FEN RESTORATION IN MANITOBA

FINAL REPORT

Presented to Forestry and Peatlands
Manitoba Sustainable Development




Editorial group: the PERG researchers Line Rochefort, Maria Strack, Pete Whittington and their research team: Martin E. Brummell, Laurence Turmel-Courchesne, Melanie Hawes & Marie-Claire LeBlanc.

June 30, 2017

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Presented to Forestry and Peatlands (Manitoba Sustainable Development) as a deliverable of the NSERC industrial CRD (2013-2018) –Addendum 1: Carbon exchange in Manitoba peatland following after-use management research agreement.

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June 2017

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1. Context

The Peatland Ecology Research Group (PERG), based in Université Laval (Québec City), has been conducting research on peatland management practices since 1992. Over the years, in partnership with the peat industry, the research group has developed a peatland restoration method, called the Moss Layer Transfer Technique (MLTT)[1], for peatlands closed after peat extraction. While the method was first tested and applied to restore bogs in Eastern Canada, it is now being transferred and adapted to other types of environments, locations and climates. This topic is one of interest within the PERG's NSERC Collaborative R&D Grant (2013-2018) "Farm, restore and model: responsible management of peatlands for a sustainable Canadian horticultural peat industry".

With the development of the peat industry in Manitoba, some sites have now reached their industrial end-of-life. In order to develop best management practices for these sites, the restoration method has to be adapted and additional strategies tested for the Prairies and Western provinces of Canada. On certain sites, bog peat has been extracted down to the underlying sedge-peat layer. In these cases where remnant surface conditions are closer to minerotrophic peat conditions, or when groundwater resurgence creates mineral-rich conditions on former *Sphagnum*-dominated peatlands, restoration actions should aim at the return of fen ecosystems. However, based on a first fen restoration project conducted in Québec[2], the method to restore fens requires improvement. Additionally, when extracted sites are spontaneously rewetted (following drainage ditches collapsing or clogging by beaver dams), revegetation can sometimes establish naturally. Therefore, could rewetting be a valid option for fen restoration? Conversely, little is known about the carbon exchanges in fens or resulting from different after-use management strategies.

These observations suggested that scientific knowledge has to be further developed for minerotrophic peatlands. The sites available for restoration in Manitoba represented an excellent opportunity to test different techniques, learn more about fen hydrology and develop scientific knowledge about carbon fluxes in natural and restored environments.

In May 2015, a research agreement (Addendum 1 to NSERC industrial CRD (2013-2018) - Carbon exchange in Manitoba peatland following after-use management) had been ratified by the Manitoba Conservation and Water Stewardship and Université Laval. This initiative is part of the Peatlands Stewardship Strategy, and is aimed towards supporting research on Manitoba peatlands. Ducks Unlimited Canada (DUC), the Canadian Sphagnum Peat Moss Association (CSPMA) and Sun Gro Horticulture also provided akin support and funding for the realization of

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[1] Quinty F. & Rochefort L. 2003. Peatland restoration guide, 2nd edition. Canadian Sphagnum Peat Moss Association and New Brunswick Department of Natural Resources and Energy. Québec, Québec. 106 pp. www.gret-perg.ulaval.ca/uploads/tx_centrerecherche/Peatland_Restoration_guide_2ndEd.pdf.

[2] Rochefort L., LeBlanc M.-C., Bérubé V., Hugron S., Boudreau S. & Pouliot, R. 2016. Reintroduction of fen plant communities on a degraded minerotrophic peatland. Botany 94(1): 1041-1051.

additional research projects in Manitoba (Addendum 2: Impact of rewetting and fertilization following horticultural peat extraction on peatland hydrology and carbon exchange). The PERG would like to thank Sun Gro Horticulture for his generous and sustained collaboration to the projects. The assistance provided during the planning and execution of the restoration work, as well as all the logistical and material support made it possible to carry out these projects on their industrial sites.

This document presents a summary of the research that began May 2015 within the CRD and the two addendums, as the projects are often intertwined and incorporated into larger research projects. The "Fact Sheet" format (section 3) aims at providing easily accessible and comprehensible information. As some of the projects are part of graduate students' research projects, preliminary results are sometimes provided. In these cases, additional results will be available in the student's thesis or scientific publications.

2. Study Sites

Research projects have been conducted on four Sun Gro Horticulture industrial peat extraction sites located in Eastern Manitoba (Figure 1).

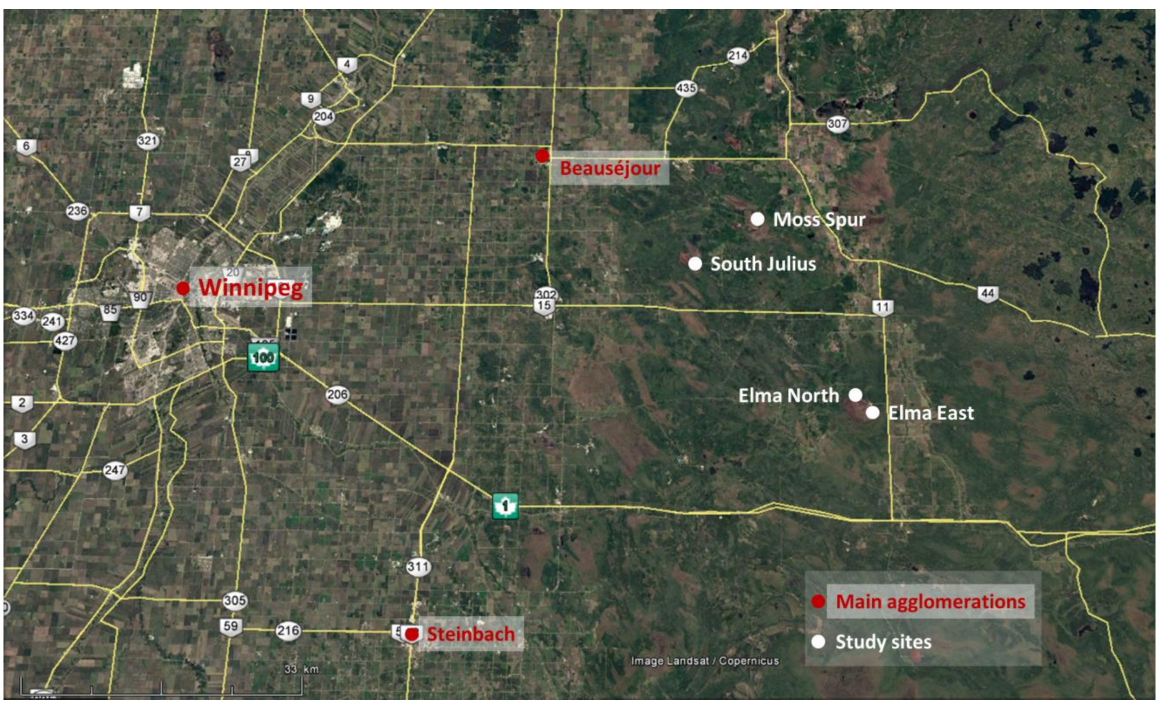


Figure 1. Location of the 4 research sites in Manitoba

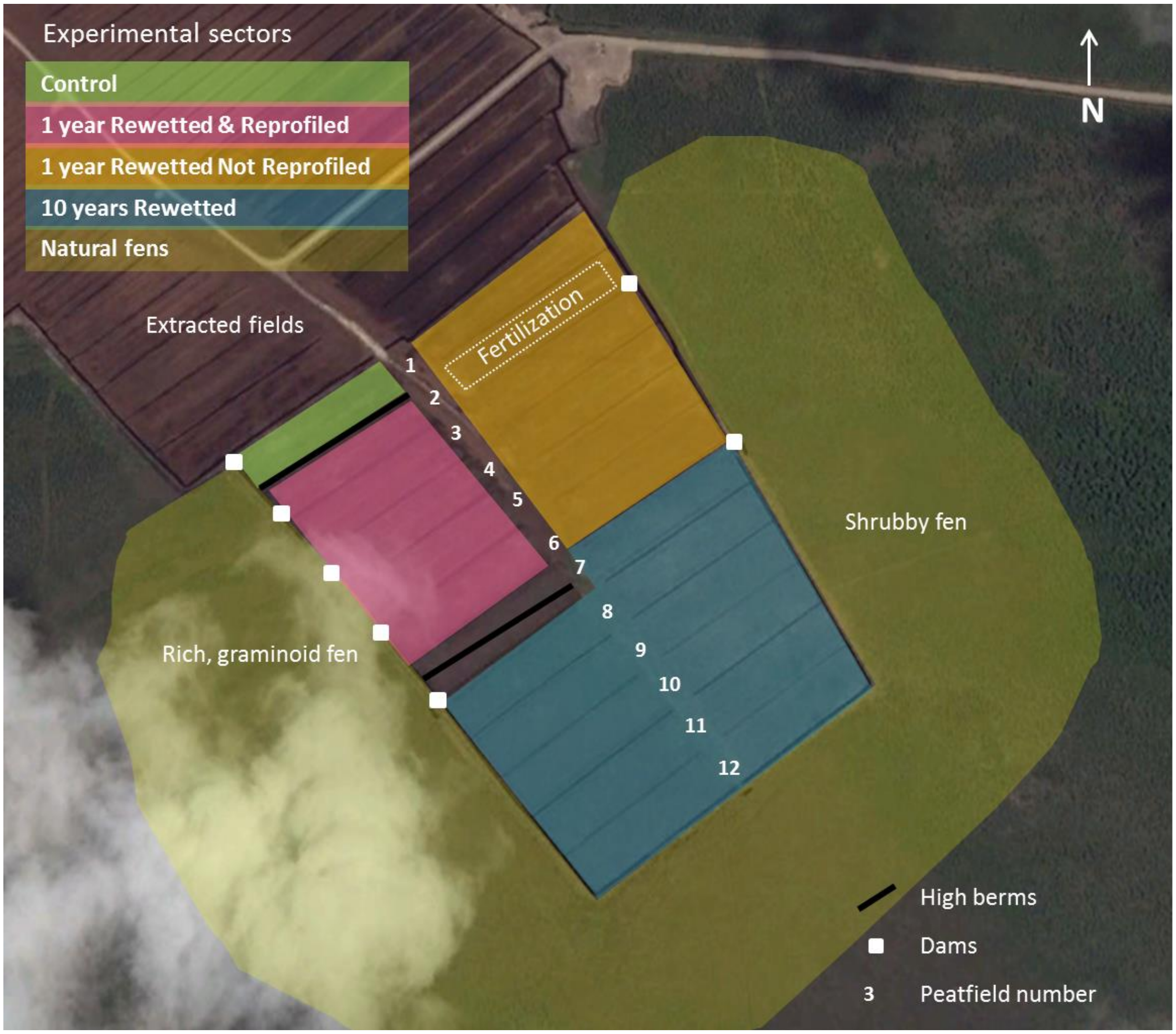
2.1 South Julius

The South Julius peatland is an active peat extraction site covering a total of 237 hectares, including a 35.5 ha experimental area located at its southeastern tip. The post-extraction peat conditions showed two distinct areas: one covered by bare peat sparsely revegetated by grasses and ruderal species, where extraction activities had ceased in 2014; the other, a regenerating, sedge-covered fen that was rewetted in 2006 (10 years ago). The remnant peat characteristics measured in both areas are presented in Table 1 1.

Table 1. Remnant peat pH condition in the two sectors (measured in June 2015).

Sector	pH	pH measured in	No. samples
Recently extracted	6.6	Peat	1
(until 2014)	5.2 (0.4)	Peat	6
Regenerating fen (Rewetted in 2006)	4.7	Peat	1

Following a field visit in June 2015 by Université Laval, University of Waterloo and Brandon University researchers, Sun Gro Horticulture and DUC staff, a restoration plan was prepared. This restoration plan included the introduction of several moss species, as well as fertilization and rewetting treatments to be applied on the recently abandoned surface. The restoration work was realized in fall 2015 by the Sun Gro Horticulture team. Unfortunately the unusually abundant precipitation received in spring and summer 2016, coupled with the blocking of the drainage ditches, led to very high water levels on the experimental area, which persisted throughout the year. The design of the experimental site was reconfigured to include five experimental sectors (Figure 2.).



Experimental sectors
Control: No modification to the surface; represents typical conditions without restoration actions.
1 year Rewetted & Reprofiled: Surface was leveled and sector was rewetted in Fall 2015; former area where multiple treatments were originally applied, now flooded. Last harrowed in Fall 2014 (to avoid weed establishment).
1 year Rewetted not Reprofiled: Sector rewetted in Fall 2015; surface not reprofiled to maintain spontaneously established vegetation. Last harrowed in 2012 (to avoid weed establishment). In June 2016, peatfield 2 of this sector was fertilized (phosphate rock, 0-13-0, 150 kg/ha).
10 years Rewetted: Drained in 2003. In 2005: surface vegetation was removed, but peat was never extracted as the deposit was too shallow. 2006: ditches were blocked and left to regenerate. Now covered with graminoïd plants and mosses (mainly *Campylium stellatum)*.
Natural fens: Untouched natural fens, including 2 plant communities: West of the experimental sectors - rich fen, graminoïd plants; East of the experimental sectors - mostly shrubby vegetation. Typical fen mosses are found in both sectors.

Figure 2. Experimental sectors of the South Julius site and restoration work details.

In spring 2016, the site was instrumented with hydrological, vegetation and carbon flux measurement equipment. Teams performed several sampling and measurement campaigns throughout the summer and fall of 2016. See sections 3.1, 3.2, 3.3, 3.6, 3.8 and 3.11 of this document for research projects related to this site. Peat and water chemistry results are also available in appendix B.

2.2 Elma North

The Elma site (approximately 800 ha in total) comprises two experimental sectors that have been named Elma North and Elma East. Actively extracted peatfields surround Elma North and Elma East, where peat extraction is now complete.

Elma North (7.5 ha) is a 4-peat fields wide (66m each peatfield) site where peat was last extracted in 2013. To avoid weed establishment, the surface was harrowed until June 2015. Water sampling to characterize remnant peat pH was not possible because the water level was very low (>1 meter) for the entire 2015 season. The post-extraction condition of the experimental sector included deep and large drainage ditches surrounding the peatfields (to allow peat extraction). During the implementation of these ditches, the material (surface peat and underlying clay) was excavated and piled in between the ditches and the adjacent natural peatland, creating a high clay berm and terrace system around the formerly extracted peatfields (Figure 3).

Figure 3. Left: Aerial view of the Elma North site before restoration. The drainage ditch and surrounding terrace is visible. Right: View from the terrace between the clay berm and natural peatland (on the left) and extracted fields (on the right).

In June 2015, the site was visited by Université Laval, University of Waterloo and Brandon University researchers, Sun Gro Horticulture and DUC staff and a restoration plan was prepared. The objective of the restoration work at Elma North was to rewet the site to typical fen conditions and to re-establish the eco-hydrological connectivity between the intact peatland and the peat extraction site.

Here's a summary of the restoration work realized in September 2015 (except when otherwise mentioned) by the Sun Gro Horticulture team (Figure 4):

1- Reprofiling: All peat fields were reprofiled using a bulldozer, flattening the dome-shaped surface and filling all former drainage ditches.

2- Checkerboard bunding: A series of bunds were created following a checkerboard (or "waffle-like") pattern to create "cells" (total 418) on the former extracted peatfields, using a bulldozer. These cells were designed to retain water on the site and to limit wind and water erosion. The distance between each bund is approx. 2 profilers' width large, creating 30 feet x 30 feet cells. The bunds were compacted (final height 30-40 cm).

3- Drainage ditch backfilling: The drainage ditch (on 3 sides of the experimental sector) was blocked and backfilled using the clay material from the berm and the terrace, then covered with the peat material (from the terrace, underneath the clay).

4- Transition zone (fen-forest margin): In order to restore the connectivity between the former cutover peatland and the adjacent ecosystem, the bog margin was remodeled to create a <30% slope. Final result was much lower than 30%. On half of each sloped section: construction of 2 rows of crescent-shape bunds (to maximize water retention). Each bund is approx. 30 cm high and 10-15 meters wide.

5- Tree plantations: One section (approx. 100 m x 30 m) of the margin was covered with Rubus sp. (raspberries) following initial bog opening. This area was cleared of vegetation. In July 2016, 480 trees (Black spruce) were planted in this sector. The trees were fertilized with Continuem 18-9-9+6(S) tea bags.

6- **Fertilization**: in July 2016, fertilization was applied on one half (north side) of the site. The fertilizer used was Guano Rock Phosphate (0-12-0), at 150 kg/ha. This will, in the future, allow for assessment of the effect fertilization has on vegetation establishment.

