.3 cm snow, and 685.5 mm rainfall annually were recorded (Environment Canada, 2008). According to paleoecological research, the 200 ha Bois-des-Bel peatland site is a treed bog and characterized by black spruce tree cover for nearly its entire development (La Voie, Zimmerman, & Pellerin, 2001). In 1972 an area of 11.5 ha were clear felled, drained and then subject to vacuum harvest from 1973 until 1980. After nearly 20 years of abandonment, in the fall of 1999 the harvested site of the Bois-des-Bel bog was used to initiate a peatland restoration project on ecosystem level. To restore the site, the steps outlined in Peatland Restoration Guide 2nd Ed. (Rochefort & Quinty, 2003) were applied.
Table 3: Steps taken to restore site at ecosystem level; restoration efforts at Bois-des Bel mire were completed in 2000. Step order and magnitude are site specific and should be adjusted to appropriate levels at each site.

<table>
<thead>
<tr>
<th>Surface preparation</th>
<th>levelling and scraping of the surface as well as creation of terraces and bunds; division of the area into eleven 30 x 300 m² fields (Figure 5 a,b,c) that are separated by drainage ditches running south into a main drainage ditch (Petrone, Waddington, Price, &amp; Carey, 2001)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant collection and spreading</td>
<td>a nearby natural site was used to collect plant fragments which were spread over the restoration site with a manure spreader</td>
</tr>
<tr>
<td>Straw spreading</td>
<td>application of a uniform layer using 3000 kg/ha straw mulch (Rochefort, Quinty, Campeau, Johnson, &amp; Malterer, 2003)</td>
</tr>
<tr>
<td>Blocking drainage</td>
<td>all but two ditches were blocked. Blocking ditches after restoration operations are completed is recommended (Rochefort et al., 2003).</td>
</tr>
<tr>
<td>Fertilization</td>
<td>application of 150 kg/ha phosphate rock (= 19.5 kg/ha phosphate) (Rochefort &amp; Quinty, 2003).</td>
</tr>
</tbody>
</table>

Since then, hydrology, physicochemical and microbial soil characteristics, carbon sink function, vegetation coverage and diversity as well as return of fauna are monitored (Table 4). In order to determine successes, in 2001 a database was created inventorying flora and fauna of a neighbouring 200 ha large pristine mire which serves as a reference (Lachance & Lavoie, 2007).

Table 4: Monitoring subjects and their frequency; several permanent and temporary stations are used to monitor restoration measures taken. Stations are located in restored, disturbed, and natural sites for comparative purposes.

<table>
<thead>
<tr>
<th>What is monitored?</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant diversity:</td>
<td>Every second year (Fall)</td>
</tr>
<tr>
<td>• Mosses, specifically <em>Sphagnum</em></td>
<td></td>
</tr>
<tr>
<td>• Lichens</td>
<td></td>
</tr>
<tr>
<td>• Liverworts</td>
<td></td>
</tr>
<tr>
<td>• Vascular plants</td>
<td></td>
</tr>
<tr>
<td>Vegetation coverage evolution and plant biomass accumulation</td>
<td>Every year (Fall)</td>
</tr>
<tr>
<td>Hydrology:</td>
<td>Every year (Summer)</td>
</tr>
<tr>
<td>• Water table depth</td>
<td></td>
</tr>
<tr>
<td>• Peat water tension</td>
<td></td>
</tr>
<tr>
<td>Carbon fluxes</td>
<td>Growing season</td>
</tr>
<tr>
<td>Peat microbial flora</td>
<td>Every year</td>
</tr>
<tr>
<td>Peat and water chemistry</td>
<td>Every year (Summer)</td>
</tr>
<tr>
<td>Amphibians and insects</td>
<td>Every year</td>
</tr>
<tr>
<td>Colonizing birds</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The parameters have been monitored since 2000 and continue to be monitored to this day. This project is a long-term project aimed at determining how the above taken measures (Table 3) affect hydrology, vegetation coverage, microbiology, carbon fluxes, fauna, and ultimately peat accumulation.