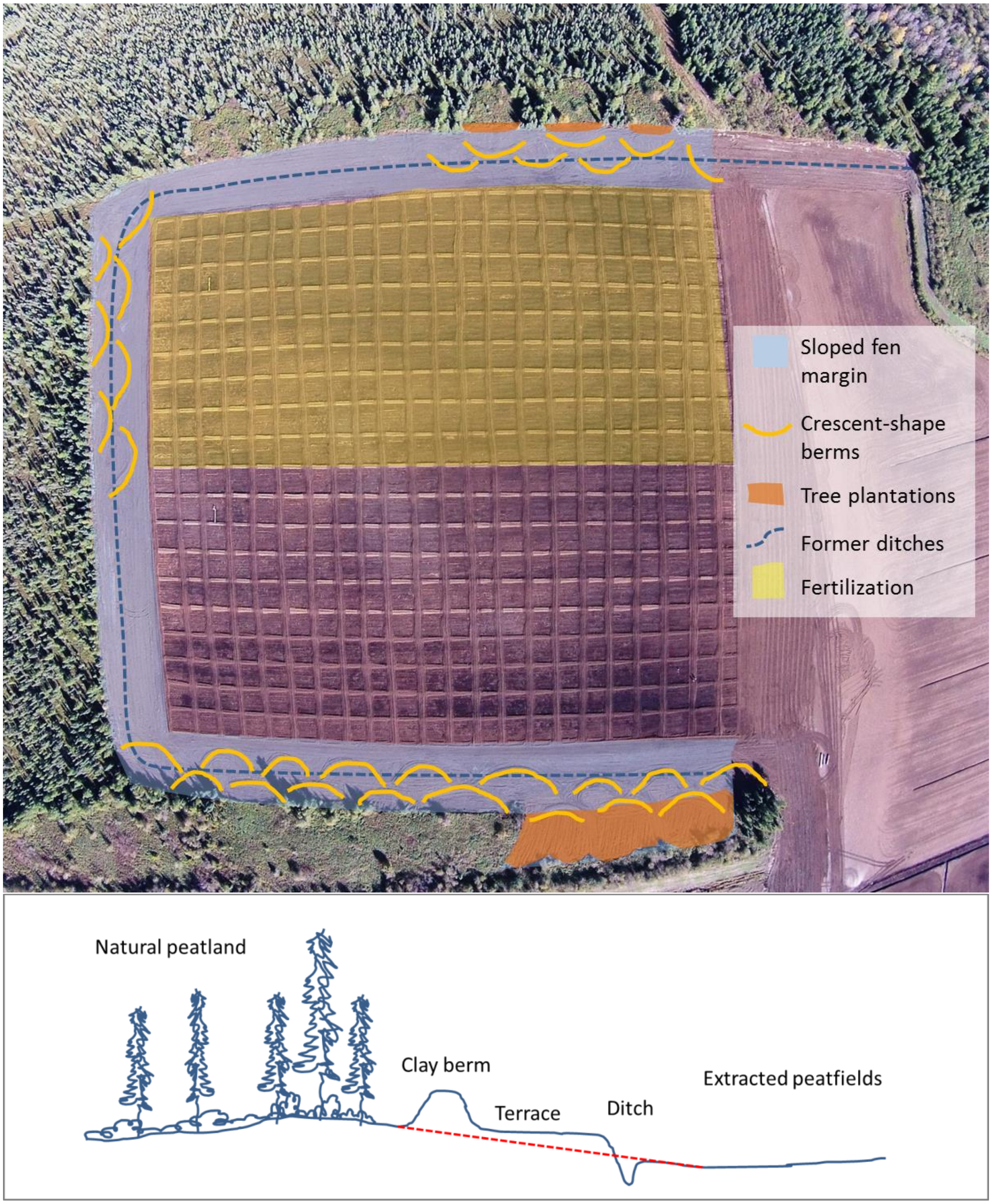


Figure 4. Top: Final configuration of the Elma North experimental sector. Bottom: Profile view of the transition zone sloping after restoration (in red).

2.3 Elma East

The second experimental sector at Elma East covers 40 ha. It was open for peat extraction in 1988, with activities ceasing in 2002. A water sample taken during a site visit in June 2015 revealed a pH of 7.8 and a conductivity of 560 µS/cm. Very little revegetation has occurred except occasional aspens, willows and ruderal grasses (Figure 5).

The sector has not yet been restored and will be used to apply, in a second phase, the techniques developed specifically for Manitoba peatlands. However, Sun Gro Horticulture provided a very precise elevation survey map of the sector that will greatly help the development of the final restoration plans. A pre-restoration survey was also conducted in fall 2015 to characterize the vegetation in place and water level at various locations throughout the site.

Figure 5. General view of the Elma East sector in June 2015.

2.4 Moss Spur

The Moss Spur site (430 ha total) was likely the first peat extraction site to be opened in Manitoba. Peat was extracted manually (using shovels) from 1936 to the 1970s, then using modern methods (vacuum) until the end of the 1990s (Figure). Once the peat extraction activities ceased, some drainage ditches were blocked, but most of them naturally collapsed or became blocked by the action of beavers. Only a few ditches are still kept active to drain the recently-opened extraction area located southwest of the experimental sector.

Thanks to the natural rewetting of the site, various plant communities re-established spontaneously. No restoration action was performed in Moss Spur. For more details about the Moss Spur site, including historical information about the extraction activities, surface physico-chemical conditions and vegetation data, consult Félix Gagnon's MSc thesis (Appendix C).

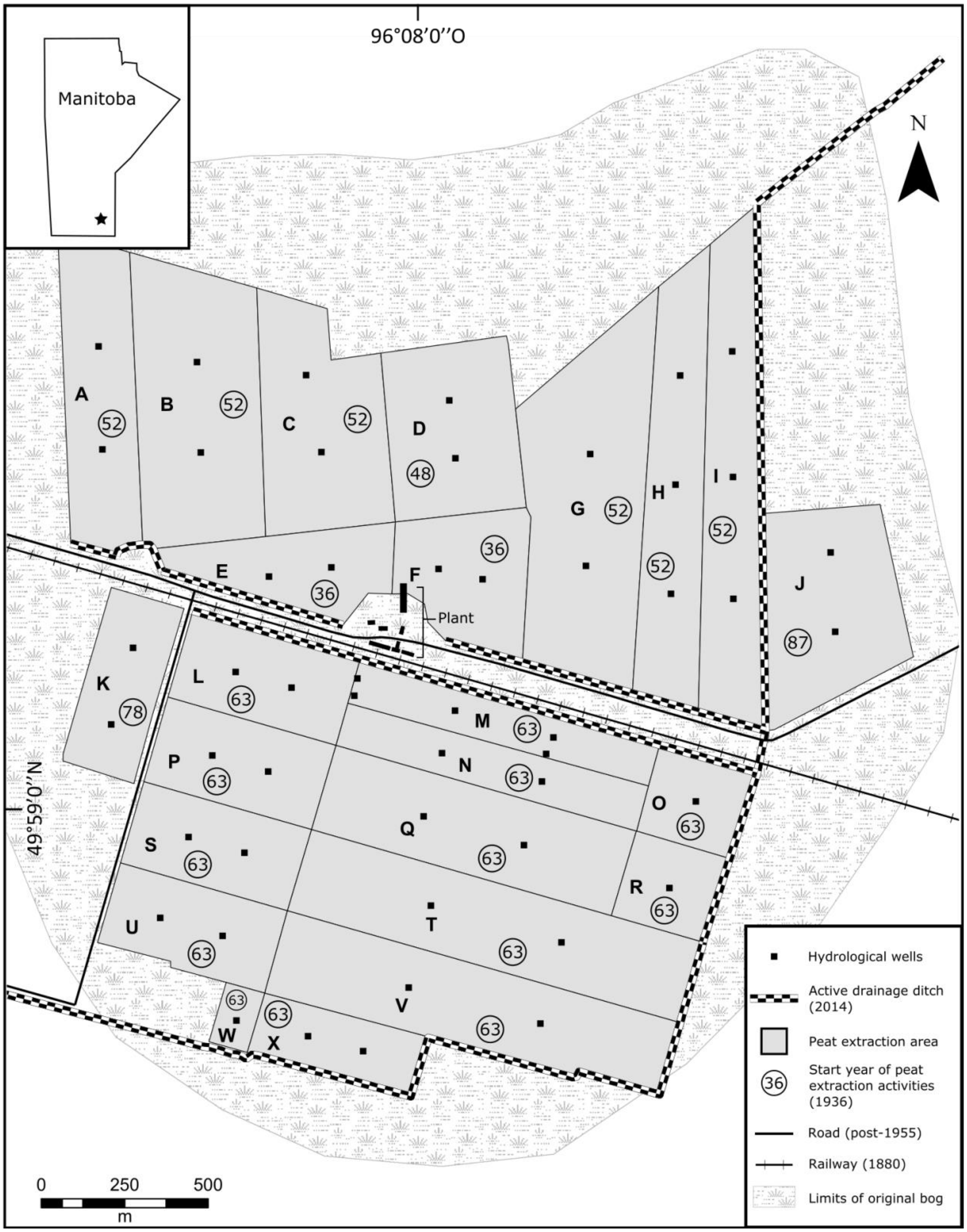


Figure 6. The 24 sectors of the Moss Spur site and year peat extraction began. Source: Félix Gagnon. 2016. La régénération spontanée d'une tourbière manitobaine après extraction de la tourbe: diversité des assemblages végétaux et propositions d'aménagement. M. ATDR thesis, Université Laval, Québec.

3. Research Projects

3.1 Rewetting as a strategy to restore extracted peatlands vegetation

Research team: Laurence Turmel-Courchesne (MSc student, Université Laval)
Line Rochefort (Research co-director, Université Laval)

Study site: South Julius peatland

Context: Extracted fens are more likely to be spontaneously revegetated than extracted bogs. Under suitable hydrological conditions (e.g. high water levels caused by collapsed drainage ditches), abandoned extracted fens can exhibit high vascular plant cover. Rewetting as a peatland restoration strategy (by blocking drainage ditches) is commonly used in Europe. In Canada, where restoration goals and backgrounds differ from Europe, little is known about the potential of rewetting as a technique to promote vegetation reestablishment on peatlands with an exposed minerotrophic residual peat layer. Yet, rewetting has been suggested as a valid restoration strategy for Canadian extracted fens (Rochefort *et al.* 2016).

Objectives: The objective of this project is to assess the effectiveness of the rewetting technique to promote the re-establishment of typical fen vegetation on an extracted minerotrophic peatland.

Methodology:
<u>Vegetation surveys</u> were realized in August 2016 in three sectors of South Julius peatland (unrestored, 1-year-rewetted-not-profiled, 10-years-rewetted). All vascular plants and moss species were identified and their cover was assessed in 1 m x 1 m evaluation quadrats (10 in the unrestored area, 20 in the 1-year-rewetted-not-profiled and 20 in the 10-year-rewetted sectors) following the method developed by the PERG (for details, see González & Rochefort 2014). Data collection will be completed in August 2017 with the survey of the reference ecosystem and of a second area of the 10-years-rewetted sector characterized by wetter conditions and different plant communities. A list of the species surveyed in 2016 is presented in the appendix A.

<u>Preferential habitats</u>: Following the method described by Poulin, Andersen & Rochefort (2013), all plant species were classified according to their preferential habitat. Vascular plants were separated into 4 categories (ruderal, generalist, wetlands and peatlands species) following Boivin *et al*. (2012), Mackenzie & Moran (2004), Marie *et al*. (2002), MDDEP (2008), Payette & Rochefort (2001) and USDA PLANTS database. Moss species were separated into 2 categories (wetlands species and other species) according to Flora of North America (1993+), Mackenzie & Moran (2004) and Payette & Rochefort (2001). Ruderal species are found in disturbed environments (e.g. roadside, eroded sites). Generalist species can be found in a large variety of habitats such as wetlands (but not preferentially), forests, prairies, etc. Wetland species can be found in peatlands (but not preferentially), as well as other types of wetlands (e.g. marshes,

swamps, etc.). Peatland species are preferentially found in peatlands (bogs or fens). Moss species were divided into wetland species (preferentially found in any type of wetland) or other species (not preferentially found in wetlands). Plant species and their corresponding preferential habitat are presented in the appendix A.

Statistical analysis**:** ANOVAS followed by multiple comparisons will be used to assess the differences between the sectors in terms of plant species cover based on their preferential habitat.

Preliminary results: Complete results will be available in Laurence Turmel-Courchesne Master's thesis which should be available in December 2017. Preliminary descriptive results are presented below (Figure 1).

Ruderal species cover is low in the rewetted sectors, especially in the 10-years-rewetted sector where they are nearly absent. The vascular generalist species follow the same pattern where they reach the highest cover in the unrestored sector and the lowest cover in the 10-years-rewetted sector. Wetland species cover is similar in the two rewetted sectors, where it is much higher than in the unrestored sector. The cover of vascular peatland species is also higher in the rewetted sectors, especially in the 10-years-rewetted sector. Mosses are virtually absent from the unrestored sector. In the 1-year-rewetted-not-profiled sector there is a low cover of *other mosses*, mainly *Bryum pseudotriquetrum* which is commonly found in disturbed fens (especially after forest fires; Mélina Guêné-Nanchen, in prep.). Peatland mosses are only present in the 10-years-rewetted sector.

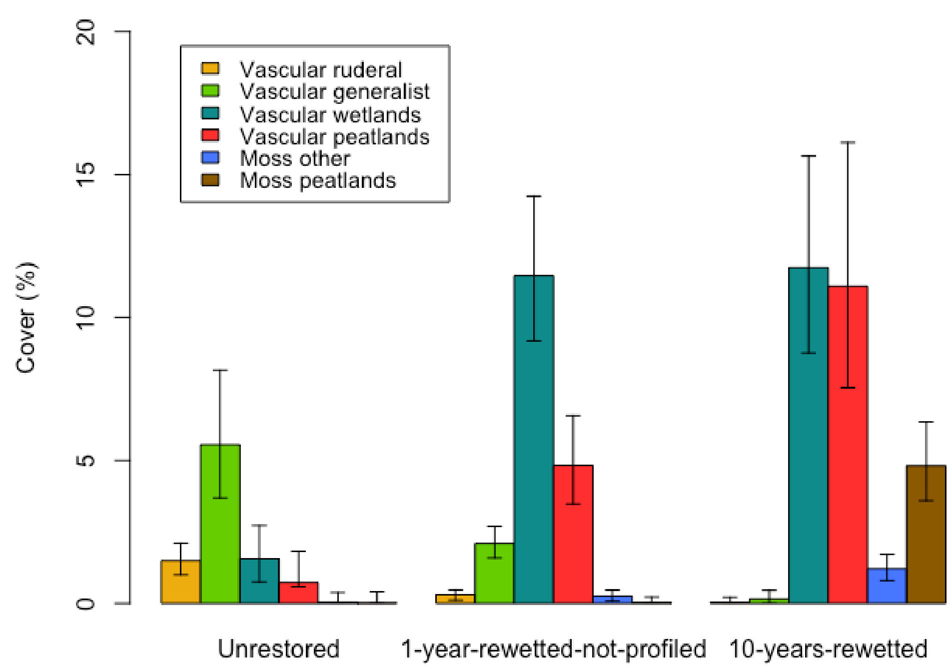


Figure 1. Mean covers of plant categories based on their preferential habitat for 3 sectors of the South Julius peatland. Error bars represent the 95% confidence interval of the mean.

Conclusion: Compared to the unrestored sector, the 10-years-rewetted sector exhibits a relatively high cover of wetland and peatland species (both vascular plants and moss species) showing that rewetting has a positive impact on peatland and wetland vegetation re-establishment. The next step will be to compare vegetation between the 10-years-rewetted sector and the reference ecosystem to determine at what extent rewetting was effective to bring back typical peatlands plant communities.

The cover of peatland and wetland vegetation, as well as the presence of mosses and low covers of ruderal and generalist species only 1 year after rewetting on the 1-year-rewetted-not-profiled sector, is encouraging. However, as the vegetation was not removed from the surface of the 1-year-rewetted-not-profiled sector before rewetting, and was not evaluated prior to the restoration work, it is not possible to confirm the impact of the technique on the vegetation. Thus, it is too early to confirm the effectiveness of the rewetting technique. Monitoring changes in vegetation in the upcoming years will be necessary.

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3.2 Rewetting as a strategy to restore extracted fens carbon sequestration function

Research team: Laurence Turmel-Courchesne (MSc student, Université Laval)
Line Rochefort (Research co-director, Université Laval)
Maria Strack (Research co-director, University of Waterloo)

Study site: South Julius peatland

Context: One of the major long-term goals of peatland restoration after peat extraction is the return of the carbon sink function. Peatland restoration generally leads to decreased carbon dioxide (CO_2) emissions and increased methane (CH_4) emissions compared to unrestored sites. Restored bogs may return to being growing season C sinks five to ten years after restoration (Waddington, Strack & Greenwood 2010; Strack, Keith & Bu 2014).

In Canada, rewetting fens after peat extraction (by blocking drainage ditches) could be an efficient restoration strategy. In Europe, this technique has been successfully used to restore the carbon sink function of industrially extracted peatlands (Tuittila, Komulainen, Vasander & Laine 1999; Wilson, Farrell, Mueller, Hepp & Renou-Wilson 2013). In Canada, the rewetting technique was suggested as a valid fen restoration strategy that may lead to the reestablishment of high vascular plant cover.

General objective: The objective of this project is to assess the effectiveness of the rewetting technique to re-establish the carbon sequestration function of an extracted minerotrophic peatland.

Specific objectives:

1) Compare CO_2 and CH_4 fluxes from rewetted, natural and unrestored sectors of the site;

2) Determine the main drivers for CO_2 and CH_4 fluxes in each sector;

3) Determine the carbon balance of dominant vegetation communities of each sector.

Methodology: Five sectors were targeted for CO_2 and CH_4 flux measurements (reference ecosystem, unrestored, 10-years-rewetted, 1-year-rewetted-not-profiled and rewetted-1-year-profiled). Fluxes were measured weekly to biweekly using the closed chamber method (May to September 2016; see Strack *et al.* 2014 for details of the method). The CO_2 flux components obtained were ecosystem respiration (ER), gross ecosystem photosynthesis (GEP) and net ecosystem exchange (NEE). A negative NEE value, i.e. the balance between GEP and ER, corresponds to a CO_2 uptake into the ecosystem. For CH_4 flux, only net exchange is obtained. During each flux measurement, water table level, air temperature, soil temperature and photosynthetically active radiation (PAR) were measured. A meteorological station located on site recorded air temperature and PAR every 20 minutes. The water table level was automatically recorded hourly in each sector from May to October 2016.

Objective 1: Ecosystem respiration (ER), gross ecosystem photosynthesis (GEP), net ecosystem exchange (NEE) and CH_4 emissions were compared among treatments. Only CO_2 fluxes under full light conditions (PAR photon flux density > 1000 μmol m^{-2} s^{-1}) were considered.

Objective 2: For each sector, water table level, air temperature, soil temperature, PAR and vegetation type will be assessed as the potential main drivers of CO_2 and CH_4 exchange.

Objective 3: For every day of the growing season, an estimation of the average CO2 fluxes will be calculated using empirical models (e.g. Strack *et al.* 2014). Estimation of the average CH4 fluxes will be calculated by multiplying the mean of the CH4 fluxes by the number of days in the growing season. Total growing season CO2 and CH4 exchange values will be summed in terms of C equivalent.

Preliminary results: Results are available only for objective 1. Results associated with objectives 2 and 3 will be available in Laurence Turmel-Courchesne Master's thesis which should be available in December 2017.

Following drainage ditch blocking operations, the surface of the 1-year-rewetted-profiled was flooded for the entire growing season of 2016. Therefore, apart from CH_4 emissions, only ER measurements were obtained from that sector. The 1-year-rewetted-profiled resembled a water body more so than a restored peatland. As a result, this site does not represent what is expected from a restoration best case scenario. Results from that sector should be interpreted with caution.

Comparisons of CO_2 fluxes: as there were no significant interactions between treatments and periods of the summer, estimates were averaged over the whole growing season (see table 1).

ER estimates were similar among sectors (except for the 1-year-rewetted-profiled), though not because of the same processes. In the unrestored sector, peat oxidation likely dominated the respiration fluxes, whereas ER fluxes likely dominated the reference ecosystem. The 1-year-rewetted-not-profiled and 10-years-rewetted sectors were likely dominated by plant respiration. In the 1-year-rewetted-profiled sector, respiration was very low given the flooding (no peat oxidation) and the absence of vegetation (no plant respiration).

The lowest GEP estimates (i.e. highest photosynthesis rates) were found in the rewetted sectors and the highest (i.e. lowest photosynthesis rates) in the unrestored sector. The reference ecosystem GEP is between the more productive rewetted sectors and the less productive unrestored sector.

NEE from the reference ecosystem and the rewetted sectors are similar, and they are all different from the unrestored sector. This indicates that rewetting can be used to rapidly return the carbon dioxide sequestration function to fen peat.

Table 1. Estimates of CO_2 fluxes ($gCO_2\ m^{-2}\ d^{-1}$) for each sector of South Julius peatland for the 2016 growing season (flux under full light: PAR > 1000 µmol $m^{-2}\ s^{-1}$). Two estimates sharing a letter are not significantly different (Tukey pairwise comparisons, α=0.05). Numbers in square brackets represent the 95% confidence intervals of the estimates.

Treatment	**Estimate ($gCO_2\ m^{-2}\ d^{-1}$)**	**95% CI**
	Ecosystem Respiration	
Unrestored	10.5 ACD	[7.4, 13.6]
1-year-rewetted-profiled	1.2 B	[-1.7, 4.0]
1-year-rewetted-not-profiled	14.2 D	[11.6, 16.9]
10-years-rewetted	10.8 CD	[7.6, 13.9]
Reference ecosystem	7.9 AC	[5.7, 10.0]
	Gross Ecosystem Photosynthesis	
Unrestored	-12.7 A	[-20.9, -4,5]
1-year-rewetted-not-profiled	-32.0 B	[-38.9, -25.1]
10-years-rewetted	-31.3 B	[-62.6, -22.4]
Reference ecosystem	-20.9 AB	[-27.0, -14.7
	Net Ecosystem Exchange	
Unrestored	-2.1 A	[-7.5, 3.3]
1-year-rewetted-not-profiled	-17.7 B	[-22.2, -13.1]
10-years-rewetted	-20.5 B	[-26.5, -14.6]
Reference ecosystem	-13.0 B	[-17.3, -8.8]

Comparisons of CH_4 fluxes: there was a significant interaction between the period of the summer and the treatments. For that reason, estimates of CH_4 fluxes are presented for each period of the summer (see table 2).

Table 2. Estimates of CH_4 emissions ($mgCH_4\ m^{-2}\ d^{-1}$) for each sector of South Julius peatland for the 2016 growing season. Numbers in square brackets represent the 95% confidence intervals of the estimates. For each period of the growing season, 2 estimates sharing a letter are not significantly different (Tukey test, 95% confidence level).

Treatment	**May - June**		**July**		**August - September**	
Unrestored	1.5	[-2.6, 7.8] A	6.9	[0.2, 18.0] AB	4	[-1.5, 13.0] A
1-year-rewetted-profiled	17.5	[4.0, 44.3] AB	1.2	[-3.4, 9.0] A	41.8	[16.0, 93.2] ABC
1-year-rewetted-not-profiled	19.7	[6.3, 44.3] AB	53.1	[27.1, 97.2] BD	49.4	[25.4, 89.7] BC
10-years-rewetted	96.6	[58.2, 156.7] B	401.3	[239.8, 667.1] C	176.6	[102.5, 299.6] C
Reference ecosystem	9.5	[3.5, 18.3] A	88.2	[54.9, 138.7] D	31.2	[15.5, 56.6] AB

Except for the 1-year-rewetted-profiled sector (not vegetated), there is a peak of CH_4 emission in the middle of the summer when water tables and vegetation productivity are at their highest. The 1-year-rewetted-profiled and the 1-year-rewetted-not-profiled show moderate CH_4 emissions, compared to those found in the unrestored sector and the reference ecosystem.

Over the growing season, the 10-years-rewetted is the largest CH_4 emitter. In July, it emitted over 4 times more CH_4 than the reference ecosystem. This is considerable and perhaps linked with high water tables and the type of vegetation dominating that sector, mostly *Carex lasiocarpa*. Graminoid species are generally associated with higher CH_4 fluxes.

Conclusion: Preliminary results suggest that rewetting is a promising strategy to restore the carbon sequestration function of extracted fens. However, there is still a potential for substantial CH_4 emissions, depending on the type of vegetation present and water table levels. Care should be taken to avoid deep inundation and standing water following restoration operations, as these will likely limit vegetation establishment and, thus, C sequestration. CO_2 exchange modelling and CH_4 exchange estimationn to determine the carbon balance at each plot (objective 3) will be the next step to determine the extent of which the rewetting technique can lead to carbon sequestration over a growing season. Given that CH_4 is 28 times more powerful than CO_2 as a greenhouse gas (on a 100-year time frame), its release can be considered to be an accurate representation of the carbon and greenhouse gas balance of each sector. Determination of the carbon exchange drivers (CO_2 and CH_4) for each treatment (objective 2) will also be performed.

References:

Strack M., Keith A.M. & Xu B. 2014. Growing season carbon dioxide and methane exchange at a restored peatland on the Western Boreal Plain Ecological Engineering 64:231-239.

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3.3 Fertilization as a strategy to restore extracted peatlands vegetation

Research team: Laurence Turmel-Courchesne (MSc student, Université Laval)
Line Rochefort (Research director, Université Laval)

Study site: South Julius peatland

Context: Phosphorus fertilization is commonly used in bog restoration as a part of the Moss Layer Transfer Technique. Within the bog restoration context, fertilization is used to promote the establishment of nurse species (mainly *Polytrichum strictum*) which facilitates *Sphagnum* reestablishment by stabilizing the peat. However, little is known about the effect of phosphorus fertilization application in ecosystem-scale fen restoration projects. On one hand, it could promote the reestablishment of typical fen sedges and mosses. On the other hand, as peat pH in fens is usually higher than bogs, it could also promote unwanted invasive or ruderal species. Fortunately, recent fertilization experiments showed promising results in promoting typical fen species (both sedges and mosses) without invasion by unwanted species. Also, as fens are, by definition, richer than bogs, it was previously believed that the addition of nutrients by fertilizing wasn't necessary to ensure rapid plant establishment. This was later reconsidered following a small-scale experiment (Rochefort *et al*. 2016).

Objective: The objective of this project is to assess the effectiveness of phosphorus fertilization (combined with the rewetting technique) to promote the reestablishment of typical fen vegetation in a post-extraction context.

Methodology:
<u>Vegetation surveys</u> were conducted in August 2016 in two areas of the 1-year-rewetted-not-profiled sector of South Julius peatland (one fertilized with phosphate rock (150 kg/ha) in June 2016 and the other unfertilized). A total of 20 1 m x 1 m evaluation quadrats were installed on each area. All vascular plants and moss species were identified and their cover was assessed following the method developed by the PERG (for details, see González & Rochefort 2014). Vascular plant species were separated into 4 categories according to their preferential habitat (ruderal, generalist, wetland and peatland species). Moss species were separated into 2 categories (wetland species and other species). Plant species and their corresponding preferential habitat are presented in the appendix A. Ruderal species are found in disturbed environments (e.g. roadside, eroded sites). Generalist species can be found in a large variety of habitats such as wetlands (but not preferentially), forests, prairies, etc. Wetland species can be found in peatlands (but not preferentially), as well as other types of wetlands (e.g. marshes, swamps, etc.). Peatland species are preferentially found in peatlands (bogs or fens). Moss species were divided into wetland species (preferentially found in any type of wetland) or other species (not preferentially found in wetlands). An additional vegetation survey will be performed in August 2017.

<u>Descriptive statistics</u> will be used to assess the differences or similarities between the fertilized and unfertilized areas of the 1-year-rewetted-not-profiled sector.

Preliminary results: Results will be available in Laurence Turmel-Courchesne Master's thesis which should be available in December 2017. Preliminary results are presented in figure 1. Fertilized and unfertilized areas exhibit similar vascular plants cover of generalist, peatland and ruderal species. The unfertilized area has a higher wetland vascular species cover (17.5±1.5%) than the fertilized area (13.9±1.6%). Both areas present a mean cover of wetland moss species very close to zero (<0.5%). The fertilized area exhibits a slightly higher *other* moss species cover (2.2 ±0.5%) than the unfertilized area (0.5 ±0.1%).

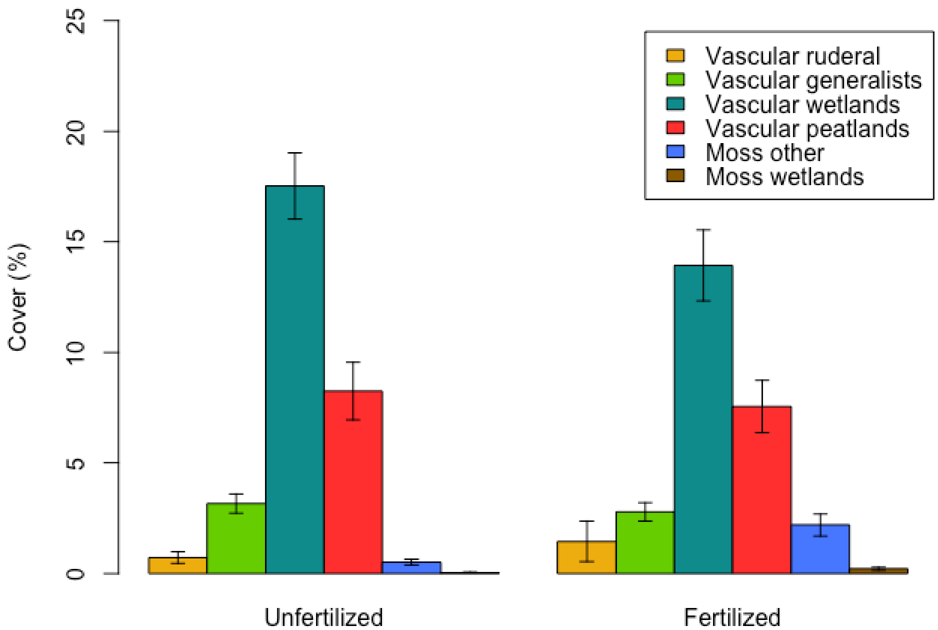

Figure 1. Mean covers of plant species based on their preferential habitat on the fertilized and unfertilized areas of the 1-year-rewetted-not-profiled sector of the South Julius peatland. Error bars represent the standard error of the mean (SE).

Conclusion: Soon (two months) after the application of the fertilization treatment, there is no clear difference between fertilized and unfertilized areas based on their cover of wetland mosses and vascular generalist, peatland and ruderal species. It is too early to know if the higher (other) moss species cover and the lower cover of wetlands vascular species in the fertilized area is caused by the fertilization treatment. More vegetation surveys will be performed again in August 2017 and in subsequent years (if funding allows) to monitor the changes in vascular and moss species covers and assess a longer-term effect of fertilization.

References:

González, E. & Rochefort, L. 2014. Drivers of success in 53 cutover bogs restored by a moss layer transfer technique. Ecological Engineering 68: 279-290.

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3.4 Spontaneous revegetation of abandoned peatlands: an option for older sites?

Research team: Félix Gagnon (MSc student, Université Laval)
Claude Lavoie (Research director, Université Laval)
Line Rochefort (Research co-director, Université Laval)

Study site: Moss Spur peatland

This project was realized by MSc student Félix Gagnon. See his thesis in Appendix C.

3.5 Carbon exchange in Manitoba peatland following after-use management

Research team: Saraswati Saraswati (PhD student, University of Waterloo)
Maria Strack (Research director, University of Waterloo)

Study site: Moss Spur peatland

Context: Although cutover peatlands can remain with little vegetation recolonization for decades, those that have an exposed minerotrophic peat layer and are effectively rewetted can have extensive spontaneous revegetation, often with wetland species (Poulin *et al*. 2005; Graf, Rochefort & Poulin 2008). As the return of vegetation can result in carbon uptake, these spontaneously revegetated sites could act as carbon sinks. Often literature values reported for unrestored cutover peatlands in Canada focus only on bare peat areas. Therefore, values for carbon and greenhouse gas exchange on revegetated areas that have not been actively restored are lacking.

Objectives: 1) Determine growing season CO_2 and CH_4 fluxes at dominant plant communities that were present at the Moss Spur peatland. 2) Evaluate whether the presence of moss had an impact on carbon exchange and 3) determine dominant controls on the measured carbon fluxes.

Methodology: Based on preliminary vegetation survey results (Gagnon 2016) we set up sampling plots in areas with 1) bare peat, 2) short sedge community dominated by *Eriophorum vaginatum* tussocks, *Rhynchospora alba* and *Trichophorum* spp., 3) mossy sedge community often with *Eriophorum vaginatum* and 30% or greater cover of *Sphagnum* and/or brown mosses, 4) *Typha* spp. with low moss cover and 5) *Typha* spp. with greater moss cover. Four replicates were used in each vegetation type, with triplicate plots on bare peat. Details of site conditions are given in Table 1. Fluxes of CO_2 and CH_4 were measured with the closed chamber technique from May to September 2015. Using measurements made in light and dark conditions, the net ecosystem exchange of CO_2 (NEE) was separated into CO_2 uptake as gross ecosystem photosynthesis (GEP) and CO_2 emission as ecosystem respiration (ER).

Table 1. Mean (standard error) growing season environmental conditions. Means are significantly different between plot types if they share no letters in common. Letter should be compared only within one column. There were no significant differences between plots types for soil temperature.

	Water table position (cm)	5 cm soil temperature (°C)	Vascular plant cover (%)	Moss cover (%)
Bare	-5.0 (2.1) a	15.8 (0.3)	2 (1) a	0 (0) a
Short-sedge	-3.0 (0.3) ab	17.2 (0.6)	59 (7) b	22 (5) ab
Mossy-sedge	1.5 (0.7) c	14.7 (1.7)	60 (14) b	41 (8) b
Typha	0.6 (0.8) bc	18.2 (0.4)	72 (7) b	6 (5) a
Mossy-Typha	9.6 (0.9) d	17.0 (0.5)	48 (6) b	26 (8) ab

We evaluated the effect of vascular plant cover, moss cover, soil temperature and water table position on CO_2 and CH_4 exchange. Total growing season fluxes were estimated using empirical models based on measured fluxes and photosynthetically active radiation and soil temperature (Strack, Keith & Xu 2014).

Results: There were significant differences between plant community types for both GEP and NEE under full light conditions (PAR > 1000 µmol m^{-2} s^{-1}) and also for ER (Figure 1). For GEP, bare plots were significantly different from all other plant community types, which were not different from each other. Bare peat had significantly lower ER than all plant community types except the mossy-sedge community. The mossy-sedge community had significant lower ER than both mossy-Typha and sedge types. There were fewer differences between plant communities for NEE; mossy-sedge and Typha plots had greater net CO_2 uptake than bare plots, but there were no other significant difference between community types. Therefore, there was no clear effect of the presence of moss on NEE.

Linear regression analysis using seasonal means indicated that only vascular plant cover significantly explained variation in GEP, NEE (both under full light conditions) and ER between plots; however, for ER, model residuals were not normally distributed unless water table was also included in the model. This suggests WT likely also plays an important role in controlling rates.