**Coillte Raised Bog Restoration Projects and Camderry Bog**

The Raised Bog Restoration Project is made up of 14 sites in the central plains of Ireland with a total area of 571.2 ha of mires in similar conditions (Figure 6). Due to peat harvest for fuel, electricity production, and horticulture, the area of mires throughout the Irish midland has been critically reduced. It is estimated that less than six percent of the original mire area remain of which more than
half are proposed as Special Areas of Conservation (SAC) (Coillte, 2008). It is further thought that
about half of all remaining pristine raised bog habitats of Europe are situated in Ireland (European
Communities, 2009). Most SAC sites contain some intact ecosystems but these mires are affected and
threatened by cutover mires surrounding them. This is because the drainage ditches dug and afforesta-
tion of the area adjacent to the intact mire have had and continue to have an impact on the entire mire
ecosystem. For instance, representative for many mires throughout Ireland, Camderry Bog is an eco-
system where the marginal area of the site was subject to peat cutting and afforestation (Figure 6).
Both peat cutting and afforestation have caused the desiccation of mire surface and loss of mire-
typical peat forming vegetation.

Manual peat cutting in Ireland dates back to prehis-
toric times when it was mainly used as a source of
fuel. Peat cutting reached a peak in the 19th century.
Nowadays, peat is still harvested for fuel use, how-
ever by means of heavy machinery (Renou, Egan, &
Wilson, 2006). When peat was cut manually, it was dug in sods and stacked to dry for future fuel us-
age (Rydin et al., 2006). Now, the use of heavy machinery requires extensive drainage of the area in
order for the machines to operate. Therefore, hydrological alterations may be more severe when peat
is cut using excavators. Additionally, many Irish mires are afforested. Afforestation requires drainage
of the mire, cultivation and phosphorous fertilization of the peat in order for forest to establish well
(Renou-Wilson & Farrell, 2007). Once a closed forest cover is established and hydrology changed,
vegetation changes occur. These changes include reduction of Sphagnum cover and replacement by
forest floor mosses. After some time, conifer litter covers floor vegetation growth and saplings may
establish. Overall, afforestation causes a change in ecosystem away from mire (Rydin et al., 2006).

Camderry Bog is located in the eastern part of County Galway, Ireland (Figure 7). The project
area is 13.8 ha large and part of a 281 ha proposed SAC. At an elevation of 80m the area is subject to
oceanic climate with mean annual temperatures and precipitation of ~9.3°C and 1000mm respec-
tively15 (MET Eireann, 2009). Additionally, Ireland’s climate is heavily influenced by the thermohal-
line circulation. Therefore, Ireland has mean daily temperatures above 0°C throughout the winter
months and a relatively humid climate all year around.

Due to afforestation the vegetation of the restoration site consisted mainly of Pine (Pinus con-
torta) and Spruce (Picea sitchensis) which were well established. Hydrological regime may have
changed although pre-restoration scientific surveys of the site revealed that the site still contains a de-
cent cover of Sphagnum where surface is moist and pools are present. The site is in the immediate

Figure 6: Camderry Bog; Part of a cluster of bogs. Cam-
derry Bog is located within the Special Area of Conserva-
tion (SAC) recognized by the EU as valuable habitat desig-
nated for conservation (striped area). Source: Department of
the Environment, 2009

Figure 7: Ireland. The 14 sites are located through-
out Ireland. The two darker dots show sites used
for demonstrative purposes and are accessible to
the public. Source: www.raisedbogrestoration.ie
vicinity of intact raised bog where *Sphagnum* and other bog typical vegetation including lichens grow. Additionally, several bog pools are present. Fauna recorded at the site include fallow deer, red squirrel, otter, stoat, and pine marten (Department of the Environment, 2009).

In 2003, a 13.8 ha large portion of the SAC Camderry Bog site was clear-felled and rid of conifer crop. Remaining vegetation debris was used to build bunds to protect establishing mire vegetation. Additionally, drainage ditches were blocked using peat dams to raise water levels. Follow up maintenance included control of regenerating saplings. To investigate if restoration measures were successful, the site’s vegetation and water level changes were monitored (Table 5). Vegetation coverage and evolution was monitored via the establishment of three 10x10m quadrants located at the southern and northern margins as well as in the centre. Any changes in water level were recorded by eight WAL-RAGs installed during restoration operations.

### Table 5: Parameters to investigate how taken restoration measurements meet the goals and objectives of restoration are shown below.

<table>
<thead>
<tr>
<th>What is monitored?</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation coverage evolution</td>
<td>Yearly for four years</td>
</tr>
<tr>
<td>Water level changes</td>
<td>Monthly for four years</td>
</tr>
</tbody>
</table>

In sum, both the Canadian and Irish mires are located in the northern hemisphere with similar climatic conditions that allow peat accumulation. They were subject to peat harvest and thus show an altered hydrological condition. Pine and spruce establishment are common for both bogs. Although both are surrounded by functional mires, the function of these sites is compromised and restoration actions were taken. The common measures taken include damming of drainage ditches and the construction of bunds. Monitoring of water levels and vegetation coverage (and) evolution are conducted at both sites to evaluate how the taken measures contribute to reaching the establishment of a self-regulating and peat-accumulating ecosystem.

### Effects of water table level changes

All hydrological aims and objectives were achieved. At both sites the applied restoration techniques raised the water table closer to the surface but also increased seasonal water table fluctuations (Shantz & Price, 2006b; Derwin, 2008). At Bois-des-Bel the water table rose to less than 40 cm below the surface, the mean volumetric soil moisture remained above 50 percent and soil-water pressure remained above -100 mb. Furthermore, elevation changes were observed, indicating a peat volume change, hence a decrease in peat BD. The decrease in peat BD affects water tension and allows mosses to access water in the peat easier. All these factors provide enhanced conditions for vegetation establishment and growth. However, due to a higher water table, increased soil moisture, insufficient vegetation coverage, and construction of bunds, surface soil froze during winter months causing establishment of temporary ponds and overland flow (Shantz & Price, 2006a). Snowmelt and pond water escaped via overland flow before the surface thawed and could therefore not be stored in the peat soil. The construction of bunds aided in retaining snowmelt water at the site which should have increased water availability for storage. However, insufficient vegetation coverage most likely allowed snow removal by wind and therefore less snow melt at the site. Hence, restoration efforts failed in fully returning the bog’s ability to store snowmelt water.

During the summer months, WALRAGs indicated a drop in water table level. This may have various reasons such as increased evaporation or ground water usage. If the soil surface is only scarcely covered by vegetation, more water from the soil can evaporate. Additionally, during the summer months ground water may be used for irrigation of neighbouring agricultural fields and thus further depleting water storage. There may be many reasons why the water table drops during summer months but whatever the reason, restored mires are affected by it. Data from Camderry Bog suggests that there is a relation between seasonal water table fluctuation and total vegetation coverage. In years when the water table was lowest during the summer, the total vegetation coverage had decreased. Apparently, the water table drop threatens vegetation survival during the summer months and decreases total vegetation coverage. This may be attributed to a possible vegetation shift resembling that of hollow to hummock vegetation shift. When the water table is close to the surface, species associated with
hollows are often found. When the water table drops below a certain threshold a shift to hummock vegetation species occurs (Breeuwer et al., 2008). Since in the summer water table depth increases, a shift to hummock species may be occurring. However, since the area may be colonized with hollow species predominantly, the shift to hummock species is not rapid enough. A decrease in overall vegetation coverage may occur because the vegetation cannot adjust rapid enough to the change in water availability.

The physical and chemical characteristics of the restored site of Bois-des-Bel peatland remained more similar to the unrestored site and only nutrient ratios showed a development trend towards the (natural) reference site (Andersen et al., 2006) while overall remaining low. Compared to the natural site pH of the restored site was less acidic while total Ca concentrations were much higher. This may have negative implications for *Sphagnum* establishment and growth since a high pH and Ca concentration are thought to be a fatal combination for *Sphagna* (Rydin et al., 2006). Since nutrient availability and physicochemical conditions of the peat determine abundance and activity of microbial communities, investigating the status of the latter one might also give indication of the status of site rehabilitation.