Average CH_4 flux over all plots during the study period showed net CH_4 emission (57 mg CH_4 m^{-2} d^{-1}). The CH_4 flux differed significantly between vegetation types. The highest CH_4 emission was observed at mossy-*Typha* plots followed by mossy-sedge plots, while the lowest CH_4 flux was observed from bare plots (Figure 2). There was a strong relationship between log(CH_4 flux) and WT ($F_{1,17}$=15.3, R^2=0.47, p=0.0011) indicating that high fluxes from particular plant communities were likely linked to wet conditions at those locations.

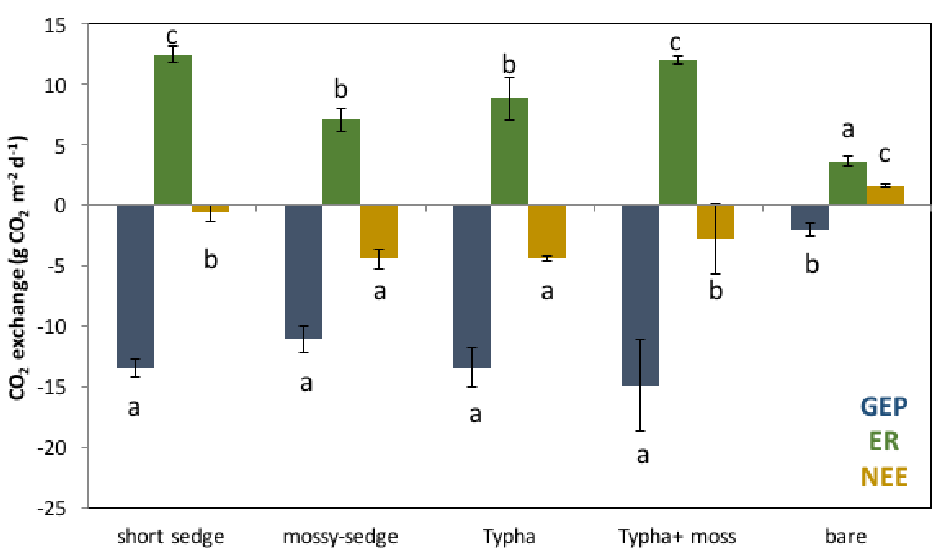

Figure 1. Growing season means gross ecosystem photosynthesis (GEP), ecosystem respiration (ER) and net ecosystem exchange (NEE). Error bars give standard error. Vegetation types have significantly different fluxes if they share no letters in common and letter should only be compared within one flux type.

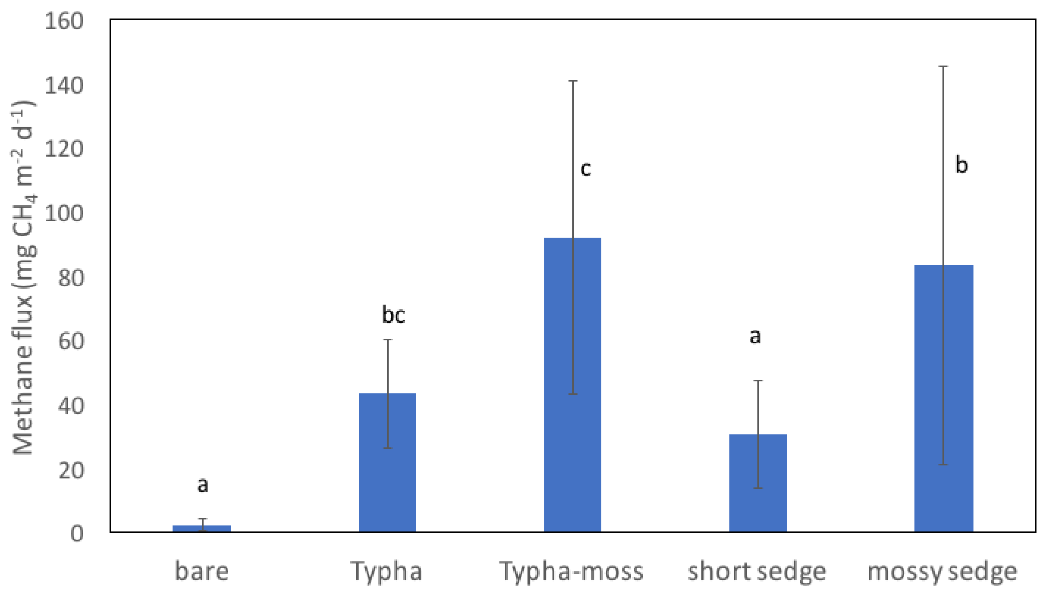

Figure 2. Mean growing season methane emissions. Error bars give standard error. Vegetation types have significantly different fluxes if they share no letters in common.

Considering total growing season carbon exchange, estimated using empirical models, bare plots were net sources of 429 ± 45 g CO_2 m^{-2} to the atmosphere over the study period. All studied plant communities were also net sources of CO_2 to the atmosphere (Table 2), but other than mossy-Typha plots, vegetated communities released less CO_2 than bare areas. Total CH_4 emissions over the study period were low from bare plots at 0.4 ± 0.3 g CH_4 m^{-2} (mean ± standard error). Vegetated plots released 5 – 14 g CH_4 m^{-2} over the same period (Table 2) with higher emissions associated with inundated conditions at moss-Typha and mossy-sedge communities.

Table 2. Totals for growing season carbon exchange calculated over a 153-day period (May 1 to September 30). Negative values indicate C uptake by the peatland from the atmosphere. Values in brackets give error of estimate.

Plot type	**GEP (g CO_2 m^{-2})**	**ER (g CO_2 m^{-2})**	**NEE (g CO_2 m^{-2})**	**Methane flux (g CH_4 m^{-2})**
Bare	-108	525	429 (45)	0.4 (0.3)
Short sedge	-713	985	334 (66)	5 (3)
Mossy-sedge	-578	825	299 (56)	13 (9)
Typha	-670	951	333 (70)	7 (3)
Typha + moss	-875	1305	500 (68)	14 (7)

Conclusion: Spontaneous revegetation of Moss Spur peatland has reduced the rate of CO_2 emissions compared to bare peat areas; however, during the study period it is estimated that all plots continued to act as carbon sources. Methane emissions were higher at vegetated areas compared to bare peat, but this is likely due to wet conditions present at these locations. As carbon exchange rates can vary greatly between years depending on weather conditions, longer term study is required to determine accurate emission factors for each plant community. It is important to account for revegetated areas of sites that have not been actively restored, as these zones have significantly different rates of carbon exchange than those areas that remain bare peat. The type of vegetation and total cover, along with hydrological conditions within revegetated areas of the site, also determine rates of carbon exchange.

References:

Gagnon F. 2016. La régénération spontanée d'une tourbière manitobaine après extraction de la tourbe : diversité des assemblages végétaux et propositions d'aménagement. M.Sc. thesis, Université Laval.

Graf M.D., Rochefort L. & Poulin M. 2008. Spontaneous revegetation of cutaway peatlands of North America. Wetland 28 : 28-39.

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Strack M., Keith A.M. & Xu B. 2014. Growing season carbon dioxide and methane exchange at a restored peatland on the Western Boreal Plain. Ecological Engineering 64: 231-239.

3.6 Nitrous oxide fluxes in peatlands

Research team: Martin E. Brummell (Post-doctoral researcher, University of Waterloo)
Maria Strack (Research co-director, University of Waterloo)

Study site: South Julius & Moss Spur peatlands

Context: Nitrous oxide (N_2O) is an important greenhouse gas generated by soil-dwelling microorganisms. It is produced through two microbial metabolic pathways: ammonia-oxidation and denitrification. Ammonia-oxidisation most often occurs under aerobic conditions, while denitrification is restricted to anaerobic conditions, and may also lead to reduction of N_2O to N_2 under severely anoxic conditions. Peatlands often include fluctuating water levels that may promote both processes, as peat-dwelling microorganisms are alternately exposed to high and low levels of oxygen availability, and ammonia oxidizers supply nitrate or nitrite for denitrifiers.

Although cutover peatlands can remain with little vegetation recolonization for decades (Poulin *et al*. 2005), those with an exposed minerotrophic peat layer, and effectively rewetted, can have extensive spontaneous revegetation, often with wetland species (Graf, Rochefort & Poulin 2008; Gagnon 2016). Vascular plants such as *Eriophorum vaginatum* (cottongrass) and *Typha* spp. (cattail) may increase or decrease rates of ammonia oxidation and denitrification by supplying oxygen to submerged peat layers through their aerenchymatous tissues (Lai, Zhang & Chen 2012). Areas of bare peat have been found to sporadically generate large, temporary fluxes of N_2O (Brummell, Lazcano & Strack 2017), though the mechanism by which these bursts occur is unclear.

Objectives: The objectives of this study were to 1) determine growing season N_2O fluxes at dominant plant communities present at Moss Spur and at a range of restoration treatments at South Julius and to 2) evaluate the role of biotic and abiotic factors in controlling N_2O fluxes.

Methodology: Based on preliminary vegetation surveys (Gagnon 2016) at Moss Spur we set up sampling plots in areas with dominant vegetation ranging from bare peat to cover by plants such as *Eriophorum vaginatum* or *Typha* spp., as well as areas with moss cover. Details of the study design and site conditions at Moss Spur are given in section 3.5 of this document (Carbon exchange in Manitoba peatland following after-use management). Fluxes of N_2O were measured with the closed chamber technique from May to September 2015. At South Julius, similar plots were established in areas with a range of restoration histories, including the 10-years-rewetted sector, the 1-year-rewetted-profiled and a nearby undisturbed fen; details of South Julius experimental design are given in section 3.1 of this document. Fluxes of N_2O at South Julius were measured with the closed chamber technique from May to September 2016.

We evaluated the effect of vascular plants cover, moss cover, soil temperature and water table position on N_2O exchange at Moss Spur; additionally, we evaluated sector restoration history at South Julius.

Results: Fluxes of N_2O occurred sporadically at both sites with the majority of measurements indicating fluxes below detection[3]. At Moss Spur, sites dominated by *Typha* spp. with high water table positions never showed a flux of N_2O significantly different from zero in 2015. Other sites showed infrequent production (*i.e.* release of N_2O to atmosphere) or consumption of N_2O, with the greatest magnitude individual flux of approximately 3.5 mg m^{-2} d^{-1} observed at a bare peat plot (Figure 1).

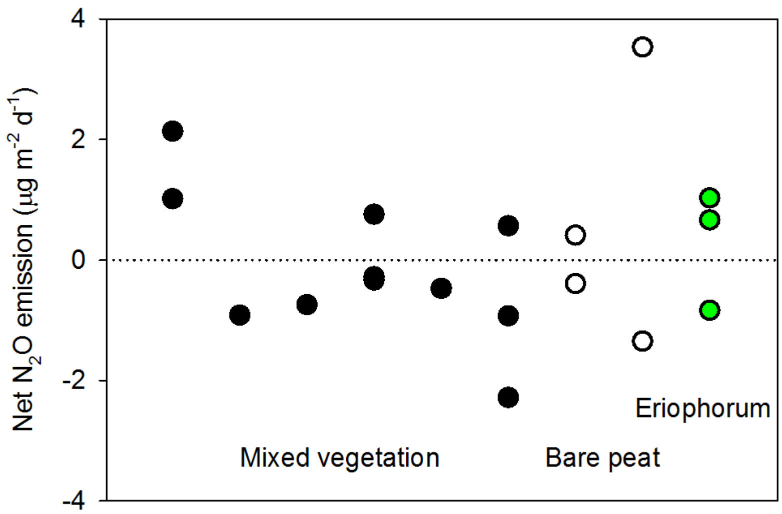

Figure 1. Fluxes of N_2O at vegetation-community plots at Moss Spur in 2015 were significantly different from zero flux 18 measurements out of a growing-season total of 162. The area with a mixture of sedges, *Typha* spp., and mosses showed the greatest activity, accounting for 11 of the periods of activity. The horizontal axis here represents plot numbers, arbitrarily assigned such that points in a column all occur at the same plot.

At South Julius, weather conditions over the preceding winter resulted in changes to some sites, with the 1-year-rewetted-profiled sector flooded to a depth of approximately 1 meter; this flooded condition persisted through the entire growing season. Plots planned for the centre of this sector were re-established at the margins of the flooded area and chambers were suspended from boardwalks with the lower 4-5 cm of the chamber submerged, directly over measurement collars.

The submerged area produced the largest individual flux measurement, of 11.9 mg m^{-2} d^{-1}, though no other non-zero N_2O flux measurements were recorded from this sector in 2016. Other sectors showed N_2O fluxes similar in magnitude to the undisturbed fen (Figure 2).

[3] The minimum detection of flux in our study was a change of 0.02 ppm by volume in N2O concentration over the 35-minute chamber measurement period.

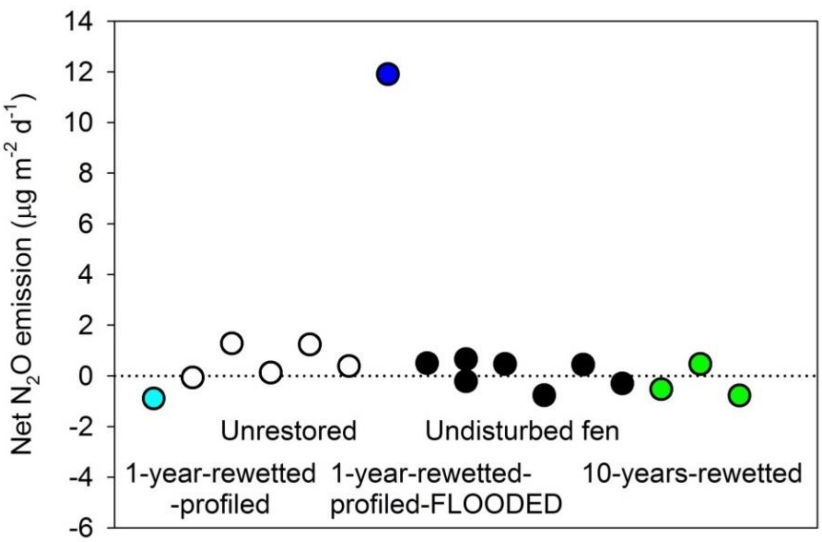

Figure 2. South Julius study sectors showed non-zero fluxes of N_2O in 17 of 153 measurements. Sectors not flooded produced or consumed similar amounts of N_2O as the undisturbed fen. The horizontal axis here represents plot numbers, arbitrarily assigned such that points in a column all occur at the same plot.

When zero fluxes based on no detectable change in N_2O concentration in the chamber during the measurement are included, mean N_2O fluxes at the sites included in this study are small (Table 1). Other studies of other ecosystems have reported a wide range of N_2O fluxes (Table 2), with some other peatlands producing minimum or maximum fluxes similar in magnitude to instantaneous fluxes displayed in Figure 1 and Figure 2. It is difficult to extrapolate such sporadic fluxes to an estimate of seasonal or annual emissions, but it seems likely that N_2O fluxes are a minor component of total greenhouse gas emissions from these peatlands when compared to the much larger fluxes of CO_2 and CH_4 as described at sections 3.1 and 3.5 of this document.

Table 1. Mean N_2O flux from study sites, all measurements including below detection limit changes in concentration over the measurement period. Negative values indicate net movement from atmosphere into soil.

Location (site and sector)	**Year of measurement**	**Mean N_2O flux (mg N_2O m^{-2} d^{-1})**
Moss Spur peatland		
Submerged *Typha*	2015	0
Mixed vegetation	2015	-0.026
Bare peat	2015	0.065
Eriophorum-dominated	2015	0.020
South Julius peatland		
1-year-rewetted-not-profiled	2016	-0.050
Unrestored	2016	0.099
1-year-rewetted-profiled-FLOODED	2016	0.28
Undisturbed fen	2016	0.020
10-years-rewetted	2016	-0.035

Table 2. Selected N_2O fluxes from published literature. Negative values indicate net movement from atmosphere into soil.

Type of Land Use or Ecosystem	Reference	Reported N_2O flux (mg N_2O m^{-2} d^{-1})	
		Minimum	Maximum
Forests (global)	Nicolini *et al*. 2013	0.30	5.2
Croplands (global)	Nicolini *et al*. 2013	-1.9	133.3
Artificial lands (global)	Nicolini *et al*. 2013	19.4	159.9
Natural Peatlands (Finland)	Mustamo *et al.* 2016	0.017	3.013
Black Spruce (Canada)	Schiller & Hastie 1996	-0.302	0.117
Tropical Peatlands (Indonesia and Malaysia)	Hadi *et al.* 2000	-1.131	6.033

Conclusion: Spontaneously-recolonizing vegetation at Moss Spur drives N_2O fluxes, with flooded *Typha* spp. showing no non-zero fluxes of N_2O while other vegetation-and-water combinations showed frequencies and magnitudes of N_2O fluxes similar to other studies in a wide range of terrestrial ecosystems. The single very large production of N_2O from the flooded sector at South Julius in 2016 suggests submerged peat has a potential for large emissions of N_2O but this single measurement is insufficient to draw broad conclusions. However, similar frequencies and magnitudes of N_2O fluxes at the undisturbed fen and the sector rewetted 10 years previously does suggest that N_2O-metabolizing microbial populations at these two sectors are likely similar. Future work at these sites would benefit from greater intensity of sampling at sites submerged in water for the duration of the growing season, with and without emergent vegetation such as *Typha* spp., as well as investigation of the microbial populations in the peat.