**Biodiversity**

Vegetation colonization of the restored sites in both Canada and Ireland had significantly increased (Mazerolle et al., 2006; Derwin, 2008). Bryophyte coverage had increased; specifically hair cap moss (*Polytrichum strictum*) which was determined to be a good nurse plant for *Sphagnum* because they alleviate frost heaving and are able to keep *Sphagnum* fragments more temperate and humid than bare peat surface (Groeneveld, Masse, & Rochefort, 2007). Increased bryophyte coverage might have been due to fertilization. While the soil at the Irish site was fertilized during afforestation, the Canadian site was fertilized as part of restoration. At the Canadian site it was determined that when the soil is fertilized hair cap moss was able to double its coverage (Sottocornola, Boudreau, & Rochefort, 2007). Therefore, even when unintentional, fertilization of the soil at some point may have helped bryophytes to increase coverage which subsequently aided in the increased surface coverage of *Sphagnum*. Surveys revealed that coverage increased (Graph 1) and where mechanical introduction occurred *Sphagnum* surface vegetation coverage was higher than hoped for (Waddington, Rochefort, & Campeau, 2003). Favourable conditions for *Sphagnum* establishment are also provided by the application of straw mulch. Covering newly spread plant fragments with straw mulch was shown to reduce water tension and daytime temperature within the soil, and increases relative humidity at the soil surface (Price, Rochefort, & Quinty, 1998). Evidently, the presence of fertilizer and straw mulch enhance the conditions for *Sphagnum* establishment where bare peat surface is initially large.

Open water area, such as bog pools further contribute to *Sphagna* establishment and growth. However, there appears to be no clear trend in whether the amount of open water area correlates to bryophyte coverage. This is somewhat surprising as open water area could provide water to vegetation even when water table is low. Additionally, dominant species found near artificial pools differed from natural pools (Mazerolle et al., 2006), possibly competing with mire-typical pond vegetation and although open water area at the Irish site decreased, species number continued to increase (Derwin, 2008). While this may be important in terms of increasing biodiversity, it may also compete more than desired with mire-typical vegetation and ultimately animals. Therefore, measures taken to increase biodiversity should be done with caution as it may not contribute to the re-establishment of mire-typical species. Hitherto, it is unclear how pools affect mire vegetation coverage. It is clear, however, that bog pools are vital for amphibians and arthropods abundance as they offer valuable summer habitats (Mazerolle, 2005). It was actually shown, that when mires are drained for agricultural purposes, amphibian and bird species richness declines (Mazerolle, 2003) while small mammals increase significantly (Mazerolle, Drolet, & Desrochers, 2001). Upon restoration arthropod abundance remained low whereas an increased abundance of amphibians were found around artificial pools along with highly specialized mire-associated aquatic beetles (Mazerolle et al., 2006). At the same time an increase in bird species richness was observed but mire specialists remained absent. Obviously, the presence of pools affects the availability and type of niches for animals. And even though artificial pools did not completely aid in returning all mire-typical fauna they may play an important role in keeping mire typical fauna and flora at the sites. It appears desirable to have at least some open water area as is typical of pristine mires to allow for re-establishment of mire-typical biodiversity.
Andersen et al. (2006) noted that restoration efforts led to increased fungal respiration in the subsurface layer while there was no increase in bacterial respiration rates, thus CO$_2$ production. However, low concentrations of CH$_4$ were measured at the restored site indicating some methanogen activity. The raising of the water table may thus have enabled some methanogenic activity. However, since CH$_4$ and CO$_2$ amount emitted via microbe respiration depend on organic material and quality available, the restored site may not have yet enough organic material to support large communities of methanogens and methanotrophes. Additionally, phosphate fertilization may have contributed to high P: C nutrient ratio. But, because carbon is required for aerobic and anaerobic respiration, a high P: C ratio is undesirable. The application of fertilizer may hinder microbe establishment. Therefore, although fertilization may have positive effects for vegetation establishment the nutrient ratio should be considered when trying to restore microbial characteristics of mires.

**Carbon Flux**

While it was expected that the net ecosystem exchange (NEE) of restored mires decreases with increasing vegetation coverage and raised water table levels, measurements revealed otherwise: mires were still releasing carbon at high rates. NEE rates showed that even after two to three years past restoration mires were still a source of carbon to the atmosphere (Petrone et al., 2001; Wilson et al., 2007). Although lower evapotranspiration rates (Petrone, Price, Waddington, & von Waldow, 2004) were observed, soil respiration prevailed (McNeil & Waddington, 2003), probably owing to summer water table decline. Wet-dry cycles of soil negatively impact vegetation growth, thereby inhibiting increased *Sphagnum* primary production necessary to offset soil respiration rates (see Hydrology). Additionally, *Sphagnum* productivity at early stages of restoration might not offset soil respiration rates because vegetation coverage is low. Lower evapotranspiration is probably due to some vegetation coverage and overall raised water levels. Increased vegetation coverage added to total vegetation productivity increase which is usually highest during growing season (summer). Indeed Wilson et al. (2007) and Waddington & Warner (2001) determined that during growing season NEE was a source of carbon from the atmosphere. During this time, vegetation productivity was higher than the decom-

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Graph 1: Vegetation coverage at Camderry Bog. Three Quadrants (10x10m) were marked and vegetation evolution was monitored from 2005 to 2008. Bryophyte vegetation increased dramatically. *Sphagnum* vegetation increased, albeit less dramatically. Nevertheless, total vegetation increased at all sites and some pine saplings re-established.
position rate and carbon might have been accumulating in the acrotelm. During winter vegetation productivity is lower than decomposition rate and pristine mires turn into seasonal carbon sources. Seasonal water table fluctuations as have been observed at restored sites (see Hydrology) might have prevented reaching maximum carbon accumulation rates during growing season as water table and temperature control carbon accumulation and release (Waddington & Warner, 2001). Additionally, extended periods of low water table in combination with little or no precipitation severely affects vegetation establishment and growth as vegetation might desiccate. This could turn mires into carbon sources even during growing season and thus to overall carbon sources despite vegetation establishment. It is often stated that the application of straw mulch contributes to restored mires being a consistent source of CO$_2$ (Waddington et al., 2003; Waddington, Rotenberg, & Warren, 2001) because decomposing straw mulch may contribute significant amounts (up to 30 percent) of CO$_2$ from mires to the atmosphere. However, no matter the location of the straw mulch, its decomposition releases CO$_2$ to the atmosphere; this emission should therefore be omitted (or considered) when NEE of mires is determined. Nevertheless, the total seasonal CO$_2$ flux of the site remained high.

Overall, although evapotranspiration rates were lowered and NEE was seasonally positive (indicating carbon absorption from the atmosphere), based on currently available scientific knowledge restoration efforts failed to return mires to net carbon sequestering ecosystem. This failure was probably mainly due to fluctuating water tables, which were low during growing season, thereby inhibiting maximum vegetation productivity and increasing aerobic peat layer. The application of a mulch layer benefits vegetation establishment and increases soil moisture. The transplantation of acrotelm may be a restoration technique that returns mires faster to carbon accumulating system (Cagampan & Waddington, 2008). It does not involve spreading of mulch and vegetation fragments and may thus accelerate restoration efforts. Instead it uses the intact acrotelm that was removed prior to peat harvest. This is thought to faster establish compared to collected plant fragments from pristine mire once a water table level close to the surface is re-established. However, this approach is very new and more research is necessary.

To summarise, the restoration techniques at both the Canadian and Irish site consisted of blocking drainage ditches and construction of bunds after the area was rid of undesirable vegetation. Additional measures undertaken at the Canadian site included application of plant fragments, straw mulch and fertilizer to enhance conditions for vegetation establishment. In addition at this site artificial pools were constructed to simulate natural conditions and encourage fauna and flora establishment. Due to these measures, the objectives were reached: the raising of the water table to a level that is thought to allow establishment of Sphagna and increased vegetation coverage, possibly due to fertilization of the soil. Water storage capacity could not be fully utilized by snowmelt water due to freezing of soil surface and insufficient vegetation, resulting in snowmelt drainage via overland flow and snow ablation respectively. Seasonal water table fluctuations and

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**Figure 8:** Model of carbon flux of functional mires. Vegetation and microbial activity are the constituents of carbon flux properties. A mires ability to accumulate and release carbon are mainly determined by microbial activity and vegetation productivity (Parish et al., 2008). Source: Faubert, 2004 in Parish et al., 2008, pg. 106.
physicochemical soil characteristics continue to affect vegetation coverage negatively. Although seasonal water table fluctuations are normal, its increase may potentially affect vegetation primary production and microorganism diversity and abundance. Additionally, vegetation of restored mires may not adapt quickly enough and thus total vegetation coverage decreases. The observed combination of basic soil and high Ca concentrations of restored mires may be fatal for *Sphagnum* and thus hindering its establishment and growth. Pools, although contributing to biodiversity also allowed non-typical mire vegetation to establish which is competing with mire-typical vegetation. Furthermore, amphibians and birds re-colonized restored areas. However, mire specialized birds remained absent. At Bois-des-Bel fungal communities have risen and some methanogen activity can be claimed. However, CO₂ production remains the same, indicating an unbalanced microbial soil community, probably due to unfavourable nutrient ratio and limited organic material necessary for microbe establishment. Although a lag time between the establishment of vegetation and microorganisms exists (Andersen et al., 2006) large seasonal water table fluctuations may prolong lag time and delay mire carbon sequestration function. Hitherto, restoration efforts have failed in enabling the establishment of microbial communities characteristic of natural bogs.