References:

Brummell M.E., Lazcano C. & Strack M. 2017. The effects of *Eriophorum vaginatum* on N_2O fluxes at a restored, extracted peatland. Ecological Engineering 106: 287-295.

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Nicolini G., Castaldi S., Fratini G. & Valentini, R. 2013. A literature overview of micrometeorological CH_4 and N_2O flux measurements in terrestrial ecosystems. Atmospheric Environment 81: 311-319.

Poulin M., Rochefort L., Quinty F. & Lavoie C. 2005. Spontaneous revegetation of mined peatlands in eastern Canada. Canadian Journal of Botany 83 : 539-557.

Schiller C.L. & Hastie D.R. 1996. Nitrous oxide and methane fluxes from perturbed and unperturbed boreal forest sites in northern Ontario. Journal of Geophysical Research – Atmospheres 101: 22767-22774.

3.7 Groundwater flow patterns in extracted peatlands

Research team: Melanie Hawes (MSc student, Brandon University)
Pete Whittington (Academic supervisor, Brandon University)

Study site: Moss Spur peatland

Context: Most of what we know about restoring peatlands in Canada has originated from Québec in the St. Lawrence Lowlands. This area has a markedly different hydrogeomorphic setting than the peatlands in Manitoba, which are part of the Western Boreal Plain (WBP). Recent work in the WBP has shown that peatlands here are more closely tied to regional groundwater flow paths; bogs may actually receive groundwater in times of extreme drought due to lower water pressures at the surface (lower water tables), thereby allowing groundwater to upwell into the peatland (Devito & Mendoza 2012; Siegel & Glasser 1987).

Spontaneous revegetation of extracted peatlands is rare (learned in Québec), in large part due to the inhospitable surface conditions of the remnant catotelmic peat for moss reestablishment. However, the Moss Spur peatland in Manitoba has done a remarkable job of growing back a significant coverage of wetland (and some peatland) vegetation. Why?

As noted above, extreme droughts (low water tables) have been shown to induce a groundwater flow reversal. Our hypothesis is that the lowered water tables due to peat extraction activities (drainage ditches) acts as a surrogate for extreme drought, allowing water to upwell into the peatland, assisting with the restoration.

Objectives: To determine the water balance of the Moss Spur peatland to assess the role of groundwater in the water balance.

Methodology: In June 2014, a vegetation survey of Moss Spur site took place. We used the initial 'quick' survey to identify ~ 5 different vegetation assemblages on the site, instrumenting them with wells and piezometers to measure water table and groundwater flows. In 2015, these sites were further instrumented with lysimeters to measure evaporation, as well as tensiometers to measure soil water tension. In 2016, only the wells and piezometers were measured, however, additional roving nests of piezometers were installed to increase our knowledge of the physical properties of the peat. In 2017, continued monitoring of the wells and piezometers is taking place.

Results: The 2015 field season experienced 575 mm of precipitation; this is ~ 200 mm more than historical records show for the area (see Table 1 in the next section). The lysimeter data show that site A has the highest evapotranspiration rate (largest slope of AET vs. PET, Figure 1), followed by sites, J, P, and M at 468, 401, 438, and 393 mm, respectfully, from May through August.

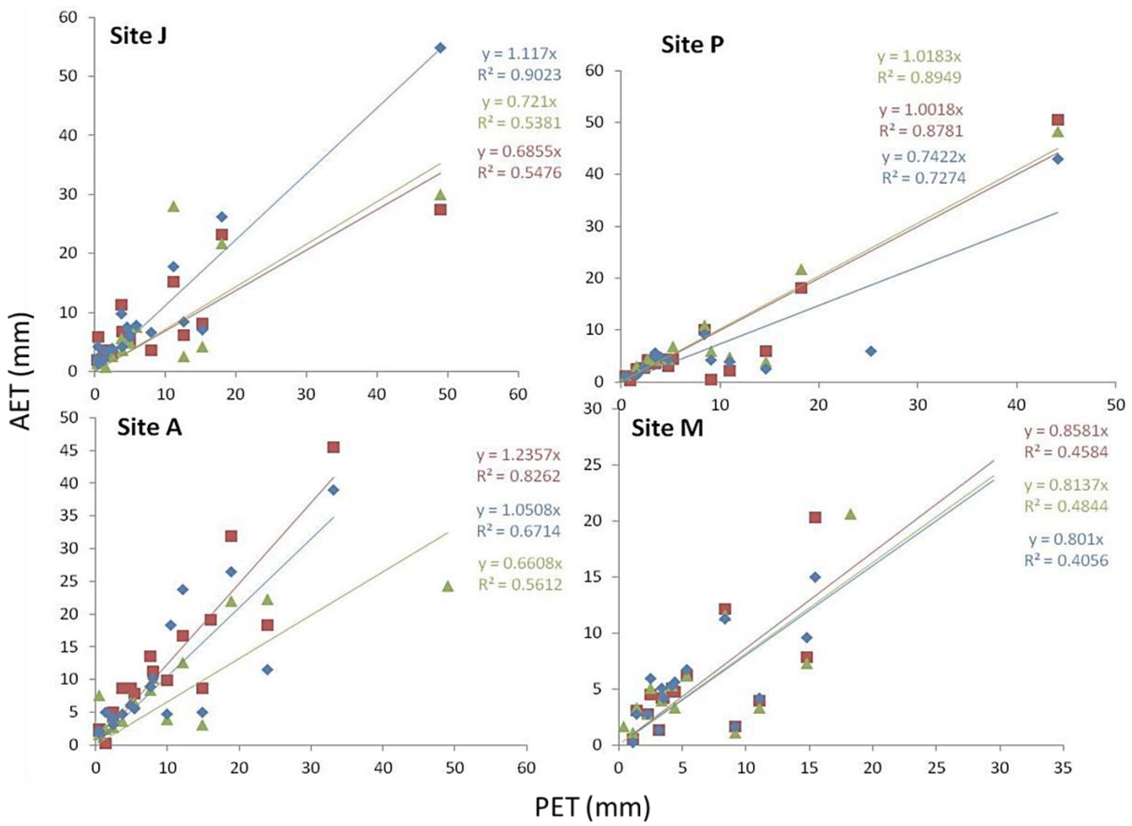

Figure 1. Alpha values (slope of each line) for the lysimeter buckets at each of the instrumented sites. AET and PET are Actual and Potential evapotranspiration, respectively.

The 2014 'quick' survey ranked each site from best to worst bog vegetation coverage; the hydraulic gradient and flux correlate with the vegetation ranking. Sites J, I, and P (see section 2.4 of this document for a map of the sectors) exhibited the most bog-like vegetation (*Sphagnum* and Labrador tea). Sites X, A, and M were dominated by vascular wetland species such as narrow-leaved cattail and bulrush. Site M was dominantly barren with minimal cotton grass coverage, much like the sites in the St. Lawrence Lowlands. Water table measurements (Figure 2) taken in 2014 were compared between sites using percent frequency of water being at or above the surface. Site J had water levels at or above the surface for 56% of the field season, ranging from 15 cm above the surface to -15 cm below. Site I did not have standing water, but ranged from just below the surface to -45 cm. Site P was flooded for 8% of the field season, with a minimum water level of -30 cm. Site X had the largest range of fluctuations, varying from 50 cm of standing water to -50 cm below the surface (64% flood frequency). Site A was flooded for 100% of the 2015 field season, and site M had an 18% flood frequency with a minimum water level of -55 cm below the surface.

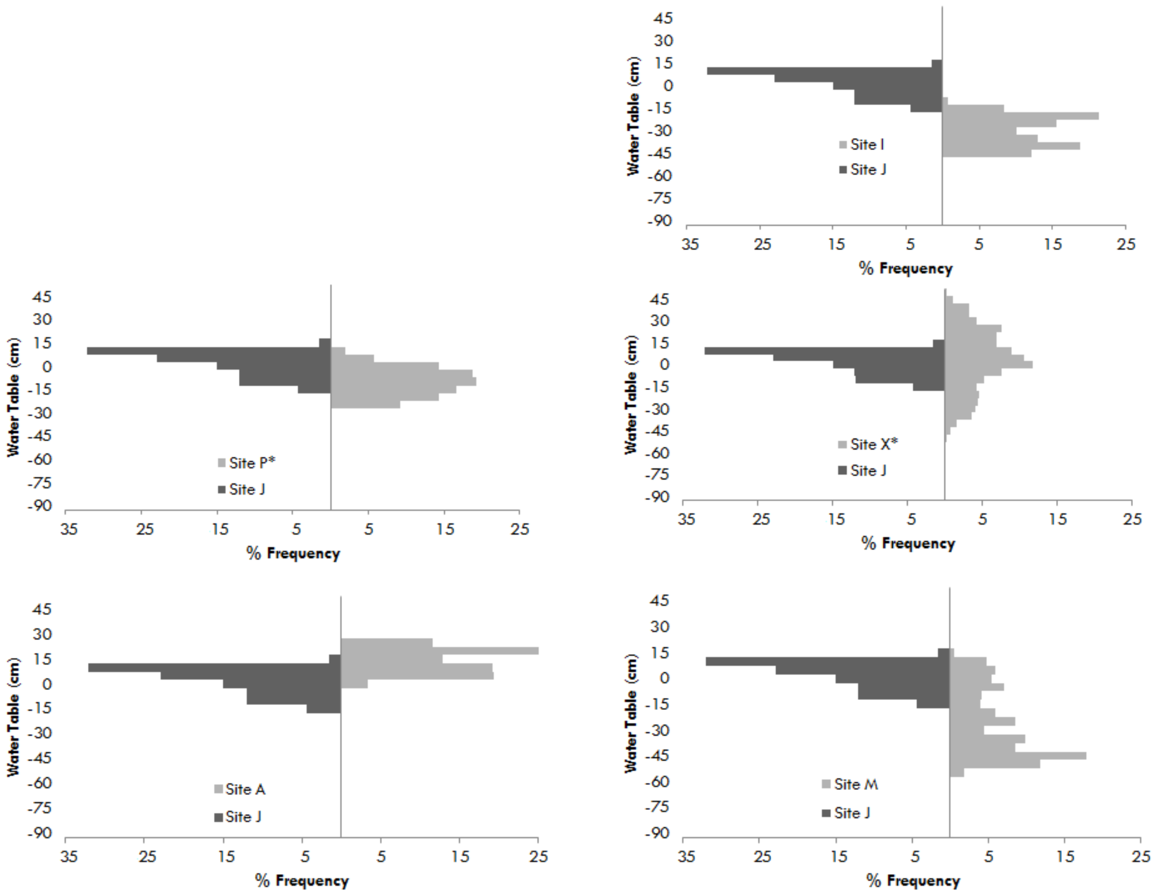

Figure 2. Water tables at each site compared to site J (the site with the best bog-like vegetation) for 2014.

In 2015, sites J, P, and I displayed specific discharges of -1.3, -0.8, and -0.1 mm/day, respectively, indicating groundwater discharge. Sites X, A, and M experienced groundwater recharge, with specific discharges of 0.1, 0.06, and 0.02 mm/day, respectively. In 2016, it was sites J, A, and X with groundwater discharge conditions (-10.8, 0.06, and -0.2 mm/day, respectively). Sites P and M had average specific discharges of 7.3 and 19.8 mm/day, respectively; site I was not measured for flux in 2016 due to access restrictions. The average 2015 water level per site was 10.7, -22,3, 0.9, 3.9, 10.3, and -8.3 cm for sites J, I, P, X, A, and M. The average 2016 water level per site was 8.8, -22.3, -3.2, 1.9, 9.6, and -19.0 cm for sites J, I, P, X, A, and M.

Sphagnum in peatlands requires the soil tension to be above -100 mb for an adequate available water supply. Tensiometers were placed at sites J, P, and M in 2015, which showed an average soil tension of 6.2, 14.6, and -7.5, respectively, within the first 10 cm of peat (Figure 3). Tensiometer data throughout the profile depth showed soil tension values were well within the > -100 mb range for *Sphagnum* establishment (Price & Whitehead, 2001).

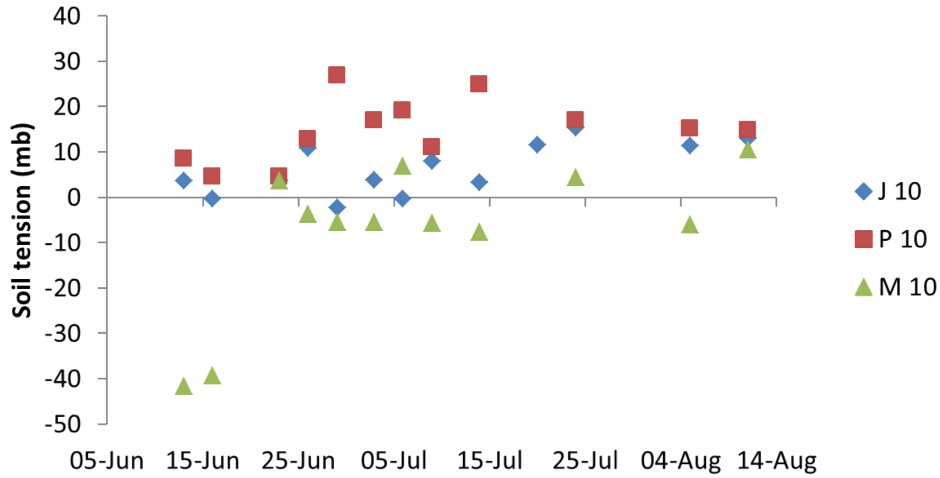

Figure 3. Soil tensions in 2015 (1 mb = 1 cm) for sites J, P and M at the 10 cm below the surface layer.

Conclusion: Large spatial variability exists across the Moss Spur peatland site, though conditions of a shallow (>-40 cm) water table and low soil tension (> -100 cm) exist throughout much of the site, suggesting that the basic requirements for vegetation re-establishment were met. The drought-like conditions likely contributed to groundwater upwelling at some locations, but was not consistent in the sites with better peatland vegetation from year to year (i.e. groundwater upwelling did not occur consistently from year to year). Site J was an exception, as it arguably had the best peatland vegetation with a large surface cover of *Sphagnum.*

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Siegel D. I. & Glaser P. H. 1987. Groundwater Flow in a Bog-Fen Complex, Lost River Peatland, Northern Minnesota**.** The Journal of Ecology. 75-3, 743-754.

3.8 Effect of rewetting techniques on the hydrology of restored peatlands

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Study site: South Julius and Elma North peatlands

Context: Typically, the surface of a remnant vacuum-extracted peat field is fairly inhospitable to *Sphagnum* moss regrowth (Price *et al.* 2003), in part due to the physical properties of the soil. Remnant catotelm peat typically has high bulk density, small pores, low water content and high soil tension. These properties combine to make water availability for any establishing vegetation very difficult (Clymo 1983). Thus, during the restoration process, the goal is to raise water tables high enough to reduce the soil tension and increase water availability (Price 2003). This is usually achieved by blocking the draining ditches in the peatland, and has been successful in Québec restoration projects, where annual precipitation (e.g., 1000 mm) is very high, compared with the prairies (e.g., 500 mm). These techniques were also used to restore bog peatlands, which have a lower water table than fen peatlands (the goal peatland for the work in Manitoba).

Due to different climate regimes between Manitoba and Québec, we elected to use different water retention techniques on the peat fields. At Elma North we used a grid/waffle-like pattern to retain as much snow in the grid as possible and thus reduce spring/precipitation runoff (Figure 1). At South Julius, we used a series of crescent-shaped bunds across the slope of the landscape mimicking the ridge/pool topography found in some patterned fen systems.

Figure 1. Elma North (left) with the waffle pattern (Fall 2015) and South Julius (right) with the bunds (Spring 2016, before the lake).

Objectives: The objective is to compare different surface re-contouring techniques and their ability to retain water to provide hydrological conditions suitable for vegetation regrowth.

Methodology:
<u>Both sites</u>: In 2015, several wells and piezometers were installed in the existing cutover peat surface and monitored from June to September. In Sept/Oct 2015, the surface re-contouring (grid at Elma North; crescents at South Julius) of the sites took place.

Elma North: In fall 2015, in addition to the waffle pattern, the edges of the cutover surface were smoothed / graded into the natural bog surrounding the site. Crescent shaped bunds were created on the slopes to encourage water retention on the slopes. In 2016, additional wells and piezometers were installed across the site to better capture the spatial heterogeneity of water table position.

South Julius: Unfortunately, significant amounts of snow/water were retained on the site over the winter causing a large build-up of head pressure at one of the lower dams. This dam gave way in late April/early May 2016 and flooded one of the neighbouring actively extracted fields. As such, a large peat dam/wall was constructed to cut-off the flow of water. Consequently, this peat dam created a lake over our research site, making further instrumentation of the site, and an assessment of the role of the bunds in water retention, basically impossible.

Results: In 2015, before re-contouring the surface, the average water table depth of the contoured area was >100 cm below the surface; in the natural areas, average water table depth was ~-46 cm (Figure 2). In 2016, post-surface re-contouring, the grid pattern at Elma North had retained snow melt and precipitation from the winter/spring season. The average water table depth in the cutover area was now -17 cm, an increase of >100 cm from 2015; the natural area averaged a depth of -18 cm. Almost all wells experienced water tables greater than -40 cm for the majority of the season (Figure 3). Although the 2016 field season experienced less precipitation (517 mm) than 2015 (573 mm), the north section (grid cells A-D, 1-19) and the west section (grid cells A-B, 16-19) of Elma were flooded throughout most of the summer. The 2016 water levels were raised >100 cm in the cutover section to -15 cm (SD= 29 cm), which were indistinguishable from the average natural area water level of -18 cm. The average specific discharge for the natural areas of Elma was 0.2 mm/day, while the west and north transition areas had average specific discharges of 0.2 and 0.5 mm/day, respectively.