Furthermore, although evapotranspiration rates had decreased, soil respiration rates prevailed, and CO₂ emission to the atmosphere continued. Despite the fact that NEE rates showed positive values during growing season, highly fluctuating water table levels, insufficient vegetation coverage, and prolonged periods with little or no precipitation can negate NEE values and continue high CO₂ emission from the restoration site. So far, measures taken to recreate natural bog habitat have resulted in occurrence of invasive (non-typical mire) species competing with mire-typical species. Moreover, while some mire-typical biodiversity was able to return mire-typical food webs are missing partially because keystone species remain absent. Additionally, growth of non-typical mire species allows for increased competition with mire-typical species, thus making *Sphagnum* establishment more difficult. Vegetation coverage, especially bryophyte coverage, increased but mire-typical flora, especially *Sphagnum* was not sufficient to establish a self-regulating and peat accumulating ecosystem. These results show that some restoration measures contribute to reaching the objectives of restoration but overall the goals of restoration are not met, yet.
Conclusion

The goal of mire restoration is the establishment of a self-regulating ecosystem capable of peat accumulation and its conservation to a status that favours mire ecosystem health. To achieve this, specific objectives were to raise and stabilize the water table and the establishment and coverage increase of mire-typical vegetation, specifically *Sphagnum*.

Overall, the objectives in the two selected restoration projects were more or less achieved but not the goal. After careful investigation it is concluded that while restoration methods at both the Canadian and Irish site have restored some vital mire functions, a self-regulating, peat accumulating ecosystem was not achieved and conservation may be in question. This conclusion is supported by a survey undertaken in the UK (Peak District National Park Authority, 2008). In this survey project representatives were asked to evaluate project restoration success. Mean overall success was rated at 67 percent after three years, indicating that some successes could be claimed but more time is required to restore a site to a fully functional ecosystem. This success rate may be an overestimate and projections too optimistic because otherwise restoration project funding may become an issue. The current inability to restore neither of the exploited bogs (Bois-des-Bel and Camderry Bog) regardless of pre-restoration condition demonstrates that these bogs are complex ecosystems with an extremely interdependent relationship of hydrology, vegetation, and peat accumulation. Vegetation establishment necessitates restored hydrology, all determining peat accumulation and vice versa. This inter-reliant relationship is typical for mire ecosystems and may contribute to not being able to fully restore Bois-des-Bel Bog and Camderry Bog after being disturbed. Nevertheless, these two sites are examples of a limited number of evaluation studies currently available. More restoration evaluation studies taking a whole ecosystem approach are necessary to confirm the success of mire restoration projects.

There may also be a matter of definition. Restoration is the return to a former state (Webster’s Dictionary, 1985). As many mires have been harvested for decades, the former state may be unknown. Even when the former state is known, the return to a state identical to that before disturbance seems unlikely. Establishing a self-regulating, functional mire ecosystem resembling that of pristine mires may be a more appropriate goal. At Bois-des-Bel for instance restoration efforts have resulted in the establishment of non-mire typical species. If however, long term these non-typical mire species are involved in peat accumulation than the goal can be reached while the area was not returned to a state identical of that before disturbance. Additionally, since the goal of favourable conservation status is very ambiguous, clarification or definition of it is very desirable to determine if the goal was reached. Although these results cannot be generalized for all restoration efforts, they may be considered as anthropological activities continue. Since so far, at Bois-des-Bel Bog and Camderry Bog the goal of restoration has not been reached, further exploitation that leave mires in similar conditions can aggravate the situation. As of now the carbon sequestering function of mires is restricted to pristine mires. That area is shrinking as peat is extracted primarily for horticulture and energy implying that not only are more greenhouse gases released from long term peat storages but also less can be sequestered. Its use not only destroys valuable habitat and consequently contributes to biodiversity decline but also contributes to climate change as carbon flux is disturbed. Since annual peat accumulation is very slow the rate of replacement is much slower than its current rate of consumption by humans. It can therefore not be considered a renewable resource. This is in congruency with the European Parliament decision (European Parliament, 2007) but not with the International Panel of Climate Change who declassified peat a fossil fuel and reclassified it a “slowly renewable resource” (International Panel on Climate Change, 2006). Regardless of this disagreement, peat use is not sustainable because mire ecosystem processes and functions are destroyed in preparation for and during peat harvest. Furthermore, according to Schilstra (2001), the three broadly defined conditions for the sustainable use of a natural resource Daly (1990) are also not met. Daly (1990) formulated three conditions for the sustainable use of natural resources: 1) Renewable resources should not be exploited at a rate higher than their regeneration level. 2. Non-renewable resources should not be depleted at rates higher than the development rate of renewable substitutes; i.e. part of the resources’ revenues should be invested in renewable substitutes so that when the non-renewable resources become unavailable, the renewable substitutes can take over completely, and 3. The absorption and regeneration capacity of the natural environment...
should not be exceeded. Schilstra (2001) argues that 1) the current use of peat exceeds its regeneration rate; 2) peat is currently depleted at higher rates than renewable resources are developed in its place, and 3) only when the changed carbon fluxes are attributed to pristine mires and forestry drained peatlands is the absorption and regeneration capacity of the natural environment not exceeded. Overall, the use of peat for commercial energy production is not sustainable regardless if peat accumulation function is restored.

While there are some successes that, bog restoration efforts Bois-des Bel Bog and Camderry Bog have failed to return these exploited bogs to peat accumulating ecosystems that are self-regulating. The restoration measures taken have led to increased favourable conditions for peat accumulation when compared to unrestored sites. However, more time is needed to determine if a self regulating ecosystem that accumulated peat can be re-established. Therefore, although this outcome may not be representative for all bogs, based on these two studies the conservation and preservation of pristine bogs may be in our best interest to maintain bog biodiversity and function.
Literature


Faubert (2004). *The effect of long-term water level drawdown on the vegetation composition and CO2 fluxes of a boreal peatland in Central Finland.* (Master of Science Laval University.).


**Endnotes**

1 This is mainly due to different classification systems of the various countries in which peat can be found. Also, as discussed earlier, some ecosystems may overlap and can or cannot be classified as peatlands, depending on its peat forming ability and record. Additionally, through anthropogenic activities such as drainage or mining, exploited mires may now fall into another category (such as mineral soils) and not be counted as mires (Rydin et al., 2006). Thus the actual area covered by peatlands is probably much larger than current estimates.


3 Here too, as with many percentages, variations occur. The numbers were taken from *Biology of Peatland* (2006) which refers to the IMCG database. However, as of 1-14-2009, updates have not occurred on the IMCG database ([http://www.imcg.net/gpd/gpd.htm](http://www.imcg.net/gpd/gpd.htm)) and numbers are unavailable.

4 The former and current extent of mires and peatland is based on estimates and regionally available data in 2002 respectively.

5 This is actually debated (Rydin et al., 2006) as the diplotelmic model was introduced for raised bogs but is also used in for general description of peatlands.

6 e.g. warblers, finches, thrushes, see Lachance & Lavoie, 2007.

7 Amphibians associated with mires include frogs, newts, salamander, and toads.

8 Arthropods associated with mires include (aquatic) spiders, insects, and (aquatic) beetles.

9 The trophic level is the place an organism occupies in the food chain of an ecosystem.

10 Bulk density is the ratio of the mass of dry solids to the total volume of the soil in which the solids are contained.

11 These aims were separate but related to the objectives outlined in Table 2. These specific aims might be considered a subset of the objective to restore hydrological conditions.

12 The other five objectives ([http://www.raisedbogrestoration.ie/about-raised-bog-project.html#objectives](http://www.raisedbogrestoration.ie/about-raised-bog-project.html#objectives)) will not be discussed here.

13 Weather Station St. Arsene, Quebec, Canada, located at 47°57'N 69°22.8'W with the climate ID 7056890 and an elevation of 76.2 m was chosen as it is the closest to the Bois-des-Bel research station according to the coordinates.
Bunds are embankments.
Data from the Birr weather station measured from 1961-1990.
WALRAG: Water Level Range Gauges. Devices that measure the water level within the peat.
Voles, shrew and mice for example.
Keystone species are inhabitants of an ecosystem where they help determine the type and abundance of other organisms (primarily through the association in the food web).