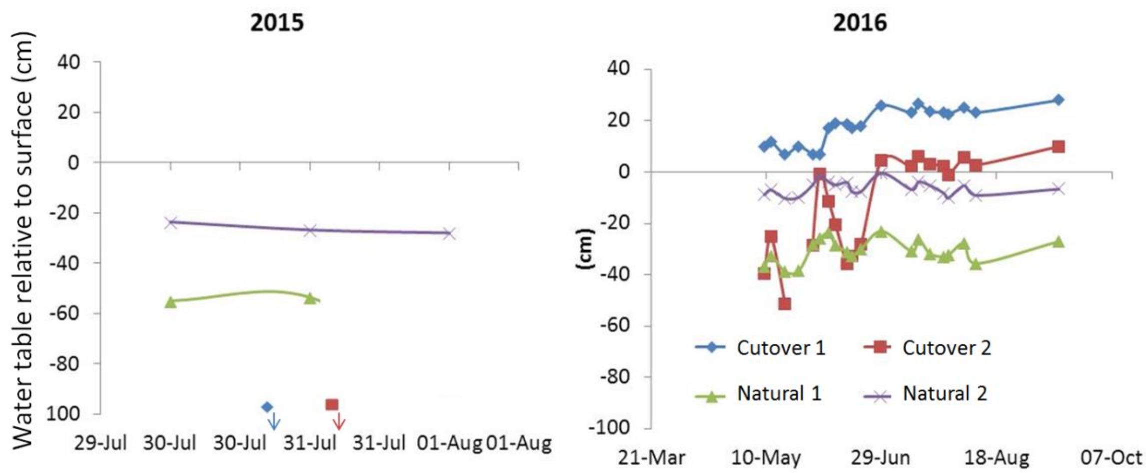

Figure 2. Water table comparisons between 2015 and 2016 for the cutover and natural sites (for wells present before and reinstalled in the same location after surface recontouring). Note the arrows for the cutover sites in 2015 denoting the water table being below 100 cm.

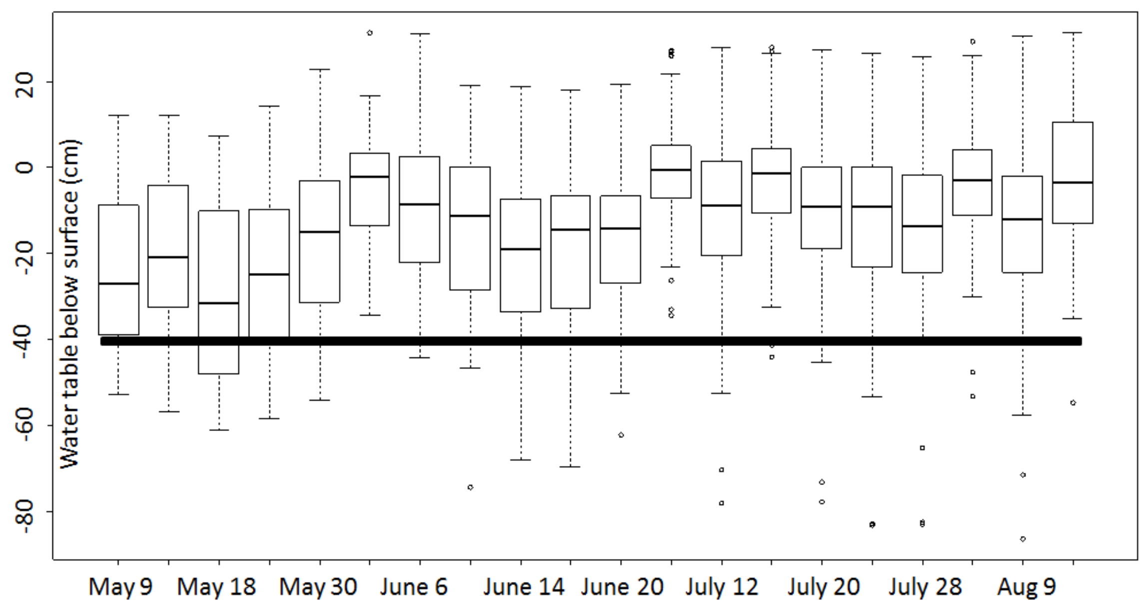

Figure 3. Boxplot showing the range in water tables for the 15 wells located within the cutover sections of the Elma North peatland. Black line indicates the -40 cm water table threshold.

Total evapotranspiration in the Elma North natural area in 2016 was ~240 mm, compared to ~500 mm in the center of the cutover grid section, likely due to the must more exposed soil surface (Table 1). Soil water tension in the cutover area averaged -21 cm within the top 5 cm of the surface, which is well within the maximum of -100 cm for efficient *Sphagnum* growth.

Table 1. Meteorological summaries of the 2015 and 2016 field seasons, showing the monthly surplus (+) or deficit (-) compared to the 30-year climate normals. ET stands for evapotranspiration.

Precip (mm)	1981-2010	2015	+/-	2016	+/-
May	58.1	149.8	91.7	82.4	24.3
June	87.5	88	0.5	128.9	41.4
July	87.1	183	95.9	72.3	-14.8
Aug	76.3	123.3	47	105.8	29.5
Sept	65.1	29.4	-35.7	127.8	62.7
Total	374.1	573.5	199.4	517.2	143.1

Avg Temp (°C)	1981-2010	2015	2016	Total ET (mm)	2016
May	11.4	12.1	14.7	Nat 1	239
June	16.7	17.4	16.6	J-11	505
July	19.3	20.6	19	A-16	287
Aug	18.5	18.4	18.1		
Sept	12.5	16.1	13.4		

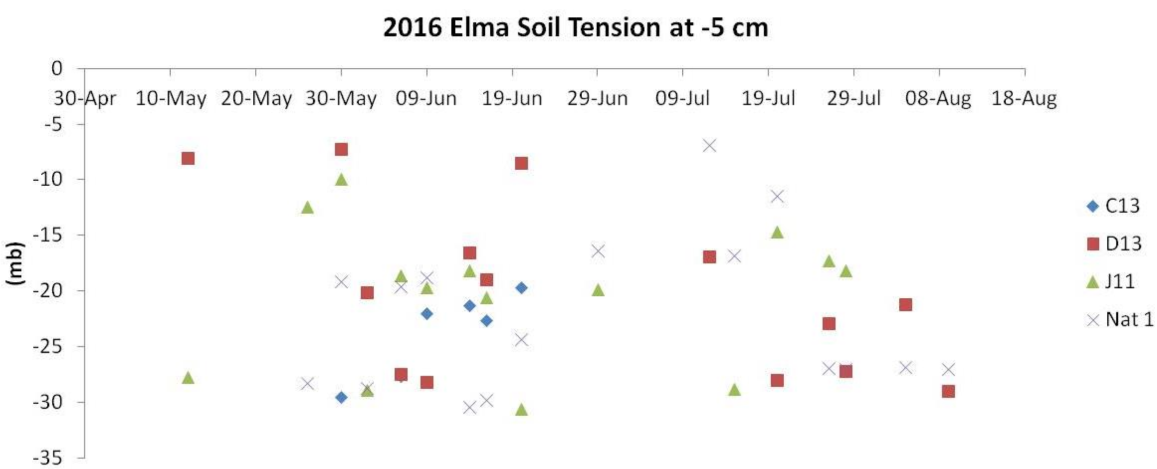

Figure 4. Soil water tension at the -5 cm layer in the Natural (Nat 1) and three cutover locations.

The experimental site of South Julius consisted of piezometer nests in a cutover site, a 10-years-rewetted site, and a reference/natural site in 2015. Surface recontouring occurred in the fall of 2015, but due to a dam break and emergency berm construction, the cutover site flooded into a lake where data could no longer be collected. The baseline water table levels from the summer of 2015 averaged -47.4, 4.6, and 15.8 cm for the cutover, 10-years-rewetted, and reference/natural sites, respectively. In 2016, the lake averaged 25.8 cm on the east edge where the well was installed in the cutover area, and the water level averaged 24.9 and 15.7 cm above the surface in the 10-years-rewetted and natural sites, respectively.

Conclusion: Re-contouring the cutover surface of Elma North has proven to effectively retain snow melt and precipitation throughout the summer, thus raising the water table level and soil water tension to be within the requirements for *Sphagnum* establishment. Unfortunately, a comparison of techniques was not possible. Plans are in place to drain the new South Julius "lake" so that the hydrological study can continue.

References:

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Price J.S., Heathwaite A.L. & Baird A.J. 2003. Hydrological processes in abandoned and restored peatlands: An overview of management approaches. Wetlands Ecology and Management, 11: 65-83.

3.9 Soil moisture patterns following peatland surface re-contouring

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Melanie Hawes (field assistance, Brandon University)

Study site: Elma North peatland

Context: Understanding the spatial distribution of soil moisture, and maintaining sufficiently high soil moisture, is critical to the re-establishment of peatland vegetation on a post peat-extracted site (Price & Whitehead 2001). Unfortunately, the in situ measurement of soil moisture can be expensive, temporally/spatially limited, and laborious. Recent advances in UAV (unmanned aerial vehicles) technology have provided a cost-effective alternative for the acquisition of high resolution aerial images. The question is: Can these "ready to fly" drones and cameras be used for soil moisture classification in recently restored peatland systems?

Objectives: Our objective was to determine if these images could be used to quantify spatial variations in soil moisture, and track changes in soil moisture through time.

Methodology: We used Elma North as our study site (and intended to compare with South Julius, but, due to flooded conditions, were unable to). The site was subdivided into 418 cells (~12 m x 12 m) separated by small peat berms making a waffle-like pattern. Soil moisture was assessed by manually inserting a 30 cm long CS615 moisture content probe into the centre of the cell on a 45° angle in every other row, and every other column (n=114 locations). In total, 3 flights were performed (May, June, July). The images (from a Phantom Vision 2+ drone flown autonomously using Pix4D on an Android phone) were processed using Agisoft Photoscan and ArcGIS. A mask was created to eliminate non-peat materials (e.g., woody debris). We then created a 0.15 m, 0.30 m and 1 m diameter buffer around each sampling point and the median spectral reflectance in the visible portion of the red spectrum was obtained.

Results: Unfortunately, the 2016 field season was much wetter than average (>200 mm surplus precipitation between May and Sept) and, as such, made the drying that we typically expect to see over the summer non-existent, as the site got wetter and wetter.

The spectral reflectance of the red colour band was inversely correlated to the dielectric constant (the un-calibrated moisture content reported by the probe) (Figure 1). For the May flight, r^2 values ranged from 0.35 to 0.41, for the June flight 0.27 to 0.29, and for the July flight 0.54 to 0.56. The r^2 was highest with the 1 m buffer, but showed no consistent trend between the 0.15 m and 0.30 m buffers.

The slope of the regression line did not vary much between buffers for the same flight (e.g., -1.59, -1.56, -1.54 for May's 0.15 m, 0.30 m, and 1 m buffers, respectively). However, the slopes were quite different between the flights with the May, June and July 1 m buffer slopes being -1.54, -0.63 and -3.36, respectively.

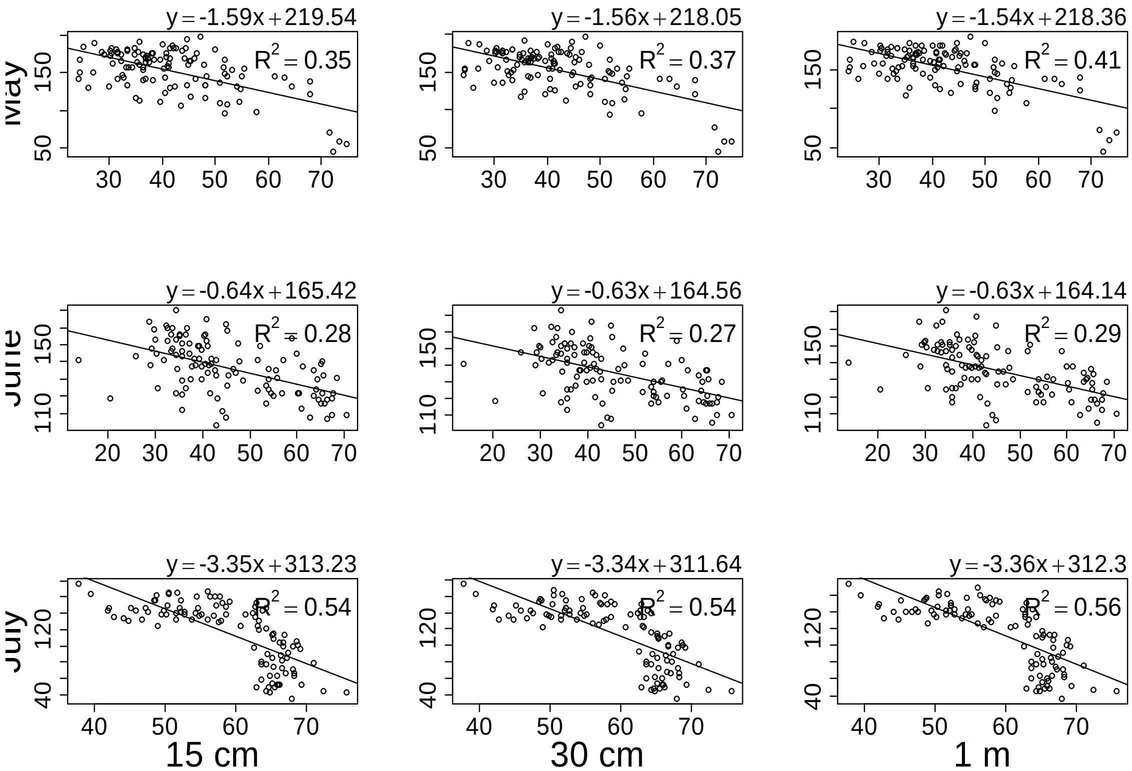

Figure 1. Dielectric constant (x-axis, unitless) vs. spectral reflectance (y-axis, unitless) for the three buffers (15 cm, 30 cm, 1 m) and three dates (May, June, July).

When combining all three flights with the 1 m buffer into a single regression (Figure 2), the r^2 was 0.48 with a slope of -1.73. Using a power relationship to better fit the obvious non-linear (curve) shape of the data the r^2 increased to 0.56. The non-linear shape was much less pronounced within each individual month.

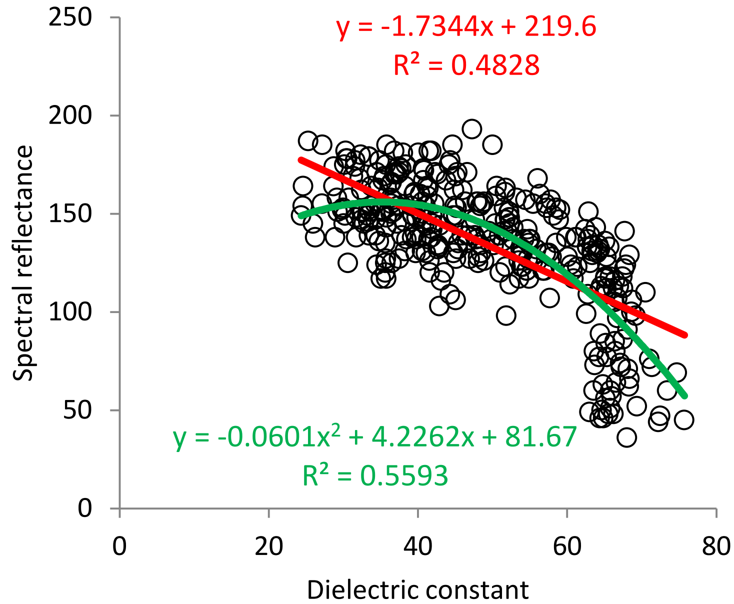

Figure 2. Dielectric constant vs. spectral reflectance for the 1 m buffers for all 3 dates.

When combining all three flights with the 1 m buffer into a single regression, the r^2 was 0.48 with a slope of -1.73. Using a power relationship to better fit the obvious non-linear (curve) shape of the data the r^2 increased to 0.56. The non-linear shape was much less pronounced within each individual month.

Conclusion: The lack of difference between the buffer sizes was likely due to the relatively homogenous nature (once the white woody debris was removed) of the cells within the peatland. By using the median value (and not mean) the impacts of any extreme colour differences were essentially removed.

We suspect that the increased correlation coefficients with the wetter soils (July > June > May) is, in part, due to the method that we used. The soil probe is 30 cm long and sampled the upper 15 cm of the peat profile. However, under "dry" conditions, only the upper few cm may have been a lighter brown, followed by wetter peat below. The probe sampled, disproportionately, the deeper, wetter peat. Under wet conditions, the homogeneity in the soil moisture profile is lower (as it is all wet), explaining the higher r^2 values. Essentially, the dry surface crust is seen by the drone, but not accurately represented with the soil moisture probe.

Reference:

Price J.S. & Whitehead G.S. 2001. Developing Hydrologic Thresholds for Sphagnum recolonization on an Abandoned Cutover Bog. Wetlands. The Society of Wetland Scientists. 21-1. (32-40).

3.10 Impacts of a drainage ditch on a treed bog

Research team: Lindsay Edwards (Undergraduate topics student, Brandon University)
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Study site: Elma North peatland

Context: During peat extraction, the peat fields must to be drained in order to maintain a sufficiently low water table to facilitate machinery circulation and peat extraction (Price *et al.* 2003). Ideally, the water from drainage ditches will flow passively to natural low points (stream/river) and then offsite. However, when there are no natural bodies of water adjacent to the extraction site, the excess water must then be discharged into the adjacent landscape, typically a wetland.

At the South Julius operation site, such conditions exist; water must be actively pumped out of the drainage ditches into a neighbouring treed bog and then to a fen. A drainage ditch (2-3 m wide x 400 m long) was constructed within the bog to get the water to the fen. Aerial images (Figure 1) obtained from the site show the trees on the west side of the ditch had died, while the trees on the east side of the ditch remained alive. Why?

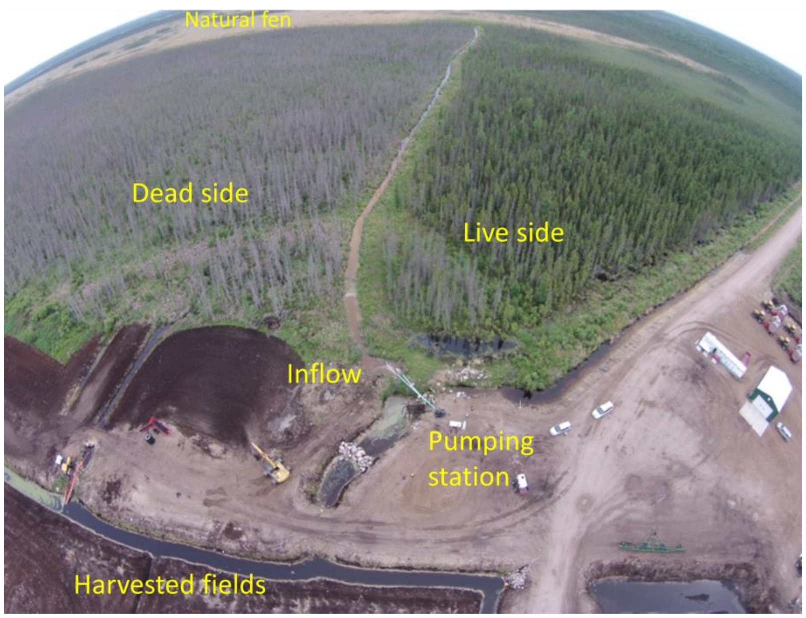

Figure 1. Drone image of the live side to the east and dead side to the west. As well, the pumping station where the water was routed from the fields and into the drainage ditch.

Objectives: The objective of this study was to determine the cause of the death of the trees.

Methodology: An initial walking survey of the site indicated that when the ditch was constructed, the contents (peat, mineral soil) from the ditch were placed on the east side of the ditch, creating a slightly raised berm. We instrumented three transects which were approximately 100 m apart that ran perpendicular to the drainage ditch, starting about 75 m from the beginning of the ditch. On each of the transects, wells were installed on the live (east) side at 2 m, top/middle of the berm, 5 m, 20 m, and 50 m from the edge of the ditch. On the dead (west) side, wells were installed at the edge of the ditch (0 m), 5 m and 20 m from the ditch edge. Situated at the north end of the ditch (nearest the fen) were two wells in the outflow; one in the lagg zone and one in the fen. A well was also placed near the inflow at the south end of the ditch. In total, 28 wells were installed. Water level at wells was measured manually with a blow stick and recorded on a weekly basis from late July to mid-August, with an additional reading at the end of September. A DGPS survey was completed along the three transects.

Results: The berm was ~35 cm higher than the dead side, and ~50 cm higher than the live side within the first 15-20 m (i.e., the dead side was 15 cm higher than the live side). The reason will be discussed below. The average water table depth of the same location (distance from ditch) on the dead side for the three transects was +18 cm, +20 cm and +16 cm for the 0 m, 5 m and 20 m distances, respectively. For the live side average water table depths were -8 cm, 4 cm, 2.7 cm and 0 cm for the 2 m, 5 m, 20 m and 50 m distances, respectively, for the three transects. The average dead side water table for the measurement time period was +18 cm and for the live side -0.5 cm (omitting the 50 m distance so the same distances were compared). The natural fen had an average water table of +13 cm and the lagg area +20 cm.

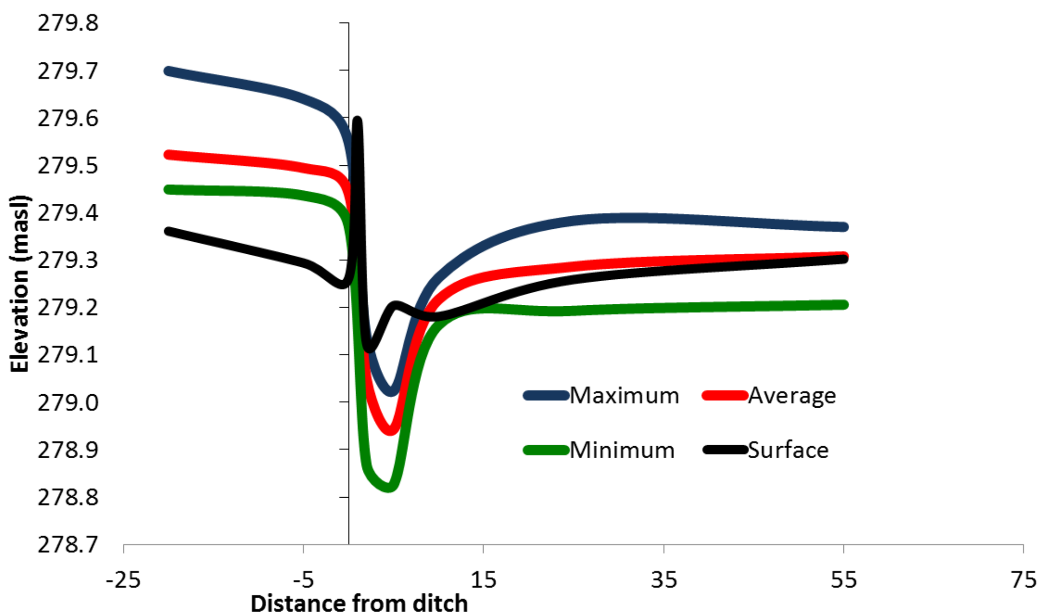

Figure 2. Water tables (coloured lines) and average surface elevation profile (black) from the three transects.

It should be noted that many of the wells on the live side were installed in depressions/hollows, as they represent a slightly more consistent “surface” as the hollows tend to be of similar elevations. Hummocks are quite variable and typically not used as the “surface” during the installation of nests of wells/piezometers. As such, the true average water table is likely much lower (10s of cm) than the -0.5 cm report here, as our measurements are biased towards the low points already.

As noted above, the dead side surface was 15 cm higher than the live side. We speculate that the mass of the berm may have helped deform the bog immediately adjacent to the berm, but also that the flooded conditions on the dead side would lower the effective stress in the peat (due to higher pore water pressure) causing the peat the swell, rising higher than its original surface.

Conclusion: Natural bogs have a lower water table than fens (NWWG 1997), and thus the higher water table on the dead side is likely what is responsible for the death of the trees on that side. There was no obvious sign of insect/disease in tree cores obtained, nor would the 2-3 m wide ditch have been sufficient to stop any outbreak. The berm helped isolate the ditch from the live side, keeping the water from flooding the live side, keeping the trees alive. It is recommended that ditches extending into the natural adjacent bog required for future operations be double bermed (both sides) to isolate the bog from the ditch. The water tables in the lagg/fen were comparable (+13 cm, +20 cm) to the dead side (+18 cm) indicating that the natural fen would have been more than capable of handling the excess water, without significant ill effect to the wetland. Not shown is a second pump further west that also flooded the dead side, but the management suggestions here would equally apply.

References:

National Wetlands Working Group. 1997. The Canadian Wetland Classification System - Second Edition. University of Waterloo, Waterloo, Ontario.

Price J.S., Heathwaite A.L., & Baird A.J. 2003. Hydrological processes in abandoned and restored peatlands: An overview of management approaches. Wetlands Ecology and Management. 11:65-83.

3.11 Effect of restoration actions on water quality at South Julius

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Marie-Claire LeBlanc (Research professionnal, Université Laval)
Line Rochefort (Research co-director, Université Laval)
Pascal Badiou (Ducks Unlimited Canada)

Study site: South Julius peatland

Context: Restoration activities can include profiling the peat surface, removing the existing vegetation, raising the water levels and using phosphorus fertilizer. While the contribution of each of these steps to the restoration method is well defined, little is known about their effect of water chemistry and quality. As suggested in the literature, water chemistry is a reliable indicator of the changes associated with restoration actions (Andersen, Rochefort & Landry 2010; Andersen, Boismenu & Rochefort (submitted 2017)). Within a peatland restoration context, peat chemistry is used to characterize remnant peat conditions, which will define the restoration objectives and targets (ex: fen vs. bog ecosystems).

With this in mind, a protocol to assess the impact of different restoration strategies on water quality was developed in summer 2015. Following the spring 2016 flooding at South Julius, the sampling protocol was modified but still managed to capture the effect of the different restoration options.

Objectives:

1) Characterize the chemistry of the unrestored, post-extraction remnant peat at South Julius
2) Compare the-chemical characteristics of water in restored, unrestored and natural sectors

Methodology: Water samples were collected in wells and drainage ditches at several locations throughout the site before (2015) and after (2016) restoration (see map at appendix B). In 2016, sampling was organized according to the treatments applied on the experimental area (see site description at section 2.1 of this document for details). Water pH and electrical conductivity were measured on site using a portable Hanna Instruments meter. Peat samples were also collected before restoration (2015) to characterize remnant peat conditions. In 2015, samples were collected at specific locations. In 2016 composite sample were collecting along transects through the peatfields (see map at Appendix B). All nutrient content analysis were conducted at Université Laval's Forestry Department laboratory. Results were compared to a national and provincial peatland chemistry database (Andersen, Boismenu & Rochefort (submitted 2017)).

Results: See appendix B for the complete chemistry data and sampling maps.

Peatland characterization: Following peat extraction activities, both the pore water and the remnant peat pH at South Julius were typical of what is observed in Canadian and Manitoba natural fens (Table 1). High EC values observed are probably associated with the extraction history of the sector, which exposes richer fen layers underlying the original bog peat surface. This situation is common in extracted peatlands, as seen in Andersen, Boismenu and Rochefort (submitted 2017), which can lead to restored fens exhibiting higher pH values than natural ones.

Table 1. Water pH and EC mean values (±SD) at South Julius site (pre restoration conditions, 2015) and Canada (and Alaska) and Manitoba natural fens mean values according to Andersen, Boismenu & Rochefort (submitted 2017).

Sector	No. samples	pH		EC (µS)	
Water chemistry					
South Julius Remnant peat	1	6.6		330	
Natural fens – Manitoba	101	6.0	(0.6)	232	(135)
Natural fens – Canada	700	6.3	(0.8)	177	(177)
Peat extracted peatlands – Canada	158	4.9	(0.8)	293	(152)
Peat chemistry					
South Julius Remnant peat	7	5.2	(0.4)		
Natural fens – Canada	504	5.3	(1.2)		
Natural fens – Manitoba	4	5.3	(0.8)		

Water nutrient loading following restoration: When comparing the water chemistry in the control (unrestored) and restored sectors, the most striking difference is that pH was always higher, and N-P-K always considerably lower when restoration actions are performed, regardless of the treatment (Table 2). Still, the effect of the restoration actions on the 1 year Rewetted sector seems to be attenuated, which could be due to the unusually high water level recorded in 2016. Finally, values observed in restored sectors are also similar to natural adjacent fen conditions.

Table 2. Water chemistry mean values (±SD) at South Julius site (in control, restored and natural fen sectors) after restoration (2016).

Sector	Nb samples	pH		EC (µS)		K mg l^{-1}		N/NH_4^+ mg l^{-1}		N/NO_3^- mg l-1		P total mg l^{-1}	
Control	5	6,2	(0,2)	334	(61)	4,7	(1,8)	1,91	(1,45)	0,204	(0,348)	0,40	(0,43)
1 year Rewetted Not Reprofiled	5	6,5	(0,2)	424	(143)	3,5	(0,4)	0,44	(0,50)	0,029	(0,009)	0,16	(0,17)
1 year Rewetted & Reprofiled	8	7,9	(0,5)	231	(44)	1,2	(0,6)	0,04	(0,02)	0,021	(0,012)	0,10	(0,03)
10 years Rewetted	5	7,5	(0,2)	259	(35)	0,8	(0,4)	0,04	(0,03)	0,012	(0,005)	0,14	(0,01)
Natural Graminoid fen	4	7,1	(0,5)	270	(42)	0,5	(0,2)	0,02	(0,01)	0,008	(0,005)	0,16	(0,01)
Natural Shrubby fen	4	7,3	(0,3)	360	(63)	1,2	(0,6)	0,01	(0,01)	0,014	(0,006)	0,11	(0,04)

Conclusion: Characterizing the remnant peat conditions of extracted sites is essential to correctly define the restoration goals to pursue. In this case, the South Julius site clearly showed minerotrophic peatland conditions, which confirms and justifies the need to restore toward this type of environment. As soon as the first year following the restoration actions, the effect of rewetting and / or refreshing the peatland surface became visible in the water nutrient loading of the site. However, results can differ depending on the treatment applied and the time since the restoration work was completed. This experience highlights the potential of peatland restoration on the water quality of the surrounding watershed. Additionally, it also stresses the need for more research and better knowledge about the impact of the restoration actions on water chemistry and quality. This information is definitely part of best peatlands management practices and could lead to more precise, focussed water monitoring of the peatland industry activities.

References:

Andersen R., Rochefort L. & Landry J. 2011. La chimie des tourbières du Québec : une synthèse de 30 années de données. Le Naturaliste canadien 135(1): 5-14.

Andersen R., Boismenu C. & Rochefort L. (Submitted 2017). A reference system for peat and water chemistry in peatlands of Canada and Alaska. Botany.

4. Conclusion

Fen restoration in North America really is in its early stage. The recognition of fen restoration as a valid and valuable restoration option for extracted peatlands is a major breakthrough for the development of best management practices and peatland ecology science. The restoration targets, the techniques to apply, the outcomes to expect (especially on carbon balance), are still to be further developed and examined. However, the research conducted in the last few years has considerably enhanced our knowledge about these ecosystems and how to best manage them.

Realising the important contribution of rewetting actions alone, without introduction of plant material, to the regeneration of typical fen plant communities, has been among the recent findings. For certain remnant peat surfaces, this method is probably the most efficient one to apply and could possibly lead to the return of fen communities and ecosystem functions. For example, at Moss Spur, the extensive, spontaneously established *Scirpus cyperinus* communities were particularly diverse, which indicates that its presence should be seen positively in the restoration process. At the same site, research concluded that the presence of groundwater resurgences strongly influences the peatland surface conditions, thus the composition and trajectory of the vegetation recovery on site.

When comparing the carbon balance between restored and unmanaged extracted sites, it also seems like rewetting should be encouraged to restore the carbon sequestration functions of peatlands. Our results have shown that carbon exchange can be returned to rates similar to natural fens in the region within a decade. Nevertheless, significant methane emissions can result from flooding, standing water and certain vegetation communities. The effect of vegetation types, water levels, weather conditions and other site characteristics have to be taken into consideration when evaluating carbon exchanges on restored sites. Deep flooding should be avoided as it limits revegetation and can lead to high levels of greenhouse gas emission, in particular CH_4, but possibly also N_2O. Precise and careful management of these sites is therefore needed.

Unlike the Québec and New Brunswick sites where peatland restoration methods were developed, in Manitoba, the shorter snowmelt period in the spring brings new challenges to restoration. Furthermore, as fens are, by definition, fed by the surrounding landscape's water flow, the water management on site has to be approached with a longer term and larger scale vision. The flooding at the South Julius site illustrates how tricky rewetting areas within actively extracted sites can be and careful consideration of the existing drainage network capacity is needed to ensure successful rewetting and maintenance of operations. In Elma North, contouring strategies to enhance water retention on site have been developed and should be part of the restoration plans whenever possible. Similarly, the return of the eco-hydrological connection between the restored and adjacent natural adjacent ecosystems should now be included in the post-extraction management plans.

Understanding the processes taking place in natural fens should be a major focus for the development of best management practices for peatlands. A solid understanding of the pristine ecosystems found in undisturbed environments is a key to developing sound and efficient restoration projects, and to subsequently evaluate their success. Restoration actions should aim at the return of the carbon exchanges naturally found in peatlands. Studying these within undisturbed conditions may help define and prescribe the best restoration actions to perform.

The refinement of fen restoration techniques specifically addressing conditions found in Manitoba is certainly needed in the upcoming years. Optimal fertilization strategies as well as ideal rewetting techniques (over up to 5 years) still have to be determined. The role of groundwater upwelling in defining and creating nutrient-rich conditions should also be investigated. The development of restoration methods to include several types of wetlands (fens, bogs, laggs, marshes…) in sites presenting multiple remnant peat and surface conditions is also of importance. Cost-effective methods to create particular habitats (ponds for waterfowl, coverage for insects and amphibians…) should also be tested.

The research conducted so far provides some initial data on peatland after-use in Manitoba, but conclusions are limited by the short duration of the studies. Peatland carbon exchange is known to vary greatly between years due to different weather conditions. The research was conducted during a very wet period, with only one growing season of data for each site. Similarly, the hydrological data collected in the past two years do not represent the regular "drought prone prairies" conditions. Longer term studies are needed to evaluate function of the restored ecosystems across a range of conditions and the resilience of these systems to disturbance.

A topic that should be further investigated to develop the best management practices for Manitoba peatlands is the understanding the effect of different stages of peatland activities (from bog opening to peat extraction and the various following restoration options) on water quality and nutrient export. A large-scale entire-ecosystem research station would provide unique and well-needed opportunities to conduct research on nutrient cycling and export and to assess the impact of peatland restoration efforts.

Appendix A – List of plant species found at South Julius (2016)

List of the species and their mean cover[1] and preferential habitat[2] in each sector of South Julius peatland. Cover of "+" indicates that the species was present with a mean cover lower than 1%.

Vascular species	Preferential habitat	Vegetation cover (%) in each sector			
		Unrestored	1-year-rewetted-not-profiled		10-years-rewetted
			Unfertilized	Fertilized	
Trees and shrubs					
Andromeda polifolia var. latifolia	Peatland	0	+	+	+
Betula pumila	Wetland	0	+	+	2
Dasiphora fruticosa	Wetland	0	+	+	1
Populus balsamifera	Wetland	0	1.1	+	0
Populus tremuloides	Generalist	+	+	1.2	0
Rhododendron groenlandicum	Peatland	0	0	0	+
Salix bebbiana	Wetland	0	1.3	1.8	+
Salix discolor	Wetland	0	3.6	5.2	1.3
Salix pellita	Wetland	0	0	0	+
Salix serissima	Wetland	0	1.8	1.6	+
Vaccinium oxycoccos	Peatland	0	+	+	+
Herbaceous					
Agrostis scabra	Generalist	3.7	2	1.4	0
Alopecurus aequalis	Wetland	0	+	0	0
Bidens cernua	Wetland	1.2	+	1	0
Calamagrostis stricta	Peatland	0	+	+	2
Campanula aparinoides	Wetland	0	0	0	+
Carex aquatilis	Wetland	+	+	1.3	3.9
Carex aurea	Wetland	0	0	0	+
Carex interior	Peatland	+	2.6	1.8	+
Carex lasiocarpa	Peatland	1	1.3	2.7	10.6
Carex leptalea	Peatland	0	1.1	0	+
Carex tenuiflora	Peatland	0	1.3	2.8	+
Carex trisperma	Wetland	+	1.3	1.5	0
Cirsium arvense	Ruderal	1	+	0	0
Cirsium discolor	Ruderal	+	+	1.2	0

[1] For vegetation survey method, see González E. & Rochefort L. 2014. Drivers of success in 53 cutover bogs restored by a moss layer transfer technique. Ecological Engineering 68: 279-290.

[2] Preferential habitat of vascular species was attributed according to Boivin *et al*. (2012), Mackenzie & Moran (2004), Marie *et al*. (2002), MDDEP (2008), Payette & Rochefort (2001) and USDA PLANTS database. Habitat preference for moss species was attributed according to Flora of North America (1993+), Mackenzie & Moran (2004) and Payette & Rochefort (2001).

Vascular species	Preferential habitat	Vegetation cover (%) in each sector			
		Unrestored	1-year-rewetted-not-profiled		10-years-rewetted
			Unfertilized	Fertilized	
Comarum palustre	Wetland	0	0	0	+
Drosera rotundifolia	Peatland	0	+	+	+
Epilobium ciliatum	Peatland	1	+	+	+
Equisetum fluviatile	Wetland	+	+	+	+
Euthamia graminifolia	Generalist	+	+	+	+
Fragaria vesca	Generalist	+	+	+	0
Glyceria melicaria	Wetland	0	0	0	+
Hordeum jubatum	Generalist	3.7	+	+	0
Juncus brevicaudatus	Wetland	0	1	+	0
Juncus bufonius	Wetland	0	+	0	0
Juncus nodosus	Wetland	0	+	+	0
Lactuca serriola	Ruderal	+	+	+	+
Lemna minor	Wetland	0	+	0	0
Lobelia kalmii	Wetland	0	+	0	+
Lysimachia thyrsiflora	Wetland	0	0	0	+
Maianthemum trifolium	Wetland	0	0	0	+
Menyanthes trifoliata	Wetland	0	0	0	1.3
Muhlenbergia glomerata	Wetland	0	0	0	+
Parnassia palustris	Wetland	0	0	0	+
Poa sp.	NA	+	4.5	10.4	0
Rhynchospora alba	Peatland	0	+	0	0
Rorippa palustris	Wetland	+	+	+	0
Rubus arcticus	Wetland	0	0	0	+
Scirpus cyperinus	Wetland	0	1	+	0
Trichophorum alpinum	Peatland	0	+	0	+
Typha sp.	Wetland	+	+	+	1
Utricularia intermedia	Peatland	0	0	0	+
Mosses					
Aulacomnium palustre	Peatland	+	+	+	+
Bryum pseudotriquetrum	Generalist	+	+	2.2	1.7
Campylium stellatum	Peatland	0	0	0	6.4
Fissidens adianthoides	Peatland	0	0	0	+
Hypnum lindbergii	Generalist	0	0	0	+
Plagiomnium ellipticum	Peatland	0	0	0	+
Pleurozium schreberi	Generalist	0	0	0	+
Polytrichastrum longisetum	Peatland	+	0	+	0
Polytrichum strictum	Peatland	0	+	0	+
Scorpidium cossonii	Peatland	0	0	0	1
Tomenthypnum nitens	Peatland	0	0	0	+

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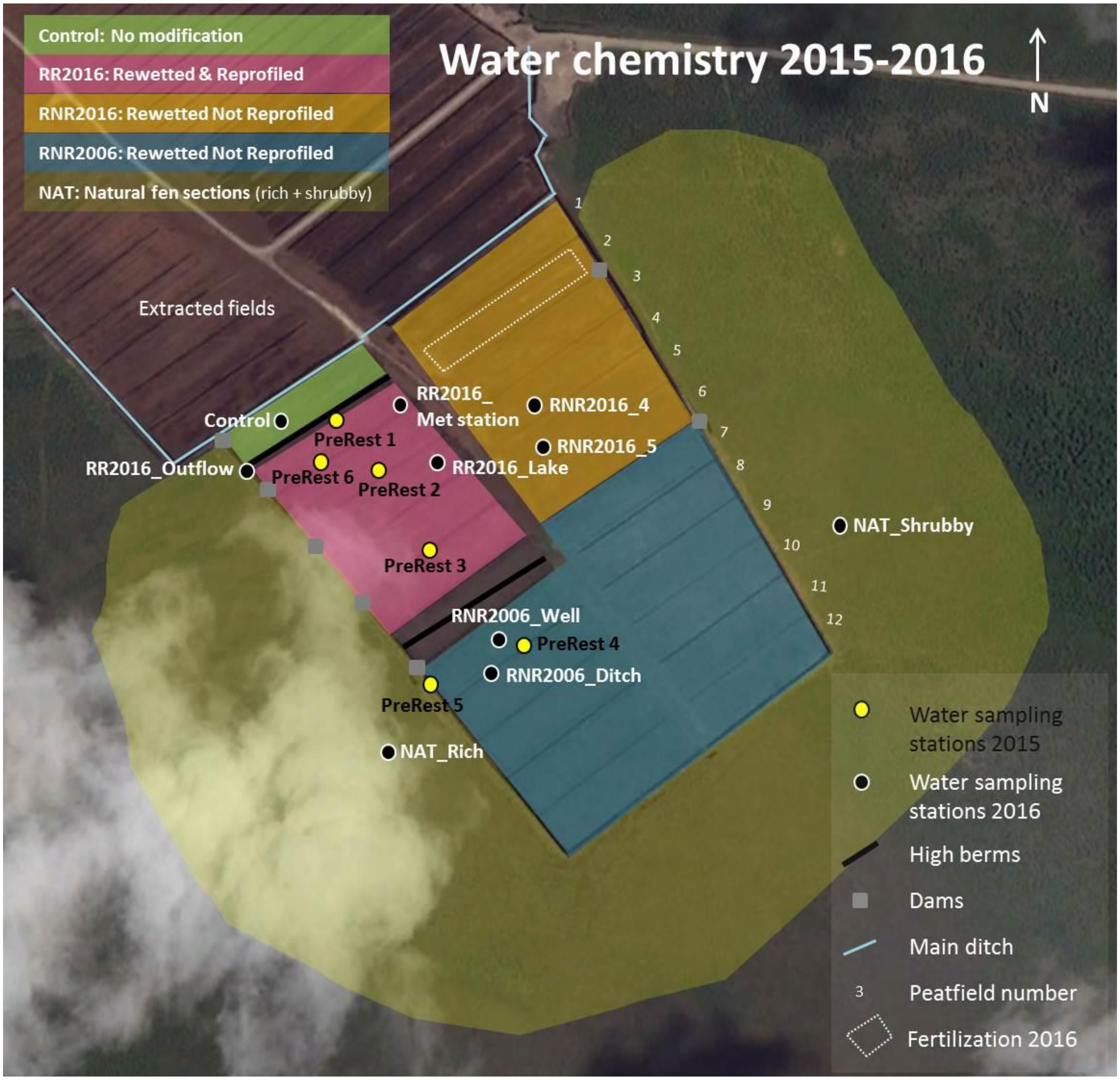
Appendix B – Water chemistry at South Julius (2015-2016)

Mean (S.D.)

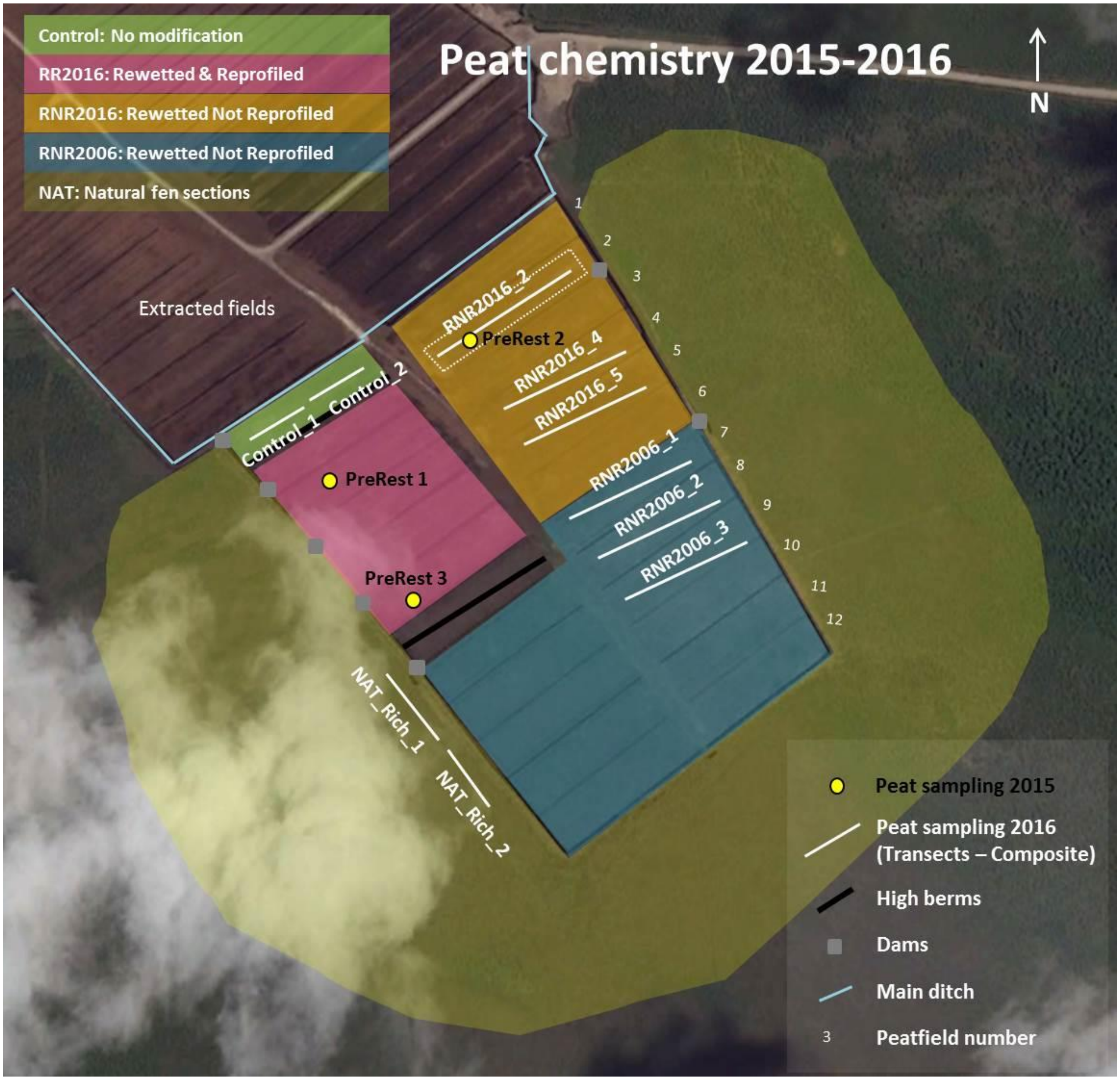
WATER CHEMISTRY	Sector	No samples	pH		EC (µS)		Ca mg l^{-1}		Mg mg l^{-1}		Na mg l^{-1}		K mg l^{-1}		N/NH_4^+ mg l^{-1}		N/NO_3^- mg l^{-1}		P total mg l^{-1}		PO_4^{3-} mg l^{-1}	
2015 PRE RESTORATION	10 years Rewetted	1																	0,44			
	1 year Rewetted & Reprofiled*	4	6,6		330														0,11	(0,05)		
	Natural Graminoid fen	1																	0,86			
2016 POST RESTORATION	Control	5	6,2	(0,2)	334	(61)	35,7	(7,2)	14,7	(3,6)	2,07	(0,40)	4,73	(1,82)	1,91	(1,45)	0,20	(0,35)	0,40	(0,43)	0,45	(0,29)
	10 years Rewetted	5	7,5	(0,2)	259	(35)	33,9	(6,1)	12,2	(1,3)	1,45	(0,26)	0,81	(0,36)	0,04	(0,03)	0,01	(0,00)	0,14	(0,01)	0,10	(0,09)
	1 year Rewetted Not Reprofiled	5	6,5	(0,2)	424	(143)	47,5	(15,4)	19,9	(5,1)	3,38	(2,17)	3,47	(0,37)	0,44	(0,50)	0,03	(0,01)	0,16	(0,17)	0,13	(0,20)
	1 year Rewetted & Reprofiled	8	7,9	(0,5)	231	(44)	26,5	(4,8)	11,6	(2,1)	1,30	(0,24)	1,21	(0,55)	0,04	(0,02)	0,02	(0,01)	0,10	(0,03)	0,01	(0,01)
	Natural Graminoid fen	4	7,1	(0,5)	270	(42)	33,1	(7,9)	12,2	(1,4)	1,33	(0,22)	0,45	(0,18)	0,02	(0,01)	0,01	(0,01)	0,16	(0,01)	0,01	(0,02)
	Natural Shrubby fen	4	7,3	(0,3)	360	(63)	42,6	(14,4)	18,4	(10,6)	3,12	(1,11)	1,19	(0,65)	0,01	(0,01)	0,01	(0,01)	0,11	(0,04)	0,00	(0,01)

PEAT CHEMISTRY	Sector	No samples	pH		EC (µS)		Ca mg g^{-1}		Mg mg g^{-1}		Na mg g^{-1}		K mg g^{-1}		N/NH_4^+ mg g^{-1}		NO_3^- mg g^{-1}		P mg g^{-1} (available)	
2015 PRE RESTO	1 year Rewetted Not Reprofiled	1	4,7																	
	1 year Rewetted & Reprofiled	6	5,2	(0,4)																
2016 POST RESTORATION	Control	2	6,3	(1,5)	224	(136)	18,8	(8,8)	2,4	(0,5)	0,05	(0,01)	0,19	(0,06)	0,04	(0,01)	0,12	(0,07)	0,04	(0,01)
	Natural Graminoid fen	2	6,7	(0,1)	137	(25)	15,8	(0,9)	1,7	(0,1)	0,07	(0,04)	0,63	(0,27)	0,07	(0,01)	0,06	(0,01)	0,03	(0,01)
	10 years Rewetted	3	6,7	(0,2)	123	(57)	24,8	(0,7)	2,5	(0,4)	0,04	(0,01)	0,39	(0,11)	0,06	(0,01)	0,04	(0,01)	0,05	(0,01)
	1 year Rewetted Not Reprofiled	3	6,0	(0,4)	101	(20)	16,1	(2,8)	2,6	(0,5)	0,04	(0,01)	0,14	(0,01)	0,04	(0,00)	0,05	(0,03)	0,02	(0,01)

Sampling locations – Water chemistry at South Julius peatland



Sampling locations – Peat chemistry at South Julius peatland



Appendix C – Félix Gagnon's thesis

(see document *Appendix C_Thesis Félix Gagnon 2016.pdf*)